Dry Gas Seals Design for Centrifugal Compressors in Supercritical CO2 Application

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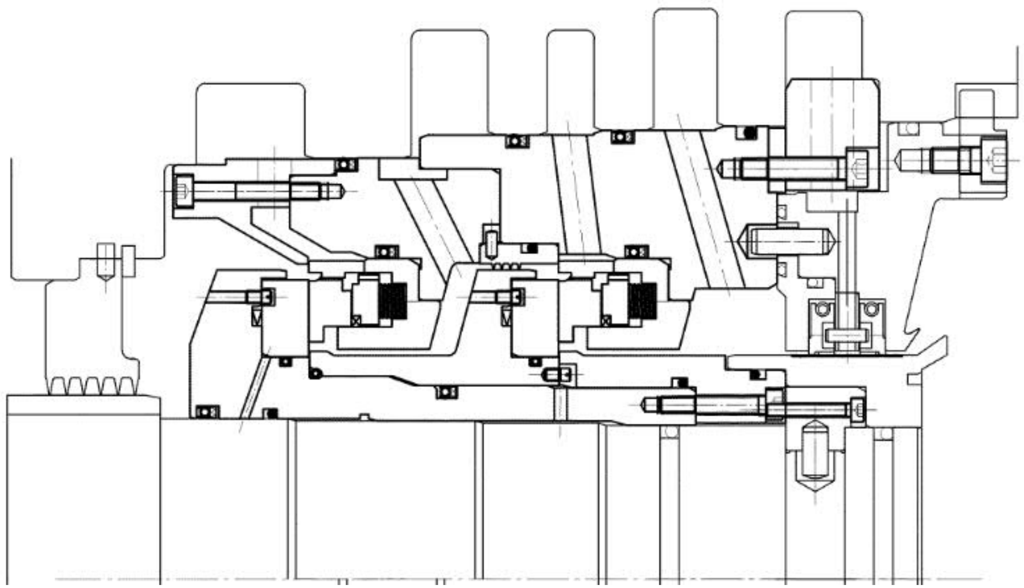
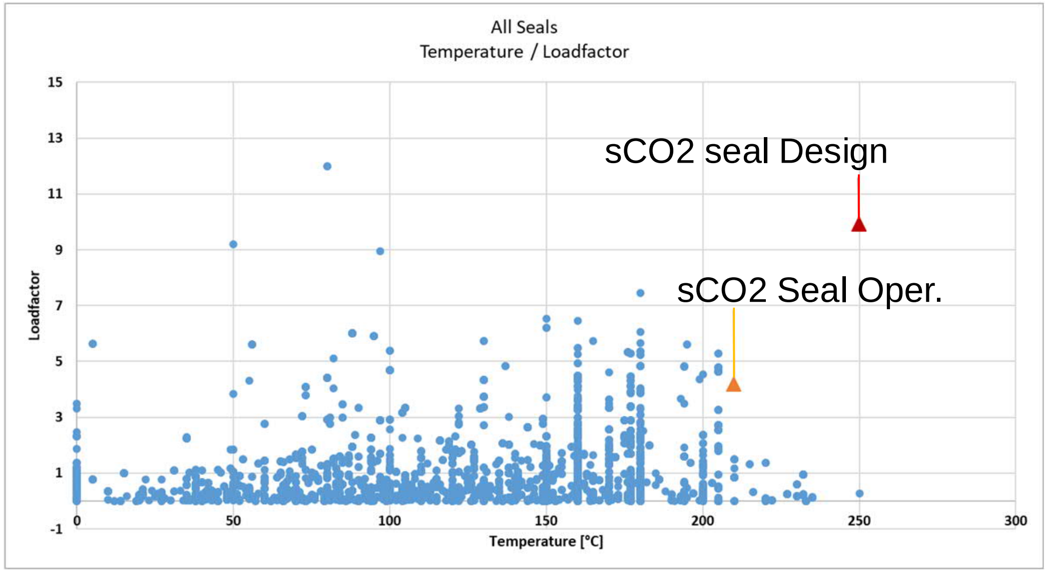
DGS Requirements for sCO2 Centrifugal Compressor

DGS design parameter

- CO2 as sealgas, in supercritical condition
- Tandem seal configuration | Bi-directional
- Lowest leakage
- Shaft size: Ø 75mm
- Pressure: static/dyn. 285/200 barg (3.625/1.885 psig)
- Temperature: -46 to 250°C (480 °F)
- Speed: 205 m/s @ OD (656 fps)

➔ To simulate the side conditions and match the simultaneous combination of all above mentioned requirements an extensive test campaign was performed.





Dry Gas Seal for sCO2 – Design Challenges

- **FLS & BH collaboration**
  - To predict the interaction between the seal and the compressor an iterative exchange of analysis was done.

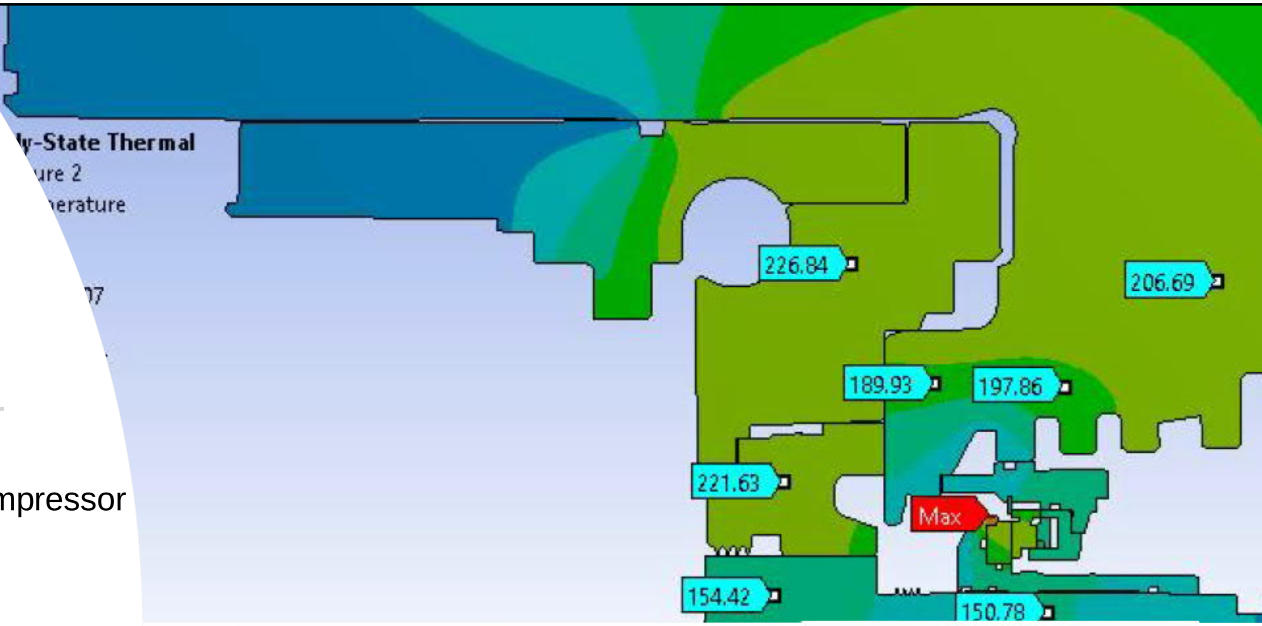
- **Compressor design analysis**
  - temperature profile @ seal cavity, including heat generation of the seal

