Natural Refrigerant Training Summit

Building a Sustainable Workforce

CO2 Transcritical Compressors: Design, Lab Testing, and Troubleshooting

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Dorin USA

NORTH AMERICAN
Sustainable
Refrigeration
Council

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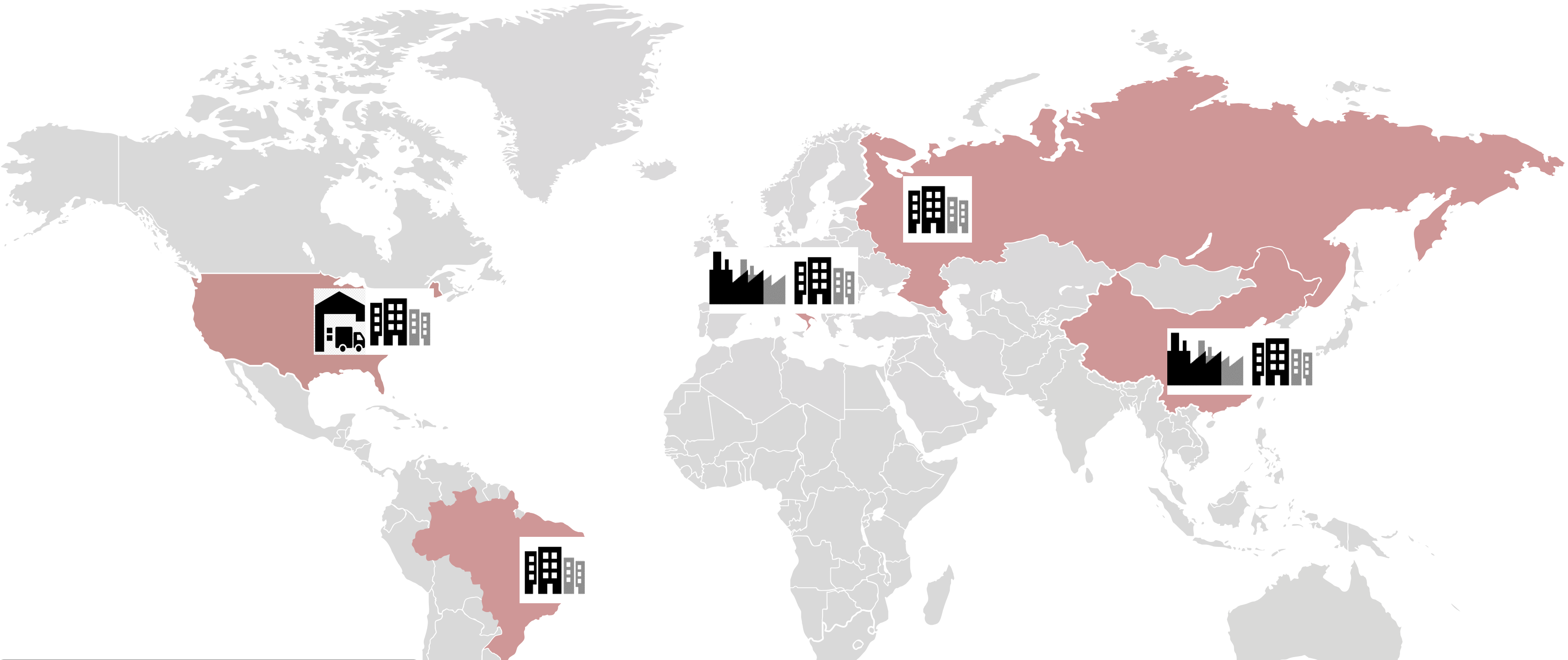
INNOVATION

CO_2 TRANSCRITICAL COMPRESSORS: DESIGN - LAB TESTING - TROUBLESHOOTING

INTRODUCTION



HQ in FLORENCE
ITALY

200 EMPLOYEES
4 PRODUCTION SITES
5 SALES OFFICES

75.000+ COMPRESSORS
(2022)

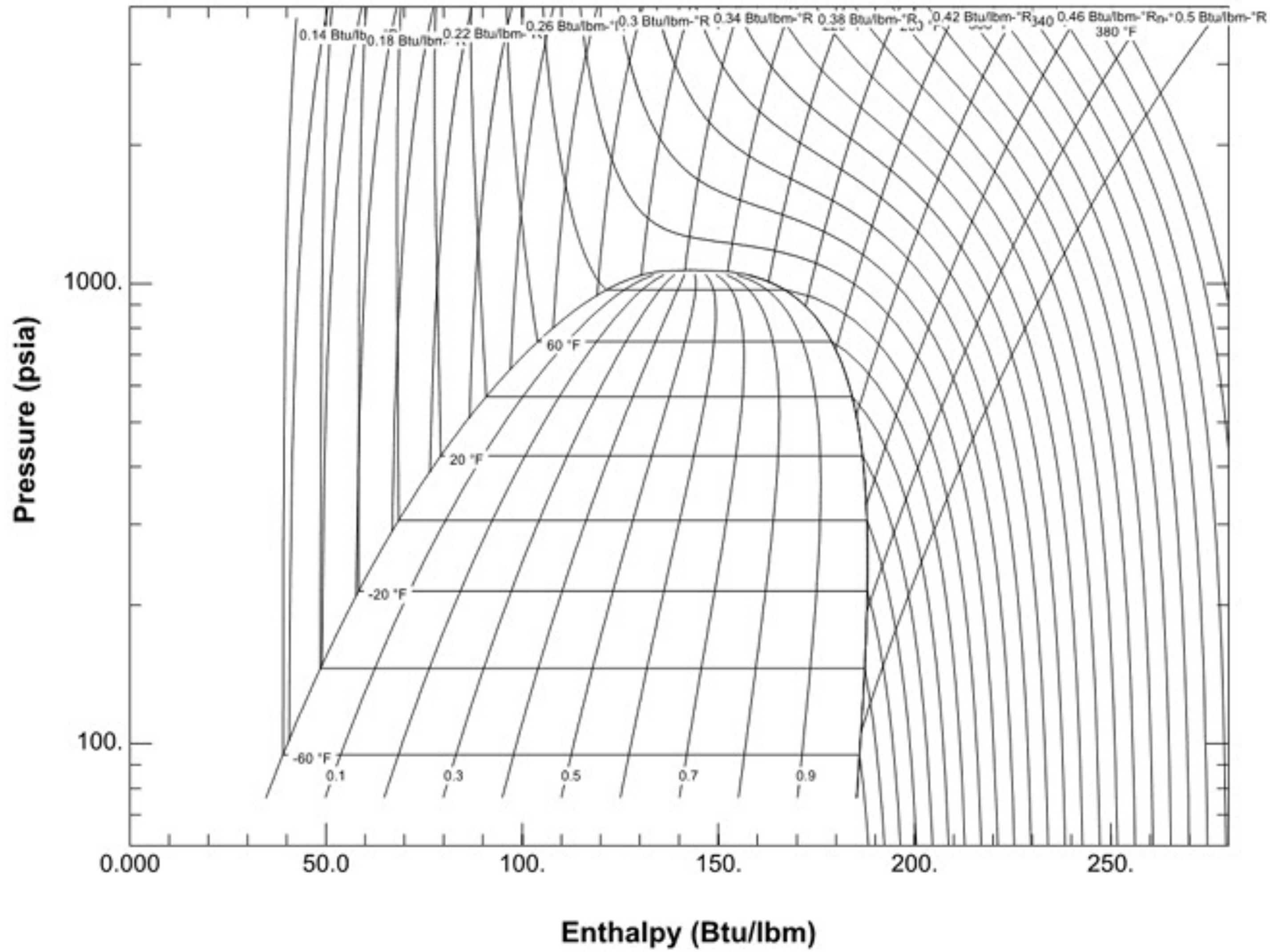
Introduction to CO2

- Carbon Dioxide (R744 – CO2)
- Environmentally benign properties (GWP = 1)
- Excellent heat transfer properties
- High COP levels
- Severe challenges from a compressor perspective

- Important Conditions to remember:
  - Critical Point = 1070psia / 87.8F
  - Triple Point = 75psia / -69.8F
  - Low Temp Evap Operation = ~180psig / -25F
  - Med Temp Evap Operation = ~400psig / +20F
  - Condensing = 1031.5psig / 86F

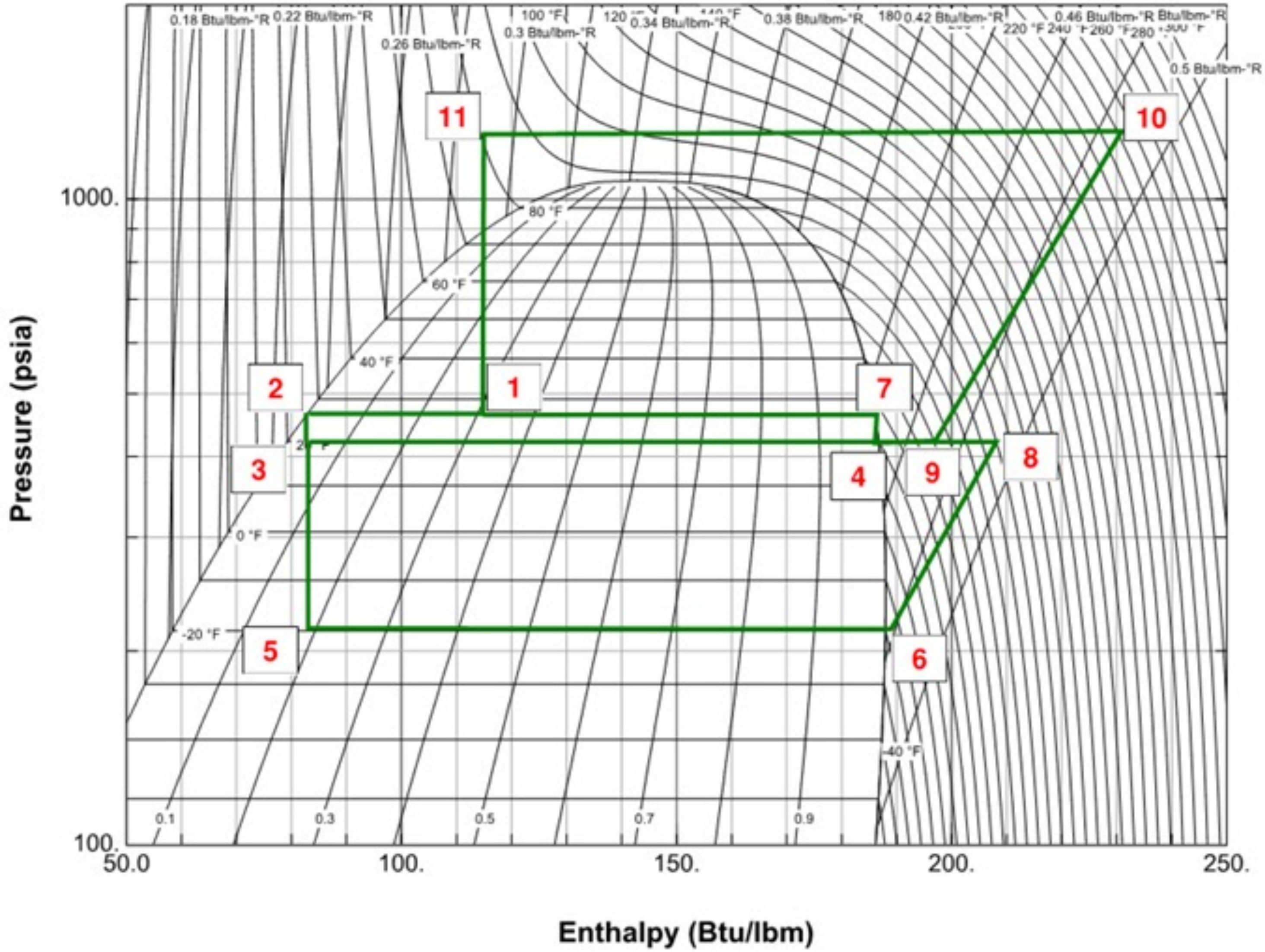
- Design and Test criteria for a 4412 cfh – 160hp CO2 transcritical compressor analyzed over the course of this training.

CO2 PH Diagram



** Diagram created using REFPROP – NIST Reference Fluid Properties*

CO2 Flash Gas Bypass System



** Diagram created using REFPROP – NIST Reference Fluid Properties*

Challenges

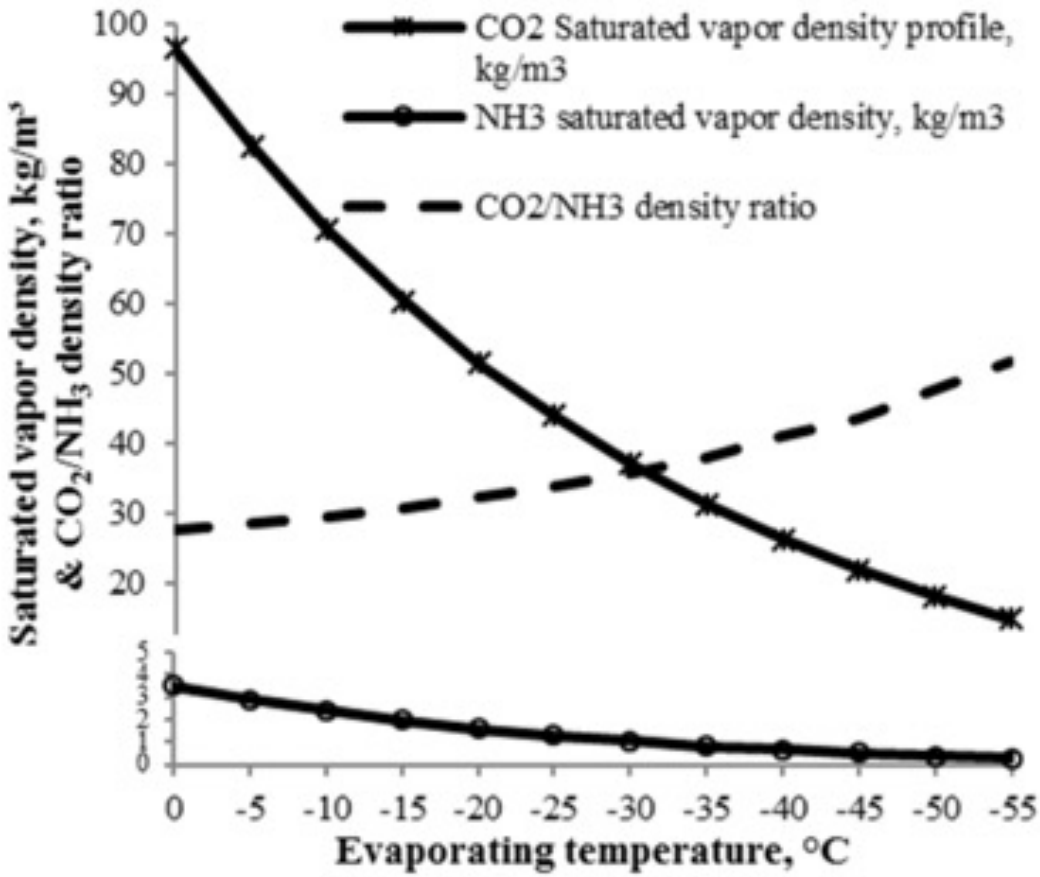
- Pressure Differential – Medium Temperature Systems

