CRYOGENIC TRANSFER SYSTEM MECHANICAL DESIGN HANDBOOK

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PREFACE

The purpose of this handbook is to provide a source of information on mechanical engineering experience gained from the design, installation, and operation of Kennedy Space Center cryogenic transfer systems from site activation for launch of the Saturn IB to the activation of Space Shuttle. The handbook does not explain thermodynamics, heat transfer, fluid mechanics, or other engineering principles. It does not provide cryogenic and material thermodynamic, physical, or transport properties. It is written to provide information which cannot be found in published text books or cryogenic properties tables. The intent is to provide a simple explanation of some of the problems and experience gained with cryogenic systems at KSC, and how they were resolved for practical application to future cryogenic system design.

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ACKNOWLEDGEMENTS

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Chapter 1

Introduction

Purpose

The purpose of this chapter is to provide a brief description of the existing cryogenic systems at Kennedy Space Center.

Cryogenic fluids used at Kennedy Space Center

The term "cryogenic" is defined as low temperature physics. Technical literature specifies the low temperature as -150 ° C (123 °K) or -240 °F (220°R) and below.

The major cryogenic fluids used at Kennedy Space Center are liquid hydrogen, liquid oxygen and liquid nitrogen. Liquid oxygen and liquid hydrogen are the oxidizer and fuel, respectively, for the Space Shuttle main engines and reactants for the fuel cell power generation system. Kennedy Space Center uses liquid nitrogen for cryogenic testing of cryogenic piping components and systems. Kennedy Space Center used liquid helium in the Apollo program. It was carried to the Saturn V launch vehicle in a vacuum-jacketed dewar.

Space vehicle application

Systems using cryogenic fluids at Kennedy Space Center to service the Space Shuttle in 1991 are:

1. The liquid oxygen system stores and transfers liquid oxygen to the Space Shuttle to oxidize fuel in the Orbiter main engines.

2. The liquid hydrogen system stores and transfers liquid hydrogen to the Space Shuttle to fuel the main engines.

3. The fuel cell servicing system provides liquid hydrogen and a high purity liquid oxygen for the orbiter power reactant system which furnishes

electrical power and water to the flight crew.

Liquid hydrogen is the space vehicle propellant with the highest known expansion ratio. Hydrogen was used as the propellant on the second stage of the Saturn IB during the early phases of the Apollo, Apollo Saturn, and the Skylab Programs. The engines on the second and third stages of the Saturn V also burned hydrogen to carry man to the moon. The second stage of the Saturn V burned hydrogen to launch the Skylab. The main engines of the Space Shuttle also burn hydrogen.

Nitrogen gas is essentially a non-reactive fluid which prevents combustion and burning. It prevents air and moisture intrusion into oxygen systems. The liquid temperature of oxygen is above liquid nitrogen. Nitrogen gas does not liquefy or solidify in the liquid oxygen because the nitrogen remains gas in liquid oxygen. It will, however, condense and freeze at liquid hydrogen temperatures.

Nitrogen is also used to purge external parts of the space vehicles to prevent flammable mixtures of hydrogen and air from developing. It also provides the pressure to operate pneumatic operators on cryogenic valves.

Helium is an inert fluid and is used to displace other reactive and condensable gases and prevent moisture intrusion into the hydrogen systems. The liquid temperature of helium is below that of hydrogen. There is no problem with helium gas solidifying or liquefying in the liquid hydrogen. Helium is used to keep air and moisture out of hydrogen systems which can lead to combustion. Helium also keeps nitrogen out of the system which would solidify in liquid hydrogen and cause rocket engine malfunction.

Brief description of vehicle servicing cryogenic systems

The following section discusses Launch Complex 39 from where Kennedy Space Center launches the Space Shuttle. The Main Propulsion System is the name given to the liquid hydrogen and liquid oxygen systems which supply the main engines on the Space Shuttle. The External Tank holds a liquid oxygen tank and a liquid hydrogen tank which supplies the main engines.

Liquid Hydrogen for Main Propulsion System

Figure 1-1 shows a simplified schematic of the liquid hydrogen system. The liquid hydrogen is loaded into an 850,000 gallon storage tankfrom trailer transporters by pressure through vacuum-jacketed, super-insulated fill manifold piping. The storage tank is spherically shaped with double walls. It is vacuum jacketed and perlite insulated and is located about 1500 feet from the launch pad.

Transfer of liquid hydrogen from the storage tank to the Space Shuttle is accomplished by pressurization. Liquid hydrogen from the storage tank passes through a control valve to an air heated vaporizer where it is vaporized and used to pressurize the tank. The vapor flows to the gas space above the liquid in the storage tank.

The liquid hydrogen elevation head in the storage tank drives liquid hydrogen through the vaporizer loop. The liquid level (elevation head) in the tank must be greater than 20% of storage tank capacity to provide an ullage pressure sufficient for sustaining the fast fill operations.

The fill operation starts with ground support piping chilldown by allowing liquid hydrogen to flow by gravity into the main transfer line for four minutes. The storage tank is then pressurized with the liquid hydrogen vaporizer to 66 psig. The Space Shuttle External Tank is maintained at 43.7 psia by cycling the External Tank hydrogen vent valve. Initial pressurization is done with a helium prepressurization system.

After ground support piping chilldown is complete, there is a period of slow fill to 2% which enables chilldown of the Space Shuttle piping and External Tank liquid hydrogen tank. Fast fill starts at 2% and continues to 98%. Flow through the slow fill valve is reinstated for topping to 100% for better flow control. After filling to 100%, there is a period of replenish through the replenish flow control valve. Liquid hydrogen flows at a rate to replace liquid hydrogen boiloff and provide a constant 100% full level. Different valves in a valve complex control the various fill rates. Fast fill and slow fill are accomplished by using larger and smaller valve sizes, respectively. Replenish flow is controlled by electrical feedback from capacitance probe liquid level sensors to a variable position control valve.

The liquid hydrogen boiloff gas vents to a flare stack and is burned.