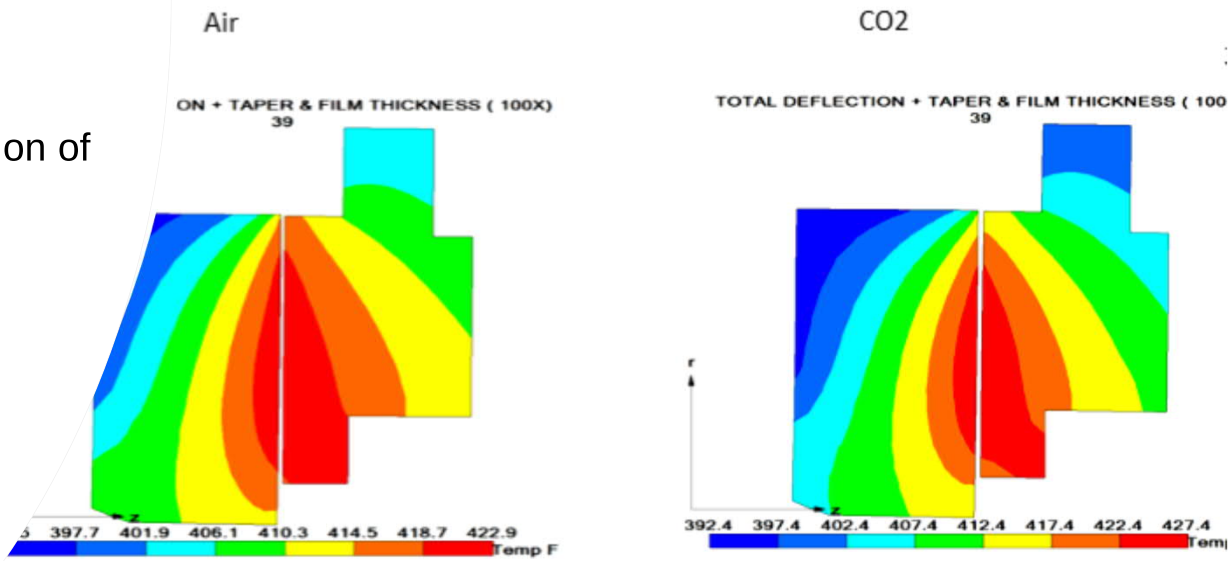
- **Seal performance analysis,** under the combination of specified operating conditions,

  - sCO2 as seal fluid
  - High temperature profile of cavity
  - High Speed and pressure (rotor windage)

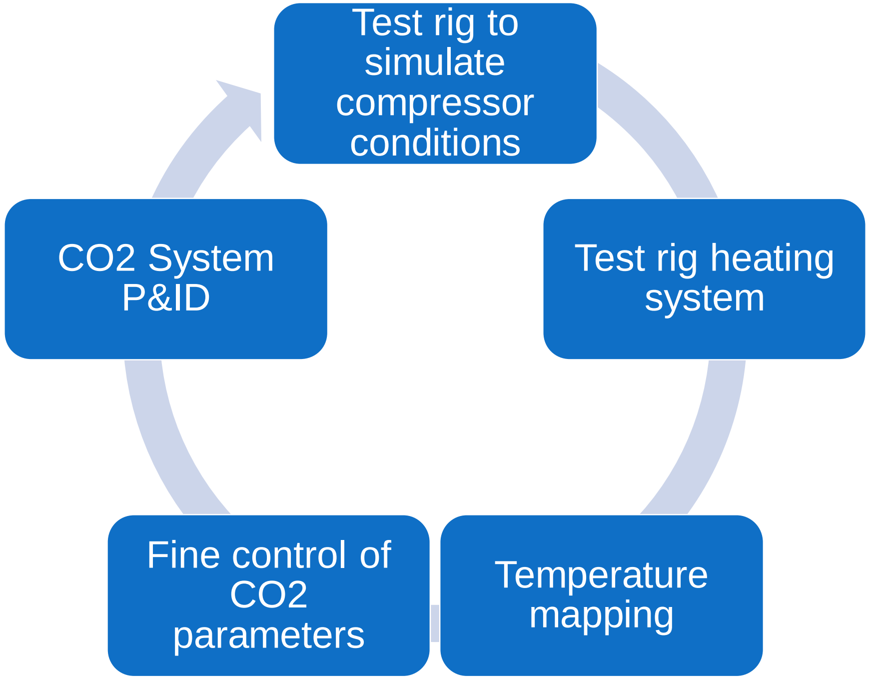
  - Test & field experience of previous projects
  - Existing analytical calculation tools