MT SYSTEM OPERATION					
-10°C (14°F) SST // 40°C (104°F) AMB. TEMP.	R404A	R134a	R449A	NH_3	CO_2
Differential Pressure [bar]	18,6	11,2	17,7	17,4	73,5
Differential Pressure [psi]	270	162,4	256,6	252,3	1066

- CO2 has a pressure differential up to 6.5x higher than other refrigerants
- Reciprocating technology best deals with this high pressure differential
- There still remains severe challenges for drive gear design

Challenges

- Volumetric Refrigeration Capacity

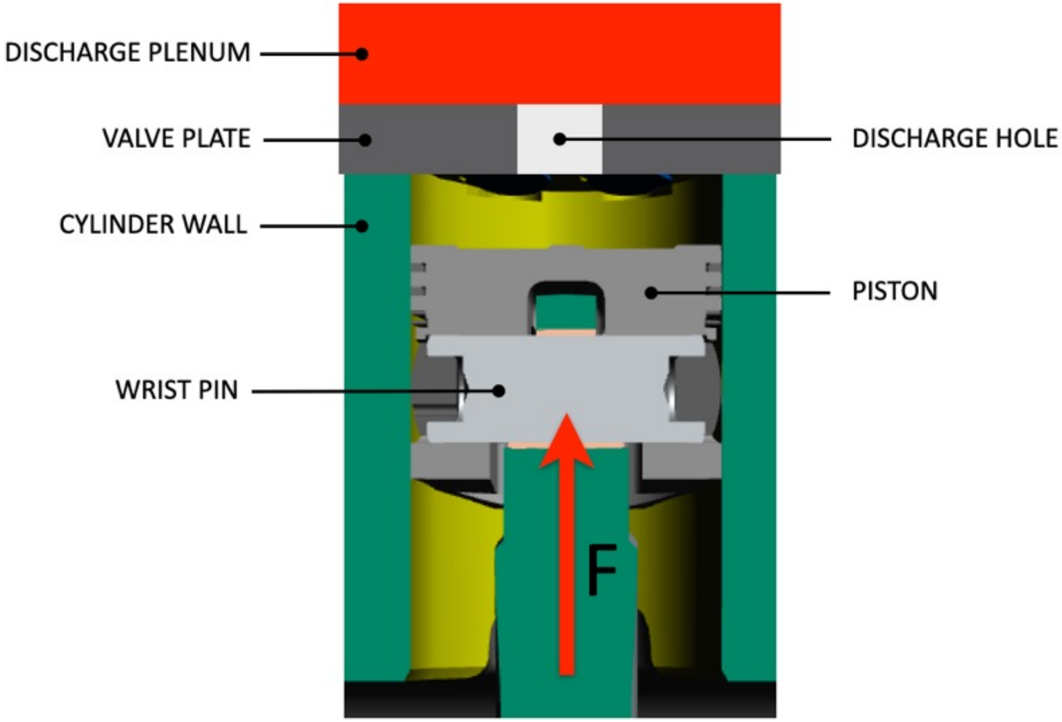


- CO_2 has a very high volumetric refrigeration capacity
- 4~12 times larger than NH_3
- Similar capacity using smaller displacements
- Much smaller pipe diameters
- Much smaller compressor bores

- Less room to unload compressor stresses
- Very high specific load on the drive gear

Challenges

- Specific Load on the Drive Gear



- CO_2 induces a very high specific load on the drive gear due to large differential pressures and small bores.

- Wrist Pin is the most challenged component

- $p = F / A$ (wrist pin specific load)
- $F = \Delta p * \text{piston top surface}$
- A = contact surface between rod end and wrist pin

Challenges

- Specific Load on the Drive Gear – Medium Temperature Systems

MT SYSTEM OPERATION -10°C (14°F) SST // 40°C (104°F) AMB. TEMP.					
140 kW [480 kBtu/h] refrigeration duty	R404A	R134a	R449A	NH_3	CO_2
displacement @ 1750 rpm [m3/h]	300	500	300	300	75
displacement @ 1750 rpm [cfh]	10560	17640	10560	10560	2640
number of cylinders	8	12	8	8	6
bore [mm]	86	95	86	86	55
bore [inches]	3,38	3,74	3,38	3,38	2,16
force [N]	1,02E+04	7,44E+03	9,53E+03	1,01E+04	1,75E+04
wrist pin contact surface [mm2]	9,42E+02	1,02E+03	9,42E+02	9,42E+02	5,09E+02
wrist pin specific load [MPa]	10,8	7,29	10,1	10,7	34,3

CO2 induces:

- ~3x the specific load of NH3, R404A and R449A.
- ~5x the specific load of R134A.

Challenges

- High Discharge Temperatures – Medium Temperature Systems

MT SYSTEM OPERATION -10°C (14°F) SST // 40°C (104°F) AMB. TEMP. // 30K (54F) SUPERHEAT					
Refrigerant	R404A	R134a	R449A	NH_3	CO_2
polytropic exponent	1,004830	1,070567	NA	1,320000	1,289373
RDT [°C]	91,3	96,2	99,5	out of envelope	155
RDT [°F]	196	205	211	out of envelope	311

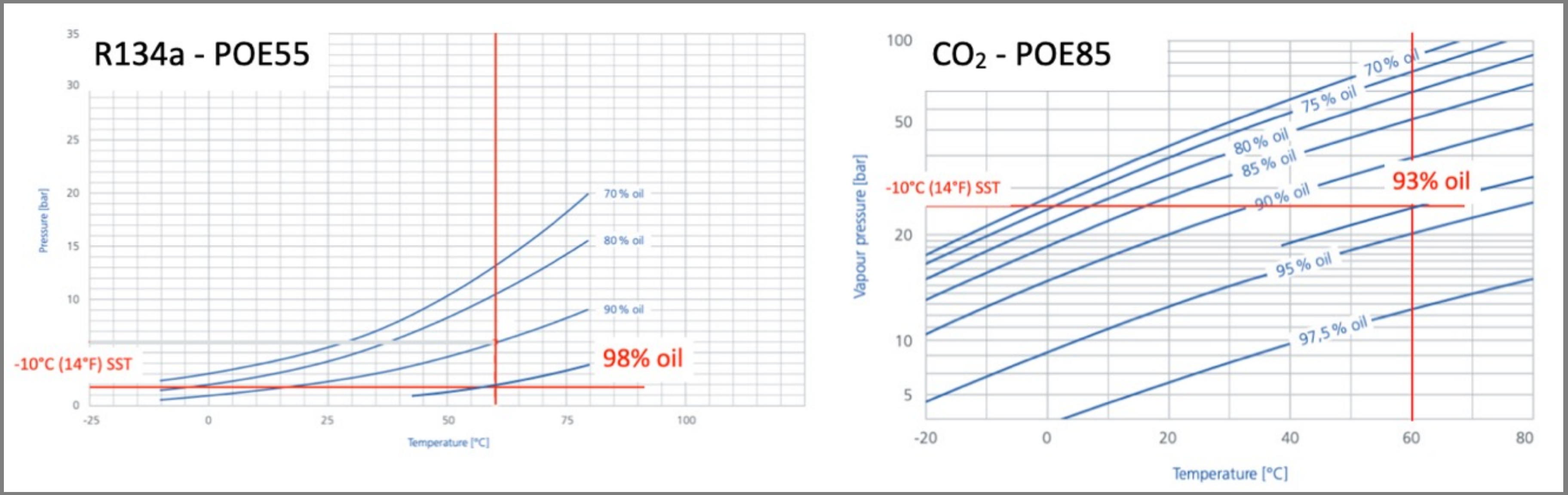
Table 4. Real discharge temperatures for various MT refrigerants systems

CO2 leads to significantly higher discharge temperatures – challenges:

- Heat Dissipation
- Lubrication

Challenges

- CO2 Solubility in Lubricants

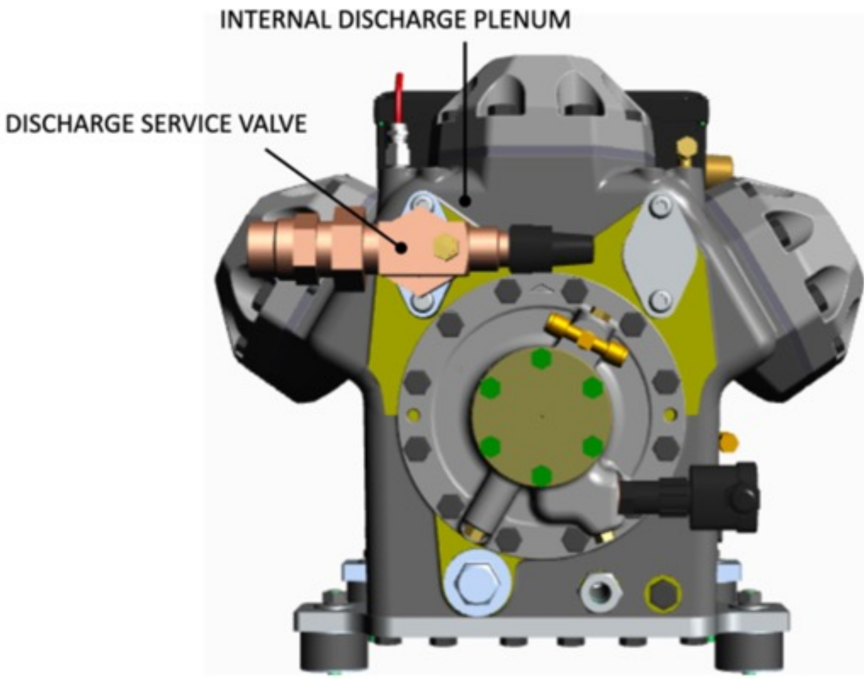


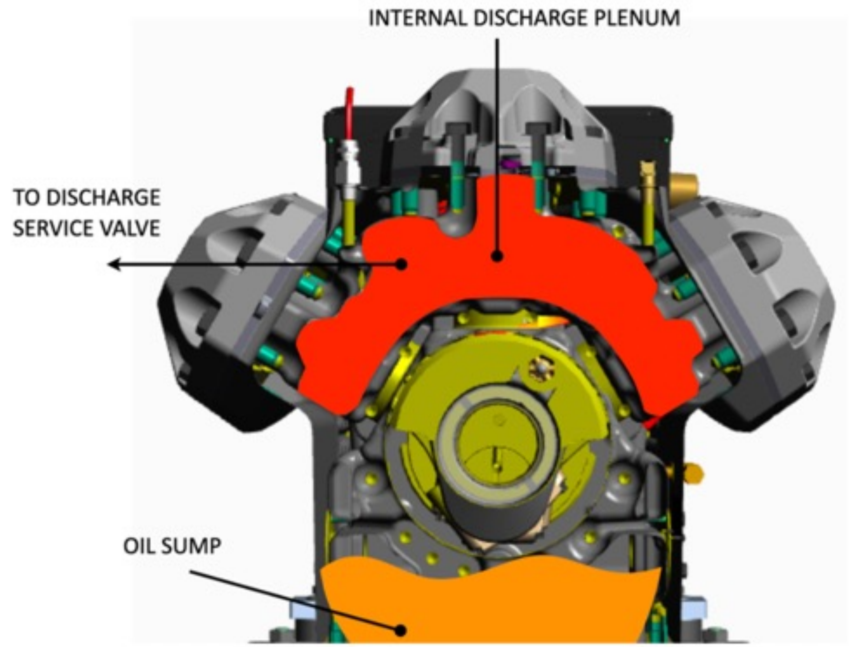
CO2 is more soluble into lubricants – challenges:

- Lower residual viscosity
- Higher oil circulation rate

CO2 Transcritical Compressor Design

- DESIGN A





Internal Discharge Plenum:

- Crank-case material – Cast Iron (thermal conductor)
- Compression heat dissipates towards the lubricant

CO2 Transcritical Compressor Design

- DES￿GN B

Figure 7. Design B - compressor with external discharge plenum

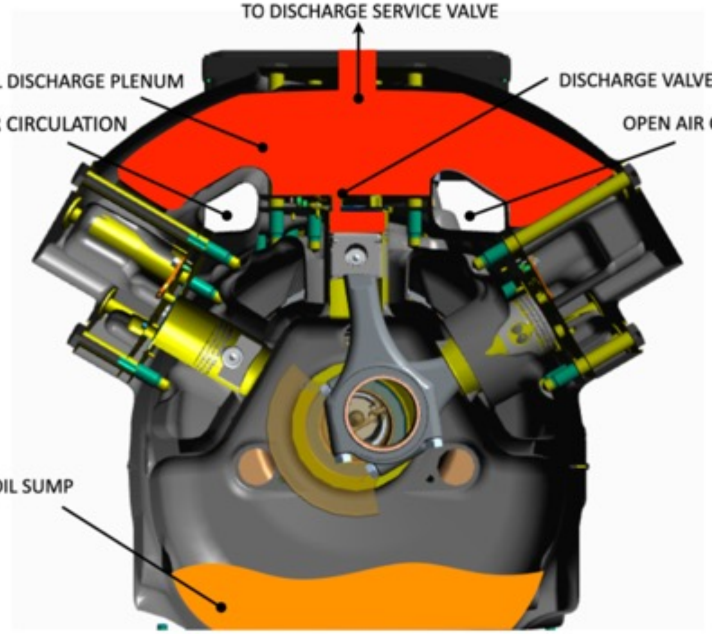


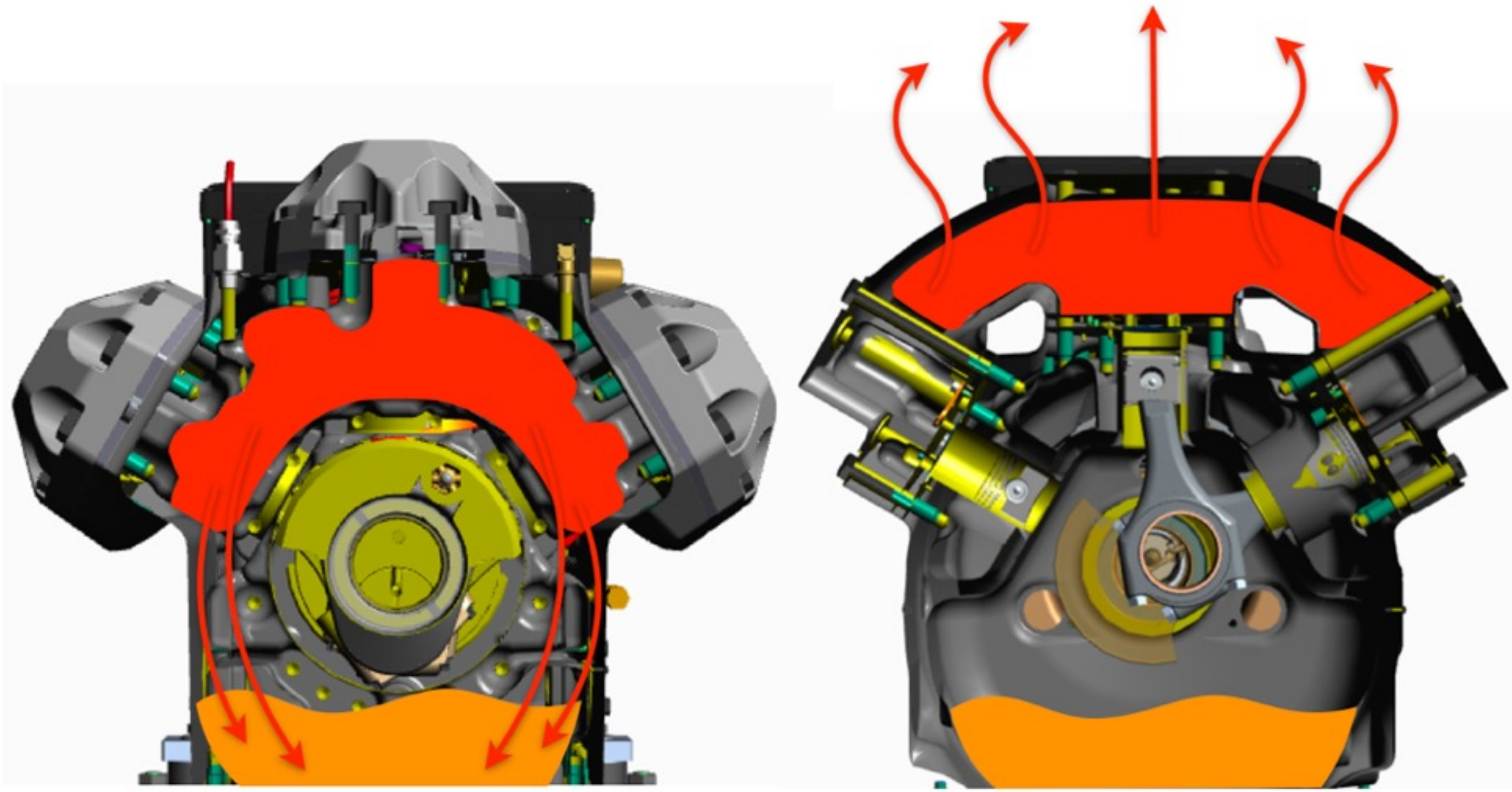
Figure 8. Interior view of a Design B - compressor with external discharge plenum

