
Connecting Components and Inner Heat Exchanger for CO2 Circuit

I. General Issues

- CO2 Circuit and its described components
- Ph diagram
- Permeation of gases in elastomers

II. Hoselines

- Requirements
 - CO2 / System related
 - Vehicle related
- Tests and Safety

III. Inner Heat Exchanger

- Possible designs
 - a) Tube in tube
 - b) Integrated in receiver
 - c) Integrated in receiver/dryer

IV. Charge/Service Ports

- Requirements
- Design Studies

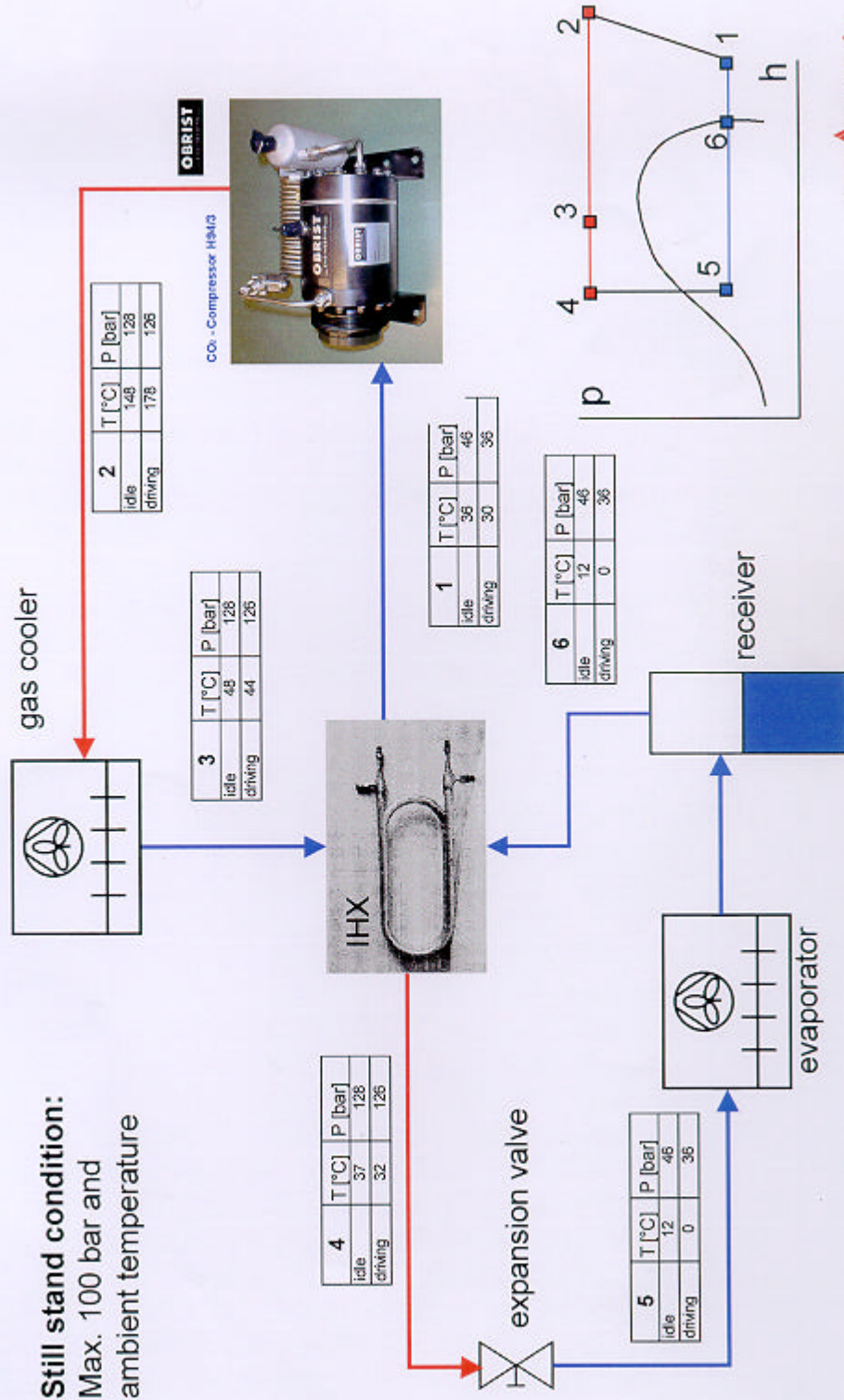
V. Connectors / Sealing

- Requirements
- Concepts



Automotive A/C CO₂-Cycle

Still stand condition:
Max. 100 bar and
ambient temperature





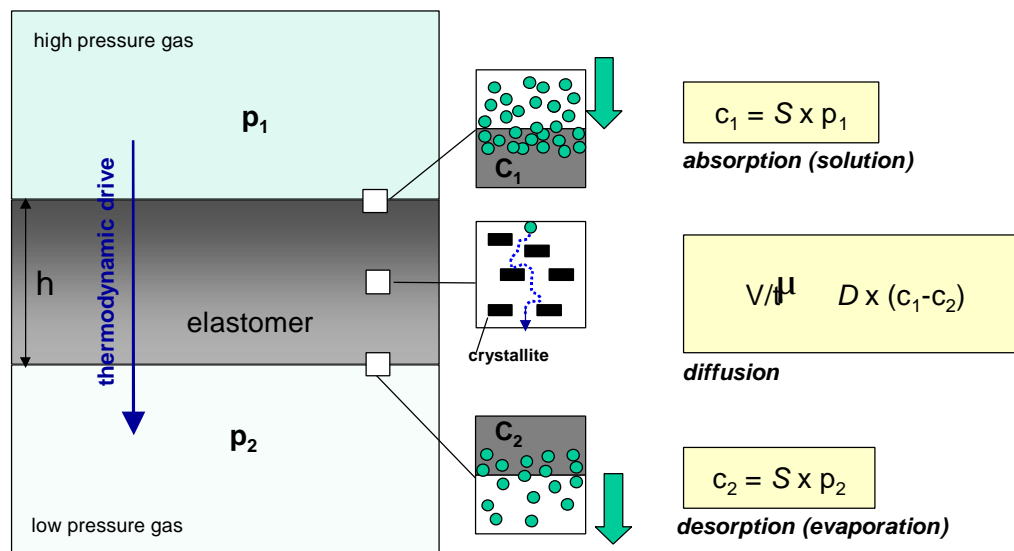
Permeation of Gases in Elastomers

Introduction

As soon as a fluid is in contact with the surface of an elastomer for a sufficient time, gases and liquids can dissolve into the elastomer and move further by diffusion. These solution and transport processes may cause modifications of the physical properties of the elastomer, which often leads to a decrease of the resistance to explosive decompression. The initial surface concentration c of both, liquids and gases, is determined by the process of dissolving. In the case of liquids, c is the mass uptake of the fluid at steady state conditions (solubility), which is usually pressure-independent. For gases, the dissolving process is dependent on pressure, which will be shown in the following considerations.

Governing equations

The entire permeation process of a gas through out a plane elastomer sample at moderately high pressures is divided up in three steps: firstly, the dissolving of gas into the surface of a sample (absorption) is governed by Henry's law. The concentration c of the gas dissolved is a linear function of the applied gas pressure p with the slope S , the Henry coefficient.



