EFRC Training Workshop

Design and operation of reciprocating compressors

Wearing parts

Gunther Machu – HOERBIGER

Contents

- Compressor valves
  - Fundamental operating principle & design criteria
  - Overview different valve designs
  - The best valve choice for the application
- Flow control
  - On / Off, variable volume clearance pockets
  - Stepless reverse flow control
- Rings & Packings
  - Fundamental operating principle & design criteria
  - Material selection, lube and nonlube operation
  - Prominent failure modes & troubleshooting

Valves for piston compressors

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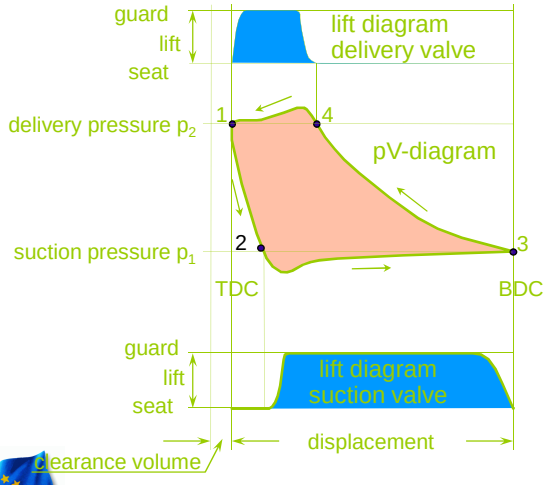
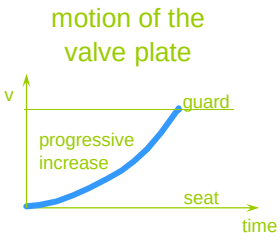
pV-Diagram and Lift Diagram





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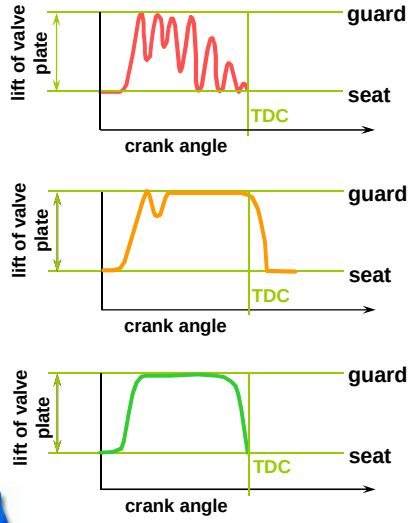
Valve dynamics



valve flutter

delayed closing

ideal motion of valve plate

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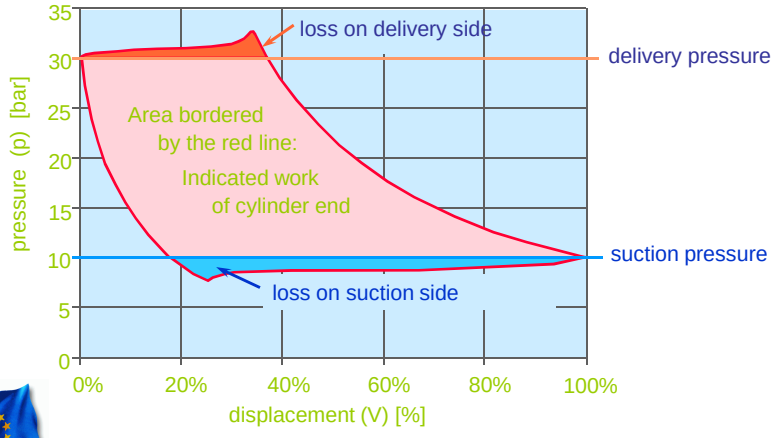
Indicated Power in the pV-Diagram

the indicated power is increased by a certain percentage due to losses



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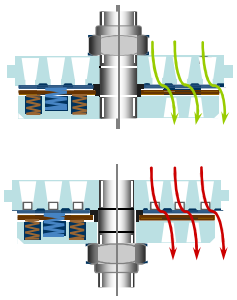
Valve losses – Ventilation losses

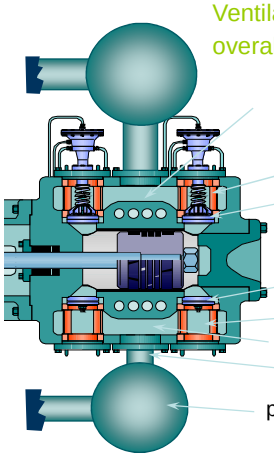
Valve losses are losses incurred in the valves

suction valve = intake



delivery valve = outlet

Ventilation losses are the overall losses incurred in:



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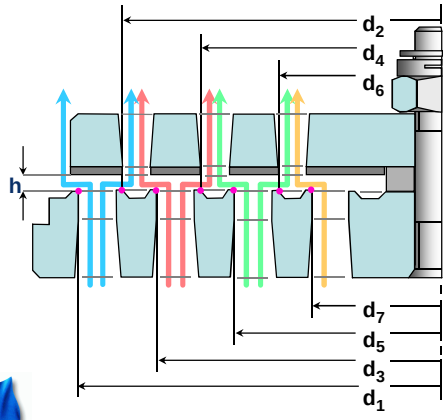
Valve Characteristics

The passage area f_e is the smallest geometric opening in the valve

$f_e = (d1 + d2 + d3 + d4 + d5 + d6 + d7). \pi . h$



$d_1 \dots d_7$ seating ledge diameter

h ..... valve lift

π 3,14159

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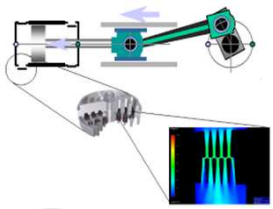
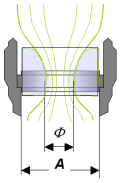
Efficiency – today's valve portfolio

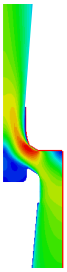
- ***Latest generation profiled plate & ring valves reach the 25% efficiency level***

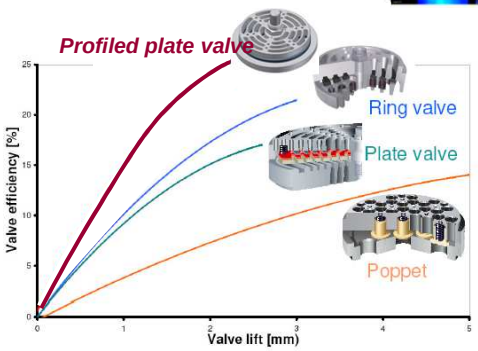


$\Phi = \alpha_\Phi * A$

α_Φ.. Valve efficiency







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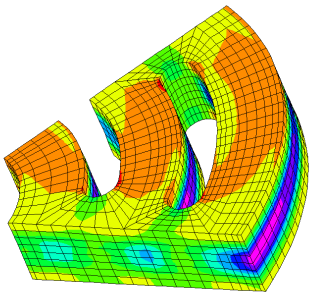
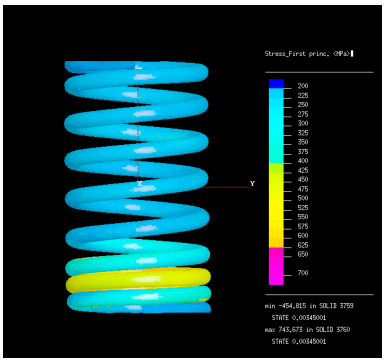
Valve Design

The impact velocity of the sealing element against the guard / seat is the most important design criteria for a compressor valve!

