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Treatment of Transient Pressure Events in Space Flight Pressurized Systems

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Position Paper

Treatment of Transient Pressure Events in Space Flight Pressurized Systems

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1.0 Introduction

This work was sponsored by the NASA Engineering and Safety Center (NESC). A technical team from the NESC/NASA and The Aerospace Corporation met regularly to develop approaches on how pressure transients could be assessed in pressurized systems. The team consulted with experts across industry, NASA, and The Aerospace Corporation to develop the contents of this document. This document presents a focused discussion on the topic of pressure transients for consideration within the aerospace community. The hope is to spur fruitful discussions regarding this topic and bring a common understanding across the propulsion, fluids, and structures disciplines.

General physics, contributing sources, and major influencing factors of pressure transients in pressurized systems (e.g., valves, lines, pressure vessels, pressurized structures) are discussed. Mitigation strategies to reduce the magnitude of pressure transients are presented. Fluid analysis techniques commonly used to predict pressure transient characteristics are presented with case studies illustrating their application. These pressure transients can cause a dynamic amplification of the structural response. Structural analysis methodologies are presented to predict this amplified stress response with case studies illustrating their application. Finally, the treatment of pressure transients in the structural verification process is presented.

2.0 Signature Page

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Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

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3.1 Acknowledgments

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4.0 Executive Summary

Transient pressure events are dynamic fluctuations in pressure caused by valve actuation, fluid system priming, fluid discharge, vibration, and a variety of other sources. Pressure fluctuations within spaceflight pressurized hardware are a regular occurrence. Analytical and experimental evidence have shown that fast-moving pressure transients can elicit an amplified structural response.

A multi-disciplinary team from the NASA Engineering and Safety Center (NESC) and The Aerospace Corporation developed a roadmap on how to treat transients in spaceflight pressurized systems. Five aspects of transients are presented: (1) Fundamental physics, (2) Mitigation strategies, (3) Prediction or measurements of pressure transients, (4) Prediction or measurements of the structural dynamic response to transients, and (5) Structural verification process.

The general physics, contributing sources, and major influencing factors of transients in pressurized systems (e.g., pressure components, pressure vessels, pressurized structures) are addressed in the main body of this work. Mitigation strategies to reduce the magnitude of pressure transients are presented. Fluid analysis techniques commonly used to predict characteristics of pressure transients are presented with case studies illustrating their application. These transient events can cause a dynamic amplification of the structural response, hereafter referred to as the "Dynamic Amplification Factor" (DAF). Case studies illustrate methods to predict the amplified stress response.

The structural design verification process requires an understanding of the critical stress states within the pressurized hardware. To this end, approaches are presented on how to consider the DAF in the structural verification process. An approach is to establish a Maximum Expected Operating Pressure (MEOP) such that the maximum stress in the structure produced by static pressure is equivalent to the maximum stress at the same critical location produced by the combined effect of steady state pressure and the magnitude of the pressure transient. An alternate approach is to adjust test levels to meet structural verification criteria without adjusting the MEOP definition. A damage tolerance approach with lower proof and burst factors is presented, which can result in weight-savings, especially when pressure transient magnitudes are significant.

Section 11 provides the general workflow on how pressure transients may be treated within pressurized systems, Section 12 provides a summary, while Sections 5 through 10 provide the theoretical and practical foundation for Section 11.

5.0 Motivation and Objective

Transient pressure events are dynamic fluctuations in pressure about a steady or quasi-steady state condition due to changes in supplied pressure, vibration, or interruption of fluid flow by in-line devices. Causes of transient events can be valve actuation, fluid system priming, fluid discharge, vibration, loss of pump power, or pulsing thrusters. Pogo instabilities are caused by feedback interactions between the fluid/propulsion/structural systems and must be considered in the design process. This feedback phenomenon requires system-level modeling of the propulsion/structural/fluid systems and are not pressure transients due to fluid flow interruption, which is the main subject of this document.

Specific to aerospace applications, pressure transient events occur during the priming process of propulsion feedlines of satellites and launch vehicles and during powered flight (e.g., sudden valve closure). These pressure transients also occur during fill and drain operations in ground support equipment (GSE) or at interfaces between the flight hardware and GSE. In this document, the discussion is limited to transients caused by flow disturbances, rather than shock and/or system vibration. Pressure fluctuations can have a significant impact on the design and operation of pressurized system in both spacecraft and launch vehicle propulsion systems. These transients need to be predicted or measured accurately to aid in the design process. Reference 1 presents an example where analytical fluid modeling techniques successfully predicted pressure transients in a pressure system of an X-vehicle.

Transients have resulted in system failures [2] and structural failures in industries such as oil, chemical, civil, aerospace, and nuclear. These failures were found to have occurred from inadvertent overload or fatigue failures that resulted from pressure transients. Common contributors to failure included: (1) Incorrect assumptions in the transient analysis that did not include worst-case operating conditions; (2) Insufficient design evaluation of elements vulnerable to high pressure transients; and (3) Lack of use of devices aimed at reducing the magnitude of pressure transients in susceptible designs. An example is illustrated in Figure 1 of a flow moving through the pipe and depicting the effects on the flow due to valve opening or closing. The pressure transient effects are strongly dependent on the speed at which the valve opens or closes.

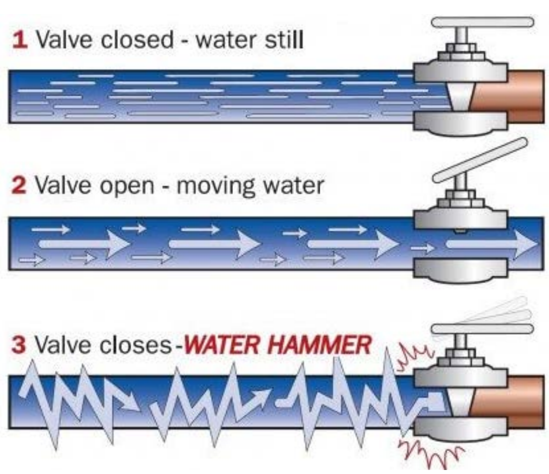
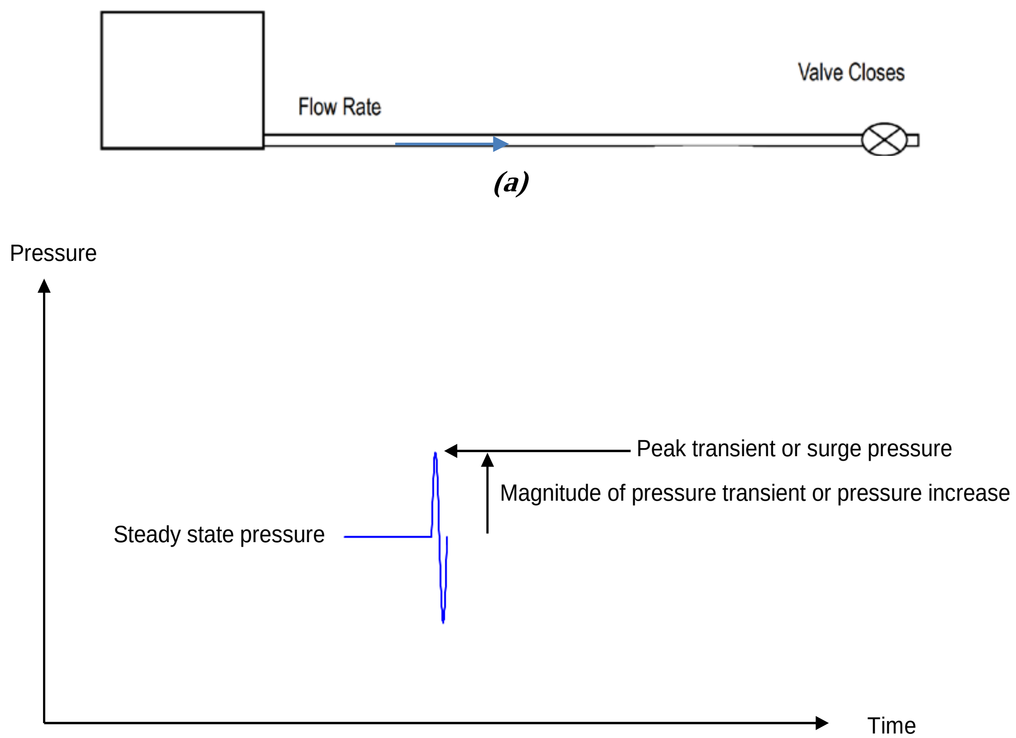


Figure 1. Illustrations of Effects of Valve Opening and Closing on Flow

The concept of a transient event is illustrated via an example problem. Figure 2a illustrates a pipe connected to a tank and a valve. A flow, initially steady, will experience pressure fluctuations within the pressurized system due to valve closure. The flow rate is such that the steady state pressure in the pipe is P_0. When the valve is closed, it will cause a rise in pressure, which will travel from the location of the valve to the tank (Figure 2b). The progression of pressure wave location as a function of time is illustrated in Figure 3. The valve closure results in a pressure wave traveling away from the closed valve. In this example, the transient event[1] causes a magnitude of pressure transient[2] that is 14.5 psi above the steady state pressure of 507.6 psi. The peak transient[3] in this example is 522.1 psi.



(b)

Figure 2. (a) A Straight Pipe Connecting a Tank and a Valve (b) Valve Closure Disrupts flow Causing a Transient Event with a Peak Pressure

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[1]Transient event occurs when the flow is steady and there is a disruption in the flow; causing a pressure wave that travels within the pressurized system.

[2]Magnitude of pressure transient or pressure transient is the magnitude of the pressure wave arising from the flow disruption. The uses the term pressure transient rather than magnitude of pressure transient.

[3]Peak pressure transient is the steady-state pressure plus the magnitude of the pressure transient.

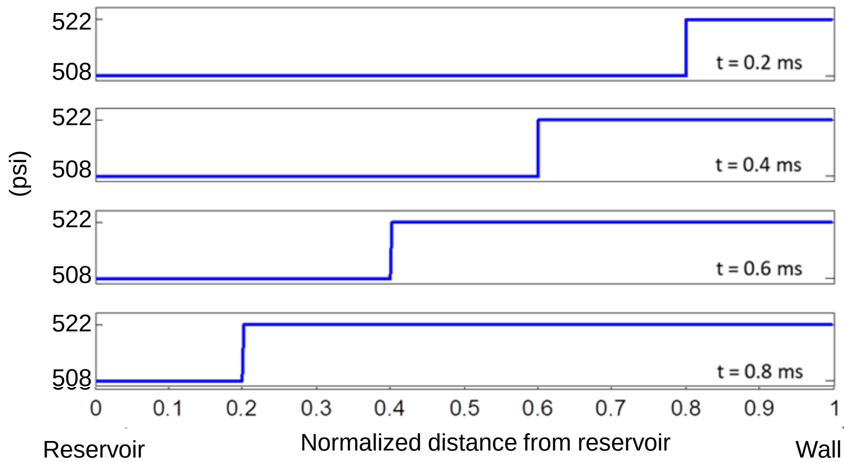

Figure 3. Progression of Pressure Wave Location as a Function of Time

The transient event may or may not cause damage to the structure depending on several conditions, which include the pressure wave speed and structural characteristics. The resulting stress in the pipe is due to the stress from steady state pressure P_0 and stress from the pressure transient.

The structural response of the pipe due to the transient event can be: (1) minimal, (2) quasi-static or static, or (3) dynamic. As such, the effects of the transient event on the structural response need to be understood to enable the design to meet the minimum structural design requirements.

This document provides a roadmap on how to treat transient events in the structural verification process of spaceflight pressurized systems. The document is organized as follows:

1. Physics of transient events and factors that influence them: Section 6.
2. Implementation strategies to reduce the magnitude of pressure transients: Section 7.
3. Methods to predict or measure the magnitude of pressure transients including case studies: Section 8.
4. Methods to predict or measure the amplification of the structural response due to the transient event including case studies: Section 9.
5. A brief survey of the treatment of pressure transients in various aerospace standards: Section 10.
6. Approaches on how the transient events can be accounted for in the structural verification process including example applications: Section 11.

6.0 Explanation of Transient Events

Objective: Explain the underlying physics of transient events and the factors influencing them.

6.1 Physics of Transient Events

Consider again the example of a tank connected to a valve by a pipe where the fluid steadily flows through an initially open valve, Figure 2. Sudden valve closure will cause the flow of fluid to stop resulting in a localized pressure increase beginning at the valve. The fluid must satisfy the boundary condition of zero velocity at the closed valve.

A compression wave is produced when the valve is closed. This wave propagates through the system at the effective sound speed of the fluid, which is affected by the response of the pipe walls to the pressure transient. The compression wave travels first upstream to the tank followed by a reflected expansion wave traveling downstream from the tank. When the fluid is water, the pressure transient events are commonly referred as water hammer events.

When the expansion wave reaches the closed valve, it reflects as an expansion wave back upstream to the tank and then subsequently reflects downstream, this time as a compression wave. This cycle of exchanging compression waves and expansion waves repeats until the effects of viscosity, damping, or other losses (e.g., friction) dissipate the waves. At that point, the pressure will reach a steady state. The magnitude of the pressure wave decreases over time due to dissipative effects. This explanation describes the physics of what occurs with steady flows. However, transient events can occur when the flow is also unsteady.

Pressure transient events can also occur when priming a system with liquid. The liquid is initially separated from the downstream region, which contains a gas or is evacuated using a valve or a burst disk. The valve or disk is sometimes quickly opened to prime the system. The timing of valve opening is controlled to limit the velocity of the fluid filling the system. The advancing liquid front propagates downstream, compressing any remaining gas, which results in a rapid pressure rise. This transient event due to priming is distinct from water hammer but the physics are the same as described in the previous paragraph. The problem could be more complicated than a single liquid—as it could also be multi-phase (e.g., gas/liquid) and/or multi-species (e.g., liquid oxygen (LOX)/helium). The treatment of pressure transients is not limited to steam hammer or water hammer but can also include multi-phase cases or multi-species cases.

6.2 Factors Influencing Pressure Transients

Several factors influence the magnitude and frequency of pressure transients and these include fluid density, compressibility, celerity (i.e., effective sound speed), fluid velocity, valve closure time, pipe geometry/material, fluid temperature, pipe networks, and loss mechanisms (e.g., viscous effects).

6.2.1 Valve Closure Time

One of the major factors affecting the magnitude of a pressure transient is how fast the valve closes as this dictates the rate of change in momentum of the fluid. The more rapidly a valve closes, the narrower the wave front is and the larger the magnitude of the compressive wave front. In the theoretical limit of an instantaneous valve closure, an infinitesimally thin wave front (i.e., shock) is produced. However, even what is considered an "instantaneous" valve closure actually occurs over a finite time. Here, "instantaneous" refers to a valve closure time that is faster than the time it takes for a pressure wave to propagate through the pipe and readjust to the flow. A valve could close partially, creating a moderate change in momentum with a correspondingly moderate pressure transient. In a liquid propellant, this occurs when a control valve (e.g., to control mixture ratio) shifts between fully open and partially closed. Valve closure in some spacecraft propulsion systems is fast enough to be modeled as instantaneous. This may not be the case in all systems such as in launch vehicles and other spacecraft.

6.2.2 Pipe Network Configuration

The orientation of the pipe axis with respect to the gravity and/or net acceleration vector can influence the severity of the pressure transient magnitude. Pipe orientation plays a crucial role in the case of a steam hammer, which is a transient event caused by a slug of condensate/liquid carried by gas flow in a pipe. If the pipe is oriented so that it allows for the condensate to be removed, then the risk of steam entraining liquid would be reduced. This is important for spaceflight under acceleration but not at micro- or zero-gravity conditions.

Other branch configurations (e.g., feedlines, interconnected pipes) can cause pressure waves to propagate upstream in these feedlines and pose the risk of constructive interference (a form of resonance) that can result in large pressure oscillations. Gradual decrease of a propellant's flowrate in the system can reduce the risk of significant pressure waves.

6.2.3 System-Level Fluid Dynamics

Another important factor is system-level fluid dynamics. Consider a simple space system consisting of a thruster with a valve, pipe, and fuel tank. The thruster may pulse repeatedly or fire for long durations to control vehicle attitude. A transient event with a characteristic frequency will arise, and if the thrusting frequency lines up with the frequency content of the pressure transient, then resonance may result in larger pressure spikes. It is also possible to pulse such that there is destructive interference between the pressure transients, dramatically reducing the pressure spikes. For most spacecraft systems the pulsing frequency is well below the system frequency, but not always.

6.2.4 Fluid Compressibility and Density

The degree of compressibility of the fluid directly influences the magnitude of the pressure spike. Fluids that are less compressible than others will cause a larger pressure spike. Because the magnitude of pressure transient is proportional to fluid density, the pressure spikes in gas systems are orders of magnitude smaller than those in liquid systems due to the difference in gas and liquid densities.

The presence of a gas and liquid mixture will greatly affect the effective sound speed and dissipation. Gas bubbles in the liquid will reduce the sound speed, which will result in a lower calculated pressure transient magnitude. This often complicates testing efforts, since small amounts of pressurant dissolved in the propellant can produce bubbles that accumulate at various points in the feed system.

Another consideration is the scenario of gas bubble compression from a liquid slug as seen during system priming. Resonance can occur, generating higher pressures than would have occurred if only liquid were present.

6.2.5 Structural Characteristics

Magnitude and frequency characteristics of the pressure transient are dependent on the pressurized systems' structural characteristics (e.g., stiffness and mass) and can significantly influence the dynamic stress response that occurs in structural components. Case studies in Section 9 will illustrate this phenomenon and highlight the timescales in which stress waves propagate through structures.

6.2.6 Damping

Typically, damping causes pressure oscillations due to a single closure to dissipate over time. Energy dissipation results from many factors including viscous damping, structural damping, flow restrictors, and friction between the wall and the fluid.