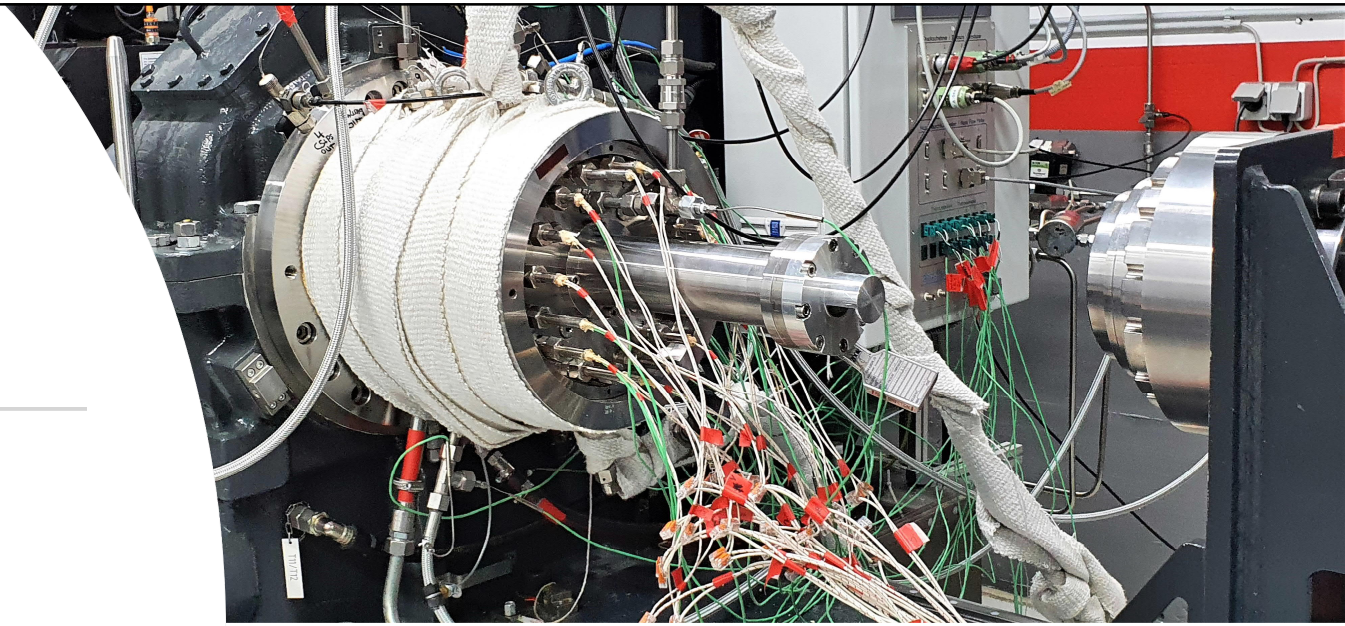
➔ ***Gap design for lowest leakage.***





DGS Test bench description





DGS Test bench description

Test rig to simulate compressor conditions

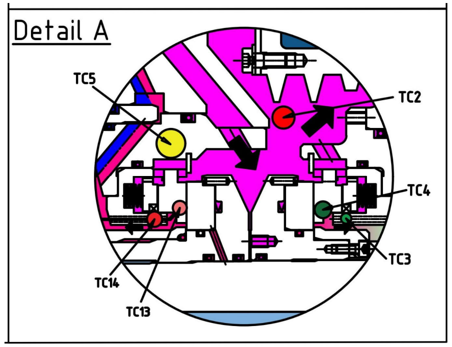
- 250 °C cavity temperature
- 2,1 Kg/min sCO2 sealgas flow @ 130 °C
- 250 Barg seal design pressure (Tester limit: 300 Barg)
- 30k rpm seal design speed (Tester limit. 70k rpm)
- Dyn. torque measurement

