RECIPROCATING CRYOGENIC PUMPS AND PUMP INSTALLATIONS

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Asia Industrial Gases Association

298 Tiong Bahru Road, #20-01 Central Plaza, Singapore 168730

Tel: +65 62760160 • Fax: +65 62749379
Internet: http://www.asiaiga.org

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PREPARED BY :

Herve BARTHÉLÉMY	Air Liquide
Dany BOURDEAUD'HUY	Praxair
Michaël PHILLIPS	BOC Gases UK
Rudi SCHAERLAECKENS	Messer Gaspack
Andy WEBB	EIGA
Paul WISE	Air Products

ASIA INDUSTRIAL GASES ASSOCIATION
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1 Introduction

Reciprocating cryogenic pumps have become key components within the gases industry handling primarily, liquid oxygen, argon and nitrogen but also other fluids such as carbon dioxide and nitrous oxide. To ensure that pumps will operate both safely and reliably it is important that pumps are correctly designed, installed, operated and maintained as required for the duty.
Pumping cryogenic fluids is accompanied by some degree of hazard. The hazards include liquid under pressure, cryogenic temperatures, volume and pressure increases due to vaporisation and the ability of oxygen to accelerate combustion.
This document gives guidance to manage these hazards.

2 Scope

This document is intended to cover primarily cryogenic reciprocating pumps and installations for liquid oxygen, argon and nitrogen. The principles contained within the document may be extended to other low temperature products such as carbon dioxide and nitrous oxide.
The document contains a summary of industrial practices and is based on the combined knowledge, experience and practices of EIGA member companies.
Note: Centrifugal liquid oxygen pumps are covered by EIGA document 148.

3 Definitions

3.1 Shall

Used only when procedure is mandatory. Used wherever criterion for conformance to specific recommendation allows no deviation. Shall can be used in text of voluntary compliance standards. (Do not use in foreword, footnote, or annex). Avoid the use of must.

3.2 Should

Used only when a procedure is recommended.

3.3 Cryogenic reciprocating pump

Consists of a motor (single, twin, or variable drive) belt drive assembly, warm end (crank drive) and the cold end.

3.4 Cold End

Pump assembly through which the cryogenic liquid passes and is elevated in pressure.

3.5 Warm End

Crank drive box.

3.6 Purge Gas

Ambient temperature, dry, oil free air, nitrogen or argon used to sweep away or prevent concentrated oxygen or moisture laden air.

3.7 Thermosiphon tank

Tanks with dedicated pump pipework with both feed and return pipework connected to the tank liquid phase. This arrangement improves pump priming by allowing circulation of liquid from tank, through the pump and back to the tank, even when the pump is not running.

3.8 Cavitation

This phenomenon occurs when the pressure in a liquid drops below the vapour pressure of the liquid at a certain temperature. At this point liquid will vaporize, thereby creating vapour bubble. These bubbles may cause a pump to lose prime or suffer heavy vibration and damage.

3.9 Loss of prime

Loss of flow through the pump.

3.10 NPSH

Net Positive Suction Head Table 1 in EN ISO 5198:98 or ISO 9906:1999

3.11 Subcooled liquid:

Is a liquid at a temperature below its boiling point.
Subcooling: can be achieved by increasing the liquid pressure above its equilibrium pressure or "bubble point".

4 Description of a Reciprocating Cryogenic Pump and Pump Installation and components

A typical cryogenic pump installation will consist of a vacuum insulated cryogenic tank, reciprocating pump, a vaporiser, interconnecting and delivery pipework. This is shown schematically in Fig 1.
Typical applications include filling of compressed gas cylinders, but there are other applications where high pressure gas or cryogenic fluid is required.

In most cases the pump will be supplied by liquid from a vacuum insulated cryogenic tank consisting of an inner vessel and an outer jacket. The tank will usually be filled from a road tanker, but may be filled directly from a production plant. There are two main types of vacuum insulated cryogenic tanks used in cryogenic reciprocating pump installations. One type is a standard conventional use tank. The other is a thermosiphon tank. The thermosiphon tank is a more recent development and both tanks are described in more detail in section 5.

The reciprocating pump takes the cryogenic fluid and compresses it to the required pressure of operation, as described in section 5.

If the product is required in the gaseous condition, then the product will pass through a vaporiser to convert it from liquid to the gaseous phase. Vaporisers can be ambient, that is relying on no additional heat input to vaporise the product, or there maybe an external heat source such as hot water, steam or hot air.

