Chapter 29 Safety Considerations in the Ground Environment

29.1 Introduction

In the history of humankind, every great space adventure has begun on the ground. While this seems to be stating the obvious, mission and spacecraft designers who have overlooked this fact have paid a high price, either in loss or damage to the spacecraft pre-launch, or in mission failure or reduction. Spacecraft personnel may risk not only their flight hardware, but they may also risk their lives, their co-workers lives and even the general public by not heeding safety on the ground. Their eyes may be on the stars but their feet are on the ground!

One additional comment: Although the design requirements are very different for human rated and non-human rated flight hardware, while on the ground that flight hardware (and its ground support equipment) doesn't care about what it is flying on. On the ground, additional requirements are often levied to protect the work force and general public.

(Authors' Note: The source material for this chapter is primarily taken from the Kennedy Space Center Handbook (KHB) 1700.7/45 SW Handbook S-100 Space Shuttle Payload Ground Safety Handbook and the authors' personal experiences.)

29.2 Scope

The scope of this chapter covers safety considerations while performing flight hardware operations in the ground environment both pre-launch and post-flight. While there are no ground safety requirements unique to just the return of a spacecraft, personnel must apply the same care and precautions as they do pre-launch.

This chapter is not intended to cover launch vehicles. While many, if not all of the principles to be discussed here may be applicable, launch vehicles by their very nature operate in a consistent environment and in order to control costs, depend very much on common configurations and stable processes. On the other hand, spacecraft tend to be unique with variation from spacecraft to spacecraft, usually dependent on mission specifications.

The principles covered in this chapter are not intended to be all inclusive but are general in nature. They are also to be considered generic; that is, they are not meant to contradict specific requirements at any particular ground processing site. All flight hardware designers and operators are required to be cognizant of the requirements of the site where they are operating.

29.3 A Word about Ground Support Equipment (GSE)

In the broadest definition of GSE, it is that equipment related to the flight hardware that does not fly. Throughout the world, there are numerous names associated with GSE – Test Equipment, Factory Equipment, etc.; but they all mean the same.

GSE generally is designed and operated in accordance with the national laws of country that produces it. While there is great commonality across the world, GSE will be beyond the scope of this chapter. Personnel are urged to open the lines of communications as early as possible with the appropriate authorities in order to ascertain the correct requirements for their GSE.

29.4 A Word about Documentation and Reviews

While the processing of the flight hardware is the primary focus, safety documentation and reviews are an essential part of the safety process. Safety documentation and reviews provide the assurance that safety considerations have been identified, incorporated and verified in the hardware and facility design and operations. Safety reviews and documentation report the compliance to safety requirements, and assessments performed to identify the risk to personnel, resources and/or mission, and the proposed or actual steps to mitigate the risk to an acceptable level.

The reviews and documentation are typically linked to major program milestones and are presented to program management, processing and launch complex operators, and sponsoring agencies for approval. Complexity of the documentation and required submittal dates and process will vary with the mission. Early contact with the approving authorities is recommended to establish an understanding of applicable requirements and their expectations.

29.5 Roles and Responsibilities

Integration and eventual launch of flight hardware requires the coordination of numerous personnel from a variety of organizations working with supporting equipment and ground infrastructure. The efforts of the mission team may require work with hazardous materials or in a hazardous environment, either as part of their own activities, or in conjunction with integrated activities.

A hardware provider is responsible for providing safe systems, equipment, facilities and materials and conducting operations in a manner that complies with established safety requirements. They are also responsible for the preparation, coordination and certification of documentation that provides assurance that their employees, other launch site personnel, and the general public are not exposed to unacceptable risk.

Employers are responsible for the safety of their personnel. Final authority and safety at the launch site rests with the range, who ensures that operations at the range are reviewed coordinated and approved to ensure range and public safety.

29.6 Contingency Planning

Even with the best design, implementation and planning, an unexpected event may occur that will challenge the best engineering team. Consideration for contingencies early in the design will aid in expediting a solution to ensure safety, and minimize the impact to hardware, schedule or cost.

