THE LEE COMPANY

ADAPTING FLUID CONTROL COMPONENTS

FOR HYDROGEN APPLICATIONS

ASSESSING THE CHALLENGES OF TRANSITIONING TO HYDROGEN FUEL

The advent of the 21st century gave rise to a heightened awareness of an endangered global environment. Major contributors and contributing factors were identified, as were the steps necessary to mitigate and slowly reverse the current trend. Throughout the world, governments, industries, and activist groups have been addressing this critical issue, and the aviation industry is stepping up to do its part.

Although aviation is a relatively small contributor to global greenhouse emissions, it is also one of the fastest growing. The major airline companies are aware that the goal of minimizing their carbon footprint is tied to the eventual elimination of the use of fossil fuels. Towards that end, commercial aviation companies have made progress; they are developing hybrid-electric propulsion systems for smaller regional aircraft and are using sustainable aviation fuels (SAFs), partially made from renewable resources, for larger aircraft. Many of the industry's major airlines have publicly announced plans to completely phase out carbon-based jet fuels from their operations in favor of a clean burning alternative—hydrogen. Billions are being invested in emerging hydrogen technologies; optimists are projecting that by the end of the decade, airlines will be flying small passenger planes powered by fuel cells or hydrogen-burning engines.

The use of hydrogen will require modifications to or replacement of current technologies that control liquid fuel. As engineers assess the impact of these significant modifications, it is important that they address the unique challenges associated with controlling pneumatics in general and hydrogen in particular. Efforts should focus on providing safe and efficient methods for storage, loading, distribution, and precision control of hydrogen.

Challenges pertaining specifically to the use of hydrogen will be discussed further in this white paper. Engineers must factor in these challenges to be better equipped to provide components that will yield efficient, safe, and high-performing hydrogen systems. They must also understand the effect a switch to hydrogen will have on the design and performance of current technologies: for example, sealing technology, flow restrictors, valves, electrically actuated valves, and filtration.

To create efficient, safe, and high-performing hydrogen systems, engineers must reimagine how fuel is **stored, distributed, and controlled.**

GENERAL CONSIDERATIONS AND CHALLENGES OF GAS FLOW

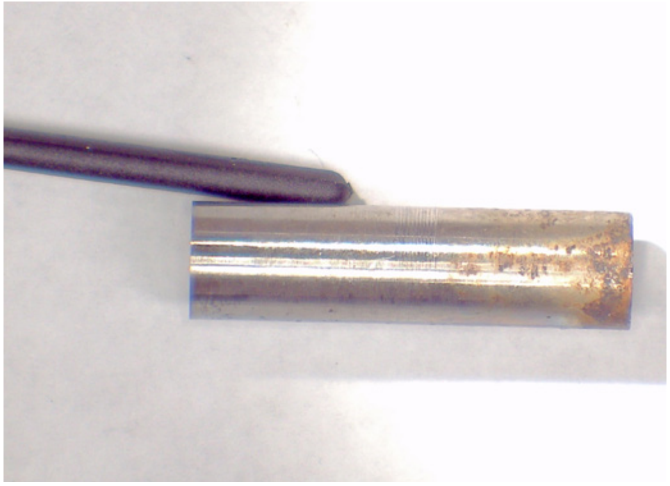
A designer of fluid systems must identify and fully understand the characteristics of the fluid or fluids that will be used in the system. The relationship between flow and pressure conditions is dependent upon the properties of the fluid, such as its viscosity and specific gravity. While every fluid is different, transitioning from a liquid to a gas increases the complexity of the process. Content that follows will deal with challenges design engineers face with regards to all pneumatic systems.

MATERIAL COMPATIBILITY

Material compatibility must be considered for any fluid control component to ensure the fluid does not adversely impact the material and vice versa. Compatibility issues may occur with liquids as well as gases. A fluid may impact a material by causing degradation or erosion. If an elastomer or polymer erodes, it will no longer function and may cause debris that results in other modes of failure within the system. Material incompatibility with metals often results in corrosion.

