Materials for Supercritical CO$_2$ Applications

Pre-Conference Tutorial

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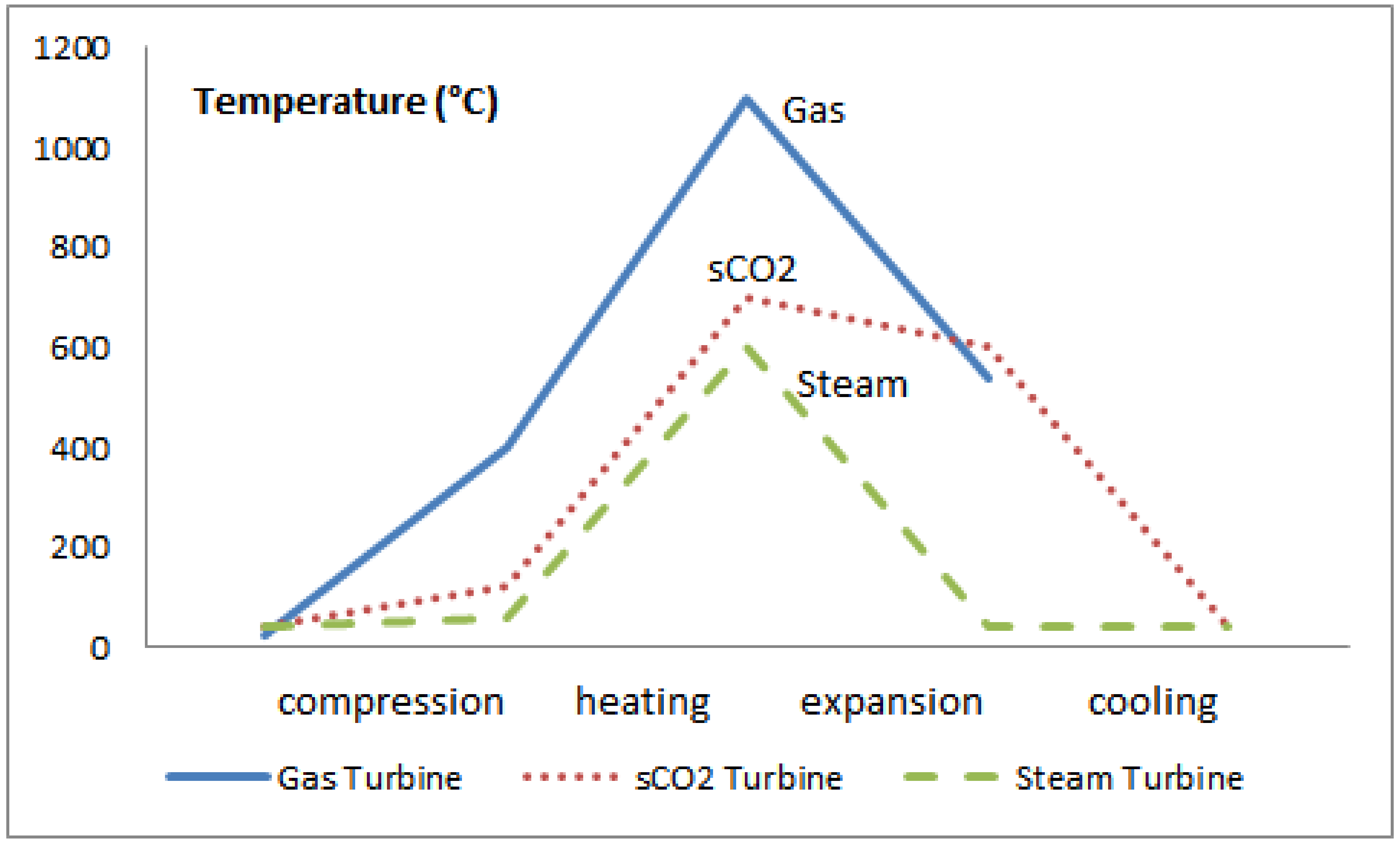
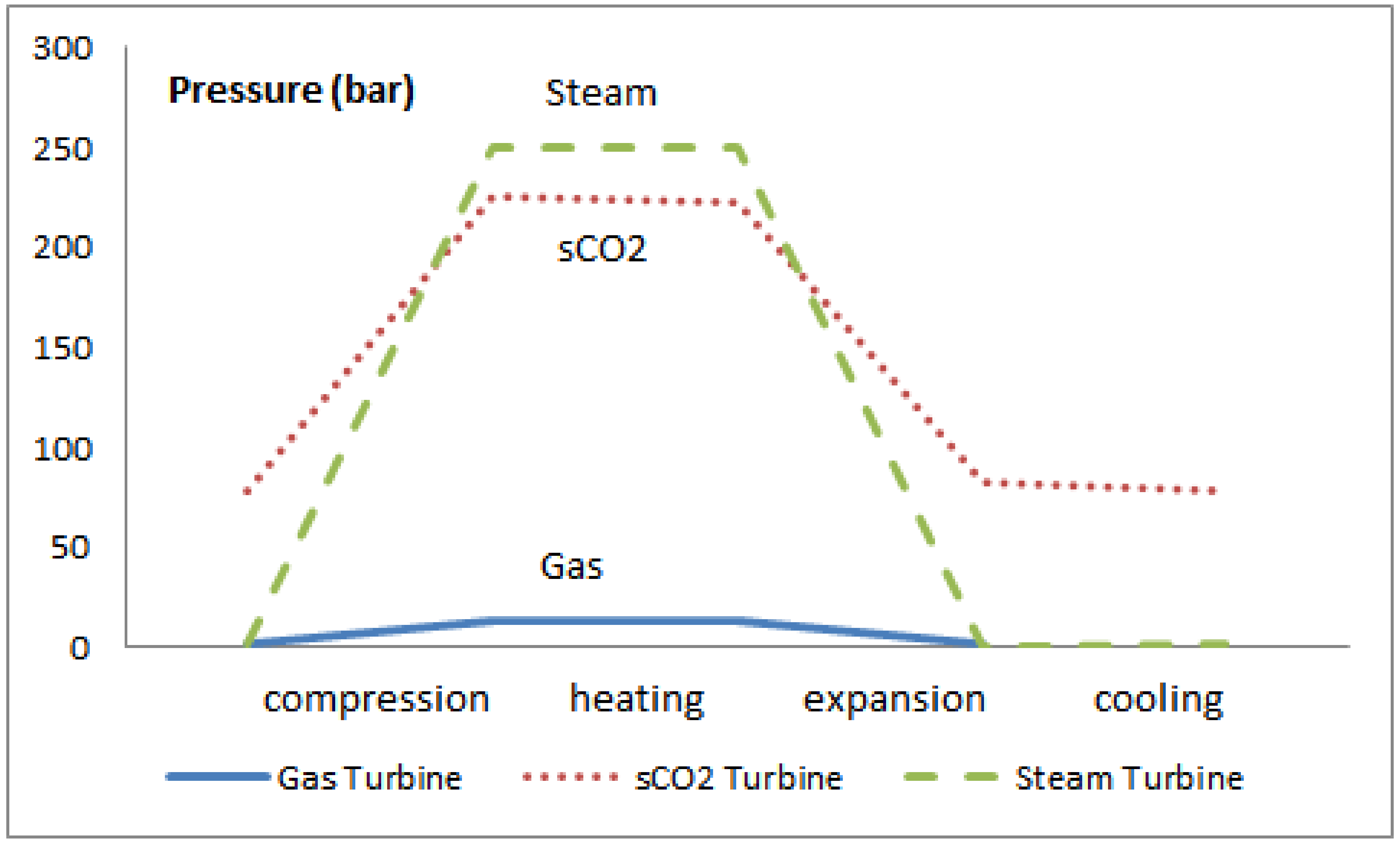
GTI ENERGY
EPRI | ELECTRIC POWER RESEARCH INSTITUTE
Carleton UNIVERSITY