Planning for a contingency falls in two major areas. Programmatic plans are developed to respond to non-operational events typically beyond a program's control, such as earthquakes, hurricanes, electrical power interruptions, or even labor disputes resulting in lengthy launch delays. Contingency plans are also developed for responding to anomalies or emergencies that may occur during ground operations such as propellant leaks or spills, or emergency power-up or down of hardware. Hardware designs should support the implementation of these plans, providing features such as accessibility to service points such as pressurant and propellant service valves, calibration requirements, battery charging, installation and removal of protective and contamination covers, and access to safing plugs to render ordnance systems safe. All operational plans should include back-out steps to safe hardware if an unintended event occurs during processing. In addition, operational capability should be addressed for limited life items, such as battery reconditioning or replacement.

29.7 Failure Tolerance

Failure tolerance in the flight hardware during ground operations is very much dependent on the failure tolerance methods used to protect the hardware on orbit. However the opportunity for human error is much greater on the ground, if only from the fact that the flight hardware can be physically accessed. This scenario is particularly true during troubleshooting. When planning spacecraft ground processing, designers must include in their analyses the interaction between the flight hardware, GSE, ground facilities, and operators. During troubleshooting, inhibits and controls often have to be removed to uncover or to test anomalies. If the processing team fails to properly plan its troubleshooting steps or monitor the test, catastrophic results can occur from the removal of too many controls. A suggested method for tracking inhibits or controls would be to place them in a matrix, where they are visible and available to the test planners. This can also serve as an aid when seeking approval for the test from local approving authorities.

29.8 Training

Employers should ensure that their employees receive adequate training for the activities they perform and knowledge of the potential exposure to hazards. Certification may be required for certain specialized tasks such as crane operations, propellant, and ordnance handlers; government, corporate and local operating requirements may vary.

Personnel shall also be trained for identifying and responding to the hazards they may encounter in the work area. This would include precautions in working with hazardous materials that may be present, personnel protective equipment required and its use, location of emergency equipment and procedures, reporting of emergencies and responding to alarms, and the location and use of emergency equipment and first aid techniques.

Personnel training should include the use of safety processes such as the lock out and tagout of equipment to prevent inadvertent energizing. Pathfinder operations conducted to enhance operational familiarization and respond to emergencies should be included in operational training requirements.

29.9 Hazardous Operations

When operating in the ground environment, the operator must keep in mind the presence of personnel and other high value hardware; as well as the facility. Spacecraft operations while on orbit can have devastating effects on the ground. For instance, the ignition of an upper stage or thruster may have minimal external effect on orbit; but, on the ground the same operation could be deadly. There are situations, were the inherent fault tolerance of a system must be compromised, or very nearly so, to achieve the validation of system operation prior to launch. There are also hazards associated with normal servicing, such as with fluids or gases. Because of these situations, the prudent operator will designate these occasions as hazardous.

The designation of which operations are hazardous are derived from hazard analyses or the requirements of the processing facility/area. In the case of hazard analyses, the designation of an operation as hazardous can be a hazard control. Processing facility requirements are often the culmination of years of experience with many of the requirements the result of accidents or near misses.

When conducting operations on the ground, whether hazardous or non-hazardous, the key to success is centered on having written step-by-step procedures as well as a structured process for their development. Well-written and well-coordinated procedures serve multiple purposes. These include assurance that the test team and support organizations are aware of the procedure, hazard controls are documented and in the correct location relative to the hazard and providing a written record of the actual test in the event of problems later in processing. The importance of written procedures can not be understated.

When planning ground operations, conducting concurrent hazardous operations is not considered a good practice. This usually involves overlapping control areas and can lead to confusion among the test team with the possibility of competing priorities.

A well run ground campaign will recognize the hazardous nature of preparing a spacecraft for launch and will have in place the procedural processes to control these hazards in order to protect people, other flight hardware and facilities.

29.10 Tools

Tools are the most essential and overlooked element, but without the proper tools, operational activities could not be performed safely. The tool can be as simple as a screwdriver or complex as computerized test equipment, but improperly selected or used on the job, they may lead to a hazardous condition.

For a hazardous operation, all tools are required to be identified in the hazardous technical operating procedure. The safety review of the procedure would include an assessment of the tools to ensure they are appropriate for the operation, to ensure that another hazardous situation would not be caused by their use, or to ensure that operational support or approval is required as a condition of their use.