A fluid may also impact a material by permeating it and causing it to swell. This swelling may negatively impact performance, such as when an elastomeric valve seat swells and becomes unable to open. Alternatively, slight swelling may be beneficial, such as when an O-ring intended to prevent leakage swells and creates an even tighter seal.

Material selection for fuel control must take into account the environment and explosion prevention, because a fuel is selected for its ability to combust. The FAA and other industry organizations have standards in place to regulate safety for fuel tanks, electronics, and other potential sources of explosions. In such cases a non-spark material is required.



Corrosion on the exterior of a metal valve body

GENERAL CONSIDERATIONS AND CHALLENGES OF GAS FLOW (CONT.)

COMPRESSIBILITY AND FLOW CHARACTERISTICS

Liquids are incompressible fluids, and their flow rate across a component is dependent upon the pressure differential upstream and downstream of the component. The magnitude of the pressure is not a factor. On the other hand, gases are compressible. This makes flow calculations more complicated because the density of the gas changes with pressure. Below are seven flow characteristics generally applicable to gas:

1. Gas flow at high pressure ratios (P1/P2 > 1.9) is directly proportional to the upstream absolute pressure.
2. Gas flow at moderate pressure ratios (1.1 < P1/P2 < 1.9) is proportional to the downstream absolute pressure, and to the pressure differential.
3. Gas flow at low pressure ratios (P1/P2 < 1.1) is proportional to the pressure differential, like hydraulic flow.
4. When restrictions appear in series, the most downstream restrictor dominates in the determination of flow rate.
5. When the absolute pressure ratio across a restrictor is above 1.9, the gas velocity will reach the speed of sound (sonic flow) in the restrictor throat. When restrictors appear in series, the overall pressure ratio must be higher to achieve sonic flow.
6. When equal restrictors appear in series, sonic flow can only occur in the most downstream restrictor.
7. Velocity of the gas stream cannot exceed the speed of sound in either a constant area duct or in a converging section.

LEARN MORE ABOUT GAS FLOW CHARACTERISTICS >

GENERAL CONSIDERATIONS AND CHALLENGES OF GAS FLOW (CONT.)

ACCURACY OF FLOW ANALYSIS

Predicting flow for gas using advanced modeling and analysis will yield a lower level of accuracy. This is particularly true for the design of a component, such as a valve, in which the gas flows through multiple internal subcomponents that create individual restrictions—in series and parallel—without one obvious dominant restriction. Empirical testing is likely required to understand the precise level of restriction created by a component. It leads to further difficulty when there is an attempt to utilize pressure drops to model the force balance of a component's operation.

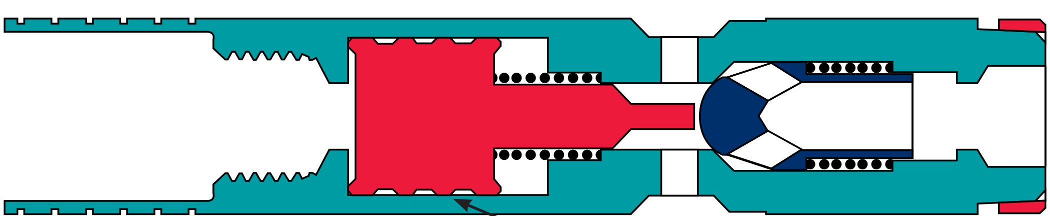
Correlation factors are often used to predict the performance of a component characterized using a test fluid that is different from the intended system fluid. However, a correlation between a liquid and a gas is much less accurate due to the differences in flow characteristics when compared to correlating a liquid to a liquid or a gas to a gas. Products intended for use with gas but designed and tested using liquid should be recharacterized using gas during system development to ensure performance is properly understood.

