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

Natural Refrigerant Training Summit

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Who We Are

A 501c3 nonprofit working to create a sustainable future for supermarket refrigeration by removing barriers to natural refrigerant adoption.

160+
member companies

55K+
food retail locations

Goals

- Build a sustainable technician workforce
- Increase funding for natural refrigerant equipment
- Improve technology options, education, and awareness

What are Natural Refrigerants?

CO_2	C_3H_8	NH_3
R744 Carbon Dioxide	**R290** Propane	**R717** Ammonia

NORTH AMERICAN
Sustainable Refrigeration Council

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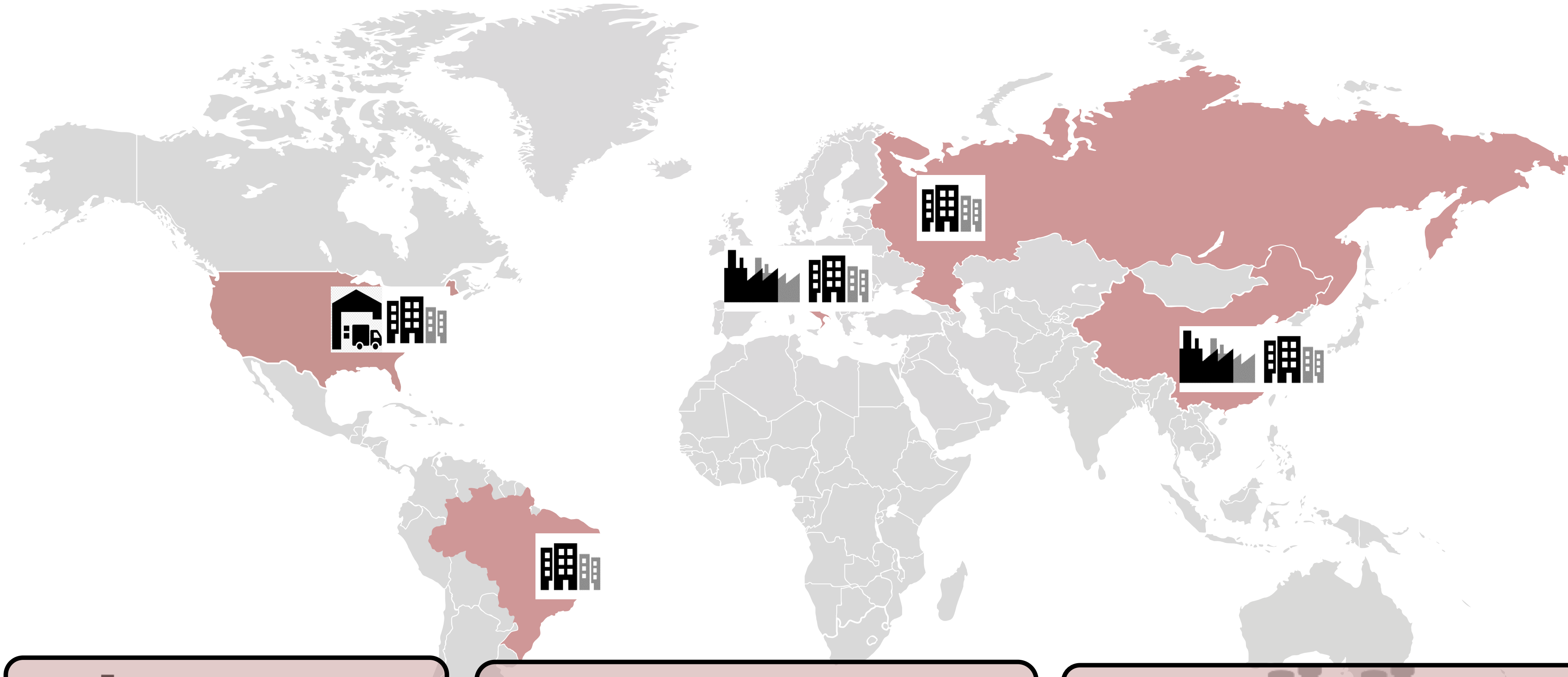
DORIN®

INNOVATION

INTRODUCTION



HQ in FLORENCE
ITALY

200 EMPLOYEES
4 PRODUCTION SITES
5 SALES OFFICES

75.000+ COMPRESSORS
(2022)

Introduction to CO_2

- Carbon Dioxide (R744 – CO_2)
- Environmentally benign properties (GWP = 1)
- Excellent heat transfer properties
- High COP levels
- Severe challenges from a compressor perspective

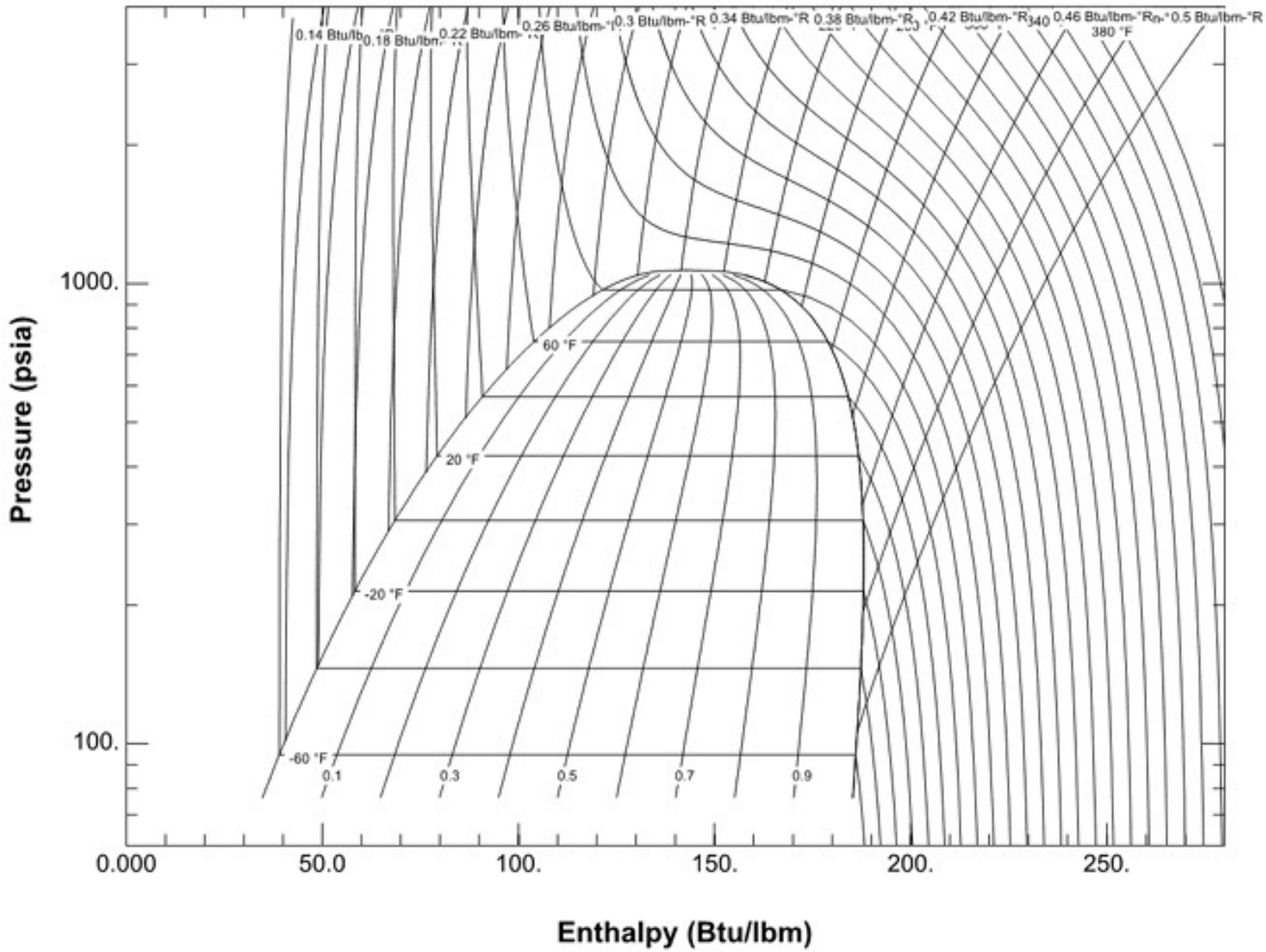
- Important Conditions to remember:
  - Critical Point = 1070psia / 87.8F
  - Triple Point = 75psia / -69.8F
  - Low Temp Evap Operation = ~180psig / -25F
  - Med Temp Evap Operation = ~400psig / +20F
  - Condensing = 1031.5psig / 86F

- Design and Test criteria for a 4412 cfh – 160hp CO_2 transcritical compressor analyzed over the course of this training.

Introduction to CO_2 – Safety

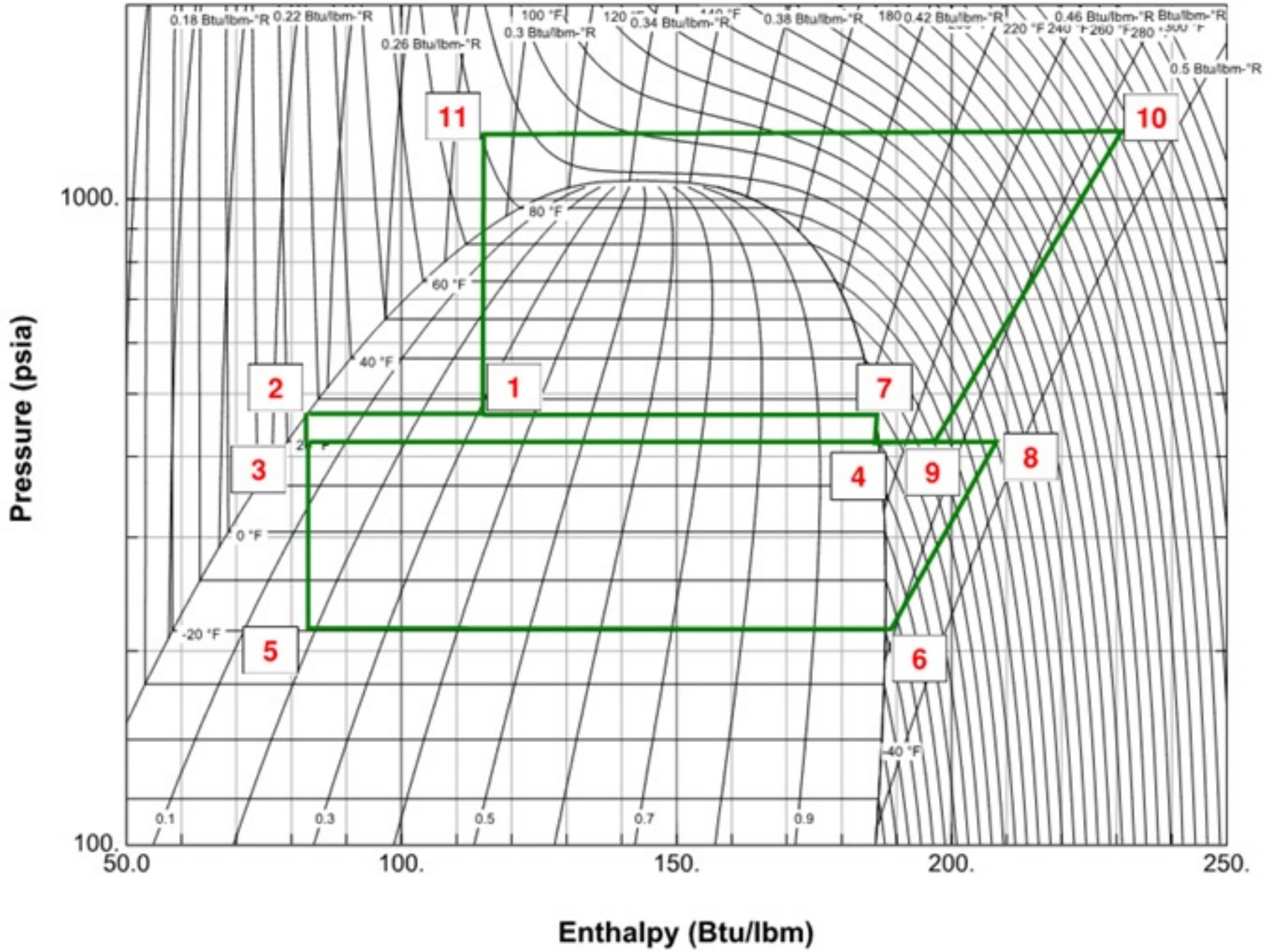
- 1% (1000 PPM) – Breathing rate increases.
- 2% (2000 PPM) – Breating rate increases and can lead to headaches/fatigue.
- 3% (3000 PPM) – Breathing rate increases and becomes labored. Slight narcotic effect. Impaired senses. Increased blood pressure and pulse rate.
- 4~5% (4000~5000 PPM) – Breathing rate increases further and symptoms of ‘intoxication’ are evident.
- 5~10% (5000~10000 PPM) – Odor noticeable. Labored breathing. Impaired senses with ringing in ears. Loss of consciousness within minutes.
- 10~100% (>10000 PPM) – Unconcisous. Prolonged exposure leads to death by asphyxiation.
- *Note – CO_2 is heavier than air, so leak detection should be placed low.*

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

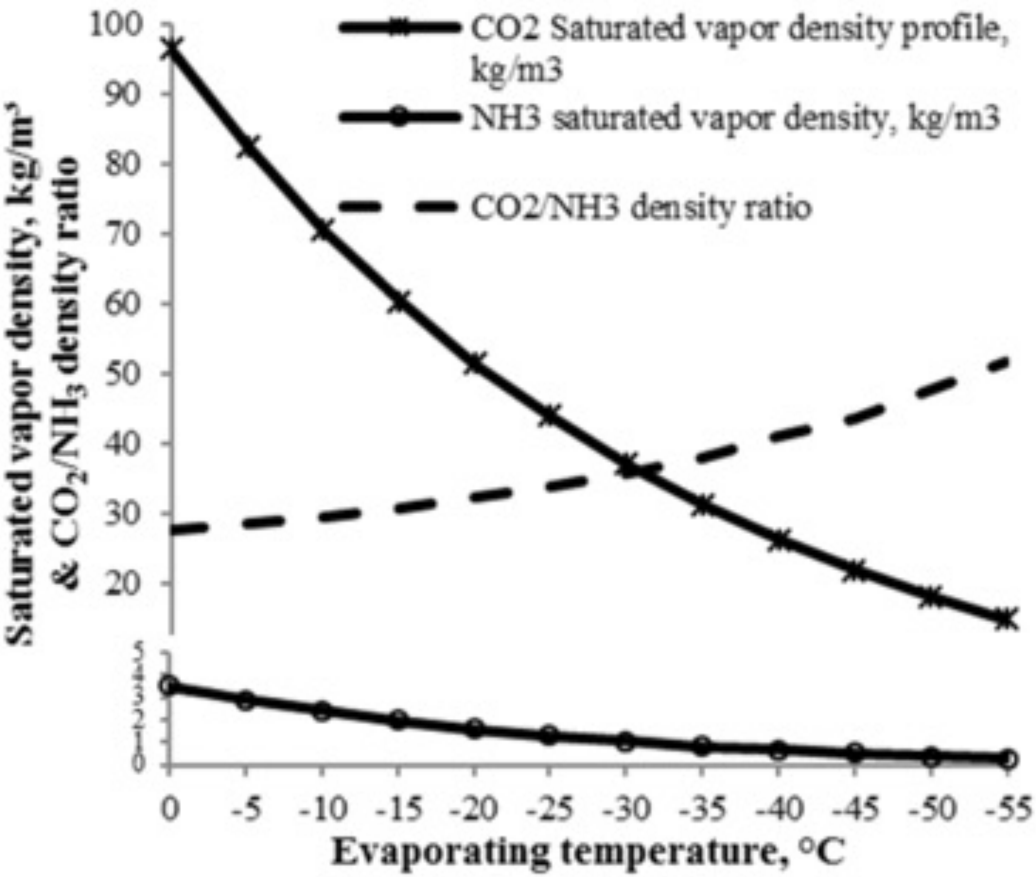
- CO2 has a pressure differential up to 6.5x higher than other refrigerants

