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Guidelines for Developing Spacecraft Structural Requirements; A Thermal and Environmental Perspective

Jon Holladay
NASA – Marshall Space Flight Center

Greg Day
The Boeing Company

Larry Gill
Carleton Technologies

ABSTRACT

Spacecraft are typically designed with a primary focus on weight in order to meet launch vehicle performance parameters. However, for pressurized and/or man-rated spacecraft, it is also necessary to have an understanding of the vehicle operating environments to properly size the pressure vessel. Proper sizing of the pressure vessel requires an understanding of the space vehicle's life cycle and compares the physical design optimization (weight and launch "cost") to downstream operational complexity and total life cycle cost. This paper will provide an overview of some major environmental design drivers and provide examples for calculating the optimal design pressure versus a selected set of design parameters related to thermal and environmental perspectives. In addition, this paper will provide a generic set of cracking pressures for both positive and negative pressure relief valves that encompasses worst case environmental effects for a variety of launch / landing sites. Finally, several examples are included to highlight pressure relief set points and vehicle weight impacts for a selected set of orbital missions.

INTRODUCTION

The first step in the development of design requirements for the spacecraft pressurized cabin is an understanding of the mission requirements and the operations concept for the vehicle. This understanding is critical to identifying the key design drivers, establishing a comprehensive set of trade studies, and applying the appropriate design margins in order to obtain the most efficient design. For most man-rated vehicles, this implies a special emphasis on safety starting with the design requirements, continuing through the design process, persisting through the hardware performance testing, and including the eventual operations and flight support.

DESIGN MARGINS

A pressure vessel is defined per MIL-STD-1522 as a container designed primarily for the storage of pressurized fluids and which (1) contains stored energy of 14,240 foot-pounds or greater, based on the adiabatic expansion of a perfect gas, (2) contains gas or liquid which will create a mishap (accident) if released, or (3) will experience a Maximum Expected Operating Pressure (MEOP) greater than 100 psia. Typically pressure vessels are manufactured from metallic or composite materials and are required to be Leak Before Burst (LBB). LBB is a design concept in which potentially critical flaws will grow through the wall of the pressurized hardware and cause pressure relieving leakage rather than eventually rupturing the pressure vessel in a catastrophic fashion. For NASA vehicles as defined in NSTS 1700.7B, the MEOP, also called Maximum Design Pressure (MDP), is determined by evaluating the system and applying the worst two credible failures. For instance, a system that nominally does not exceed 100 psia may experience two failures (i.e. a failed-on heater and a failed-closed pressure relief valve) that force the system to a much higher pressure. Any safety margins are then applied to the pressure experienced in the two-fault failure scenario. Unless otherwise defined, the applied design burst factor is a minimum of 1.5, and will be followed by a thorough non-destructive inspection. For manned flight vehicles which are normally; high cost, low cycle, single application, qualification of the design to burst pressure, or qualification, is typically not required. Testing however is required greater than or equal to 2.0 for both the MDP and maximum negative pressure differential to which the hull will be exposed for normal and contingency operations or as a result of two credible failures. When performing qualification the yield strength of the hardware can be exceeded. In all cases habitable volumes should be designed to LBB criteria.

It should be noted that this discussion is intended to familiarize the reader with safety considerations for hardware development, and as such, should not be used as a reference for hardware certification. MIL-STD-1522A and NSTS 1700.7B are the typical references utilized for NASA for man-rated vehicles and associated structures.

PRESSURE RELIEF HARDWARE DESCRIPTION

The pressure shell of a manned spacecraft must be structurally designed to withstand differential pressure differences in both the positive and negative directions. Figure 1 provides the standard convention for defining positive and negative pressures. As shown, positive pressure relief valves are used to prevent an over-pressurization of the pressure shell. Negative pressure relief valves are used to prevent high external pressures from crushing the module. Control of the pressure differential across the vehicle pressure shell is obtained by utilizing pressure control hardware. This hardware can be a simple burst disc where there is a low probability of needing pressure relief and/or it is not critical if the volume is accidentally vented. Since burst disks are irreversible, they are not typically used in a stand-alone fashion or for manned spaceflight. Typically valves are utilized as a method of limiting the pressure differential across the structure, and valve cracking pressures must be based on hardware structural capabilities, valve throughput, valve redundancy, and expected pressure differentials.