LUBRICITY MAY INCREASE VALVE LIFE EXPECTANCY AND STABILITY

Valves used in traditional fuel systems benefit from the lubricity of the fuel. Lubricity reduces friction between sliding components and provides damping. The result is the potential of reduced wear on the valve and an improved potential cycle life. Pneumatic systems must address related issues using alternative methods.

LUBRICATION

Most valves rely on internal metal subcomponents with sliding fits to achieve proper performance. A liquid fuel provides lubrication between this metal-to-metal contact. Pneumatic operation will lead to increased friction and potential galling issues. Special coatings and/or surface treatments may be required to offset these issues.

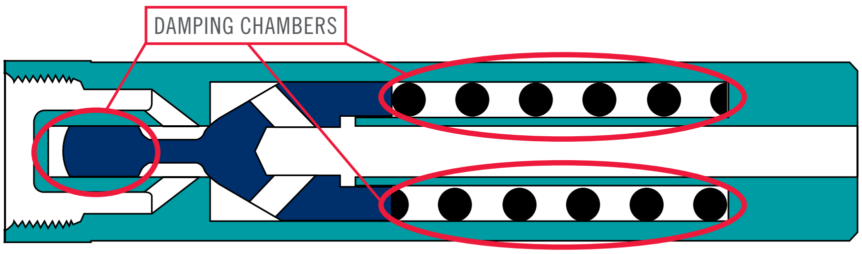


Example of a valve requiring sliding metal-to-metal fits to achieve proper performance

GENERAL CONSIDERATIONS AND CHALLENGES OF GAS FLOW (CONT.)

DAMPING

Many common valve designs—such as those for check valves, pressure relief valves, or solenoid valves—utilize a spring to hold a poppet or ball against a seat to provide the valve seal. An imbalance of forces—acting upon the spring and moving mass—creates instability if the valve is forced to operate at an intermediate pressure between the closed and fully-open positions. The instability results in an unpredictable flow and pressure. There is also the potential for audible chattering while the valve repeatedly transitions between the open and closed positions. The instability may also dramatically increase the number of cycles the valve is subjected to as well as generate very high pressure rise and decay rates within the valve. The result may be damage to the valve that impacts performance, generates contamination or debris, or even causes complete failure of the valve or system.



Example of a configuration that uses multiple damping chambers to increase valve stability in hydraulic applications

Valves are often designed to incorporate damping chambers or dashpots. These features provide damping to minimize the potential for instability in liquid applications, but they will not function similarly with gaseous flow. The valve and/or system designer must use alternative solutions to ensure stable performance. Potential design improvements may include:

- The selection of high hardness materials and the use of coatings and/or surface treatments to protect internal components during operation.
- Modifications to dimensions of the individual areas and restrictions within the valve.
- A reduction in the component's rated cycle life.
- A system design that ensures a minimum flow rate or specific pressure parameters that avoid operation in an unstable condition.

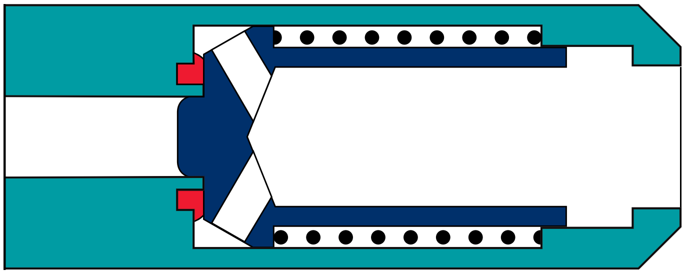
GENERAL CONSIDERATIONS AND CHALLENGES OF GAS FLOW (CONT.)