Stresses in the

-Sealing Element and
-Closing Springs





are directly proportional to the impact speeds!

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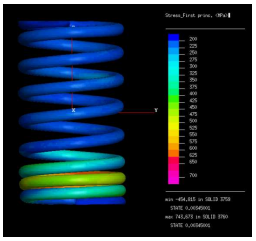
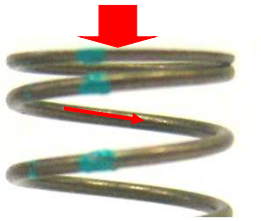
Spring design

- **Dynamic & static spring criteria**
  - Solid height stress
  - Individual coil contact
  - Lift off



Shock



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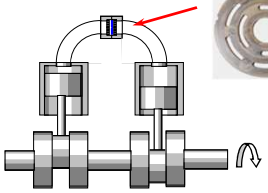
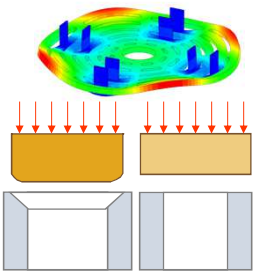
Non-metallic sealing elements requirements



Impact resistance
(impact loading – pressure / speed / valve lift)

Flexural strength
(differential pressure, unloading with finger type unloader



Compressive Strength
(differential pressure / seat geometry-seat land)

Temperature resistance
(melting point)

Dimensional stability
(temperature / moisture absorption)

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Valve Designs

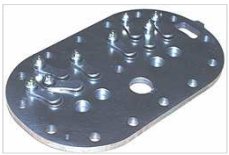
Valves with different types of sealing elements

Steel plates

Plastic profiled rings

Plastic plates

Poppet valves



Steel reed valves

PIK flapper valves

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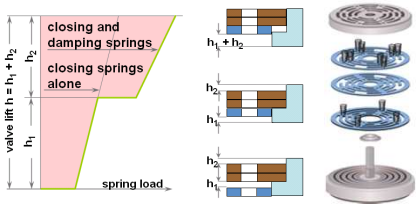
Now, what can be done

Measures to reduce impact speeds: advanced designs

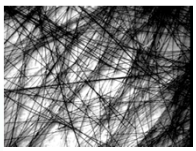
double damped valves

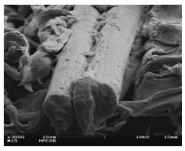


ring valves with sync. plates

Advanced nonmetallic sealing elements:

- ***can withstand higher impact speeds***





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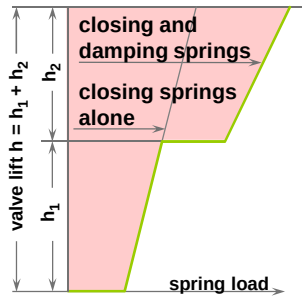
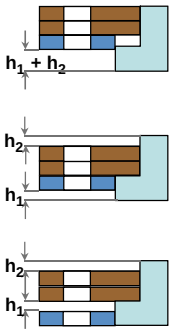
Measures to reduce impact stresses

Principle of Double Damping

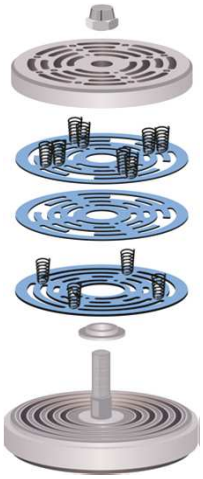
Advantage 1: Increase in spring load
Advantage 2: Reduction of tumbling
Advantage 3: Reduction of opening impact



Spring load



damping principle



valve design

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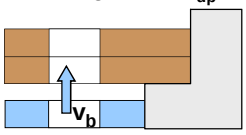
Damping

Impulse Law

Before the impact:

damper plates not yet moving, mass m_{dp}



valve plate with mass m_{vp} and velocity v_b

After the impact:

speed of valve plate is reduced

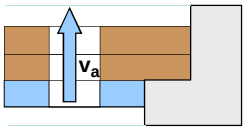


plate pack moves with velocity v_a

Impulse Law:

$$v_a = v_b \cdot \left(\frac{m_{vp}}{m_{vp} + m_{dp}} \right)$$

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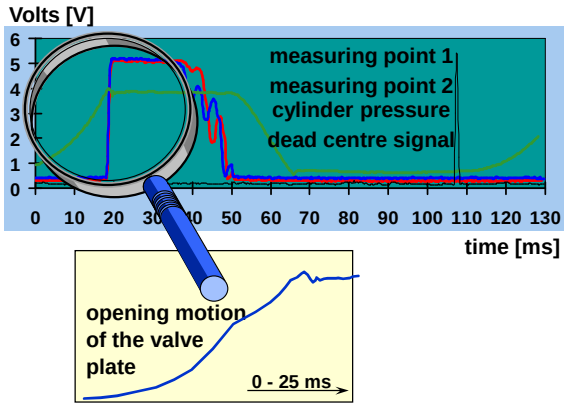
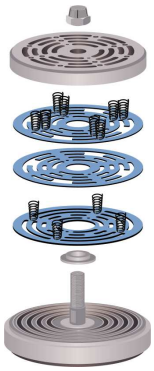
Effect of double damping





- reduction of opening impact
- strong damping springs against sticktion on the guard
- reduction of closing impact velocity
- reduction of tumbling motion of valve plate

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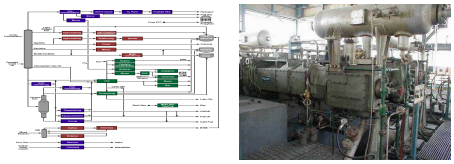
Product Selection based on Application

Process characteristics

- Changing conditions, dirt, liquids,….



Experience

- Known effects & proven solutions

The “Best” Product

- Ring valve or plate valve

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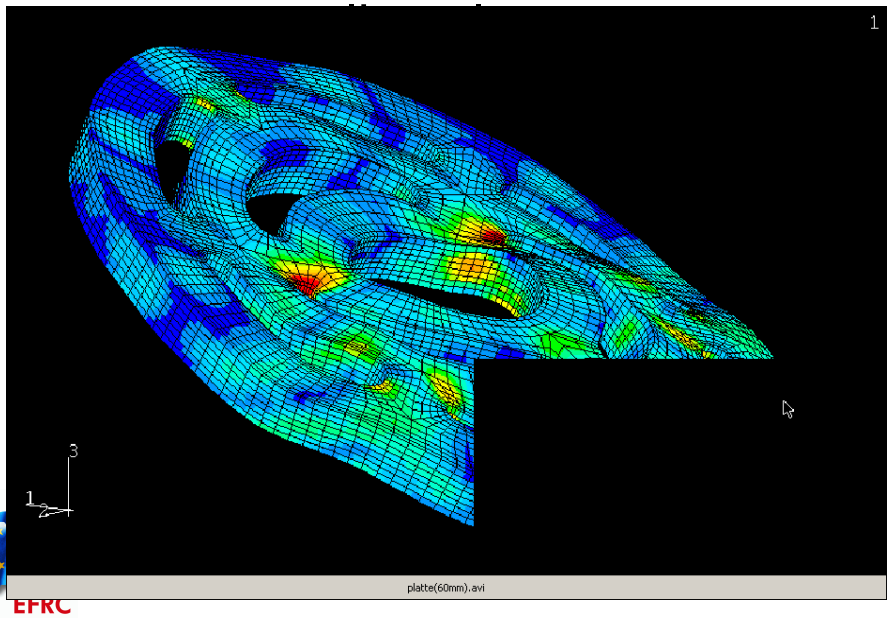
Impact at an angle – stresses in the