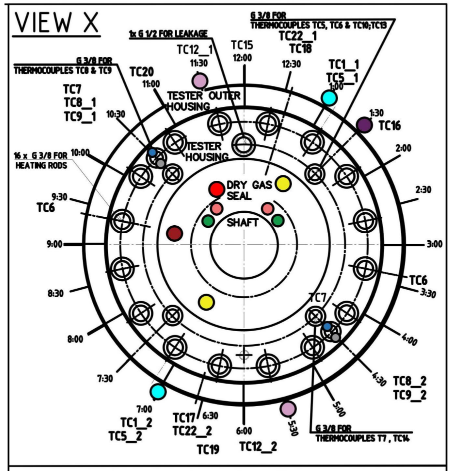
Test rig heating system

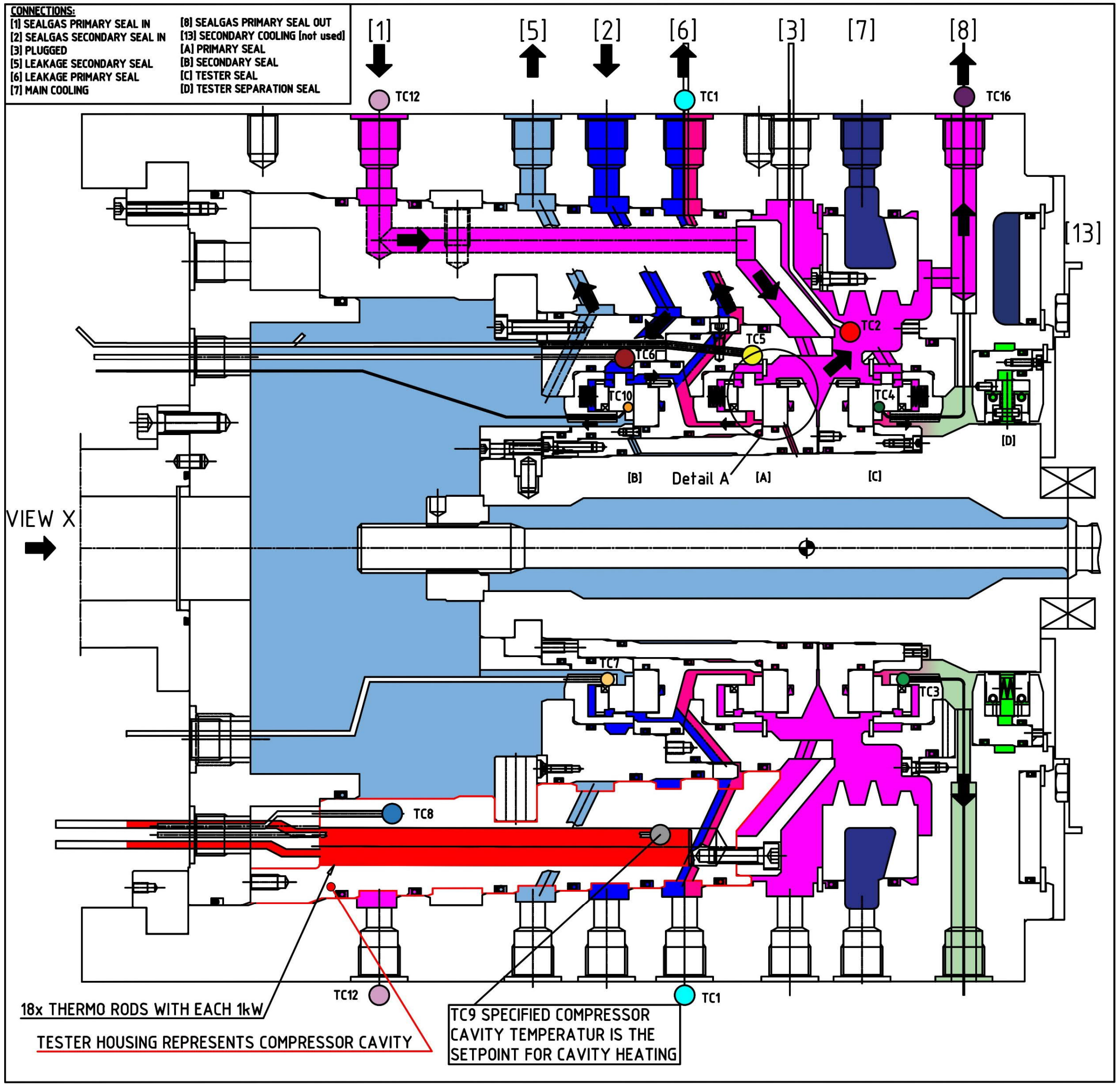
- 18 kW Thermo rods
- 34 kW gas heater

Temperature mapping

- ∑ 48 thermocouples





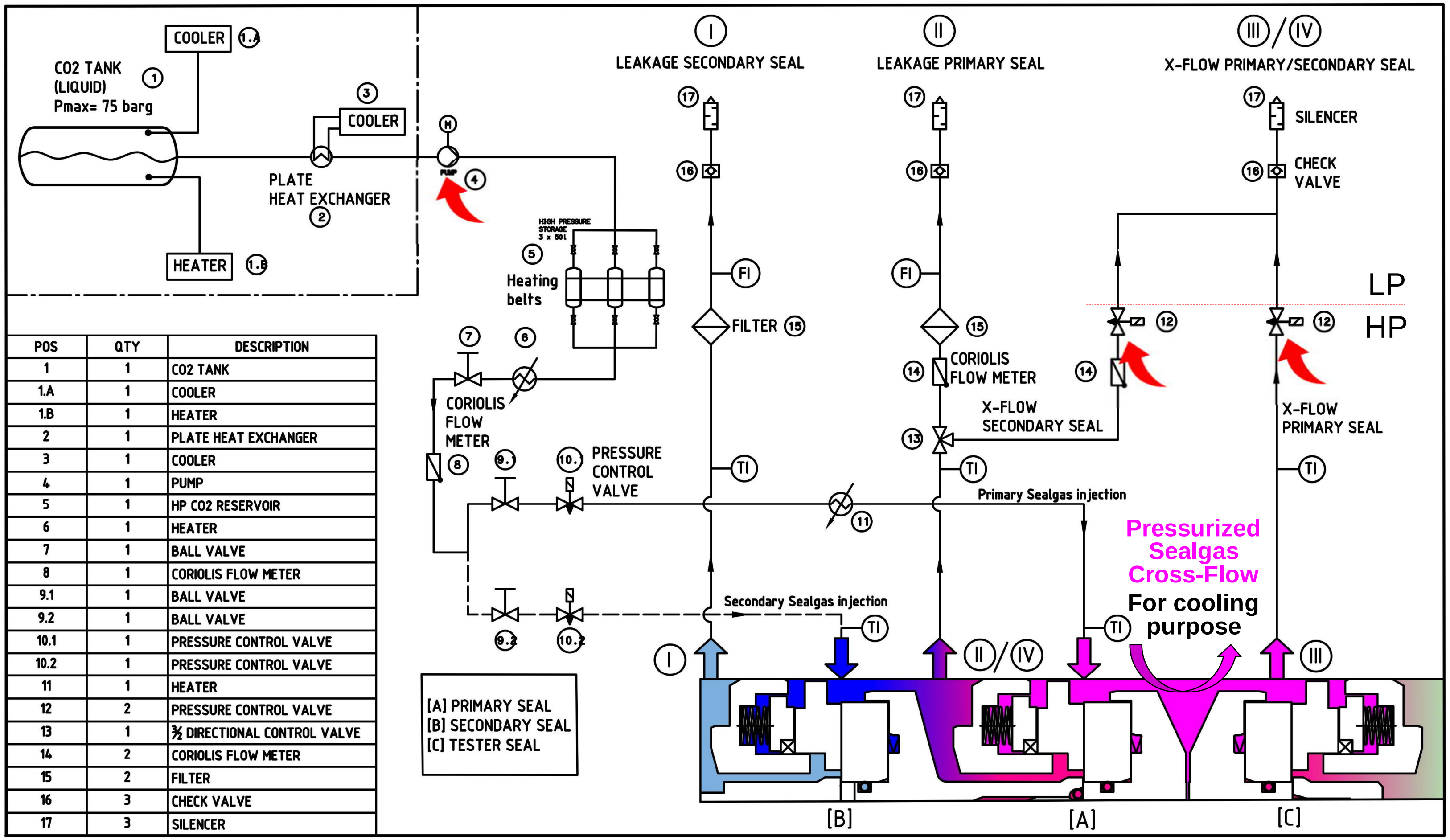


DGS Test bench description

Control of CO_2 parameters

- Keep CO_2 liquid in the HP-pump.
- Ice formation in and after Cross-Flow PCV’s.

CO_2 System P&ID



POS	QTY	DESCRIPTION
1	1	CO2 TANK
1.A	1	COOLER
1.B	1	HEATER
2	1	PLATE HEAT EXCHANGER
3	1	COOLER
4	1	PUMP
5	1	HP CO2 RESERVOIR
6	1	HEATER
7	1	BALL VALVE
8	1	CORIOLIS FLOW METER
9.1	1	BALL VALVE
9.2	1	BALL VALVE
10.1	1	PRESSURE CONTROL VALVE
10.2	1	PRESSURE CONTROL VALVE
11	1	HEATER
12	2	PRESSURE CONTROL VALVE
13	1	3/2 DIRECTIONAL CONTROL VALVE
14	2	CORIOLIS FLOW METER
15	2	FILTER
16	3	CHECK VALVE
17	3	SILENCER

DGS Test procedure & results analysis

MAIN PARAMETER TRENDS

LEAKAGE RATE

TEMPERATURES @ DIFFERENT SEAL LOCATION

SPEED INFLUENCE TO TEMPERATURE

FLOW INFLUENCE TO TEMPERATURE

DGS Test procedure & results analysis

MATRIX TEST

➔ Extract of extensive testing @ <u>Compressor operating</u> conditions

➔ Focus on Temperature constrains

- Cold startup (liquid & amb.)
- Sealgas at tester inlet: 130 °C (266 °F)
- Warm operating 100 °C (212 °F)
- Hot operating 210 °C (410°F)
- Hot oper. @ design temp. 250 °C (482 °F)

<table>
<tr><th colspan="9">PRACTICAL TEST CAMPAIGN TO VALIDATE ANALYTICAL MODEL</th></tr>
<tr><td colspan="3">COLD
MATRIX TEST</td><td colspan="2">WARM
MATRIX TEST</td><td colspan="4">1 HOT
MATRIX TEST</td></tr>
<tr><td>4 Start up
from
liquid conditions</td><td>Start up
from
transient conditions</td><td>Operating
to
steady state</td><td>Start / Stops
to
steady state</td><td>Speed cycling
to
steady state</td><td>Start / Stops
to
steady state</td><td>2 Speed cycling
to
steady state</td><td>Start / Stops
to
steady state</td><td>3 Speed cycling
to
steady state</td></tr>
<tr><td>Cooled Cavity
Flooded Startup
Liquid CO2 ➔ gas</td><td colspan="2">Ambient Cavity
Startup to steady state
Transient ➔ sCO2</td><td colspan="2">100°C heated Cavity
Main Compr. simulation
sCO2</td><td colspan="2">210°C heated Cavity
Bypass Compr. simulation
sCO2</td><td colspan="2">250°C heated Cavity
Bypass Compr. simulation
sCO2</td></tr>
<tr><td>Validation of Pressurized, longterm Stop</td><td colspan="8">Validation of operational parameter</td></tr>
</table>

P	max. static / dynamic	:	130 / 85	Barg
Rpm	max.	:	29.768	rpm (205 m/s)
T	max. Cavity	:	250	°C