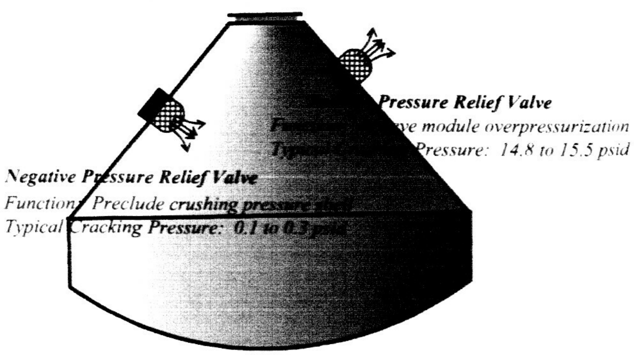


Figure 1: Description of Pressure Relief Valves

NEGATIVE PRESSURE RELIEF VALVES

The function of the Negative Pressure Relief Valve (NPRV) is to prevent the build up of an excessive negative pressure differential across the vehicle's hull that might lead to structural collapse. Such a situation might occur during ground operations or reentry, where the internal pressure has fallen below that of ground ambient. Typically, the cracking and reseat pressures for NPRVs are in the 0.1 to 0.3 psid range.

The valve design pictured in Figure 2 is based on a classic direct acting, spring loaded poppet configuration. The poppet is cone shaped with an integral shaft and a molded silicone seal in place around the rim of the cone. For redundancy, it includes an overall cover which counters the risk of cabin pressure loss should the poppet develop a leak. The cover deploys automatically when conditions require the valve to flow. An inlet debris screen is built into the inlet side of the unit to prevent debris located outside the cabin from entering the valve and inhibiting its sealing action.

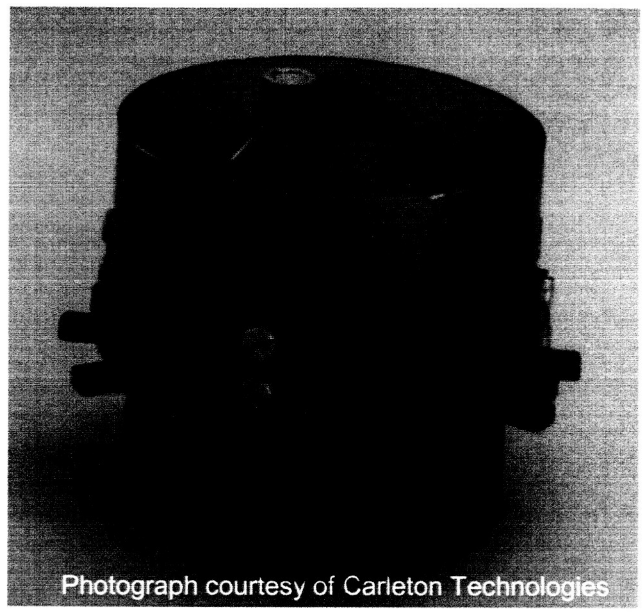


Figure 2: Typical NPRV Design

POSITIVE PRESSURE RELIEF VALVES

The function of the Positive Pressure Relief Valve (PPRV) is to prevent the build up of an excessive pressure differential across the vehicle's hull that might lead to rupture (burst). Such a situation can occur when compressed gas is released into the vehicle's cabin or during a fire in the cabin. Typically, the cracking and reseat pressures for PPRVs are in the 14.8 to 15.5 psid range.

The item pictured on the left in Figure 3 is a sophisticated mechanical relief valve which employs an independent pressure sensing diaphragm and a poppet which is pressure compensated by a bellows. It also incorporates an electrically operated butterfly valve which is used to pneumatically isolate the relief valve. The butterfly valve itself has a manual override, the handle to which can be seen in the photo. This unit is mounted on the interior side of the cabin pressure bulkhead. The cylindrical device, pictured on the right in Figure 3 is a non-thrusting vent for the relief valve which is mounted externally.