Hence the diffusion of gas from high pressure surface to low pressure surface is governed by Fick's laws, and finally evaporation into the low pressure gas region again involves Henry's law. By combining these laws in an appropriate form, the general gas permeation equation is derived:

$$\frac{V}{t} = P \cdot \frac{A}{h} \cdot (p_1 - p_2)$$

For steady state conditions the volume of gas V/t released by permeation through a given plane elastomer layer of thickness h and area A is increasing linearly with the pressure gradient (p_1-p_2) between the high pressure side and the low.

The permeation coefficient P (permeability) is defined as the product of diffusion coefficient D and the solubility coefficient S and has been shown pressure independent.

At extreme pressures, the permeability of an elastomer is no longer a constant, but becomes reduced. The modification is due to elastomer densification for hydrostatic reasons, which inhibits diffusion and promotes a shift of glass transition temperature T_g of the elastomer to elevated values.

The permeability P is not only a function of pressure, but also corresponds significantly with temperature. Similar to the diffusion coefficient D and solubility coefficient S , the changes correlate with temperature in an Arrhenius-type relationship:

$$P = P_0 \cdot e^{-\frac{E_p}{RT}}$$

where E_p is the activation energy for permeation and P_0 a typical constant. Experimental results have shown that the permeation rate is increasing dramatically with enhanced temperature.