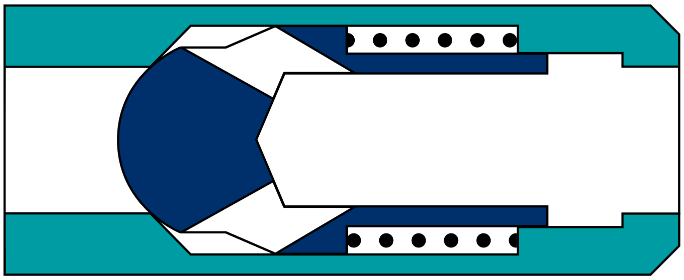
LEAKAGE

Leakage in a fuel system can reduce system performance and efficiency. Fuel is one of the primary costs of operating an aircraft and any decrease in fuel efficiency is a significant concern. Leakage may cause a change in flow or pressure conditions or may result in a loss of fluid mass during operation or while the system is idle. Components are designed to minimize the risk of potential leakage across seals used for installation and retention, valve seats, and sliding fits.

Liquid leakage is governed by its viscosity; the lower the viscosity, the faster the leak through a potential leak path. Gas viscosity is generally much lower than that of a liquid; for example, air viscosity is roughly 50 times lower than that of water.

For hydraulic systems, valves were developed with metal-to-metal sealing components that typically meet acceptable leakage ratings—primarily because viscous liquids struggle to pass between the seal's mating surfaces. However, for gaseous fluids, there may be a significant leakage rate through the microscopic imperfections on a sealing surface. These microscopic imperfections are difficult to control in a manufacturing environment, resulting in high leak rates and a wider variance in leakage from part-to-part. This issue applies to internal leakage across valve seats and to external leakage around a component—depending upon a valve's method of retention and the housing in which it is installed. External gaseous leakage can be significantly affected by surface finish quality.





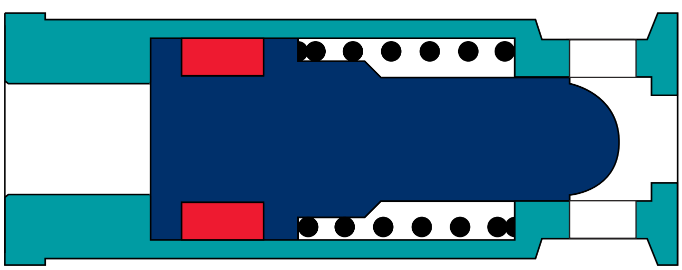
Two check valve configurations highlighting the potential changes necessary to incorporate an elastomeric or polymeric valve seat to reduce leakage.

GENERAL CONSIDERATIONS AND CHALLENGES OF GAS FLOW (CONT.)

SELECTION OF THE PROPER SEALING MATERIALS

The most common solution to reducing leakage across valve seats is the use of softer sealing materials paired with the metal. The softer material will compress to reduce or eliminate potential imperfections. Soft seats are typically employed using polymeric materials (such as PTFE, FEP or PEEK) or elastomeric materials (such as FKM, EPDM, FFKM, or CR). However, the use of polymers and elastomers in lieu of metal materials is an imperfect solution; there are limiting factors with regards to operating temperatures, pressures, and life cycle ratings. It is important to understand the significant performance trade-offs that occur with each type of sealing component material. Proper system performance relies heavily on the selection of materials that offer the necessary balance between leakage rate, pressure range, temperature range, and durability.

Some valve designs rely on internal components with very tight sliding fits to act as seals—for example, 3-port valves such as pilot-operated check valves and shuttle valves. Bypass leakage through sliding fits must be accounted for during component design. Without secondary seals, increased leakages associated with pneumatic operation may render these valve designs inoperable. Secondary seals and valve seats have the same design trade-offs. In addition, the necessary movement of the seal creates wear due to friction, thus the design and performance requirements are even more difficult to achieve.