- Reciprocating technology best deals with this high pressure differential

- There still remains severe challenges for drive gear design

Challenges

- Volumetric Refrigeration Capacity

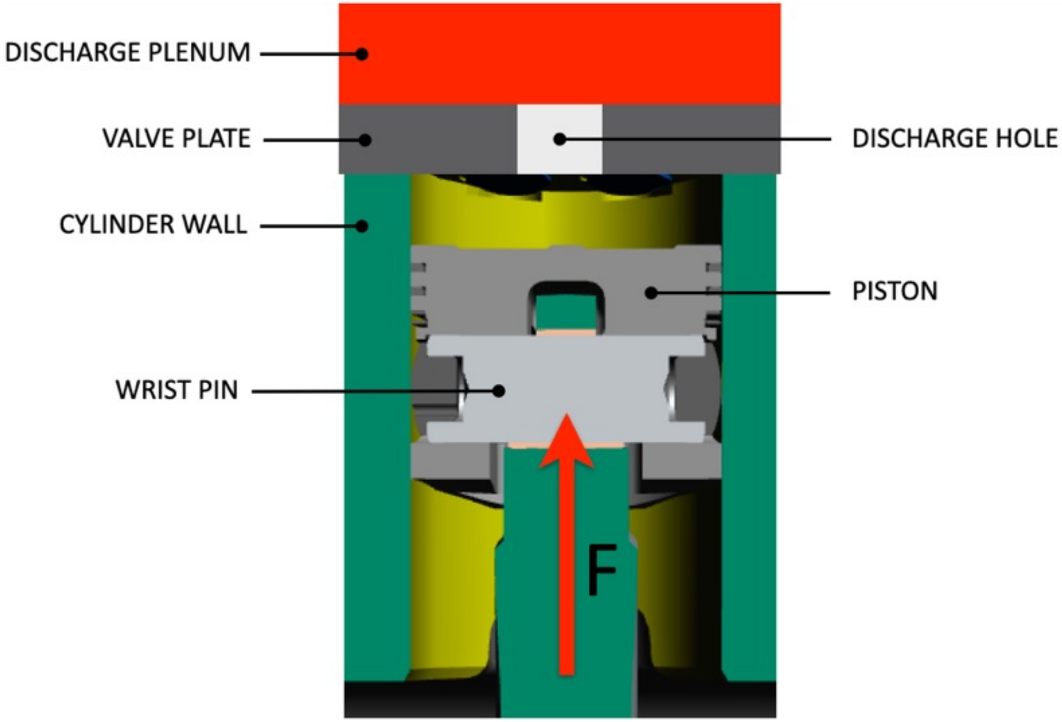


- CO_2 has a very high volumetric refrigeration capacity
- Similar capacity using smaller displacements
- Much smaller pipe diameters
- Much smaller compressor bores

- 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 = Δp * 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
PSI	1566	1075	1465	1552	4975

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

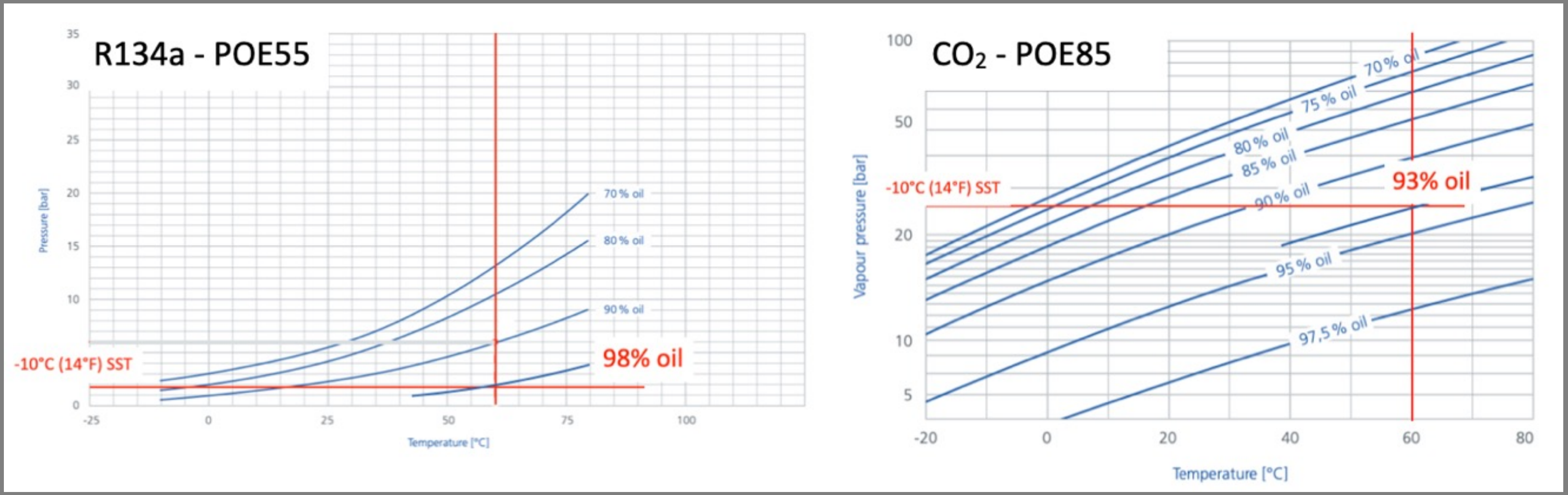
Table 4. Real discharge temperatures for various MT refrigerants systems

CO2 leads to significantly higher discharge temperatures – challenges:

- Heat Dissipation
- Lubrication

Challenges

- CO2 Solubility in Lubricants

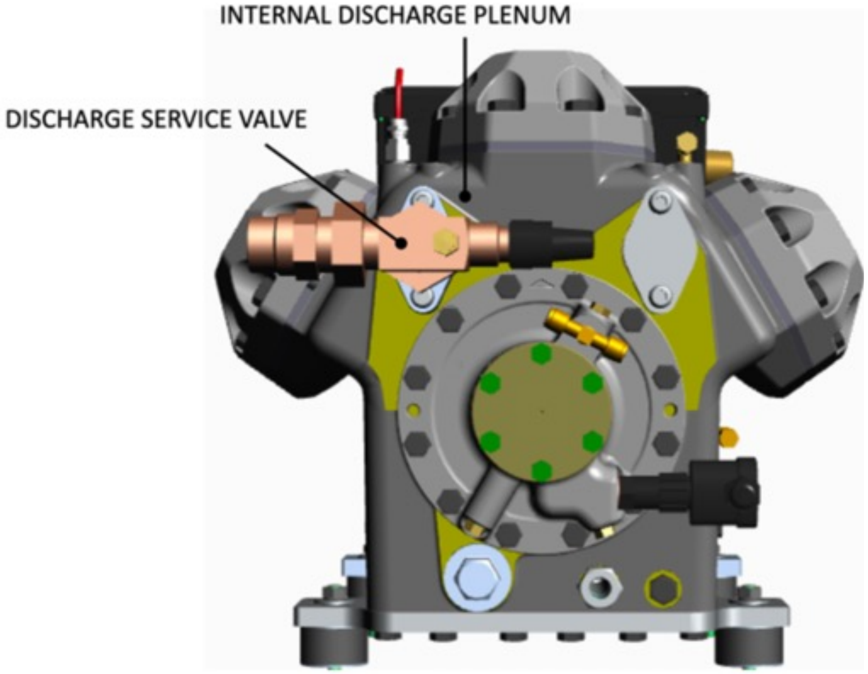


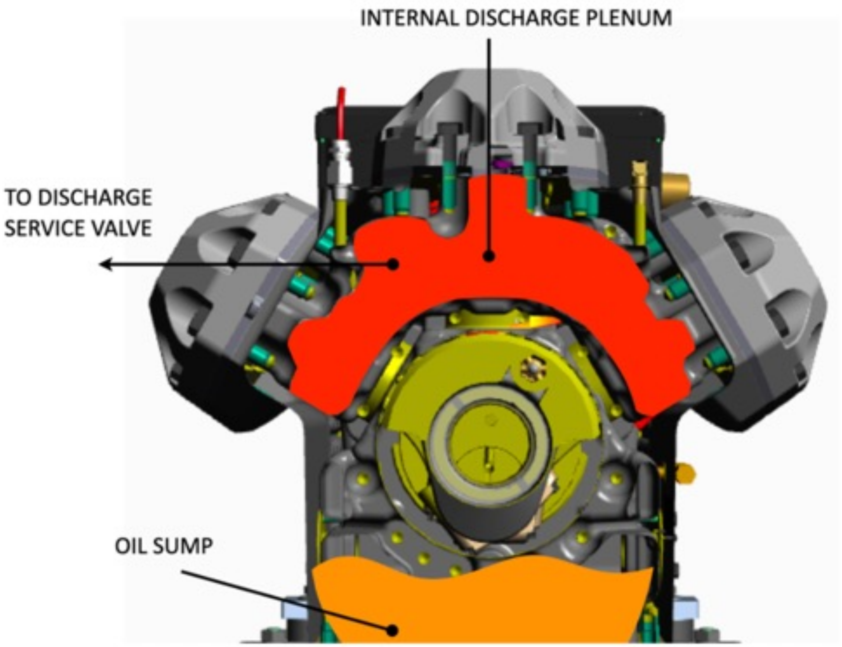
CO2 is more soluble into lubricants – challenges:

- 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

- DESIGN B

Figure 7. Design B - compressor with external discharge plenum

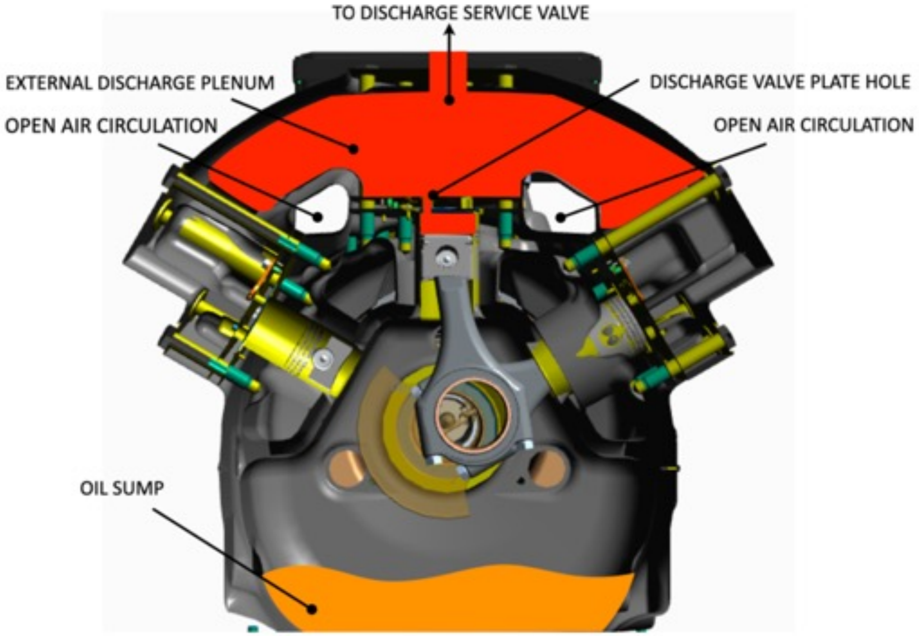


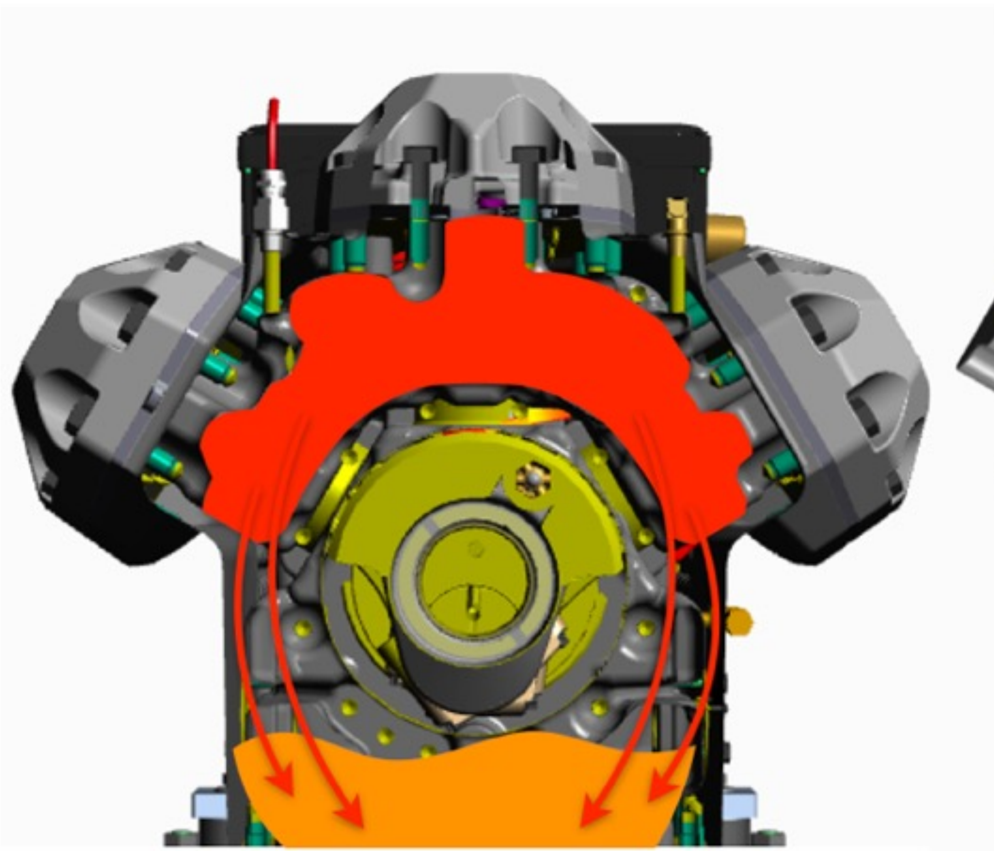
Figure 8. Interior view of a Design B - compressor with external discharge plenum

External Discharge Plenum:

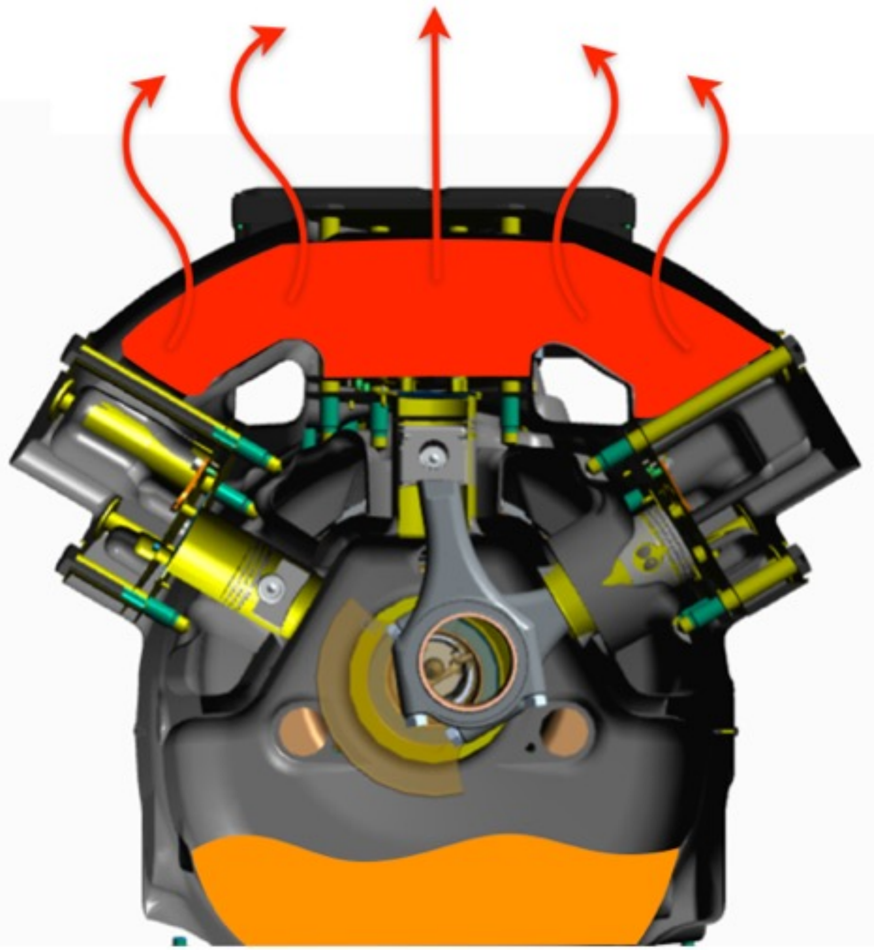
- Open air circulation allows thermal insulation between HP and LP sides
- Lower heat dissipation towards the oil sump

CO2 Transcritical Compressor Design

- DESIGN A vs DESIGN B



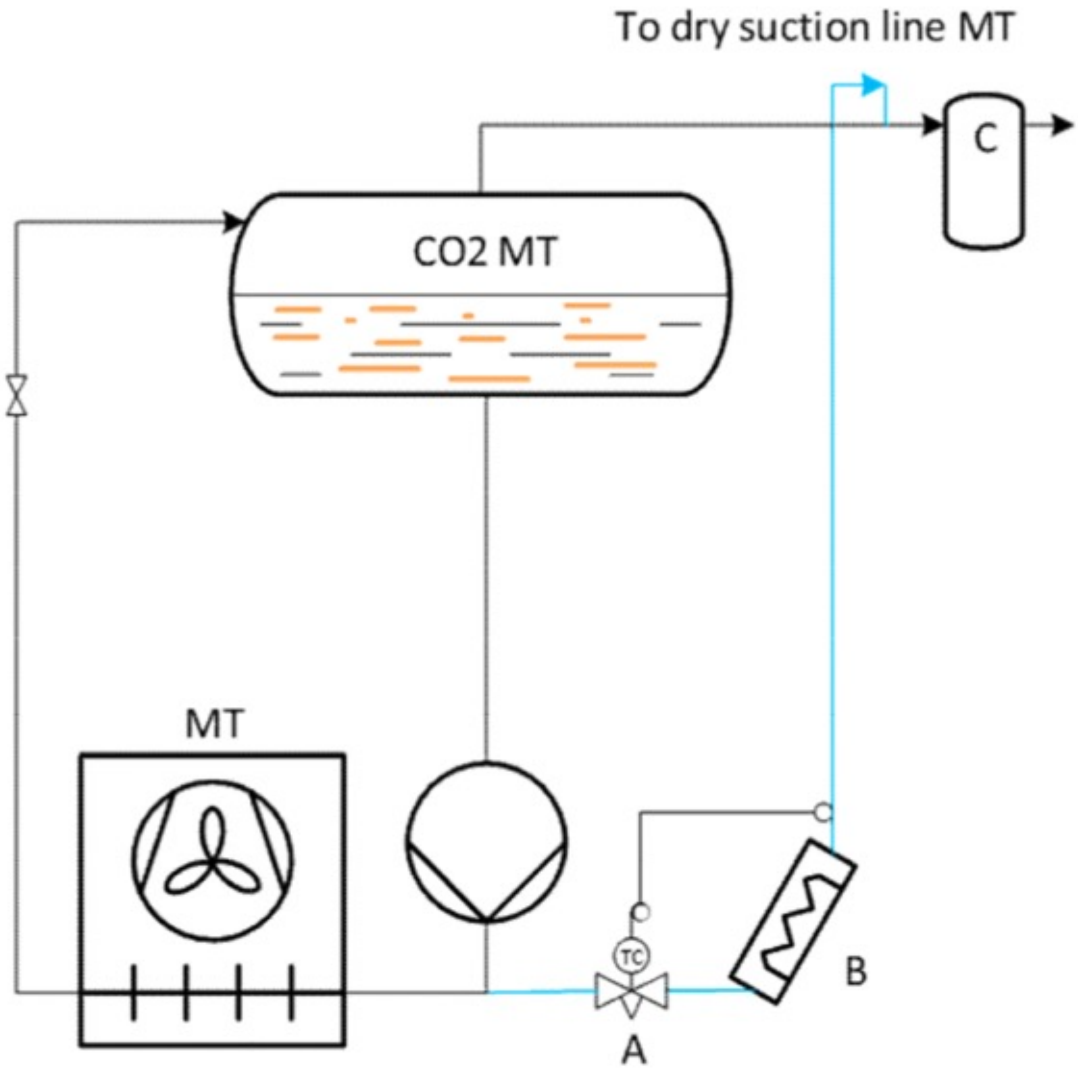
DESIGN A:
COMPRESSION HEAT DISSIPATION TO OIL SUMP



DESIGN B:
COMPRESSION HEAT DISSIPATION TO SURROUNDING AMBIENT

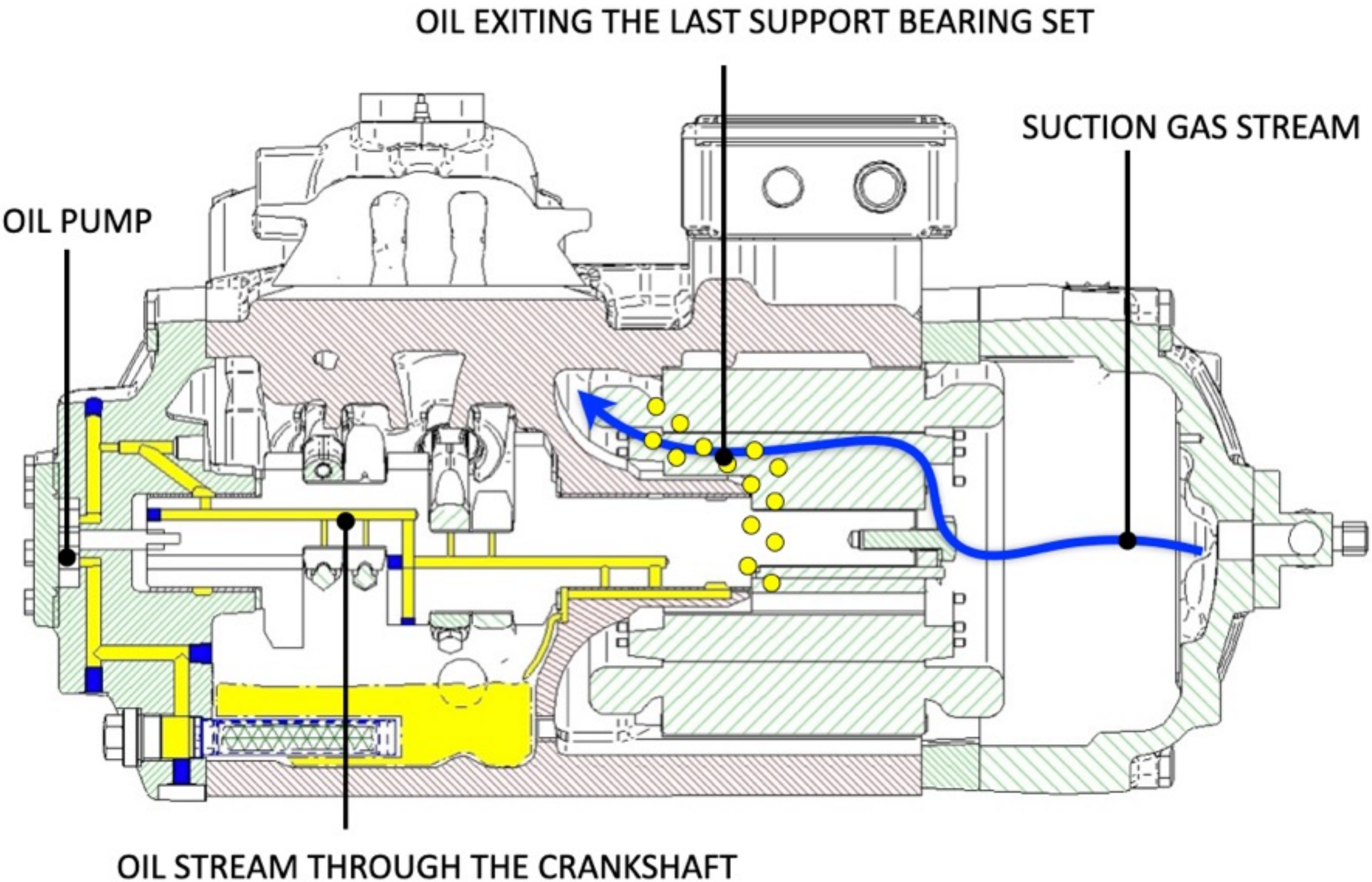
CO2 Transcritical Compressor Design

- Compressor Oil Circulation Rate (OCR)



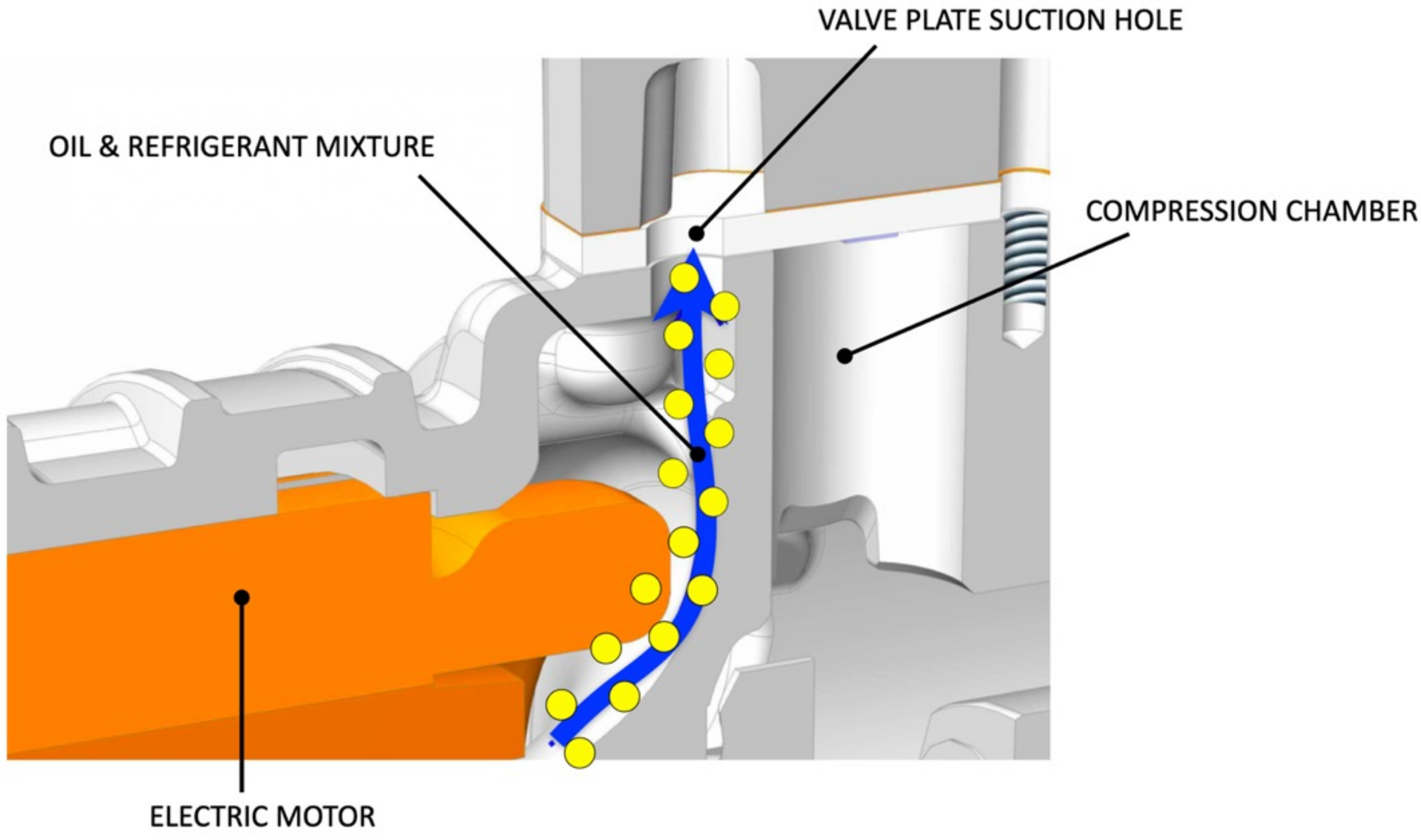
- Rectifier is triggered by low oil level into the reservoir.
- Pump energy is “wasted” to feed the rectifier.
- Liquid portion is bypassing the evaporator.