DGS Test procedure & results analysis

CONSISTANT TEST STEPS @ DIFFERENT CAVITY TEMPERATURES

HOT MATRIX TEST

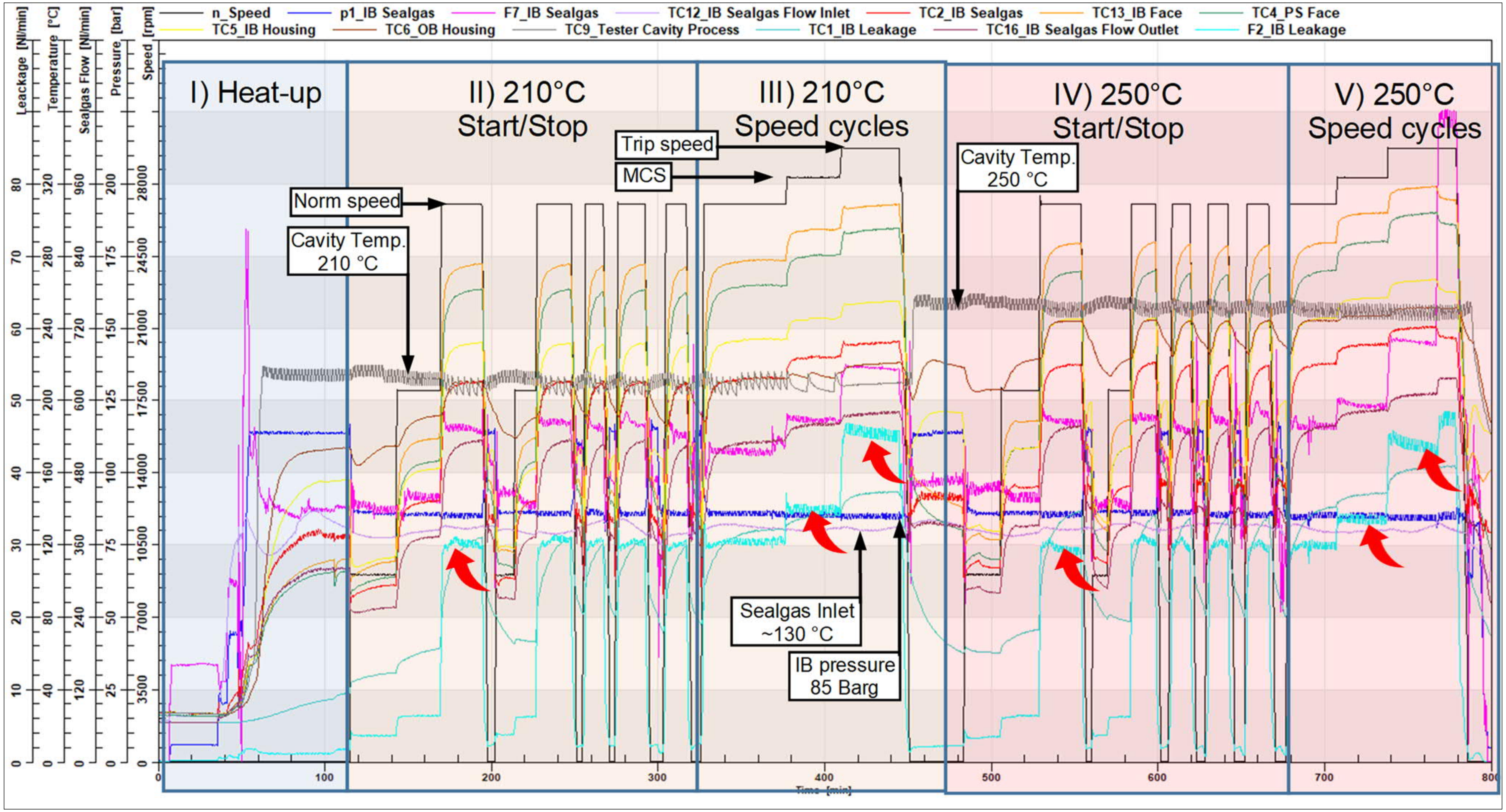
Main parameter trends

- Seal cavity temp. heated up to **210 °C & 250 °C**
- Norm-, maximum continuous- and trip speed.
- Multiple **start-stop** and speed cycling scenarios.

➔ Hold time up to overall **steady state** temperature readings.

➔ **Stable & repeatable, seal leakage achieved.**

n	=	speed	[rpm]
p	=	pressure	[Barg]
F	=	flow	[Nl/min]
TC	=	temperature	[°C]



DGS Test procedure & results analysis

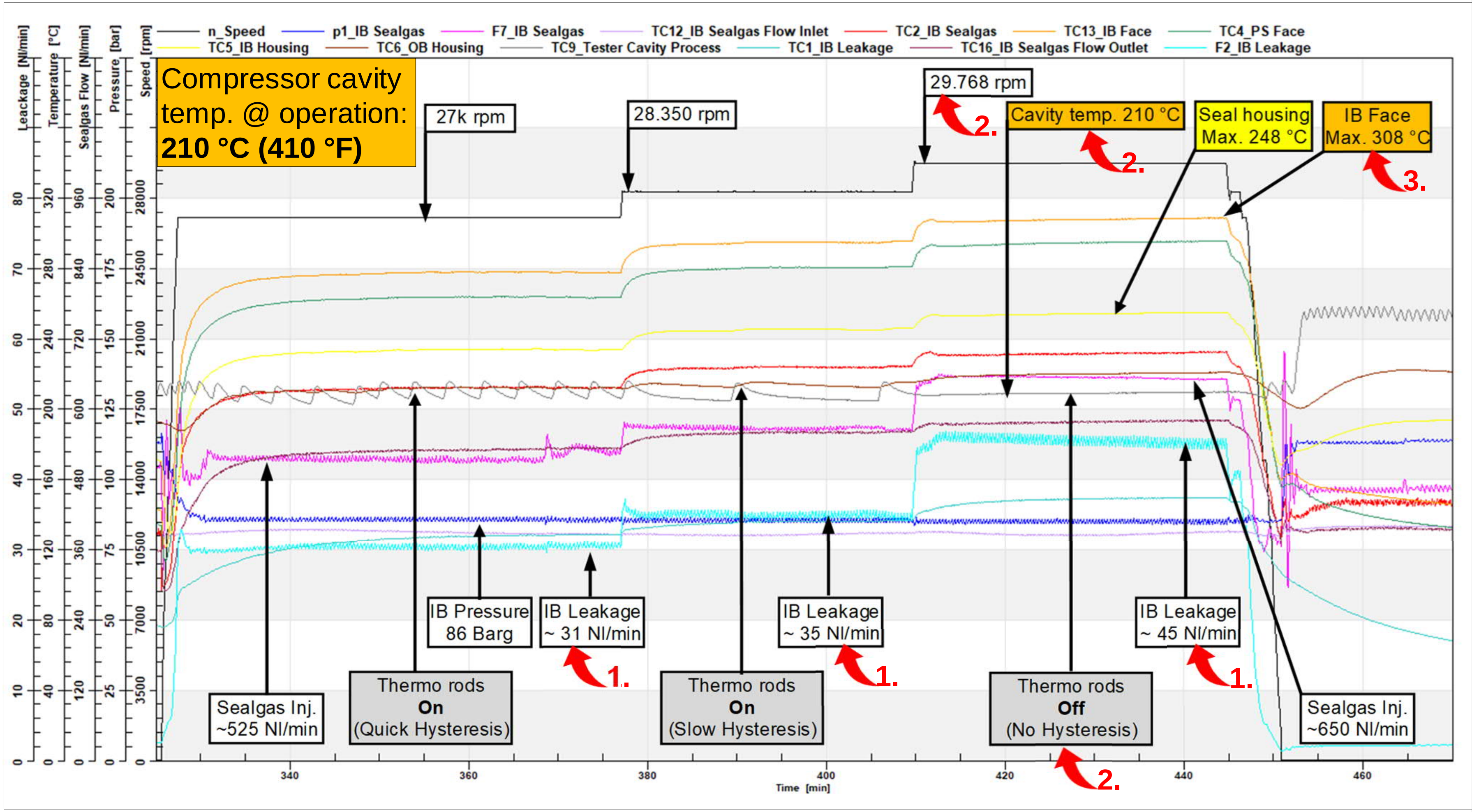
SEAL LEAKAGE CHARACTERISTIC & INNER ENERGY FROM SEAL

HOT MATRIX TEST
210°C heated cavity

1. **Leakage shows typical increase with speed.**
   ➔ Low, stable leakage trend.