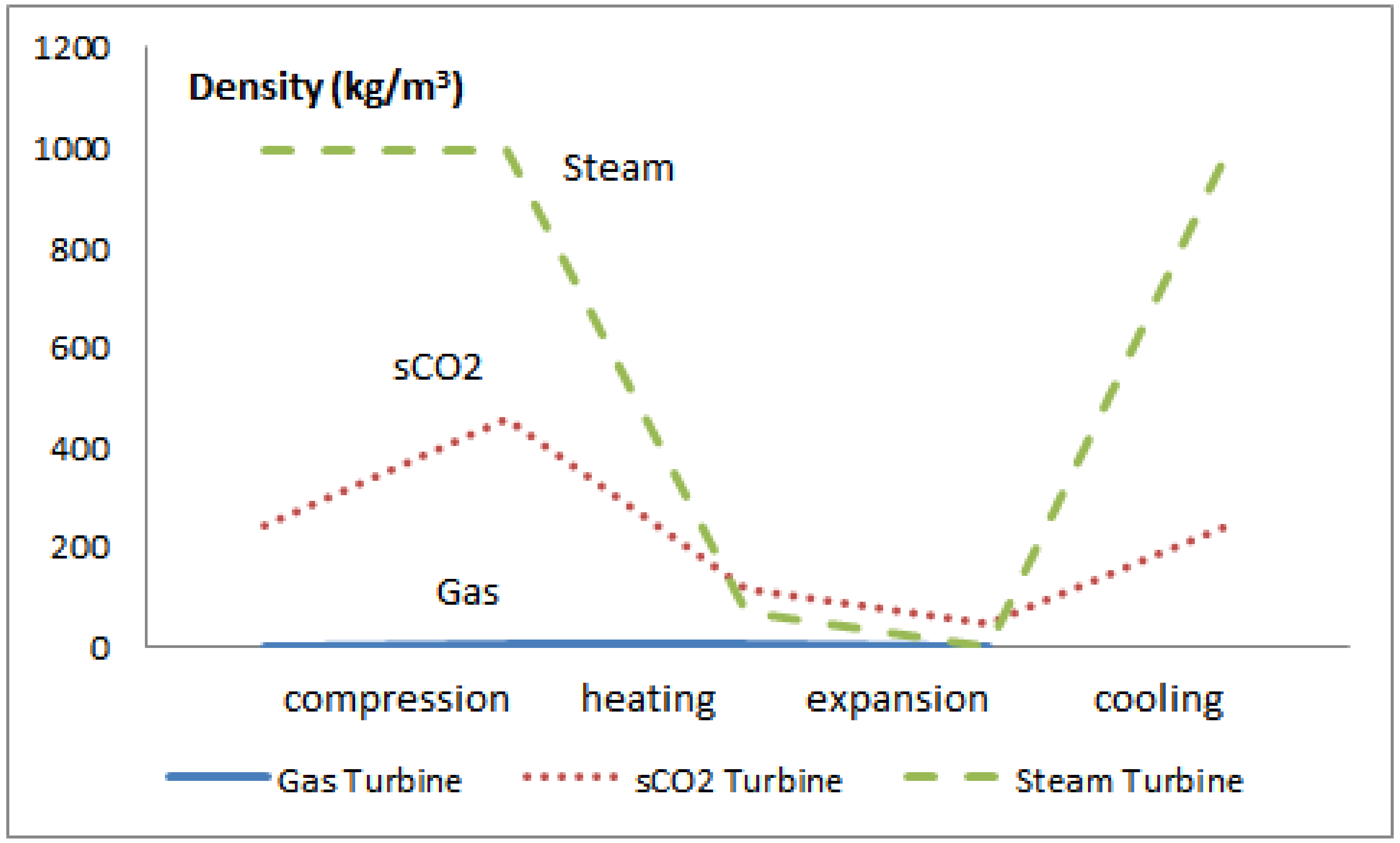
Materials for sCO_2 Applications - Outline