CO2 Transcritical Compressor Design



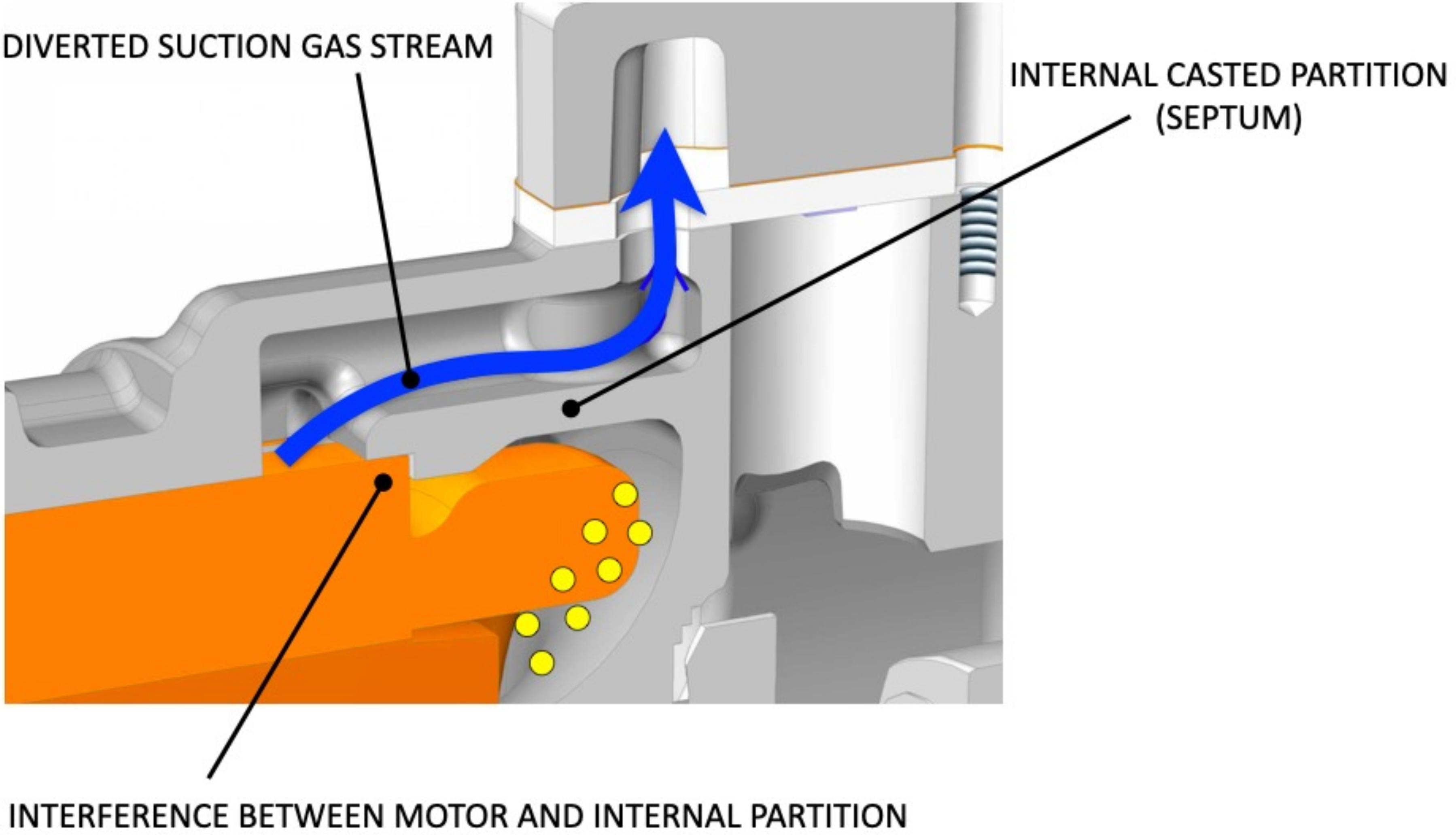
CO2 Transcritical Compressor Design

- DESIGN C



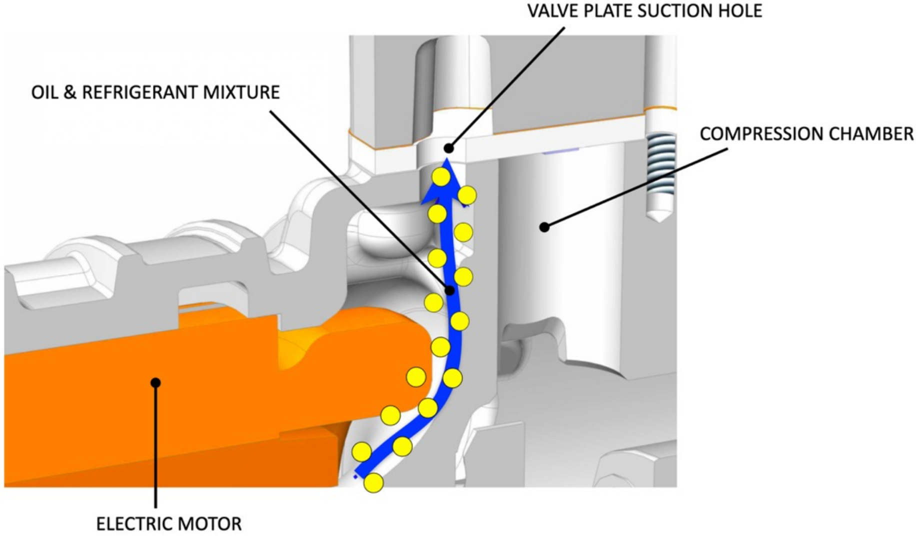
CO2 Transcritical Compressor Design

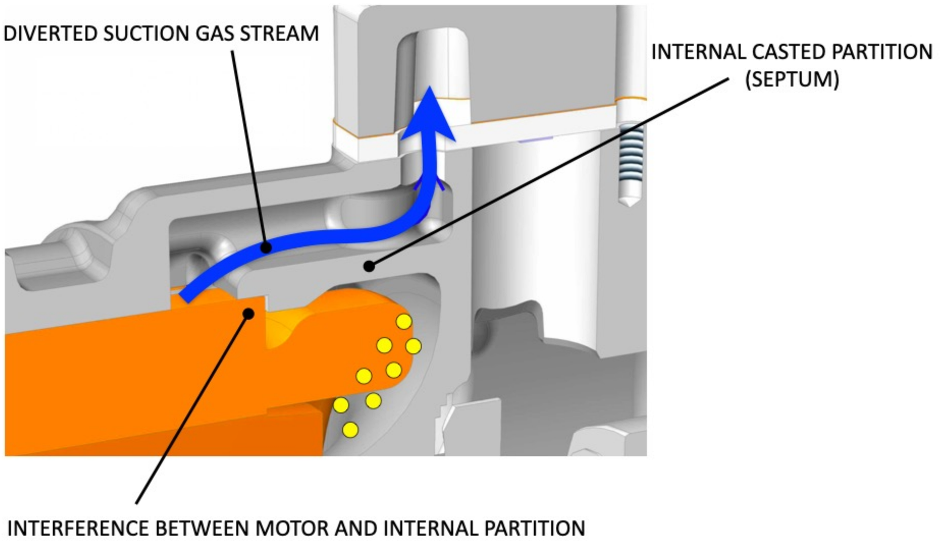
- DESIGN D



CO2 Transcritical Compressor Design

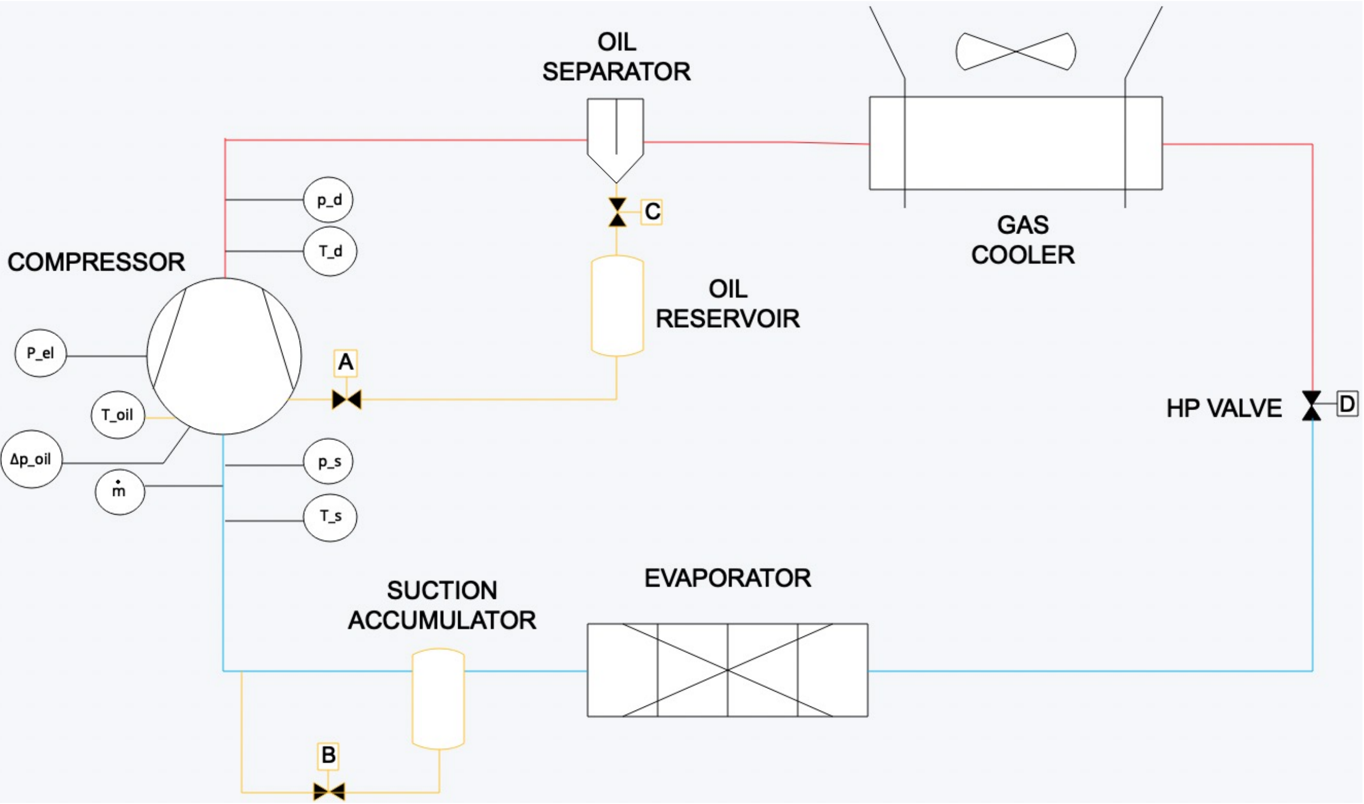
- DESIGN C vs DESIGN D





CO2 Transcritical Compressor Lab Testing

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

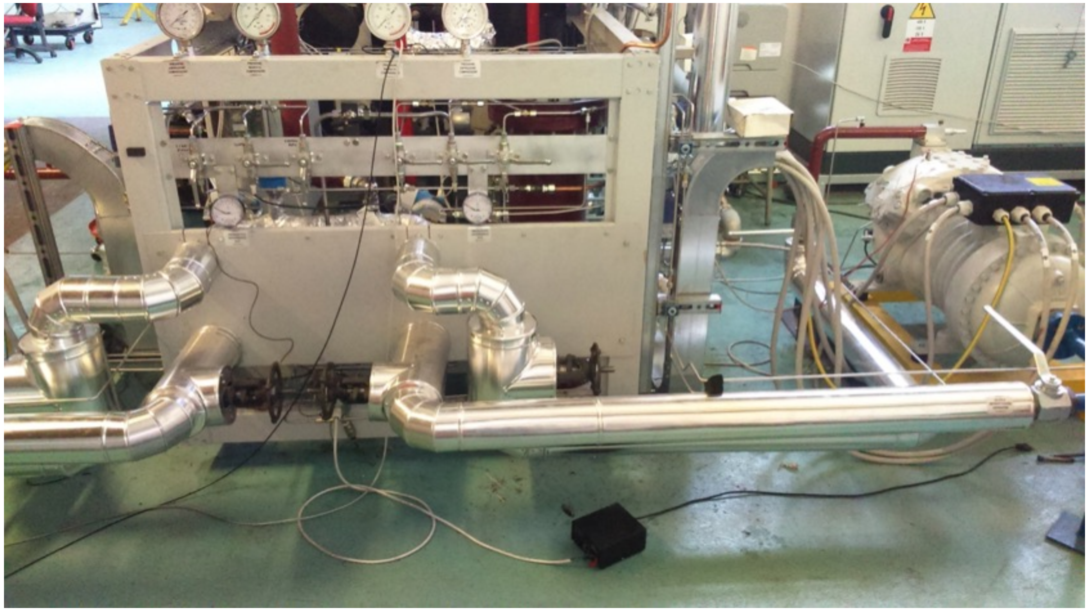


p_s: Suction Pressure
T_s: Suction Temp.
m: Refrigerant Mass Flow
Δp_oil: Oil Diff. Pressure
T_oil: Oil Temp.
P_el: Power Consumption
p_d: Discharge Pressure
T_d: Discharge Temp.

*Valve A: allows compressor oil sump feed from oil reservoir
*Valve B: allows oil return from suction accumulator
*Valve C: allows oil return from oil separator to oil reservoir
*Valve D: controls pressure and temperature in gas cooler

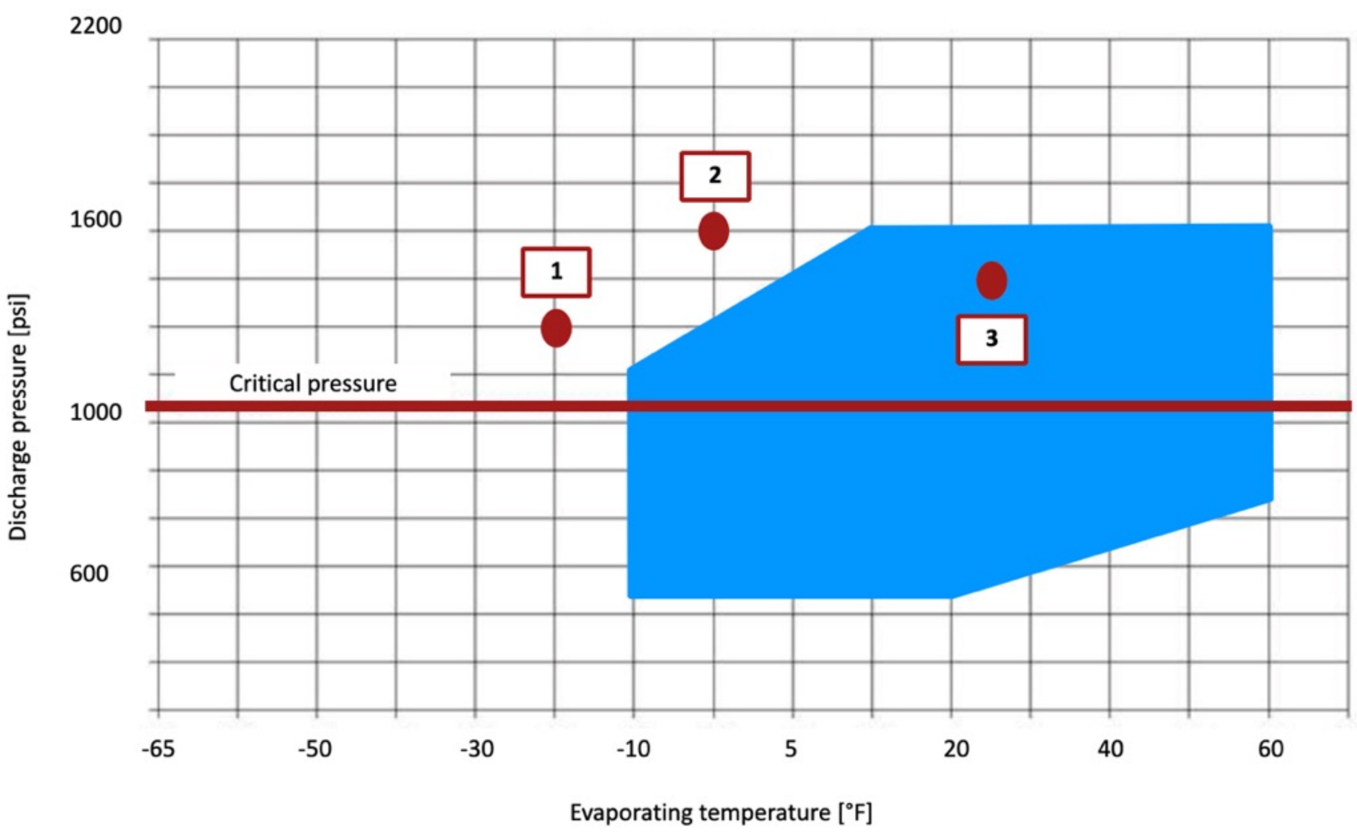
CO2 Transcritical Compressor Lab Testing