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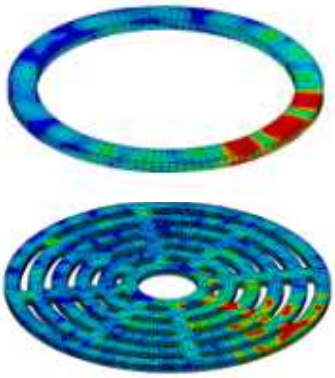
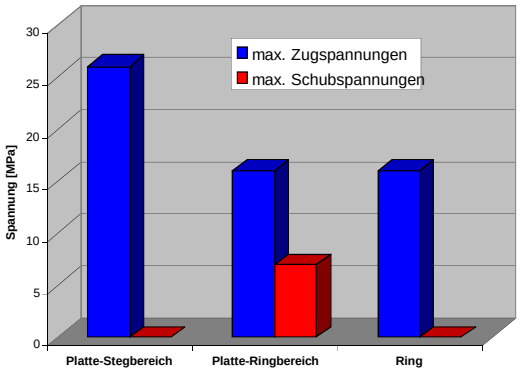
Advantages of ring valves

No stress concentration effects!

Stresses in plates and rings





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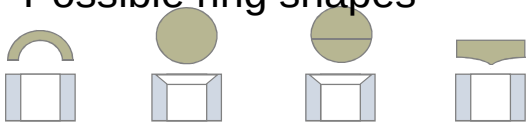
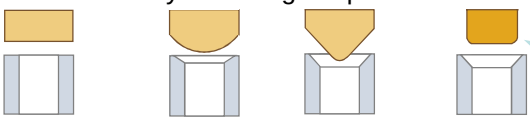
Valve types with plastic rings

- Possible ring shapes



currently used ring shapes:



usual flat rings

this ring shape combined with special seat geometry
give the best results on Phi-values

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Valve types with plastic rings

for gases with low molecular weight
(H_2- applications) and for dirty gases

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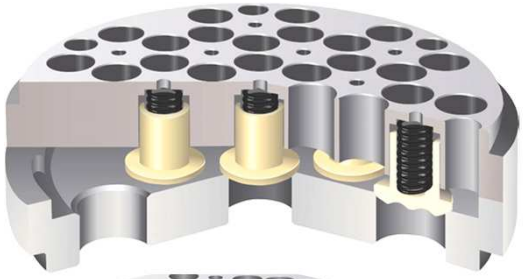
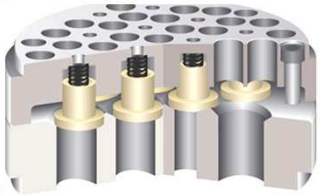
Poppet valves

Valve with
standard poppets





Valve with
mini-poppets

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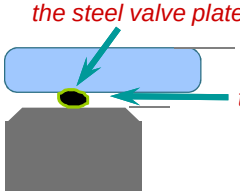
What can be done – valve materials

Resistance to dirt particles – e.g. polypropylene

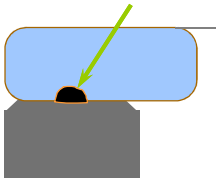
the steel valve plate is hard - danger of breakage



the valve seal is not tight

Plastic valve plate with embedded particles

The plastic valve plate can deform,
the particle is embedded



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Characteristics of plastic materials

"One-dimensional theory" of elastic impact

According to the one-dimensional theory of the elastic impact of a bar with velocity **v** against a hard surface, the forces in the bar produce a stress **σ** given by the formula

$$\sigma = v^*\sqrt{E^*\rho} \quad \text{respectively} \quad v = \sigma / \sqrt{E^*\rho}$$

	symbol	steel	plastic
modulus of elasticity	E	$2{,}1 \times 10^{11}$ N/m²	$1{,}3 \times 10^{9}$ N/m²
density of material	ρ	$7{,}85 \times 10^{3}$ kg/m³	$1{,}5 \times 10^{3}$ kg/m³
tensile strength	σ_{or}.σ_{adm}	$3{,}0 \times 10^{8}$ N/m²	$2{,}0 \times 10^{7}$ N/m²
impact velocity	v_{or}.v_{adm}	7,93 m/s	14,32 m/s

Plastic materials can impact with double the velocity of steel!

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Materials for Compressor Valves

- Materials generally
- Materials for plate valves
- Materials for ring type valves

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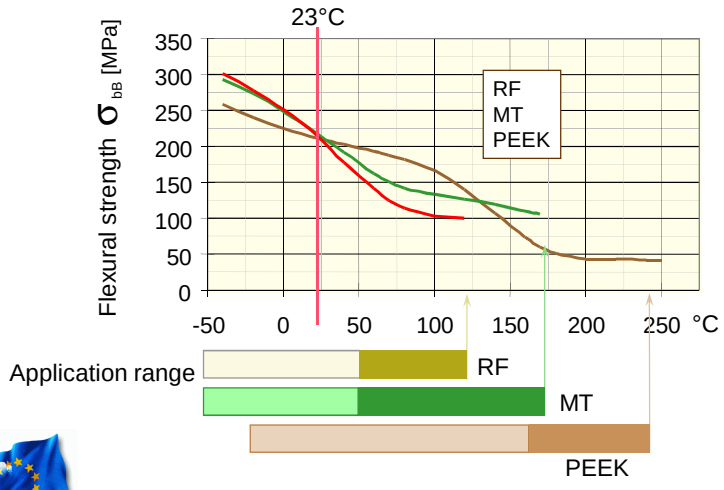
Characteristics of plastic materials

Flexural strength in dependence of temperature



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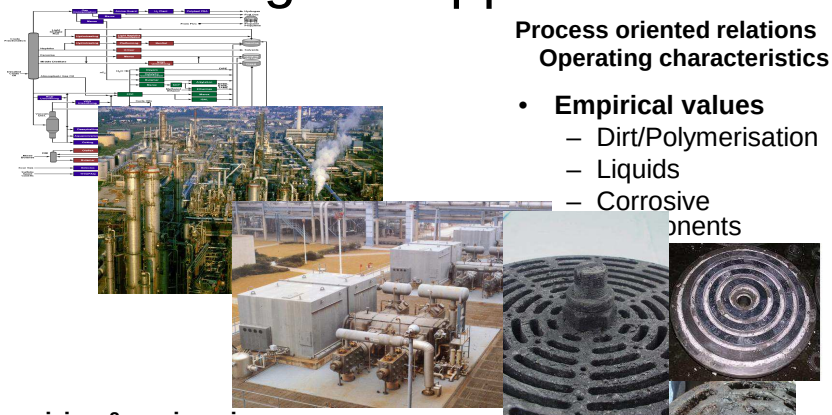
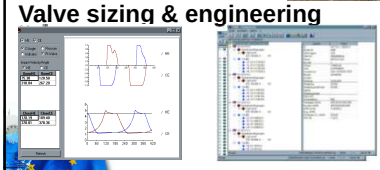
Knowledge of Application