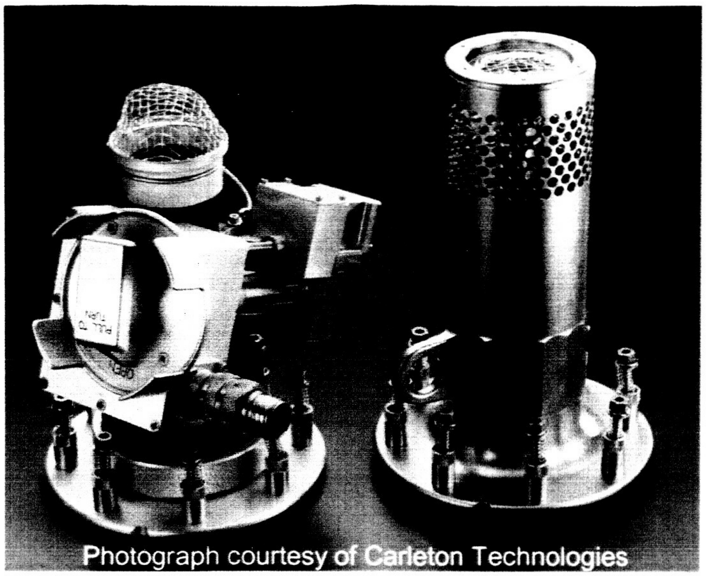


Figure 3: Typical PPRV Design

TYPICAL MANNED MISSION SCENARIOS

During the on-orbit mission phases when the external pressure falls to zero, the positive pressure differentials are maximized. Conversely, the ground operations phases present the highest negative differential pressures due to the ambient temperature and pressure effects. This information is graphically displayed in Figure 4. For recent manned spacecraft (Shuttle, ISS, MIR), the spacecraft internal atmospheric pressure has been nominally maintained at 14.7 ± 0.2 psia.

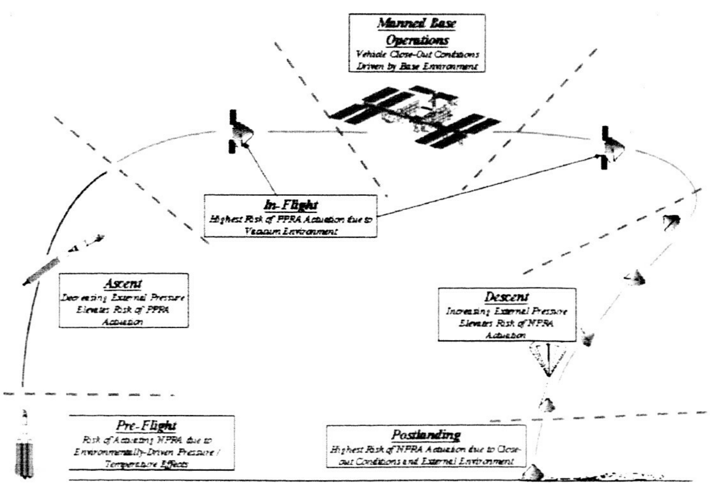


Figure 4: Differential Pressure by Mission Phase

VEHICLE ENVIRONMENTS

Each of the mission phases from prelaunch through post-mission recovery has associated temperature and pressure ranges which must be factored into the overall vehicle design. Initially, ground operations and their effect on NPRVs will be discussed (PPRVs will not crack during ground operations), and then the orbital mission phases and their effects on PPRVs will be presented (NPRVs will not actuate during orbital operations).

GROUND OPERATIONS AND NPRVS - Ambient conditions at the launch and landing sites need to be considered in the design of pressurized compartments. At the launch site, once the pressurized compartment is closed out and sealed, external conditions (facility or ambient) will dictate the differential pressure across the module pressure shell. Following landing, manned vehicle are typically vented fairly rapidly to support crew retrieval. Access to unmanned vehicle can either be fairly rapid or quite lengthy.