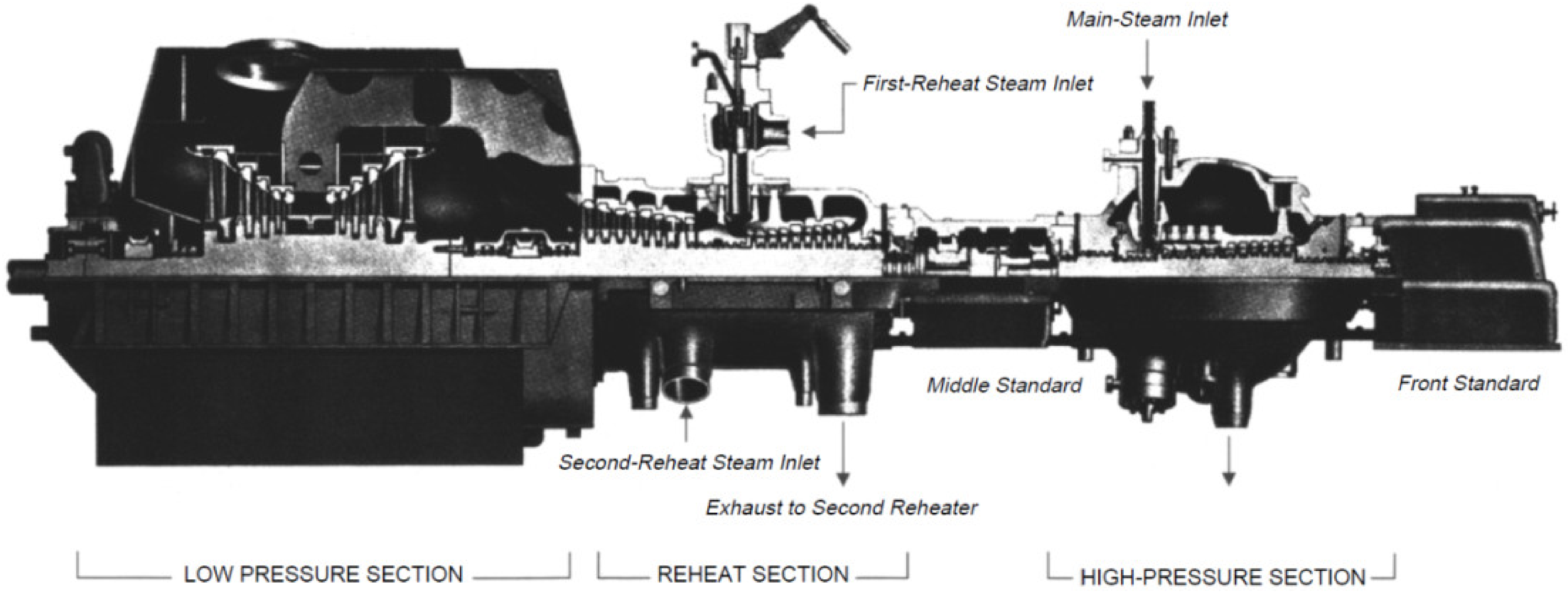
- **Heat engines (steam turbines, gas turbines, sCO_2 Brayton cycles) – higher temperatures lead to higher efficiencies**
  - e.g. gas turbine blades (increased strength, cooling, coatings)
- **Materials selection based on**
  - Properties for performance (strength – design codes, creep, toughness)
  - Cost
  - Compatibility with service environment
  - Lifetime
  - Processing (availability, fabricability, weldability, repairability)
- **Tutorial outline**
  - Power cycles and materials options (existing materials, AUSC development)
  - sCO_2 materials challenges
    - Corrosion and other testing
  - sCO_2 materials selection