While tools obviously are selected to accomplish a task, other criteria may affect their selection or use. For example, working in the vicinity of sensitive instruments may require the use of non-magnetic tools. Tools that generate high temperatures may require 'hot work' permits, special shields or barriers, removal of combustible material, and fire protection equipment.

Electrical test equipment poses additional hazards in addition to grounding concerns and potential exposure to energized electrical circuits. Electrical equipment shall only be used in the environment it is designed for. Operating areas where a potential exists for a propellant leak requires the equipment to be explosion proofed, hazard-proofed, or purged.

Pathfinder operations should be planned to demonstrate the adequacy and function of the tools and equipment for an operation. In this assessment, special attention should be given to areas including ease of use, accessibility, visibility, and personnel protective equipment that may be required for the operation that may impact performance.

Equally important as selecting the appropriate tools is accounting for them. Hand tools should be tethered at all time to prevent a tool from being lost, or accidentally dropped and resulting in hardware damage or personnel injury. A tool control plan should be instituted to ensure that all tools are identified and accounted for. In addition, tools may require segregation to prevent undesired reactions. For example, the same tools used on a hydrazine system should not be used on an oxidizer system.

29.11 Human Factors

Human factors can affect the interface between personnel and the flight hardware. The spacecraft designer must be cognizant of these issues when considering the how the spacecraft will be serviced on the ground. The placement about the spacecraft of servicing panels and connections is critical in avoiding errors leading to accidents. For instance, the placement of a battery connection that requires the technician to stand with his back to the connection point and reach over and behind his head to accomplish the task is fertile ground for an accident (and it was). Some accidents such as this can be prevented by design (in this case, scoop proof connectors); but not always.

The prevention of human error is essential. It is important to design hardware with this in mind. Design is the preferred solution; but procedural controls can be used if necessary. The labeling of equipment controls is critical. When developing procedures for real-time operations or troubleshooting; the interface of personnel with the flight hardware shall be considered. This is especially important is the location of the work is in an area not previously intended for access.

Exposure of personnel to hazardous materials shall be avoided where possible through the implementation of adequate design features, such as redundant seals. In the event this may not be possible or there is active handling of hazardous materials, such as during fueling, personnel shall be provided the appropriate protective gear.

Physical contact with the flight hardware (spacecraft or individual experiment); needs to be accounted for in the design. This includes contact with sharp surfaces or protrusions, rotating surfaces and high or low temperatures. Adequate shielding, barriers, guards, or procedures for moving or removing the items shall be used. Adjustments needed for electrically powered areas are best made with the power off; otherwise, shock protection must be provided.

The interaction of personnel with hardware must be accounted for at all times whether for routine processing or troubleshooting.

29.12 Biological Systems/Materials

Biological systems cover the range from plant growth experiments to human medical experiments. Because the possibilities of injury or potential harmful effects; hardware containing biological material requires special attention. This attention applies to both launch and return.

Although a biological experiment or sample may have a low toxicity on orbit; this doe not necessary translate to the ground environment; especially in the area of sample preparation. A low toxicity material on orbit, like vinegar, will be a higher toxicity when in the form of glacial acetic acid on the ground. The protection of personnel, both on the ground and in flight, is directly linked to the hazard presented by the material.

A special biological system that requires advance planning is trash containing biological material. Special care must be taken when handling this material. Not only the potential presence of biologically active material needs to be considered but also the presence of contaminated physical material such as needles and swabs. It is important that all personnel handling such material be made aware of the contents in order to avoid inadvertent contamination.

Whether in the form of a live virus, a human blood sample or trash, it is the responsibility of the investigator/operator to assure the compliance with all programmatic and legal requirements. A close coordination with the appropriate authorities is required.

29.13 Electrical

Electrical ground support equipment and facilities should be designed to industry consensus standards. Equipment designs should ensure that a connection can not be inadvertently reversed or mated, personnel are provided protection from accidental contact of energized components, and grounding or bonding schemes to ensure that equipment is at ground potential at all times.

Special attention should be placed on battery charging and conditioning operations. Equipment design should incorporate protective devices such as fuses, diodes, and voltage and current limiters, and have temperature and pressure monitoring ability. Continuous monitoring by personnel should occur during charging and conditioning operations.