Ambient weather conditions at a variety of locations were researched to provide a spectrum of environmental conditions. In order to bracket typical continental United States (CONUS) conditions, weather conditions at Vandenburg Air Force Base (VAFB), Edwards Air Force Base (EAFB), Kennedy Space Center (KSC), and White Sands Missile Range (WSMR) were evaluated. KSC provides both launch and landing capabilities. Launch pads are typically 16 feet above mean sea level (MSL), and the runway is 9 feet MSL. EAFB, with a runway elevation of 2,302 feet MSL, provides a higher altitude site (with resulting lower ambient pressures) for runway landings. VAFB provides a launch capability for expendable launch vehicles (ELVs) with pad altitudes of 368 feet MSL. Finally, White Sands Missile Range currently provides a landing site at an altitude of 4,239 feet MSL. All of these sites are currently used by NASA or the USAF for Shuttle / ELV launch and landing operations (primary and contingency), so they provide a reasonable bound of expected continental U.S. conditions.

To expand the ambient weather envelope to encompass non-CONUS locations, a Dead Sea location (Sedom, Israel) was considered to bracket extreme altitude conditions. There was no need to examine higher altitude sites since they have lower ambient pressures. The Dead Sea site was included as a hypothetical case as it possesses the lowest altitude on Earth and will be used to illustrate the effects of higher pressure at lower altitude locations. The following table summarizes the temperature and pressure ranges for each of these locations.

Table 2: Environmental Temperature and Pressure

	Altitude	Temperature (°F)		Pressure (psia)	
	(MSL, ft)	Low	High	Low	High
KSC	9	19	99	14.5	15.0

VAFB	368	25	100	14.4	14.8
White Sands	4,239	-14	112	12.4	12.9
EAFB	2,302	4	113	13.3	13.9
Sedom	-1,275	50	102	---	15.7
Ferry Flight	10,000	-13	---	9.86	10.6

<u>Facility Effects</u> – KSC has the capability to tailor the vehicle close-out conditions to obtain specific atmospheric densities and dew points. As an example, the Multi-Purpose Logistics Module (MPLM) is closed out at a pressure slightly higher than ambient to preclude inadvertent negative pressure relief valve actuation due to atmospheric changes. Once the module is closed-out in readiness for flight, then the facility environmental control needs to be examined to ensure that temperature swings will not affect the module hardware. Current Space Station payloads are processed inside the Space Station Processing Facility (SSPF). Per KCI-HB-5340, the SSPF internal temperature is maintained at 71 ± 6°F. In addition, a positive pressure is maintained inside the SSPF to minimize contamination. This slightly elevated pressure ranges provides at least 0.02 inches of water over the external ambient conditions.

<u>Ground Transportation</u> - Payloads are typically transported to the launch pad in conditioned containers to protect them from the effects of ambient temperature swings and localized contamination (salt, sand, water, etc). The container environment is typically over-pressurized to maintain a slight inside-to-outside pressure gradient to minimize contamination (~0.02 inches of water), and fairly tight temperature control is available. Per KCI-HB-5340.1, the transportation handler internal temperature is maintained at approximately 71 ± 6°F. In addition, the internal pressure will be at least 0.02 inches of water over the external ambient conditions. At the launch pad, environmentally-controlled enclosures are typically available to protect payloads during installation on the launch vehicle. For the Space Shuttle program, the Payload Changeout Room (PCR) provides a temperature-controlled environment with the same specification as the SSPF.

<u>Launch Vehicle Purge</u> - Once the pressurized module is installed on the launch vehicle, air or nitrogen purges are typically used to maintain the appropriate temperature levels. The purge is used to offset the effects of the environmental diurnal cycle. For the Space Shuttle payload bay, typical purge parameters include flow rates of 112 to 240 lb_m/hr, temperature ranges from 45 to 100°F, and pressure increases over ambient of up to 0.3 psia. During this time frame, the internal pressure must be maintained high enough to prevent transient external effects from actuating the NPRVs. In the past, payloads trying to maintain a constant temperature have varied the purge temperature as a function of the external environmental temperature. During the day, as the external temperature rises, the internal purge temperature is biased lower; and the internal purge temperature is biased higher during the evening when ambient temperatures decrease.