Power Cycle Comparisons

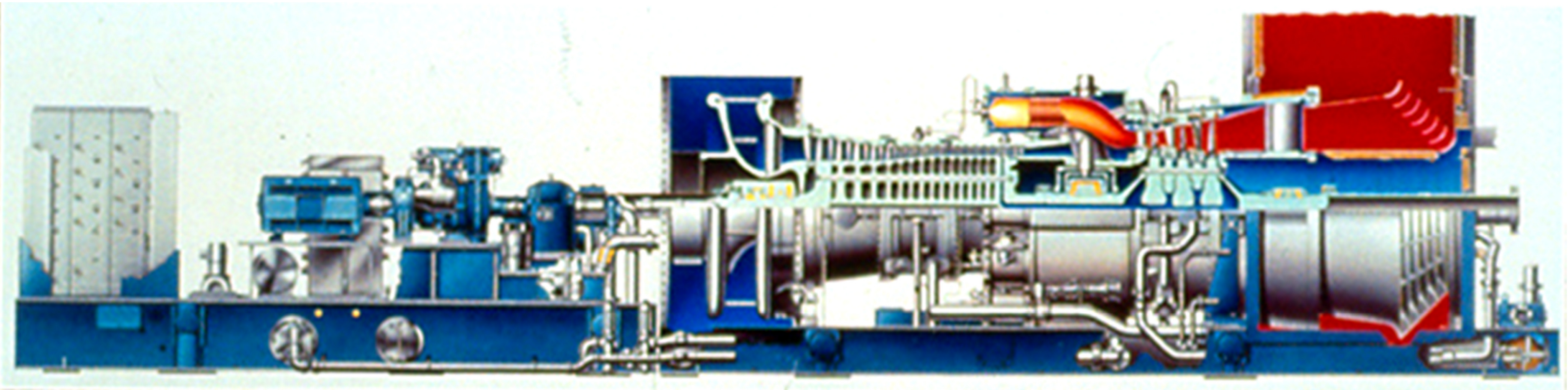






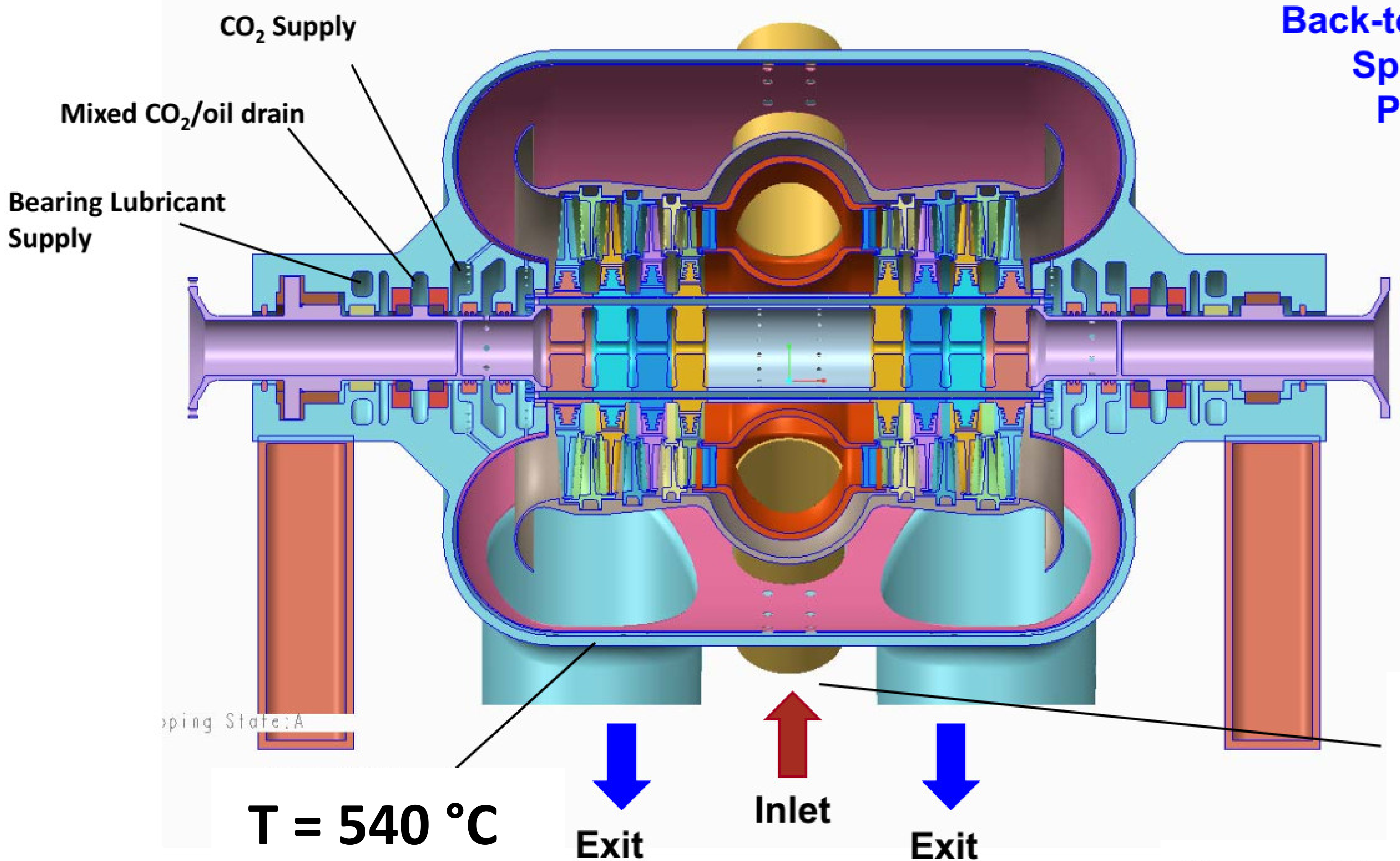


[Philo 6 Steam – Electric Generating Unit, ASME International, 2003]



[GE Power Systems]

sCO$_2$ Turbomachinery (550 MW$_e$ Plant)