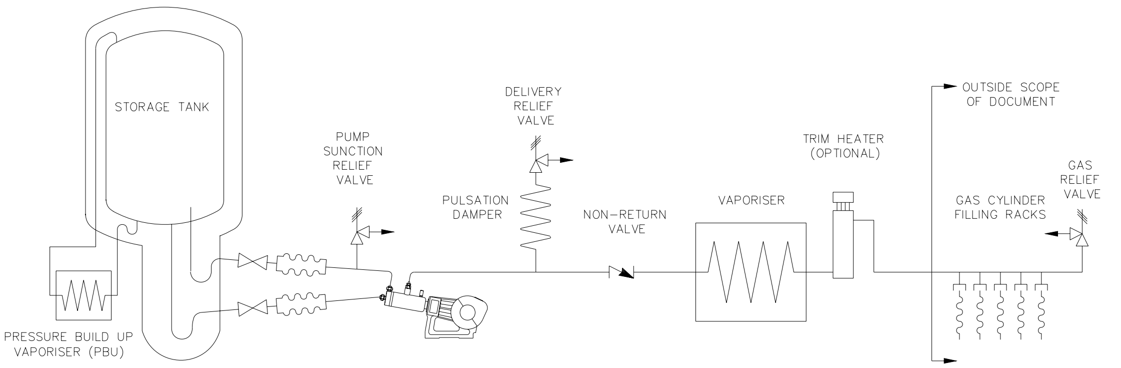


Fig 1 Typical Cryogenic Pump Installation

5 Description of Individual Components

5.1 Tanks

Most new installations will use a tank with dedicated pump feed and return piping, rather than a conventional tank. The most common tank with dedicated pump pipework is a so called ‘thermosiphon’ tank. The piping arrangement on a thermosiphon tank (see 5.1.1) and a conventional tank (see 5.1.2) are described below.

5.1.1 Thermosiphon Tanks

The thermosiphon tank piping arrangement is illustrated in Fig 2.
The pump feed and return pipework ensures good suction conditions to the pump when running and during standby. The rate of tank pressure rise and therefore vent losses are also reduced.
The thermosiphon tank design incorporates both the suction and return pipes in a vacuum insulated leg which descends from below the tank to a point almost level with the ground.
The pump suction pipe descends from the centre of the inner vessel, to a low point within the vacuum insulated jacket extension. This then rises and exits the vacuum jacket, continually rising towards the pump. A liquid return from the pump suction rises back towards the vacuum jacket extension. After penetrating the vacuum jacket it is then connected through the inner vessel lower dished end. The return connection is usually made closer to the vessel outer diameter than the suction feed. The return pipe is usually extended internally up from the dished end to ensure that the warmer return liquid rises away from the lower pump suction feed nozzle.
Shallow gas traps are included on both feed and return pipes within the vacuum jacket extension to stop external pipes remaining ‘wet’ and therefore iced when a pump is isolated.
Heat gained to the external pump pipework reduces the cryogenic liquid density sufficiently to generate a thermo siphon circulation of liquid from suction to return pipework even when the pump is not running.
For effective operation designers should ensure that a sufficient height difference exists between suction and return tank connections and keep the depth of internal gas traps to a minimum.