Frequently, commercial-off-the shelf electrical equipment is utilized to support ground processing operations. This equipment should only be used in accordance with the manufacturer's intent and in the intended environment; any modification or integration with other equipment should be carefully assessed.

In the event that troubleshooting, maintenance, or repair of electrical equipment is required, the activities should be performed in accordance with a documented process, and in accordance with accepted industrial practices. Special precautions are mandatory, such as lockout and tagout of devices to prevent the accidental application of power to equipment undergoing service.

29.14 Radiation

Radiation in the ground environment is classified in two categories– non-ionizing and ionizing. Safety controls are requires for radioactive materials (flight and ground calibration emitting sources), radiation producing equipment, including x-ray devices and RF emitters, lasers, and optical emitters (high intensity light, infrared, etc.). Safety requirements in the ground environment provide specific engineering and operational controls for both types. All radiation sources and associated equipment shall be designed to ensure that personnel exposures and potential for release are as low as reasonably achievable, but not exceeding the applicable regulatory limits.

Flight radioactive sources should be installed as late in the countdown as practical, and be handled only by approved personnel. Radioactive sources not in use should be secured against unauthorized access. Controls should be established to permit access only to authorized personnel, and personnel exposure should be monitored.

Major radiological sources such as radioisotope heater units and radioisotope thermoelectric generators pose a greater risk and have additional requirements. Dedicated processing facilities may be required, with more stringent controls placed on the storage, access, use and operations associated with major sources. Approval for flight requires an increased coordination, with the accompanying analyses, safety assessments, and coordinated contingency planning.

In addition to exposure limits, non-ionizing sources and their controls should be assessed to preclude inadvertent operation. Integrated hazard assessment should also be performed to ensure that RF transmission does not inadvertently affect launch vehicle or spacecraft systems.

Optical and lasers systems require engineering controls including beam stops, limit stops, interlocks and shields. Materials used as targets or subject to exposure should be non-flammable and not emit toxic materials. Appropriate personnel protective equipment should be utilized to protect from hazards associated with specific wavelengths, temperature extremes, and gases.

29.15 Pressure Systems

The design requirements of pressure systems are well defined in other chapters in the book or in other locations. Of greater concern is the operation of these systems on the ground.

An important datum to track is the level that the pressure system has been tested. Each new level of pressurization introduces different stresses to the system. As these pressures are increased, remote pressurization may be required in order to protect personnel.

Special care should be taken to ensure that any venting done by a pressure system, whether planned or unplanned, is done in such a way as to not create a hazardous condition. Also it is good practice to design pressure system connections such that it is physically impossible to mix incompatible fluids such as hypergolic fuels and oxidizers.

The increasing use of composite overwrapped pressure vessels (COPVs) requires special mention. At all times COPVs are very sensitive to impact; but even more so in the ground environment because of the ease of access. It is important that an impact protection plan be developed and adhered to. Compliance with national or local standards is necessary for successful processing.

While on the ground, all pressure systems require the utmost care and respect to avoid immediate or future damages.

29.16 Ordnance

Ordnance devices can vary in size from small hand-held safe devices to larger devices that can initiate a chain of events causing injury or death. Initiation of ordnance devices will occur whether the ignition input is intentional or inadvertent; the low energy inputs provide design advantages but result in potential safety hazards. As these devices cannot be functionally operated, statistical reliability, production controls, and ground processing controls ensure performance and safety.

All ordnance shall be stored as determined by its hazard classification and compatibility. Faraday caps shall be installed on ordnance until electrical connections are made. Ordnance test equipment shall limit the energy input to the device.

Ordnance devices and systems are required to be designed to preclude inadvertent firing when subjected to such environments such as shock, vibration, and static electricity encountered during ground processing. Ordnance circuit, hardware design, and accessibility shall permit circuit interrupts as close to the device and as possible, and connection as late as possible prior to launch.

29.17 Mechanical/Electromechanical Devices

Flight hardware that contains deployment mechanisms must have the necessary controls in place to prevent inadvertent activation. These mechanisms include such items a solar arrays or sample gathering devices. Even if deployment is non-hazardous, controls are highly recommended to assure mission success. Special care must also be taken during troubleshooting or repairs to prevent injury or damage.