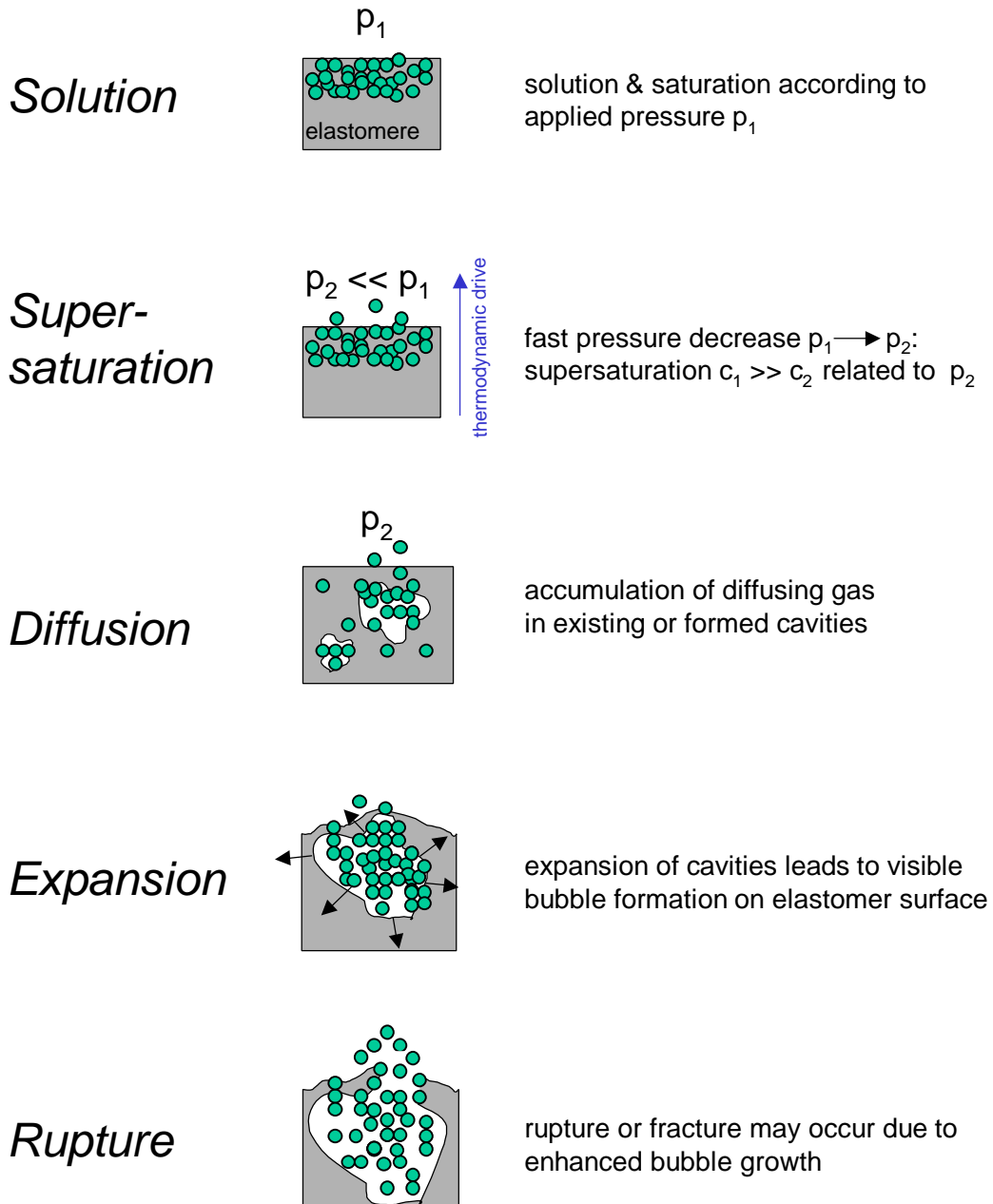
Unfortunately especially CO_2 combines thermodynamic properties, which lead to a high solubility as well as a moderate diffusion velocity in elastomers. Compared to other natural gases the permeation rate therefore is significantly higher.

Explosive Decompression

After having been saturated by solution of a gas, the surface concentration c_1 of this gas in an elastomer remains constant as long as the applied pressure p_1 is constant.

As soon as this pressure is reduced rapidly to p_2 , the related surface concentration c_2 , which can be calculated using Henry's law, should be much lower than the current concentration c_1 . From this moment on the thermodynamic drive according to the gradient (c_1-c_2) begins to equalize the supersaturation in order to achieve the equilibrium concentration c_2 in the elastomer surface.