Process oriented relations
Operating characteristics

- **Empirical values**
  - Dirt/Polymerisation
  - Liquids
  - Corrosive
  - onents

Valve sizing & engineering



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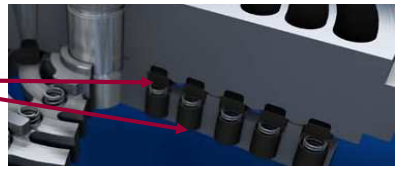
What can be done - knowledge of Application

- **H2 from steam reforming**
  - ***The problem:***
    - *Chemical reaction taking place: CH4 + H2O -> H2+CO -> H2+CO with C-particles → extremely abrasive!*
  - ***The solution:***
    - *use valve design with spring savers and nonmetallic inner parts*



- **CCR catalytic reforming**
  - ***The problem:***
    - *organic chlorine used in process (cannot be seen from gasanalysis)*
    - *extreme corrosion through chlorides on valve seat / guard and springs*
  - ***The solution:*** *correct material specification*

- **LDPE - Polyethylene Booster Primary**
  - ***The problem:***
    - *Frequent polymerisation in 1st stage*
    - *Sticky white substance which cloggs springs, spring pockets → highly loaded sealing element and springs*
  - ***The solution:***
    - *usage of nonmetallic sealing elements with high impact resistance, optimized dynamic design of springs*

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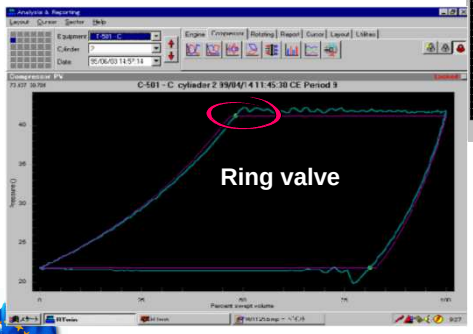
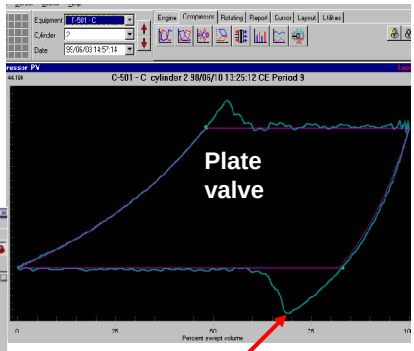
What can be done – valve design

Hydrogen Compressor

The problem:
Plate valve failing after short amount of time – pV reading revealed sticktion effects

The Solution:
Changed to ring valve -
lifetime now 16.000 h





Sticktion effect:
huge pressure overshoot due to delayed opening of sealing element

The profiled geometry of ringvalves (line contact) leads to less sticktion

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What can be done – valve design

Operating Company

Site	Map Ta Phut, Thailand
Service	CCR Net Gas Booster

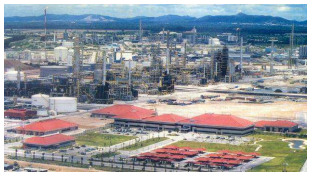
Compressor lubricated

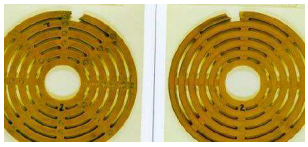
Operating conditions

Gas	Hydrogen Rich Gas (MW 8)
Suction Pressure	5,6 bara
Final Pressure	47,5 bara

The Problem:
originally fitted with non-metallic plate valves
Discharge valve failures after
1 day to 2 months operation due to severe liquid carryover

The solution:
Ringvalves fitted
Valve run time improved to 26000 h





In ringvalves each ring can move independent from the others, making it easier to cope with liquid slugs

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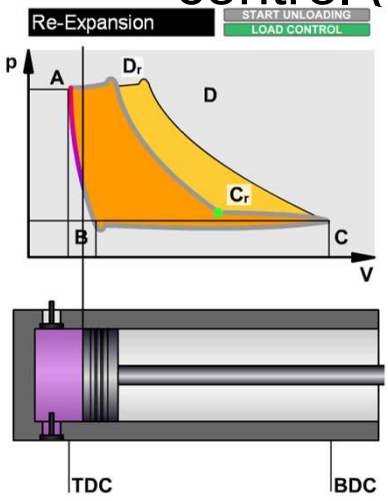
Working principle – Stepless control (1)



Animation

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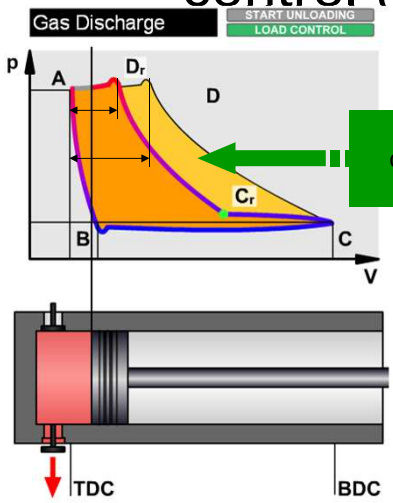
Working principle – Stepless control (5)



Area enclosed by pV graph is equivalent to the energy consumed

Energy savings compared to recycle valve control

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Stepless control saves energy

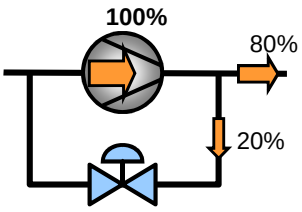
Only the gas flow required by the process is compressed (no recycling)

Typical application:

1,300kW compressor

80% average load

Energy costs €0.06 per kWh



Recycling is waste of energy:

Power loss: 1,300 x 0.2 = 260 kW

Losses: 2,080,000 kWh / year

Recycle valve is waste of money:

With stepless reverse flow control:

€ 124,800 energy savings / year

Plus savings in CO_2-emissions

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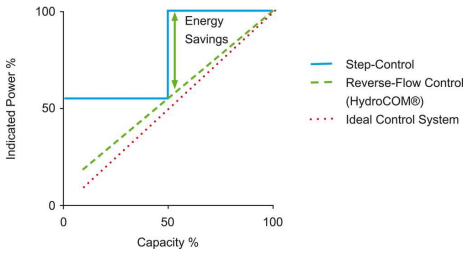
Stepless control vs. ON / OFF

Capital costs of a multistage compressor with reverse flow control are lower than of a compressor with 50%, 75% and 100% step control.