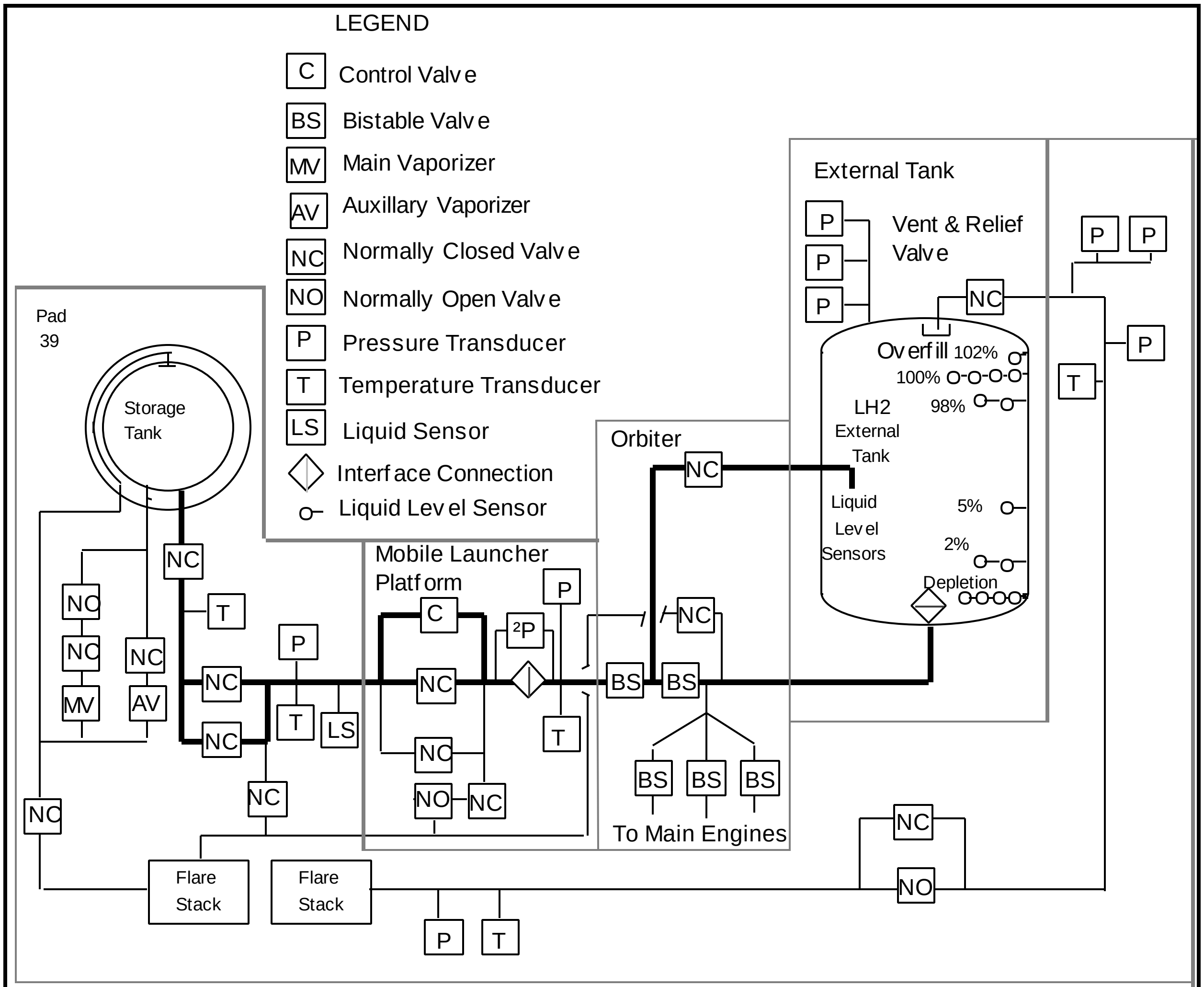

Fig. 1-1 Simplified diagram of Launch Complex 39 liquid hydrogen system

Liquid Oxygen for Main Propulsion System

Figure 1-2 shows a simplified schematic of the liquid oxygen system. The liquid oxygen storage tank is a 900,000 gallon double-walled spherically shaped tank. It is insulated between the walls with perlite and filled with nitrogen gas to keep out moisture. The nitrogen gas is supplied by a pressure regulating system which allows the annulus to “breath” with differences in ambient temperatures and barametric pressures. Liquid oxygen is pressure loaded from trailer transporters into the storage tank which is approximately 1500 feet from the launch pad.

Transfer of liquid oxygen from the storage tank to the Space Shuttle is accomplished by a variable speed centrifugal pump. The storage tank ullage is pressurized to assure the net positive suction head pressure of the pump is provided. Pressurization is accomplished by passing liquid oxygen through a control valve to a water heated vaporizer. Liquid oxygen is vaporized, and the pressurized gas (9 psig) flows back to the tank ullage. The vaporizer uses water flowing over heat exchanger coils to provide vaporization heat.

The fill operation starts with ground support piping chilldown by flowing liquid oxygen slowly into the transfer line. The liquid oxygen is initially pumped through the cross country lines to the valve complex and back to a dump basin. This enables removal of sensible heat from the line without subjecting the vehicle piping to pressure transients. With more dense fluids like liquid oxygen, pressure spikes due to two phase flow transients are a concern. Avoidance of pressure spikes is discussed in more detail in Chapter 2.

A variable speed pump is used to pump liquid oxygen to the Space Shuttle. This enables the desired flow to be achieved without adding excessive pump horsepower heat to the liquid oxygen by throttling valves.

After the ground side chilldown is complete, there is a period of slow fill to 2%, fast fill to 98%, then topping to 100%. Finally, replenish continues until a few minutes before launch. Topping off from 98% to 100% is accomplished at the slow fill rate to allow better flow control. Fast fill and slow fill are accomplished by using large and smaller valves, respectively. Replenish flow is controlled by electrical feedback from capacitance probe liquid level sensors to a variable position remote control valve.

Liquid oxygen boiloff from the External Tank is passed though louvers at the top of the External Tank which interfaces with a vent hood. The hood has canvas seals inflated with heated nitrogen gas. The cold oxygen vent gas is mixed with warm nitrogen and vented to the atmosphere near the Fixed Service Structure, away from the Space Shuttle. This is done to prevent water in the atmosphere from freezing and falling on the Thermal Protective System (tiles) of the Orbiter.

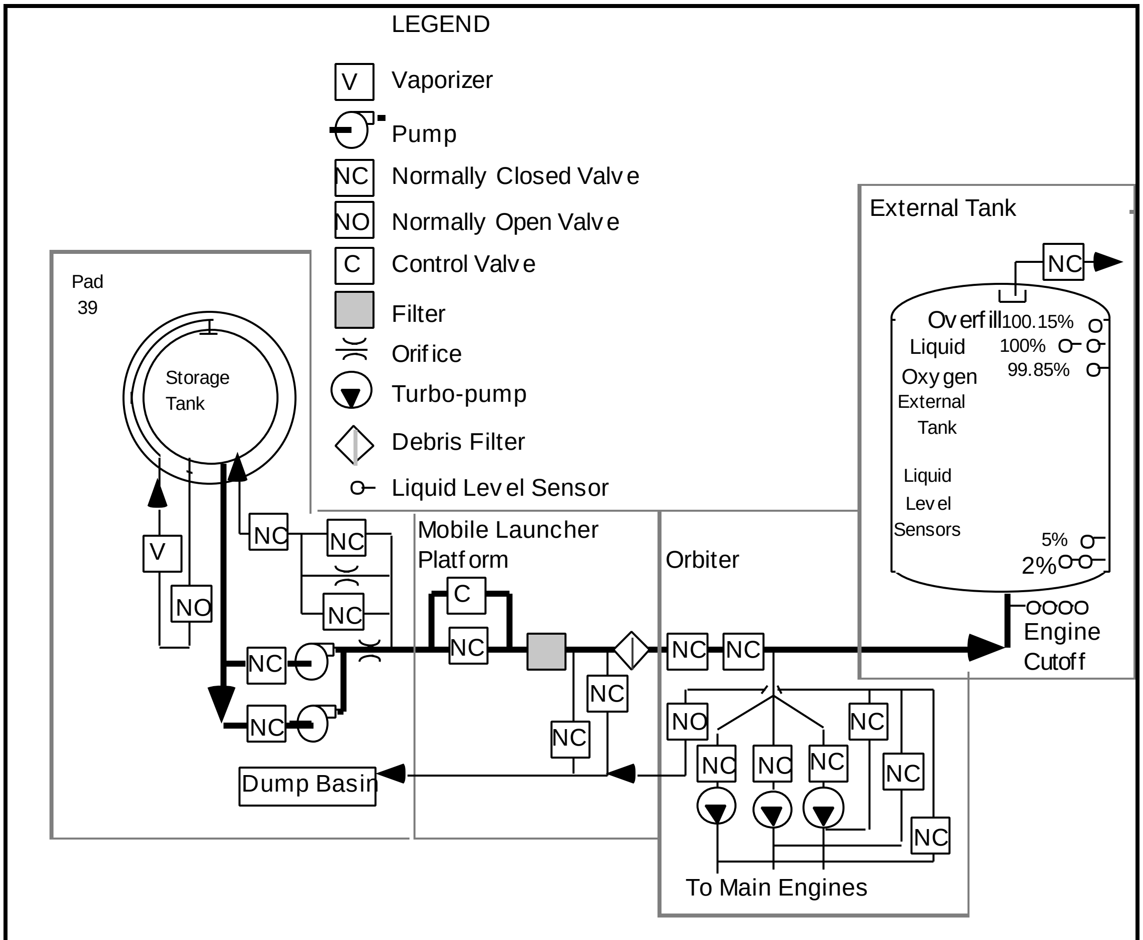

Fig. 1-2 Simplified diagram of Launch Complex 39 liquid oxygen system

Fuel Cell Servicing Systems

The orbiter's fuel cell tanks are loaded at the pad using tanker trailers. Liquid hydrogen and high-purity liquid oxygen are transferred into the respective tanks at low pressure. After the tanks are filled, high pressure valve skids are used to bring the tanks up the flight pressure for supercritical hydrogen and oxygen storage.