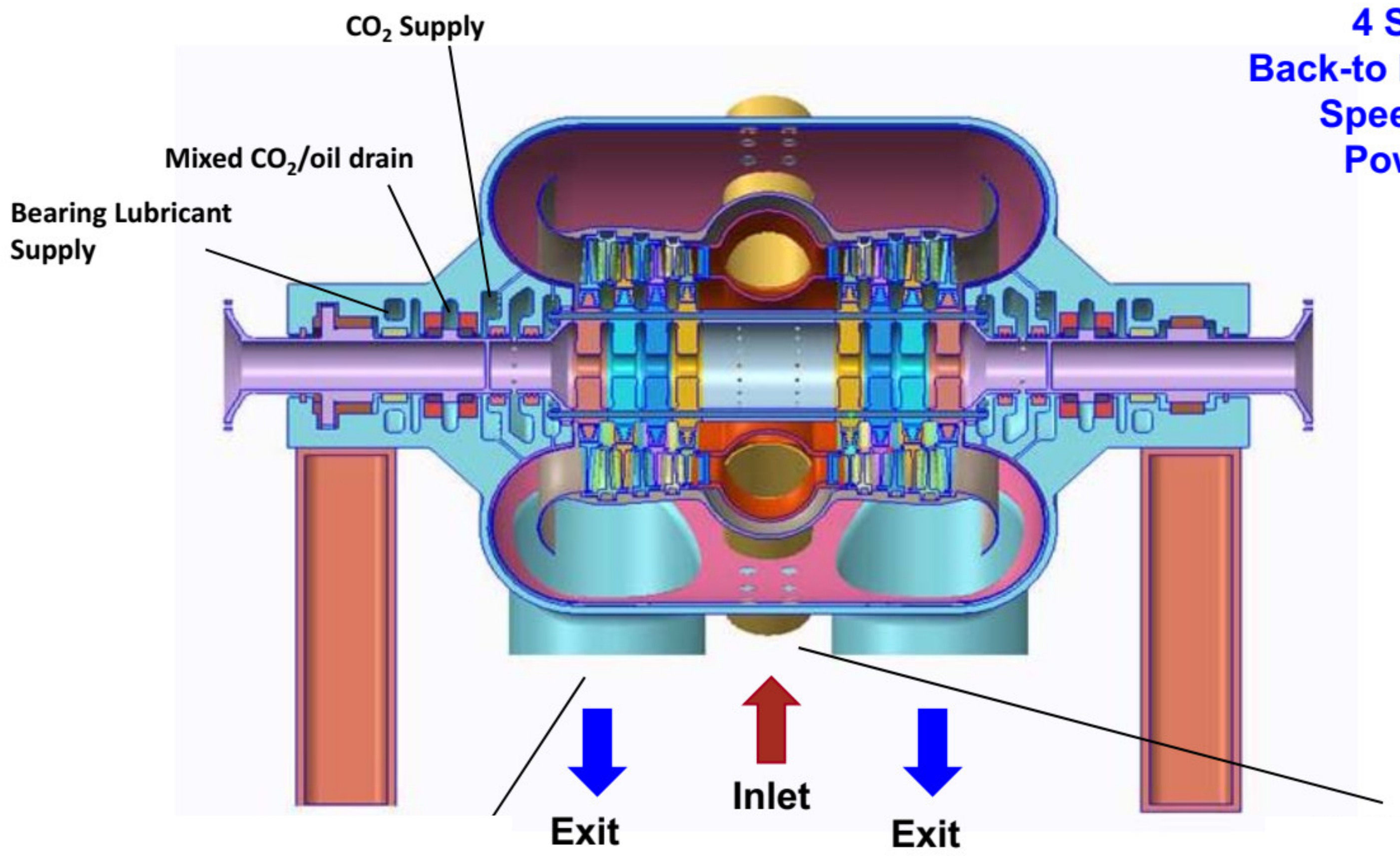


4 Stage Turbine
Back-to-back configuration
Speed = 3,600 RPM
Power = 550 MW

T = 540 °C
P = 8 MPa

T = 700 °C
P = 28 MPa

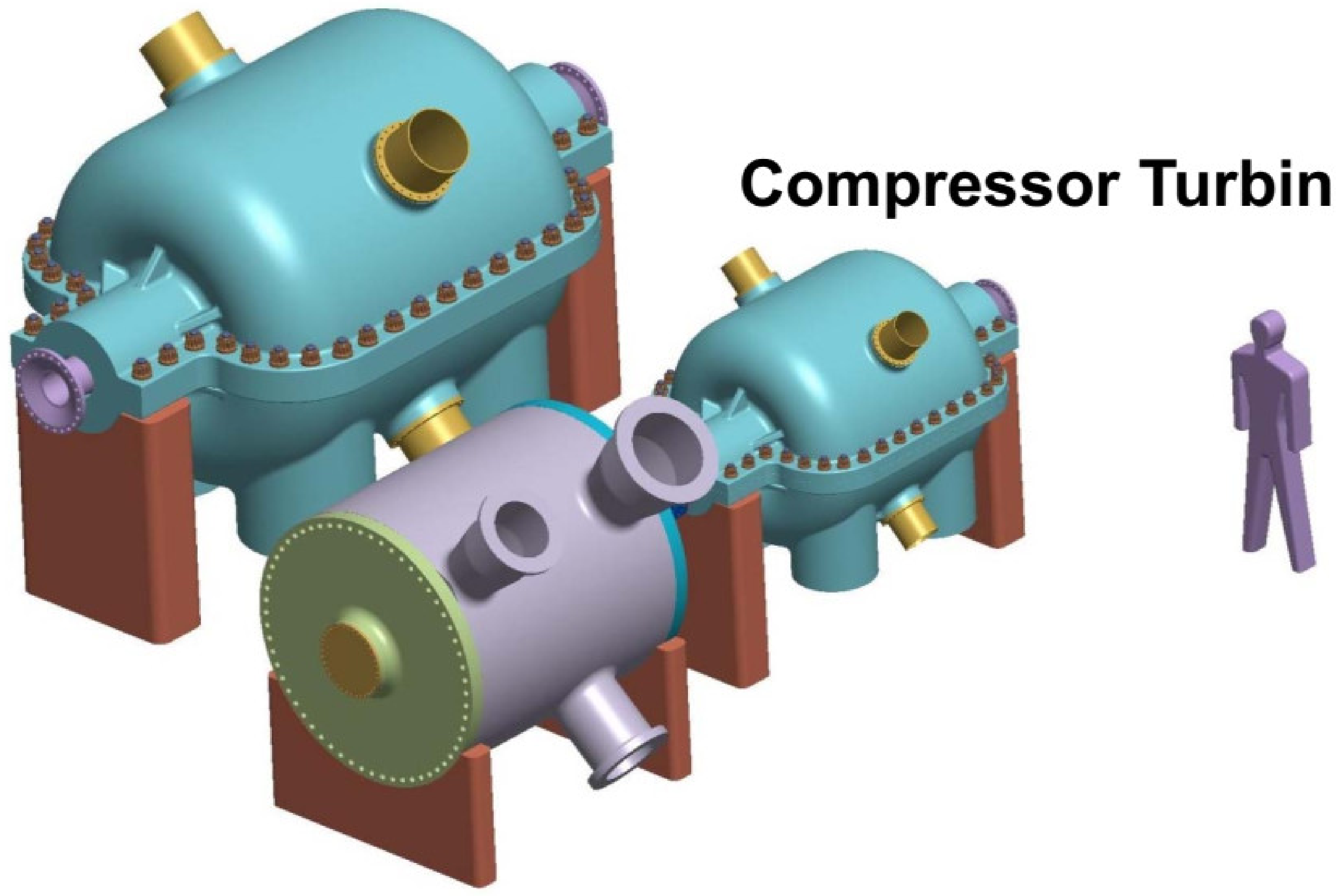
Power Turbine