6.2.7 Fluid Storage Vessel

Composite overwrapped pressure vessels (COPVs), metallic pressure vessels (MPVs), and pressurized structures (e.g., stage tanks) are considered fluid storage vessels based on the relationship between their relatively large storage volume and the comparably small cross-sectional area of the inlet and outlet tubing in the systems they supply.

Transient events usually have minimal impacts on fluid storage vessels. Physically, this is because the fluid storage vessel is typically large in comparison to inlet geometry, such that an approaching pressure wave dissipates quickly within the structure. As a fluid wave goes from a pipe into a large plenum, the energy of the wave dissipates with the inverse of the square of the distance ($1/r^2$). A short transition region where the pipe first flares out into the pressure vessel leads to a reduction in the magnitude of the pressure transient before it dissipates within the vessel. This flare feature is not always used in designs. Although the fluid storage vessel will not experience any appreciable pressure rise, the pressure wave will be present in the short transition region leading into the structure, reducing the unsteady pressure magnitude throughout the transition region. Precise values of the pressure transient will depend on pipe geometry, fluid properties, initial flow rate, and pressure. Typical practice is to ignore the transition region in analysis, which yields conservative pressures when the transition is present in the hardware. Fluid storage vessels are mathematically represented as boundary conditions that force the pressure to remain steady, so there are no transients.

Under launch vehicle or spacecraft accelerating or decelerating (due to engine shutdown) conditions, the hydrostatic pressure in fluid storage vessel helps establish a pressure boundary condition that can be held constant given the timescale of the system fluid dynamics relative to the startup transients of the propulsion system. With the pressure boundary node held constant, the velocity can change in accordance with the incident pressure wave. A compression incident wave, behind which the pressure is higher than the boundary pressure at the fluid storage vessel, induces flow from the pipe into the fluid storage vessel and the wave reflects as an expansion wave. This expansion incident wave reflects as a compression wave while inducing a flow from the fluid storage vessel into the pipe. Therefore, transient effects should result in a minor change in the fluid storage vessel liquid volume due to flow into or out of the pipe under gravity or acceleration. If acceleration reduces to 0g, the hydrostatic pressure in the fluid storage vessel goes to zero independently of valve activity. The pressure at the fluid storage vessel is then equivalent to the ullage pressure, and the amount of flow will change accordingly. This is consistent with observed flight and ground test data.

7.0 Strategies to Limit Pressure Transients

Objective: Highlight strategies that can be implemented to mitigate the effects of pressure transients.

Designing the system to minimize the magnitude of pressure transients is the preferred approach to ensuring safe operation of the system. Various strategies can be selected to control or reduce the magnitude of pressure transients. These strategies include sizing of pipes and fittings; selection and location of control devices; and procedures to manage the system start-up, operation, and shutdown.

7.1 Industry Standards

Very few industry standards impose requirements to limit pressure transients during operations. While regulations such as American Society of Mechanical Engineers (ASME) standards are typically not applied to pressurized spaceflight hardware. However, it is insightful to examine how pressure transients are treated in those few specifications that do address these aspects. ASME Section VIII [ref. 3] require protecting pressure vessels from surges or large pressure transients by providing adequate overpressure protection. ASME codes provide caution that water hammer should be avoided, or its impact considered in the design. ASME codes state that: “Occasional variations of pressure and/or temperature may occur in a piping system. Such variations shall be considered in selecting design pressure and design temperature. The most severe coincident pressure and temperature shall determine the design conditions unless all of the following criteria are met… The total number of pressure-temperature variations above the design conditions shall not exceed 1,000 during the life of the piping system.” The limit of 1,000 cycles is used as a threshold below which fatigue verification due to pressure cycling may be excluded. Otherwise, fatigue capability should be evaluated to verify the hardware can accommodate pressure cycling. ASME also discusses managing overpressure through system design or through a combination of design and pressure relief devices when the pressure is not self-limiting. For single devices, “the pressure rise is not allowed to be more than 10 percent or 3 psi above the maximum allowable working pressure, whichever is greater.”

In defining maximum operating pressure for pipelines, 49 CFR § 195.406 [ref. 4] requires that each operator must provide adequate controls and protective equipment to control the pressure so that the pressure in a pipeline during surges or other variations do not exceed 110 percent of the operating pressure limit during normal operations.

Aspects of the NASA Goddard Space Flight Center (GFSC) Open Learning Design (GOLD) rules [ref. 5] were specifically developed for use at NASA GSFC but have been employed elsewhere. One of the requirements is aimed at protecting liquid propulsion systems from over-pressurization. Propulsion system design and operations are required to preclude damage due to transient events (e.g., water hammer) as it can result in damage to components or manifolds, leading to failure of the propulsion system, damage to facilities, and/or safety risk to personnel. Hence, it is required to perform pressure surge analysis based on worst-case operating conditions to determine the maximum magnitude of the pressure transient. If the maximum peak pressure is greater than system proof pressure, then the design must incorporate features to reduce its peak value below proof pressure. If it is anticipated that the pressure transient magnitude could be higher, then programs have increased the proof pressure above what it would have been specified. The key, however, is to accurately predict the magnitude of the pressure transient. The NASA GSFC GOLD rules require the following:

1. Demonstrate by test that maximum surge pressure is less than proof pressure of the affected components and tubing manifolds;
2. Demonstrate by test that surge suppression features, if applicable, do not lead to violation of flow rate and pressure drop requirements; and
3. Demonstrate by analysis that flight hardware and/or on-orbit procedures will prevent operation of the propulsion system beyond the conditions assumed in its pressure surge analyses and tests.

Not all programs require demonstration by test, although sometimes testing is performed for model validation purposes. Direct measurement by test would require testing of a flight-like feed system using actual propellants. That is neither feasible nor always required for systems that are within the range of system parameters (e.g., line sizes and pressures) that have previously been analyzed, tested, and/or flown.

In ASME Section VIII, 49 CFR § 195.406, and GSFC GOLD rules, it is either required or recommended to design a pressurized system to protect the system from over-pressurization by using devices and controls. However, some pressure transients in spacecraft propulsion systems are generally controlled by isolation from pressure sources except when the activity is pressure regulated during flight operation. There may or may not be a fault control to prevent overpressure depending on the mission risk tolerance.

7.2 Best Practices

Sudden changes in the fluid velocity should be avoided where possible to minimize the magnitude of pressure transients. Most systems and operating procedures are generally designed and formulated to minimize sudden velocity changes. The following subsections address select best-practice strategies to limit the magnitude of pressure transients.

7.2.1 Valve Closure Schedule

Sudden closure of valves causes pressure transients, so an approach to mitigate these transients is to perform simulations of the pressurized system's response to optimize relative valve closure timing. Valve scheduling refers to the choices made in how much time is allowed between valve actuations to reduce potential for resonance conditions or to produce destructive interference between pressure transient events. Even with optimized valve schedules, pressure transients are still possible, and should be determined to avoid unexpected system behavior.

Although it is desirable in some circumstances to close valves as quickly as possible (e.g., during a system anomaly), care should be taken in closing them only as fast as is needed. Slower valve closures result in lower overpressures. In the application of a pump-fed liquid propellant launch vehicle engine, adjustable throttling valves should be used to gradually reduce the flowrate to the engine during shutdown.

7.2.2 Orifices

Orifices and cavitating venturi can be used to reduce overpressure experienced at upstream critical components but at the cost of added pressure losses during nominal operation. Cavitating venturis can be designed to minimize this additional pressure drop during normal operation.

7.2.3 Check Valves

If there were a pressure transient issue, an orifice would be a preferred mitigation approach before employing a check valve. Check valves are notoriously problematic because chattering is a consistent issue. There are situations where a check valve is required, and in those instances, it could help with limiting transient events originating downstream.

A check valve isolates the pressure wave from sensitive components located upstream. The additional pressure drop during steady state operation is smaller when compared to an orifice. Furthermore, the closure of the check valve will generate a pressure wave, which must be accounted for in the system analysis. Finally, the stagnant fluid trapped between the check valve and the pipe's end is hydraulically locked and can experience dramatic pressure increase due to a rise in temperature, potentially leading to system failure. At first glance, it appears that this concern is not unique to a check valve but could also apply to a closed valve. However, there is a difference between the two scenarios. The closed valve scenario is only one valve. The upstream system is connected to the bottle/tank, so the fluid can expand with temperature. The downstream side is connected to a thruster, so it is vented. If a check valve is added, then there is an intermediate volume with trapped liquid, which can be damaged if the temperature rises. Generally, it is rare to see check valves used to mitigate pressure transients on spacecraft.

7.2.4 Pressure Relief Valves (PRVs)

PRVs provide a way to direct a pressure wave outside the system under evaluation, rather than allowing it to move upstream. The relief valve is activated only when a prescribed minimum pressure is exceeded. As with the check valve, the response time of the relief valve must be assessed. Since some fluid (e.g., liquid or gas) will be expelled, consideration must be given to any additional hazards (e.g., fires, exposure of personnel to toxic propellants) or performance impacts (e.g., contamination of the spacecraft, combustion with atmospheric air, loss of fuel available to mission).

One design susceptible to hazards involves the use of LOX and gaseous oxygen (GOX) relief valves that utilize a GOX accumulator to minimize inadvertent activation. When operated, depending on the design and pressures, the valve poppet and seat can chatter during the initial GOX venting resulting in potential ignition. This is not an issue if the valve poppet/seat are made of the correct materials. An oxygen compatibility analysis should always be performed.

PRVs have the tendency to trap bubbles, which could migrate to the engine and lead to bubble ingestion. Pressure-relief devices are rarely used in spacecraft propulsion systems since they then become the “weak point” in protecting ground personnel from exposure to toxic propellants. Relief valves can reduce the reliability of the system for flight.

7.2.5 Accumulators

An accumulator is a type of surge volume that reduces the magnitude of pressure fluctuations by absorbing much of the incoming wave. Accumulators greatly reduce the magnitude of pressure transients and can be placed in-line or out-of-line. In addition, the location relative to the valve and fluid storage vessel must be considered given that nodes and anti-nodes will exist within the fluid along the pipe. Accumulators must be traded against system weight and volume considerations. Accumulators can be compliant care; therefore, care must be taken to ensure that they do not introduce feed-system coupled instabilities (i.e., “chugging”) in liquid propulsion systems.

Note that accumulators without bellows are generally not used in propulsion system manifolds due to gas bubble ingestion concerns.

7.2.6 Piping Design

Pressure transient magnitude can be reduced by using large-diameter pipes and feedlines. This reduces pressure losses from friction, reduces flow speed, and minimizes the overpressure caused by a valve closure. Piping network configuration can be designed by tailoring system stiffness so that the system can absorb the kinetic energy of the liquid and mitigate potential damage from an amplified structural response. Through fluid-structure interaction, it is possible for the piping design to influence transient effects.

However, this may not be possible because there might not be enough system volume to accommodate larger pipes. Increasing pipe diameter can result in weight increase, which can impact performance.

8.0 Quantification of Pressure Transients

Objective: Present methods to predict or measure pressure transients including case studies.

The design of any pressurized system should be accompanied by a fluids analysis or test to characterize the pressure profiles and when possible to verify the controls used to limit pressure transients. Two methods used in the predictions of pressure transients are presented in Sections 8.1 and 8.2. Alternatively, test or flight instrumentation can be used to characterize pressure transients. While it may appear that the flight phase is too late to characterize pressure transients, there are instances where there is no other choice. Attitude control systems, for example, typically function as a system for the first time during flight. Note that flight instrumentation typically installed on spacecraft can rarely capture the pressure transient response accurately due to the low-frequency sampling rate; however, this does not prevent the ability to install higher sampling rate instrumentation systems to capture transient effects accurately.

8.1 The Joukowsky Equation

The Joukowsky equation is used to predict the change in pressure (ΔP) that will result if the transient event occurs "instantaneously," and the pressure predictions tend to be conservative. The Joukowsky pressure transient prediction is superimposed with the static pressure to determine the maximum theoretical pressure in the pipe. The Joukowsky equation gives the magnitude of the pressure transient:

$$\Delta P = -\rho \, a \, \Delta V \tag{1}$$

where ΔP is the pressure transient, ρ is the fluid density, a is the wave speed or celerity, and ΔV is the change in velocity. Physically, a is the propagation speed of the pressure wave that is generated as it travels through the system.

The pressure transient magnitude is directly related to the speed of the resulting pressure wave, which is described by the term celerity. A relationship between the wave speed and the change in pressure can be derived for sudden flow path closures using conservation of mass and conservation of linear momentum per Appendix A. The wave speed is given by:

$$a = \frac{\left(\frac{\beta}{\rho}\right)^{\frac{1}{2}}}{\left(1+\frac{\beta D}{E\,t}C\right)^{\frac{1}{2}}} \tag{2}$$

where β is the fluid bulk modulus, E is the pipe modulus, D is the inner diameter of the pipe, t is the pipe thickness, and C is the boundary factor (Figure 4). The factor C depends on the Poisson's ratio (μ) of the pipe material and, for thick-walled pipes, the diameter and wall thickness. Figure 5 contains Boundary Factor C for Case I: Pipe rigidly anchored at upstream end only; Case II: Pipe rigidly anchored against longitudinal movement; Case III: Pipe contains expansion joints; and Case IV: Rigid pipe. Thick-walled equations are used for $D/t \leq 25$.

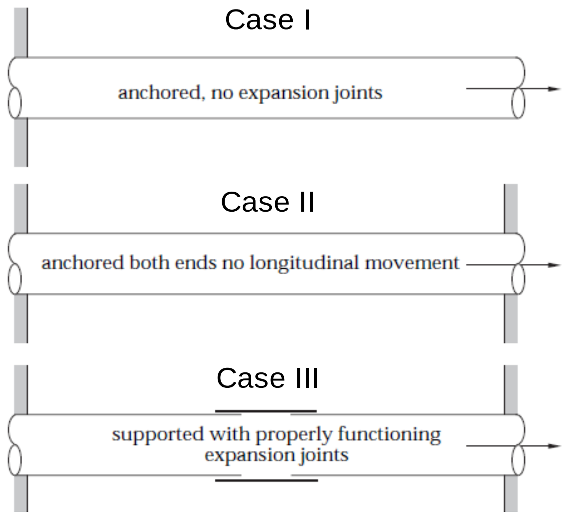

Figure 4. Various Boundary Conditions that Could Affect Boundary Factor C

Boundary Case	Thin Walled Cylinder	Thick Walled Cylinder
I	$1 - \frac{\mu}{2}$	$\frac{2t}{D}(1+\mu) + \frac{D}{D+t}\left(1 - \frac{\mu}{2}\right)$
II	$1 - \mu^2$	$\frac{2t}{D}(1+\mu) + \frac{D}{D+t}(1-\mu^2)$
III	1	$\frac{2t}{D}(1+\mu) + \frac{D}{D+t}$
IV	0	0

Figure 5. Boundary Factor C for Four Cases

Note the pressure rise is proportional to the density. In most applications involving liquid flow in a pipe, a constant liquid density can be assumed as there are negligible fluid density changes at the speeds involved. Fluid density changes are small because the Mach numbers are very small ($M \ll 1$) for most of the applications encountered in pressurized systems with liquid working media.

It is generally accepted that pressure transient calculations that use the Joukowsky equation are applicable for steady state or quasi-steady flows, whereby the flow behavior changes occur on timescales longer than the acoustics that characterize the pressure transient.

Limitations to the maximum pressure predicted by the Joukowsky equation exist. The maximum pressure could be higher than that predicted by the Joukowsky equation due to two-phase flow, pipe size changes, piping containing tees, systems where pressure drops to the vapor pressure of the liquid in the piping system, or the interaction of multiple pressure transient sources. As the pressures predicted by the Joukowsky could be non-conservative in these cases, a more advanced transient fluid model may be required.

8.2 Advanced Transient Fluid Models

The analysis of pressurized systems subject to pressure transients is not a trivial task due to potential system-level dynamics complicated by potential of fluid-structure interactions. If these fluid-structure interactions are minimal, then the analysis is more straightforward. Fluid modeling can range between solving the Joukowsky equation to utilizing computational fluid dynamic (CFD) model. Typically, one-dimensional (1D) fluid models are adequate for predicting pressure transients in pressurized systems. A more detailed two-dimensional (2D) or three-dimensional (3D) model can be developed to capture losses and other geometric effects but requires increased effort to build and validate the model.

Equations governing 1D hydraulic transients are a pair of coupled, first-order partial differential equations involving continuity and momentum equations. Finite difference schemes can be used to solve the governing partial differential equations. However, it can be challenging to accurately capture flow discontinuities due to a numerical artifact characterized by fictitious large oscillations caused by the finite difference schemes. These oscillations are caused by the jump discontinuity in pressure and velocity because of a pressure transient event. These can be eliminated using the finite difference scheme such as the higher order upwind scheme. The method of characteristics in Appendix B can also be used to solve time-dependent flow problems that involve discontinuities in pressure and velocity without being affected by these artificial oscillations. In this method, the two partial differential equations of fluid motion, continuity, and momentum, are converted into four ordinary differential equations. These equations are then expressed in finite difference form and solved numerically. The method for the transient solution of flow can include viscous losses.

More advanced approaches have been developed and incorporated into fluid codes. One such code is the NASA Generalized Fluid Systems Simulation Program (GFSSP), which provides a recourse to 3D Navier-Stokes CFD analysis by constructing a fluid network consisting of a group of flow branches [ref. 6]. GFSSP is a general-purpose program for analyzing steady state and time-dependent flow rates, pressures, temperatures, and concentrations in a complex flow network. The program was primarily developed to analyze internal flow of turbopumps and transient flow of propulsion systems. GFSSP employs a finite volume formulation of mass, momentum, and energy conservation equations in conjunction with the thermodynamic equations of state for real fluids and energy conservation equations for the solid. The system of equations describing the fluid network is solved by a hybrid numerical method that is a combination of the Newton-Raphson and successive substitution methods [ref. 6].