Example of a bypass valve design that
requires a sliding seal for proper performance

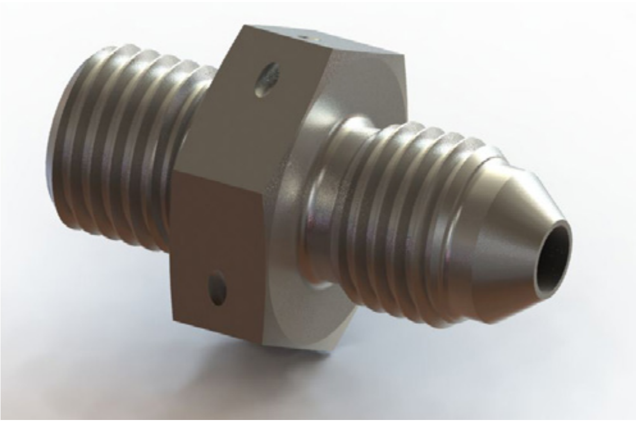
GENERAL CONSIDERATIONS AND CHALLENGES OF GAS FLOW (CONT.)

Material selection is also determined by conditions such as operating pressures (transient and static), cycle life, and temperatures. This is especially pertinent to seal material selection. Generally elastomeric (rubber) seat materials are best for use at temperatures from -65°F to 275°F and maximum working pressures up to 5000 psi. Polymeric (plastic) seat materials are best for use at temperatures from -320°F to 400°F and maximum working pressures up to 15,000 psi. (Note: Polymeric soft-seats require 500 psid minimum to achieve zero leakage performance versus elastomeric soft-seats that require 5 psid minimum).

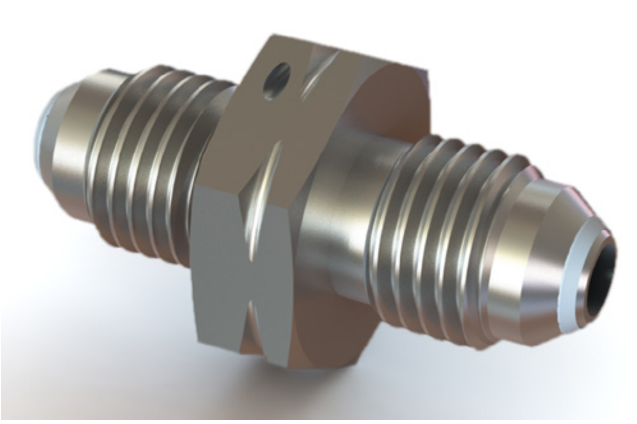
These materials can exhibit vastly different properties at different temperatures, and this must be taken into account. For example, at elevated temperatures, an elastomeric seal may begin to soften; this may lead to a “stickiness” that increases the required differential pressure to open a valve. Alternatively, at lower temperatures, an elastomeric seal may harden and reduce its ability to deform; it may perform more like a hard-seat seal with increased leakage rates.

FITTING ENDS

There is a significant amount of tubing and fitting ends throughout fuel systems. In hydraulic systems, threaded metal fitting ends commonly provide an acceptable leak free connection. In applications in which eliminating leakage is critical, an elastomeric O-ring may be included to further reduce potential leak rates. In high pressure pneumatic systems, fittings with integrated PTFE ring seals are often required.



Example of a common hydraulic fitting



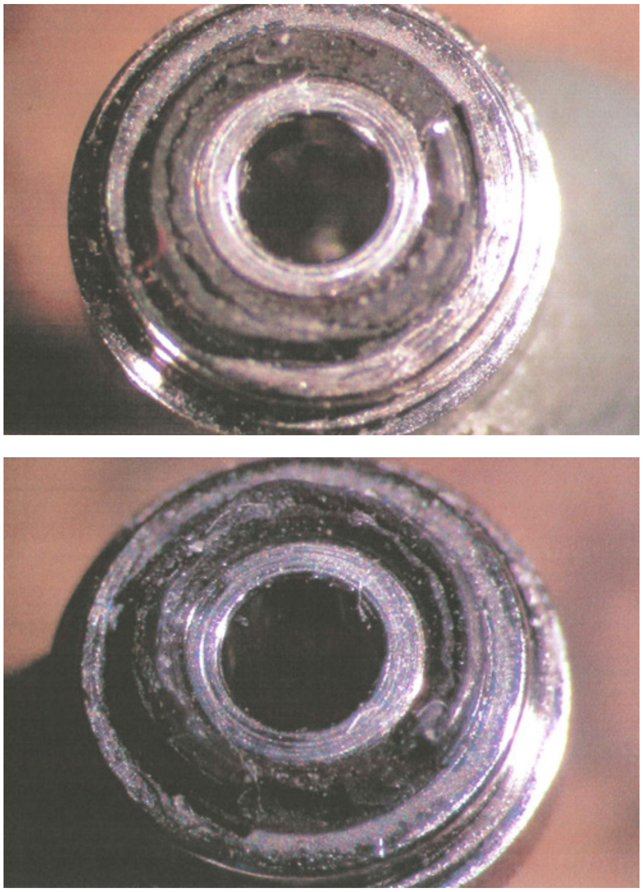
Example of a pneumatic fitting with a PTFE O-ring installed