2. **@ Trip speed**, thermo rods: **off**. All temp. steady state.
   ➔ **Energy** from seal-windage is in **balance** to thermo rod energy, while achieving the specified compressor operating cavity temp.

3. **IB seal face temp**. = 308 °C (586 °F) @ Compr. operating cavity temp.



DGS Test procedure & results analysis

INNER ENERGY AND THERMAL CONTROL OF THE SEAL

HOT MATRIX TEST
250°C heated cavity

1. @ **Trip speed**, thermo rods: **on!**
   All temp. in steady state.

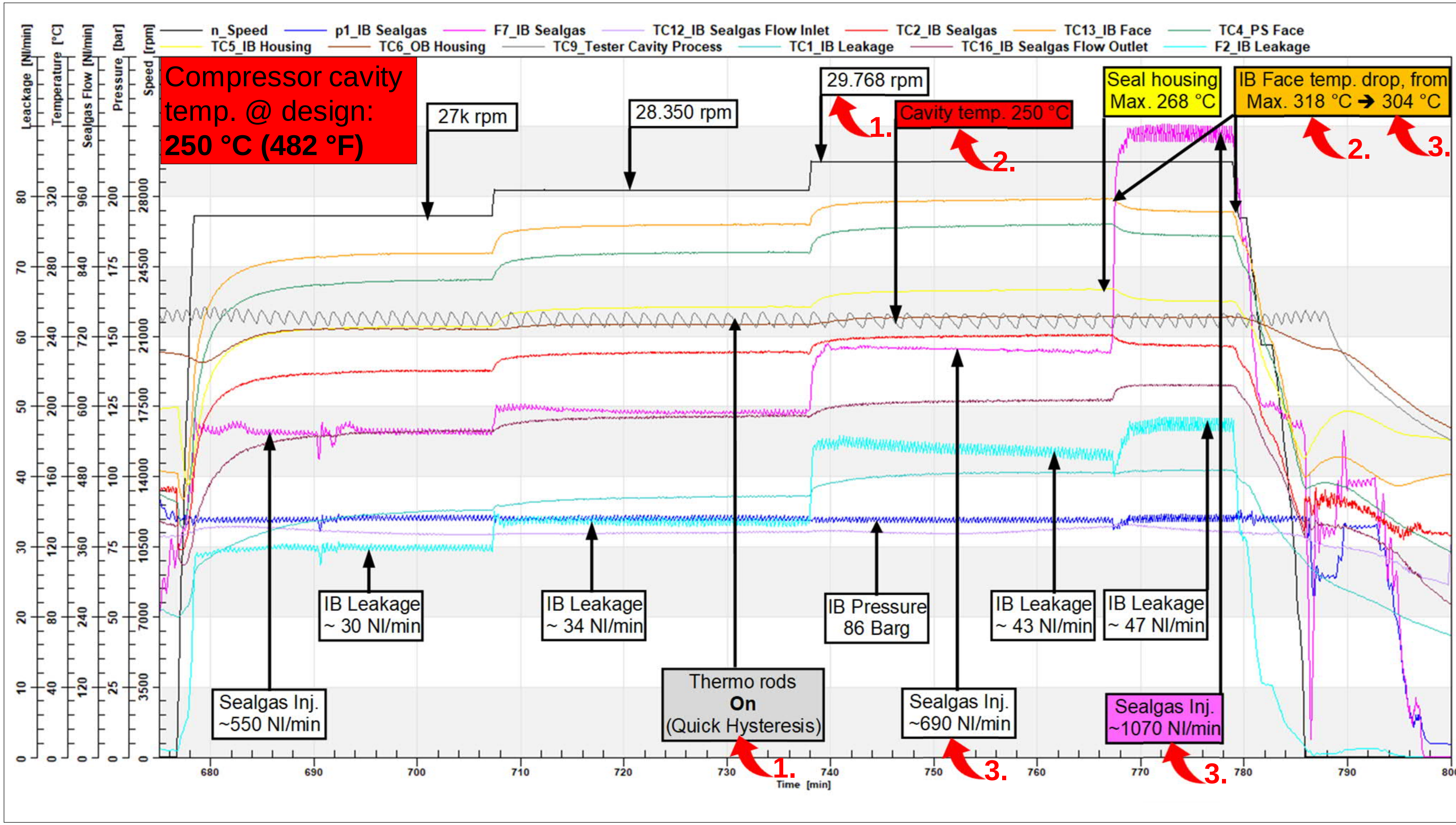
➔ **Energy** from seal-windage is **less** than thermo rod energy.

2. **210°C to 250°C cavity temp.**
   - Cavitytemp.: +40°C (const. energy input)
   - Facetemp.: +10°C, only

➔ **Energy** from seal windage is not sufficient to achieve the compressor cavity design temp.

3. **Sealgas Cross-Flow** increase, from 1,2 to1,9 Kg / min.