8.3 Measurements of Pressure Transients

Instead of predicting pressure transient magnitudes using simple or sophisticated fluids models, it is possible to develop subsystem tests that incorporate Test-Like-You-Fly (TLYF) operational aspects (e.g., valve closure schedule). The test hardware can be instrumented with pressure transducers to characterize the behavior of pressure transients. It is not uncommon to gain an additional understanding of the system during flight tests and, later, during the life of the program. It is imperative that a judicious effort be applied in the design phase to minimize likelihood of unexpected or catastrophic responses during flight to reduce costly redesigns and delta-qualification. More importantly, relying on flight data late in the program to resolve pressure transient questions invites in-flight failures, which is an unacceptable approach for short production or one-of-a-kind spacecraft.

8.4 Case Studies Simulating Transient Events

Several case studies are presented illustrating the application of liquid transient codes to predict the response of the fluid due to transients. These cases are not intended to help in the design of propulsion systems, but are used to illustrate how 1D equations can be used to study pressure transients for various cases and to appreciate the magnitude and timescales of these pressure transients. The first case study simulates pressure transients entering a fluid storage vessel, while the remaining case studies simulate pressure transients in pressure components within a pressurized system.

8.4.1 Case Study 8-1: Pressure Transients Effects on Fluid Storage Vessel

Transients due to pressurized system operations generally have minimal effects on COPVs, MPVs, and pressurized structures, because these vessels are spacious and act as pressure boundary condition.

A case study is used to illustrate the pressure magnitude reducing as the pressure wave enters a fluid storage vessel. Note that depending on where the inlet/outlet manifolds are located, the pressure wave behavior may be 3D in nature. While understanding the pressure wave behavior within the fluid storage vessel can require a 3D or an axisymmetric fluid flow simulation, the problem can be treated as a quasi-1D problem.

The 1D fluid equations are solved using the method of characteristics described in Appendix B, except the flow rate Q is replaced by flow speed u, and the varying area A is a function of axial distance x. The flow area of the pipe will vary from a constant area in the pipe section to an increasing area due to the flare into the fluid storage vessel. The variable area term is retained to address quasi-1D flow, and the solution breaks down as the flow area grows to the point that the quasi-1D assumption is no longer valid.

The conditions analyzed are an initial flow rate of 0.088 lb/s, bottle pressure of 508 psi, pipe area of 0.62 in^2 and pipe entrance at the fluid storage vessel of 6.2 in^2. The speed of sound is 39,370 in/s, density is 0.036 lb/in^3 and it is assumed that the valve closes "instantaneously," Figure 6. The magnitude of the pressure transient from the Joukowsky equation is 14.5 psi.

Before valve closure occurs, the advection term will cause the pressure and velocity to vary across the region of area change. For ease of calculation, the advection terms were neglected. It is not possible to impose the correct initial conditions in the variable area region, so this is handled by only applying these conditions immediately before the wave reaches the variable area region.

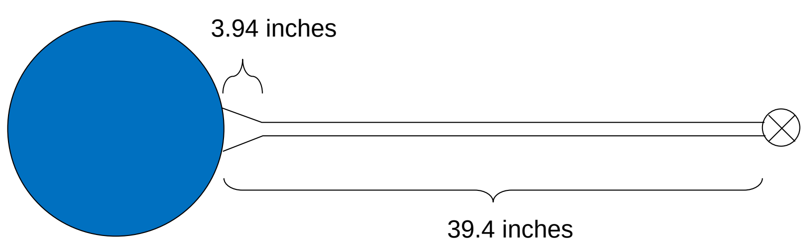

Figure 6. Schematic of Case Study: Fluid Storage Vessel, Flare, Pipe, and Valve

Since the method of characteristics also simulated an "instantaneous" valve closure, the method of characteristics correctly recovered the Joukowsky pressure of 14.5 psi as shown in Figure 7, thus validating the numerical model. A pressure transient travels from the closed valve through the tube to the fluid storage vessel due to valve closure. The pressure wave weakens as it enters the fluid storage vessel. The pressure transient wave travels until it reaches the transition from the straight pipe section to the fluid storage vessel. As expected, the pressure transient wave proceeds into the flare rapidly diminishing in magnitude while the expansion wave moves towards the valve. For this configuration, the pressure transient magnitude drops by 50 percent by the time it reaches the fluid storage vessel. This wave pressure reduction cannot be generalized to other geometries, fluid properties and flowrates, and should be calculated for each specific case. The pressure wave will further drastically reduce in magnitude and dissipate when it reaches the larger spacious fluid storage vessel immediately after the pipe flare.

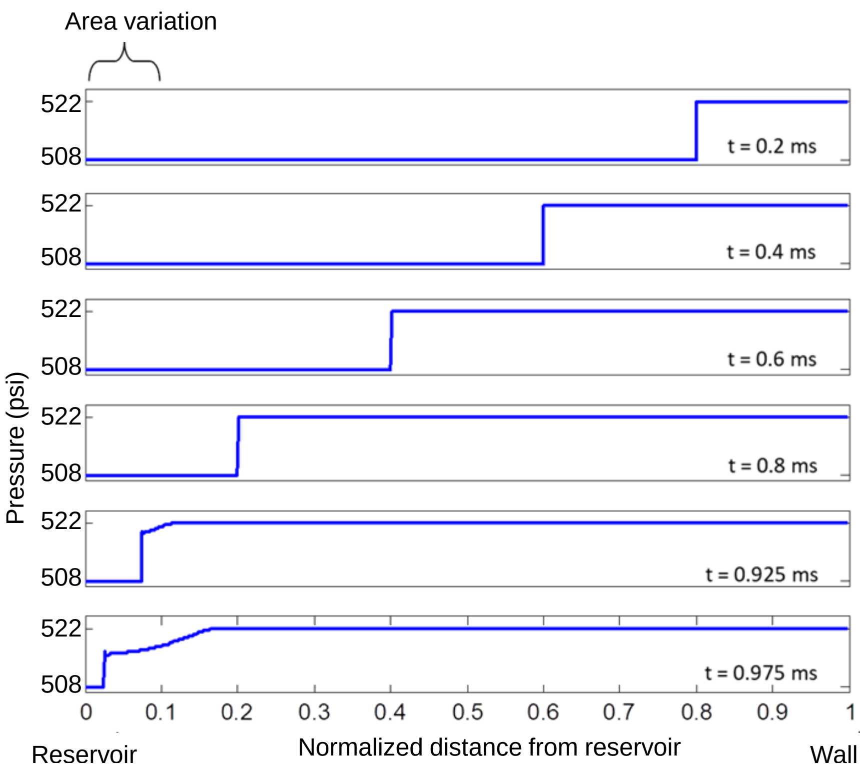

Figure 7. Fluid Storage Vessel, Flare, Pipe, and Valve

8.4.2 Case Study 8-2: Pipe Connected to a Single Valve

Two relevant examples of the application of GFSSP are documented in reference 7. The first example is a simulation of fluid transient following sudden valve closure. The example consisted of liquid oxygen at 500 psia and 200 °R flowing through a 400-ft-long, 0.25-in inside diameter pipeline at a mass flow rate of 0.1 lbm/s. The corresponding downstream pressure is 450 psia. At time zero, a valve at the end of the pipe begins a 100-ms rapid closure. GFSSP can simulate the liquid's response to the sudden valve closure, including the maximum expected pressure transient in the line.

The second example in reference 7 models the fluid transients in pipes due to sudden opening of a valve and deals with pressure transients in a pipe with entrapped air. This problem is different from the previous example as the flow regulating valve is suddenly opened as compared to suddenly closing. This example was validated against experimental data [ref. 7], as shown in Figure 8. The example problem considered a 1.025-inch-diameter long pipe attached to a fluid storage vessel filled with water. The pipe was closed at the other end. Entrapped air was considered in this problem. A valve separates the water from the air and is closed until about 0.15 s, and then gradually opens to 100 percent at about 0.4 s. The predicted peak pressure magnitude was within 7 percent of experimental data, while the frequencies of pressure oscillations were comparable.

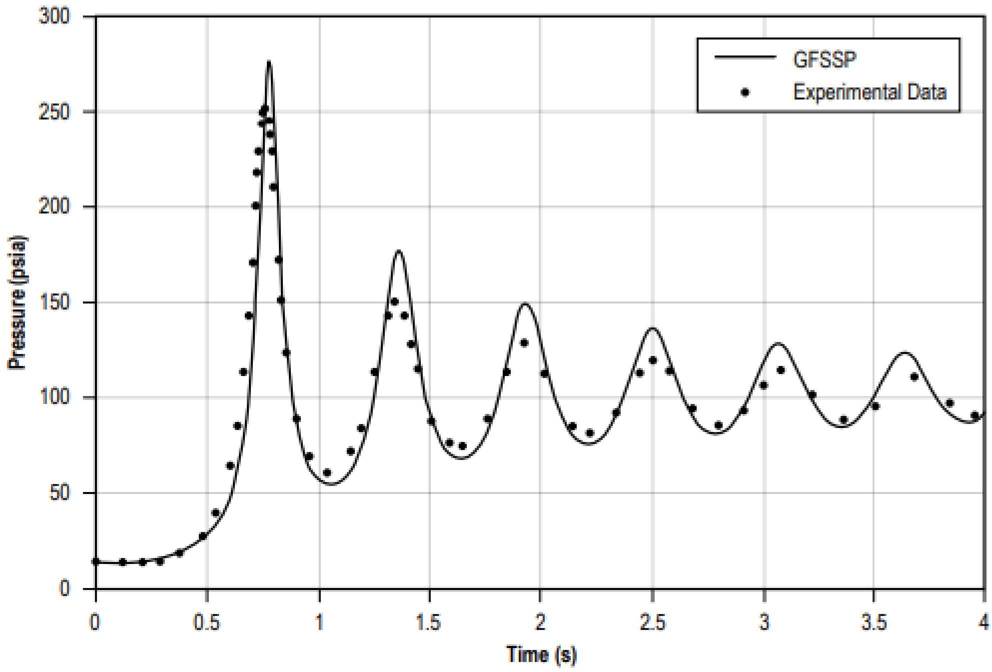

Figure 8. Example from Reference 7 Illustrating Good Correlation of GFSSP Pressure Transient Prediction Compared with Experimental Data for a Valve Suddenly Opening

A third example is considered. A single 1D fluid element is used to model the connection between a tank and a valve. Flow parameters selected are such that tank pressure is maintained at 200 psia with a LOX outflow rate of approximately 350 lbm/s. A single valve fluid node is assumed to be fully open initially and gradually close over 500 ms following a given characteristic valve closure profile, Figure 9.

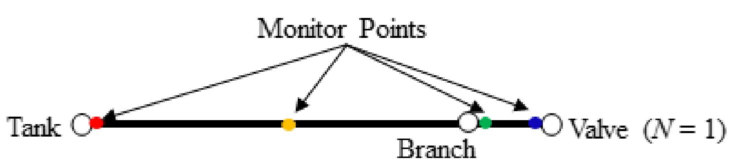

Figure 9. Tank Connected to a Pipe and Single Valve
Pressure is monitored at various points in the system.

Figure 10 shows the solution obtained from the 1D equations in Appendix B. For instantaneous valve closure, the solution matches the overpressure predicted by the Joukowsky equation. The gradual valve closure model predicts a pressure transient that is several times lower than the instantaneous valve closure model, demonstrating that the Joukowsky equation predicts a conservative pressure transient. The Joukowsky equation is often used in the preliminary design phase due to ease of use, but often, sophisticated models are conducted to reduce conservatism. This problem illustrates the timescales involved in analyzing pressure transient events.

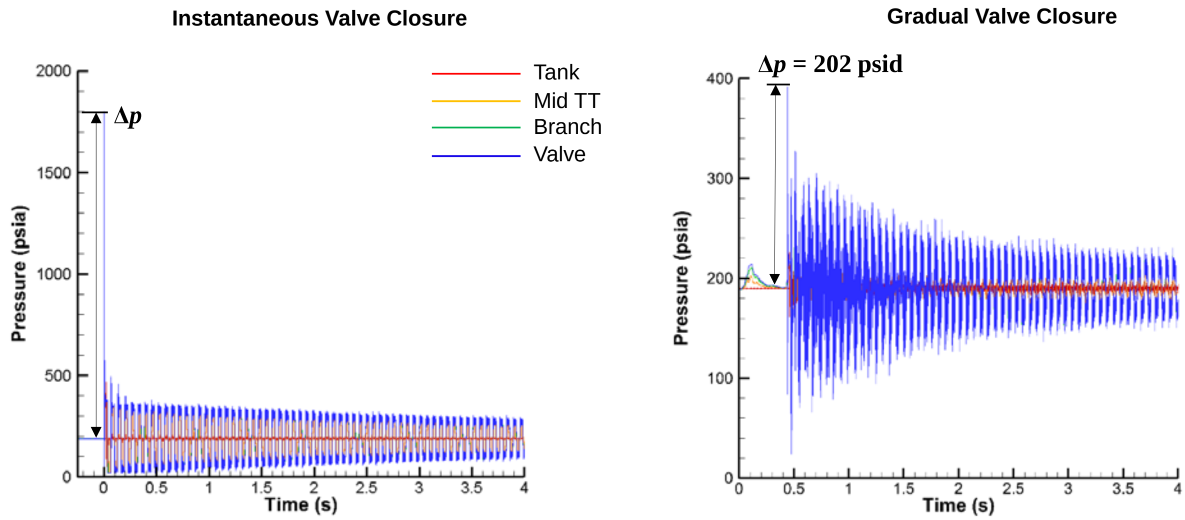

Figure 10. Pressure Responses Comparing Gradual Valve Closure with Instantaneous Closure

8.4.3 Case Study 8-3: Pipes Connected to Multiple Valves

Analysis was performed to estimate pressure transient overpressures due to valve closures in a pressurized system consisting of a network of pipes connecting to a single node. 1D fluid elements are used to model pipes that are connected by nodes, each of which represent a flow component (e.g., valves, orifices, tanks, and branches), Figure 11.

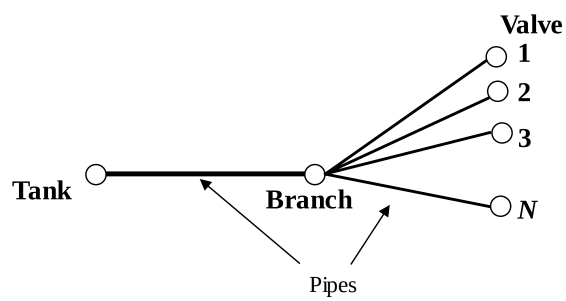

Figure 11. Tank Connected to Pipes and Valves

A single 1D fluid element is used to model the connection between the tank and the branch node. The pipes connecting the branch and the valve nodes are represented with 1D fluid elements. The branch node plays the role of a sump or manifold, but with no pressure loss across it. Flow parameters selected are such that tank pressure is maintained at 200 psia with a LOX outflow rate of approximately 350 lbm/s.

In this case study it is assumed that there are several valves (i.e., nodes), which close over 500 ms. The analysis predicts a pressure rise and oscillations, and the character of the pressure oscillations varies along the pressurized system, Figure 12. These predictions can be directly fed into a structural dynamic model to better understand any dynamic amplification resulting from the pressure transient loading. The process to evaluate the DAF due to pressure transients is discussed in Section 9 and illustrated through several case studies.

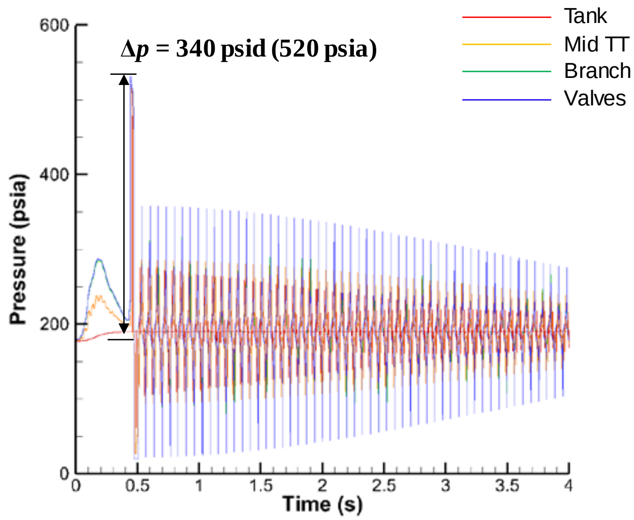

Figure 12. Predicted Pressure Rise for Several Valves Closing Gradually

8.5 Parameters for Estimating Pressure Transient ΔP

The Joukowsky equation requires the β – fluid bulk modulus, E – pipe modulus, D – pipe inner diameter, t – pipe thickness, and boundary factor C (Figure 4). The factor C depends on the Poisson's ratio (μ). The method of characteristics to solve fluid flow problems requires a subset of the parameters in Table 1.

Table 1. Typical Analyses Data to Estimate Dynamic Structural Response Due to Transient Event

Constituent	Data requirements
Piping	Configuration of pipe network, pipe lengths, inside diameter and wall thickness, elevation, Young's modulus of the pipe, pipe friction factor, design pressure
Valve	Closing and opening time, stroke speed, and relevant dynamic characteristics
Tank	Operating pressure, gas volume, tank geometry
Pump	Flow, speed, torque value, torque characteristics, design pressure, flow rates
Fluid	Bulk modulus, density, viscosity

9.0 Structural Dynamic Response

Objective: Present methods to predict or measure the amplification of the structural response due to transients and illustration via several case studies.