The supersaturated gas intends to come out of solution diffusing towards the elastomer surface and accumulating in cavities, which already exists or which were formed during the dissolution process.



Continuous collection of gas leads to an expansion of the involved cavities expressed by a visible bubble formation at the surface.

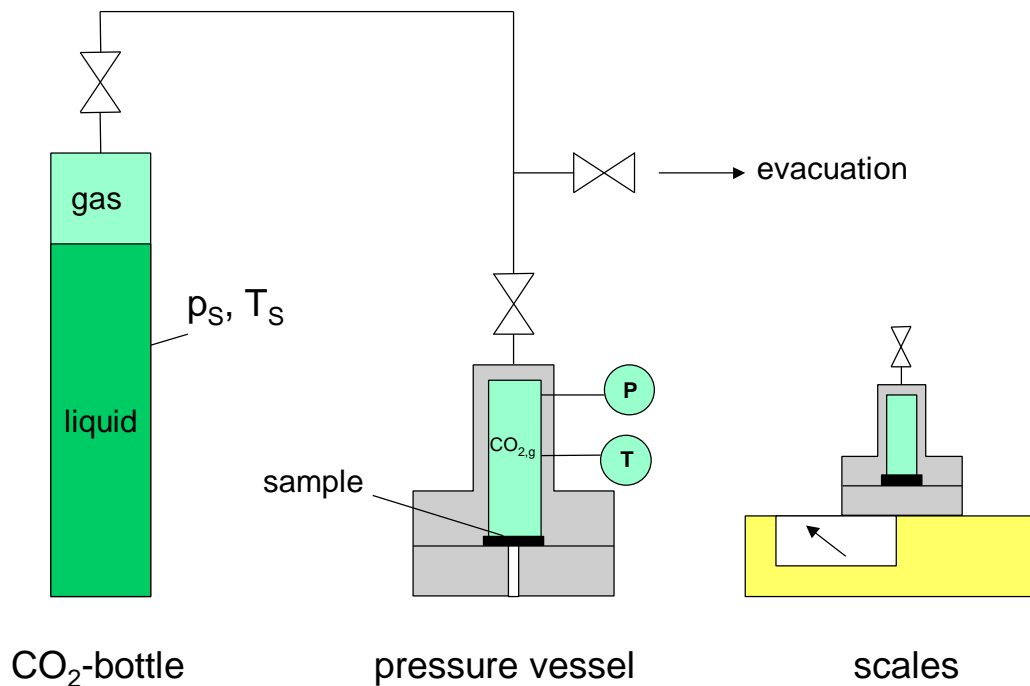
Finally the surface may be ruptured and fractures may occur due to an enhanced bubble growth.

Compared to other gases CO₂ again shows a remarkable behavior concerning the explosive decompression impact in elastomers. The outstanding solubility in elastomers combined with only moderate diffusion velocities are likely responsible for the strong reaction, which can be observed.

Permeation measurements

The Aeroquip permeation test rig is supposed to be a tool to select the most promising polymer with respect to a low permeation rate of CO₂. Additionally the experimental set up as well as the evaluation procedure allows to determine the leakage rate of complete hose lines at elevated temperatures (180 °C) and pressures (130 bar).

A constant volume pressure vessel is filled with gaseous CO₂ at ambient temperature conditions (T_S) until pressure equilibrium is achieved in order to avoid overcharge.



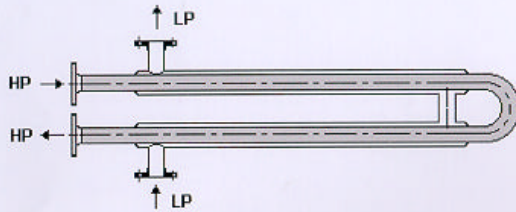
After the appropriate CO₂ charge is weighed, the pressure vessel is placed in a temperature controlled chamber. During the permeation process a pressure transducer and a thermocouple deliver the data of current gas properties.