Nitrogen

Nitrogen is used to purge the liquid oxygen systems and provide pressure to operate the actuators on pneumatically operated valves. Nitrogen is also used for various Space Shuttle purges such as the External Tank inner tank, nose cone, aft compartment, and payload bay. It is piped as a gas in a 6,000 psig transfer line from an air separation plant south of Kennedy Space Center.

No cryogenic nitrogen piping systems used for launch operations are located on Kennedy Space Center. Liquid nitrogen used to support cryogenic tests is transported by trailer transporters.

Helium

Helium is used to purge the liquid hydrogen systems to prevent a hydrogen and air mixture which could result in an explosion. Helium is used for various purges in the liquid oxygen systems such as engine and disconnect carrier plate purges. It is also used for External Tank liquid oxygen feed line bubbling to prevent geysering. Air entry could result in solid oxygen or solid nitrogen in the engine piping. Helium is loaded from trailer transporters into 6,000 psig bottles at the launch pads on the east side of the flame trench.

During the Apollo program, slush helium was used. Because there was little room in the Apollo spacecraft, slush helium was used to enable helium gas to be stored in a low volume for use during Apollo program missions. Slush helium is partial solid and partial liquid and can be stored longer than liquid because additional heat is required to change the solid to a liquid. The helium was carried to the spacecraft in a portable dewar.

Chapter 2

Undesirable Flow Conditions

Purpose

The purpose of this chapter is to provide information based on KSC experience of some flow conditions which yielded undesirable results. The conditions are covered so that they might be avoided in future cryogenic system designs and operations. Each condition is discussed briefly in separate subtopics.

Pipe Bending from Partial Channel Flow

Liquid hydrogen flow is accomplished by pressurizing the liquid hydrogen storage vessel with hydrogen gas. Liquid is drained from the bottom of the storage vessel, passed through a liquid hydrogen vaporizer, and back to the gas space above the liquid in the tank. Flow though the vaporizer is controlled by a flow control valve which receives feedback from the ullage pressure in the storage tank. The vaporizer is made from aluminum pipe, and heat passes from the air to the liquid hydrogen in the pipe. The vapor then flows to the tank ullage.

The problem encountered during the vaporizer actuation was uneven chilldown due to the liquid flowing into the bottom of the liquid vaporizer horizontal piping. Liquid hydrogen flowed into the pipe with partial channel flow. Liquid was at the bottom of the pipe with gas at the top. Since the liquid hydrogen was in the bottom of the pipe, the pipe was colder at the bottom than at the top. The liquid hydrogen has a greater ability to absorb heat from the pipe than the gas because of its greater mass. This caused the piping to bow upward as the bottom of the pipe shrank more than the top of the pipe. This caused weld failures in the aluminum piping.

This type of partial channel flow should be avoided. The problem was corrected in this situation by inserting a pipe concentrically in the vaporizer pipe. Holes were drilled in the pipe to force the liquid hydrogen flow circumferentially to the top and sides of the vaporizer piping providing more even chilldown and thermal contraction. Cryogenic system design should assure the elimination of undesirable two phase flow which may result in pipe bowing. See Figure 2-1.

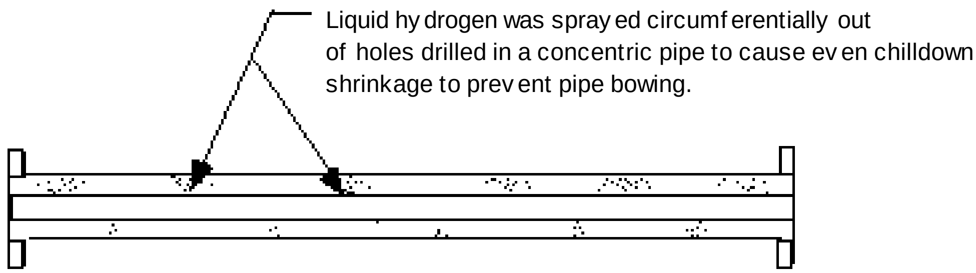

Fig. 2-1 Method of preventing pipe bending in liquid hydrogen system vaporizer piping

Another bowing problem occurred in the hydrogen burn pond (which preceded the current flare stack). During hydrogen venting, hydrogen gas that boiled off was vented from the system and flowed to a hydrogen burn pond. The burn pond provided a water barrier between the burning hydrogen gas and the hydrogen gas flowing from the system. The hydrogen gas flowed though a series of pipes branching out under water to a vertical pipe ending just above the water line. The vertical pipe was covered with a stainless steel cap. Hydrogen gas passing from the system bubbled though the water around the cap and to the surface of the water. Here it was ignited by electrical heaters and burned. The water prevented air from going back into the pipe. See Figure 2-2.