Gas Cooler



Compressor and Sensors Assembly

CO2 Transcritical Compressor Lab Testing



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

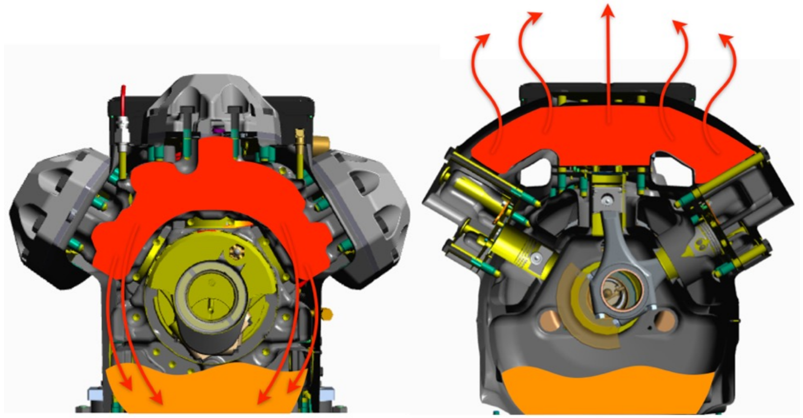
#2: Max Pressure Diff. –
285psi suction
1500psi discharge
Challenge = Max Load

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

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

CO2 Transcritical Compressor Lab Testing

- DESIGN A vs B: Performance & Reliability:



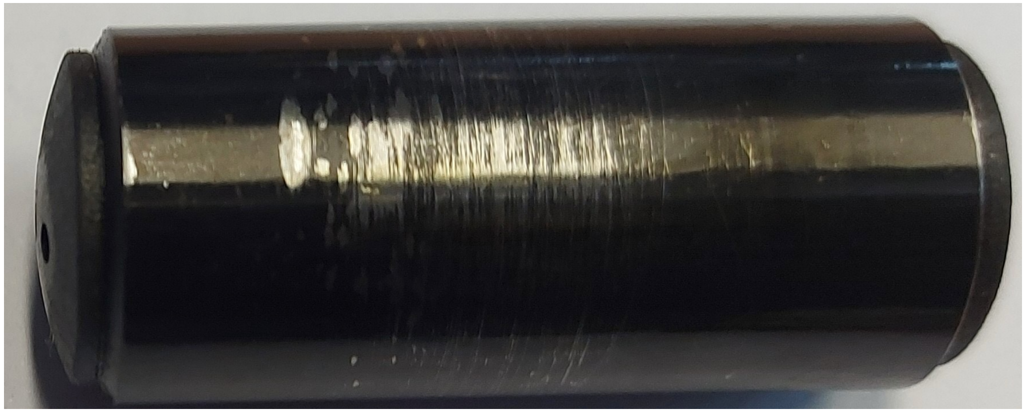
DESIGN A:
COMPRESSION HEAT DISSIPATION TO OIL SUMP

DESIGN B:
COMPRESSION HEAT DISSIPATION TO SURROUNDING AMBIENT

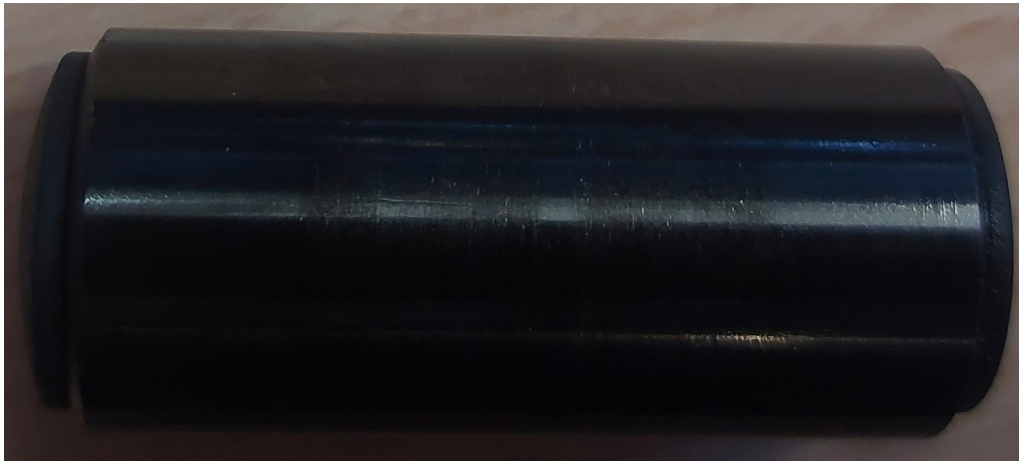
TRANSCRITICAL COMPRESSORS TESTS: DISPLACEMENT 4412 cfh @ 60Hz							
reliability and performance test		Design A			Design B		
p_s (suction pressure)	[psi]	200	285	435	200	285	435
p_d (discharge pressure)	[psi]	1200	1500	1300	1200	1500	1300
T_s (suction temperature)	[°F]	-4	14	40	-4	14	40
T_oil (oil temperaturee)	[°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.

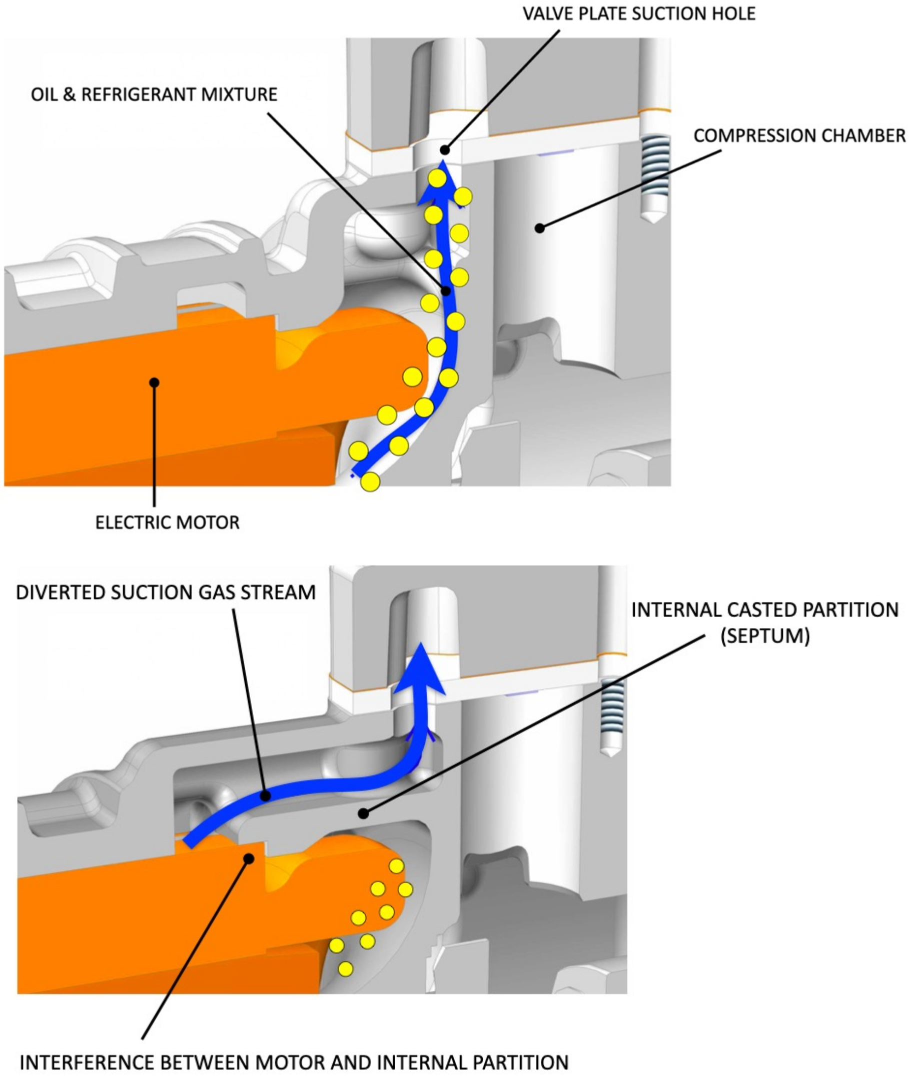
CO2 Transcritical Compressor Lab Testing

- DESIGN C vs D: Oil Circulation Rate

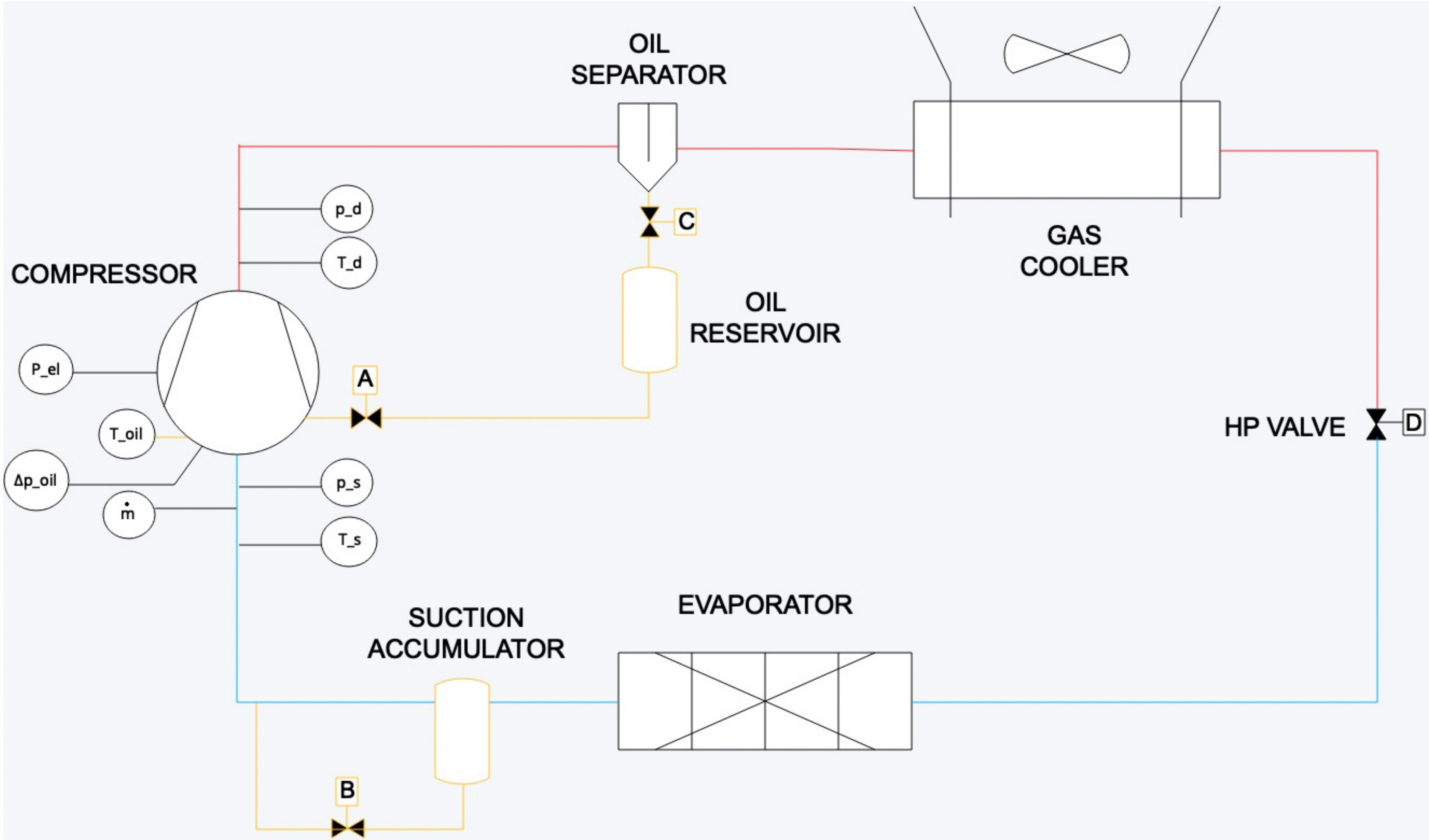
Test performed at typical MT conditions: 435psi suction / 1300psi discharge

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

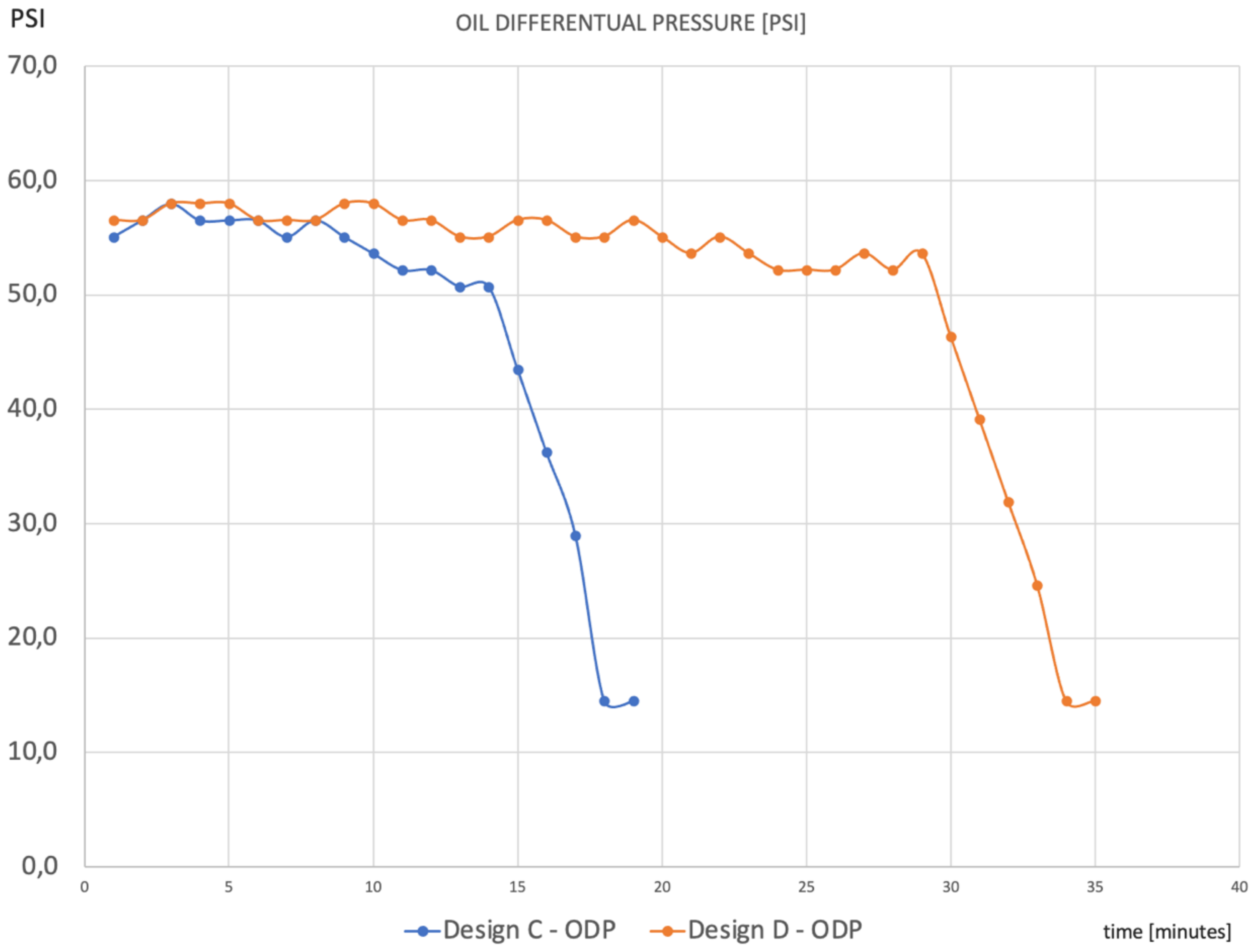
Oil differential pressure switch trigger time was measured and compared for both design C & D.