External Discharge Plenum:

- Open air circulation allows thermal insulation between HP and LP sides
- Lower heat dissipation towards the oil sump

CO2 Transcritical Compressor Design

- DESIGN A vs DESIGN B

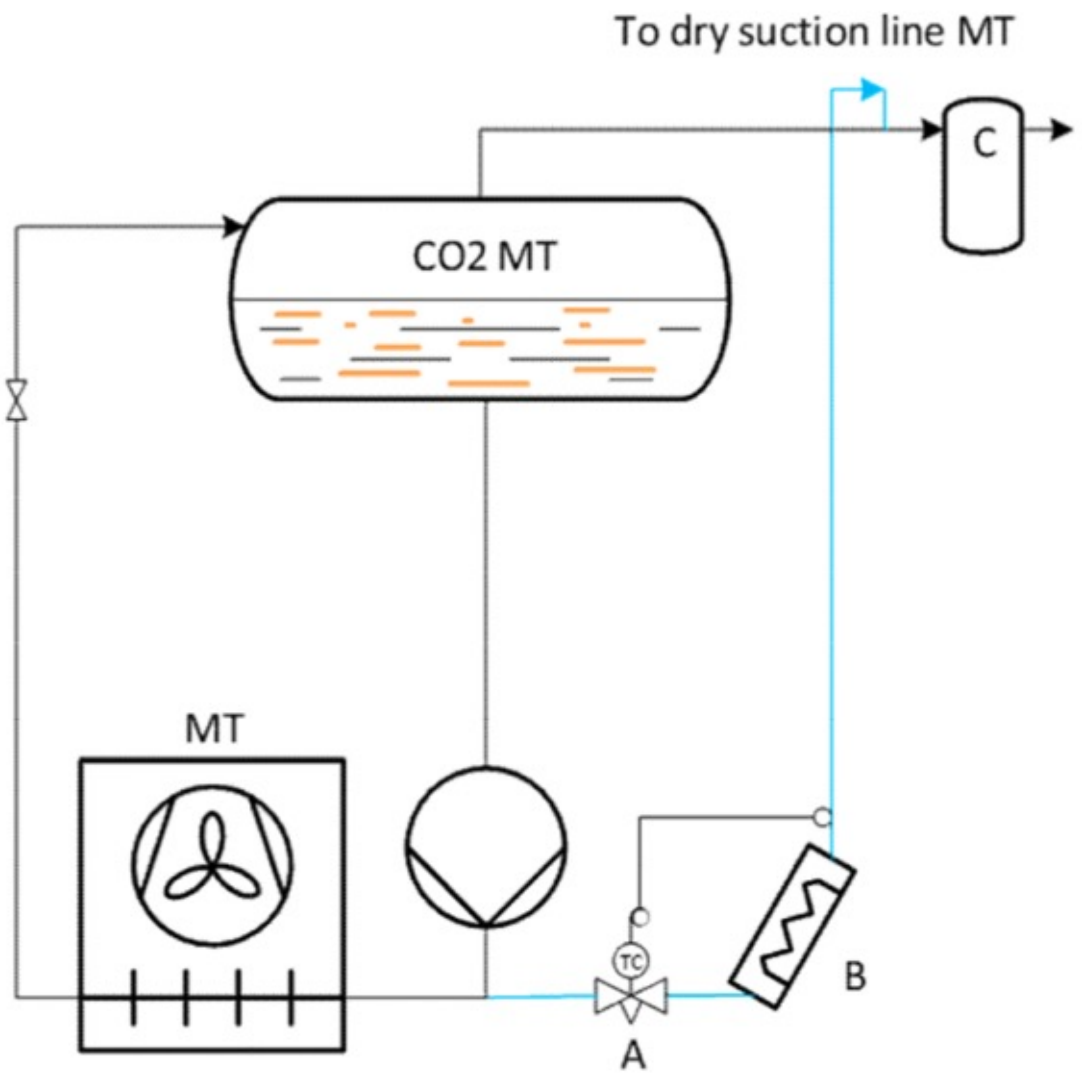


DESIGN A:
COMPRESSION HEAT DISSIPATION TO OIL SUMP

DESIGN B:
COMPRESSION HEAT DISSIPATION TO SURROUNDING AMBIENT

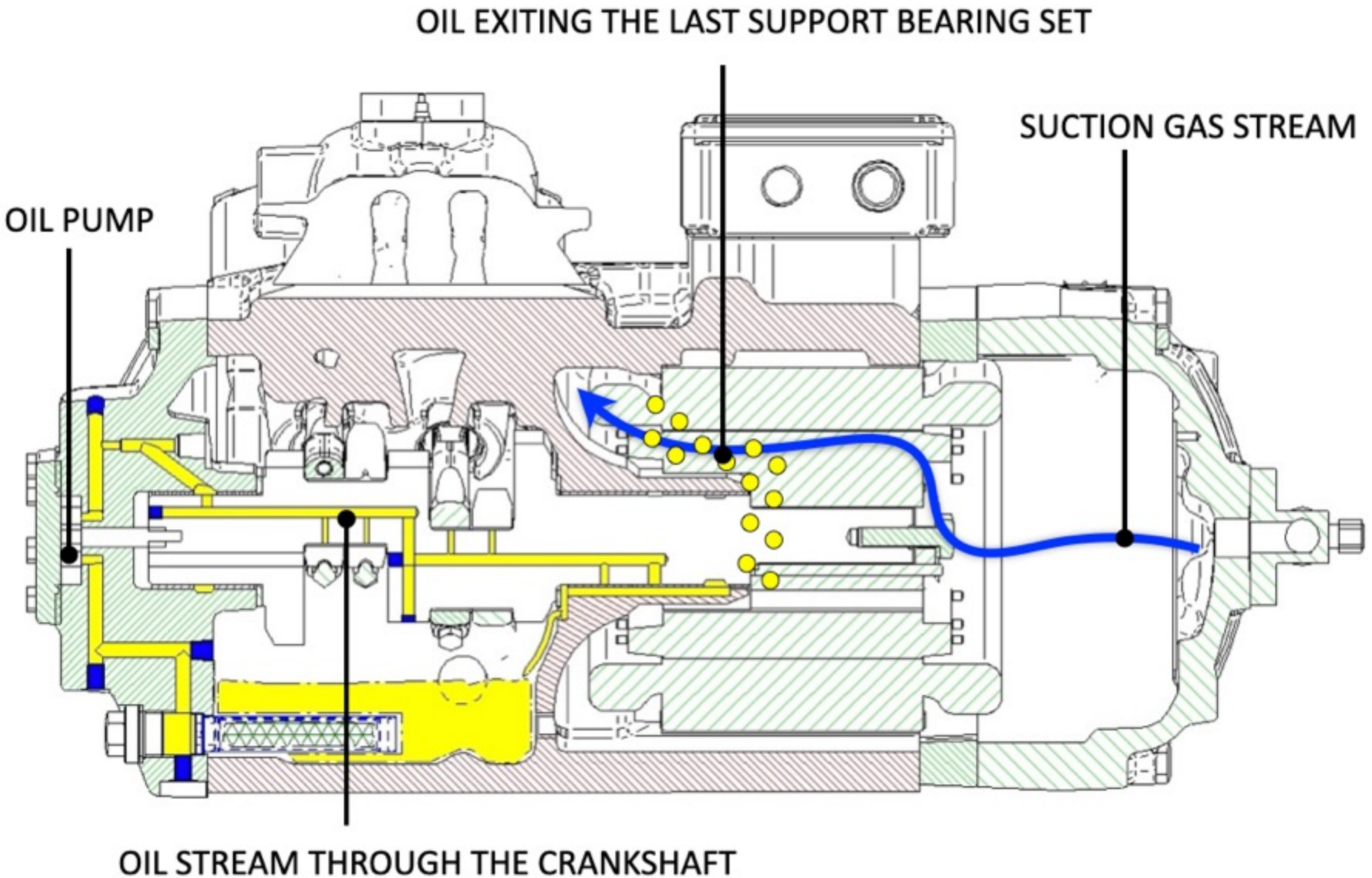
CO2 Transcritical Compressor Design

- Compressor Oil Circulation Rate (OCR)



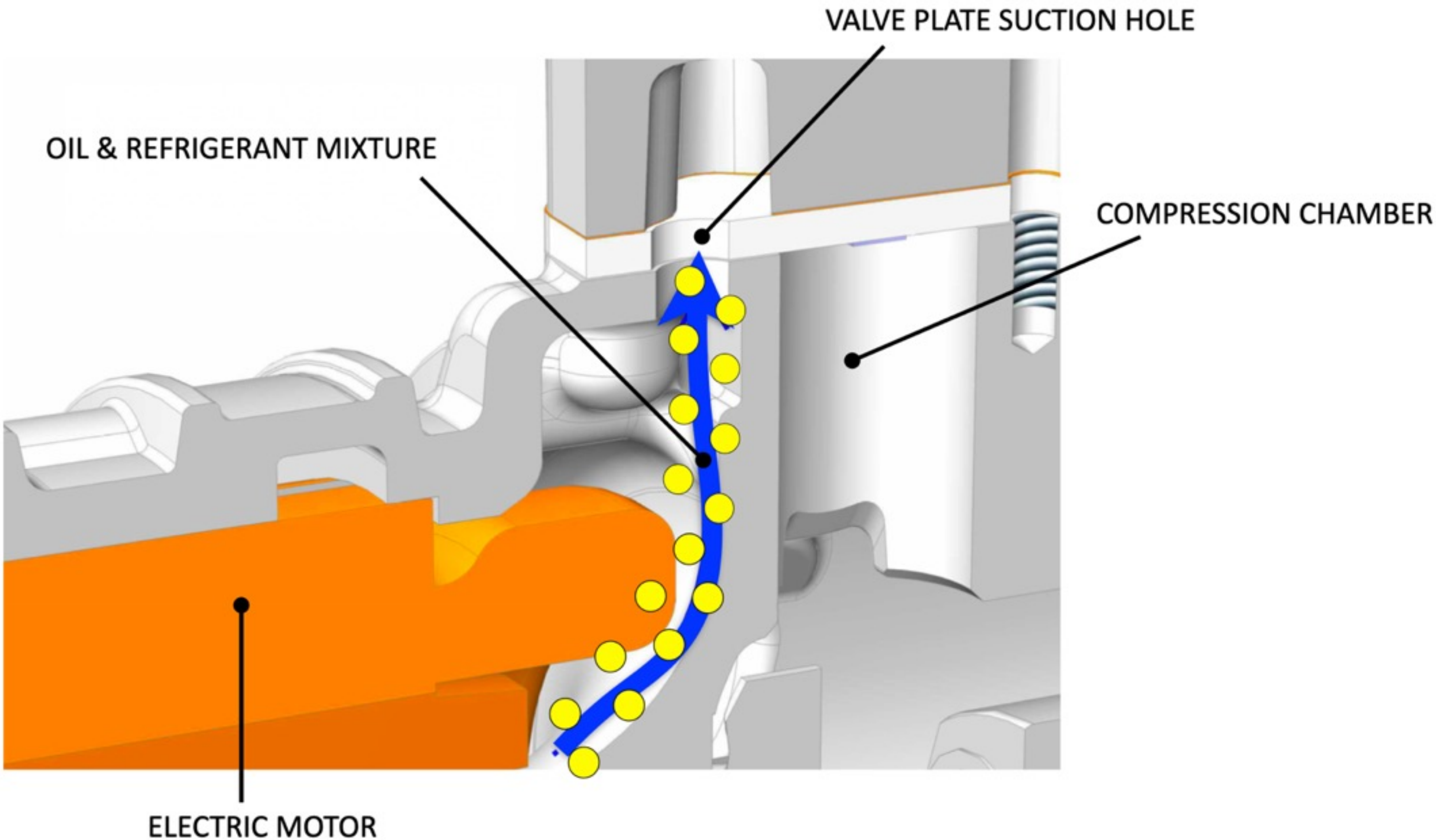
- Rectifier is triggered by low oil level into the reservoir.
- Pump energy is “wasted” to feed the rectifier.
- Liquid portion is bypassing the evaporator.