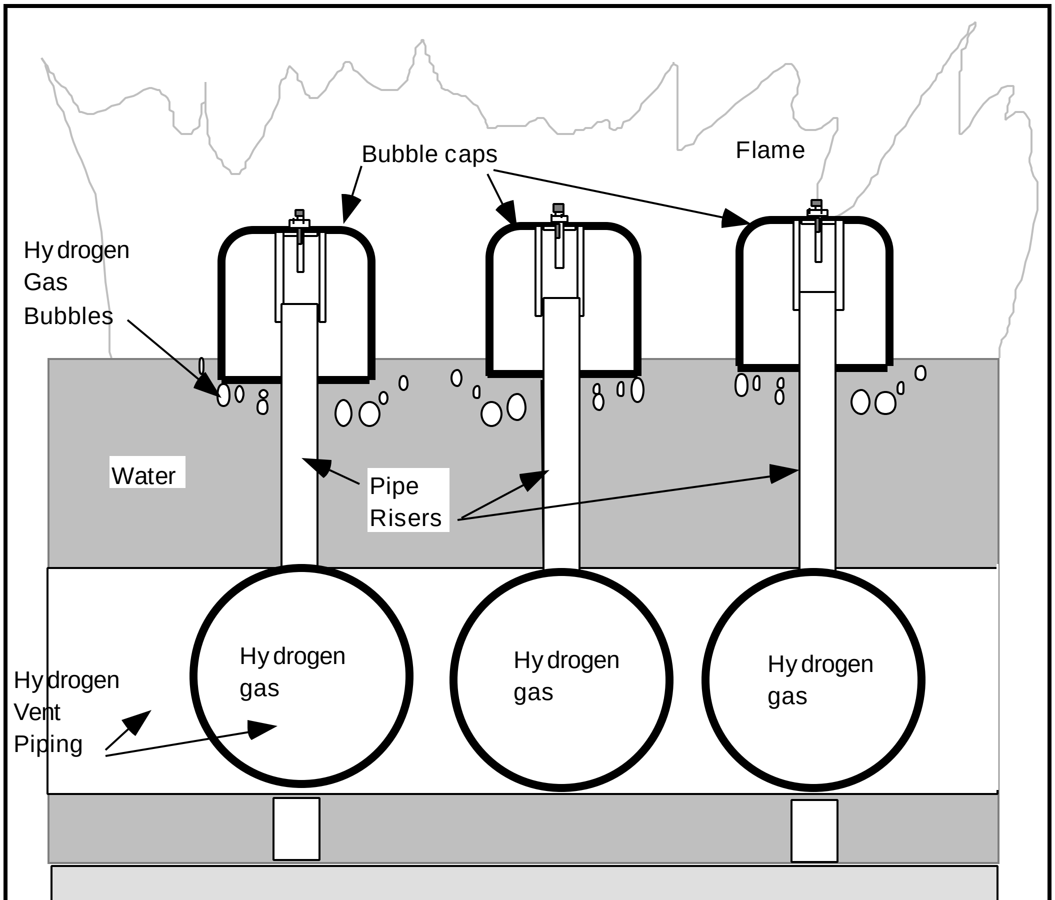

Fig. 2- 2 Elevation cut-away view of hydrogen burn pond piping

During burn pond activation, it was found that the bubble caps were not large enough. The water was freezing from the -300°F hydrogen gas and blocking the gas flow. It was necessary to replace the caps with caps of a larger diameter. The new caps were manufactured from a disk plate welded to a section of pipe. The existing bubble caps were fabricated as one piece with a curved cross section between the cylinder and end piece. With the -300 °F hydrogen under the cap and the 4,000 °F burning temperature above the caps, bowing of the plates on the manufactured caps caused many of the plates to crack. The caps had to be changed to the original curved pipe cap design. Galvanic corrosion of the aluminum in the presence of stainless steel was also a major problem which is covered in Chapter 4.

Avoidance of Hammer Effect at Storage Tank Outlets

During activation of the liquid oxygen system in 1965, a bang was heard by personnel witnessing activation tests in the vicinity of the liquid oxygen storage tank. It happened when the 18-inch, remote-controlled, 10,000 gallon-per-minute, variable-speed pump suction valve was opened.

To minimize heat transfer, a vapor space was provided by installing a vapor trap in the piping from the inner tank to the outer tank. The pipe exits the bottom of the inner tank and turns upward between the two tanks. The pipe then bends downward to the 18-inch shut-off valves as shown in Figure 2-3. The gas space in the trap was under pressure from the liquid sitting in the inner tank. During liquid oxygen system activation tests, the butterfly hand valve to the main liquid oxygen pump was opened. Some liquid dumped into the tee piping where it was warmed. Vapor filled the space between the remote control butterfly valve and the vapor trap. As the remotely-controlled 18-inch butterfly valve was opened, the compressed vapor in the vapor trap vented quickly due to the opening characteristics of the butterfly valve. The liquid oxygen hit the partially opened butterfly disk of the 18-inch butterfly valve.

This hammer effect was large enough to cause the flexible hose between the hand valve and the remotely- controlled valve to break. It was impossible to get to the hand valve and shut the flow of liquid oxygen off. About 800,000 gallons of liquid oxygen poured out of the tank. The resulting vacuum pulled a suction on the inner tank which partially collapsed.

The problem was corrected by providing a vent valve in the vapor trap to allow it to be filled with liquid oxygen as shown in Figure 2-3. The hand valved where modified to make them remotely-controlled to enable the valves to be closed from the launch control center. The procedure was changed to open the vent valve and fill the vapor trap with liquid oxygen before opening the remotely-controlled valves. Flexible hoses were strengthened by providing rods between the flanges to prevent them from pulling apart. Other repairs were necessary such as repairing the liquid oxygen 10,000 gallon per minute pump base plates cracked by thermal contraction and replacing damaged flexible hoses. The inner liquid oxygen storage vessel was repaired by filling it with water and applying hydraulic pressure to force it back to its spherical shape.

During the design of the cryogenic system, the roles of liquid and gas during valve cycling must be considered. The 18-inch butterfly valves had orifices installed in the controllers to close the valves slowly to prevent the water hammer effect. However, this installation and operational sequence caused an extreme water hammer rather than avoiding one. Condensing of relatively warm oxygen vapor trapped in areas of the system piping can also cause severe water hammer as pressurized liquid meets the gas.

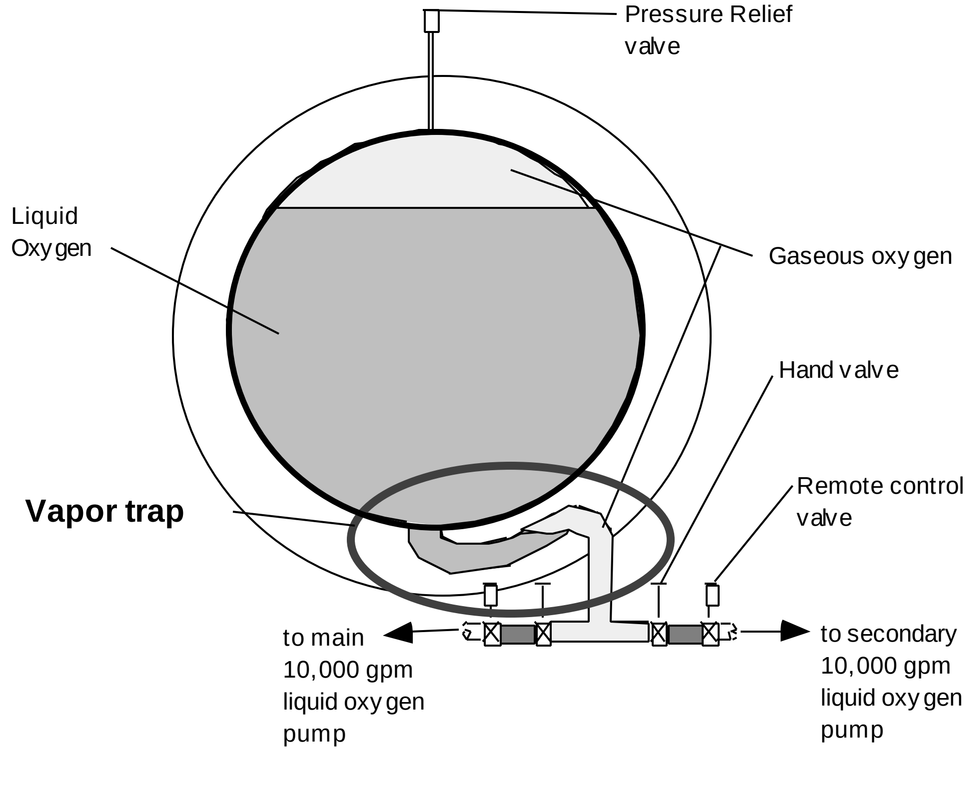

Fig 2-3 Sketch of liquid oxygen tank vapor trap

The modification to allow venting the vapor trap and filling the vapor trap with liquid oxygen was successful throughout the Apollo program. This modification was not used for the Space Shuttle program because the 18-inch pipe lines were not required. The 10,000 gallon per minute pumps in the 18-inch pipe lines were not used for fast filling Space Shuttle and were removed from the system. Fast fill of the Space Shuttle was accomplished with the 1,000 gallon per minute variable speed pumps which had been used to slow fill the SII and SIC stages of Saturn V.