GENERAL CONSIDERATIONS AND CHALLENGES OF GAS FLOW (CONT.)

PRESSURE VARIATION / EXPLOSIVE DECOMPRESSION

When a valve opens a seal, there is potential for the pressure to rapidly decrease, as happens when a pressure relief valve opens specifically for that purpose. If gaseous fluids are employed and elastomeric valve seals are used to improve leakage, this introduces a new challenge:
explosive decompression.

All elastomers are permeable, so gases under pressure may penetrate into an elastomeric seal. Under very high pressure conditions, a larger quantity of gas will permeate into the seal. When gas pressure around the seal is released, gas trapped inside the seal expands. It may escape harmlessly, or it may form blisters on the surface, rupture, and leave cracks or pits. This phenomenon is called explosive decompression, and it can permanently destroy the seal's ability to function properly. The severity of the damage is dependent upon a number of factors, including the properties of the gas, the properties and size of the elastomer, the initial pressure, and the rate of decrease in pressure.



Example of an elastomeric seal damaged by explosive decompression

TEMPERATURE AND FLUID DENSITY

The design of a fluid control system must take into account the operating temperature range because of the relationship between temperature and fluid density. Assuming a constant pressure, an increase in temperature will decrease fluid density as the fluid expands. For liquid fluids like hydraulic oils, fuels, and water, the decrease in density also decreases viscosity; this may lead to a higher propensity for flow (and leakage) at a given differential pressure. For pneumatic fluids, decreased density will excite the molecules of the fluid to a level that inhibits flow and increases viscosity.

GENERAL CONSIDERATIONS AND CHALLENGES OF GAS FLOW (CONT.)

TESTING CONSIDERATIONS

Testing with gases tends to be less safe when compared to testing with liquids. Since gas is compressible, the potential energy achieved when gas escapes a damaged tube, hose, or connection may lead to more damage. However, there is well-established pneumatic test equipment to help mitigate these concerns.

System testing for airplanes during the development phase should include the replication of types of fluid and range of conditions experienced during flight. However, fuels or propellants may be more costly, less safe to handle, or potentially more difficult to attain than more commonly used fluids.
It is also impractical to acceptance test component hardware at every possible combination of system or environmental conditions. The solution may be to verify performance by correlating design requirements to an appropriate manufacturing acceptance test. Performing testing on a substitute that is readily available, relatively inexpensive, and safe to use—such as air—will save on costs. Ultimately, it is important to select a fluid that will provide an easy and accurate correlation.

In general, component performance testing on gas is a much cleaner process as compared to similar testing with hydraulic oils, fuels, or other correlative liquids. Savings realized from reduced clean up can be reallocated to more rigorous cleaning of parts and to packaging requirements; some hydrogen or reactive gas applications may require cleanroom packaging or alternative component assembly procedures.

HYDROGEN-SPECIFIC CHALLENGES

The topics previously discussed apply to flow control for any gas; controlling hydrogen introduces an additional set of challenges that must be taken into consideration. Fortunately, space launch vehicles have been using hydrogen as a propellant for decades, and some of these challenges are well understood. In many cases, solutions are already in existence.