<u>Postlanding</u> - Following entry through the Earth's atmosphere, the internal conditions are quite different from the prelaunch conditions. The close-out conditions may have changed by docking with an orbital / planetary facility, the on-board pressure control hardware may have been monitoring and adjusting the pressure / temperature, residual soakback heating from the entry phase may impact the internal temperatures, etc. In addition, the reentry heating effects are severe and the external environmental effects are dependent on the landing site location. While there is no protection from the landing site pressure, purges can be applied fairly rapidly (usually within 8 hours of touchdown) at primary and secondary landing sites.

<u>Ferry Flight</u> - Unless the vehicle returns to its launch site, postlanding transportation effects will need to be considered. Air transportation is typically utilized due to the rapid and secure transfer of the vehicle. If rapid payload access is not required after landing, then the module may remain sealed until arrival at an environmentally-controlled facility. The Space Shuttle Program requires up to three days to transport the Shuttle atop the Shuttle Carrier Aircraft (SCA) from a secondary landing site (i.e. Edwards Air Force Base) back to Kennedy Space Center. Figure 5 illustrates the Space Shuttle ferry flight configuration.

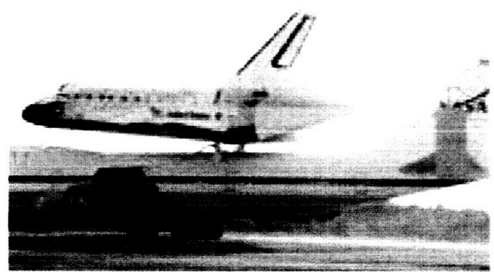


Figure 5: Space Shuttle atop the SCA

Pressurized modules may have specific requirements that require their design be compatible with the temperature and pressure profiles associated with ferry flights from secondary landing sites back to the ground processing facility. Based on Shuttle Carrier Aircraft (SCA), information, flight profiles are typically selected with maximum altitudes of around 10,000 feet to minimize the cold temperature exposure. Table 2 includes typical ferry flight environments.

<u>Summary of Ground Operations and NPRVs</u> - A summary of these various ground operations scenarios is presented in Figure 6. As shown, the largest negative pressure differential occurs during the postlanding

mission phase, when a maximum pressure differential of up to 4.0 psid is possible.

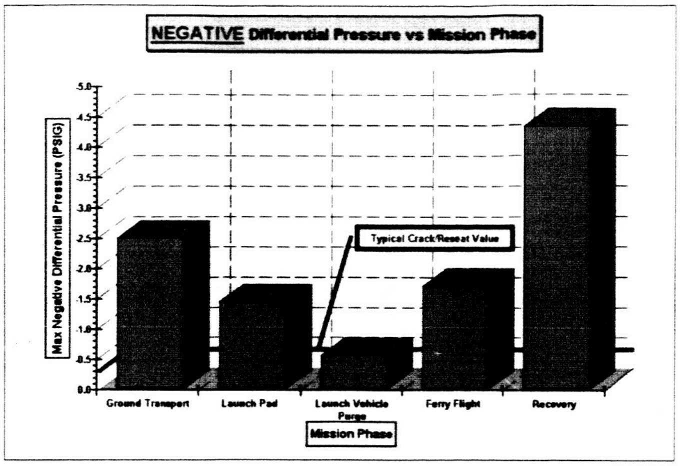


Figure 6: Summary of Pressure Differentials During Ground Operations

ORBITAL OPERATIONS AND PPRVS

On-Orbit Flight - Except for the transient liftoff and return to Earth (if applicable), the external pressure will be essentially zero during this mission phase, so there are no issues with actuating negative pressure relief valves. However, it is during this mission phase where the probability of actuating a positive pressure relief valve is greatest. The external thermal environment can vary over a wide range based on the vehicle optical properties, solar heating, planetary heating, and deep space cooling. Figure 7 demonstrates the temperature excursions of an adiabatic flat plate in a full sun, full space view. The module internal thermal environment is much more benign due to the widespread use of insulation and heaters. Limiting the internal temperature swings also effectively limits the pressure fluctuations.