4 Stage Turbine
Back-to back configuration
Speed = 6,000 RPM
Power = 220 MW

T = 540 °C
P = 8 MPa

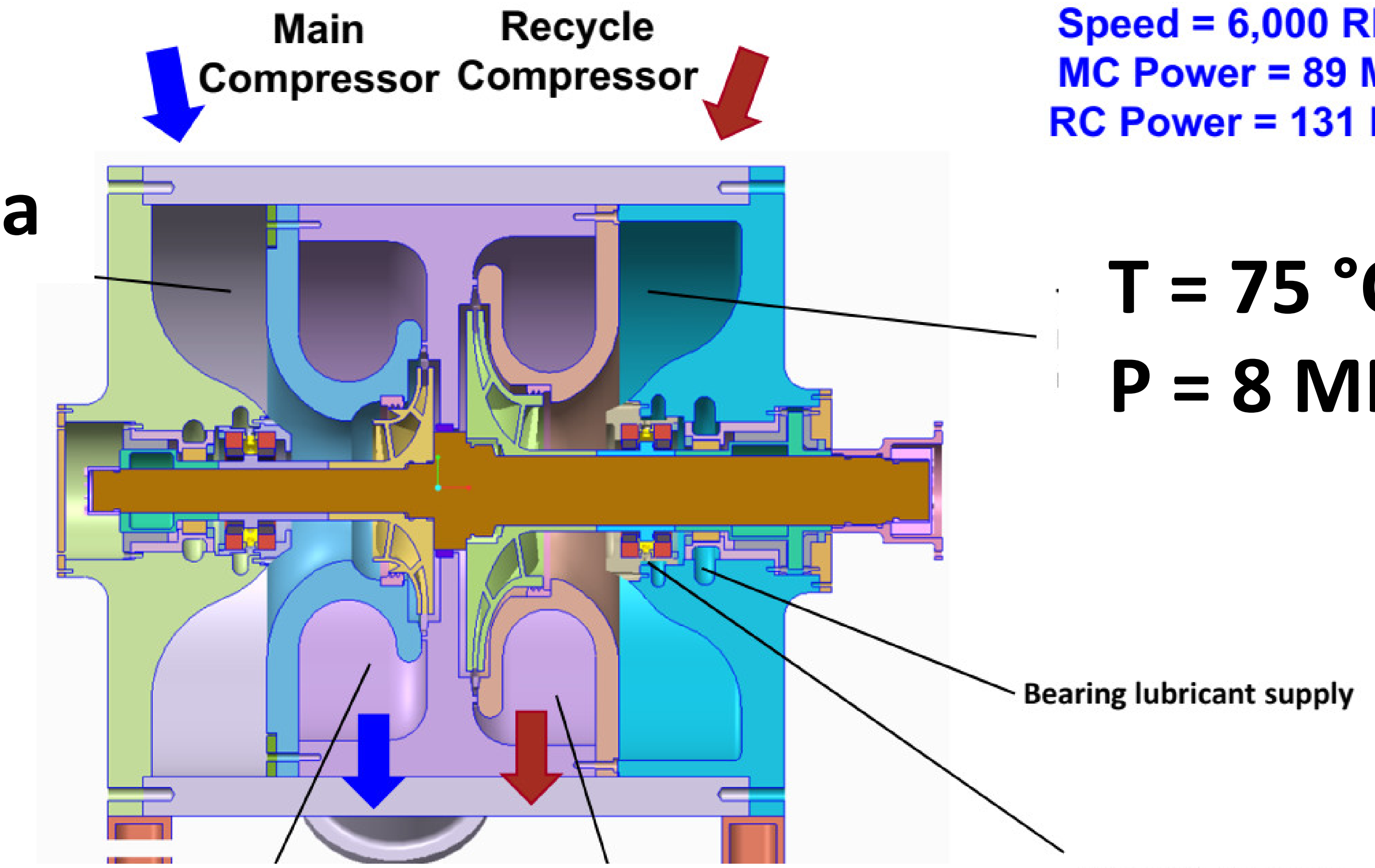
T = 700 °C
P = 28 MPa



Compressor Turbine

Compressors

[Eastland, 2015]