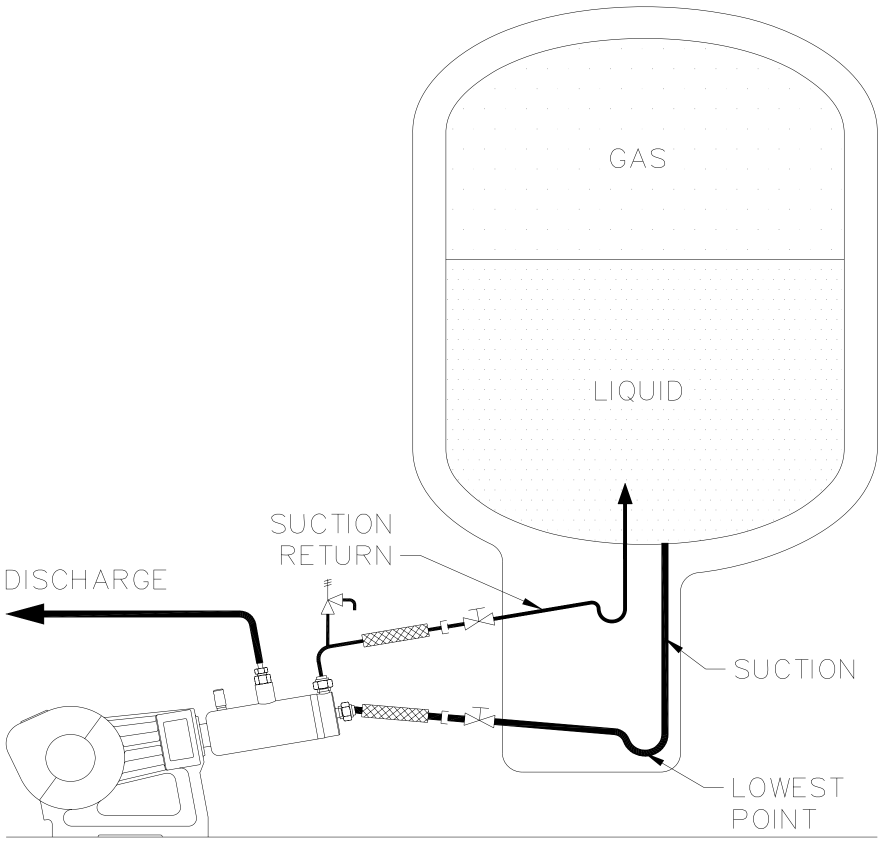


Fig 2 Thermo siphon tank arrangement

5.1.2 Standard conventional use tanks piped for pumps

Standard, conventional use, tanks, as described in Fig 3, are usually piped up with the pump suction feed from the bottom of the tank and a vapour return to the top of the tank.
The pump suction feed may be from a pipe dedicated for this purpose or one used for tanker filling or other process duties.
The disadvantage of this liquid feed-vapour return arrangement is that once the tank level falls below a certain level, the feed to the pump becomes effectively a long single pipe containing at least one gas trap. Should the pump be shutdown for even a short period, the liquid in the suction pipework rapidly reaches its boiling point and the pipe becomes gas locked.
Pump priming can only be achieved by product venting or by the use of liquid vapour separators at a high point on the suction pipework. Such separators can vent the vapour but cannot re-establish subcooled liquid (with adequate NPSH). Separators also increase the risk of liquid spillage from the tank.
Vapour return lines from pump suction should not be piped into the tank main relief valve line because the relief valve pipe can become flooded and be unable to protect the tank from overpressure.
In addition it can cause the relief valve (and bursting disk) to discharge the full tank content to the ground.