CO2 Transcritical Compressor Lab Testing



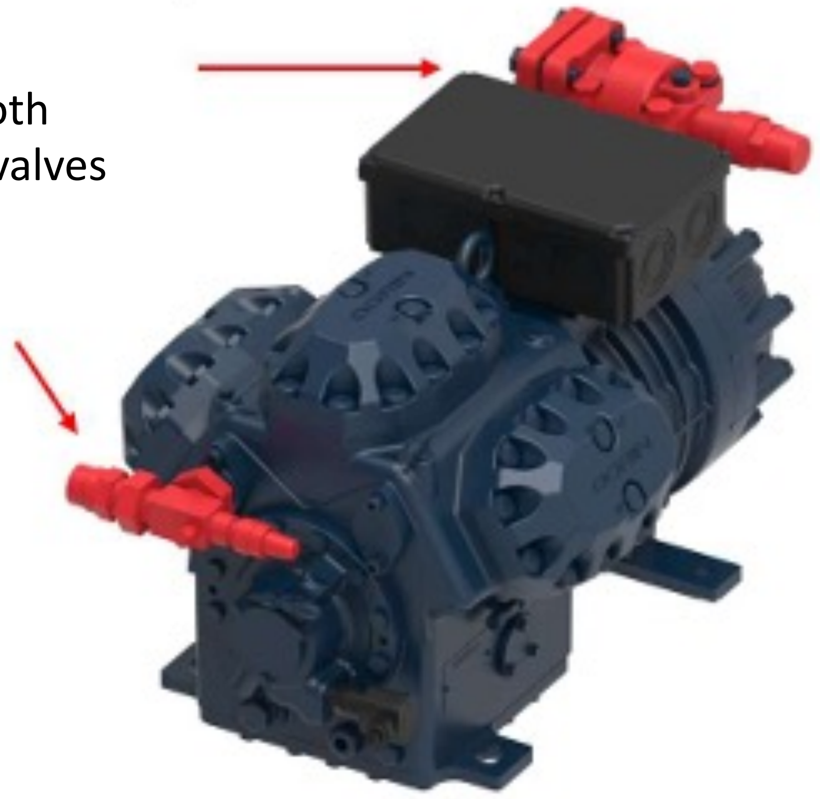
CO2 Transcritical Compressor Lab Testing



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

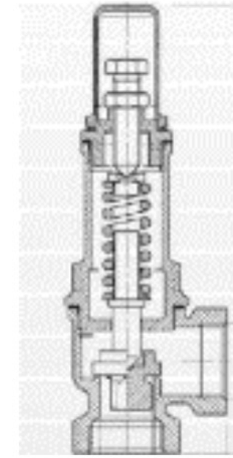
- Safety Devices (varies by size of compressor):

Motor Protection

Oil Pump

Crankcase Heater

LP / HP Relief Valve



Electronic Protection Module

Max Discharge Temp. Sensor

Oil Differential Pressure Switch

MOTOR PROTECTION (REL)

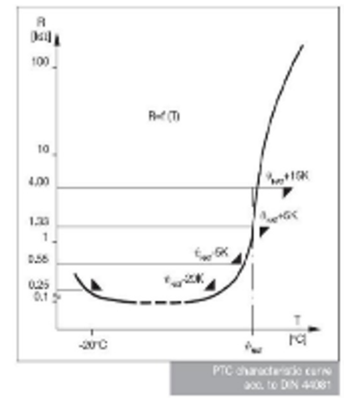
INT69 / INT69TM / INT69TML

Thermistor Module is standard equipment for all 4, 6 and 8 cylinders compressors.

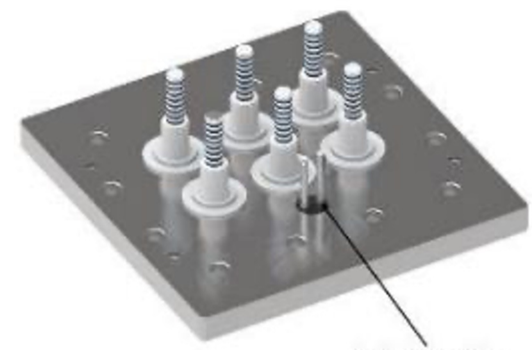
In these compressors PTC thermistors are embedded in each winding (3 for STAR/DELTA motors, 6 for PWS motors) and connected in series and end with two faston on the connection plate.

If motor winding temperature rises over limit, resistance at thermistor pins increases over the threshold and the electronic module switch the contactor giving the alarm sign.

H6÷H7 ranges are equipped with INT69TM which does not allow to start before 5 minutes after the alarm sign.



Technical Bulletin (BT007)



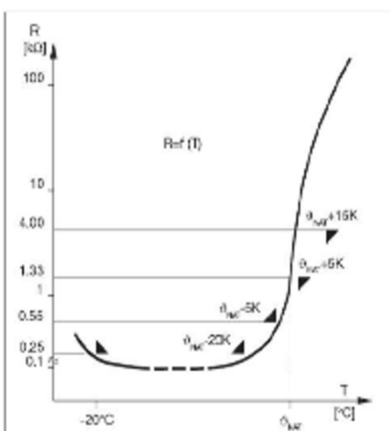
MAX DISCHARGE TEMPERATURE SENSOR (TMAX)

A PTC sensor monitoring the discharge temperature is a standard equipment for all 4, 6 and 8 cylinders compressors and for ATEX compressors.

The thermistor is connected in series with the PTC chain embedded in the motor and its resistance is read by the electronic module.

If discharge temperature rises over the limit, resistance increases over the threshold and the electronic module switch the contactor giving the alarm sign.

Technical Bulletin (BT007)



PTC characteristic curve acc. to DIN 44081

OPTICAL OIL LEVEL SENSOR (ALL)

To have a proper lubrication of moving parts is key for correct and safe operation of the compressor.

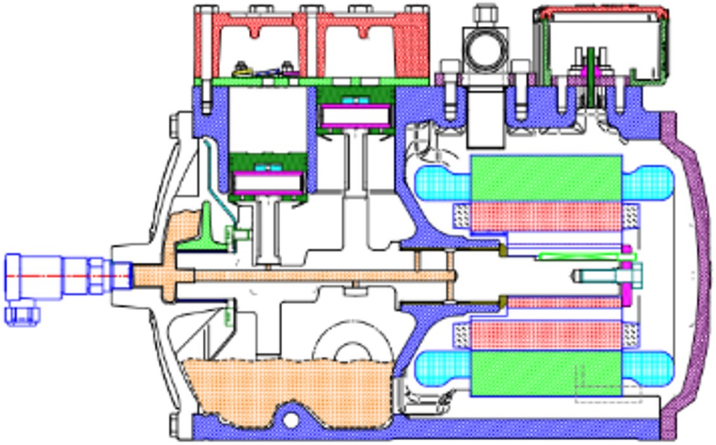
All 4 cylinder compressors without oil pump are lubricated by means of a splashing disc that collect the lubricant in the oil sump and splash it all around filling, in the same time, the oil pocket in the cylinder's flange.

From the oil pocket lubricant flows through the crankshaft and lubricates connecting rods and bearings by centrifugal force.

To monitor the presence of oil for shaft lubrication DORIN offers as accessory an optical oil level sensor based on an infrared LED and a light receiver. Infrared reflection/refraction depends on the oil level in the pocket, if it drops below the limit for more than 30 s, the sensor stops the compressor and the red light start flashing.

The sensor must be connected in series with the compressor module and with the other alarm of the system.

Technical Bulletin (BT007)



OIL DIFFERENTIAL PRESSURE SWITCH (ODPS)

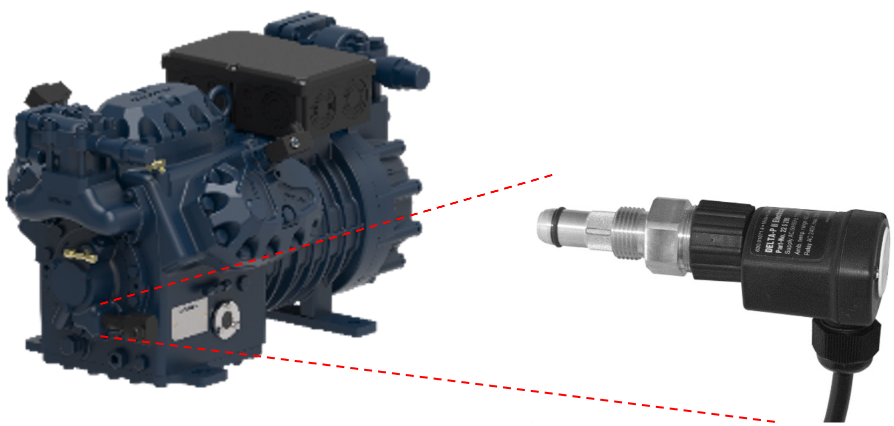
Larger 4, 6 and 8 cylinders compressors H5-H6-H7 are equipped with an oil pump and oil collected in the oil sump is pumped under pressure into the shaft to lubricate connecting rods and bearings.

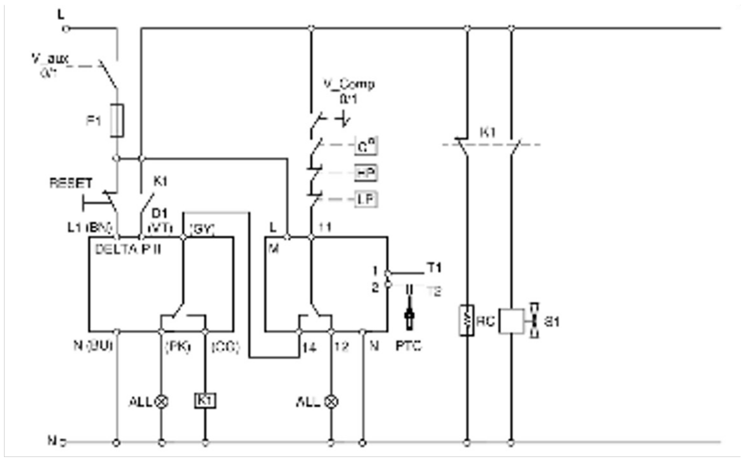
To monitor the differential pressure between the oil and the compressor's sump DORIN supply as standard equipment an electronic oil differential pressure switch (DELTA P II).

If the oil differential pressure drops below 12.3 psi ± 2 psi for more than 90 s, the switch stops the compressor giving an alarm signal.

The oil pressure switch must be connected in series to both thermistors module and all other protections foreseen in the system chain of alarm like in the following scheme.

Technical Bulletin (BT007)





CRANKCASE HEATER (CH)

WHAT IS

A resistance inserted in the oil sump that generate heat when powered

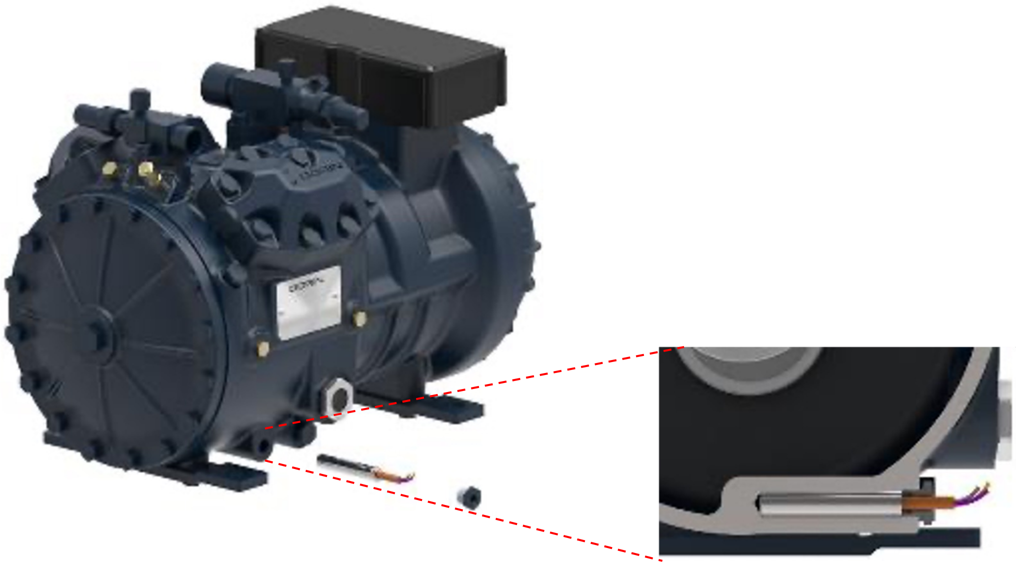
WHY TO USE

Always suggested in order to keep the Toil > Text. during compressor stop and avoid oil migration and condensation in the oil.
At compressor start the pressure in the sump drops and this liquid refrigerant can evaporate violently causing large amount of foam (Flash Gas).
Crankcase heater is always recommended to evaporate gradually liquid refrigerant diluted in the oil and avoid Flash Gas at restart.