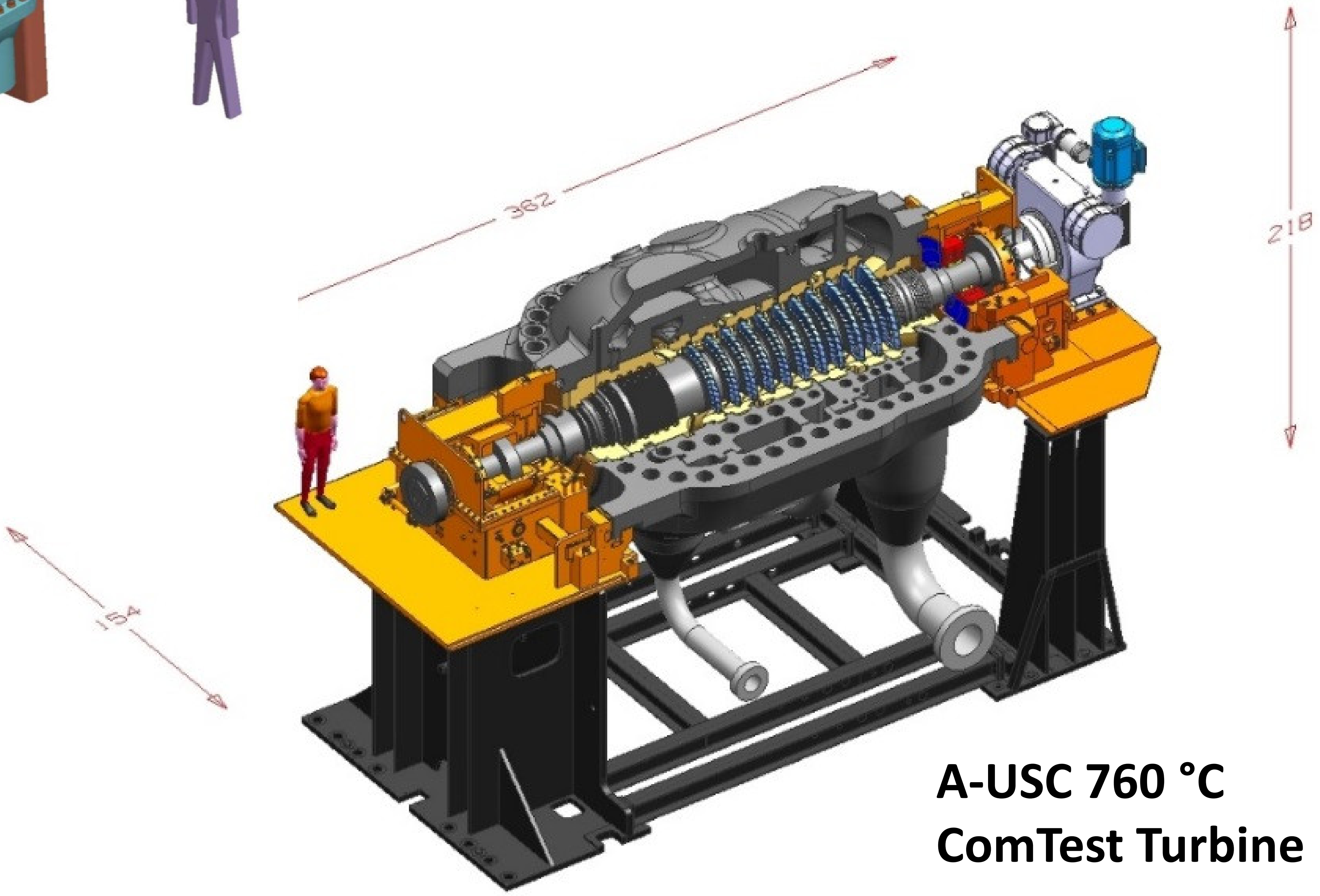
Speed = 6,000 RPM
MC Power = 89 MW
RC Power = 131 MW