CO2 Transcritical Compressor Design



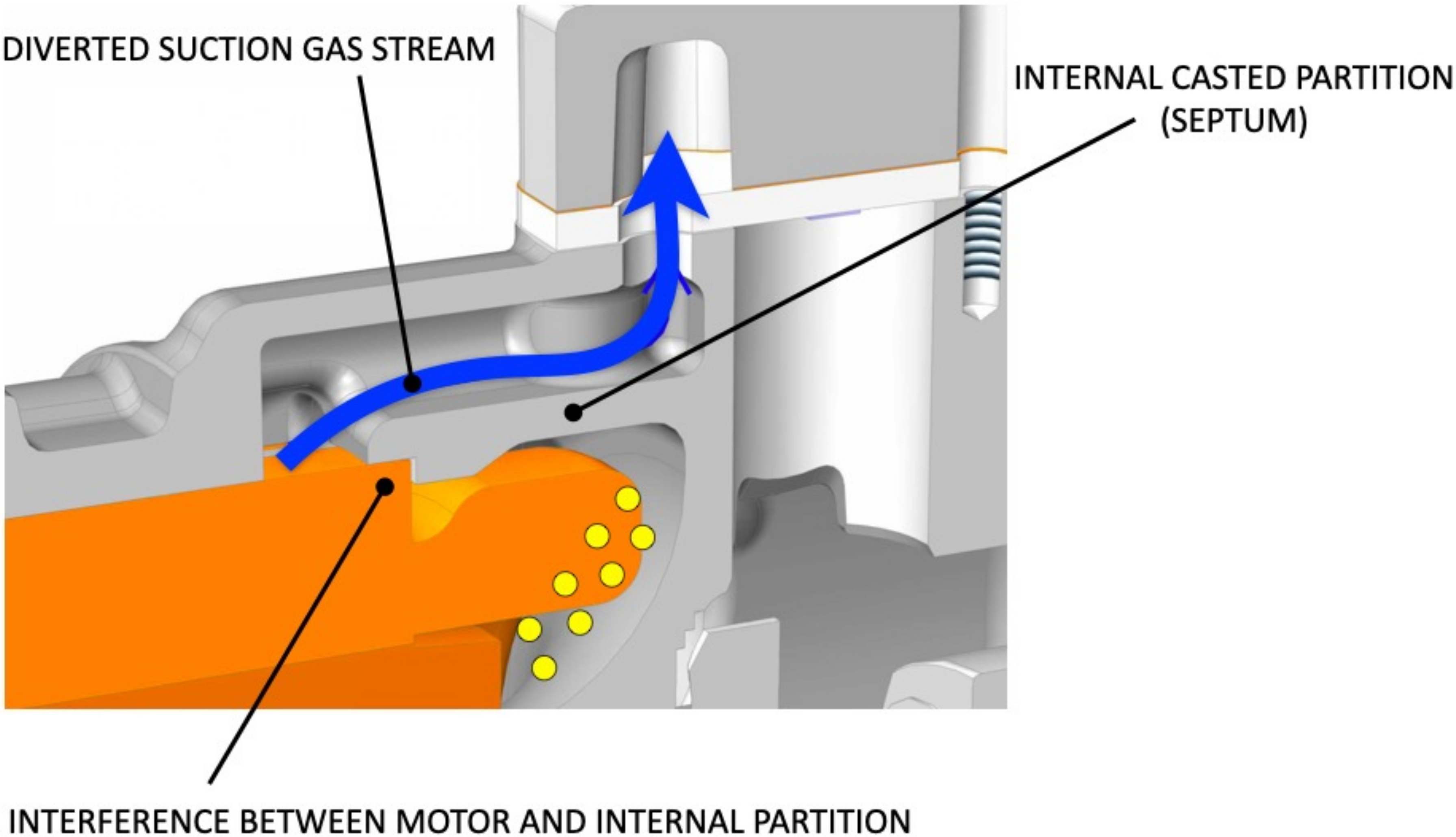
CO2 Transcritical Compressor Design

- DESIGN C



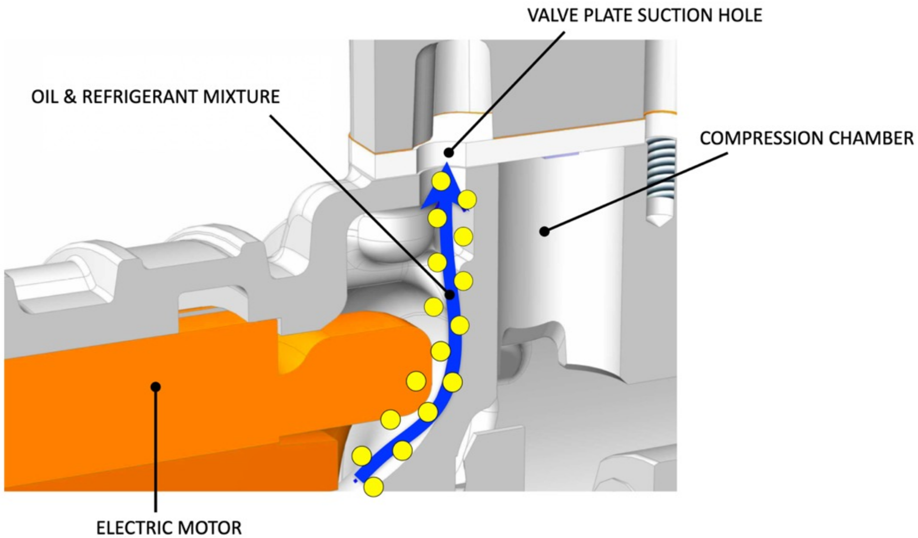
CO2 Transcritical Compressor Design

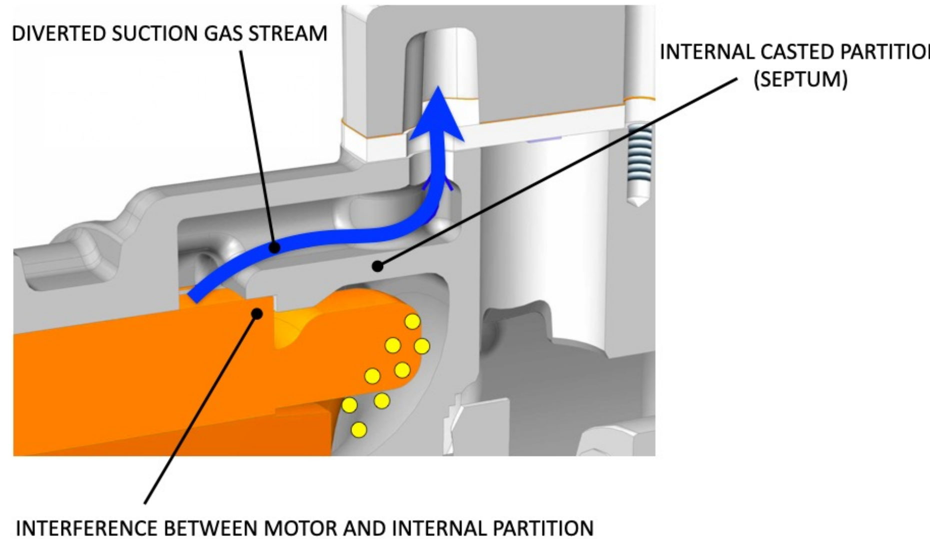
- DESIGN D



CO2 Transcritical Compressor Design

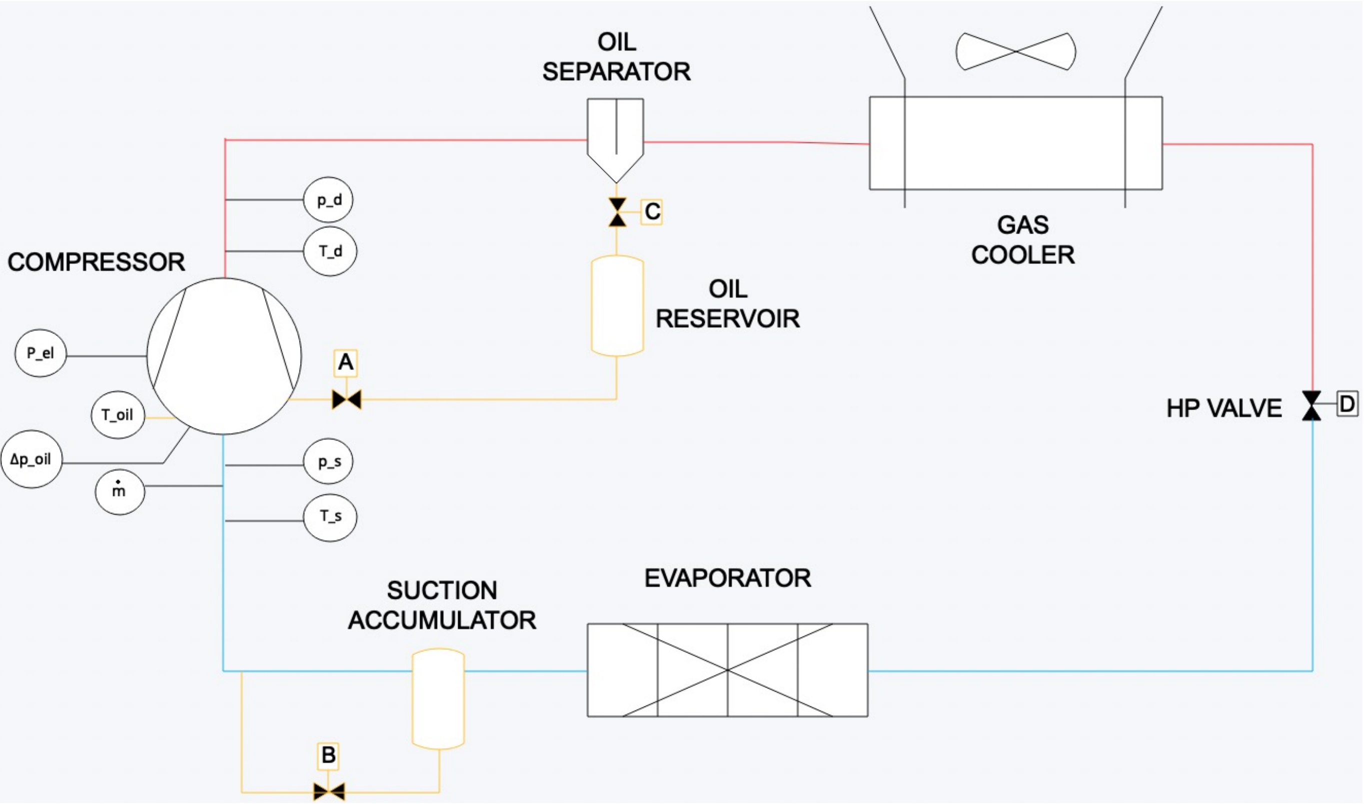
- DESIGN C vs DESIGN D





CO2 Transcritical Compressor Lab Testing

- DESIGNS A – B – C – D have been tested in a CO2 Lab

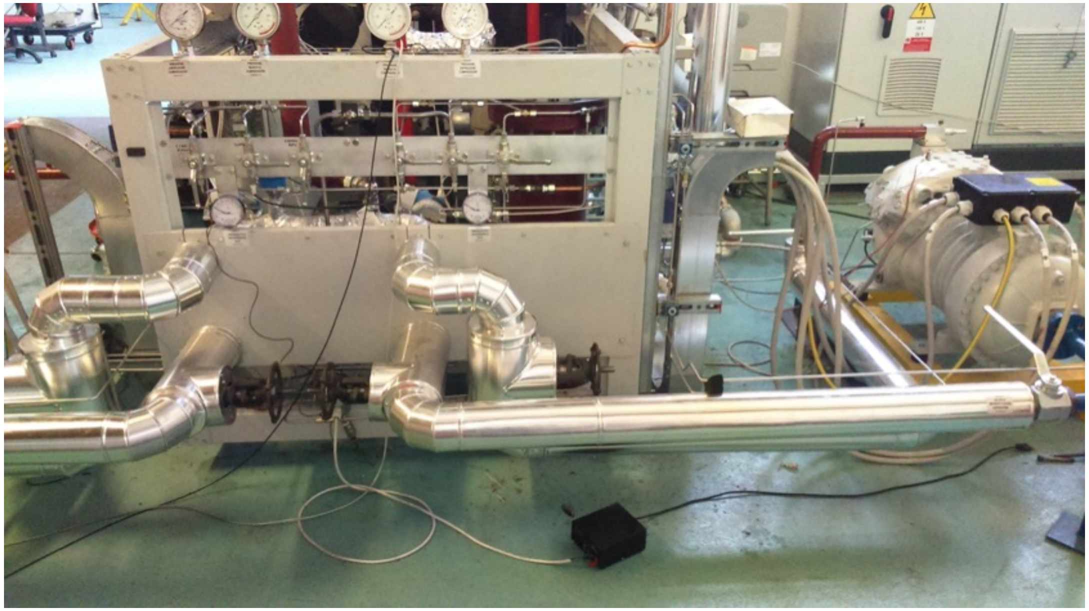


p_s: Suction Pressure
T_s: Suction Temp.
m: Refrigerant Mass Flow
Δp_oil: Oil Diff. Pressure
T_oil: Oil Temp.
P_el: Power Consumption
p_d: Discharge Pressure
T_d: Discharge Temp.

*Valve A: allows compressor oil sump feed from oil reservoir
*Valve B: allows oil return from suction accumulator
*Valve C: ?
*Valve D: ?

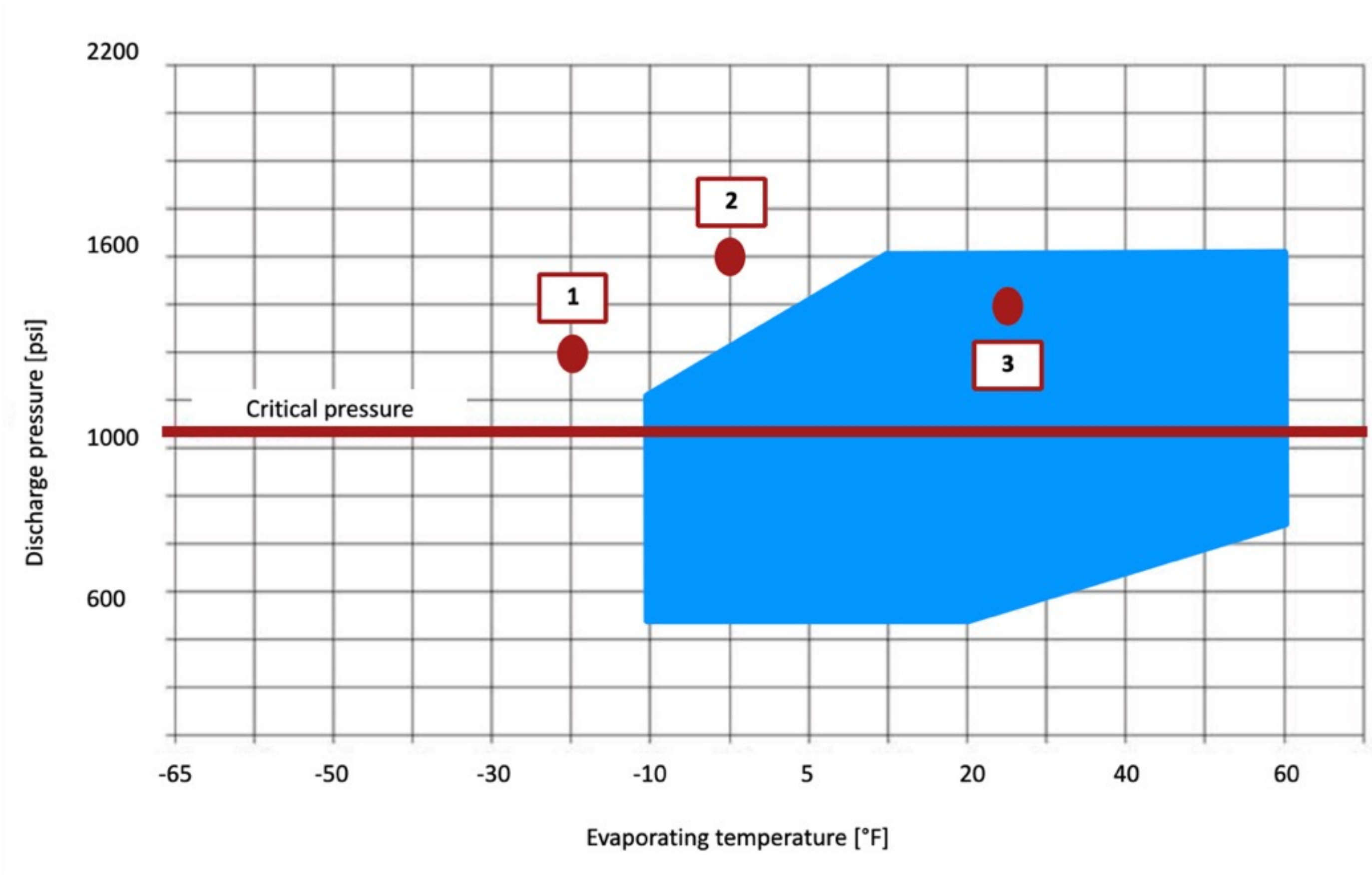
CO2 Transcritical Compressor Lab Testing