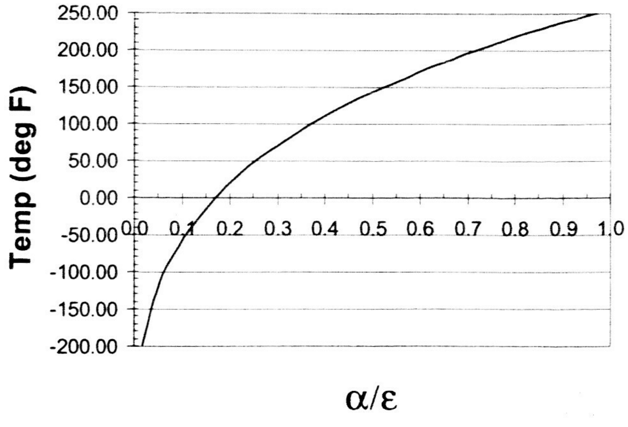


Figure 7: On-Orbit Heating Effects

Orbital Destination - The pressurized module must also be compatible with the environment at its destination. This could include the orbiting International Space Station, a lunar outpost, or possibly a Mars base. The ISS is maintained at a "shirt-sleeve" environment which permits crew activity in typical temperature and pressure ranges (65 to 80°F and 14.5 to 14.9 psia). Assuming that lunar / Mars bases also adopt a "shirt-sleeve" environment, then orbiting vehicle can expect to dock at locations with these same atmospheric parameters. While docked, the vehicle will inhibit its internal pressure control system and rely on the host vehicle to provide atmospheric control. This will involve deactivating both the make-up gas supply function and the overpressurization protection offered by relief valves. When leaving the extraterrestrial base, the pressurized vehicle will be closed-out at the base pressure and temperature, as it is prohibitively expensive to globally adjust the base atmosphere in order to obtain the desired close-out conditions for the departing vehicle. This lack of control over the close-out conditions will be an important factor in looking at the vehicle's re-entry into the Earth's atmosphere.

In light of the new NASA space exploration initiative, conditions at other planetary bodies were considered. Lunar pressure levels are negligible, so lunar conditions are encompassed by the orbital flight environments. The atmospheric pressure of Mars is also quite low ranging from 0.1 psia to 0.13 psia. The International Space Station (ISS) provides a potential waypoint for a manned mission, so the ISS conditions are tabulated. Finally, Venus was not considered as it possesses a toxic uninhabitable environment (high-speed sulfuric acid clouds, high surface temperatures (220 °C, and enormous pressures of 90 atmospheres). The following table summarizes the temperature and pressure ranges for each of these locations.

Table 3: Environmental Temperature and Pressure Ranges

Altitude	**Temperature (°F)**		**Pressure (psia)**	
(MSL, ft)	Low	High	Low	High

In-Flight / Lunar	---	60	80	14.5	14.9
ISS / Mars base	407 km	65	80	14.5	14.9

Summary of Flight Operations and PPRVs – A summary of these various flight scenarios is presented in Figure 8. As shown, the largest positive pressure differential occurs following ground close-out due to the possibility of higher ambient pressure.

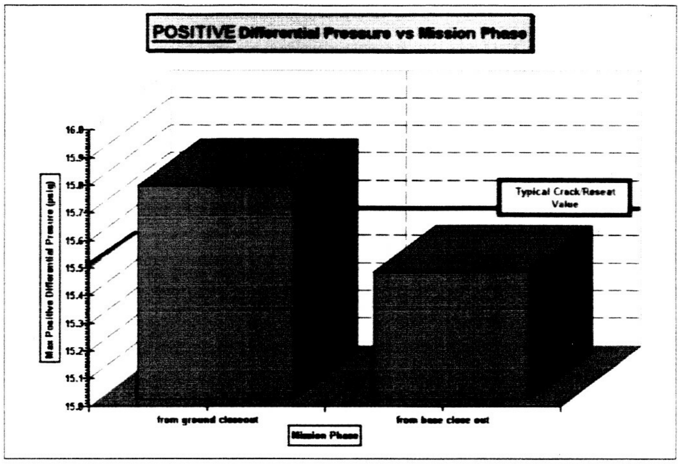


Figure 8: Summary of Pressure Differentials During Flight Operations

Leakage– In addition to the metabolic oxygen consumption requirements, manned spacecraft must also carry onboard stores of nitrogen and oxygen to offset any leakage from the pressurized compartment to the external vacuum of space. Leakage and contingency gas make-up requirements should be addressed early in the manned vehicle design cycle in order to appropriately size the gas tanks. System-level leakage values for recent manned space hardware are shown in the following table. Typical leakage values for a pressurized module are in the range of 0.11 to 0.28 lbm/day. This approach yields a top-down leakage requirement that should be attainable based on previous manned hardware programs.