The permeation rate is evaluated by recording the transient pressure decrease on the high pressure side in a data logging system. Hence, the change of mass of CO₂ in the pressure vessel is calculated on the basis of the resulting pressure time curve at constant temperature. The mass of CO₂ released through the elastomer sample by permeation leads to the requested permeation rate and finally to the permeation coefficient P.



different drafts of Internal heat exchanger

1. tube in tube



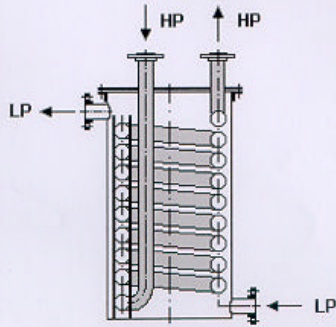
Pro

- very good heat transfer performance with extruded aluminium profiles
- liquid refrigerant drops will be completely vaporized

Cons

- additional component for the system but the way from evaporator to compressor will be needed anyway
- required length

2. winded tube combined with receiver



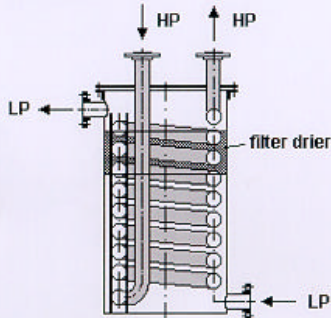
- heat exchanger and receiver will be only one component in the system

- receiver charge will be variable
→ worse heat exchange
- smaller refrigerant surface
→ worse heat transfer performance
- refrigerant charge increases
→ bigger receiver will be needed



different drafts of Internal heat exchanger

3. winded tube combined with receiver and filter drier



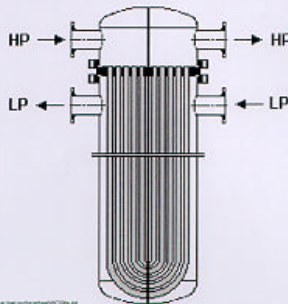
Pro

- heat exchanger, receiver and filter dryer will be only one component in the system
- possible moisture problems could be eliminated with the filter dryer

Cons

- receiver charge will be variable
→ worse heat exchange
- smaller refrigerant surface
→ worse heat transfer performance
- refrigerant charge increases
→ bigger receiver will be needed

4. bundle of tubes combined with receiver



- heat exchanger and receiver will be only one component in the system
- heat transfer performance will be better than with 3. and 4.

- receiver charge will be variable
→ worse heat exchange
- refrigerant charge increases
→ bigger receiver will be needed

II Hoselines

Requirements

The CO2 system will change parameters that requires new hose and tube materials. While tubes are available the most critical impact will be for polymere materials as they are used in current R 134 systems. The tabels system and vehicle related requirements show parameters which are relevant for hose material and design.

System Related Requirements:

	Specification	Assumption	Comment
fluid	R744		
lubricant		PAG, Ester	
test fluid	R744		
operation pressure			
high side	130 bar	160 bar	Systems without controlled high side
low Side (suction)	46 bar		
standstill	100 bar		
proof pressure		320 bar	2 x operating pressure
impulse pressure		176 bar	1,1 x o.p.
burstpressure			
a)		≥ 640 bar	4 x o.p.
b)		< 320 bar	2 x o.p. and pre aging
operation temp			
CO2			
high side	160°	180°	
low side	10°		
ambient temp.	-35° - 140°		

In addition to the CO2 system, there are the normal vehicle related requirements.

Vehicle Related Requirements

		proposals
vibration	acceleration frequence	250m/s ² 0 – 300 Hz
ambient conditions	temperature fluids ozon UV	-35 / 140°C tbd
life time	aging	1000h

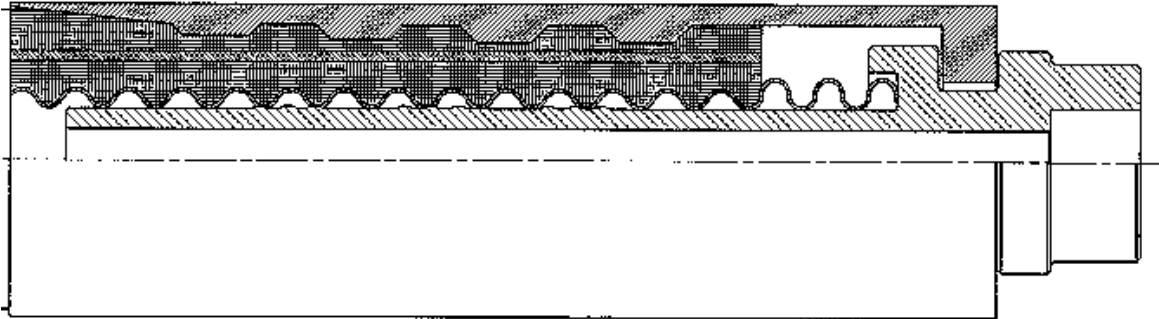
The materials shall build a barrier to the CO2 molekules, and must be stable against decompression of absorbed CO2. Chemical resistance to CO2, lubricant, fluids on the outer side and durable to above mentioned temperatures reduce the amount of candidates.