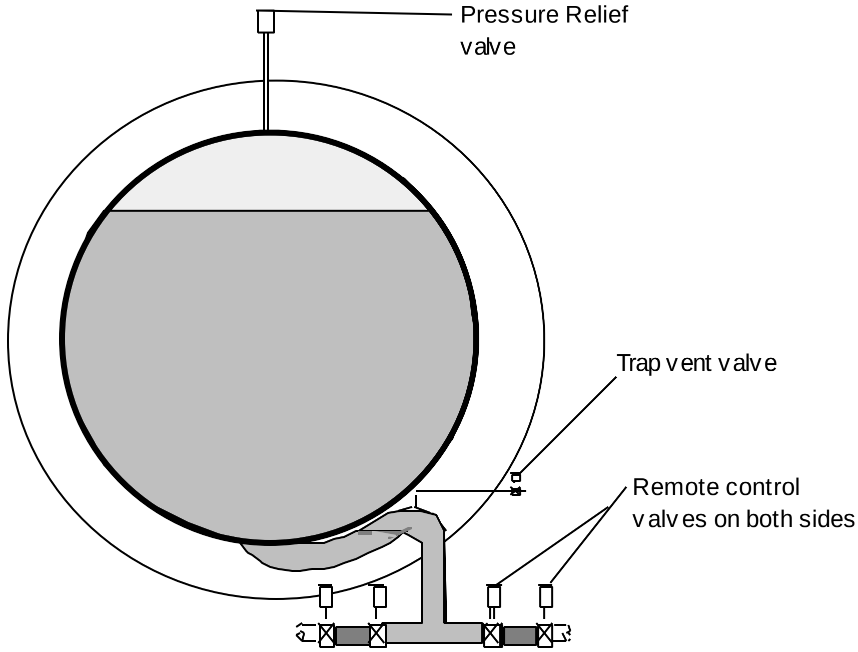

Fig 2-4 Sketch of liquid oxygen system piping modifications

Slug Flow

The Saturn V launch vehicle consisted of a SIC first stage powered with RP-1 (kerosene) fuel and liquid oxygen oxidizer. Its SII second stage and a SIVB third stage were powered with liquid hydrogen propellant and liquid oxygen oxidizer. A 14-inch uninsulated line was used to fast fill liquid oxygen with a 10,000 gallon per minute liquid oxygen pump to the SI and SII stages of the Saturn V. A 6-inch vacuum jacketed line was used to slow fill, fast fill and top off the SIVB stage of the Saturn V and slow fill and top off the SII and SI stages with a 1,000 gallon per minute pump. The SIVB stage was loaded first, the SII stage was loaded second and the SIC stage was loaded last.

Before loading the SIVB stage, the 14-inch uninsulated pipe line was chilled down. Liquid oxygen was left without flow in the entire uninsulated 14-inch pipe line while the 6-inch vacuum-jacketed line was used to completely fill the SIVB stage and slow fill the SII stage.

While the SIVB was being filled, the liquid oxygen in the uninsulated 14-inch pipe line became saturated under the static pressure of liquid oxygen to the elevation of the SII Stage. When liquid oxygen flow was restarted in the 14-inch line to fast fill the SII stage, the pressure on the saturated liquid oxygen in the line was suddenly reduced as it flowed to a higher elevation toward the SII stage. This caused spontaneous boiling and slug flow as shown in Figure 2-4. The gas pockets accelerated the slug flow. Columns of liquid were forced down the pipe with considerable kinetic energy against the SII baffles. The flow baffles in the bottom of the SII stage liquid oxygen tank were damaged.

This problem was corrected by a change in procedure. Before starting fast fill to the SII stage, all of the liquid oxygen in the 14-inch line was pumped to a dump basin. Fast fill to the SII stage was then started with liquid oxygen which was not saturated. Slug flow was no longer a problem. In the design of the cryogenic system, the operation sequence plays an important role. The system should not be operated in a sequence which allows the fluid to become saturated. It is best to design and operate the system to assure continuous flow. It is best to chill down the ground support piping used to load the space vehicle tanks to a location as close to the vehicle connection as possible.

Slug flow with liquid hydrogen is not as big a problem as with liquid oxygen because it does not carry the same kinetic energy during flow. The liquid oxygen is about 16 times more dense than liquid hydrogen.

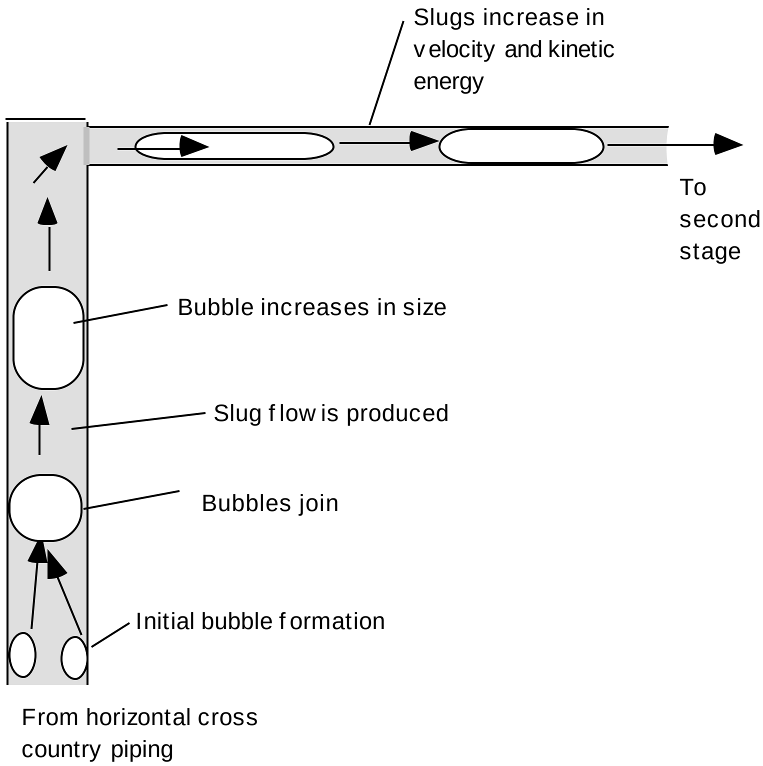

Fig. 2-5 Sketch of slug flow formation when pumping saturated liquid oxygen to a higher elevation

Geysering

The flow condition described under "Slug Flow" above is similar to geysering because it occurs in a vertical pipe. The ideal configuration for a geyser is when a long cryogenic pipe extends from a cryogenic tank. The cryogen is allowed to warm in the vertical pipe. As the liquid warms, it becomes saturated. Bubbles from boiling accumulate on the pipe walls. The bubbles stay attached to the walls by surface tension until they get big enough for buoyant force to break them loose.

As the bubbles rise, they collide and join to form a large bubble. The static head under the large bubble decreases by the diameter of the bubble. This causes accelerated boiling at the bottom of the bubble. The greater the bubble becomes, the greater the pressure reduction, the larger the bubble becomes, and the greater the upward acceleration. As the bubble rises, the static head rapidly reduces. The process perpetuates with greater and greater energy and gases and liquids are thrown into the main tank.

The evaporation of the cryogen causes cooling and the cold liquid falls back into the pipe. The gas under the liquid is condensed by the cooling process. The gas also condenses under the pressure of the falling liquid. The liquid fills the pipe and pressure hammers the bottom piping. This hammer effect possibly causes piping damage.