- No energy savings can be achieved with 0%, 50% and 100% step control only.
- Therefore 50%, 75% and 100% load steps are required for efficient operation:
  - ➔ At least two (2) cylinders per stage are needed.
  - ➔ Higher capital costs compared to one (1) cylinder per stage with stepless control



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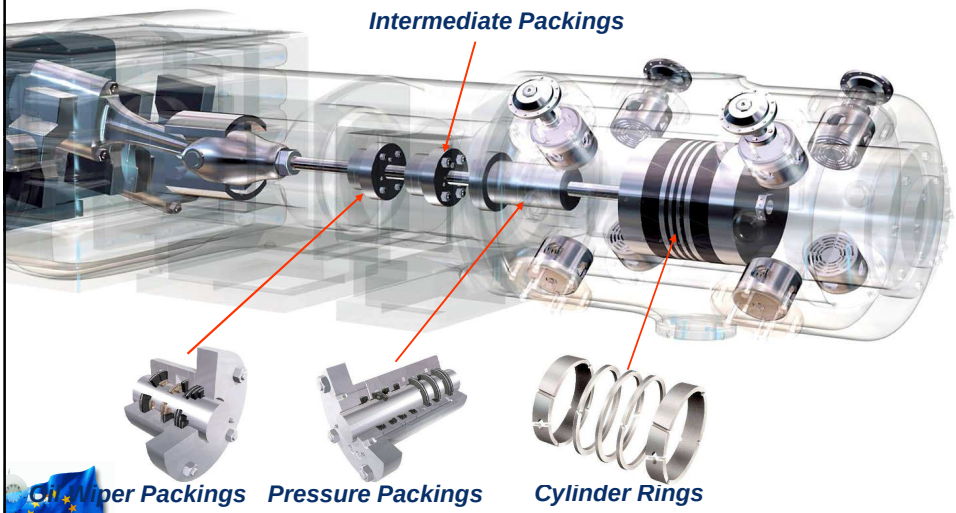
R&P Products



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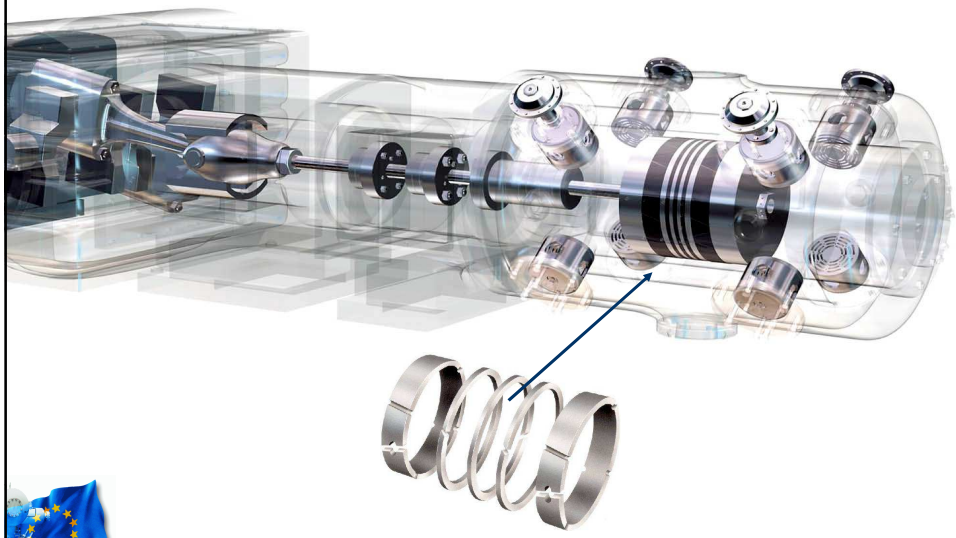
Cylinder Rings



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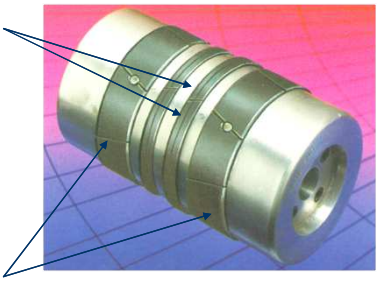
Cylinder Rings - Basics

Piston rings



Rider rings

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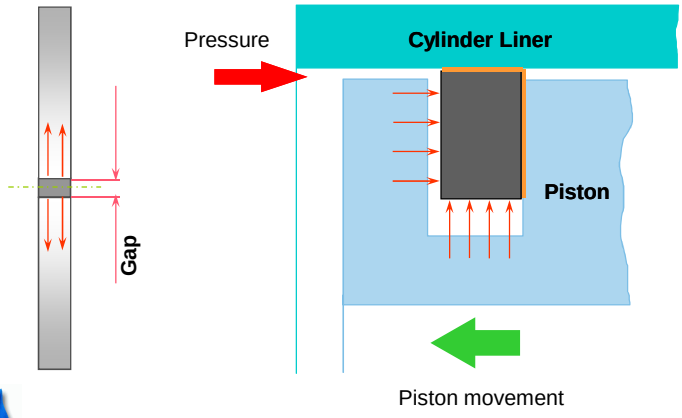
Piston Ring - Basics

Purpose of the piston ring is to seal the compression space.



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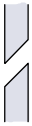
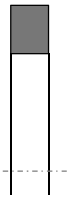
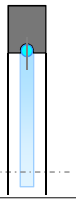
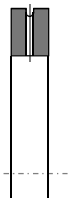
Piston Ring - Basics

Ring Styles:

	Straight cut	Angle cut	Overlapped cut
Cut:			
Profiles:	Standard	With expander	Pressure balanced
			

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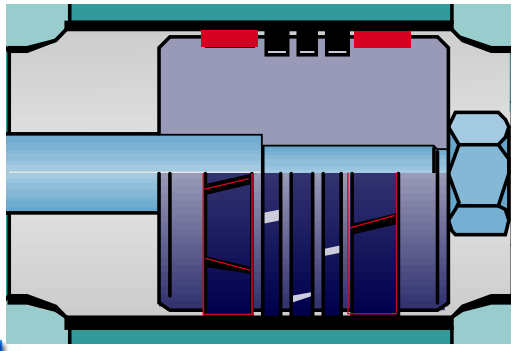
Rider Ring - Basics

Purpose of the Rider Rings is to bear the piston and prevent it from contacting the liner.

The Rider Ring should not seal the gas !



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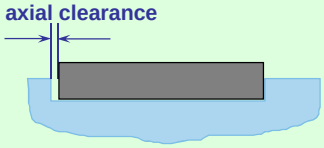
Fault Analysis FAQ's: Cylinder Rings

axial clearance

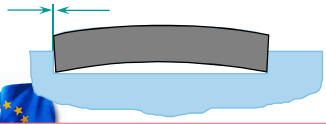


Correct design of axial clearance is important for good operation

axial clearance is too great

The ring moves backwards and forwards in the piston groove hitting both groove side faces causing the ring and the groove side faces to be damaged.

axial clearance is too small



Ring is deformed so that it bellows within the groove.