9.1 Physics of the Structural Dynamic Response

Pressure oscillations cause stress or strain oscillations. In addition, some pressure oscillations can occur at frequencies that coincide with the natural frequencies of the structure, thus setting up a resonant condition where stress magnitudes can increase with each oscillation. In particular, the structural responses of a component can be amplified by pressure transient events due to the following reasons:

1) The structural members of the component (e.g., pipe wall) oscillate in the wake of the pressure wave front, which produces local membrane and bending stresses within the component.

2) Pressure waves reflect back and forth within the pressure component and can excite the natural frequencies of the component (e.g., pressure waves excite the radial natural frequencies in a pipe wall).
3) Stress waves reflect at boundary conditions causing local stress fluctuations near the boundary conditions.

Leishear [ref. 8] investigated the maximum stresses due to pressure transients without damping using finite element models (FEMs). The models only studied stresses near the wave front. Those analyses indicated that at the pressure wave front, a sudden change in loading caused local bending moments in the pipe wall. Because stress is proportional to pressure and pressure differentials, stresses were generally lower away from the wave front. In addition, the strains in pipe walls were found to have local increases ahead of the pressure wave in the fluid because the stress waves in the structural solids traveled faster than the pressure wave in the fluid. In addition, even larger strain increases were observed behind the pressure wave front, producing a condition referred to as an aftershock, Figure 13.

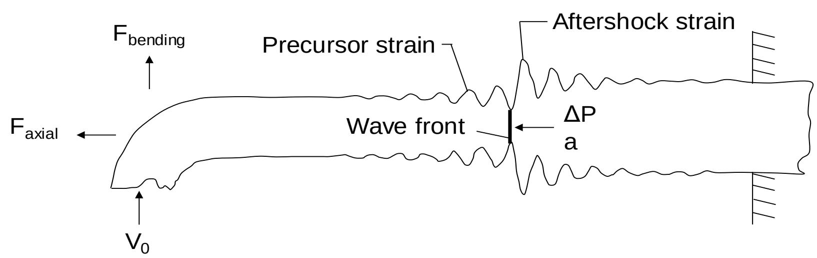

Figure 13. Schematic Illustrating a Precursor and Aftershock Strains in Vicinity of Pressure Wave Front

In addition, it was postulated by Cao [ref. 9] that longitudinal stress waves in a pipe can be generated by hoop stress oscillations caused by a pressure wave traveling the length of a pipe. The speed of a longitudinal stress wave is typically calculated as the speed of sound in the pipe structure, which can be at least two times the speed of sound in the working fluid. The longitudinal stress waves can cause a pipe to stretch or shrink. Experimental data confirmed that longitudinal stress waves occur in front of the predominant pressure waves [ref. 9]. Longitudinal stresses were measured to be smaller in magnitude than circumferential stresses, consistent with the Poisson's ratio of the pipe material. Recall that the magnitude of the contraction of a solid material in one direction (e.g., longitudinal direction) due to loading in the perpendicular direction (e.g., hoop direction) is defined as the Poisson's ratio of the solid material.

Significant aftershock stresses behind the dynamic pressure wave and smaller precursor stresses were reported in simulations presented in reference 8. An independent FEM was developed that simulated a transient event and confirmed the existence of aftershock and precursor stresses and is shown in Figure 14.

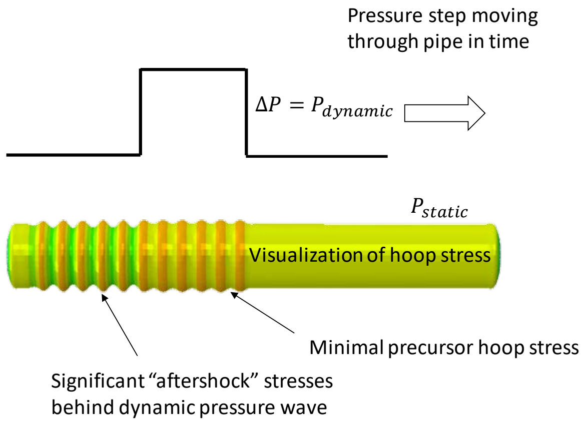

Figure 14. FEM Confirms Existence of Aftershock and Precursor Strains

9.2 Dynamic Amplification Factor (DAF)

The characteristics of the pressure transient can be such that the structure (1) minimally responds, (2) responds quasi-statically (e.g., slowly), or (3) responds dynamically with an amplification above the static response.

The DAF is a key factor in the approaches proposed for how to treat transient events. The DAF scales the static pressure load in a static analysis in such a way that it produces a stress level equivalent to that obtained by a dynamic analysis. The DAF is defined as the ratio of stress obtained in a dynamic transient analysis to that obtained by a static analysis.

Gradual pressure changes reduce the magnitude of the structural dynamic response. If the pressure is applied slowly enough, then the applied pressure is equivalent to a static pressure (i.e., DAF = 1.0). Resonance may occur if the pressure transient frequency is nearly equal to the piping natural frequencies or attached components, which may result in a DAF > 1.0. If the pressure is applied very rapidly and the structural response to this load is negligible, then it is possible that DAF is between zero and 1. Some programs have been successful in assuming that pressure transients are too fast for the plumbing to react so that DAF = 0.0, but this may not always be the case. Other programs ensure that the proof pressure bounds the peak pressure by effectively employing a DAF of 1. This could be an adequate assumption in cases where the frequency content of the pressure transient is lower than structural frequencies. An analytical methodology is presented in this section on how DAF can be estimated to verify these assumptions.

To illustrate the DAF concept an example calculation follows: A pipe is subject to a steady state pressure of 5,000 psi and a pressure transient with magnitude 1,000 psi:

1. The stress due to the steady state pressure was calculated as 10 ksi.
2. The resulting stress due to the steady state pressure in combination with the magnitude of pressure transient applied statically in a static analysis was calculated as 12 ksi.
3. The stress from a dynamic model applying the steady state pressure and the pressure transient resulted in 15 ksi.

Assuming the system behaves linearly, the three different approaches yield a DAF of 2.5:

1. DAF is calculated as (15 ksi – 10 ksi)/(12 ksi – 10 ksi) = 2.5.
2. The same assessment was performed but the dynamic analysis for step (3) was performed differently. The pressure transient was applied but not the steady state pressure, so the

stress from the dynamic model was calculated as 5 ksi. The DAF calculation in this case is (5 ksi)/(12 ksi – 10 ksi) = 2.5.

3. Step (2) is analyzed differently in that the static analysis considered the pressure transient magnitude and not the steady state pressure, which resulted in a stress of 2 ksi. The DAF calculation in this case is (15 ksi – 10 ksi)/2 ksi = 2.5.

The first method for calculation works for nonlinear material systems, while the second and third methods are limited to linear systems.

Many structural analysis and experimental observations indicate a DAF of 2.0 [refs. 10–12]. For example, the ratio of the dynamic response (i.e., pipe wall stress) to the static response of a mass-spring system, is equal to 2.0 [ref. 13]. In valves, the DAF can be less than 2.0 because precursor strains are not expected to form in the valve body [ref. 14]. Various approaches to estimate DAF are presented in Sections 9.3 through 9.7.

9.3 DAF Based on Single-Degree-of-Freedom (SDOF) System

Simple dynamic analysis can be performed to define the DAF. Most simplified approaches ignore the local stress response within the structure, including stress waves. However, the purpose of the following discussion is to illustrate that a SDOF system subject to a step load ("boxcar" function) can yield a DAF = 2.0.

Consider the pressure transient problem modeled as a SDOF system with one characteristic deflection. The equivalent mass and spring stiffness for an undamped system can be constructed. For the purposes of the foregoing discussions, the system natural period is T and τ is the duration of the step load. For τ much smaller than T, the response is small, and the structure has insufficient time to respond to the load. For some value of τ, the maximum DAF can be found to be 2.0 for the undamped case but could be smaller when damping is included. With τ much greater than T, the structure responds quasi-statically. Reference 15 provides the maximum response to various forms of the load inputs (e.g., triangular, sinusoidal). The DAF does not rise above 2.0 in the identified cases, but this is not unilaterally true for any general transient. A discussion on the dynamic behavior of hydraulic structures are found in reference 16, a discussion on simplified calculation methods and experimental investigations are shown in reference 17, and general techniques of structural dynamics for SDOF systems subject to shock loads are found in reference 18.

9.4 DAF based on Shell Vibration Equations

A more representative analysis approach is to consider shell vibrations due to a transient pressure load. Hoop stresses due to a moving shock front in either a gas- or liquid-filled cylinder can be approximated using vibration theory. Equations of motion combined with hoop stress equations provide insights into the phenomenon of flexural resonance, which creates pipe stresses significantly higher than the stresses expected from a slowly applied pressure loading. In references 19 and 20, approximate equations were presented to study stresses in a shock wave in a pipe. Vibration theory has provided a good approximation of the maximum hoop stresses and strains in a pipe wall, based on comparisons of theory to experimental data [ref. 21]. The DAF was found to be as high as 3.4 for an aluminum pipe. DAFs were shown to vary with respect to factors including wave velocity, location of measured strains, axial vibrations, damping, and the constraint conditions of the pipe ends.

The equations presented in references 19, 20, and 21 are applicable to other materials and pipe geometry, and the DAFs will change in accordance with the selected parameters. Values of the DAFs may approach 4.0 in some cases [ref. 22].

9.5 DAF Based on Finite Element Simulations

A system-level dynamic analysis can be performed to predict the dynamic amplification due to the pressure transient event. The first step is to characterize the fluid pressure wave as a function of time, and the travel time across the system. The pressure wave travel speed, amplitude, and shape, which contains the frequency content of the pressure wave, are important characteristics of the fluid that need to be defined in order to perform a structural dynamic analysis. The analysis should consider wave reflections from boundaries as it can result in further dynamic amplification.

The dynamic analysis can be frequency response spectrum, shock spectrum, time history, modal, or harmonic analyses. Assumptions can judiciously be made if data are unavailable, but it is recommended that any assumptions be based on equivalent or operational experience, test data, and/or sensitivity analysis. As guidance, typical analysis data to estimate the dynamic structural response due to a transient event are provided in Table 1.

A dynamic structural analysis that models the effects of traveling pressure waves requires significant attention to detail as modeling assumptions can result in erroneous DAF. The following guidance is provided when performing a pressure transient analysis:

1. Prior to computing the response for any case, it is instructive to examine typical pipe structural modes. Perform a modal frequency extraction procedure to understand the dynamic characteristics of the pressurized fluid system and guide decisions relative to analysis assumptions and inputs. Compare pipe finite element modeling predictions to theoretical predictions whenever feasible. These types of comparisons can identify issues with the modeling such as the errors in the use of inconsistent units. For a pressure wave traveling in a pipe, it is useful to compare finite element frequency predictions to the theoretical ring natural frequencies found in reference 23. The natural frequency of a ring/radial mode of a pipe requires defining pipe properties such as E (modulus), ρ (density), and r (radius) [ref. 23]:

$$f_n = \frac{\sqrt{E/\rho}}{2\pi r} \tag{3}$$

2. Characterize the pressure traveling wave input: magnitude, speed of travel, and character of the wave (e.g., square input, sine input, etc.), and ensure consistency in the dynamic model.
3. Incorporate any structural support to the piping system into the model, as stresses can be amplified at these locations.
4. Prior to the transient analysis, pressurize the system to ensure that pre-stress effects are considered, as these effects can suppress "ring" modes.
5. Select an appropriate initial FEM mesh size and time step in the simulation, and then perform a mesh and time step convergence studies to achieve confidence in DAF.
6. Perform a dynamic transient analysis to determine the system response from time dependent loads, which can include valve actuation rates.

7. Simulate the response of a simple traveling wave on a pipe to ensure the results are as expected and compare transient response against known analytical and experimental data [ref. 9, 20, 24] to ensure the model is anchored.

Six case studies are considered in Sections 9.5.1 thru 9.5.6 with the intent of illustrating that the DAF can be greater than zero or even greater than 2.0. All case studies demonstrate that the DAF depends on the pulse shape, frequency content of the pulse, and duration of the pulse relative to the structural modes. The pulse characteristics are driven by, for example, valve closure. The stress response reduces with increasing damping and can result in reduced DAFs.

9.5.1 Case Study 9-1

Consider the following pipe geometry: 36-inch length, 1-inch diameter, and 0.083-inch wall thickness. The aluminum modulus was selected as 10 Msi, Poisson's ratio of 0.3, density of 0.000254 lbf-s^2/in^4, and 2 percent structural damping. An Abaqus® axisymmetric FEM was developed to study the transient nonlinear response of a pressure wave traveling through the pipe, Figure 15. The natural frequency predicted by the model was within 2 percent of the approximate analytical solution in reference 23. A static finite element analysis with 5,000 psi internal pressure was followed by a dynamic implicit analysis that simulated a traveling wave in a pipe constrained at both ends. Four types of transient traveling waves were considered: half-sine wave, square, unit step, and unit step with reflections against the wall, Figure 16. The magnitude of the pressure transient was 1,000 psi for the half-sine wave and 600 psi for the square wave such that the area under the pressure-time curve was equivalent. The methodology on how to implement the traveling pressure wave within the Abaqus® finite element software is provided in Appendix C.

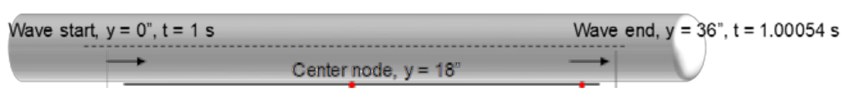

Figure 15. Traveling Pressure Wave Profile at 0.1 ms
The dashed line represents the centerline of the pipe for an axisymmetric model.

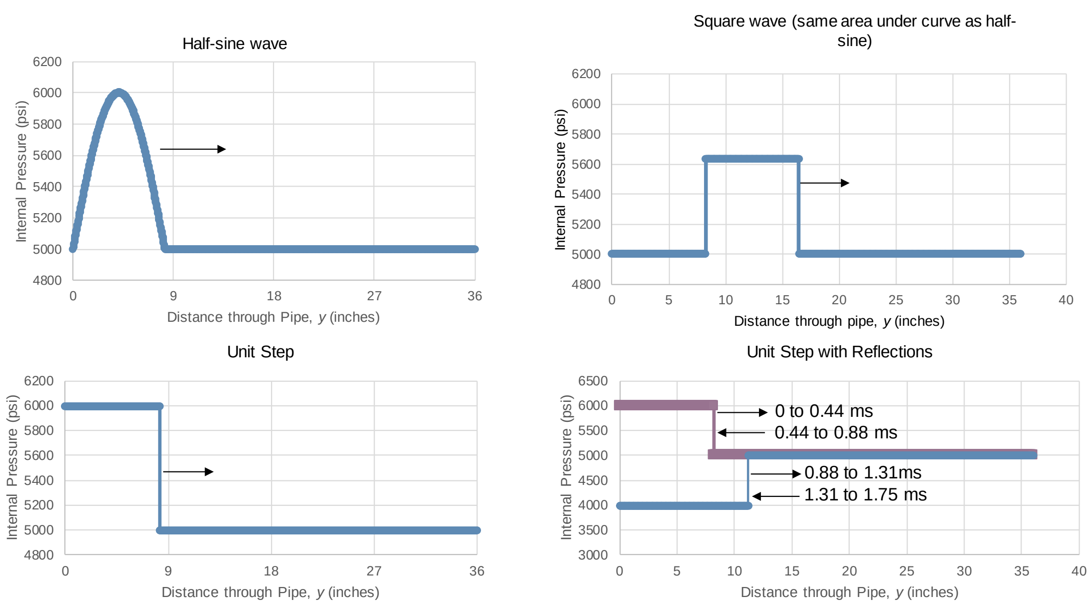

Figure 16. Traveling Half-Sine Wave (top left), Square Wave (top right), Unit Step (bottom left), and Unit Step with Reflections (bottom right)

Figure 17 shows the half-sine traveling pressure wave profile at 0.1 ms. In this case study, the static stress from the steady-state 5,000 psi pressure was calculated as 33 ksi. The static stress that would have resulted from applying the pressure transient of 1,000 psi as a static load was calculated as 6.6 ksi. The maximum dynamic stress considering the dynamic nature of the load and the static steady-state pressure was 40.3 ksi, as shown in Figure 18. Therefore, the DAF was calculated as (40.3 ksi – 33 ksi)/6.6 ksi = 1.1.

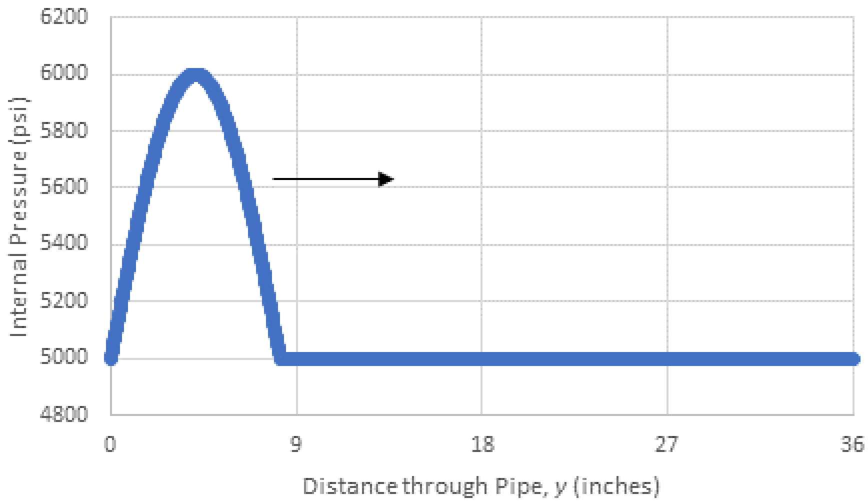

Figure 17. Half-Sine Traveling Pressure Wave Profile at 0.1 ms

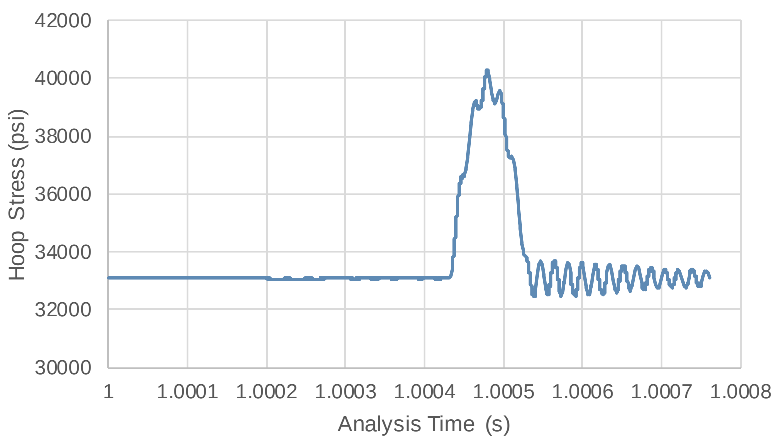

Figure 18. Hoop Stress Response as a Function of Time at a Point on Surface of Pipe Subjected to Half-Sine Pressure Transient Pulse of 1,000 psi.