29.18 Propellants

Propellants utilized in space vehicles vary in composition, form and reactive properties. A single launch vehicle and spacecraft may include inert Xenon gas, multiple solid rocket motors composed of homogeneous or composite propellants, Aerozine-50, nitrogen tetroxide, RP-1, and liquid oxygen. As each of these materials has distinct physical and reactive properties and the potential for a catastrophic hazard, the safety considerations during ground processing are extensive and result in closely monitored ground operations.

Considerations in the storage, transfer, and handling of propellants include material compatibility of system components, separation from reactive materials, capability to isolate system leaks, and electrostatic properties of materials. Emphasis is also placed on protecting the personnel performing propellant operations or subsequent processing activities with the use of protective garments, toxic vapor detection, venting and scrubbing of vapors, explosion-proofing of electrical equipment, and emergency planning.

An excellent source of information for the properties and hazards of propellants is Chemical Propulsion Information Agency (CPIA) Publication 394, Hazards of Chemical Rockets and Propellants.

29.19 Cryogenics

In general, cryogenic systems must comply with the same requirements as apply to propulsion systems. However, due to their unique physical properties, additional requirements are often levied.

These additional requirements deal with prevention of the inadvertent conversion of liquid to gas and its subsequent pressure rise. The use of pressure relief devices or insulation is required in those parts of the system where this is a possibility. The liquefaction of air must also be taken into account when designing cryogenic systems. Joints in cryogenic systems are recommended to either butt-welded, flanged, bayonet or hub type.

In addition to these requirements, the servicing of flight hardware with cryogenics is subject to the requirements of the processing site.

29.20 Oxygen

Safe design development and operation of oxygen systems require special knowledge and understanding of design practices, materials, the ignition mechanism, manufacturing techniques and operational controls.

Materials that are highly reactive must be avoided, and those less reactive but still flammable should be protected from all ignition sources. Cleanliness of oxygen systems is important; particles could ignite or cause ignition when impacting other components of the system and organic compounds such as hydrocarbon lubricants can ignite easily.

Oxygen systems should be analyzed to ensure leak prevention, adequate ventilation, suitable design of system components and system cleanliness. Systems should be designed with sufficient redundancy to provide adequate fault tolerance to provide for system integrity and personnel safety.

29.21 Ground Handling

In general terms, the handling of flight hardware is enveloped by the need to sustain flight dynamics. This is a truism as long as the dynamics to be experienced on the ground fit the envelope.

Two special cases need to be considered during the design phase. The first involves which attach points will be used during ground handling and the second is accounting for the potential for tip-over. In the first case, if the spacecraft is using its flight attach points for handling, then further analysis is not required. If other points will be used, then the designer must ensure the expected loads are allowable for those points. This is especially important for those spacecraft being launched on a rocket where the loads are transmitted through the base. In the second case, all flight hardware should have a center-of-gravity analysis performed to ensure the hardware does not tip, fall, slide or allow for any type of sudden load shift while be handled on the ground. This should be of particular interest to those pieces of hardware that are lifted from below the center of gravity.

29.22 Software Safety

Software safety assessment is required in the ground processing environment to ensure that flight or ground software does not contribute or cannot cause a hazardous condition from occurring, or alter system(s) configuration to the point where the potential risk of a hazard increases.

Embedded systems can exercise or provide real-time control of a system without any direct user interface. Commands could inadvertently open valves, power transmitters, start sequence timers, allow power to relays, and remove other systems/safety inhibits. The use of mechanical interrupts such as safing plugs, or safe and arm devices, provide a positive verifiable inhibit.

At the highest level, ground safety assessments should ensure that critical commands are identified and adequately blocked from execution. Sufficient independence should exist for software inhibits, and be supplemented by controls such as watchdog timers and improper sequence detectors. Safety critical software should be closely configuration controlled to segregate ground test and flight software.

29.23 Summary

As with life, the preparation for a mission in space is often fraught with as much peril as the journey itself. The preparation for the launch of a spacecraft is a dynamic event with numerous hurdles to overcome. The return of a spacecraft or experiment can also be perilous as the mission team may let its guard down because, after all, isn't the mission over? The mission team that can focus on and clear these hurdles is well on the way to a successful mission.