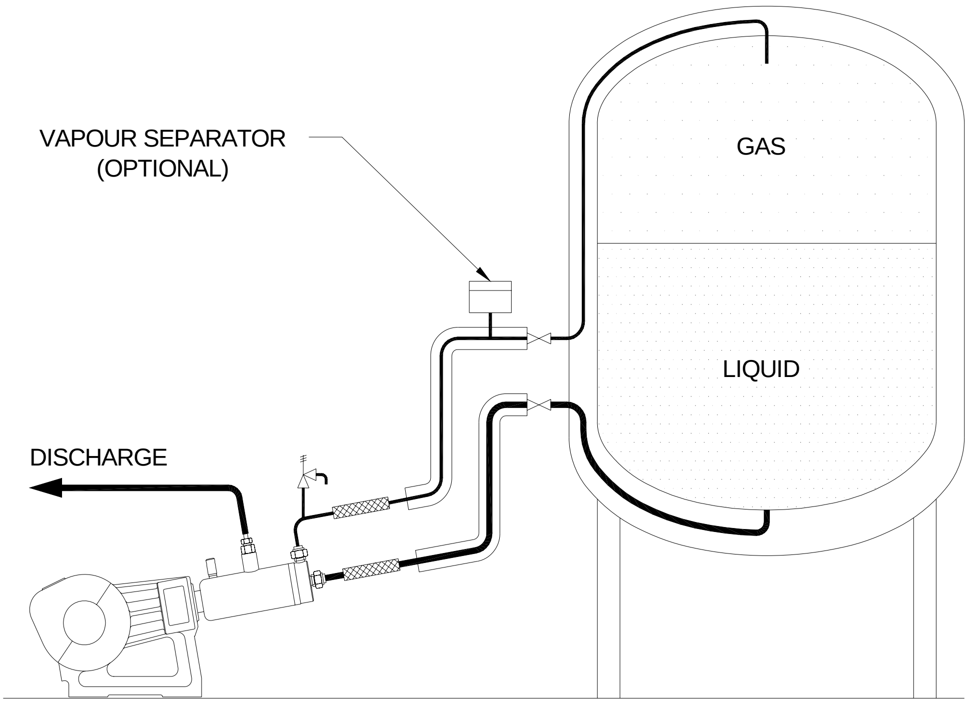


Fig 3 Standard tank arrangement

5.1.3 Pressure Build up and Tank Pressure

Standard and thermosiphon tanks may incorporate a "Pressure Build Up" vaporiser (PBU). If the system experiences pumping problems the pressure build up vaporiser can be used to increase the NPSH or subcooling.

5.2 Pump

The reciprocating pump compresses the cryogenic fluid to the required pressure of operation.
Pump design has progressed and evolved over the years as filling to higher cylinder pressures has increased.
A variety of pump configurations are in use. All have in common provision for vapour escape; ideally back to the storage tank.
Modern designs enclose the ‘cold end’ piston, barrel, suction and discharge valve assembly in a vacuum jacket.

The pump is usually driven by an electric motor.

The pump components are described below. Recommended materials are covered in section 6.