Table 2 shows the DAF for a straight pipe subjected to the four pressure profiles in Figure 16. The DAF is presented for two locations, one at the center of the pipe length and one at the “peak response” location. The DAF values in Table 2 correspond to the maximum stress at any point in time. The peak response location was at the boundary where there is a local bending caused by wave interference and reflection. The DAF away from the boundary is near 2.0.

Table 2. Dynamic Amplification Factor for Various Wave Types

Wave type	Center Node DAF	Peak Stress Node DAF	Peak Stress Node Distance from Start
Half-sine	1.1	1.1	35.4"
Square	1.9	3.6	35.01"
Step	1.9	2.9	35.03"
Step with reflections	1.9	2.9	34.18"

9.5.2 Case Study 9-2

Starting with the model from Case Study 9-1, a parametric study was performed to investigate DAF and the relationship between forcing frequency and ring natural frequency subjected to the same half-sine pulse as used in Case Study 9-1, shown in Figure 17. In this case study, ω^* is defined as the ratio of pressure wave frequency to the ring natural frequency of the pipe in rad/s.

$$\omega^* = \frac{\omega}{\omega_n} = \frac{r\omega}{\sqrt{E/\rho}} \quad (4)$$

Twenty-eight models were generated varying r, E, ρ, wall thickness, and wave speed. The maximum stress during the transient response was used to compute a DAF against the equivalent static stress prediction.

Figure 19 shows the DAF relationship when the forcing frequency approaches the pipe radial natural frequency, or when $\omega^*$is near 1.0. A DAF of 2.0 is shown to be present for values of ω^* near 1.0, and a DAF = 1.0 for quasi-static responses for low values of ω^*, and minimal amplification for values of ω^*significantly greater than 1.0. In Case Study 9-1, the geometric and material conditions resulted in an $\omega^* = 0.08$, which matched the predicted DAF of 1.1.

Many spaceflight pipe configurations will result in a ω^* below 0.1 due to parameters such as typical wall thickness and material densities. The conditions of each individual system need to be evaluated to determine the system's sensitivity to the loading conditions in question. The presentation of DAF in Figure 19 can be useful to develop design curves.

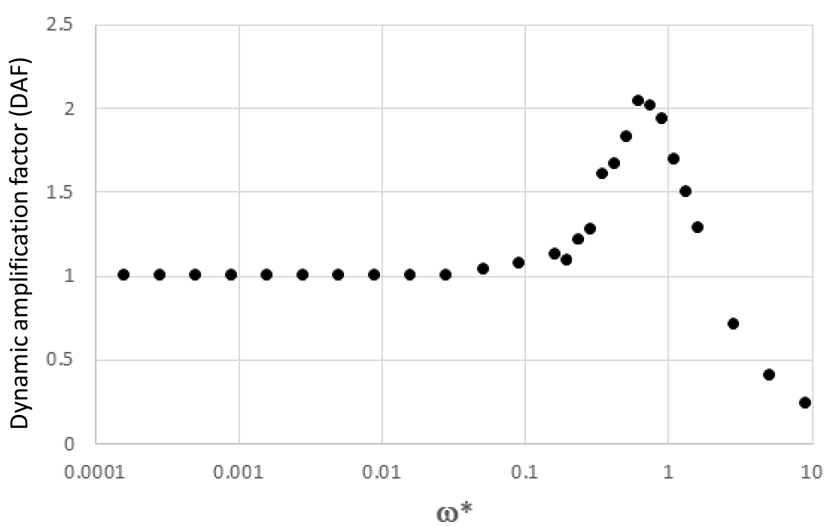

Figure 19. Parametric Study Leveraging Case Study 9-1 to Illustrate DAF for a Range of Frequency Ratios

9.5.3 Case Study 9-3

The dynamic structural response due to a traveling pressure wave can be performed using a plane strain finite element analysis (FEA) of the pipe cross-section rather than three dimensional models. A thick cylindrical pipe under a plane strain boundary condition is analyzed. The pipe has an outer diameter of 0.25 inches, an inner diameter of 0.194 inches, and a Poisson's ratio of 0.3. Since plane strain boundary conditions are applied (i.e., both axial ends can only expand radially), all the structural modes of vibration are in the plane of the cross section, similar to a SDOF problem where the degree-of-freedom is radial expansion. A pressure is applied along the inside radius as a half-sine or a rectangular wave for a specified duration, after which the pressure drops to zero. The hoop stress at the inner diameter is computed, and the peak value during the simulation is divided by the hoop stress arising from applying a pressure statically.

Conceptually, Case Study 9-3 presents similar conclusions to Case Study 9-2, where dynamic amplification is plotted against the relationship between forcing frequency and pipe radial natural frequency. Case Study 9-3 specifically shows how the DAF can vary over a range of frequency ratios for varying wave shape. The maximum DAF was found to be near 2.0 for both wave shapes. However, the rectangular wave shows an amplification over a much larger frequency ratio range, Figure 20. The dynamic response for a square wave is more complicated than a half-sine wave because the Fourier transform representation of the square wave contains many more frequencies than the single frequency represented by the half-sine wave, which only has one peak.

Notable limitations in this plane-strain analysis method include no considerations for boundary reflections or mode shapes in the axial direction.

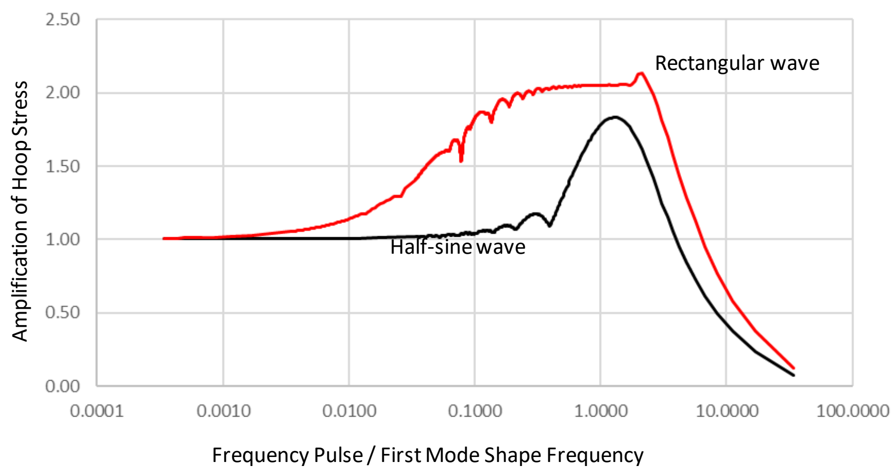

Figure 20. DAF Due to Pressure Pulse for a Rectangular Wave and Half-Sine Wave

9.5.4 Case Study 9-4

In this case study, a traveling wave in an axisymmetric pipe with an inside radius of 0.097 inches, outer radius of 0.125 inches, and length of 12 inches is considered. At the left edge of the pipe a rectangular wave is initiated. The wave travels across the pipe at a speed of 39,370 in/sec. Ahead of and behind the pulse, the applied pressure is equal to zero, and only the elements within the zone of the moving pulse have a finite pressure applied. This traveling wave in a pipe using an axisymmetric model inherently results in a more complicated dynamic response compared to the plane strain model in Case Study 9-3, because the traveling pulse has the capability to also excite longitudinal structural modes of the pipe. For the assumed geometry and material properties corresponding to steel, the first set of structural modes are associated with pipe flexural modes. The maximum DAF for this case study was determined to be 1.3.

9.5.5 Case Study 9-5

In references 8 and 22, a study to understand dynamic stress response in steel and aluminum pipes due to a step pressure input was analyzed using the Abaqus® software. FEA was used to determine the hoop, axial, and radial stresses in the pipe wall. FEA results were evaluated to find the stresses in the pipe wall and the maximum stress on the inner pipe wall. In these references, the maximum dynamic hoop stress was twice the magnitude of the static stress that would be expected from an equivalent static load (DAF = 2.0) regardless of boundary conditions at the pipe end. The analyses in these references captured the complicated nature of axial stresses and their wave reflections.

9.5.6 Case Study 9-6

In reference 9, a reservoir-pipe-valve system with a horizontal pipe connected to an upstream reservoir, and a valve located downstream of the pipe was considered. In this study, prior to valve closure, the flow in the pipe had a constant velocity. Immediately after sudden valve closure, the flow stopped and the pressure in the vicinity of the valve increased significantly. The increased pressure traveled back and forth between the valve and reservoir before it damped out. The authors developed a model to study the transient response using the Abaqus® solver and using axisymmetric shell elements. The time increment in the transient simulation was based on the relative value of the Courant number and the pressure transient wave speed. The studies presented in this reference, demonstrated that viscous damping played a crucial role in the stress predictions. Simulations were performed with structural damping ratios as high as 3 percent. The constant-average-acceleration finite difference time integration scheme was selected. Analysis indicated that the speed of the longitudinal stress wave is that of the sound speed in the pipe and nearly four times the pressure wave speed in water. The DAF was found as a function of normalized valve closure time, which was defined as the valve closure time multiplied by the excitation ring frequency.

9.6 DAF Based on Fluid-Structure Interaction (FSI) Analysis

In reference 25, a comprehensive study was performed that collected and discussed numerical and experimental research work in the field of FSI. A novel frame of reference for the classification of FSI models based on pipe degrees-of-freedom was presented. Further, this reference organized numerical research according to this classification, while an extensive review on experimental research was presented by institution. This reference also described the role of FSI models in the analysis of historical accidents. The authors demonstrated, numerically and experimentally, that FSI may generate overpressures higher than values estimated by the Joukowsky equation.

Physics of FSI phenomena are challenging to implement in common engineering practices and involves the potential risk of underrated designs. While no specific recommendations are provided relative to this finding, it is important that the designer be aware of the potential for fluid-structure interaction effects.

9.7 DAF Based on Tests

Specialized bench tests can be conducted in a test configuration involving a high-pressure fluid storage vessels, pipes, and valves simulating the pressure transient loading. The test configuration requires instrumenting the part with accelerometers, strain gages, and pressure transducers. The sampling rate selected should be sufficient to capture the full fluid, dynamic, and structural response to appropriately quantify DAF. TLYF principles apply and should attempt to induce a pressure transient in a flight-like hardware configuration in terms of fluids, geometry, length, materials, and other relevant materials. These tests provide data to benchmark analysis approaches. In addition, the data can be used to conduct sensitivity studies relative to effects of valve closure characteristics on the resulting structural dynamic amplification.

In reference 20, a study was conducted to measure and predict the structural response due to transient loading. The load was characterized by a step pressure propagating axially in the gas within the shell. The moving load excited flexural waves in the shell and produced a net radial deformation due to the difference in pressure across the shock wave. Calculations and experiments to characterize the structural response of a shell to internal transient loading were presented. In their experiments and FEA, strains exceeded the static strain by a factor of up to 3.5.

Several references related to experimental methods are discussed in reference 9 and a relatively common test setup is described in reference 24.

10.0 A Survey on the Treatment of Pressure Transients in Aerospace Standards

Objective: Provide a brief survey of the treatment of pressure transients in various Aerospace Standards.

All industry aerospace standards require defining the system MEOP to enable the verification of structural design test and analysis requirements. Qualification, acceptance, and analysis structural verification requirements rely on the appropriate definition of MEOP, which may include pressure transients. In this section, a discussion on how transient events are treated within the various aerospace standards is presented.

10.1 AIAA-S-080A

The AIAA-S-080A [ref. 26] standard for “Space Systems—Metallic Pressure Vessels (MPV), Pressurized Structures, and Pressure Components,” require MEOP be considered as: “The pressure system shall be analyzed to determine the maximum expected operating pressure (MEOP) throughout the service life. The system analysis shall account for the effects of temperature, transient peaks, vehicle acceleration, and relief device tolerance.” This definition requires a system analysis to account for the effects of pressure transients that generally occur in pressurized systems.

10.2 International Organization for Standardization (ISO) 10786:2011

ISO 10786:2011 [ref. 27] “Space systems — Structural components and assemblies,” states that the MEOP includes the effects of temperature, transient peaks, relief pressures, regulator pressure, vehicle acceleration, phase changes, transient pressure excursions, and relief valve tolerance. Similar to AIAA-S-080A, this standard requires that the MEOP include the effects of transient pressure excursions.

10.3 NASA

NASA-STD-5001B [ref. 28] states that the MEOP shall include “the effects of temperature, transient peaks, vehicle acceleration, and relief valve tolerance.” The document defines the term Maximum Design Pressure (MDP) as the highest possible operating pressure including transient pressure excursions. MDP, in the NASA vernacular, includes some aspect of fault tolerance. Traditionally NASA has set MDP for human-rated systems based on two credible failures that will affect pressure. For non-human systems, MDP has been set to be equal to MEOP.

NASA Johnson Space Center (JSC) 65828 states "that the MDP for a pressurized system is the highest pressure defined by the maximum relief pressure, maximum regulator pressure, maximum temperature and transient pressure excursions based on two credible system failures."

10.4 European Cooperation for Space Standardization (ECSS)

ECSS-E-ST-32C Rev. 1 [ref. 29] defines MEOP "as the highest pressure that a system or component is expected to experience during its mission life in association with its applicable environment" with a note stating "that the effect of pressure transient is assessed for each component of the system and used to define its MEOP". The document requires an assessment of the effect of pressure transients to define MEOP.

ECSS-E-30 Part 5.1A [ref. 30] requires that the MEOP be assessed for pressure transients and that the propulsion system account for the potential pressure transients to avoid performance issues and possible structural damage.

10.5 - Space and Mission Systems Center (SMC)

Per SMC-S-005 (2015) [ref. 31], analysis is performed to establish the MEOP and includes leak rates, flow rates and other relevant performance parameters for all pressurized hardware within the pressurized system. For systems with zones operating at different pressures, the MEOP for pressure components and/or pressure vessels within each zone is determined. Examples of zones include portions of a system upstream and downstream of a pressure regulator and portions of a system isolatable by closure of a valve. The MEOP includes variation of pressure with temperature during the service life; system pressure rise allowed due to valve back pressure relief, regulator lockup behavior, and relief valve settings; vehicle acceleration; and required fault tolerance aspects that affect maximum pressure.

Single-fault tolerant systems with a pressure regulator must include the increased pressure provided by the redundant regulator stage lockup condition as the primary stage failure must be tolerated as part of the expected condition.

MEOP definition for pressurized structures and pressure vessels need to include the peak transient but to note that "hydraulic transients typically have little magnitude within a pressure vessel; while MEOP may not include pressure transients in pressure components if it only persists for a fraction of a second." Here, hydraulic transients relate to priming surge and water hammer, which are both incompressible fluids. The intent was not to cover gas systems with a pneumatic transient.

SMC-S-005 defines the peak magnitude of pressure transient "as maximum value of a pressure wave associated with the sudden opening or closing of a valve or with ignition, and that persists for only a fraction of a second."

SMC Launch Enterprise also developed LE-T-012 "Tailoring of Structural Standards" [ref. 32] to tailor the definition of peak transient in SMC-S-005 to provide further clarity: "The maximum value of a pressure wave in a system filled with liquid and associated with the sudden opening or closing of a valve. Such transients generally persist for only a fraction of a second and their magnitude is drastically reduced when transmitted to locations containing gaseous species and/or flexible walls.” The word “generally” was added relative to SMC-S-005, while the definition was expanded to be more comprehensive.

10.6 Federal Aviation Administration (FAA) Advisory Circular (AC) and Federal Aviation Regulations (FAR)

FAA AC 33.64-1 Guidance for Pressurized Engine Static Parts [ref. 33] uses “normal working pressure,” “maximum working pressure,” and “maximum possible pressure” and require pressure surges be considered from normal operation of valves and orifices. In FAR 25 – 25.979 [ref. 34] “maximum pressures” in fueling systems are to include surge likely to occur during fueling, and the maximum surge pressure is established with any combination of tank valves being either intentionally or inadvertently closed.

However, FAA’s AC 25.1435-1 [ref. 35] for hydraulic systems states that the Design Operating Pressure is to include transients, but short-term transients can be excluded from the strength assessment. However, short-term pressure transient must be included in fatigue life assessments.

10.7 Discussion and Industry Practice

All standards and regulations require that pressure transients be assessed or considered when defining MEOP. There is limited guidance on the treatment of transient events in the structural verification process and so that has led to some discussion on how to best approach this problem.