Gas Cooler



Compressor and Sensors Assembly

CO2 Transcritical Compressor Lab Testing



#1: Max Pressure Ratio –
200psi suction
1200psi discharge
Challenge = Max Disch. T

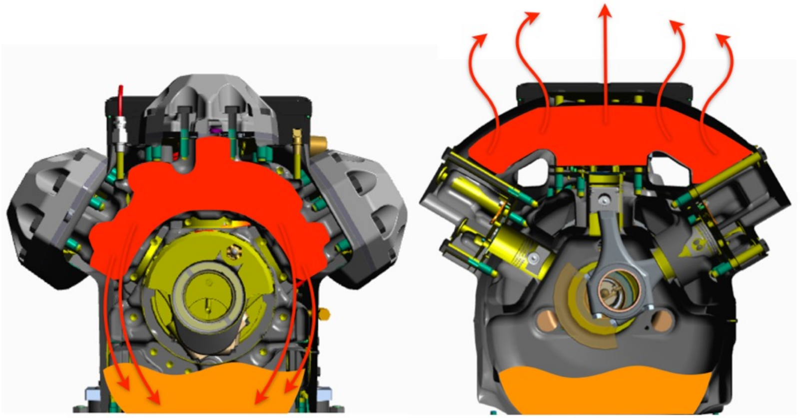
#2: Max Pressure Diff. –
285psi suction
1500psi discharge
Challenge = Max Load

#3: Typical MT Conditions –
435psi suction
1300psi discharge

*2000hrs continuous run
*200k short cycles
(5s on/5s off)

CO2 Transcritical Compressor Lab Testing

- DES�GN A vs B: Performance & Reliability:



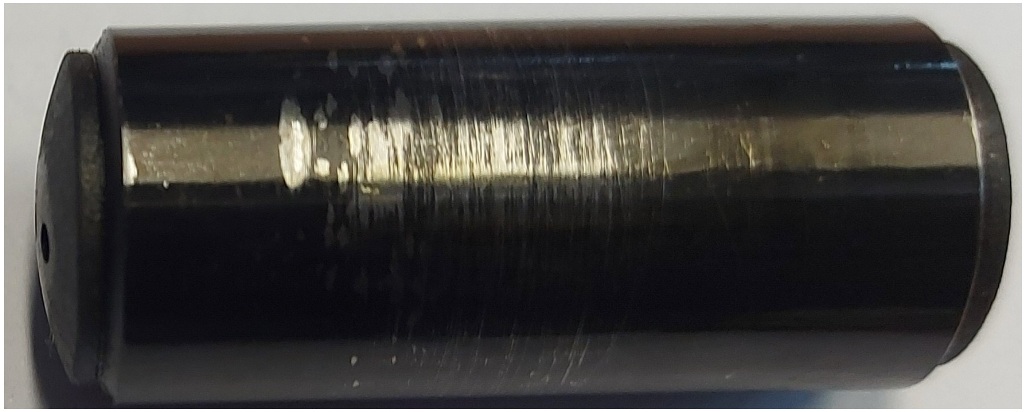
DESIGN A:
COMPRESSION HEAT DISSIPATION TO OIL SUMP

DESIGN B:
COMPRESSION HEAT DISSIPATION TO SURROUNDING AMBIENT

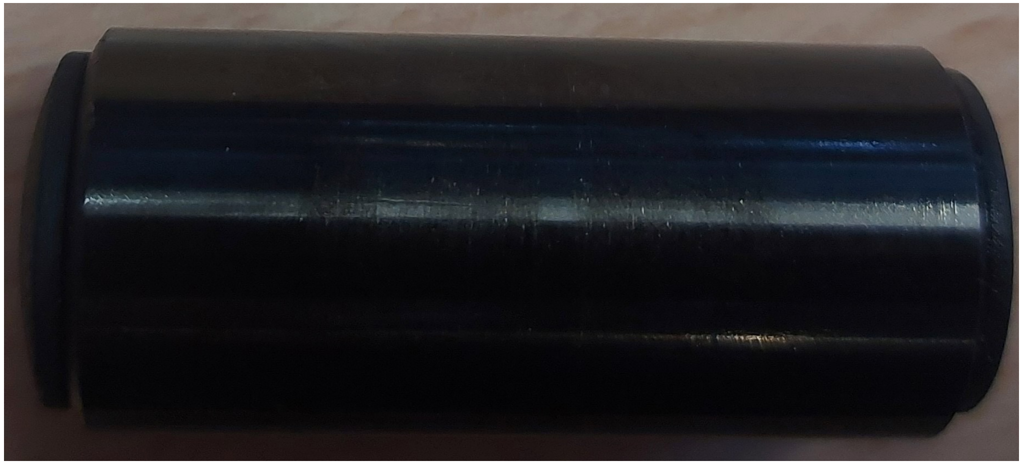
TRANSCRITICAL COMPRESSORS TESTS: DISPLACEMENT 4412 cfh @ 60Hz							
reliability and performance test		Design A			Design B		
p_s (suction pressure)	[psi]	200	285	435	200	285	435
p_d (discharge pressure)	[psi]	1200	1500	1300	1200	1500	1300
T_s (suction temperature)	[°F]	-4	14	40	-4	14	40
T_oil (oil temperaturee)	[°F]	167	158	155	125	118	113
T_d (discharge temperature)	[°F]	329	300	230	310	282	215
Oil Residual viscosity	[cSt]	13	10	9	25	22	16
m (mass flow)	[lb/h]	4857	7424	15905	5094	7751	16362
P_el (power consumption)	[kW]	116	143	165	112	138	161

CO2 Transcritical Compressor Lab Testing

- DESIGN A vs B: Performance & Reliability:



A – Severe wear on wrist pin.



B – No wear on wrist pin.

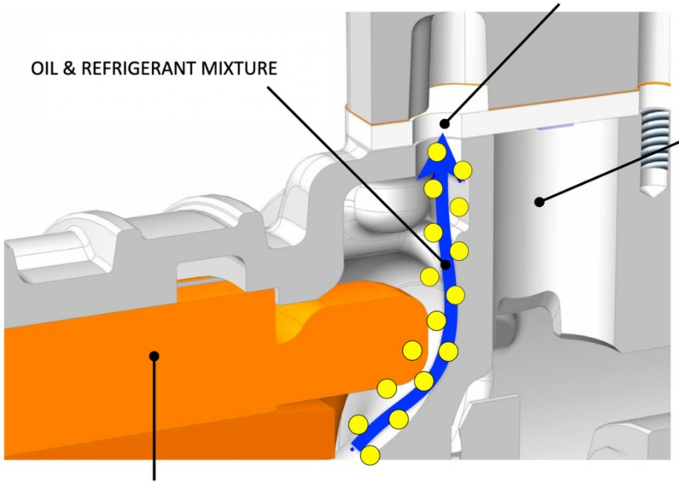
CO2 Transcritical Compressor Lab Testing

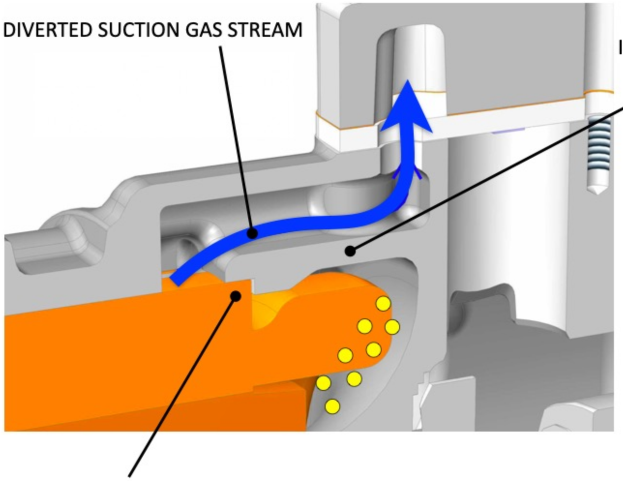
- DES GN C vs D: Oil Circulation Rate

Test performed at typical MT conditions: 435psi suction / 1300psi discharge

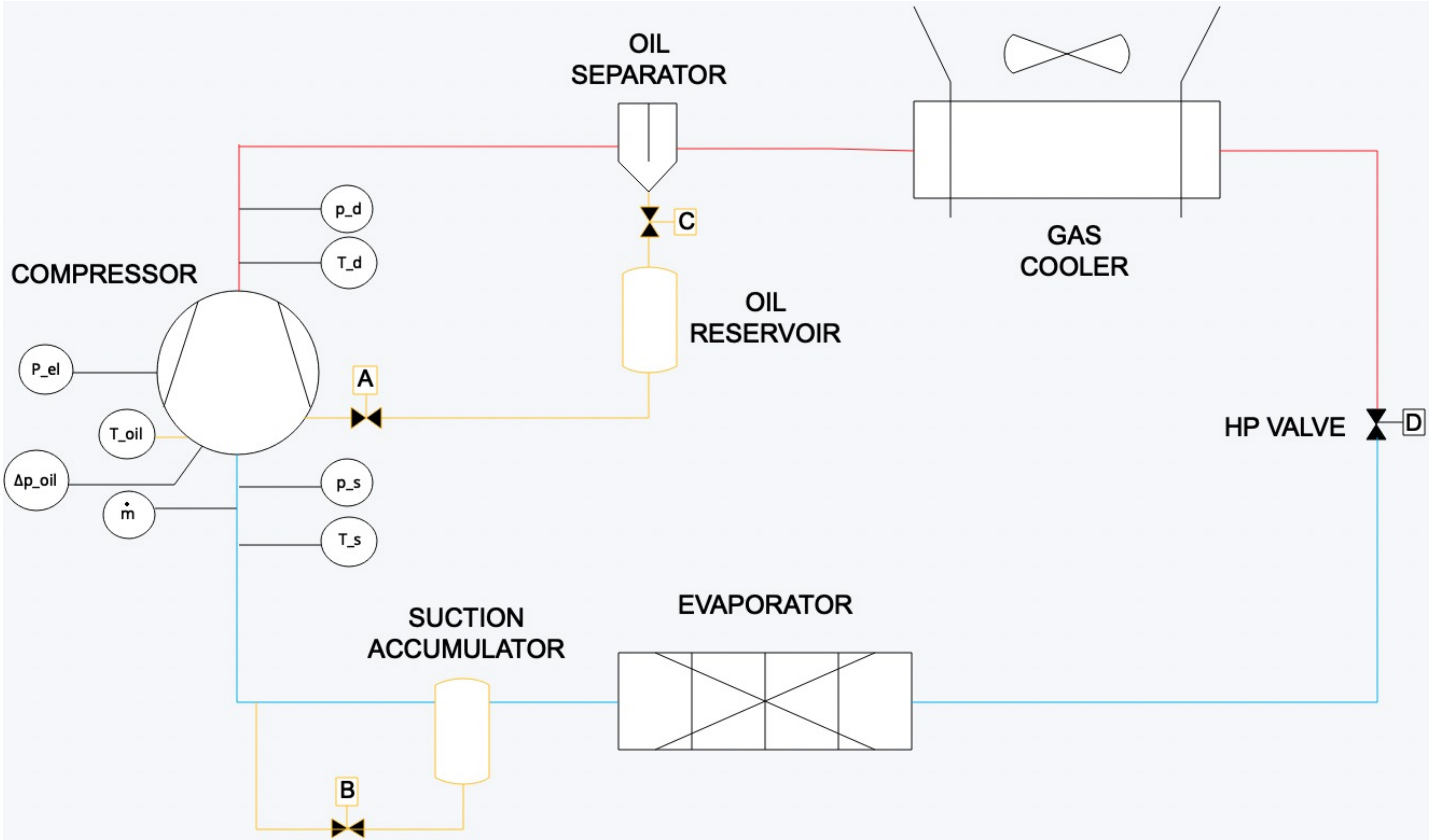
Oil return ports closed, no oil return from system to the compressor.

Oil differential pressure switch trigger time was measured and compared for both design C & D.