Table 4: Spacecraft Leakage Requirements

Vehicle	Leakage Requirement
Space Shuttle	0.275 lbm/day
ISS - U.S. Laboratory	0.114 lbm/day
ISS – Node 1	0.117 lbm/day
ISS - MPLM	0.15 lbm/day
Spacelab	2.98 lbm/day

Usually late in the hardware qualification process, a system-level pressurized compartment leak test will be completed to quantify the actual leak rate. Once this actual leakage is known from the test data, this leakage rate must be accounted for in the overall vehicle pressurization analyses. For short-term missions, nominal leakage will be negligible, and for manned vehicle flight operations, leakage can be neglected because the Pressure Control Subsystem (PCS) will be monitoring and maintaining the pressure within the crew compartment. For longer-mission duration unmanned vehicles, this leakage factor must be included in the overall vehicle mass loss analysis.

In addition to atmospheric leakage, consideration must be given to internal leakage from pressurized containers. Any container located inside the pressurized compartment must be evaluated and leakage (both nominal and contingency) impacts defined to ensure the overall system compatibility. The PPRA must be sized to accommodate the sudden leakage of a pressurized bottle. In addition, preflight analyses must be completed to ensure that the contents of pressurized gas bottles will not create an unhealthy atmosphere for the crew. To alleviate these concerns, pressurized bottles are typically packaged in another compartment which is physically separate from the crew compartment.

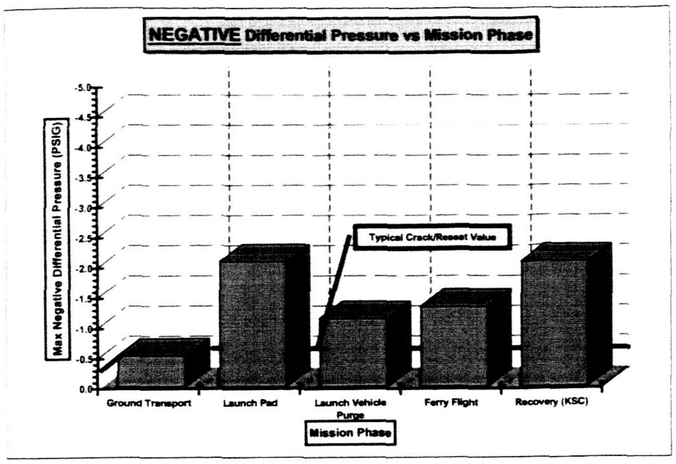
Since leakage across the pressure shell is offset by make-up gas and pressurized bottle leakage can be precluded by packaging these items in a separate compartment, leakage will be ignored for the remainder of this paper.

EXAMPLE CASES

Three example cases are presented herein to illustrate the required relief valve cracking pressure. In the first instance, an early version of the Crew Exploration Vehicle (CEV) will be launched from KSC, deliver a payload to orbit, and return to Earth at KSC. In the second scenario, an identical mission profile will be flown except that the vehicle will land at Sedom (hypothetical situation to illustrate the effects of the ambient environment). The vehicle will then require a ferry flight back to KSC. Finally, the third scenario simulates launching an unmanned pressurized cargo vehicle from ISS to a manned Mars outpost.