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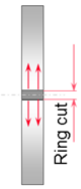
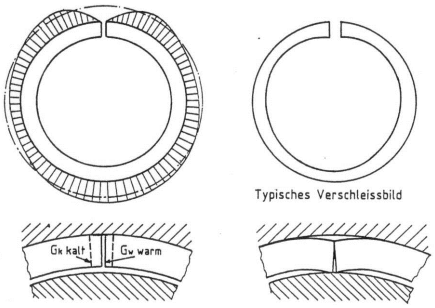
Fault Analysis FAQ's: Cylinder Rings

Is there accelerated wear ?

Are the end gaps the correct size - i.e. gap between segments of the rings?

- If this is too small for both rider rings and piston rings, the ring could expand and close this gap up causing ring to jam.
- If this is too large in the case of piston rings the ring will leak a larger volume of gas.
- Beware of standard rings on worn piston grooves (i.e. oversize ring grooves).





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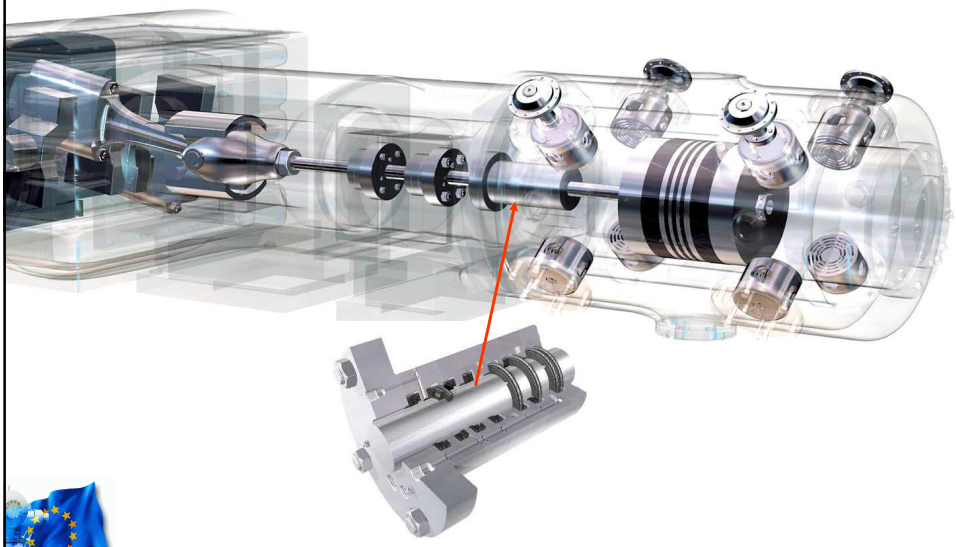
Pressure Packing



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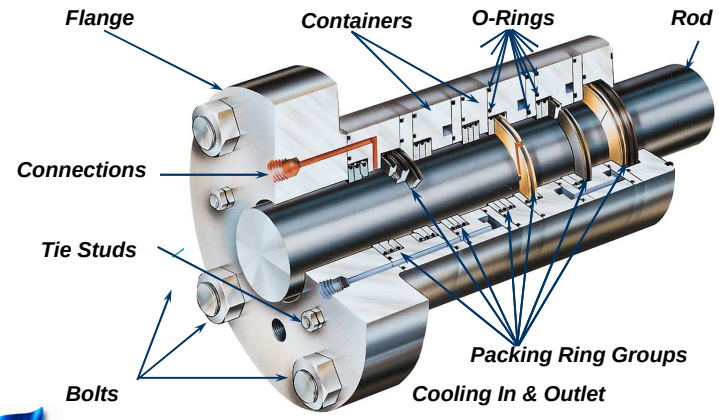
Pressure Packing - Basics

Function: Seal the compression chamber against the intermediate piece.



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Pressure Packing - Basics

The gas pressurises the ring segments and forces them onto the rod and against the container.

If the packing is not pressurised the garter spring will hold the rings in place around the piston rod.

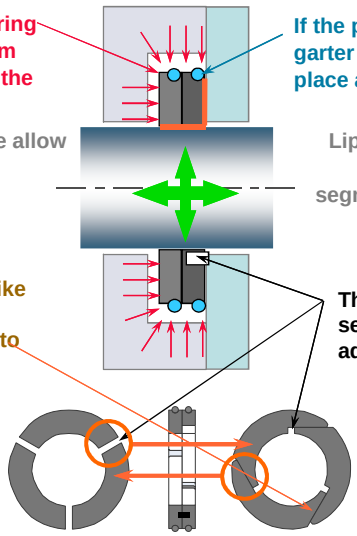
Axial and radial clearance allow rings moving within the container:
- Sealing remains
- Leakage is prevented

Lipseals can not compensate rod movements. Therefore ring segments are used which conform to the rod dynamics.

Tangential cut rings act like a camera lens.
The rings are positioned to each other with a peg.

The clearance of the ring segments allows automatic adjustment due to the wear.

The gaps between the segments are covered by the other ring



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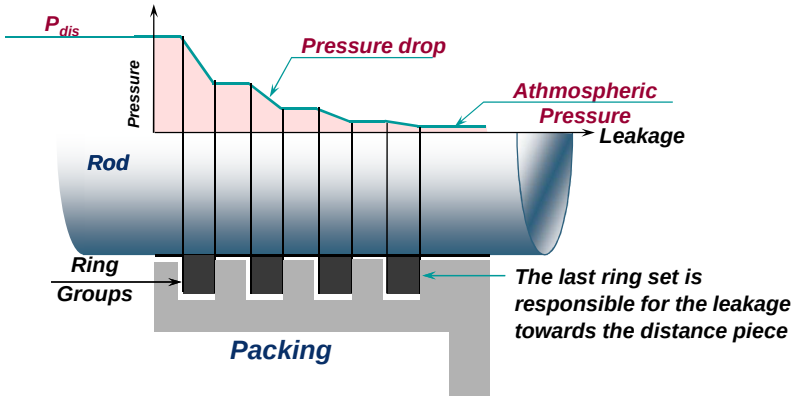
Pressure Packing - Basics



Rule of thumb for the packing:

Each ring set reduces the pressure by half of the prior one. If one ring set has worn down the pressure has to be reduced by the remaining ring pairs.

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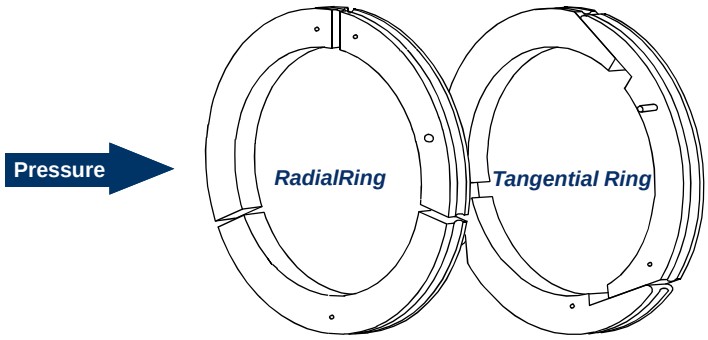
Pressure Packing - Basics



Function:	seals if gas is compressed.
Mounting:	Rings are positioned to each other by a peg in the tangenial ring. Thereby the gaps of the tangential ring are covered by the radial ring.
Wear:	In case of wear the gaps decrease to zero. Rings without a gap have to be exchanged.
Application:	Historical standard-ring set for pressures up to 20 bar.