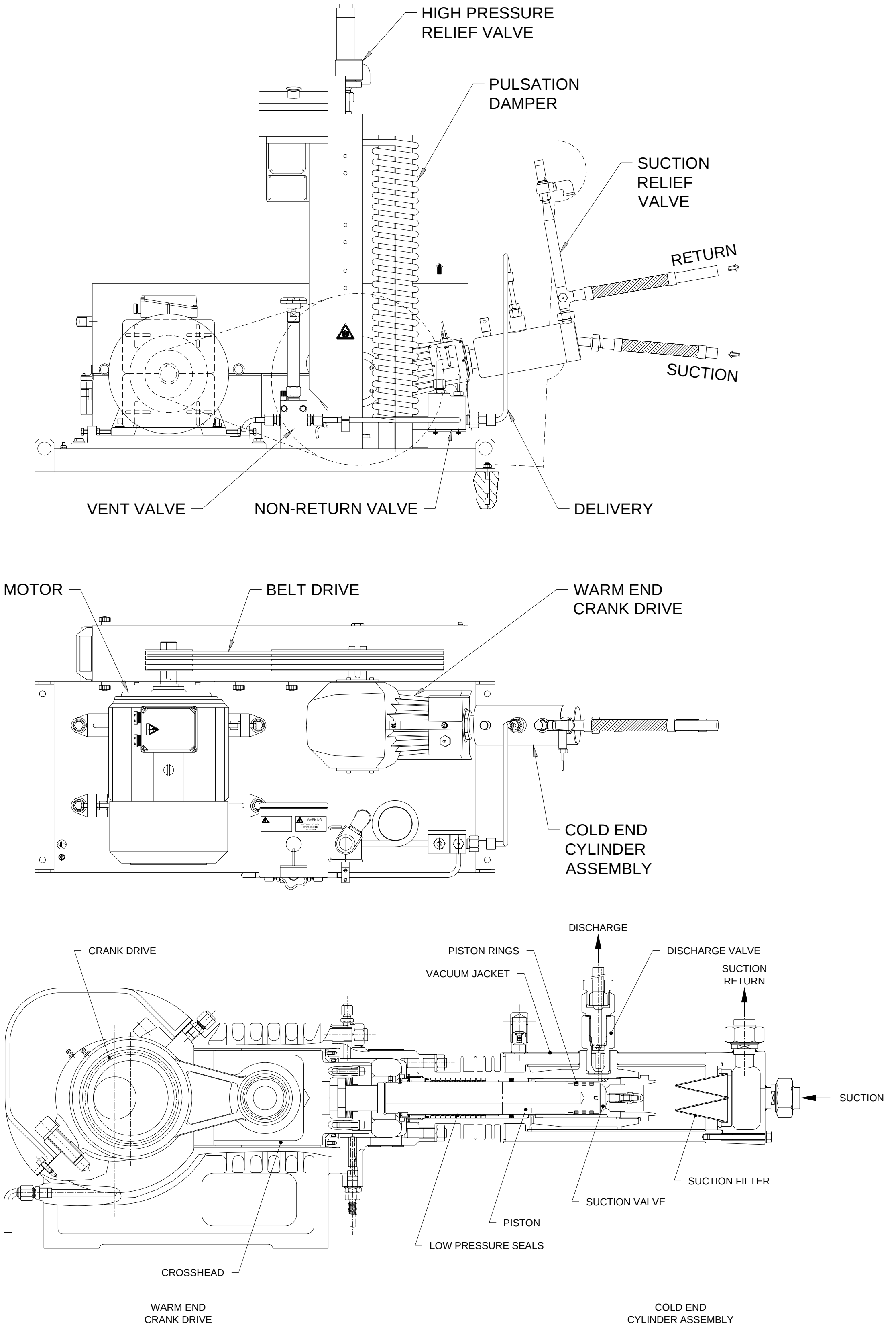


Figure 4 Typical Reciprocating Pump Components

5.2.1 Suction Filter

Pumps require a suction filter. Fine mesh filters (typically 150 microns) are usually incorporated within the pump suction chamber. Filters should have a large surface area and be readily accessible for inspection or maintenance.
The design of the filter and selection of filter material for oxygen service is a critical issue, see Table 1.

5.2.2 Cylinder Assembly

The main components are the piston, piston rings, cylinder and suction and discharge valves.
Piston rings are often made from a compound including PTFE or similar. Such plastics have a much larger coefficient of expansion than that of the surrounding metals. It is therefore important to ensure that pumps are adequately cooled before operating, to minimise piston ring wear and the risk of overheating.

5.2.3 Gland seals

Leakage to atmosphere of cryogenic liquid from the piston assembly is prevented by 'low pressure' gland seals around the piston rod. These can be damaged by frozen moisture on the piston rod or excess play in the piston rod due to wear in the 'warm end' drive.
Cryogenic liquid leakage through worn gland seals has resulted in brittle failures of warm end drives and also oxygen related fires. Avoidance and detection of such leakage is important. The use of an electrical seal heater or 'clamp on' heater is recommended, and/or the application of a warm dry gas purge around the exposed piston rod.
Note: the electrical seal heater should be in use during cold standby only.

5.2.4 Warm End Drive

The piston is normally driven forwards and backwards by a crank drive and crosshead assembly. These are usually of simple standard design, rated for the pressure and flow rate expected for the 'cold end'. Smaller, lower duty crank drives often have dry running crossheads and pre-packed grease lubricated main rolling element bearings. Higher duty crank drives are usually oil lubricated.
For pumps in oxygen service the design and selection of the lubrication system is particularly important.

5.2.5 Cold and Warm End Connection

The warm and cold ends are often joined and separated by a bolted assembly that ensures both correct alignment and transmission of forces and that any leakage of cryogenic liquid is kept away from the warm end.
Correct tightening of bolts is important to avoid fatigue related bolt failures. This is usually achieved by using a torque wrench and appropriate lubricant on the washers, stud and nut threads.

5.2.6 Electric Motors

Electric motors may be single, dual or variable speed. The use of variable speed drives gives additional flexibility for controlling filling rates and temperatures, for example when filling small cylinders.

5.3 Vaporisers

Ambient vaporisers are typically constructed from stainless steel or Monel piping surrounded by aluminium fins, (for material selection for vaporisers in Oxygen service see Table 1). Where there is insufficient space for an ambient vaporiser, or where the vapour generated during operation may be unacceptable, vaporisers that require an external heat source can be used. These includes fan assisted ambient vaporisers steam or those using a boiler. An ambient vaporiser should be sized for the product, flow and expected ambient conditions using accurate and detailed weather data for the region of operation.

To supplement ambient vaporisers in cold climates, ‘trim heaters’ (typically electrically heated) are sometimes fitted downstream of the ambient vaporiser.
In hot climates, bypasses are sometimes fitted to reduce the temperature of the outlet gas.
In some cases safety systems will be needed to prevent low temperature fluid being delivered downstream of the vaporiser(s) in the event of vaporiser overload or failure. EIGA doc 133 gives guidance on where this is appropriate.