HYDROGEN-SPECIFIC CHALLENGES (CONT.)

STORAGE

A primary question for aircraft designers will be whether to store the hydrogen in its gaseous state or as a liquid. Storage as pressurized gas typically requires the tanks to be pressurized at 415 Bar / 6019 psi. At this pressure, the hydrogen fluid would have energy per unit volume eleven times lower than kerosene fuels in existence today. If the gas needs to be stored at any higher pressures, the fuel tanks must be redesigned with increased wall-thickness; this will conflict with typical aircraft weight limits. Alternatively, hydrogen may be used in its liquid state at atmospheric pressure. Storage of hydrogen as a liquid requires cryogenic temperatures, because the boiling point of hydrogen at one atmosphere pressure is −252.8°C.

The type and shape of storage container for hydrogen fuel presents its own challenges. Currently, cylindrical tanks are the most common hydrogen storage method. In high pressure pneumatic applications, the cylindrical shape allows for optimal distribution of pressure within the internal walls of the tank. For cryogenic applications, the cylindrical shape efficiently isolates the cooled hydrogen from the higher temperature external environment. Most commercial aircraft carry jet fuel in large tanks located in the voids of the structural elements of the wings. The shape and size of the wingboxes will not accommodate cylindrical tanks, so alternative storage locations must be considered. When evaluating locations, it is important to keep in mind that the center of gravity of an aircraft must be kept relatively constant during flight as fuel is consumed. Depending on the aircraft and its fuel consumption, designers are considering moving fuel storage to other locations inside the fuselage, where space is already a valuable commodity, or mounting tanks below the wing.

TEMPERATURE

To reach its liquid state, hydrogen must be stored at extremely low temperatures below -253°C (-423°F). Such low temperatures and the process of filling aircraft tanks will require the purchase of new equipment and infrastructure at significant expense. In addition, this temperature will affect the performance of pneumatic components in a variety of ways and will require the careful selection of appropriate materials, especially elastomers or polymers. Many of these materials become very brittle at such low temperature extremes.

Storing hydrogen as a liquid requires cryogenic temperatures

HYDROGEN-SPECIFIC CHALLENGES (CONT.)

OPERATING PRESSURES

Most commercial aircraft fluid systems operate at pressures between 103 and 206 Bar (1500 and 3000 psi). Storage of hydrogen at 350 Bar will dictate component designs for higher operating pressure. This may require the selection of appropriate material to improve durability. Some military aircraft hydraulic systems are rated for similar pressures. However, they are not pneumatic systems.

LEAKAGE

Even when hydrogen is stored cryogenically in liquid form, it transitions to a gaseous state as it passes through the propulsion system and associated components. Hydrogen has extremely small molecules and allows for leakage past sealing surfaces at a rate greater than other gases such as air or nitrogen. In fact, hydrogen can leak through sealing materials. This characteristic, and the extreme storage temperature requirements, creates further limitations upon the selection of materials that offer the necessary balance between leakage rate, pressure range, and durability.

HYDROGEN EMBRITTLEMENT / MATERIAL SELECTION

When hydrogen is utilized, there is a major concern regarding the potential occurrence of hydrogen embrittlement. This phenomenon impacts all types of materials including typical aerospace metals such as carbon and alloy steels, titanium alloys, and nickel alloys. Hydrogen is a diffusible gas; it can, therefore, easily work its way into the crystalline structure of a material following prolonged exposure that occurs during service, storage, or material manufacturing. This infiltration of hydrogen into the material may lead to cracking and other catastrophic failures, as the ductility and load-bearing capacity of the material are compromised. Depending upon the environment and stress levels, hydrogen embrittlement—in the form of reduced tensile strength and cracks—may also occur following short-term hydrogen exposure.

Prevention of hydrogen embrittlement begins with proper material selection—a very complex process. Some materials are determined to be sufficiently resistant to hydrogen embrittlement, but they can still fail under certain conditions. The selection of materials is application dependent. It requires an understanding of: fluid compatibility with the working fluids of an application, required temperature and pressure ranges, exposure time, loading conditions, and functional requirements.