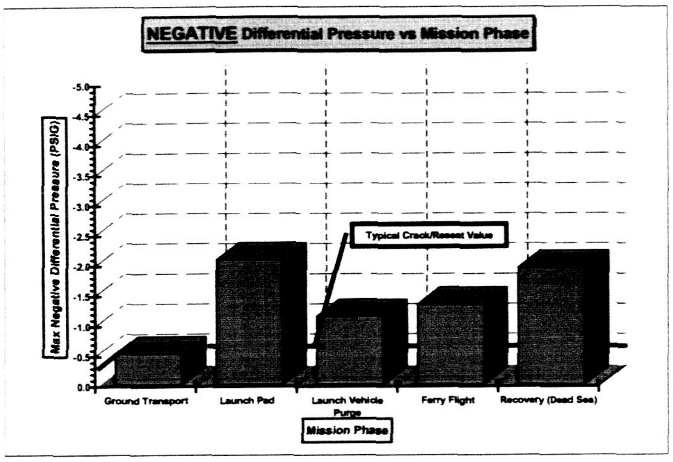
SCENARIO #1 DESCRIPTION

Crewed CEV which launches from KSC, transports some payload to orbit, and returns to KSC.



SCENARIO #2 DESCRIPTION

Same as scenario #1 except return is at Sedom, Israel



STRUCTURAL DESIGN CONSIDERATIONS

NPRVs and PPRVs provide a common hardware implementation for pressure control, but the operational implementation is often dictated by program management. Some programs prefer that valves only actuate during off-nominal scenarios, and the nominal mission timelines are designed to preclude pressure relief valve actuation. Other programs allow pressure relief valve operation during both nominal and contingency scenarios. To simplify the operational aspects and reduce total life-cycle cost, the valve design should incorporate cracking pressures with some margin to preclude inadvertent actuation. Oftentimes, hardware programs take the opposite approach and set very tight cracking pressures to reduce minimize the pressure differentials across the pressure shell which translates into some weight savings. This approach ignores the real cost associated with operational work-arounds required to implement valve designs with tight cracking pressures: launch site close-out requirements, potential need for slight over-pressurization, variable purge requirements to maintain tight thermal constraints, limited orbital temperature capabilities, postlanding purge and heater requirements, and finally contamination effects from pressure relief valve actuation in an uncontrolled environment.

The design trade-off boils down to setting tight valve cracking pressures to minimize structural weight versus increased structural weight to minimize recurring downstream operational impacts.

CONCLUSION

The space vehicle structure must be designed to accommodate the maximum positive and negative pressure differentials across the pressure shell. The design implementation approach is crucial to ensuring a solution that addresses the technical issues yet minimizes the operational impacts. Each program must individually weigh the hardware weight impact against the downstream recurring operational costs for the vehicle.

ACKNOWLEDGMENTS

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REFERENCES

1. MIL-STD-1522A (USAF), "Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems", 28 May 1972

2. NSTS 1700.7B, "Safety Policy and Requirements for Payloads Using the Space Transportation System", January 1989

3. ANSI/AIAA S-080-1998, "Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components", 13 Sept 1999

4. K-STSM-14.1.16, "Space Station Processing Facility Handbook / Guide"

5. K-STSM-14.1.10, "Pad Rotating Service Structure Handbook / Guide"

6. KCI-HB-5340.1, "Payload Facility Contamination Control Implementation Plan"

7. Terrestrial Environment (Climatic) Criteria Handbook for Use in Aerospace Vehicle Development; NASA-HDBK-1001, 11 August 2000

DEFINITIONS, ACRONYMS, ABBREVIATIONS

CONUS: Continental United States
°F: Degrees Fahrenheit
EAFB: Edwards Air Force Base
ELV: Expendable Launch Vehicle
Ft: Feet
hr: hour
ISS: International Space Station
KSC: Kennedy Space Center
lb_m: pounds, mass
LBB: Leak Before Burst
MDP: Maximum Design Pressure
MEOP: Maximum Expected Operating Pressure
MSL: Mean Sea Level
NASA: National Aeronautics and Space Administration
NPRV: Negative Pressure Relief Valve
PCR: Payload Changeout Room
PPRV: Positive Pressure Relief Valve
psia: Pounds per Square Inch, Absolute
psid: Pounds per Square Inch, Differential
SCA: Shuttle Carrier Aircraft
SSPF: Space Station Processing Facility
VAFB: Vandenburg Air Force Base
WSTF: White Sands Test Facility???