5.4 Piping and Piping Components

Piping shall be suitable for the pressure, temperature and fluid being pumped.
The piping assembly should be designed and installed to take into account the stresses caused by temperature cycling and vibration from a low temperature reciprocating system.
Pipework between tank and pump should be as short as possible and have continuous slopes, Low points and long horizontal runs should be avoided. The bore of this pipework should be selected according to the pump flow rate requirements. Fluid velocity is optimised when the loss of NPSH due to heat inleak is equal to the loss of NPSH due to frictional pressure drop.
Fittings and adapters with sharp bends or changes of section should be avoided to keep pressure losses to a minimum.
Piping should be adequately supported and allow for contraction/expansion due to temperature cycles.
Lines to thermal relief valves should rise or include a gas lock to prevent icing of the valve.
Flexible hoses reinforced by external braiding are often used on the suction side of pumps to isolate the tank and suction valves from pump vibration. Where no other provision for suction pipework thermal contraction is made these flexible hoses should be installed slightly compressed to anticipate the reduced pipe length of approximately 3mm per metre during cool down.
Consideration should be given to access for ease of pump removal and to the possible requirement for the system to be warmed or purged with a dry warm gas before and after maintenance.

5.5 Valves

Ball valves are commonly used between tank and the pump for isolation of liquid for operation, maintenance or emergency. These valves should have extended spindles and may be operated manually or automatically.
Note some designs of ball valves when in cryogenic service require the ball to be drilled on its upstream side to ensure that any liquid that may be trapped can escape.
On Liquid Oxygen systems a remotely operated actuated valve should be fitted on at least the liquid feed valve(s) as the primary form of protection in the event of an oxygen pump fire. Actuated valve(s) should also be considered for inert gas service. These valves shall be fail closed, i.e. they shall close in the event of loss of pneumatic or electrical supply.
Automatic systems may utilise these valves for process isolation.
Actuated valves may be fitted with limit switches to confirm whether the valve is open or closed.
In addition or alternatively a low pressure switch may be fitted on the pneumatic supply to the actuator to detect loss of pressure.
A pressure relief valve shall be installed at any point where liquid may become trapped between two valves.
A non return valve should be fitted in the downstream pipework to prevent backflow of high pressure gas in the event of a pipe break or fire.
Manual or automated valves are sometimes fitted between this non return valve and the pump discharge valve to aid priming or reduce back extrusion of the pump discharge valve when sitting warm.
Where there is any possible method of isolation in the discharge pipe a full flow relief valve shall be fitted. The relief valve shall be sized for full pump flow and set at no higher than the design pressure of the system.
The relief valve shall vent to a safe area.
Valves shall be manufactured to a recognised standard such as ISO 21011 Valves for Cryogenic Service

6 Material Selection

Materials for components need to have adequate properties e.g. mechanical, low temperature, lubricating, material compatibility, for the system operating temperature, pressure and process gas. For guidance see ISO 21028 (low temperature properties) and ISO 21010 (process gas compatibility).

Additionally for installations that will be supplying medical and breathing gas, account needs to be taken of the potential release of toxic gas by some materials.
Some halogenated materials such as PTFE may give off toxic gases from decomposition or burning: see EIGA 73 (Design considerations to mitigate the potential risks of toxicity when using non-metallic materials in high pressure oxygen breathing gas systems).
Combustion of such materials within cryogenic pumps is usually an obvious event and should be followed by quarantining of any downstream cylinders etc.

The use of such materials should be eliminated where an ignition may not immediately be detected e.g. no soft seal valves and kept to a minimum where their elimination is not practical.

Liquid oxygen pumps shall be constructed so that possible oxygen leakage cannot contact any hydrocarbon lubricant. Where this cannot be prevented with certainty, the use of oxygen compatible lubricants meeting the requirements of ISO 21010 shall be considered. It should be noted, however, that such oxygen compatible lubricants are less able to protect the bearing against corrosion (they have poor wetting properties and do not provide a corrosion protective film).
Oxygen compatible lubricants are also inferior to hydrocarbon based greases in their ability to withstand load and speed. Simple substitution of oxygen compatible lubrication without taking the overall design/duty into consideration may make a failure and therefore possible ignition more likely.
Oxygen compatible lubricants may also have some adverse reaction with some materials such as aluminium.

The following two tables give a non exhaustive list of commonly used materials for the construction of oxygen pumps and pump installations.