➔ **Sealgas Cross-Flow cools the Seal.**



Liquid CO2 test setup & test results

LIQUID CO2 TEST SETUP

LIQUID CO2 CONDITIONS ON THE DIAGRAM

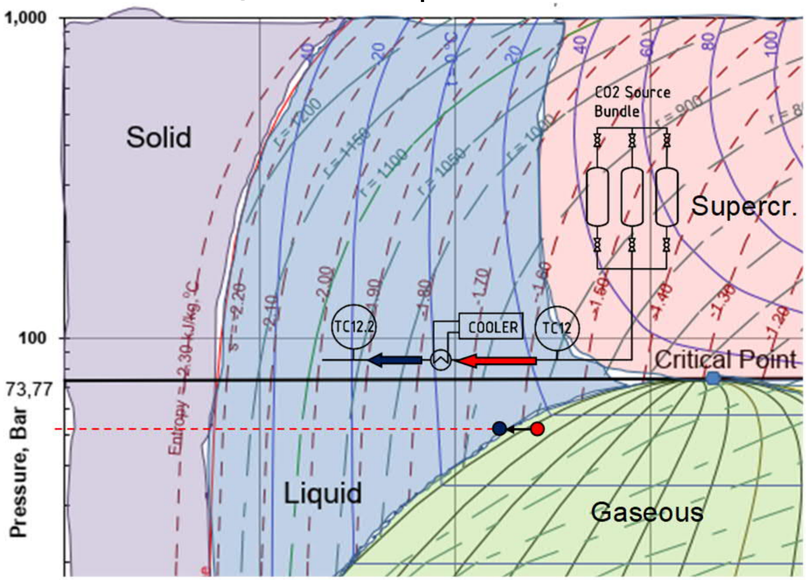
MAIN PARAMETER TRENDS

DRY ICE FORMATION RISK

Liquid CO2 test setup

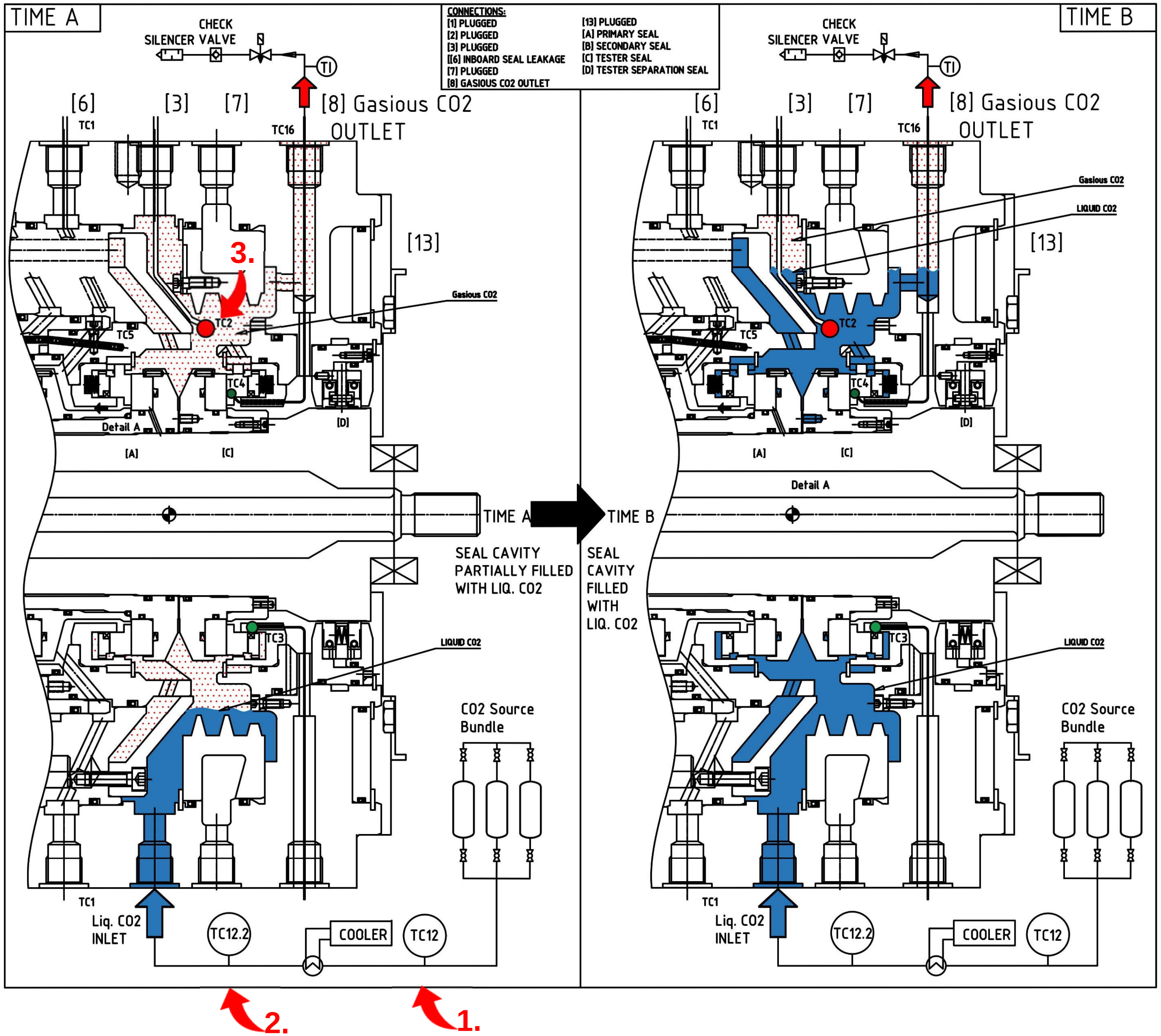
Liquid CO2 conditions on the diagram

- From boiling line to liquid phase. Temperature reduction @ constant pressure



- **Temperature monitoring of liquid CO2:**
  1. prior cooler (TC12)
  2. after cooler (TC12.2) and
  3. **above the seal (TC2)**

➔ **Ensures flooding of the seal with liquid CO2.**



Liquid CO2 test result

FLOODING THE SEAL WITH LIQUID CO2

Main parameter trends

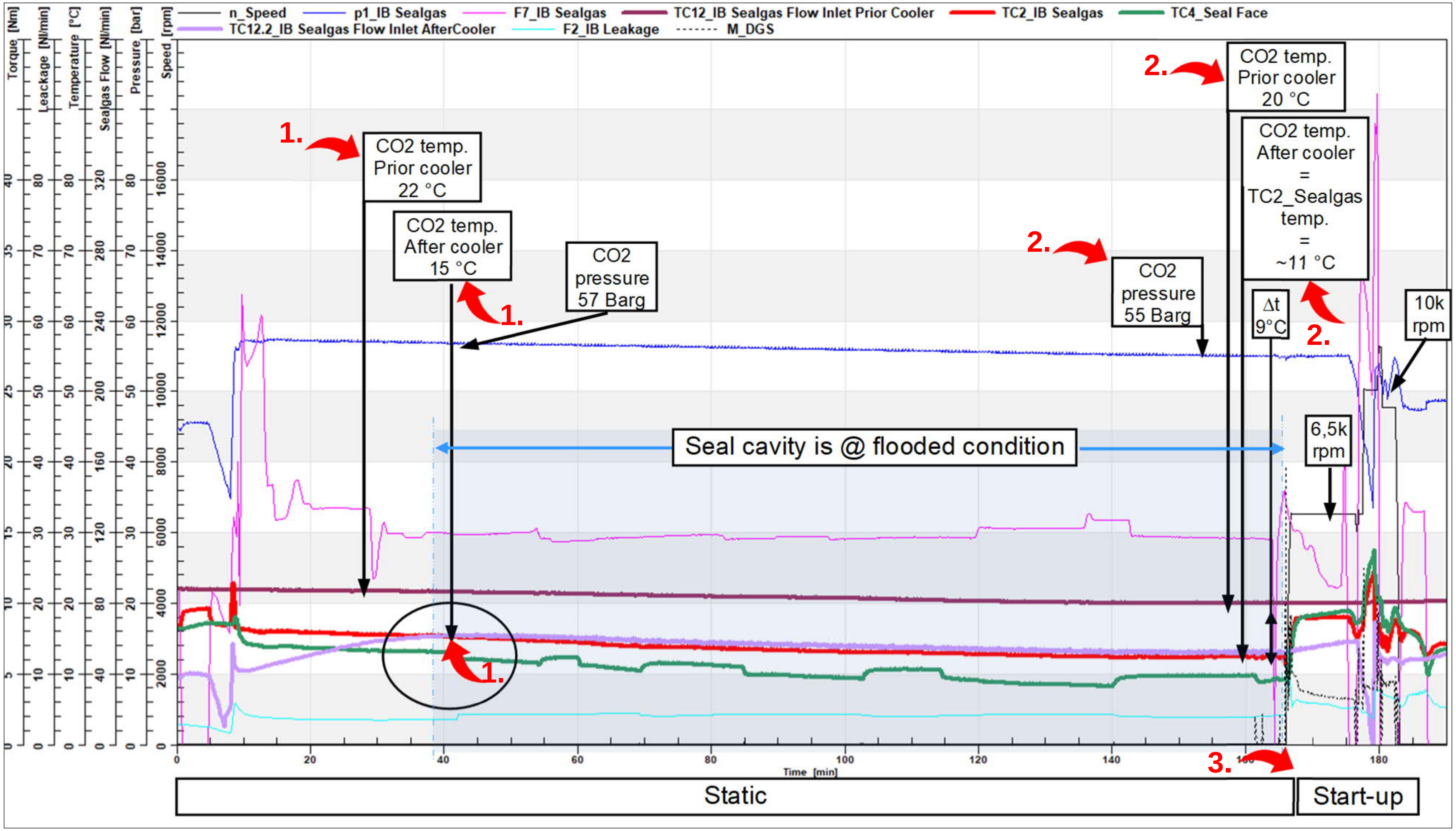
1. **CO2 liquefaction**
   CO2 Temp. @ 57 Barg:
   - Prior cooler = 22°C.
   - After cooler = 15 °C
   - Above seal = 15 °C