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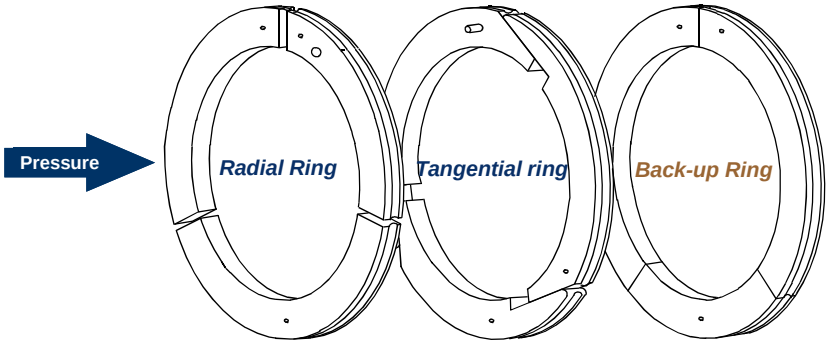
Pressure Packing - Basics



Funktion: Single acting standard ring parit with back-up ring.
Back-up ring has 0,1 to 0,2mm clearance to piston rod.

Application: Historical standard ring group for pressures above 20 bar.

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Pressure Packing - Layouts

Packing Features:

Main features of pressure packings are:

- Lube or non-lube
- With or without cooling
- With or without vent
- With or without purge

Types and numbers of ring groups within a packing are depending
Of the design criterias !

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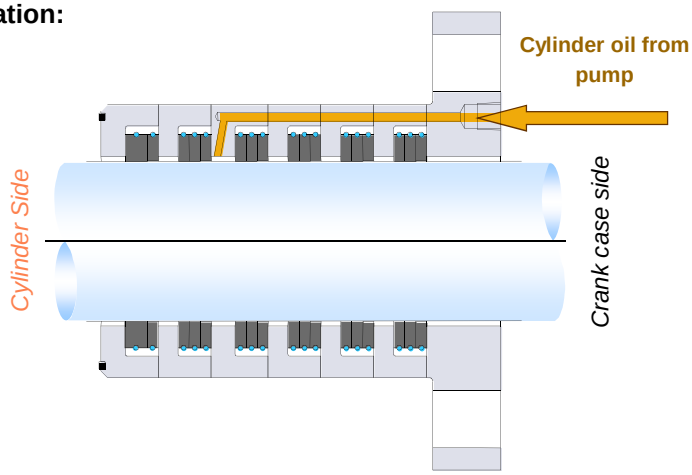
Pressure Packing - Layouts

Lubrication:



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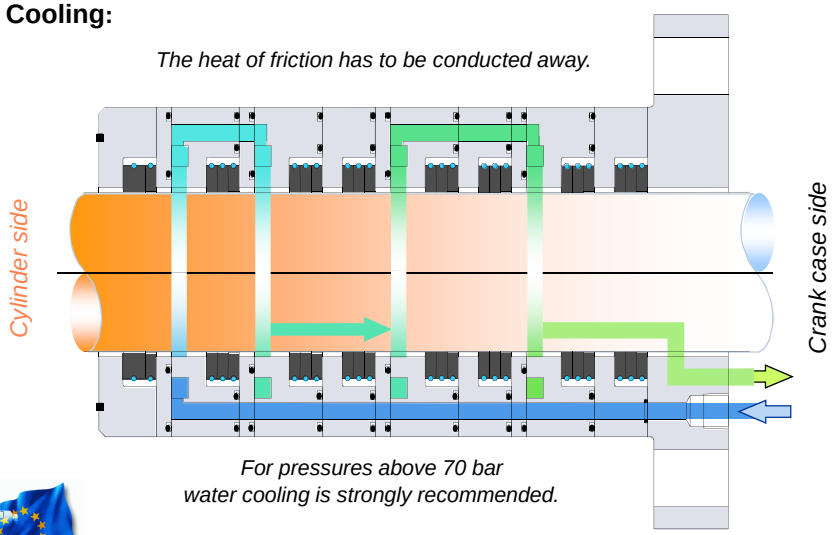
Pressure Packing - Layouts

Cooling:

The heat of friction has to be conducted away.



For pressures above 70 bar
water cooling is strongly recommended.

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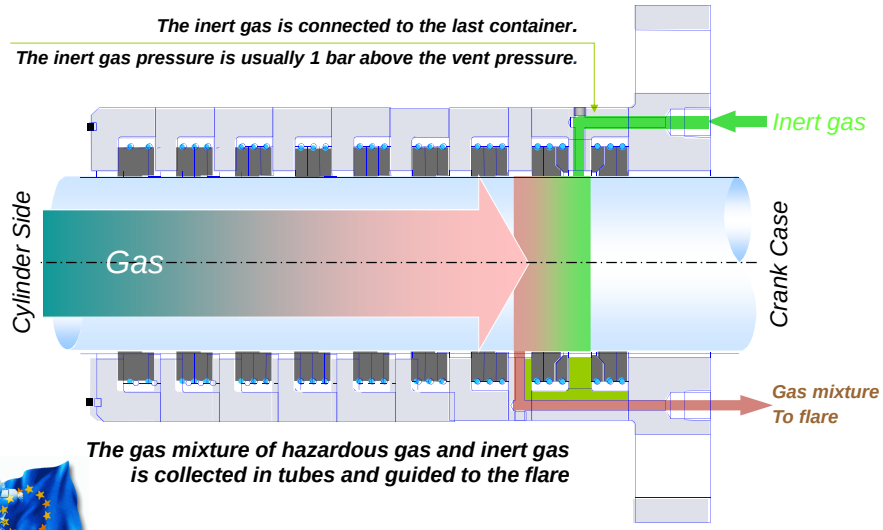
Pressure Packing - Layouts

Purge:



The gas mixture of hazardous gas and inert gas is collected in tubes and guided to the flare

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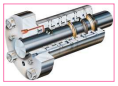
Fault Analysis FAQ's: Pressure Packings



Are the cups within the pressure packing reconditioned every time new wearing parts are fitted ?

Wearing parts will leak if the cup face quality is poor i.e. corroded.

Is there discoloration of the Bronze wearing parts ? e.g. bluing

This would suggest there is a lubrication failure, leading to overheating. There could be blackening of the rings due to over use.

Is the vent line temperature increasing ?

This would suggest the packing is leaking and should be either reconditioned or replaced.

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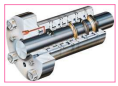
Fault Analysis FAQ's: Pressure Packings

Have the rings been assembled the correct way around ?

This is critical with single acting rings i.e. single acting pressure breaker or radial / tangent ring pairs. It is important that the single acting side of the pressure breaker and the radial cut ring of the pair face the cylinder or the pressure.



Is there any circumferential scarring or polishing on the ring faces ?

This indicates pressure retention between the cups within the packing.