Table 1

‘Typical materials of construction for reciprocating liquid oxygen pumps’

	ITEM	MATERIALS	COMMENT
1	Pump body	Monel, Stainless Steel	Aluminium alloys should not be used.
2	Sleeve (cylinder liner)	Monel, Inconel, Stainless Steel	
3	Piston	Monel, Silicon Bronze, Stainless Steel, Beryllium Copper for LP section.	
4	Piston Ring	PTFE with 60% Bronze filling, PTFE with Carbon filling.	For medical installations, see above and EIGA doc 73
5	Piston ring spring (energiser)	Beryllium Copper, Stainless Steel	
6	Guide (rider) ring	PTFE with 60% Bronze filling, PTFE	
7	Piston Low pressure seal	PTFE with 15% glass fill	For medical installations, see above and EIGA doc 73
8	Suction Valve Seat	Monel, , Stainless Steel	
9	Suction Valve	Monel, Inconel, Nickel coated Stainless Steel, Stainless Steel	
10	Discharge Valve (poppet valve)	PCTFE, PTFE with 15% Glass fill, Monel	For medical installations, see above and EIGA doc 73
11	Discharge valve spring (if fitted)	Beryllium Copper	
12	Discharge valve body	Monel, Stainless Steel	
13	Discharge Valve Gasket	Copper	

Typical materials of construction for oxygen pump installations (piping, valves, vaporiser, etc)

1	External fittings, connections	Monel, Stainless Steel	
2	Piping	Monel, Stainless Steel	
3	Valves (isolation, non return)	Monel, Tin Bronze, Phosphor Bronze, Stainless Steel	
4	Pulsation damper	Monel, Stainless Steel	
5	Vaporiser	Monel, Stainless Steel	

7 Instrumentation

The instrumentation fitted to a cryogenic pump and pump installation will depend upon the operational requirements of the installation and fluid pumped.

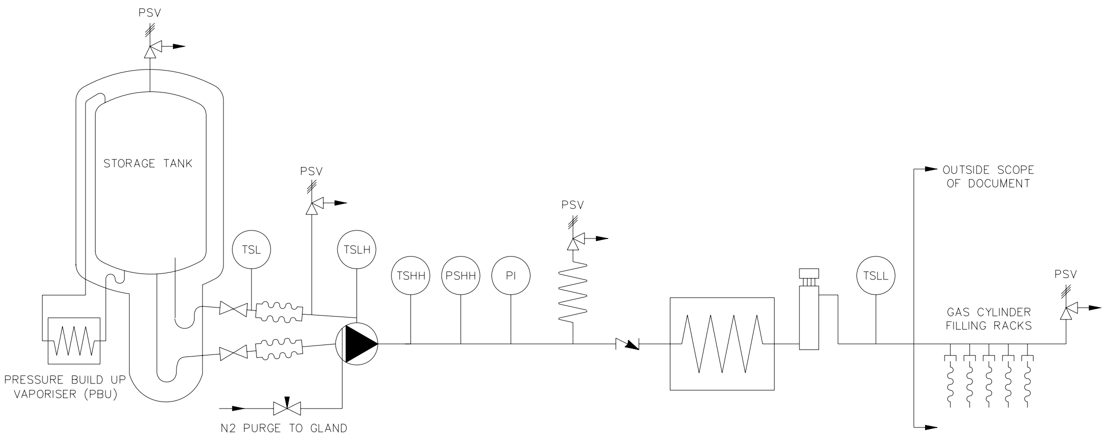
As a minimum all pumps shall have:
1. A loss of prime shutdown system to prevent overheating and damage and in the case of pumps in oxygen service, potential ignition.

This is normally a 'high' temperature trip (TSHH) on the pump discharge line. This has to be overridden for a short period on start-up to allow the pump to be primed.
The start up timer override should be set at as short a time that will allow the pump to reliably prime.

Other methods of loss of prime protection include a low current trip. These are difficult to configure and are less reliable on variable speed pumps.

Differential pressure trips are usually unsuitable for typical reciprocating pump installations as the discharge pressure will not normally fall on loss of prime.

The appropriate Safety Integrity Level for the loss of prime shutdown system should be determined. The system should then be designed and installed to meet this level.



Other instrumentation may include:

2. A high discharge pressure trip (PSHH)
This will shut the pump down before the discharge relief valve lifts.

3. Suction return low temperature permissive start/trip. (TSL)
This is a temperature probe positioned to notify the system that the desired cool down temperature has been reached and that the fluid condition remains acceptable during operation.

The set point should be as low as possible consistent with the warmest liquid that might be expected in the storage tank. (The higher the operating pressure of the tank, the warmer the potential liquid temperature).