Example of cracking caused by hydrogen embrittlement

HYDROGEN-SPECIFIC CHALLENGES (CONT.)

WATER MANAGEMENT

The reaction in a hydrogen fuel cell produces water or water vapor as an effluent, as is the case with most combustion processes. This process must be managed inside components with moving parts and for systems with drains or vents for fluid traps. It is an important issue when one deals with freezing. It will not apply to a cryogenic application on the liquid hydrogen side, but will for an application such as automotive/military APU where water must be managed. The water is deionized, and that may result in leeched ions from metallic components.

TESTING CONSIDERATIONS

It is especially challenging and less safe to test using hydrogen because of its highly combustible nature, and more so, when performance is evaluated at elevated temperatures. Testing costs are significantly higher for hydrogen than for gases such as air or nitrogen. Additionally, testing costs for qualification at required cryogenic temperatures exceed testing costs at more typical ranges down to -40°C (-65°F). Testing at temperatures below -150°C (-302°F) requires unique equipment and processes that are not commonly available.

When components are manufactured, it may be economically advantageous to consider the use of air, nitrogen, or helium in place of hydrogen during acceptance testing. However, there is a downside. The flow of these gases is not identical to hydrogen. Due to differences in viscosity, in actual use hydrogen may allow components to become unstable under conditions in which they will behave normally with test fluids. For more accurate testing, it is recommended that initial qualification should occur under actual system operating conditions with hydrogen fluid.

ELECTRICAL COMPONENTS

Fluidic components with electrical control (such as solenoid valves or motor driven pumps) may be required to be intrinsically safe or explosion- and fire-proof. This is due to potential exposure to a flammable gas. Hydrogen has low electrical conductivity, a characteristic that makes static electricity buildup a concern and signals the probable need for proper grounding and bonding.

Industry regulators will likely drive the need for mitigating steps. Many industries already have such requirements, including:

- **ATEX** (Appareils destinés à être utilisés en Atmosphères Explosives) Directive 2014/34/EU
- **IECEx** (International Electrotechnical Commission Explosive)
- **NEMA** (National Electrical Equipment Manufacturers Association)
- **NFPA 2** (National Fire Protection Agency)

HYDROGEN-SPECIFIC CHALLENGES (CONT.)

APPLICABLE RESOURCES

While hydrogen propulsion is new to commercial aircraft, it has been used in space launch vehicles for years. As a result, there is a readily available wealth of knowledge and experience pointing to solutions for these new challenges. NASA and Sandia National Laboratories are widely considered experts when it comes to the use of hydrogen. Some useful resources include:

- **AIAA Guide to Safety of Hydrogen and Hydrogen Systems** (G-095-2004)
- **Metallic Materials Properties Development and Standardization Handbook – 15** (MMPDS-15)
- **Aerospace Structural Metals Handbook**

HOW CAN THE LEE COMPANY HELP?

For more than 70 years, The Lee Company has been a leading innovator and supplier of miniature, precision fluid control products to a wide range of industries including aerospace, space, oil & gas, automotive, off-highway equipment, medical equipment, and scientific instruments. Lee products are recognized worldwide for superior quality, reliability, and performance.

The Lee Company has a wide range of components available today that have been designed to be the smallest and most reliable options for both liquid and pneumatic applications. We also continue to research product development specific to hydrogen and cryogenic performance. With a history of solving unique problems engineer-to-engineer, approximately 50% of Lee products are custom designed to meet the requirements of a specific application. Among our custom product capability, The Lee Company offers a variety of material options, optimized flow performance, high pressure capability, and extreme environmental resistance.

The Lee Company has a team of Technical Sales Engineers available around the world to work one-on-one with our clients to solve their unique fluid control problems. Contact us today to learn more about how The Lee Company can customize a solution for your unique needs.

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