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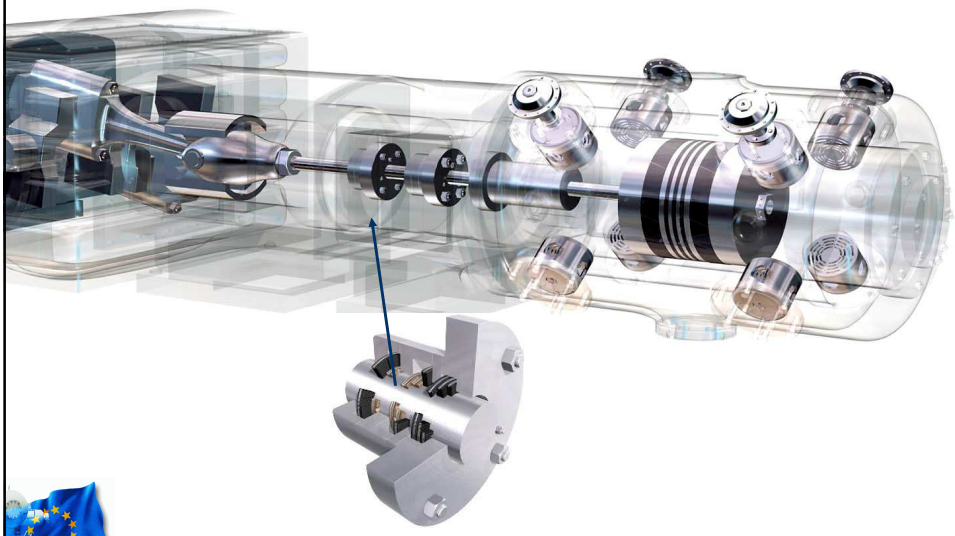
Wiper Packing



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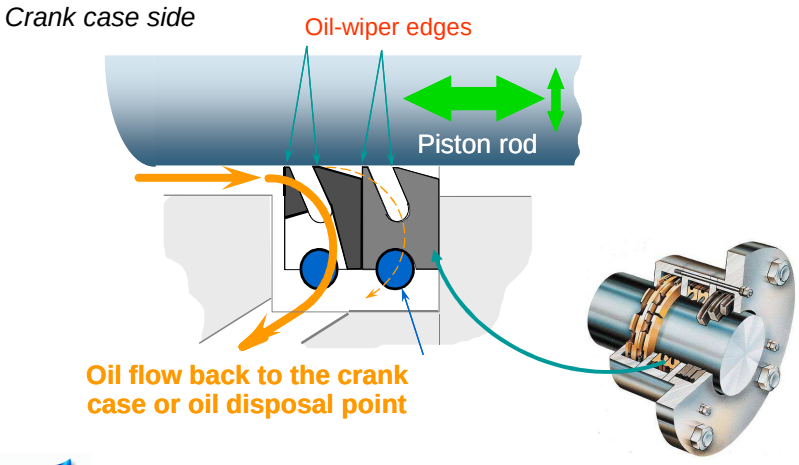
Wiper Packing - Basics



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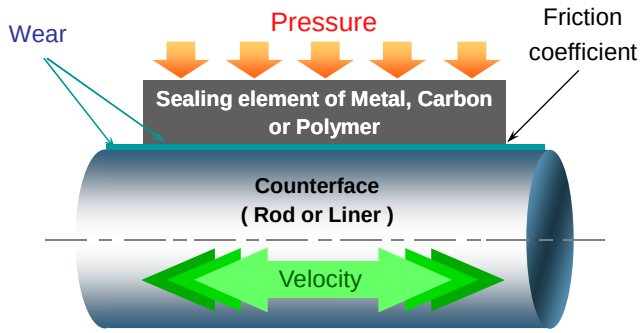
Counterface Conditions



Wear rate proportional to **Pressure** and **Velocity**
(There is also a **temperature** effect in practice)

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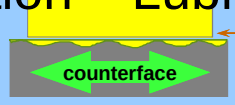
The critical question in material selection – Lubrication ?

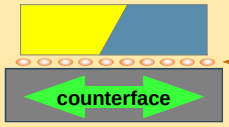
Non - Lube



Transfer Film
μ=0.10 Typ

Soft seal material bedding into counterface

Lube



Oil
μ=0.02 Typ

Soft or hard seal material

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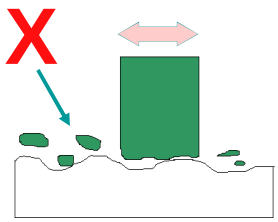
Non-Lube Operation – The Transfer Film

2 Modes of Wear:

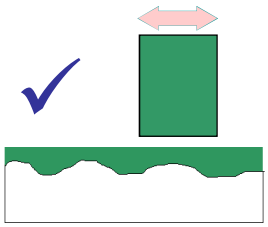
- **High Wear Mode**
  - **Adhesive** wear behaviour
  - Polymer to metal
  - **High friction**

  ➔ **High wear – SHORT LIFE**



- **Low Wear Mode Transfer Film**
  - Polymer to polymer running
  - **Low friction** which is load independent

  ➔ **Low wear – LONG LIFE**



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Non-Lube Operation – Bedding-

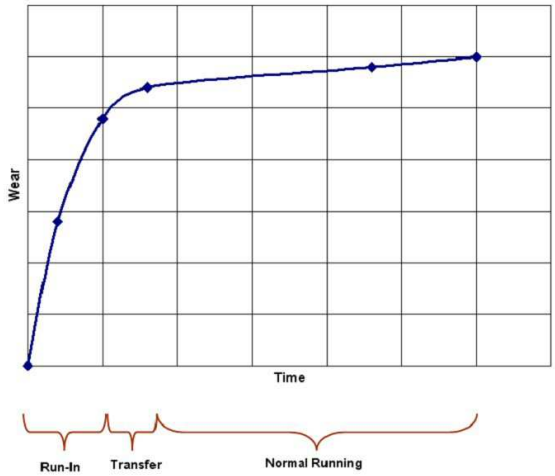

Fig 1: Bedding-in Process

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Basics – PTFE Compounds

PTFE Compound:

Pure PTFE => very low coefficient of friction but also a ***quite low wear resistance***. If there's no transferfilm present, it ***wears down very fast***.

Fillers are added ***to increase*** the ***wear resistance*** and the mechanical properties. These fillers are (Carbon fibres, graphit dust, glass fibres, ceramic dust, metall dust, polymer dust, MoS2, ...)

PTFE with bronze | **PTFE with glass fibres** | **PTFE with carbon**

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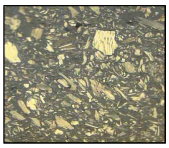
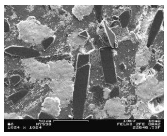
R&PMaterials - Features

- **Glass-filled PTFE** like
  lube machines, low and mean pressure

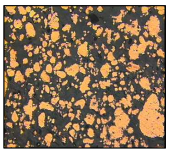


- **Bronze-filled PTFE** like
  non-lube machines, humid gas and high temperatures



- **Carbon- / Graphite-filled** PTFE
  lube and non-lube machines, humid gas

- **PPS-filled PTFE**
  non-lube machines, dry gas



- Materials **based on PEEK**
  lube machines, high pressure

- **Resin-based** materials
  non-lube machines, bone-dry gas

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