4. Gland leakage low and high temperature. (TSLH)
This a temperature probe located between the cold and warm end. This will notify the system of piston gland seal leakage (TSL)
Note: this should be fitted as standard on liquid oxygen pumps.
The same temperature probe may be used for high temperature detection to give warning of possible cold end/warm end mechanical issues (TSH).

5. Vaporiser discharge low temperature. (TSLL)
This a temperature probe located after the vaporiser to ensure that the gas flowing downstream is not too cold, with the risk of embrittlement of the cylinders etc.
The appropriate Safety Integrity level for this low temperature shutdown system should be determined. The system should then be designed and installed to meet this level.
Temperature elements may be resistance bulb (PT100) or thermocouple. Whichever is selected the system shall shutdown in the event of element or detector going closed or open circuit.
The temperature sensing element should be installed at an appropriate distance downstream of any vaporiser bypass line return (to allow for mixing).

6. Discharge pressure gauge.(PI)
This gauge is positioned at the pumps discharge outlet (after the pulsation unit) for monitoring the discharge pressure of the pump.

7. Nitrogen purge to the internals of the warm end drive.
This purge is fitted to some pumps to prevent the ingress of moisture. A manually adjusted flowmeter is often fitted to indicate and regulate this flow.
The potential for overpressurisation of the warm end drive should be considered and if necessary a low pressure relief valve should be fitted.
If the purge to the crank drive is shared with one to the pump gland area, a non return valve should be considered to prevent any liquid gland leakage being directed to the warm end.

8. Emergency stop button.
This 'hard wired' emergency stop should be included within the control circuit to stop the pump and close any liquid and vapour return actuated ball valves fitted'

TAG	INSTRUMENT	TYPICAL VALUES	STATUS
TSHH	loss of prime shutdown system	for air gases -120^{o}C	Mandatory
PSHH	high discharge pressure switch	Less than relief valve	Recommended
TSL	Suction return low temperature permissive start		Optional
TSLH	Gland leakage low and high temperature	-50^{o}C+50^{o}C.	Recommended for LOX pumps
TSLL	Vaporiser discharge low temperature	-20^{o}C	Mandatory where bypass fitted
PI	Pressure gauge positioned at the pumps discharge		Optional
	Nitrogen purge to the internals of the warm end drive		Optional. Recommended where O_2 compatible grease used

8 Insulation

The requirement for any insulation will depend on the liquid conditions and pipework arrangement. When insulation is used, the type and material will depend upon a number of items, including the product being pumped, and volume of product through the piping. Insulation should be compatible with the fluid being pumped and condensed air where such condensation may occur.

9 Installation

Equipment is usually securely bolted to a concrete plinth.
Consideration should be given for access for operation and maintenance. Piping and cable routes should be considered early in the design stage to minimise (and combine where possible) the number of runs. Suction pipework should be short and direct. Delivery pipework and cabling may be long and run to keep the installation clear for operation and maintenance.
For oxygen installations the use of safety zones or barriers should be considered.
Any risk assessment should take into account, duty of the pump (pressure flow etc), materials of construction, lubricant, safety devices/instrumentation, installation location etc.
A barrier on at least one side of an oxygen pump (to protect the driver or filler for example) is often employed, with a 3m safety zone marked on sides without a barrier. Fully enclosed pumps are not desirable as leaks and faults may go un-noticed until a failure occurs.
Fully enclosed pumps are not desirable as leaks may lead to enrichment and faults may not be detected.

10 Operating Pumps

A number of problems can occur during the operation of a cryogenic reciprocating pump. Pump manufactures should supply comprehensive operating and trouble shooting information.
However in addition a list of common problems and solutions are detailed below.

1 Pump fails to produce expected flow or pressure:
-Ensure that both the feed and return line valves are open
-Check tank liquid levels and liquid condition
-Check for blocked filters
-Check for damaged, stuck or leaking suction or discharge valve(s)
-Check for worn or loose drive belts

2 Piston gland seal leakage:
-Check seals for wear and running hours
-Check crank drive for worn crosshead guides (allowing excessive piston lateral movement)
-Check gland purge or heater is not allowing ice formation on rod

3 Noisy Pump:
-Check for damaged bearings
-Check for partial loss of prime/cavitation.

11 Maintenance

Maintenance should be carried out on cryogenic pumps in accordance with the manufacturer's recommendations. In addition to routine maintenance checks should be carried out during pump operation for signs of leakage and other items that may need rectification. This will include listening for abnormal noises, increased temperatures etc.