HOW TO USE

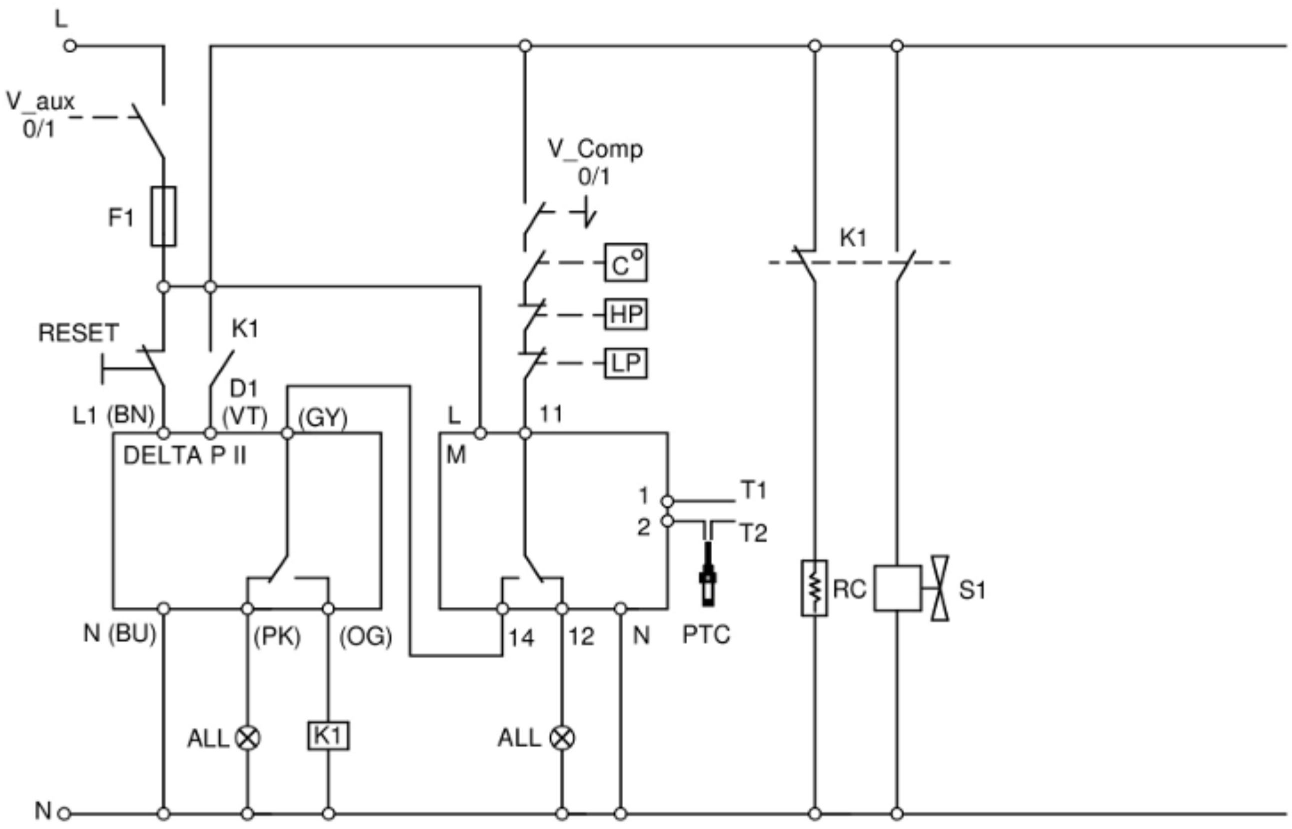
- Start after a long stop:
  - T_{oil}-T_{amb} ≥ 20 K (36°F)
- Continuous compressor operation:
  - Compressor OFF / heater ON.

Technical Bulletin (BT001)



CO2 Transcritical Compressor Troubleshooting

- Electrical Connection Scheme of Safety Devices:



V_aux = Aux Power Supply
V_Comp = Compressor Power
F1 = Fuse
K1 = Contactor

RC = Crankcase Heater
S1 = Solenoid
M = Protection Module (INT69)
DELTA P II = Oil Diff. P Switch

HP = High Pressure Switch
LP = Low Pressure Switch
PTC = Discharge Temp. Sensor
1-2/T1-T2 = Thermistors

CO2 Transcritical Compressor Troubleshooting

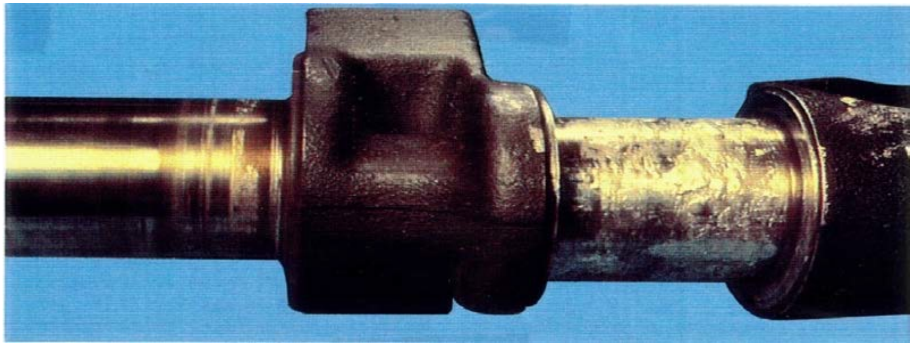
Diagnosing Compressor Failures

- 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

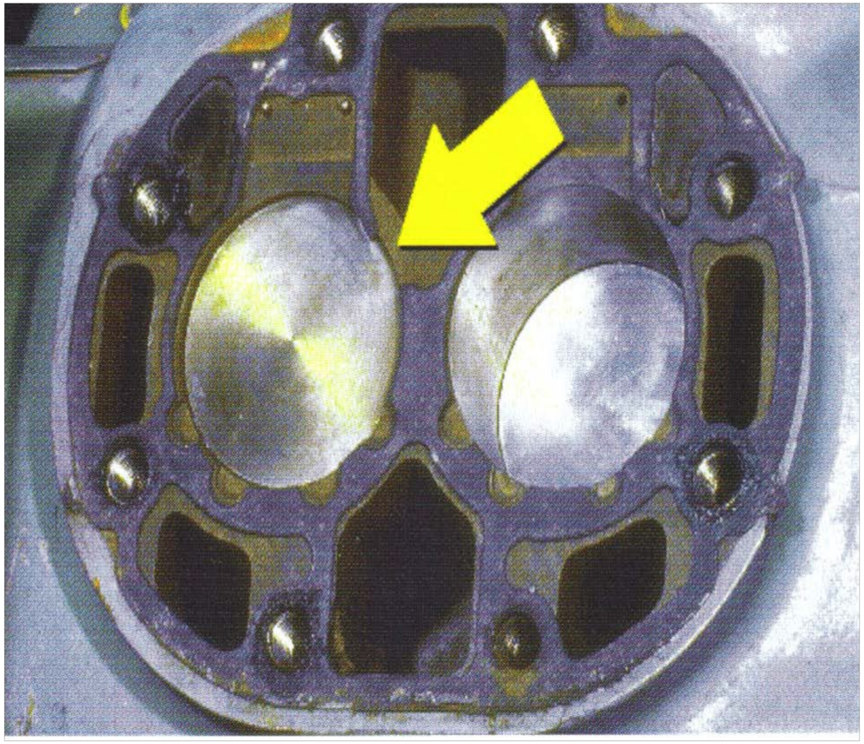
- Lubrication / Seizing – Lack of lubrication will lead to a compressor seizing or locking up. During a teardown this will show up as dry-surfaces accompanying damage from seized part.



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

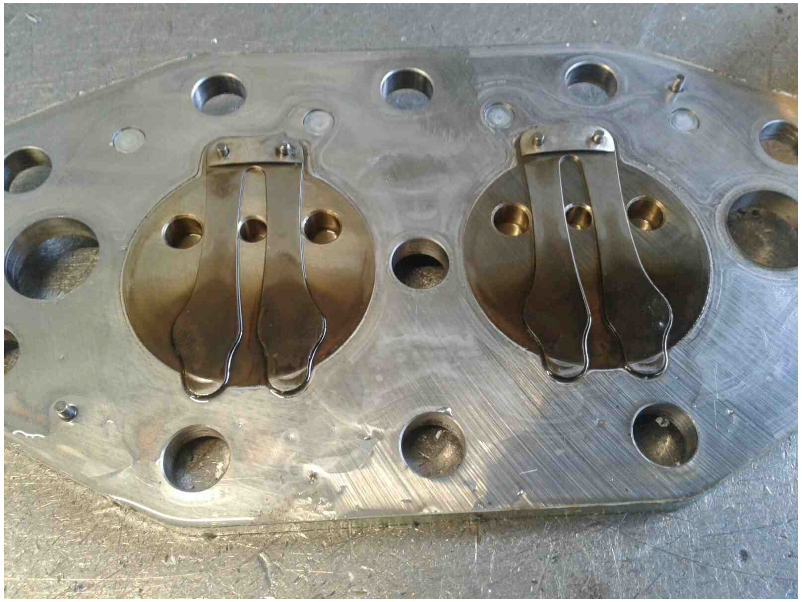
CO2 Transcritical Compressor Troubleshooting

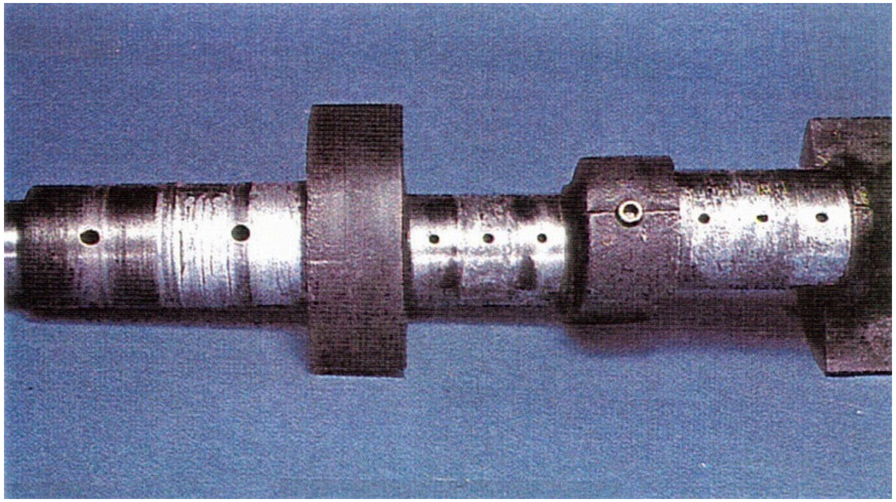
- Slugging – Typically top-end damage. Valves will be brittle and Cylinders/Valves will be dry.



CO2 Transcritical Compressor Troubleshooting

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



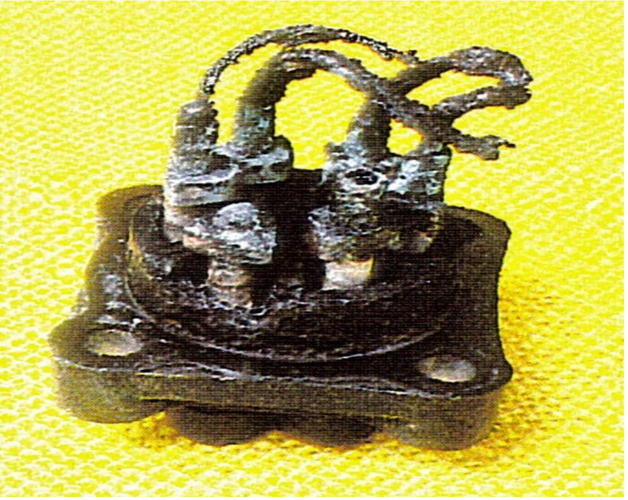


Caused by: Blow Gasket, Improper Head Gasket Install, Blown Discharge Valve, High Superheat, and Non-Condensables.

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:

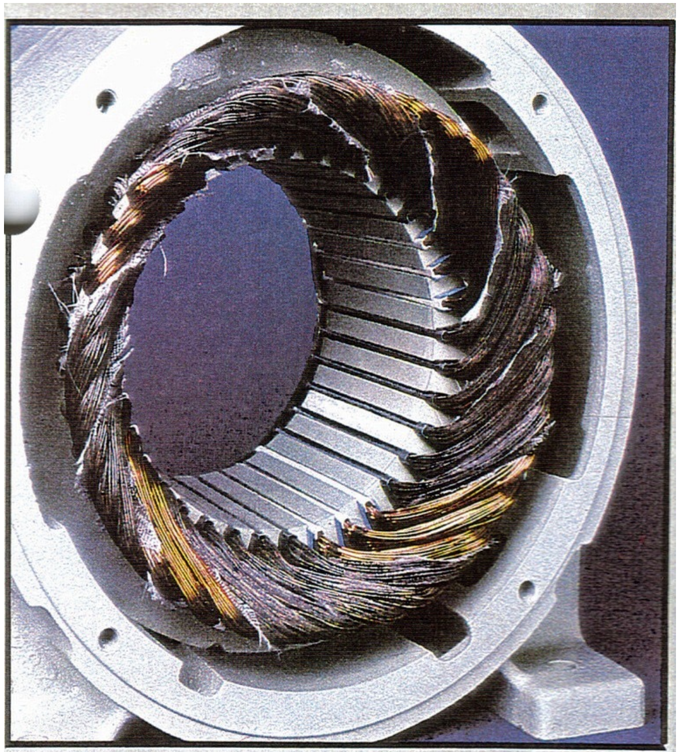
Klixon: 06L's, 06D's, Etranes (except small motor) / Just want continuity
Thermisters: M & R Tranes, JG/JS Yorks - ohm range below

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

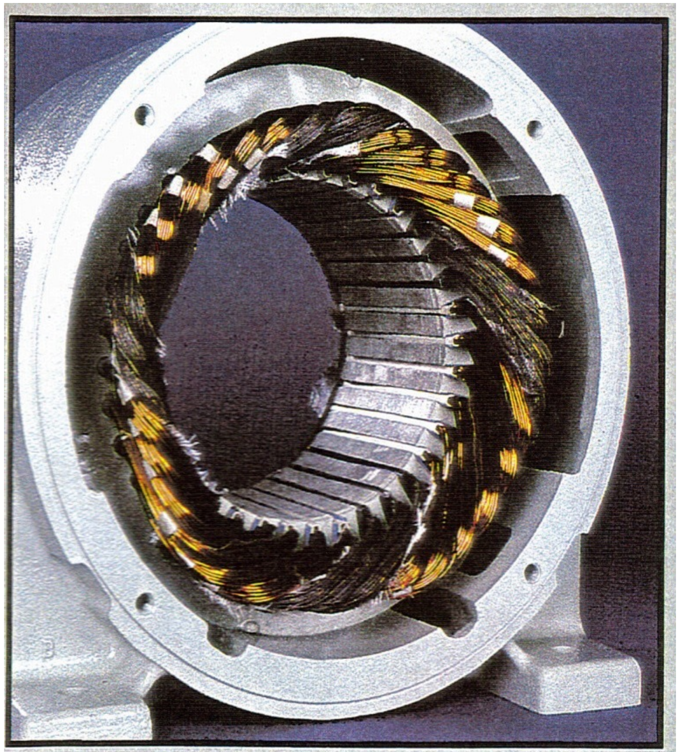
Common to: 1 ____ 2 ____ 3 _____ Ground Check (OK) ____ Open Check (OK) ____

CO2 Transcritical Compressor Troubleshooting

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



1 Winding Single-Phased (Y - Connected)



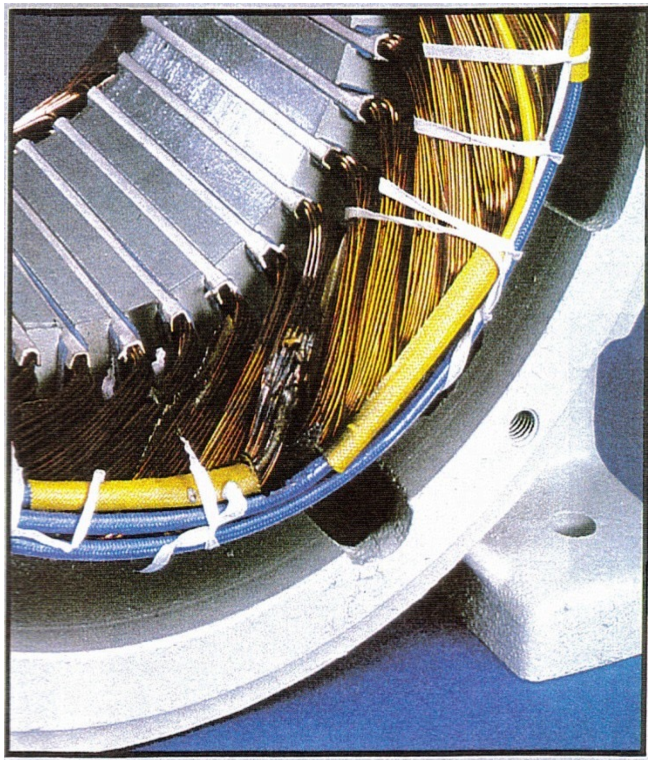
2 Winding Single-Phased (△- Connected)

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).