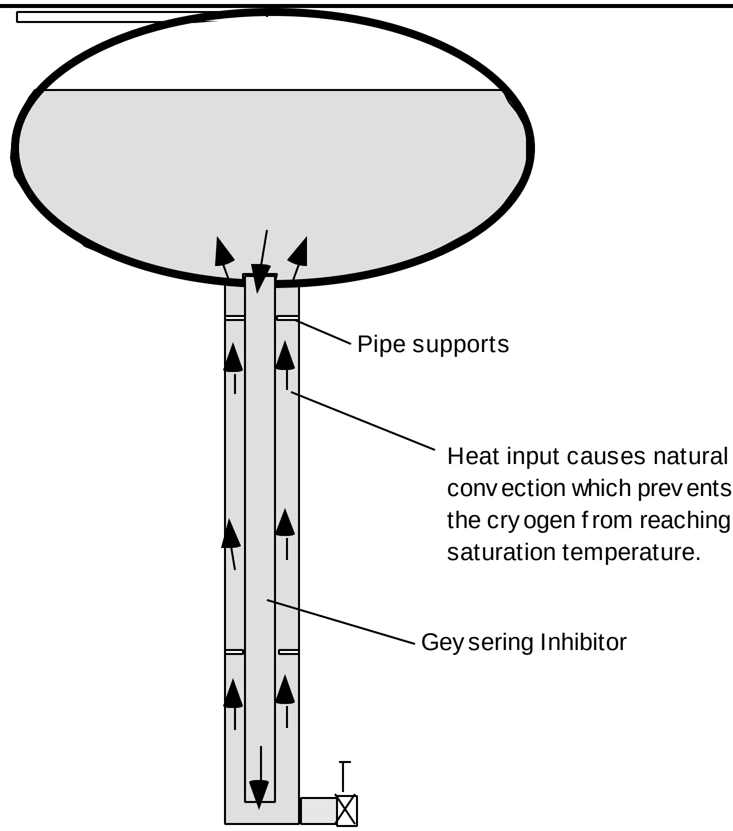

Fig. 2-6 Sketch of Geysering Inhibitor

A method has been developed to prevent geysering. It requires the installation of a concentric pipe inside the main pipe which extends into the cryogenic tank. This geysering inhibitor causes the liquid in the annulus of the pipe to be warmed and pushed up by natural circulation. Cold liquid moves down the center pipe. This process has been tested, and it was found that the natural convection prevented the cryogen from become saturated in the pipe, thus preventing geysering. The diameter of the concentric pipe was selected such that the cross sectional area of the concentric pipe was nearly equal the cross sectional areas between the pipes. (See Figure 2-5.)

Cryogenic Component Testing

During the cryogenic leak testing of butterfly valves to be used in the liquid oxygen system, they were submerged in liquid nitrogen and leak checked with helium gas. The valves leaked even though the same model valves had been operational in the liquid oxygen without any leak problems for several Saturn V launches.

Analysis of thermal contraction of the valve parts as a function of time revealed the cause of leakage. Shrinkage of the outer parts of the valve before the inner parts shrunk caused seat leakage. During normal operation, the valves were chilled down from the inside out which did not open leak paths.

The effect of thermal contraction as a function of time should be considered during component design and system operation. This should also be considered during component testing to assure that no adverse effects are present.

Rebound Principle

During hydrogen burn pond activation, the burn pond piping kept filling up with water. Analysis of this problem revealed the water was being syphoned into the burn pond piping as a result of the rebound principle.

A sketch of the rebound principle is shown in Figure 2-6. It was found that dimension A was greater than dimension B. Liquid was pushed out of the bottom of the burn cap (to dimension A) by hydrogen gas. When the bubbles passed, the water level rebounded. It reaches a level above the pond water level equal to the distance it was pushed down minus the liquid head energy loss of the process (dimension B). Consequently, the water rebounded above the level of the riser pipes and water flowed into the riser pipes. The burn pond piping was filled with water.

This problem was corrected by adjusting the bubble cap height such that dimension B is greater than dimension A.

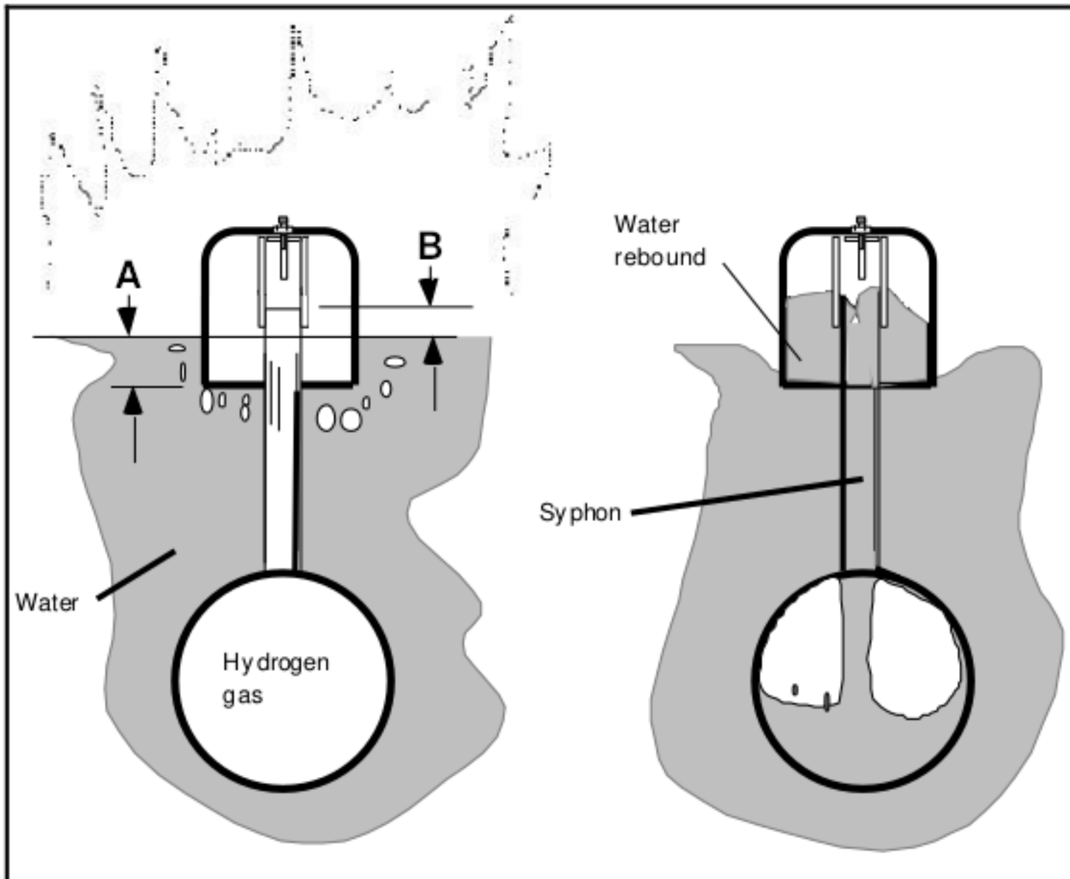

Fig. 2- 7 Burn pond syphoning

Flare Stack Design

The hydrogen system was later modified to use flare stacks to burn the vented hydrogen gas which were manufactured by Flaregas Incorporated and had no problems.

Care should taken in the flare stack design and installation to avoid adverse results of the chimney effect. This occurs when the vent line is under a helium purge or when it is flowing hydrogen gas. The gas in the stack is less dense than the atmosphere. If there is a leak in the flare stack piping, the upward movement of the gas in the stack can pull in air. This may result in a hydrogen air mixture and explosion. Consequently, care should be taken to eliminate any air inlets or leaks into the flare stack.

Summary

In summary, the following items should be considered about flow in a cryogenic system design:

1. Assure that the lessons learned in this chapter are applied where appropriate.
2. Visualize what is happening to the liquid and gas as a function of time during any operations. Consider the entire system operation to completion of flow and securing of the system.
3. Provide for continuous flow to prevent saturation of liquids or hot spots in the system. This may prevent slug flow, geysering, and excessive pressures when flow is resumed.
4. Accomplish chilldown slowly to avoid pressure and flow transients which may result in excessive pressure spikes.
5. Consider the effects of heat transfer on the system and all components in the system and the effects of stresses caused by thermal contraction. This is a prime concern during partial channel flow.
6. Assure that there is no way for air to enter the liquid hydrogen piping. Oxygen in the air will solidify in liquid hydrogen, and flow could cause an electrostatic charge and explosion. Nitrogen in the air will solidify in liquid hydrogen and possibly cause engine damage.
7. Assure that all cryogenic systems are purged with the proper inert gas during inactive periods.
8. Assure that there are no fluid traps in the system so that the system can be quickly drained and emptied.
9. Include system revert, contingency, and testing sequences in the analysis.
10. Consider the effects of gas condensation by pressurized liquid.

Chapter 3

Undesirable Piping Stress Conditions

Purpose

The purpose of this chapter is to provide information gained from undesirable stress conditions in cryogenic piping.

Thermal Shrinkage

During a loading of liquid hydrogen on the Saturn V launch vehicle, a fire sensor alarm went off. It brought attention to a hydrogen fire in the vent line from a helium heat exchanger on the tower. The vent line was closed. A helium purge was turned "ON" and the fire was out in about 20 seconds.