Likelihood of damage due to transients really depends on the frequency characteristics of the structural system compared to the pressure wave characteristics. Various points of views in the aerospace community have circulated as to what constitutes a transient event if it is on the order of microseconds or several milliseconds. When defining MEOP, some aerospace programs have ignored transients (i.e., DAF = 0) or added the steady state pressure to the pressure transient magnitude (i.e., DAF = 1.0). This body of work suggests that DAF can be greater than zero and even greater than 1.0. It is possible that the proof (e.g., 1.5) and burst factors (e.g., 2.5 or 4.0) applied to the MEOP in the structural verification process of pressure components may have inadvertently protected for situations where the amplified structural dynamic response was significant (e.g., DAF $\geq$ 1).

Common practice in satellite systems has been to allow peak pressure to be above MEOP but below proof. Specifically, Department of Defense (DoD) programs have not allowed the peak pressure transient to exceed the proof pressure, while some commercial programs have allowed it. Standard spacecraft bus configurations for many DoD programs, NASA spacecraft, and commercial spacecraft have not reported failures caused by pressure transients when the peak pressure was enveloped by proof pressure and those programs did not use the DAF concept. However, it is unclear whether the DAF in those applications was less than 1.0 or the proof and burst factors specified in AIAA-S-080A for pressurized components may have inadvertently protected components from failure.

New applications deviating from standard bus heritage practices require a closer understanding of DAF. When the proof pressure does not envelope the peak pressure transient or the DAF concept is not adopted, then risk mitigations need to be put in place and can include robust qualification test program, analysis, inspections, and adopting designs that are not susceptible to workmanship issues.

Per analytical simulations and experimental data, the structural response can be affected even if the pressure transients persist only for a short time (e.g., fractions of a second). It is argued that instead of a subjective time threshold to define a pressure transient, the structural impacts be evaluated using physical models or through measurements. In Section 9.0, methods for determining whether an amplified dynamic structural response were presented. In the next section, two approaches are presented on how pressure transients may be treated in the structural verification process.

11.0 General Workflow for the Treatment of Transient Events

Objective: Present approaches on how transients can be accounted for in the structural verification process with accompanying example applications.

The design of a pressurized system is complicated and requires an iterative process across disciplines. Therefore, communication across disciplines is paramount in ensuring the pressurized system is robust. The step-by-step process to treat pressure transients in pressurized systems is presented in the workflow depicted in Figure 21. Light blue color boxes represent those activities typically performed by the fluid dynamics/propulsion discipline, the gray boxes are those performed by the dynamics discipline, and the light green boxes correspond to those performed by the structures discipline. The steps do not need to track a sequential order and are explained in the following sections.

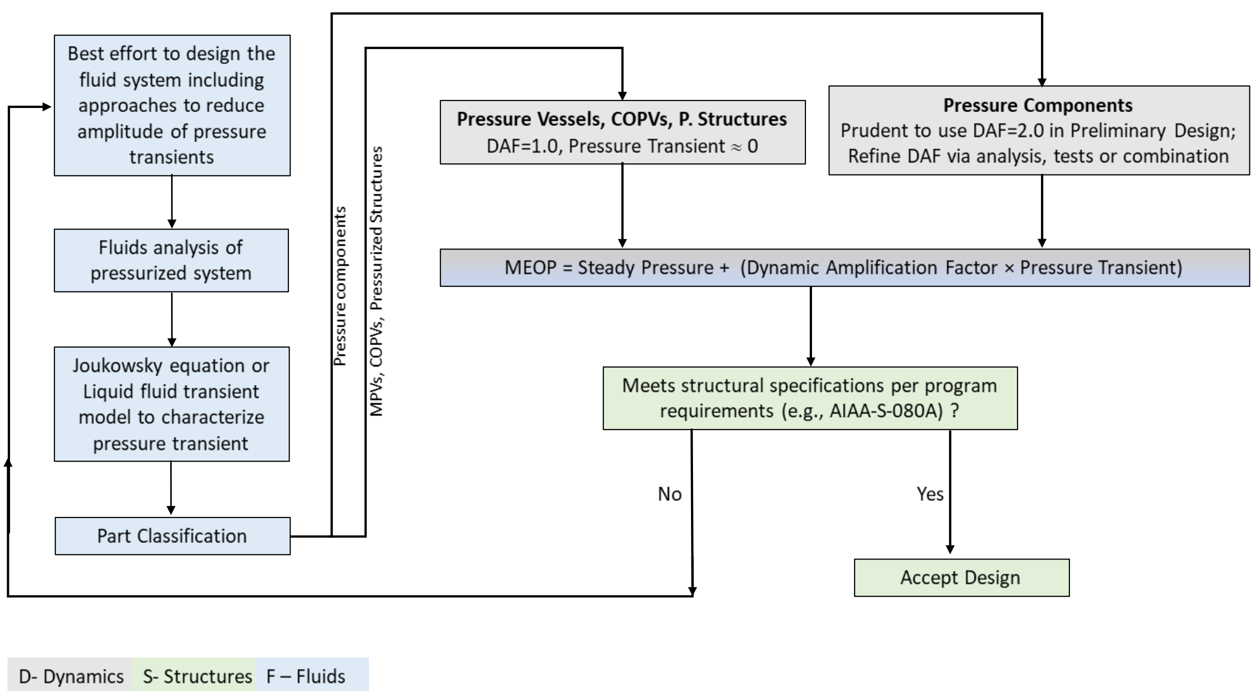

Figure 21. General Workflow for Design and Structural Verification of Pressurized System Hardware

11.1 Step 1 – Pressurized System Design

Mitigation strategies should be employed in fluid system design to minimize the pressure transient magnitude. These strategies were presented in Section 7. These strategies include sizing of pipes and fittings, selection and location of control devices, and procedures to manage the startup, operation, and shutdown.

11.2 Step 2 – Pressure Transient Characterization

A fluids analysis of the pressurized system is conducted to characterize pressure transients. Three methods were discussed in Section 8:

1. Joukowsky equation: The Joukowsky equation tends to be conservative and can provide an upper bound on the magnitude of the pressure transient ΔP. The calculation requires β – fluid bulk modulus, E – pipe modulus, D – pipe inner diameter, t pipe thickness, and boundary factor C (Figure 4). Factor C depends on the Poisson's ratio (μ).
2. Method of characteristics: A liquid fluid transient model using the method of characteristics provides a less conservative and more accurate estimate of the pressure surge and should be pursued whenever feasible. This model generally requires all or a subset of parameters in Table 1.
3. Testing: Pressure transients can be measured using pressure transducers from flight-like bench testing, which simulate operations of the pressurized system (e.g., valve schedule).

Fluid pressure transient characterization is key in DAF development. The pressure wave speed, frequency, amplitude, and shape are important characteristics that need to be defined to perform a structural dynamic analysis. The analysis should consider wave reflections as it can result in further dynamic amplification.

11.3 Step 3 – Part Classification

The DAF depends on the part classification. Figure 22 provides a decision diagram that allows determination on whether the part is intended for fluid storage or if it acts as a pressure component. Pressure components are intended to primarily sustain fluid pressure and are a conduit for fluid transfer. Examples include valves, fittings, regulators, and lines. Parts intended for fluid storage include COPVs, MPVs, and pressurized structures. Pressurized structures are intended for fluid storage but carry vehicle structural loads.

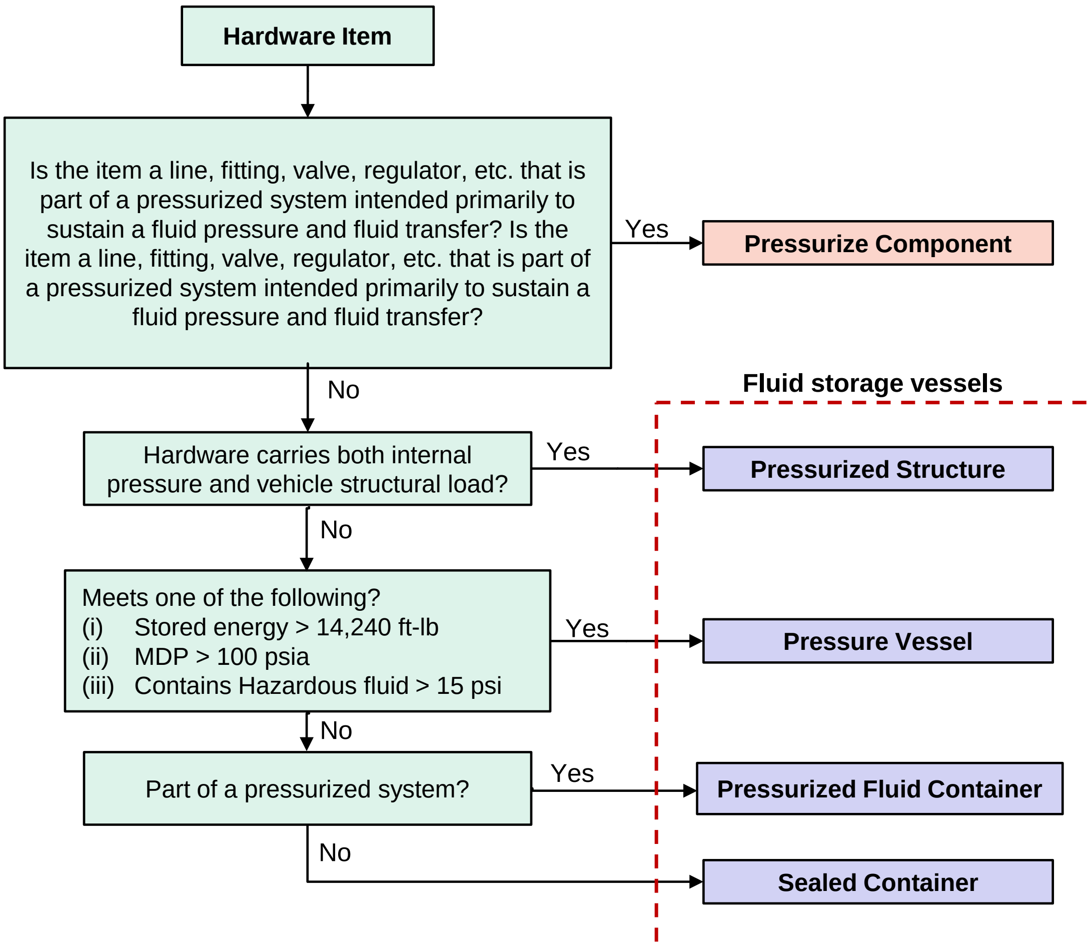

Figure 22. Part Classification into Fluid Storage or Pressure Component

11.4 Step 4 – DAF Calculation

11.4.1 DAF for Fluid Storage Vessels

The DAF for parts intended to store fluid is 1.0, as pressure transient magnitudes tend to be small compared to the fluid pressure. COPVs, MPVs, and pressurized structures are considered storage vessels based on their relatively large volume. It is unlikely that a pressure transient due to flow disruptions will be of significant magnitude. Pressure transients in these systems are likely to result in a static response.

Pneumatic fluid storage parts, such as COPVs, are unlikely to experience significant stress due to overpressure waves because the waves will be small in magnitude. The reason is that the density and sound speeds are low, and the overpressure is proportional to density and sound speed.

Generally, impacts to mass penalty are expected to be minimal, and so it is recommended that a DAF = 1.0 be used when structurally assessing COPVs, MPVs, and pressurized structures. As an example, if a COPV was pressurized to 5000 psi, and a pressure wave entered the vessel with magnitude 100 psi, the structural evaluation should be performed by considering a total pressure of 5100 psi.

Primary structures like pressurized structures (e.g., stage tanks) rarely experience pressure transient type events due to disruptions in the flow. However, these structures experience vehicle accelerations and dynamic transients from flight events (e.g., liftoff, main engine cutoff, etc.) and from atmospheric flight loads. A comprehensive fluid and structural analysis should be performed to quantify the dynamic amplifications when there is uncertainty on the effects of the pressure transient within the fluid storage vessel.

11.4.2 DAF for Pressure Components

In the preliminary design stages, specifically for pressure components (e.g., valves, lines), the designer may not have sufficient information to determine the system's structural response. Without configuration-specific analysis or testing for a pressure component, it is recommended that the maximum attainable value of DAF be computed based on a sensitivity study such as the one described in Case Study 9-2, Section 9.5.2. Further, if the frequency content of the pressure transient is much greater than any of the structural frequencies, then the DAF is likely much less than 1.0. Applicable data from heritage systems can be leveraged to estimate DAF. With no information available, it is prudent to use a DAF = 2.0 in the preliminary structural design process as many structural analysis and experimental observations indicate a DAF of 2.0 [refs. 10–12].

Higher-fidelity structural models are recommended to refine the value of DAF as this factor can range from near zero to values greater than 2.0 in certain applications. As more information is known about the structural and fluid design, this factor can be appropriately refined. The DAF is crucial in establishing target pressure levels required for the verification of structural requirements. The DAF can be measured by specialized tests or predicted using analytical procedures presented in Section 9. The following information is required when using the finite element procedure to estimate DAF:

a. Geometry of the pressurized system.
b. Pressure transient pulse shape, frequency content of the pulse, and duration. This information needs to be requested from the fluid mechanics/propulsion disciplines.
c. Steady state loads.
d. Boundary conditions that could cause waves to reflect.
e. Material properties including modulus of elasticity, density, and damping.

11.5 Step 5 – Establish MEOP

Typically, the MEOP is defined by the fluids and propulsion teams with minimal or no input by the structural analyst. The structural analyst should ensure that the loading conditions are well-understood and are properly defined for analysis or test rather than blindly adopting them from a different discipline. Structures, structural dynamics, and propulsion disciplines should work as a team to ensure the structure is safe for all expected loads, both static and dynamic.

Depending on the analyst/designer, the MEOP may include, partially include, or ignore pressure transient effects. A common justification to ignore the pressure transient effect in establishing MEOP is that it is assumed that a pressure transient lasting only a fraction of a second can be ignored. One of the goals of this document is to raise awareness that even fast-moving pressure transients can cause an amplified dynamic structural response.

Burst and proof pressure test levels are determined based on the value of MEOP and the burst/proof factors specified in structural standards. For this reason, it is important that an integrated cross-disciplinary team of engineers work to ensure that the assumptions behind MEOP are understood and appropriately defined.

Besides pressure transient effects, MEOP, per AIAA-S-080A, need to include other effects such as the effects of temperature, vehicle acceleration, and relief device tolerance.

However, there is always the problem of how to handle dynamic loading events such as pressure transients from the static point of view. Stated another way, how can dynamic loads such as time dependent pressure waves be converted to static-equivalent loads or otherwise accounted for?

The approach undertaken for the treatment of pressure transients is analogous to the way launch vehicle and spacecraft designs are generally qualified. The design is qualified by analysis and test using a limit load definition that considers the effects of static loads and quasi-static loads from coupled loads analysis.

The following recommendation is provided on how pressure transients can be incorporated in the MEOP definition to correct for dynamic stress effects in a way similar to how MEOP is corrected for temperature and acceleration effects. The MEOP can be defined mathematically as follows:

$$\text{MEOP} = \text{Steady state Pressure} + (\text{DAF} \times \text{Magnitude of the Pressure Transient}) \qquad 5$$

In this way, the pressure transient effect is accounted for by defining MEOP through the determination of the DAF. The DAF scales the static pressure load in a static analysis in such a way that produces a stress level equivalent to that obtained by a dynamic analysis. The DAF is defined as the ratio of stress obtained in a dynamic transient analysis to that obtained by a static analysis. The proposed recommendation does not correct MEOP for dynamic amplification from external vibration sources, as these vibratory loads typically affect component interfaces. Consider the following three cases intended to illustrate how the MEOP changes depending upon the behavior of the transient in a pressure component. Recall that for fluid storage vessels, DAF=1.0. In all cases it is assumed that the pressure wave is a half-sine pulse and that Figure 19 is applicable. The parameter ω^* is defined as the ratio of pressure wave frequency to the pipe radial natural frequency in Equation 4. The steady state pressure is 5,000 psi and the pressure transient amplitude is 1,000 psi.

Case 1 $\omega^* \sim 0$: According to Figure 19, DAF is calculated as 1.0. Therefore, MEOP is defined as follows: MEOP = 5000 psi + 1.0 × 1000 psi = 6000 psi. There is no dynamic amplification and the structure responds statically to the traveling wave.

Case 2 $\omega^* \sim 1$: According to Figure 19, DAF is calculated as 1.8. Therefore, MEOP is defined as follows: MEOP = 5000 psi + 1.8 × 1000 psi = 6800 psi. The structural response is amplified beyond the static response, and so MEOP should account for this effect as shown by the MEOP calculation.

Case 3 $\omega^* \sim 10$: According to Figure 19, DAF is calculated as 0.25. Therefore, MEOP is defined as follows: MEOP = 5000 psi + 0.25 × 1000 psi = 5250 psi. The structural response is less than if the pressure were to be applied statically, and so MEOP is less than Cases 1 and 2.

The DAF should not be confused with the dynamic uncertainty factors (DUF) or modeling uncertainty factor (MUF). DAF differs from the MUF and DUF, in that DAF is a correction factor calculated from analysis or test, while the DUF and MUF are factors used to mitigate risks early in the program. The DUF and MUF are used in the preliminary structural sizing and analysis to account for uncertainty early in the design process. The DUF differs from the MUF in that only the launch vehicle transient responses are subjected to the uncertainty factor; the steady state portion of the load is not.

11.6 Step 6A – Structural Verification for Fluid Storage Vessels

Fluid storage vessels generally include COPVs, MPVs, and pressurized structures (e.g., stage tanks). These structures require structural qualification tests, proof tests, fatigue tests, and damage tolerance assessment. The structural verification requirements for NASA programs hardware items classified as fluid storage vessels are contained in NASA-STD-5001B [ref. 36], AIAA-S-081B [ref. 37], AIAA-S-080A [ref. 26], and NASA-STD-5019A [ref. 38]. The structural analyst should ensure that the appropriate standard flowed down by the program is used in the structural assessment process.