Design

The inner diameter of hose will be 6mm. At the moment there is no difference between discharge and suction side. For initial prototypes a corrugated tube of stainless steel is the inner barrier.

This steel tube is covered by an extruded rubber and reinforced with either an aramid or steel braid.

Further tests will show what could be a balance of durability, safety, flexibility and noise dampening performance.



Safety and Tests

Until written specifications are issued we apply tests of material and hoses lines:

- a) *burst pressure*
increase of pressure (DIN20024)
Hold a pressure of 200 bar for one minute without leak
Further increase in 100 bar steps, hold pressure of every step for one minute
Expected **mindest pressure without leak or defect. 640 bar**
- b) *pull of force*
specimen are made with a minimum of 200mm free hose length. The tension test machine runs at a speed of 25mm/min.
min force: 3600 N
- c) *burst pressure and pull of force after preaging*
The specimen are aged at 180°C in an air oven for 168 h and tested as shown at a) and b)
requirement: min. 75% of the values of unaged specimen
- d) *Permeation*
specimen filled with CO₂ and stored in an oven for 240h at 100°C and 180°C;
loss: £ 2,0 g/a
- e) *Preaging + Vibration*
Specimen are filled with CO₂ at 40 to 50 bar, then preaged 100h at 90° and 20h at -35°C.
After preaging a vibration is applied, Frequenzsweep 10 to 200 Hz acceleration 210 m/s²

Rubber compounds tend to reduce physical properties when they are exposed to temperature, ozone, UV light. To ensure an acceptable range of properties in service some tests are applied for this materials.

führen:

a) *physical properties of unaged material:*

tensile strength DIN53504
elongation at break DIN53504
modulus at 50% and 100% elongation DIN53504
hardness DIN53505
tear resistance DIN53507 Methode A und B
Compression-Set nach DIN 53517

b) *physical properties after aging*

aging at 180°C für 168h (steps at 24h, 48h, 72h und 96h) and tested as a)

Tensile strength tear resistance shall not change more then 35% after 100 h aging.
Elongation at break not change more then – 50% or + 20%.

IV. Charge / Service ports

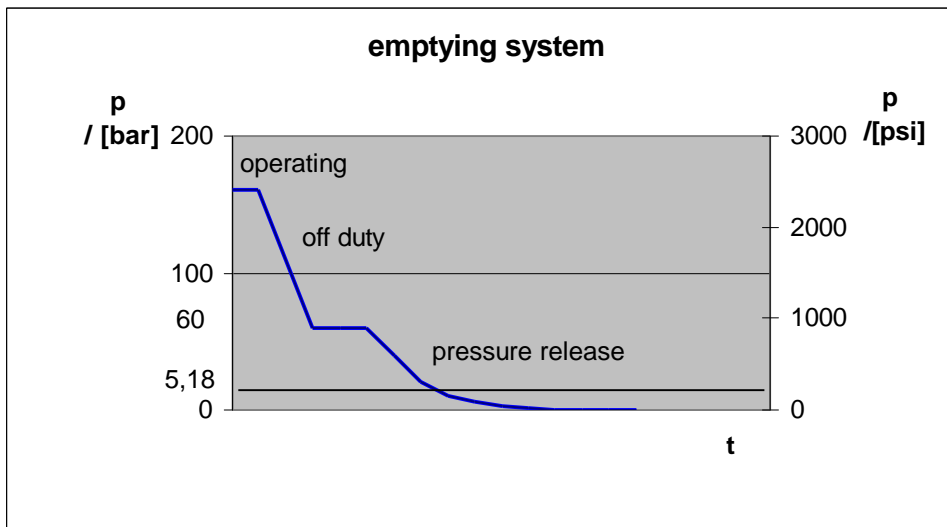
Service valves have three major tasks:

- I. Evacuating the system to take of air and moisture: Valve shall offer a maximum opening and high flow
- II. Charging the system with the correct mass of refrigerant: The valve shall offer a high flow
- III. Emptying or controlled releasing the refrigerant at service: The valve must be able to controll the expansion of the CO2