Subsequent investigation showed that a bellows in the hydrogen vent line had broken because of thermal shrinkage. The bellows section was not long enough to allow sufficient contraction. The thermal shrinkage of the hydrogen vent line was recalculated, and additional expansion bellows were installed to provide the shrinkage capacity required.

Thermal shrinkage was also a problem in the liquid oxygen fill manifold piping on Launch Complex 39B. Bellows were also replaced with larger bellows to allow more expansion without being over stressed.

The calculated values of stress on bellows usually exceed the elastic limit and enter the plastic range. Consequently, the calculated stress values can be very high, and care should be taken to provide sufficient bellows for thermal contraction.

Stresses Imposed by the Environment

After several years of usage, the vacuum-jacketed liquid hydrogen line sections on launch Pad 39A began to lose vacuum. This is critical because the loss of vacuum increases heat transfer to the liquid hydrogen. This vacuum decay will increase the boiloff rate in the flight vehicle liquid hydrogen tank. The tank pressure will increase from the additional hydrogen boiloff gas venting to the burn facility. The increase in pressure in the tank will cause the hydrogen to boil at a higher temperature and lower density. If the density decreases excessively, there will not be enough hydrogen mass in the fuel tank to fulfill the launch mission. The desired vacuum level should be a pressure of 10 microns or lower.

An end section of the vacuum jacketed pipe was examined. A leak was found in the piece between the inner and outer pipe shown in Figure 3.1. Since the piece zigzags back and forth, it will be called a jagged section. The jagged section between the inner and outer pipe was fabricated by rolling a stainless steel cone. It was seam welding lengthwise. The cone was then cut horizontally into sections. Every other section was rotated and seam welded. The intent of this configuration was to provide a long conductive heat transfer path between the inner and outer pipe. The space between the inner and outer pipe was filled with wrappings of aluminum-mylar film and thin sheets of foam. A vacuum was pumped in the space between the pipes.

The inner pipe was made from invar because it has a low thermal coefficient of expansion. The outer pipe was made with small expansion bellows to provide for some thermal expansion. A bimetallic invar-to-stainless-steel weld was made by the piping manufacturer to enable a field weld of stainless-to-stainless. The end connection was enclosed with a mechanical coupling which was bolted together with a rubber seal.

Investigation revealed that leaks were at the seal welds in the jagged sections between the inner and outer pipes. Investigation also revealed the jagged piece was a rigid member. It was also apparent that the weld that held the slices together were stress concentration areas because of the sharp radius of the root of the connection. Further analysis revealed that the temperature change of the outer pipe from the sun during the day to no sun at night caused a stress in the leak area. The small bellows in the outer pipe did not prevent the stresses. The stress alone was not excessive. When evaluated for cycling enough times for fatigue failure, it was determined the number of sunrises experienced since the pipe was installed was the number of cycles required for fatigue failure. A condition imposed by the piping environment had caused the failure.

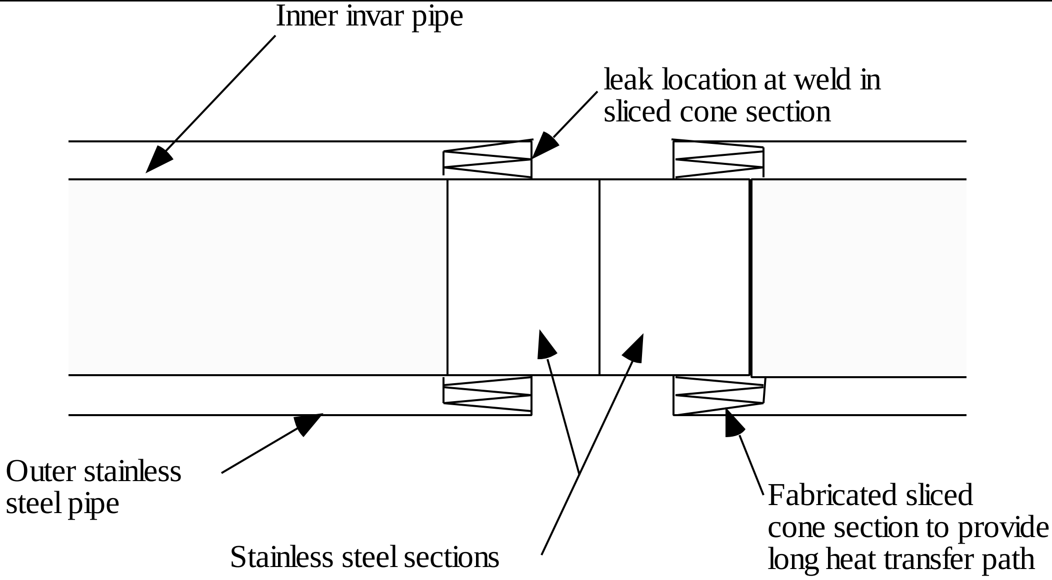

Fig. 3.1 Section drawing of vacuum jacket ed pipe end section

To eliminate this problem, the end closures were redesigned and reconfigured as shown in Figure 3-2. A hole was punched in each of the jagged sections. A new conical piece designed to take the fatigue stresses was installed. A welded closure was installed over the end connections.

Vacuum pump-out ports are installed on each section on the outer pipes. The holes punched in the jagged sections enable pumping a vacuum in each section of pipe. This enabled the modification to be done without removing the sections.

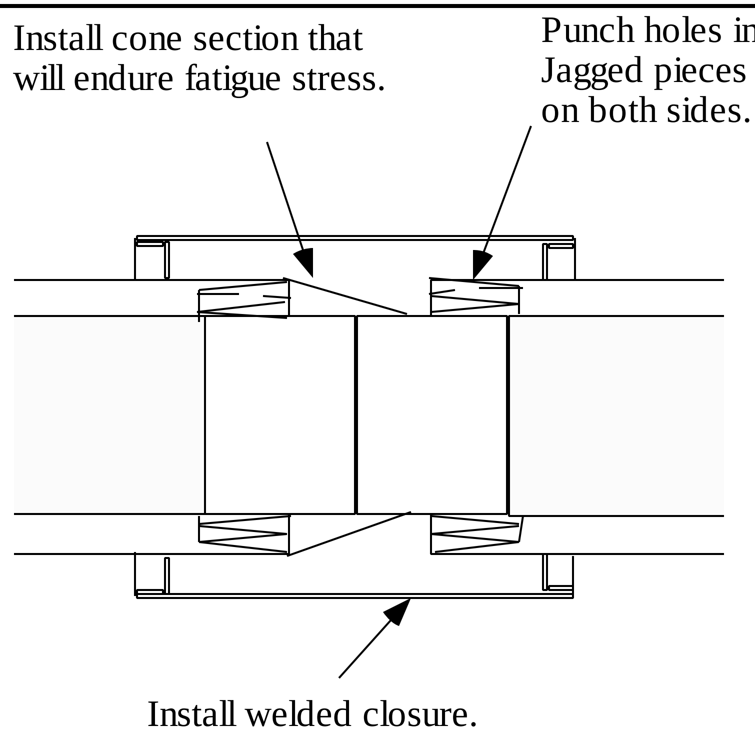

Fig. 3-2 Redesign of liquid hydrogen vacuum jacketed pipe

Stress Imposed During Bellows Testing

When performing pressure tests on bellows and flexible hoses, a force is created at the end of the bellows. The force equals the product of the test pressure and the circular cross sectional area of the bellows. The force can easily stretch and distort the bellows and create substantial end forces on the system guides and anchors. To keep this from happening, the ends of the bellows should be held so the bellows will not stretch. See Figure 3-3.