➔Seal is flooded with liquid CO2.

2. **After 120 min**
   CO2 Temp. @ 55 Barg:
   - Prior cooler = 20°C.
   - After cooler = 11 °C
   - Above seal = 11 °C

➔Seal is flooded with liquid CO2 for 120 min, in static conditions.

3. **Start-up** of the seal from 0 to 10k rpm.



Liquid CO2 test result

LOW TORQUE DURING START-UP OF THE SEAL

Dry ice formation risk

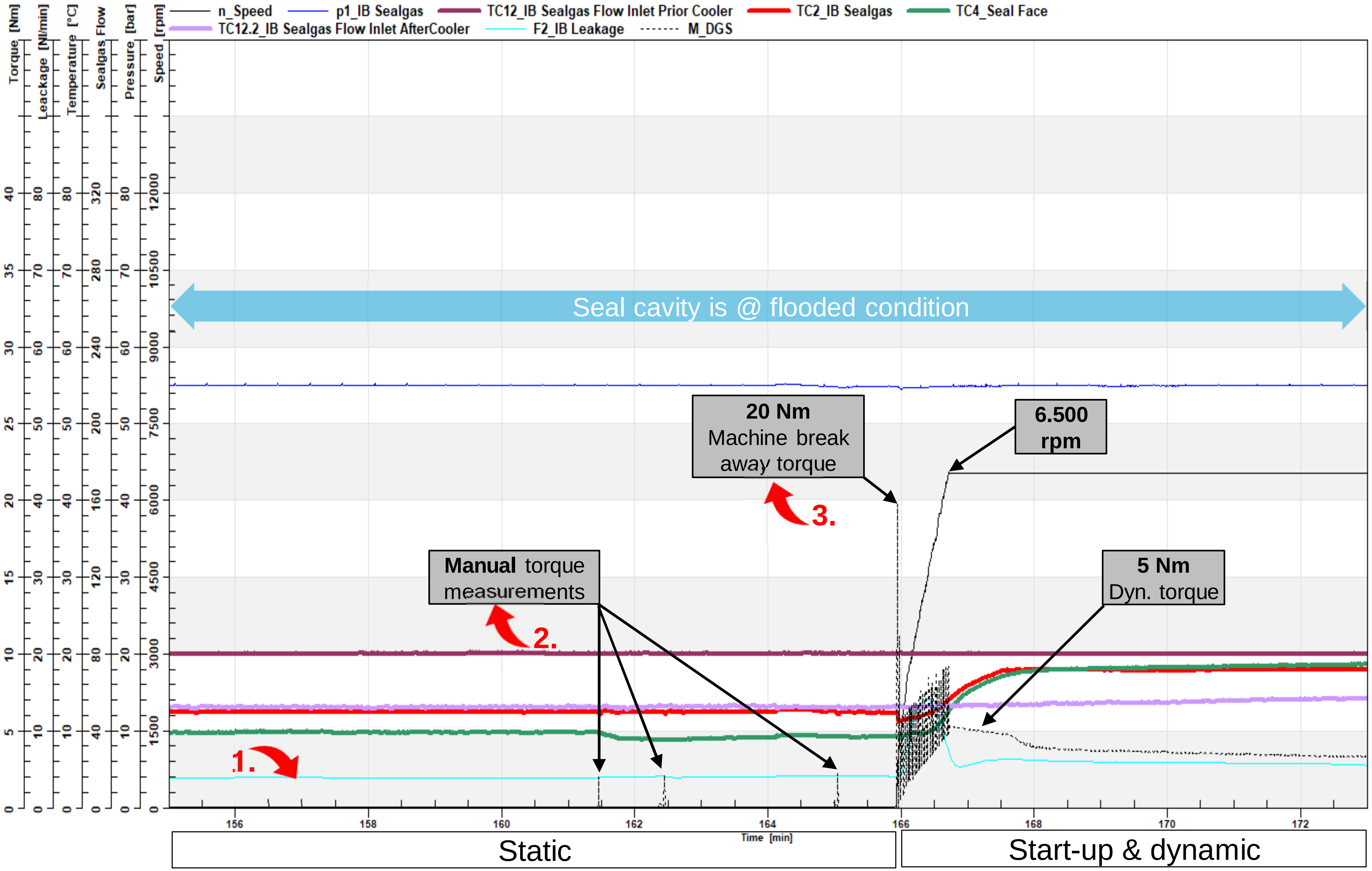
1. **Low static leakage of 4 Nl/min.**

➔ minimize the risk of dry ice formation in the primary-vent-line.

2. **Manual torque** measurements **below 5 Nm.**

3. **start-up,** out of liquid CO2 phase shows the same, low machine-break-away-torque, like the start-up measurements @ sCO2 conditions.

➔ **No dry ice formation @ seal on primary-vent-side.**



Project Summary

BH – FLOWSERVE collaboration was the key driver to cope with the challenges of this project.

➔ The test results validated theoretical models and enhanced the design knowledge for high temperature turbo machines.

➔ The test proved the seal's capability & reliability to meet the un-explored sCO2 operating conditions and confirmed that, Flowserve Gaspac seal can operate with:

- **Multiphase CO2 (liquid to supercritical)**
- **High speed up to 205 m/s @ 200 Barg**
- **High temperature 250 °C Cavity temperature**
- **High dynamic pressure, up to Low and stable leakage characteristic**

➔ Dry Gas Seal technology can cover *operating conditions of sCO2 applications and match turbomachine's design requirements, offering lowest emission and circuit refilling necessity.*

GOING BEYOND…

The present market request shows an increasing trend of extending operating conditions, which requires further enhancement of Sealing Technology.

Thank You for your attention!