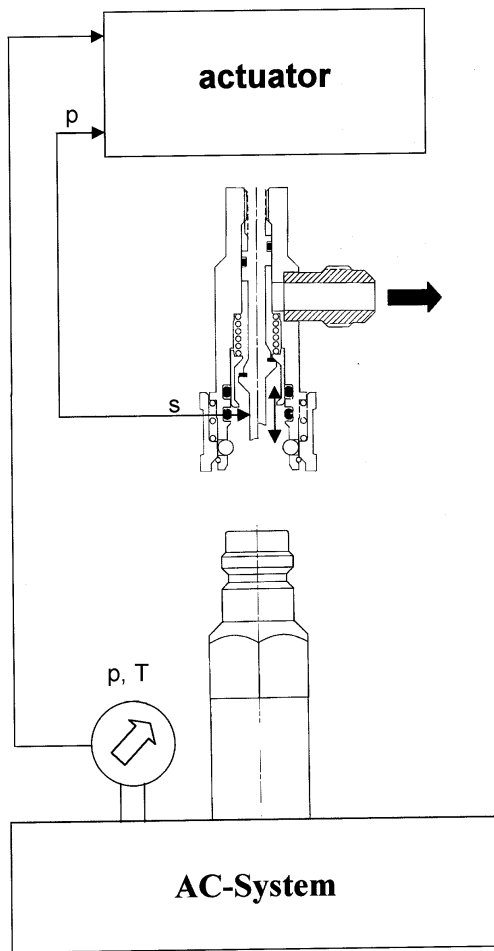
In addition ports are used to connect sensors and switches. The three tasks show specific items to be addressed to fit function and safety requirements. For evacuating the system a high flow is required to reach a certain pressure level within a short periode of time. A similar flow rate and time frame is expected for charging the system. The valve port and the adapted filling port shall fit together without leaks. Valve shall close while adapter is docked and little pressurized gas should be captured to avoid forces during plugging off.

While evacuating and charging are functions handled by current ports and only the pressure is a differens, the controlled pressure relief is a unique function required for CO2 systems. A high pressure drop would cause explosive decompression of polymere materials and dry ice build that could block areas of the system.

One possible solution can be to reduce the pressure at higher levels fast and slow the expansion at critical levels.



Possible solutions can be to use two different ports for a high and a low flow, different force levels lead to dedicated valve positions with either high or low flow or an actuator controls the valve position during service.



The actuator controlled adapter allows to open the service valve depending of pressure and temperature. Related to valve position the flow rate is high or low.

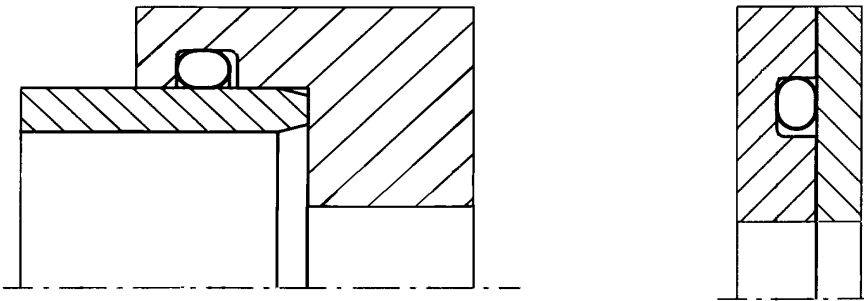
V. Connectors / Sealing

As current systems CO2 circuits have several joints that need to be connected. Pressure and the strength is not a critical area and well known at other applications such as Power Steering, brakes etc. But to seal the CO2 and minimize the leak of the joints is an issue. The seal is the key design element of that problem and there are different ways to go:

- Seal is for single use only
- Seal shall be used multiple times

For a seal, that must be changed after use a metal type gasket may offer the required low leak rate, while rubber or polymere gaskets will have a given permeation rate and therefore a loss.

An axial seal will combine an additional metal face that can support.



Another principal difference is to have joints with or without selfsealing devices in it. Depending on safety aspects when handling the system there might be requirements to avoid danger when opening a pressure system.

Currently only authorised personel is allowed to maintain and open the system. The likelihood that a pressured system will be opened is not given. This procedure will be the best regulation for CO2 systems as well, because a solutions with a self sealing coupling will create pressure drop, additional parts and costs.