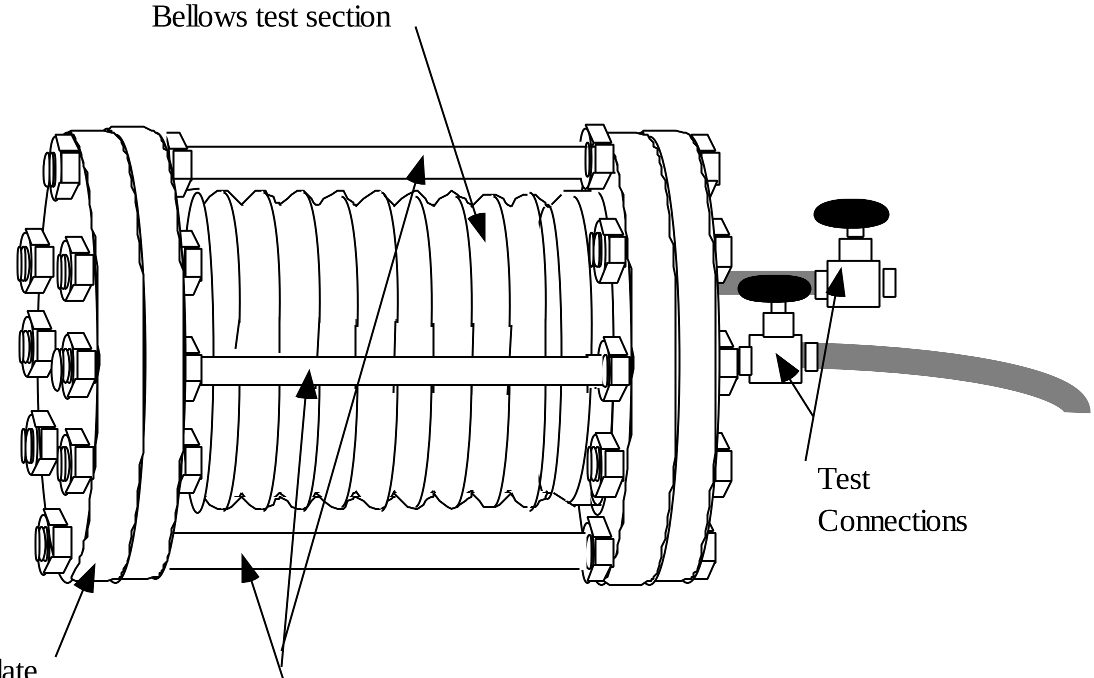

Fig. 3-3 Typical method of preventing bellows from stretching during pressure tests

Offset Stresses in Bellows

If a bellows section is installed in a manner that pipe shrinkage causes it to go out of centerline alignment, failure may occur. When it moves, excessive stresses may be generated by strain and system pressure. To keep this from happening, guides should be installed to assure that bellows movement is on the centerline. Guides may be made from pipe rollers of slides. Teflon pads should be used on sliding guides to protect the bellows section from damage by scraping the guides.

Other Undesirable Stress Concerns:

The following other types of stresses should be considered in the system design:

1. Vibration from flow though flexible lines and bellows.
2. Vibration from flow over system instrumentation.
3. Stresses imposed by the launch environment.
4. Stresses resulting from adverse flow conditions covered in Chapter 2.

Chapter 4

Undesirable
Material Application

Purpose

The purpose of this chapter is to provide information on experience gained during material selection.

Welding Problems Resulting from material Selection

During the Apollo Space Program, lessons were learned about material selection. The 14-inch liquid oxygen cross-country transfer line on Launch Complex 39A was constructed with aluminum alloy piping. Stainless steel was selected for Launch Complex 39B. The reason for changing material dates back to problems encountered in welding aluminum piping on Launch Complexes 34 and 37.

Aluminum was originally chosen for Launch Complexes 34, 37, and 39A for economical reasons because aluminum material is not as expensive as stainless steel. Difficulties were encountered in welding the aluminum piping because of problems with fit-up, position welding, lack of penetration, and cracking. Welding rings were used in low pressure gas lines to reduce these problems, but cleaning requirements precluded welding ring use in cryogenic piping. The original intent was to have all welded piping systems. The welders had extreme difficulty in making acceptable in-place welds from all positions. Plans were revised and flanges were installed on long cross-country pipe lines at approximately 200-foot intervals. This enabled the piping to be rotated. All welding could be performed at approximately the 1:00 o' clock position for improving the control of fit-up and penetration. This procedure produced acceptable welds.

During the 1963-64 installation period on Launch complexes 34 and 37, the Launch Complex 39A cryogenic system package was in preparation. It was released during the first quarter of 1964, requiring aluminum piping and components. Launch Complex 34 and 37 aluminum pipe welding experience showed that cost saved welding stainless steel would be greater than cost saved using cheaper aluminum material. This determination was too late to incorporate into the Launch Complex 39A design which was already in fabrication.

Welding problems were also encountered while installing additional supports on the relief valves on the Launch Complex 34 liquid oxygen system. While performing this work, it was discovered that the old aluminum pipe was extremely difficult to weld because of formation and propagation of cracks in the weld metal. It was believed that the salty atmosphere adversely affected the aluminum piping.

Galvanic Corrosion

Aluminum piping also caused galvanic corrosion in the hydrogen burn pond between the aluminum piping and the stainless steel bubble caps. It was necessary to coat the aluminum piping with epoxy. The burn caps were coated with organic zinc rich paint. This provided a barrier between the metal and the burn pond water which was the electrolyte, and kept the aluminum piping from plating onto the stainless steel bubble caps. Stainless steel bubble caps were used to withstand the temperature of the burning hydrogen above the water in the burn bond.

Aluminum piping was also a problem when it was necessary to connect with stainless steel piping of a stainless steel component. on Launch Complex 39A, teflon cylinder inserts had to be used in the flange joints to provide an electrolytic separation between the dissimilar metals. On Launch complexes 34 and 37, sacrificial aluminum washers were used with stainless steel nuts and bolts on flanged joints. The aluminum washers would plate on the stainless steel when the sea mist provided the electrolyte for galvanic corrosion. This presented the question of how long would the washers last before they had to be replaced. All piping on Launch Complexes 34 and 37 has been removed and this is no longer a problem.

Stainless steel pipe and components were used for the cryogenic systems on Launch Complex 39B and have required less fabrication and maintenance problems. Stainless steel is recommended over aluminum for future cryogenic piping system installations.

Hastelloy C-22

During the activation of the Launch Complex 39A Fuel Cell Servicing System, there was a problem with stainless steel bellows failure. Bellows for this system were 0.008 inches thick. The corrosive environment of the Kennedy Space

Center launch pads caused bellows failure resulting from chloride along with crevice corrosion. This resulted in the stainless steel bellows being replaced with Hastelloy C-22 which is much less corrosive in the Kennedy Space Center environment.

Stainless steel bellows used in expansion joints and flexible hoses in other cryogenic systems at Kennedy Space Center launch pads are nominally 0.020 inches thick. These thicker bellows also began failing from crevice corrosion and are being replaced with Hastelloy C-22 bellows when stainless steel bellows fail or when new designs are required. In conditions where bellows or threaded fasteners are subject to crevice corrosion, Hastelloy C-22 is recommended instead of stainless steel.

Other Material Considerations

Other considerations which should be taken into account in material selection for cryogenic system design are:

1. Use materials in the cryogenic transfer system which are chemically compatible with the cryogen being transferred.
2. Use materials which will be suitable for the full range of temperature exposure.
3. Use materials which will provide the desired physical, heat transfer, and electrical properties.
4. Use materials in liquid oxygen systems which are not adversely sensitive to impact in liquid oxygen.
5. Do not use materials which are subject to hydrogen embrittlement such as Inconel X in high pressure gage Bourdon tubes in hydrogen systems.
6. Do not use materials which are subject to excessive corrosion in their service environments.
7. Use materials and component designs which are suitable for cleaning.