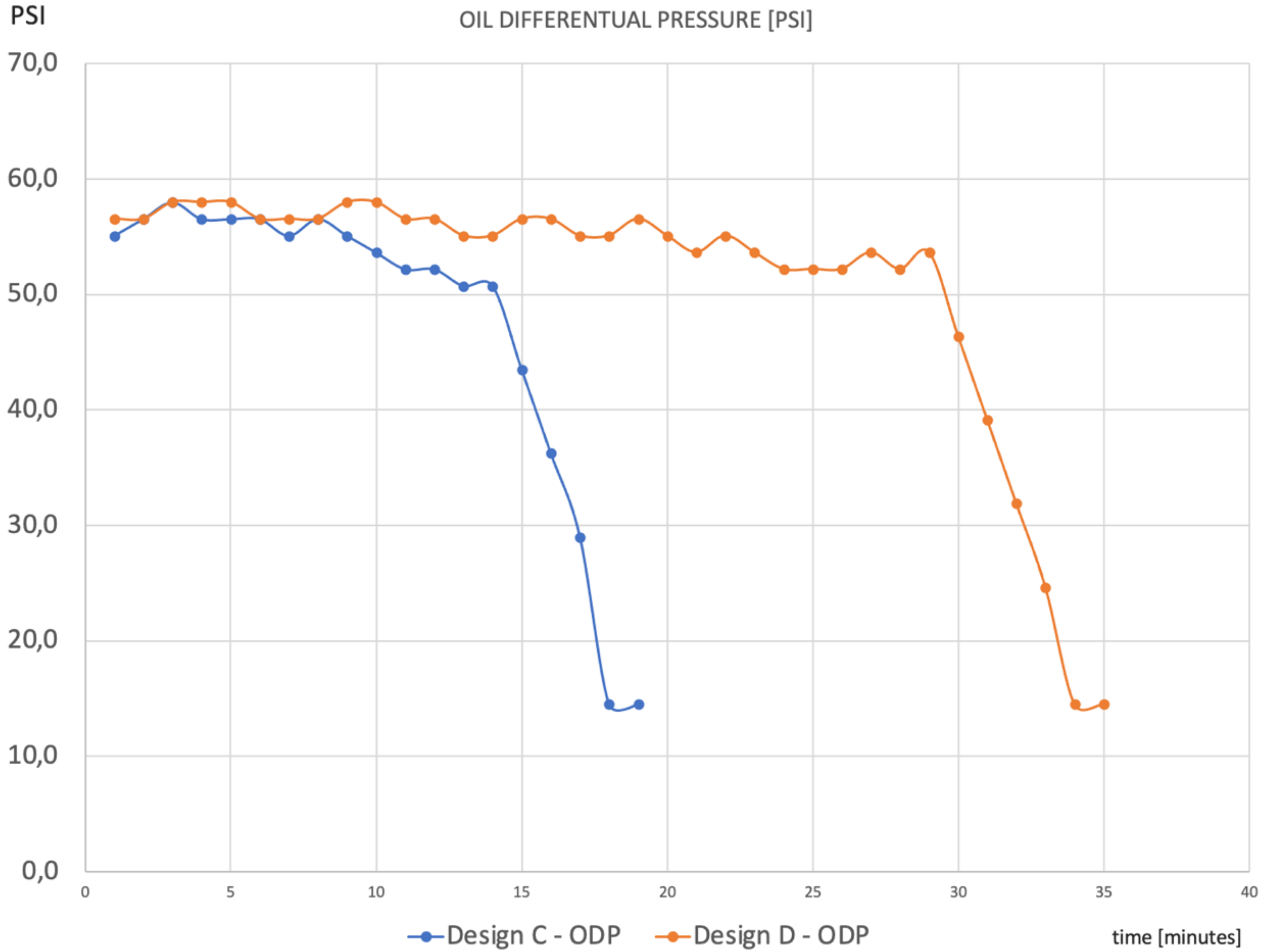




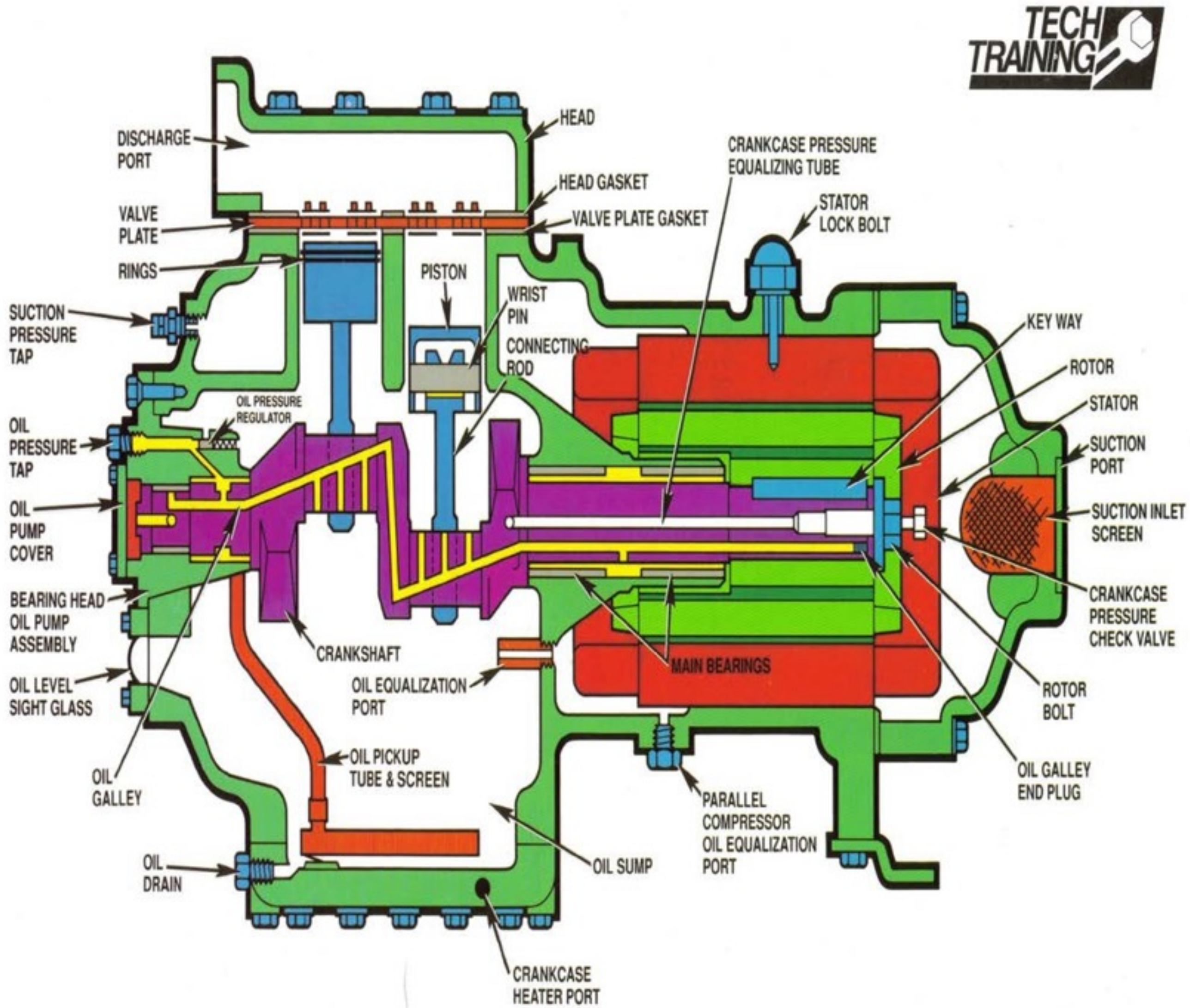
CO2 Transcritical Compressor Lab Testing



CO2 Transcritical Compressor Lab Testing



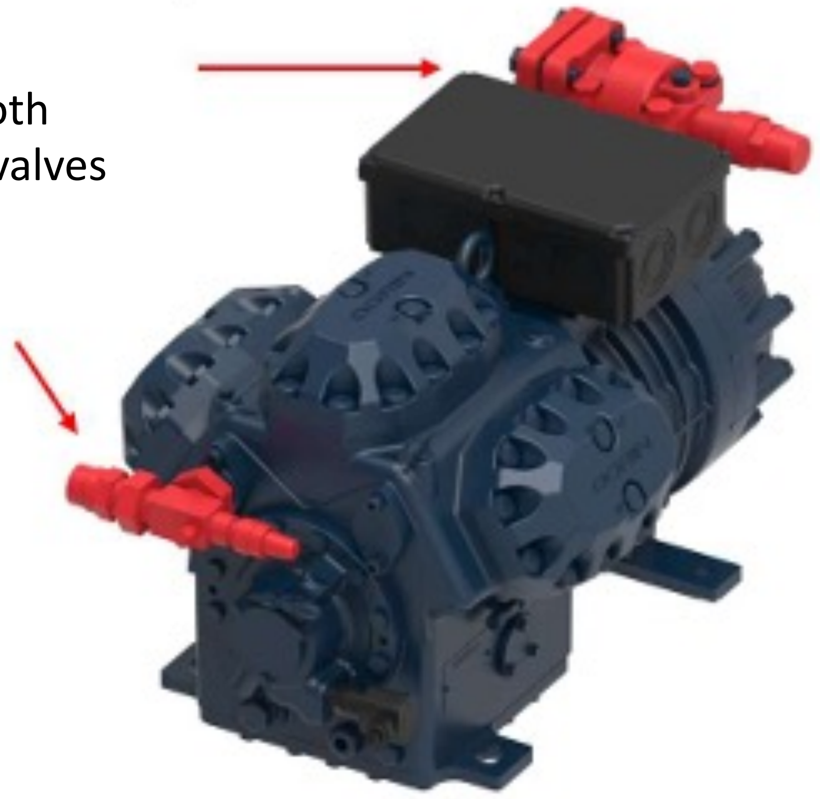
Parts of a Semi-Hermetic Compressor



CO2 Transcritical Compressor Troubleshooting

- Before working on any compressor in the field, make sure to follow system instructions for turndown and proceed to isolate the compressor. After compressors are powered off and isolated, open both service valves to relieve pressure.

Open both service valves



CO2 Transcritical Compressor Troubleshooting

- Check the nameplate for information on the compressor:

CO2 Transcritical Compressor Troubleshooting

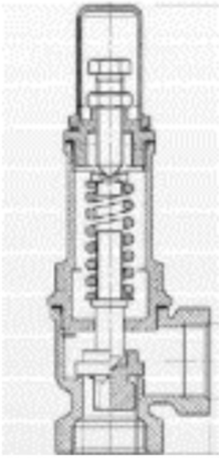
- Safety Devices (varies by size of compressor):

Motor Protection

Oil Pump

Crankcase Heater

LP / HP Relief Valve



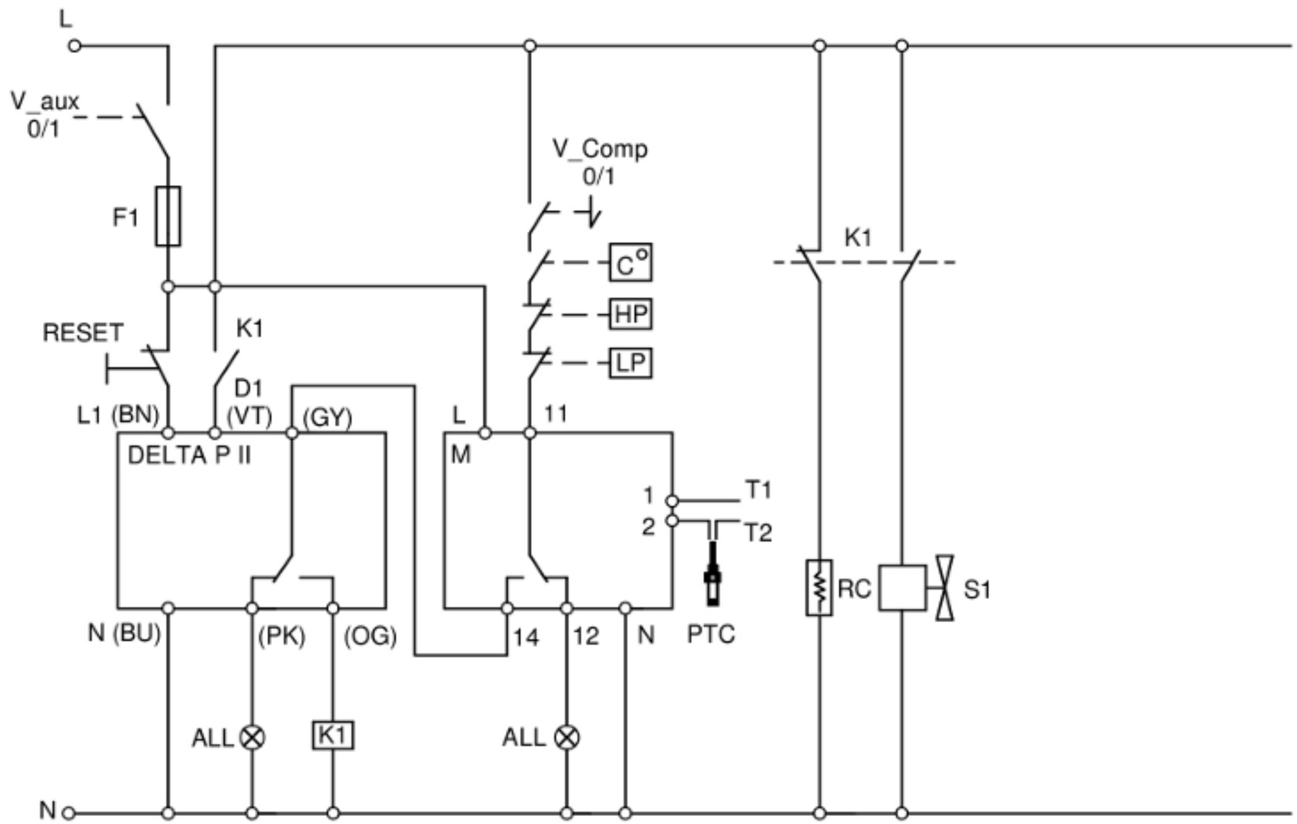
Electronic Protection Module

Max Discharge Temp. Sensor

Oil Differential Pressure Switch

CO2 Transcritical Compressor Troubleshooting

- Electrical Connection Scheme of Safety Devices:



V_aux = Aux Power Supply	RC = Crankcase Heater	HP = High Pressure Switch
V_Comp = Compressor Power	S1 = Solenoid	LP = Low Pressure Switch
F1 = Fuse	M = Protection Module (INT69)	PTC = Discharge Temp. Sensor
K1 = Contactor	DELTA P II = Oil Diff. P Switch	1-2/T1-T2 = Thermistors

CO2 Transcritical Compressor Troubleshooting

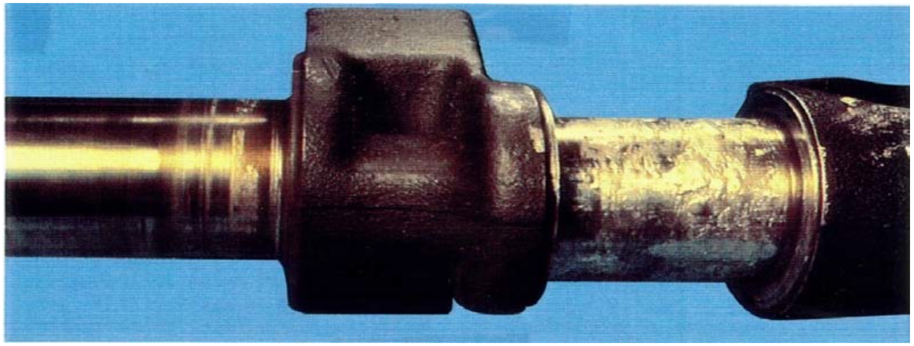
Diagnosing Compressor Failures

- Types of Mechanical Failures:
  1. Lubrication / Seizing
  2. Slugging
  3. Heat
  4. Contaminants

- Types of Electrical Failures:
  1. Single Phase
  2. Burn Spots
  3. Rotor Lock
  4. Overload
  5. PW Failure

CO2 Transcritical Compressor Troubleshooting

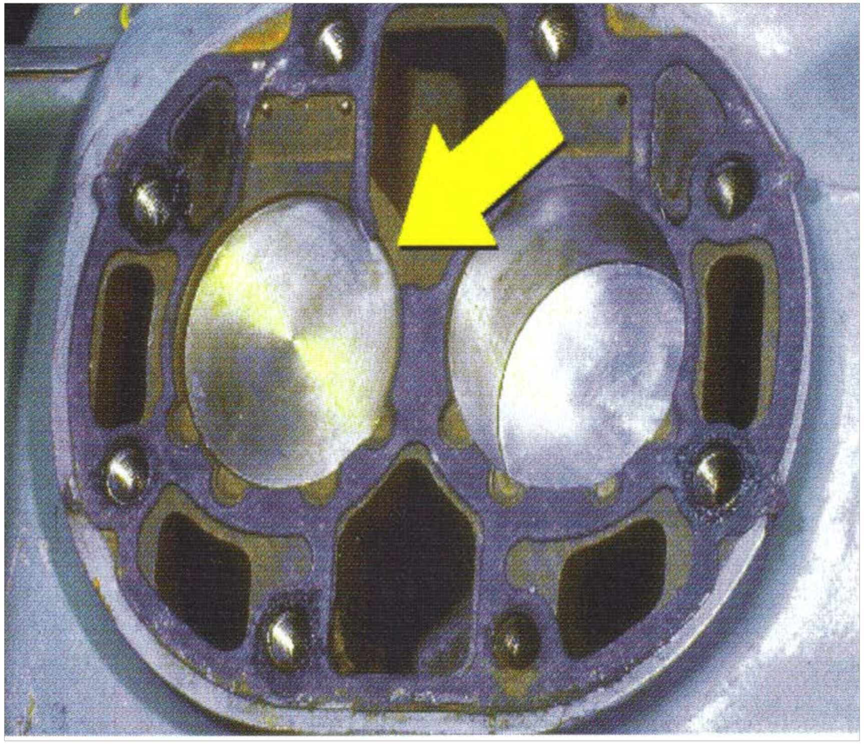
- Lubrication / Seizing – Lack of lubrication will lead to a compressor seizing or locking up. During a teardown this will show up as dry-surfaces accompanying damage from seized part.