Note, SMC-S-005-2015 states that in requirement 4.1.1-7 "The MEOP of pressure vessels and pressurized structures shall include the peak transient pressure incident on these units resulting from system operation. It should be noted that hydraulic transients typically have little amplitude within a pressure vessel." Although this requirement mentions the transient pressure that could occur in a pressure vessel, such transients are not expected to manifest. The statement includes pressure transients to be comprehensive in covering unusual pressure vessel designs, which for some reason could produce a pressure transient.

The value of MEOP for fluid storage vessels should use Equation 5 with a DAF=1 as the basis of the structural verification process, which is consistent with SMC-S-005, unless there is evidence that a transient can cause a dynamic amplification beyond static application of pressure.

11.7 Step 6B – Structural Verification for Pressure Components

Pressure components are components where the primary loading is driven by pressure. Examples include lines, fittings, and valves. These components generally require analysis and proof tests. The structural verification requirements for NASA programs hardware items classified as pressure components are contained in NASA-STD-5001B [ref. 36], AIAA-S-080A, and NASA-STD-5019A [ref. 38].

The structural verification process is such that the analysis and test requirements are defined relative to MEOP. Typically, MEOP is managed by the fluids and propulsion disciplines with minimal or no input by the structural analysts. Consequently, it is important to understand whether MEOP was calculated using Equation 5, as the proof and burst pressure test/analysis levels are established based on MEOP.

Ideally, propulsion, fluids, and structures disciplines should converge to a single value of MEOP set for that part using Equation 5. If Equation 5 is not used in the calculation of MEOP, then this pressure should be recalculated by the structural analyst using this equation for the sole purpose of establishing the correct proof and burst pressure levels for analysis and test. Note that this recalculation of MEOP is an internal calculation to the structures team to establish the test levels.

Two structural verification approaches for pressure components are presented in the following sections: (1) No damage tolerance and (2) Damage tolerance.

11.7.1 Pressure Components: No Damage Tolerance

Per AIAA-S-080A, the proof test pressure is 1.5 × MEOP and the burst pressure level is 2.5 × MEOP for the majority of pressure components except lines and fittings less than 1.5 inches in diameter, which use a burst factor of 4.0. No damage tolerance is required with this approach, but additional requirements are imposed by NASA-STD-5019A.

The premise is that the “elevated” proof factor screens for gross workmanship issues. The “burst” factor keeps the operational stress levels relatively low and reduces the risk for flaw growth during the service life of the component. The components need to meet the external load requirements in AIAA-S-080A Table 1. However, it must be noted that this approach does not assure infinite life. To illustrate this proof test logic observation, consider an aluminum 6061-T651 pipe 2-inch nominal diameter, 0.065-inch pipe wall thickness, and 47-ksi ultimate strength. The pipe was sized for positive structural margins at the burst pressure level. The largest critical flaw passing proof test was determined to be a crack 1.26 inches long and 0.047 inch in depth. This critical flaw survives a finite number of MEOP cycles, thus illustrating that infinite life cannot be assured.

11.7.2 Pressure Components: Damage Tolerance

The approach outlined in Sections 11.5 and 11.7.1 can result in a structure with significant weight penalty. Returning to Case 2 in Section 11.5, the MEOP was found to be 6,800 psi by accounting for the dynamic amplification due to the pressure transient compared to 5,000 psi without the pressure transient effects. The burst pressure level with a burst factor of 2.5 is calculated as 17,000 psi based on the MEOP with pressure transient effects included compared to 12,500 psi without the pressure transient. Including the pressure transient effects increases the pipe thickness and weight by 36 percent.

An approach that results in lower weight designs is to reduce the proof/burst factors and implement a damage tolerance approach to mitigate concerns that a flaw will propagate to failure in service. This approach requires further study by NASA before it can be adopted. The minimum proof pressure is 1.1 × MEOP and minimum burst pressure is 1.4 × MEOP for human spaceflight or 1.25 × MEOP for non-human-rated systems. The approach requires a structural qualification test to qualify the design. Damage tolerance verification requires demonstrating stable crack growth and non-detrimental leakage or mission ending rupture to four times the service life using the entire fatigue load spectrum with an initial flaw size defined by: (i) proof test logic considering a range of critical surface flaws ($0.2 \leq a/c \leq 1$) that pass the proof test (1.1 × MEOP), or (ii) nondestructive inspection evaluation to 90 percent of probability detection and 95 percent confidence. The load spectrum includes pressure transients (e.g., number of cycles and corresponding stress levels) and pressure cycles from all other events. External loads must meet the requirements per AIAA-S-080A Table 1.

Applying the damage tolerance approach to the case study presented in this section, the burst pressure level would be calculated as 1.4 × 6800 psi = 9.520 psi with pressure transient effects included, which is lower than the burst pressure levels of 12,500 psi and 17,000 psi with no damage tolerance. An argument is made that this is a viable robust approach in the evaluation of pressure components that can result in significant weight savings. The approach outlined here is essentially like the approach used for pressurized structures. Note that pressurized structures such as stage tanks contain large stored energy and contain process sensitive welds.

There are limitations with the damage tolerance approach for pressure components, which include:

1. Proof test logic may not result in an acceptable damage tolerance for pressure components as there might be situations where the flaw size results in a thru-crack. Proof test logic requires approval by a responsible fracture control authority.

2. It should be noted that not all pressure components are designed to be inspectable so the damage tolerance approach may not be possible for those cases.
3. Some instances involve a wall thickness too thin to consider a flaw configuration from NASA STD-5009A [ref. 39]. To remedy this, a special non-destructive evaluation (NDE) method needs to be developed and qualified to 90 percent of probability detection and 95 percent confidence. If a validated special NDE technique cannot be developed, then the damage tolerance approach is infeasible.

11.8 Case Study per the Recommended Workflow

The workflow in Figure 21 is illustrated for a pressure component made of Inconel 625 subject to a steady state pressure of 190 psi and pressure transient effects as those illustrated in Case Study 8-2 and Figure 10. For the purposes of this example, thermal effects, external loads, and accelerations are not considered.

Case A:

Based on the Joukowsky equation, Figure 10, the pressure transient amplitude is calculated as 1,610 psi so that the peak pressure is 1,800 psi. During preliminary design, it is unknown whether the structure will respond to the transient event since it lasts for a fraction of a second. The design recommendation is to apply a DAF of 2.0 on the pressure transient amplitude. The value of MEOP is calculated using Equation 5: (190 + (1610 × 2)) = 3410 psi (Table 3, Case A).

Case B:

As design parameters mature and more information of the system is known, the program determines that the pressurized subsystem is a significant weight driver and needs to be mass optimized. The pressure transient is characterized as a half-sine wave. The normalized parameter ω^* was calculated to be 0.6 using Equation 4, and with Figure 19 the DAF was estimated to be 1.2. Recall this design curve was generated performing a parametric dynamic analysis study. Using the Joukowsky pressure transient prediction, the MEOP is calculated as (190 + (1610 × 1.2)) = 2122 psi using the updated DAF (Table 3, Case B).

Case C:

Separately, a refined fluids analysis using the Method of Characteristics (MOC) is performed to improve the pressure transient estimation. The pressure transient based on this analysis is 202 psi, Figure 10. The combination of the refined fluids and structural analysis provide a MEOP that is calculated as (190 + (202 × 1.2)) = 432 psi (Table 2, Case C).

The proof pressure and burst pressure levels for the no damage tolerance approach discussed in Section 11.7.1 are shown in Table 3. The proof factor is 1.5 and burst factor is 2.5.

Table 3. Proof and Burst Pressure Levels with No Damage Tolerance Section 11.7.1. All pressure units are psi.

Case	Static Pressure	Pressure Transient	DAF	MEOP	Proof Pressure	Burst Pressure
A - Preliminary design DAF, Joukowsky equation	190	1610	2	3410	5115	8525
B - Predicted DAF, Joukowsky Equation	190	1610	1.2	2122	3183	5305
C- Predicted DAF, MOCs	190	202	1.2	432	648	1080

The proof pressure and burst pressure levels for the damage tolerance approach discussed in Section 11.7.2 are shown in Table 4. The proof factor is 1.1 and burst factor is 1.4. In this study, the burst pressure level decreased from 8,525 psi to 605 psi when incremental refinements were made to the fluid and structural analysis, and when damage tolerance was implemented. The reduction in burst pressure level for a uniform pipe resulted in more than a ten-fold reduction in weight.

Table 4. Proof and Burst Pressure Levels with Damage Tolerance Section 11.7.2. All pressure units are psi.

Case (psi)	Static Pressure	Pressure Transient	DAF	MEOP	Proof Pressure	Burst Pressure
A - Preliminary design DAF, Joukowsky equation	190	1610	2	3410	3751	4774
B - Predicted DAF, Joukowsky Equation	190	1610	1.2	2122	2334	2971
C- Predicted DAF, MOC	190	202	1.2	432	475	605

12.0 Summary

12.1 Pressure Transients

1. Transient events have caused structural failures in pressurized systems due to strength or fatigue failure modes.
2. Pressure transient events can occur due to valve actuation, engine shutdown, system priming, and fluid discharge. Factors influencing pressure transients include densities, compressibility, sound speed, fluid speed, valve closure time, pipe geometry/material, and branches in the pipe network.
3. Mitigation strategies exist to reduce the magnitude of pressure transients by adjusting the valve closure schedule and/or by implementing orifices, check valves, pressure relief valves, and accumulators into the design.
4. The Joukowsky equation is used to predict an upper bound pressure transient. Cases exist where this equation can underpredict the pressure transient in cases such as cavitation, pipe size changes, or the interaction of multiple pressure transient sources. A 1D fluid transient model using the MOC to solve the equations has been successfully used to predict pressure transients. 2D and 3D CFD models can be used to further refine model predictions.
5. Case studies were presented illustrating pressure transient predictions and timescales due to disruptions in the steady state flow.

12.2 DAF

1. Pressure oscillations can cause stresses to fluctuate at the structure natural frequencies and mode shapes, and the structural response can be dynamically amplified due to resonant conditions or stress waves reflecting near boundary conditions.
2. FEMs suggest that the sudden load causes local bending moments in the pipe wall at the pressure wave front. Precursor strain develops ahead of the pressure wave in the fluid, because the stress wave (e.g., shear, longitudinal, or flexural) in the solid structural member travels faster than the fluid pressure wave. An aftershock strain, much larger than the precursor strain, develops behind the pressure wave front. Longitudinal stress wave arrives prior to the predominant pressure wave, and these are smaller than circumferential stresses.

3. A DAF is defined as the ratio of stress obtained in a dynamic transient analysis to that obtained by a static analysis. The characteristics of the pressure transient can be such that the structure (1) minimally responds (i.e., DAF $\ll$ 1.0), (2) responds quasi-statically when pressure acts gradually (i.e., DAF~1), or (3) responds dynamically with an amplification above the static response (i.e., DAF>1.0), typically when there is resonance.
4. The DAF can be estimated using testing, analysis, or design equivalent heritage experience. With no information available, it is prudent to use a DAF = 2.0 in the preliminary structural design process. Analytical techniques include SDOF analysis, shell vibration equations, fluid-structure interaction analysis, and FEA. A FEA can be complicated and does require benchmarking against experimental data. Case studies were presented that illustrate the calculation of DAF for various scenarios.
5. Through analytical studies it was found that the DAF depends on the frequency content and duration of the pulse relative to the structural modes, pulse shape, and damping.

12.3 Treatment of Pressure Transients in Aerospace Standards

1. Aerospace standards require assessment of pressure transients when defining MEOP, but there is limited guidance on how transient events are evaluated within the structural verification process.
2. Standard bus configurations for DoD programs have been successful without the use of the DAF concept. The DAF may have been less than 1.0 or the proof and burst factors specified in AIAA-S-080A for pressurized components may have inadvertently protected components from failure. New applications deviating from standard bus heritage practices require a closer understanding of the DAF. When a program elects to allow the peak pressure transient to exceed the proof pressure or the DAF concept is not adopted, then risk mitigations need to be put in place, which can include robust qualification test program, analysis, inspections, and adopting designs that are not susceptible to workmanship issues.
3. Various points of view in the aerospace community have circulated as to what constitutes a transient event. It is argued that instead of using a subjective time threshold to determine how to treat a pressure transient, the magnitude of the pressure transient be determined using physical models or through measurements.

12.4 Treatment of Transient Events in the Structural Verification Process

1. For COPVs, MPVs, and pressurized structures: The DAF is typically 1.0 with no dynamic amplification. Pressure waves entering these structures tend to be small and dissipate within the large space. When in doubt, a comprehensive fluid and structural analysis should be performed to establish a DAF.
2. For pressure components: Design curves can be developed to estimate DAF. In the absence of test or analytical data, it is prudent to use a DAF of 2.0 in the preliminary design phase. The DAF can be updated by performing a parametric study and refined with a high-fidelity model or test.
3. An approach is to modify MEOP to include DAF: Steady state Pressure + (DAF × Magnitude of the Pressure Transient). An alternative is to directly adjust proof and burst test levels in the structural verification process so that it includes DAF.

4. For pressure components, weight reductions can be achieved by using lower proof and burst factors with damage tolerance implementation. The approach requires further study before wide adoption within the Agency.

13.0 Recommendations

1. For pressure components, investigate the merits of using a damage tolerance approach using lower proof and burst factors to achieve weight-savings when pressure transients or DAF are significant.
2. Develop design curves for different materials, pressure wave characteristics, and geometries that can be conveniently used to calculate DAF.
3. Develop test validation cases beyond those documented in the literature to compare analytical predictions to experimental measurements.

14.0 Definitions

Compression wave: A wave that moves through a fluid at the speed of sound, characterized by an increase in pressure.

Courant number: This non-dimensionless number arises while solving the time marching problems. This condition is named after the respective scientists Richard Courant, Kurt Friedrichs, and Hans Lewy who introduced it in 1928. This number presents itself in finite-difference approximation of general partial differential equations governing the advection phenomenon. In an explicit time-marching problem such as the wave motion equation it depends upon the velocity, time step and the length of the interval between two nodes.

Dynamic amplification factor (DAF): Scales the static pressure load in a static analysis in such a way that produces a stress level equivalent to that obtained by a dynamic analysis. It is defined as the ratio of stress obtained in a dynamic transient analysis to that obtained by a static analysis. The factor provides a comparison between the structural dynamic stress response to the static stress response due to the pressure transient.

Entrainment: The transport of one fluid body by shear forces generated by a neighboring fluid body.

Expansion wave: A wave that moves through a fluid at the speed of sound, characterized by a decrease in pressure.

Fluid Storage Vessel: Storage tank including, composite overwrapped pressure vessels (COPVs), pressurized structures, and metallic pressure vessels (MPVs).

Hydrostatic pressure: Pressure caused by the weight of the fluid within a storage structure. This value depends on the height of the fluid, fluid density, and acceleration.

Joukowsky equation: Method of determining the pressure transient magnitude that will be experienced in a fluid piping system due to instantaneous flow disruption such as valve closure.

Maximum design pressure (MDP): This term can be used for design and testing of pressure vessels and related pressure components. The basic difference between MDP and MEOP is the degree of consideration of potential credible failure within a pressure system and the resultant effects on pressure during system operation. MDP is associated with human-rated systems and is based on the worst-case combination of two credible system failures. For non-human-rated hardware, pressurization due to failure conditions are not included and the terms MDP and MEOP are equivalent. Note: It is not uncommon for programs to only require consideration of a single failure to determine MDP.

Pressurant: A gas used to drive a fluid through a fluid system.

Pressure transient: Magnitude of the pressure wave arising from the flow disruption. See Figure 23.

Proof test logic: Minimum proof load such that the maximum flaw size that survives proof can meet the damage tolerance requirements for the entire service life.

Quasi-steady flow: Considered a transient flow. The variation of variables such as pressure and velocity with time is gradual and over short time intervals appears to be steady. In these situations, the fundamental fluid dynamics are essentially the same as for steady flow, but account must be taken of the overall changes taking place over a period. An example of a quasi-steady flow is the flow that results when a large tank is drained through a small outlet pipe.

Single devices: Equivalent to single fault-tolerant devices.

Steady flow: Flow is one in which the conditions (velocity, pressure and cross- section) may differ from point to point but do not change with time.

Transient or transient event: Occurs when the flow is steady and there is a disruption in the flow; causing a pressure wave that travels within the pressurized system. Pressure surge is a common nomenclature as well. Pressure waves can be a transient sudden rise or fall of pressure in a pipeline. Pipeline surges can be positive or negative and are mostly caused by the sudden closure of a block valve. If the pressure surge is more than the rated capacity of a pipeline it can cause ruptures in the piping system.

Ullage pressure: Liquid propellant rockets store propellants in tanks. Cryogenic tanks are never completely filled, to prevent severe pressure drop in the tank after engine start. The pressure in the space between the top of the propellant load and the top of the tank is known as ullage pressure.

Unsteady flow: If at any point in the fluid, the conditions change with time, the flow is described as unsteady.

Water hammer: Applies to pressure systems with water as the working fluid. Phenomenon that occurs in piping system where valves are used to control the flow of liquids or steam. Water hammer is the result of a pressure surge, or high-pressure shockwave that propagates through a piping system when a fluid in motion is forced to change direction or stop abruptly. Water hammer can occur when an open valve suddenly closes, causing the water to slam into it, or when a pump suddenly shuts down and the flow reverses direction back to the pump. Since water is incompressible, the impact of the water results in a shock wave that propagates at the speed of sound between the valve and the next junction in the piping system.