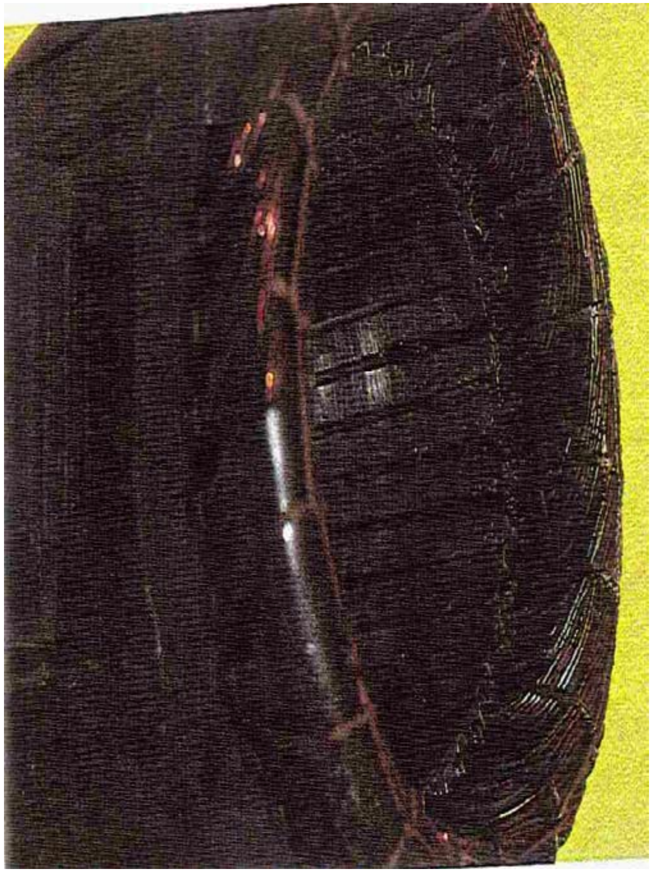
7 Winding Grounded in the Slot



12 Winding Damaged by Voltage Surge

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

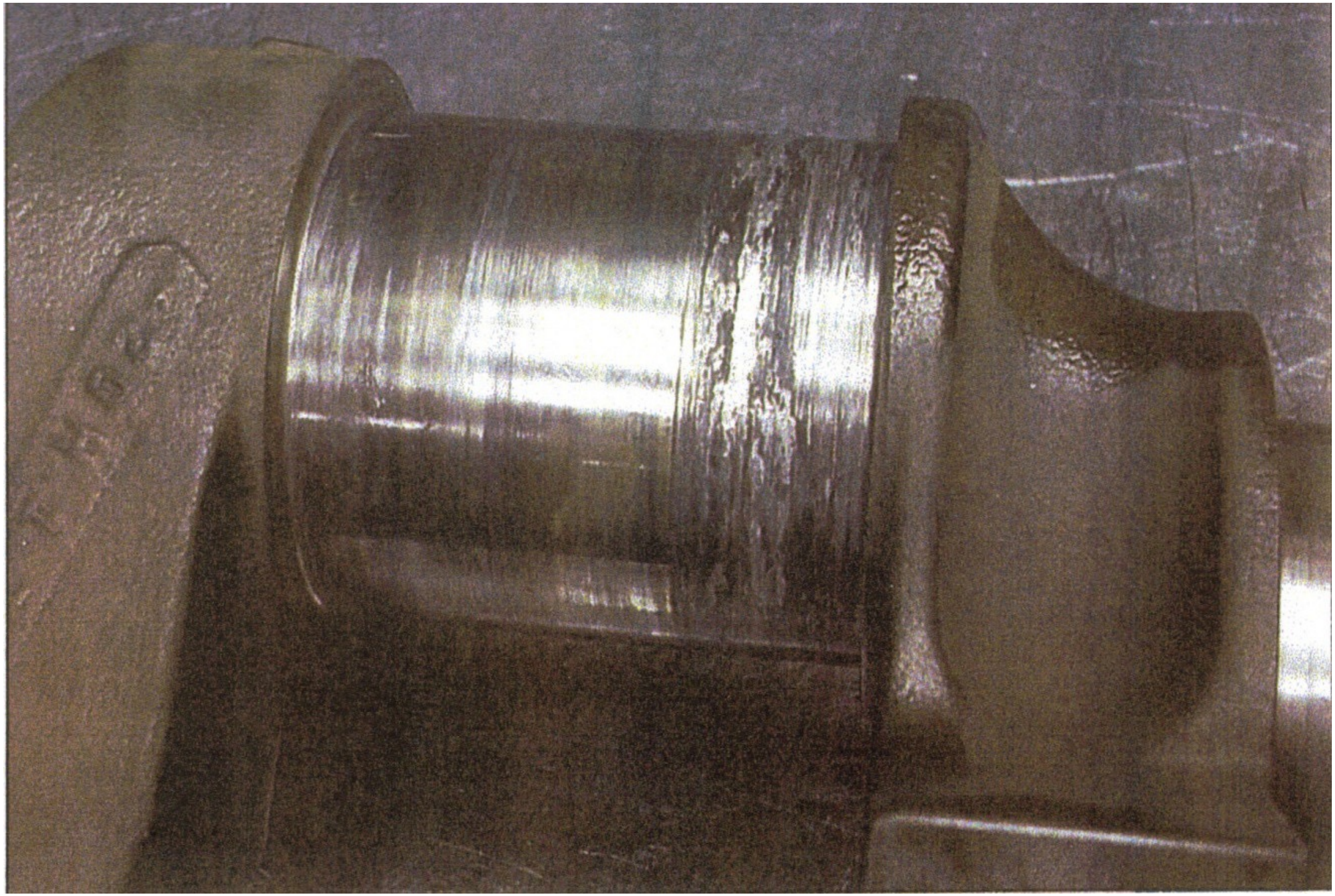
- Overload – Thermal deterioration of the insulation in all phases of the stator, typically caused by load exceeding rating of motor.

CO2 Transcritical Compressor Troubleshooting

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

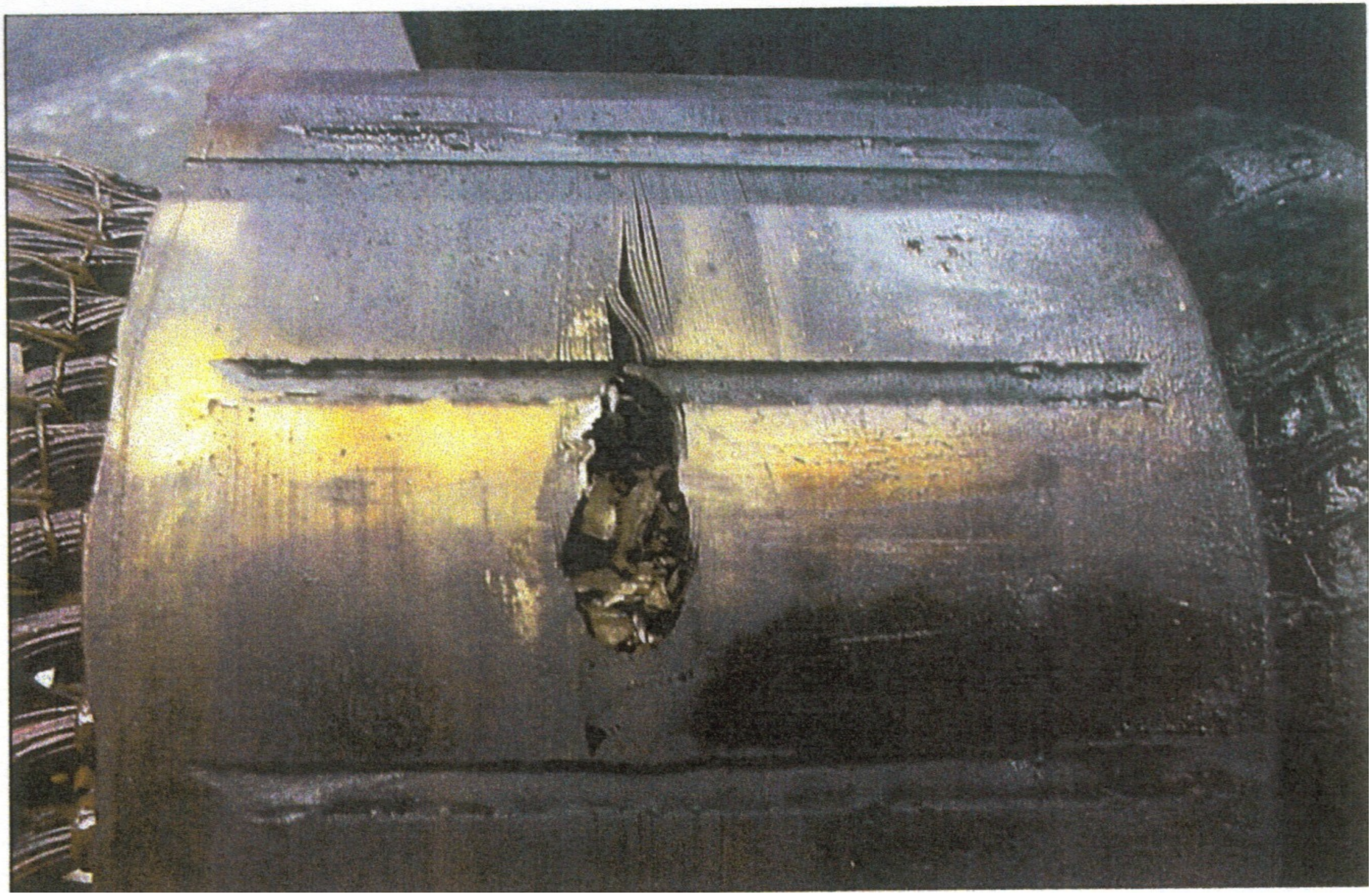
CO2 Transcritical Compressor Troubleshooting

- What caused this?



CO2 Transcritical Compressor Troubleshooting

- What caused this?



CO2 Transcritical Compressor Troubleshooting

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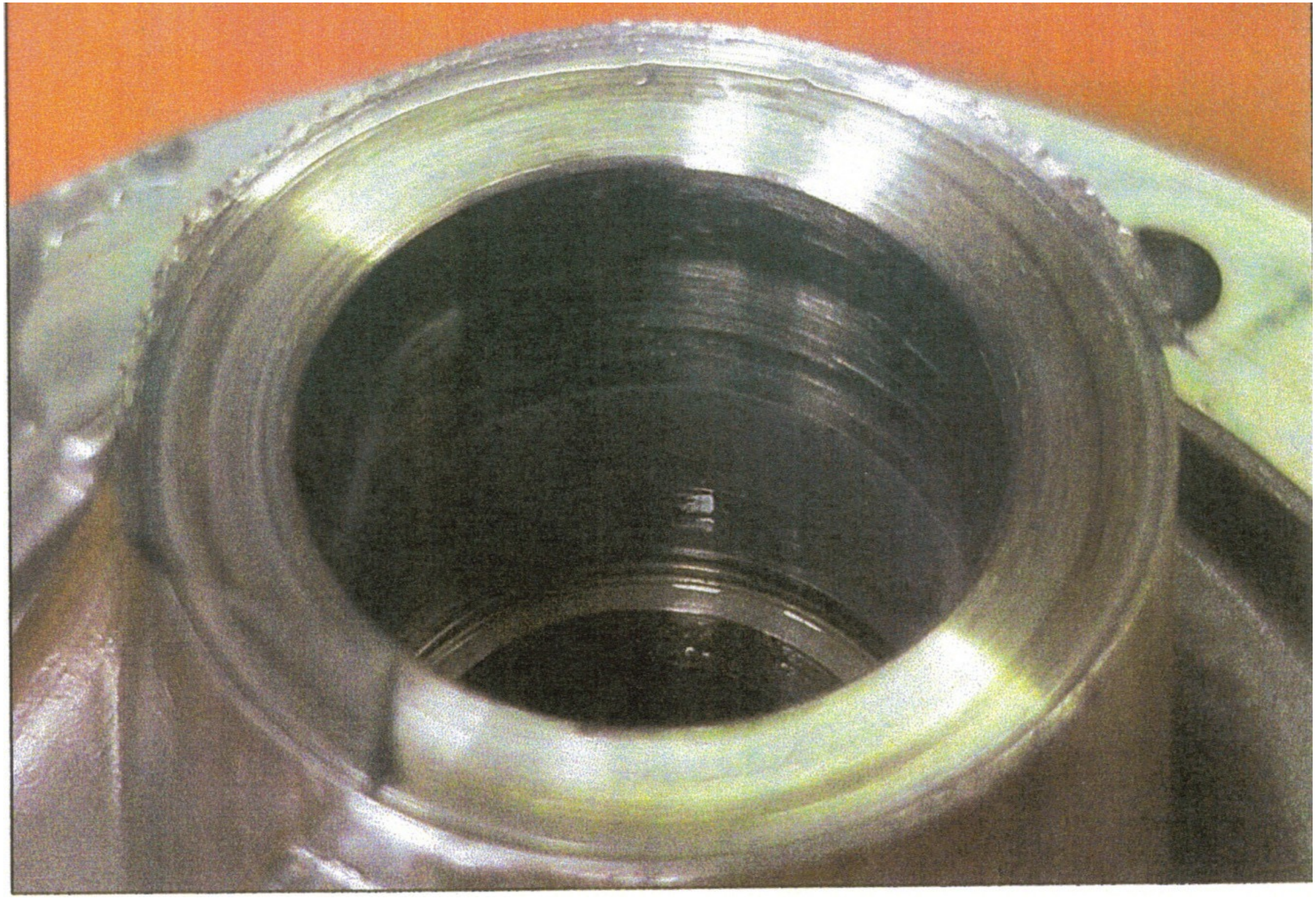

Teardown of CO2 Compressor

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

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