Prevention by making sure compressor has correct oil charge (~2/3 of sight glass) and there is no issue with oil returning to compressor.

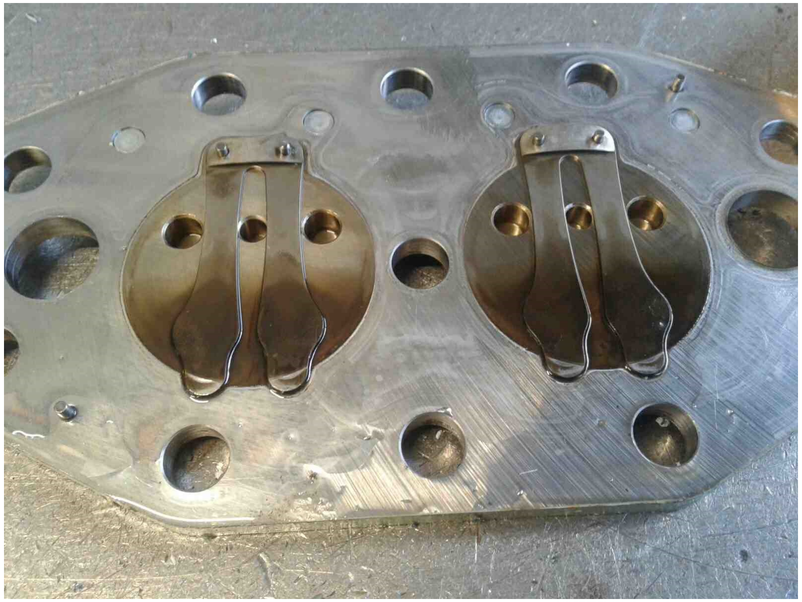
CO_2 Transcritical Compressor Troubleshooting

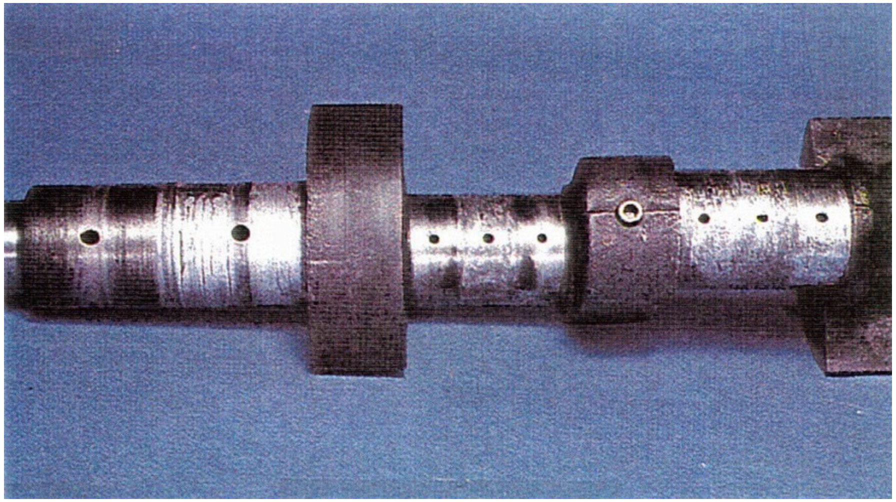
- Slugging – Typically top-end damage. Valves will be brittle and Cylinders/Valves will be dry.



CO2 Transcritical Compressor Troubleshooting

- Heat – Typically top-end damage. Discoloration will be present.



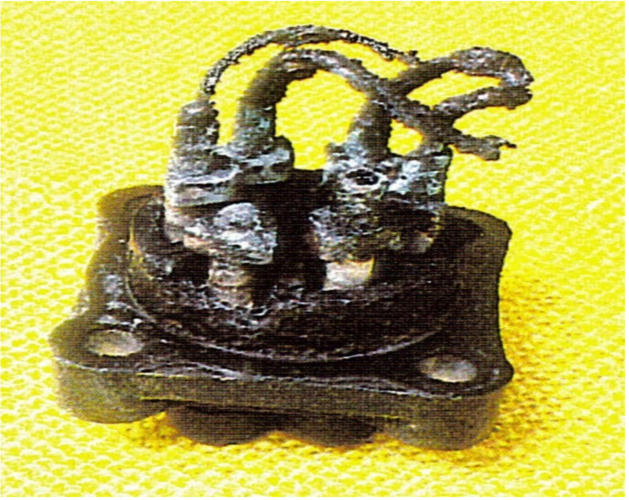


Caused by: Blow Gasket, Improper Head Gasket Install, Blown Discharge Valve, High Superheat, and Non-Condensables.

Prevention for technicians: Catch initial stages during check and install gaskets correctly.

CO2 Transcritical Compressor Troubleshooting

- Contaminants – Similar to heat symptoms but includes a sludge residue.



Caused by non-condensables (moisture, oxides, dirt, etc) that are introduced during improper oil change. Prevention would be to ensure clean oil and no contaminants are introduced during any repair work.

CO2 Transcritical Compressor Troubleshooting

- Electrical Failure – Confirmed by Motor Ohm Test

Motor Ohm Test – 5-40hp

Voltage	ohms	9 Lead		6 Lead		3 Lead
460	1.0 - 1.4	L1-4 ____	L7-8 ____	L1-2 ____	L7-8____	L1-2 _____
208	.3 -.5	L2-5 ____	L8-9 ____	L2-3 ____	L8-9____	L2-3 _____
208/230	.4 -.6	L3-6 ____	L9-7 ____	L3-1 ____	L9-7____	L3-1 _____
DV	.3 -.7					

Ground Check (OK) ____ Open Check (OK) ____

Overloads:

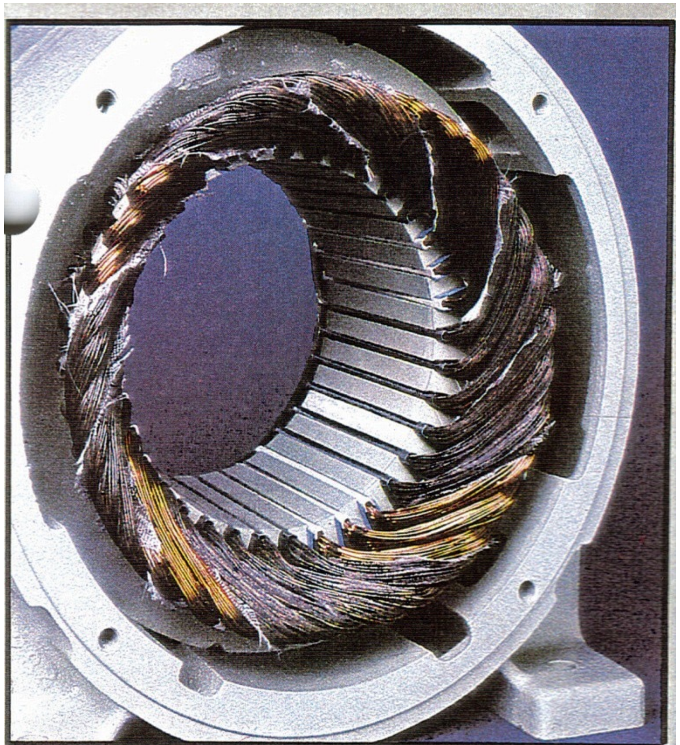
Klixon: 06L's, 06D's, Etranes (except small motor) / Just want continuity
Thermisters: M & R Tranes, JG/JS Yorks - ohm range below

Copelands & Yorks - Kriwan - 50-80 ohm range / TI's on older motors 1100-1400 ohm range
Tranes M & R's - Robert Shaw - 75 ohm range
York – Kriwan 50-80 ohm range

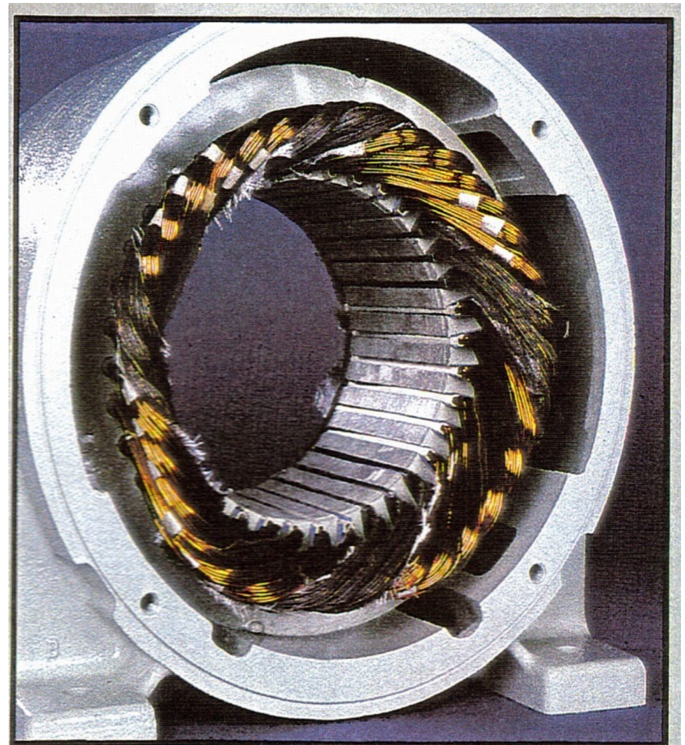
Common to: 1 ___ 2 ____ 3 _____ Ground Check (OK) ___ Open Check (OK) ___

CO2 Transcritical Compressor Troubleshooting

- Single Phase – Open in one phase power supply to motor



1 Winding Single-Phased (Y - Connected)

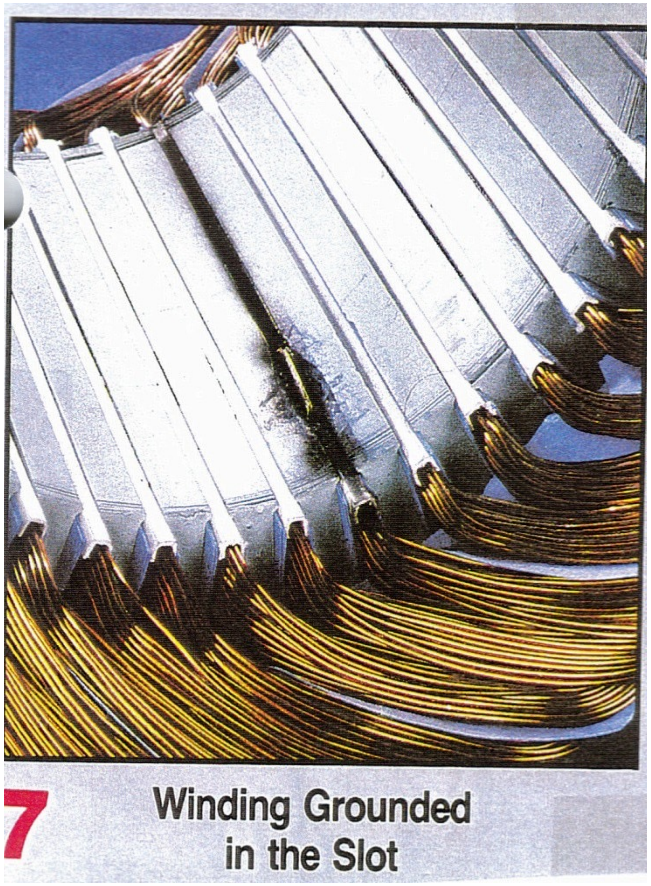


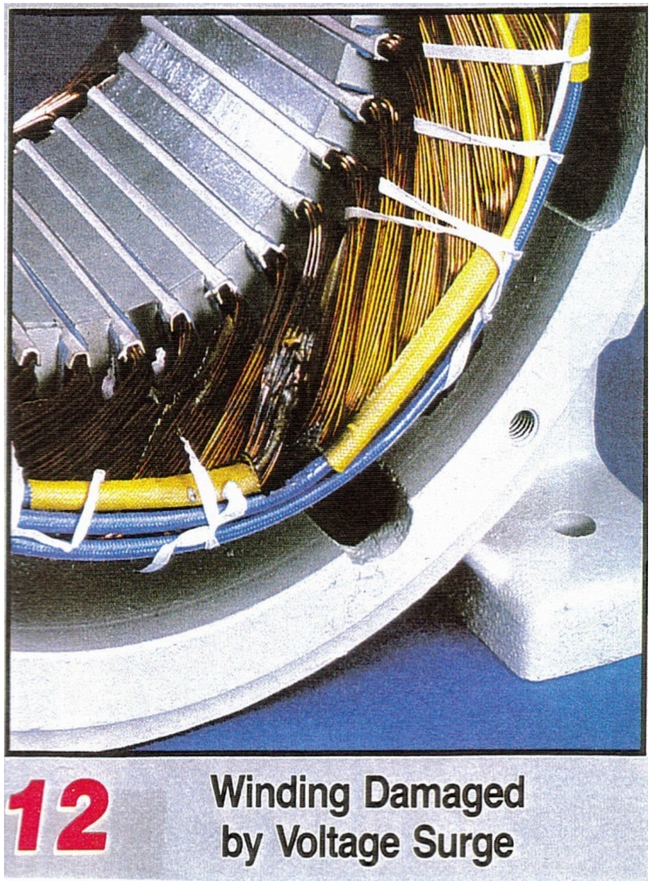
2 Winding Single-Phased (∆- Connected)

Caused by blown fuse, open contactor on P/W Start, time delay for contactors, or bad connections. At this point, the you can only diagnose issue to prevent on replacement.

CO2 Transcritical Compressor Troubleshooting

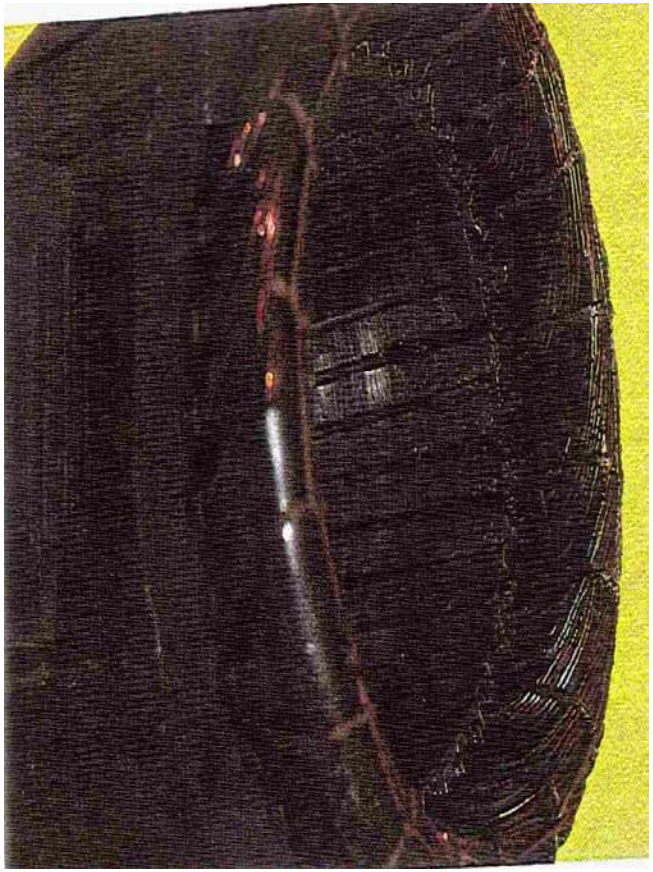
- Spot Burns – Developed due to chattering contactors or surge of power (lightning strike).