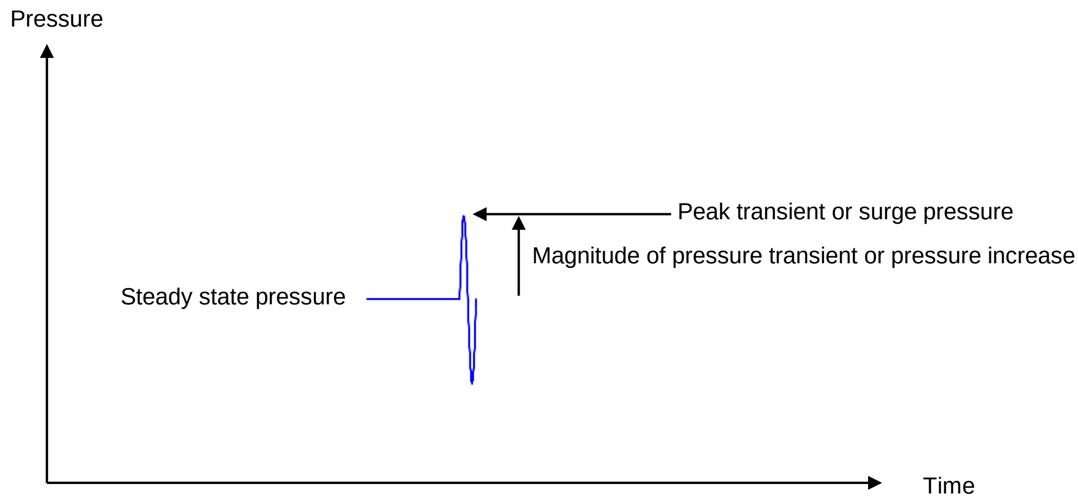

Figure 23. Terminology Illustration of Pressure Transient Term Relative to Peak Transient

15.0 Acronyms

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AC	Advisory Circular
AIAA	American Institute of Aeronautics and Astronautics
ASME	American Society of Mechanical Engineers
CFD	Computational Fluid Dynamics
COPV	Composite Overwrapped Pressure Vessel
DAF	Dynamic Amplification Factor
DoD	Department of Defense
DUF	Dynamic Uncertainty Factors
ECSS	European Cooperation for Space Standardization
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FEA	Finite Element Analysis
FEM	Finite Element Method
FSI	Fluid–Structure Interaction
GFSSP	Generalized Fluid System Simulation Program
GOLD	GSFC Open Learning Design
GOX	Gaseous oxygen
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
ISO	International Organization for Standardization
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LaRC	Langley Research Center
LOX	Liquid oxygen
MDP	Maximum Design Pressure
MEOP	Maximum Expected Operating Pressure

MOC	Method of Characteristics
MPV	Metallic Pressure Vessel
MSFC	Marshall Space Flight Center
MUF	Modeling Uncertainty Factor
NASA	National Aeronautics Space Administration
NDE	Nondestructive Evaluation
NESC	NASA Engineering and Safety Center
PRV	Pressure Relief Valve
SDOF	Single Degree of Freedom
SMC	Space and Missile Systems Center
TLYF	Test-Like-You-Fly

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Appendix A. Derivation of the Joukowsky Equation

First a control volume is defined, and external forces are applied with frictional forces neglected, rendering the wave speed stationary.

$$\Sigma F_z = \dot{m}(V_{out} - V_{in})_z \quad \text{A-1}$$

$$F_z - F_{z+\Delta z} = \dot{m}[(V - \Delta V + a) - (V + a)] \quad \text{A-2}$$

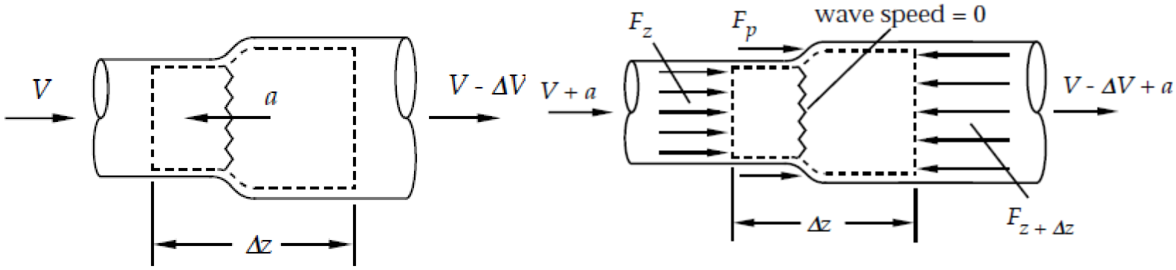

Figure A-1. Wave Speed Control Volume and Free Body Diagram

Substituting in for the following physical relationships

$$F_z = pA, \;\; F_{z+\Delta z} = (p + \Delta p)(A + \Delta A) \quad \text{A-3}$$

$$\dot{m} = \rho A(V + a) \quad \text{A-4}$$

results in

$$pA - (p + \Delta p)(A + \Delta A) = -\rho A(V + a)\Delta V \quad \text{A-5}$$

Neglecting higher order terms and acknowledging that change in area ΔA is small and in general $a \gg V$, and ΔP can be found:

$$\Delta p = \rho(V + a)\Delta V, \Delta p = \rho a \Delta V \quad \text{A-6}$$

Appendix B. One-Dimensional (1D) Transient Models

Equations governing 1D hydraulic transients are a pair of coupled, first order partial differential equations. Assuming axial fluxes of mass and momentum dominate radial variation of flow field variables and that 1D flow assumption is valid for practical applications, the governing equations can be written as:

Continuity equation:

$$\frac{\partial p}{\partial t} + \frac{1}{A}\rho\, a^2 \frac{\partial Q}{\partial x} = 0 \tag{B-1}$$

Momentum equation:

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \alpha\, sin\,\theta + \frac{1}{A^2}\frac{f}{2D}Q|Q| = 0 \tag{B-2}$$

where p is the pressure, Q is the volume flow rate, $\alpha \sin\theta$ is the acceleration component parallel to the flow direction, A is the flow cross-sectional area, D is the diameter, and f is the friction factor of the line. Given the right-hand side of the continuity and momentum equations is zero, the two equations can be combined using a multiplier λ as:

$$\lambda\left(\frac{\partial p}{\partial t} + \frac{1}{A}\rho a^2 \frac{\partial Q}{\partial x}\right) + \frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \alpha\, sin\,\theta + \frac{1}{A^2}\frac{f}{2D}Q|Q| = 0 \tag{B-3}$$

Rearranging the pressure and volume flow rate terms gives

$$\lambda\left(\frac{\partial p}{\partial t} + \frac{1}{\rho\lambda}\frac{\partial p}{\partial x}\right) + \left(\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\lambda\rho a^2 \frac{\partial Q}{\partial x}\right) + \alpha\, sin\,\theta + \frac{1}{A^2}\frac{f}{2D}Q|Q| = 0. \tag{B-4}$$

We now consider the total derivatives of p and Q given by

$$\frac{dp}{dt} = \frac{\partial p}{\partial t} + \frac{dx}{dt}\frac{\partial p}{\partial x} \tag{B-5}$$

$$\frac{dQ}{dt} = \frac{\partial Q}{\partial t} + \frac{dx}{dt}\frac{\partial Q}{\partial x} \tag{B-6}$$

and note the equivalence of the velocities in the advection terms, which gives:

$$\frac{dx}{dt} = \frac{1}{\rho\lambda} = \lambda\rho a^2. \tag{B-7}$$

Thus, the multiplier and velocities are given by:

$$\lambda = \pm\frac{1}{\rho a}, \frac{dx}{dt} = \pm a. \tag{B-8}$$

The combined partial differential equation can now be recast as ordinary differential equations along the right-running (i.e., plus) characteristic lines C_p, where $\frac{dx}{dt} = +a$

$$\frac{1}{\rho a}\frac{dp}{dt} + \frac{1}{A}\frac{dQ}{dt} + \alpha \sin\theta + \frac{1}{A^2}\frac{f}{2D}Q|Q| = 0 \tag{B-9}$$

and along the left-running (i.e., minus) characteristic lines C_m, where $\frac{dx}{dt} = -a$

$$-\frac{1}{\rho a}\frac{dp}{dt} + \frac{1}{A}\frac{dQ}{dt} + \alpha \sin\theta + \frac{1}{A^2}\frac{f}{2D}Q|Q| = 0. \qquad \text{B-10}$$

The characteristic lines are straight with slope $\pm 1/a$. The ordinary differential equations, which are only valid along these characteristic lines, are known as the compatibility equations. Using the three-point stencil in space and two-point stencil in time as shown in Figure B-1, the compatibility equations are replaced with finite difference approximations as:

$$\pm\frac{\Delta p}{\Delta t} + B\frac{\Delta Q}{\Delta t} + \frac{\alpha S}{\Delta t} + \frac{R}{\Delta t}Q|Q| = 0 \qquad \text{B-11}$$

where $\Delta p = p(x_i, t_{j+1}) - p(x_{i-1}, t_j)$, $\Delta Q = Q(x_i, t_{j+1}) - Q(x_{i-1}, t_j)$ along C_p, $\Delta p = p(x_i, t_{j+1}) - p(x_{i+1}, t_j)$, $\Delta Q = Q(x_i, t_{j+1}) - Q(x_{i+1}, t_j)$ along C_m, and:

$$B \equiv \frac{\rho a}{A}, S \equiv \rho \Delta x \sin\theta, R \equiv \frac{1}{2}\frac{\rho f}{A^2 D}\Delta x.$$

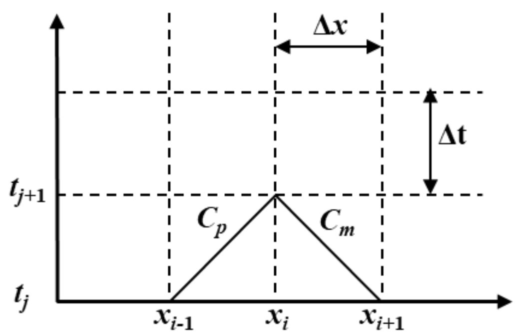

Figure B-1. An x-t Diagram – Abscissa Represents Space and Ordinate Represents Time
The right-running wave propagates along characteristic line C_p, and left-running wave propagates along the characteristic lines C_m.

Thus, the pair of equations implicit in time with unknowns p and Q are given by

$$p(x_i, t_{j+1}) = C_p - B\,Q(x_i, t_{j+1}) \qquad \text{B-12}$$

$$p(x_i, t_{j+1}) = C_m + BQ(x_i, t_{j+1}) \qquad \text{B-13}$$

where:

$$C_p = p(x_{i-1}, t_j) + (B - R|Q(x_{i-1}, t_j)|)Q(x_{i-1}, t_j) - S\alpha \qquad \text{B-14}$$

$$C_m = p(x_{i+1}, t_j) - (B - R|Q(x_{i+1}, t_j)|)Q(x_{i+1}, t_j) + S\alpha. \qquad \text{B-15}$$

Referring to Figure B-1, these equations imply that at a given non-boundary (i.e., interior) spatial point x_i in a line, the pressure at the next time step depends on pressure and flowrate information at the left adjust point in space for a right-running wave, and information at the right adjust point in space for a left-running wave. Moreover, it depends on pressure at the current time, but flowrate at the next time step, which is an implicit equation in time. Given the set of two equations with two unknowns, p and Q, an algebraic solution for the unknowns is given as

$$p(x_i, t_{j+1}) = \frac{1}{2}\left(C_p + C_m\right) \tag{B-16}$$

$$Q(x_i, t_{j+1}) = \frac{1}{2B}\left(C_p - C_m\right) \tag{B-17}$$

where the pressure and flowrate at an interior point can explicitly solved. A boundary point will require another equation that satisfies the physics of the flow component to which the line connects to a tank, valve, or other components.

Turbulence is challenging to model but, because the flow oscillates, even laminar losses can be difficult to simulate accurately. Two caveats are:

1. Turbulence is always difficult to model, so calculated turbulence losses should be suspect.
2. The correct numerical solution technique must be used, meaning a poor choice could lead to artificial amplification of the pressure wave intensity.

One way to detect this would be if negative absolute pressures are observed. Regardless, the best way to avoid artificial amplification is to solve the differential equations along the wave using the method of characteristics described in this appendix.

Appendix C. Abaqus® Implementation of the Pressure Transient Analysis

Each software may require a unique approach to creating pressure transient profiles. In Abaqus®, the implicit solver can be used to model nonlinear transient response due to the pressure transient. Defining the pressure wave characteristics and applying the traveling wave requires that the load be defined temporally and spatially in a dynamic step. This is accomplished with a series of loads that are activated in turn to simulate a traveling wave.

In the example of a rectangular-shaped pressure wave, per Equation C-1, the “floor” function can be used in the Abaqus® “analytical field” to specify the shape of the rectangular wave:

$$\text{Magnitude} = \text{floor}\left(\frac{\text{L} - \text{y}_1 + \text{y}}{\text{L}}\right) - \text{floor}\left(\frac{\text{L} - \text{y}_2 + \text{y}}{\text{L}}\right), y_1 < y_2 \qquad \text{C-1}$$

The term “Magnitude” in this context refers to the Abaqus® construct used to multiply applied loads. The Magnitude in Equation C-1 is a multiplier to pressure and the value is equal to 1 when y is between y_1 and y_2 and zero otherwise. The parameter y_2 corresponds to the position of the wave front, while y_1 corresponds to the position of the wave trailing end. The parameter “length” is the total length of the pipe, and “y” is the input into the analytical field that corresponds to the depth into the pipe with y = 0 at the beginning of the pipe where the wave starts. The pipe end where the wave ends occurs at y = 36 inches. This analytical field input can be used to define an instantaneous waveshape based on location of the wave profile.

At 0.2 ms, the rectangular wave will have travelled 16 inches through the pipe. The front of the wave will be around 16 inches into the pipe and the back of the wave around 8 inches into the pipe, as shown in Figure C-1.

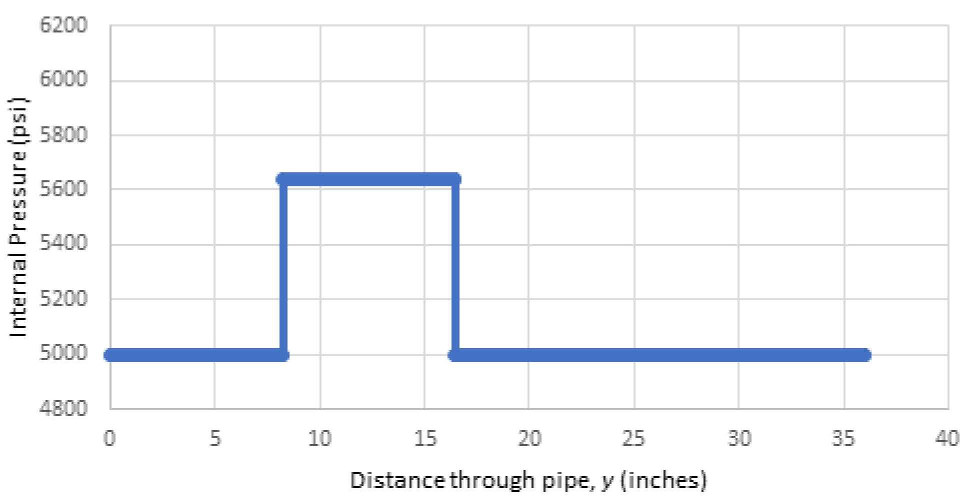

Figure C-1. Traveling Pressure Wave Profile at 0.2 ms

Abaqus® does not have the ability to include temporal dependence in an analytical field, so the wave profile for a given time must be set active only at that time. This requires that a wave profile is created for each time increment of the dynamics step and activated only at that time. The wave profile in Figure C-1 should only be active at 0.2 ms. At all other times, this wave profile should be set to have a magnitude of zero, effectively deactivating it. This is done with the Abaqus®

"Magnitude," which is used to set a relationship between the load and time. The tabular Magnitude is set with three values: 1 at 0.2 ms and zero greater and less than 0.2 ms. This sets the load to be active at the given time and inactive at all other times.

Generating these loads is difficult to complete manually, as the analysis used in this effort discretized the wave into 500 wave profiles occurring in 0.002-ms increments to 1 ms. An Abaqus® macro modified with Python™ was used to create these loads with the appropriate wave profiles and temporal magnitudes.

Defining a half-sine wave requires a unique approach. Consider the following pressure wave:

$$p(y,t) = \begin{Bmatrix} Psin(\omega t - ky) \; if \; \omega t \geq ky \\ 0 \; else \end{Bmatrix} \quad \text{C-2}$$

where the following expression is expanded as:

$$\sin(\omega t - ky) = \cos(\mathrm{k}y)\sin(\omega t) - \sin(ky)\cos(\omega t) \quad \text{C-3}$$

This expansion allows applying this load within Abaqus® by separating the load into spatial and temporal terms. Spatial and temporal magnitudes can be used in the same manner as the rectangular wave. Unlike the rectangular wave, two loads are now applied at each time increment, one to get each of the terms: $\cos(\mathrm{k}y)\sin(\omega t)$ and $\sin(ky)\cos(\omega t)$. These terms linearly combine to get the pressure wave shape defined previously. Like the rectangular wave, the "floor" function was used in analytical field to make the load zero everywhere but within the half-sine wave. This analytical field was multiplied by $\cos(\mathrm{k}y)$ or $\sin(ky)$ to create the respective term. A tabular Magnitude was used to activate the load profile at the appropriate time increment. This tabular magnitude was multiplied by $\sin(\omega t)$ or $\cos(\omega t)$ to create the respective term.

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A multi-disciplinary team from the NASA Engineering and Safety Center (NESC) and The Aerospace Corporation developed a roadmap on how to treat transients in spaceflight pressurized systems. This document presents a focused discussion on the topic of pressure transients for consideration within the aerospace community.

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