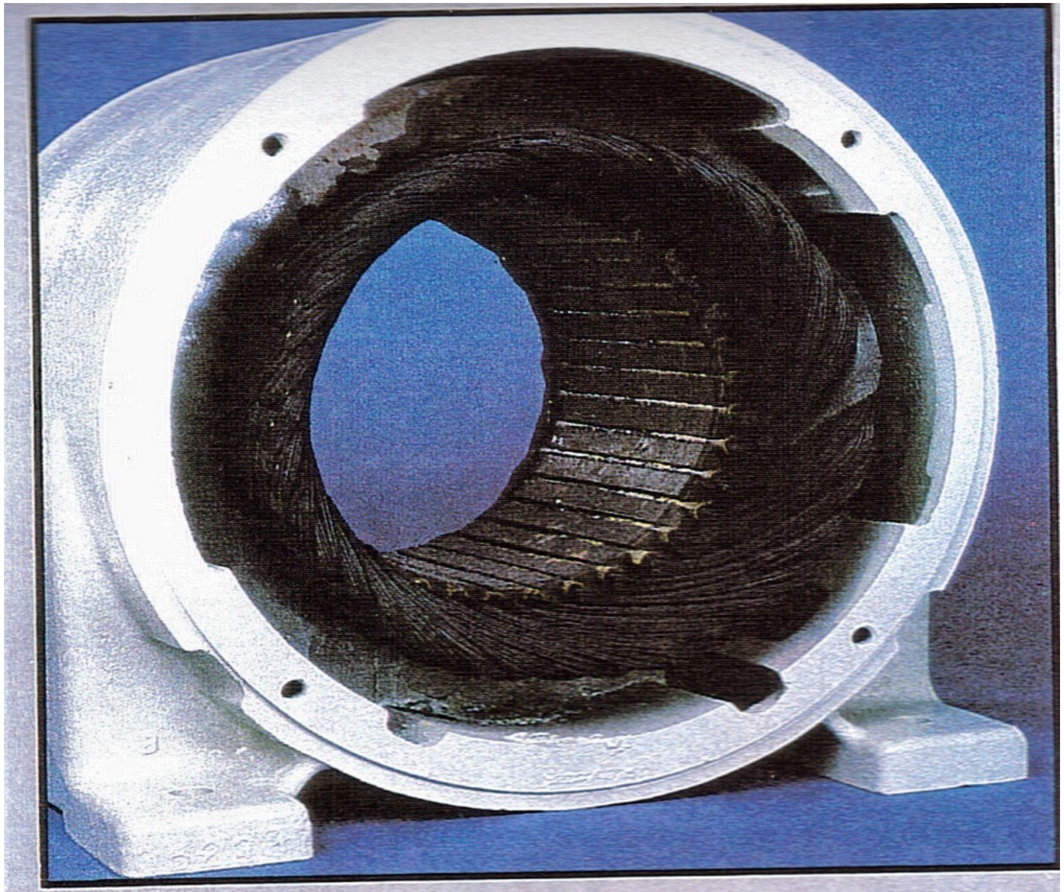
CO2 Transcritical Compressor Troubleshooting

- Rotor Lock – Rotor rubs on stator and a short occurs. Caused by main bearing wear (lack of lubrication/heat).



CO2 Transcritical Compressor Troubleshooting

- Overload – Thermal deterioration of the insulation in all phases of the stator, typically caused by load exceeding rating of motor.



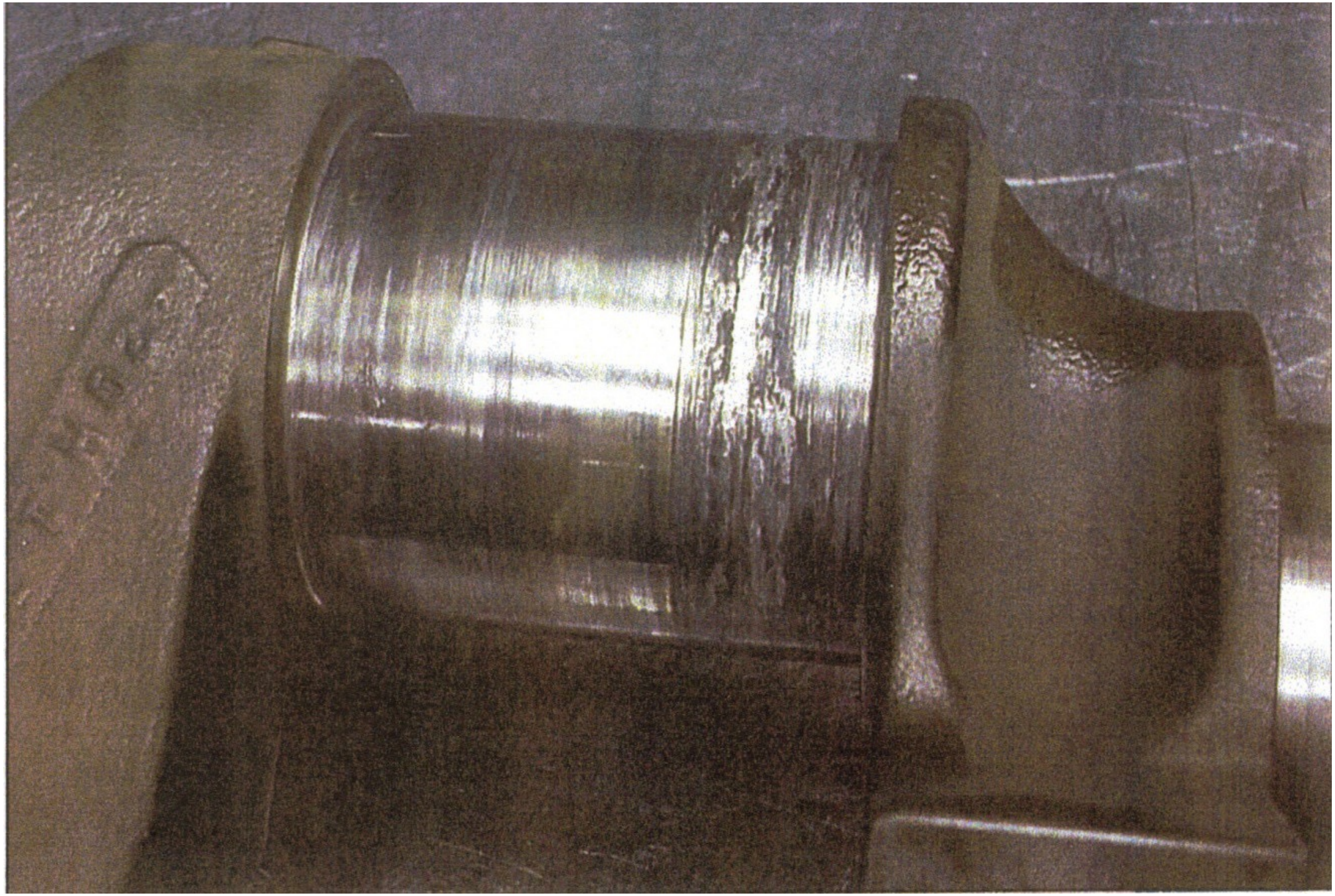
10 Winding Damaged Due to Overload

CO2 Transcritical Compressor Troubleshooting

- Part Wind Failure – Caused by time delay between contactors or faulty operation of contactor. Prevented by dry-run of compressor.

CO2 Transcritical Compressor Troubleshooting

- What caused this?



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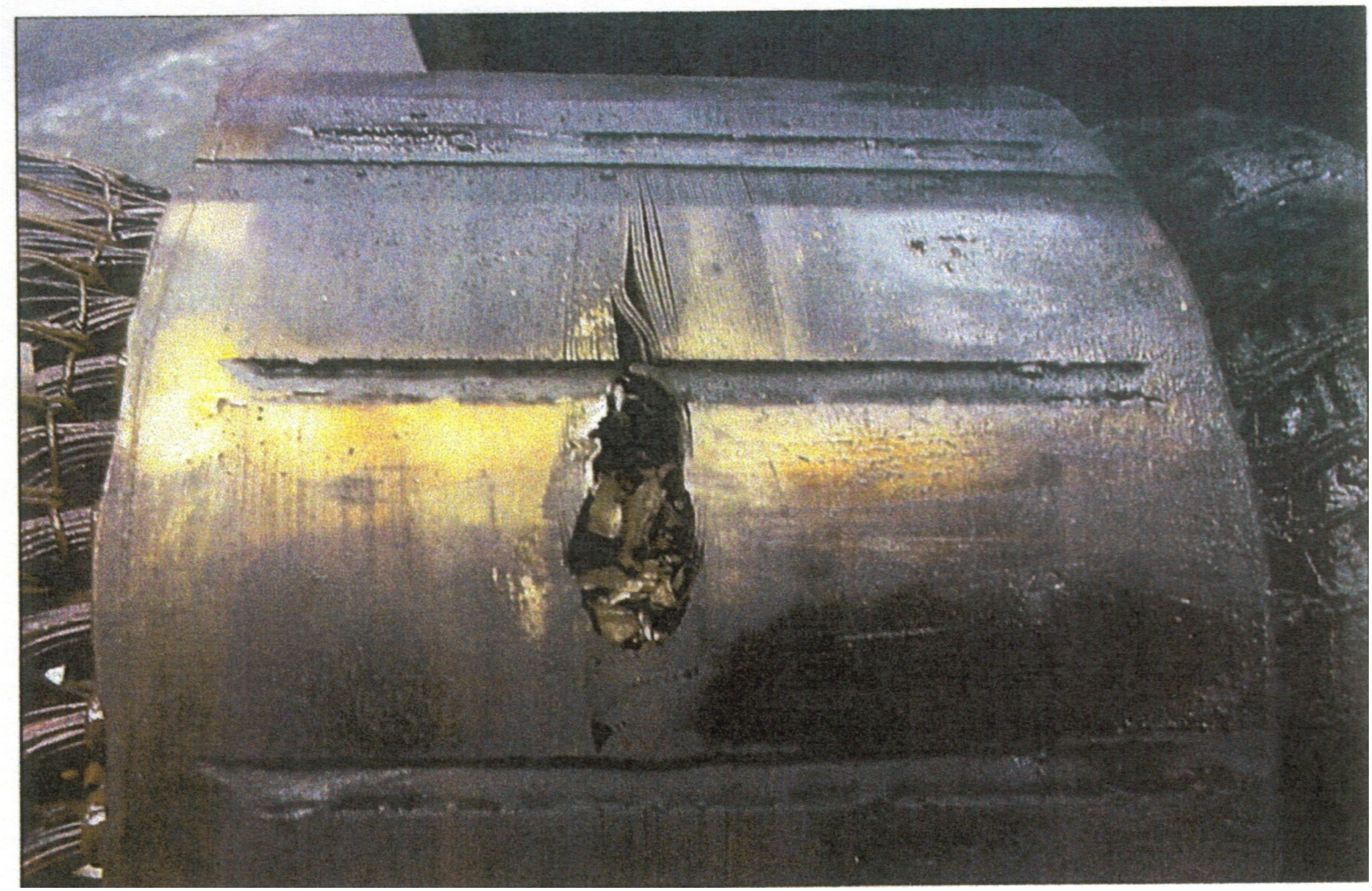

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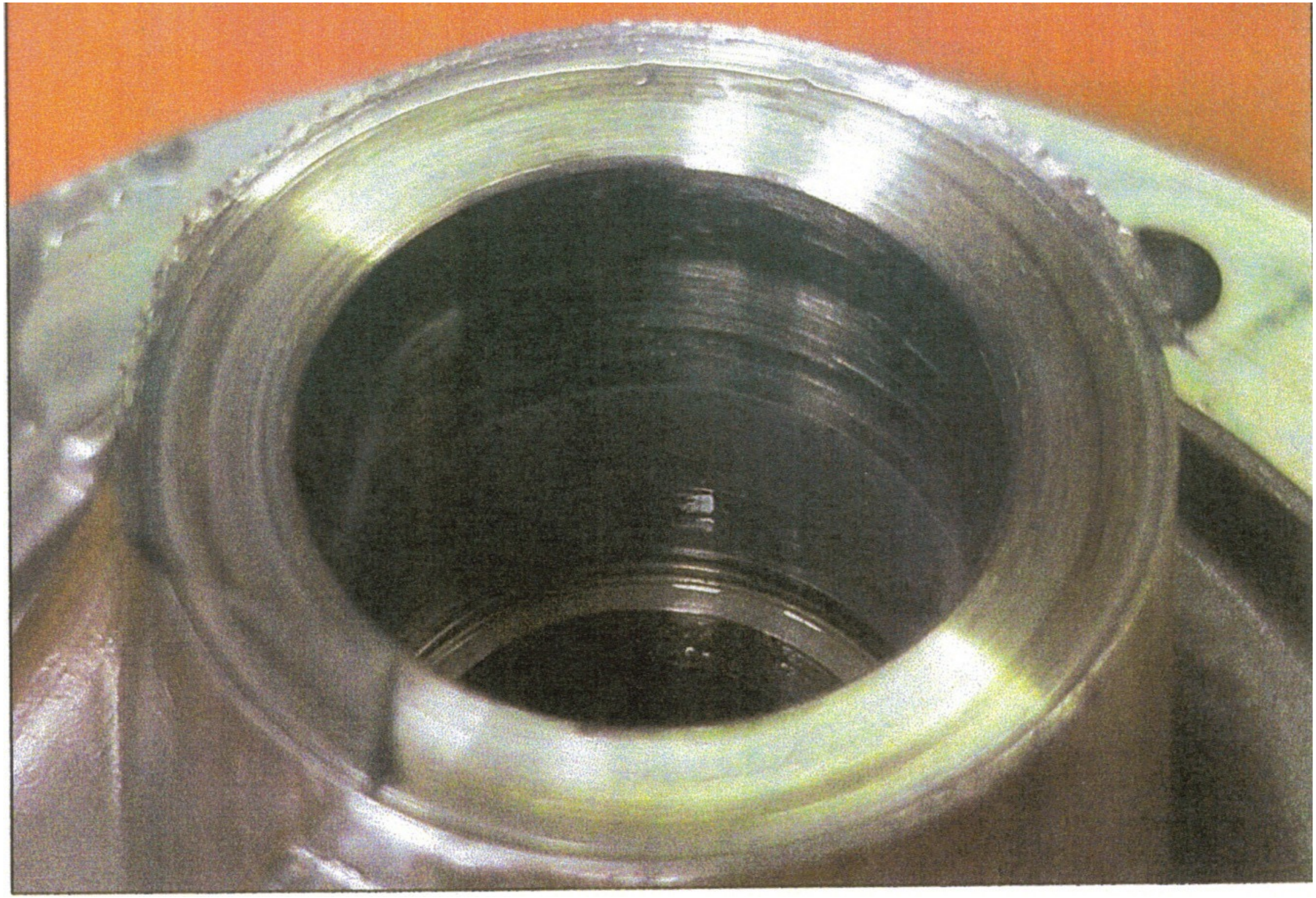

Teardown of CO2 Compressor

We have brought a CO2 Compressor and will have a hands-on teardown.

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