T = 32 °C
P = 8 MPa

T = 75 °C
P = 8 MPa

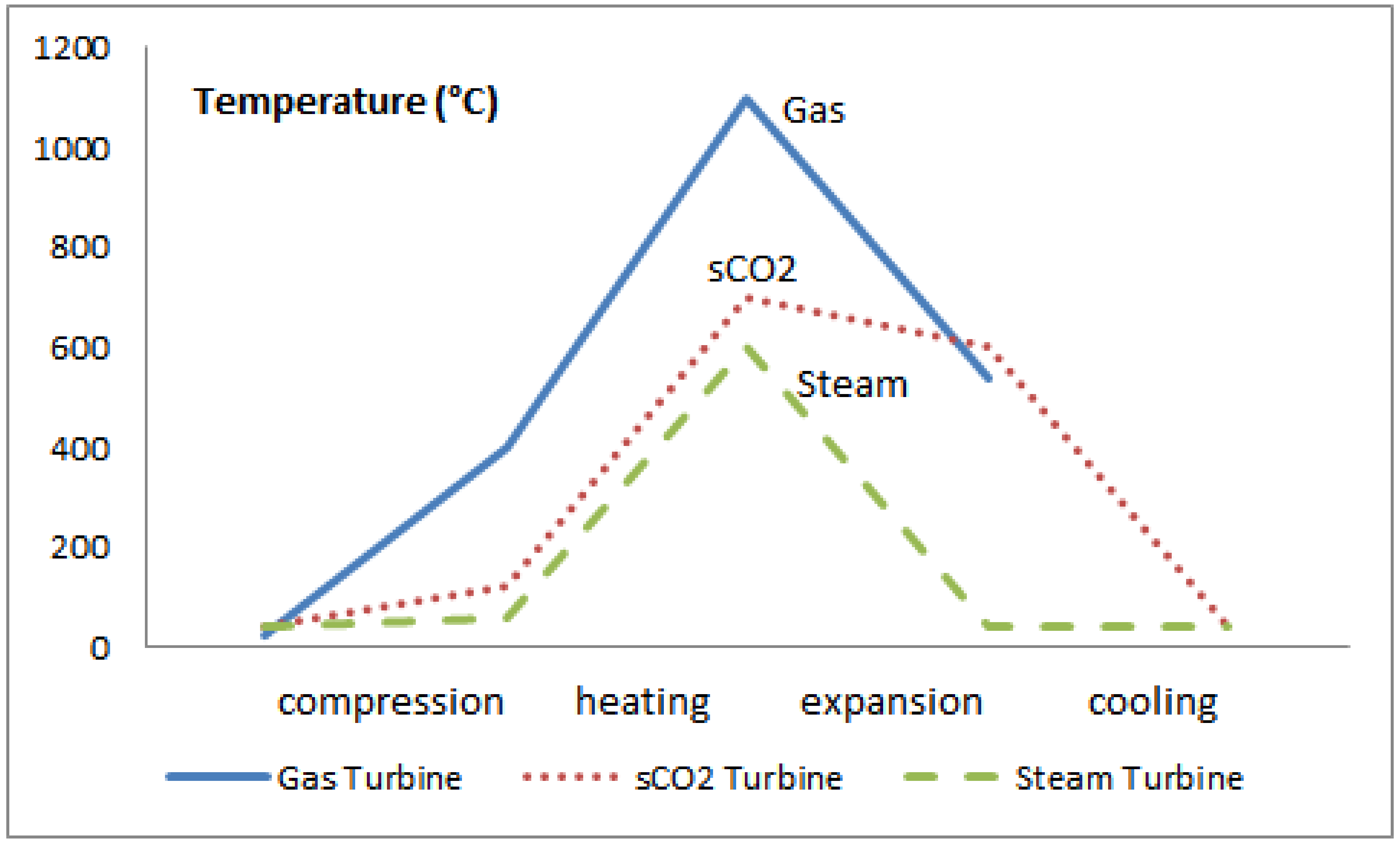
T = 70 °C
P = 28 MPa

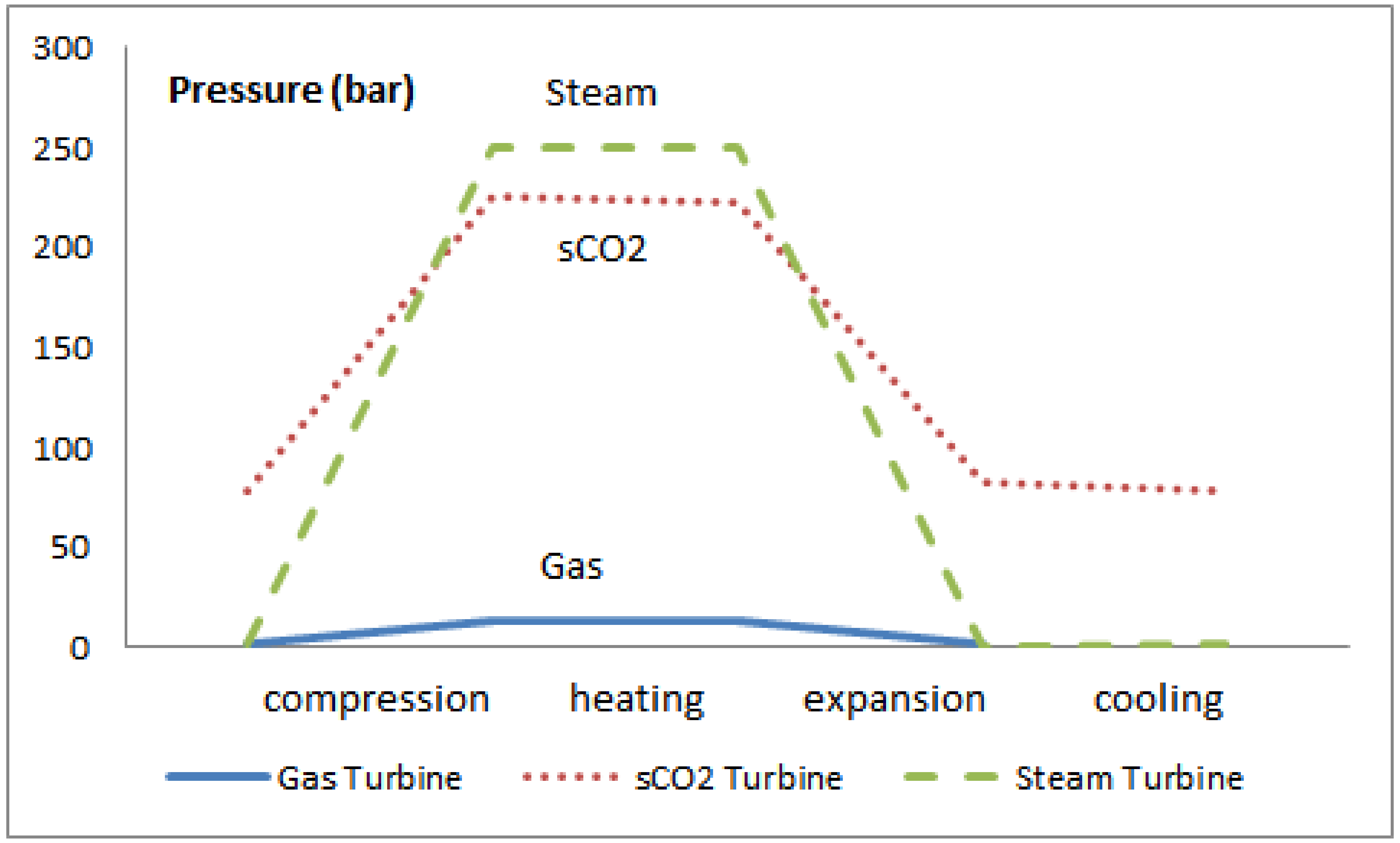
T = 200 °C
P = 28 MPa

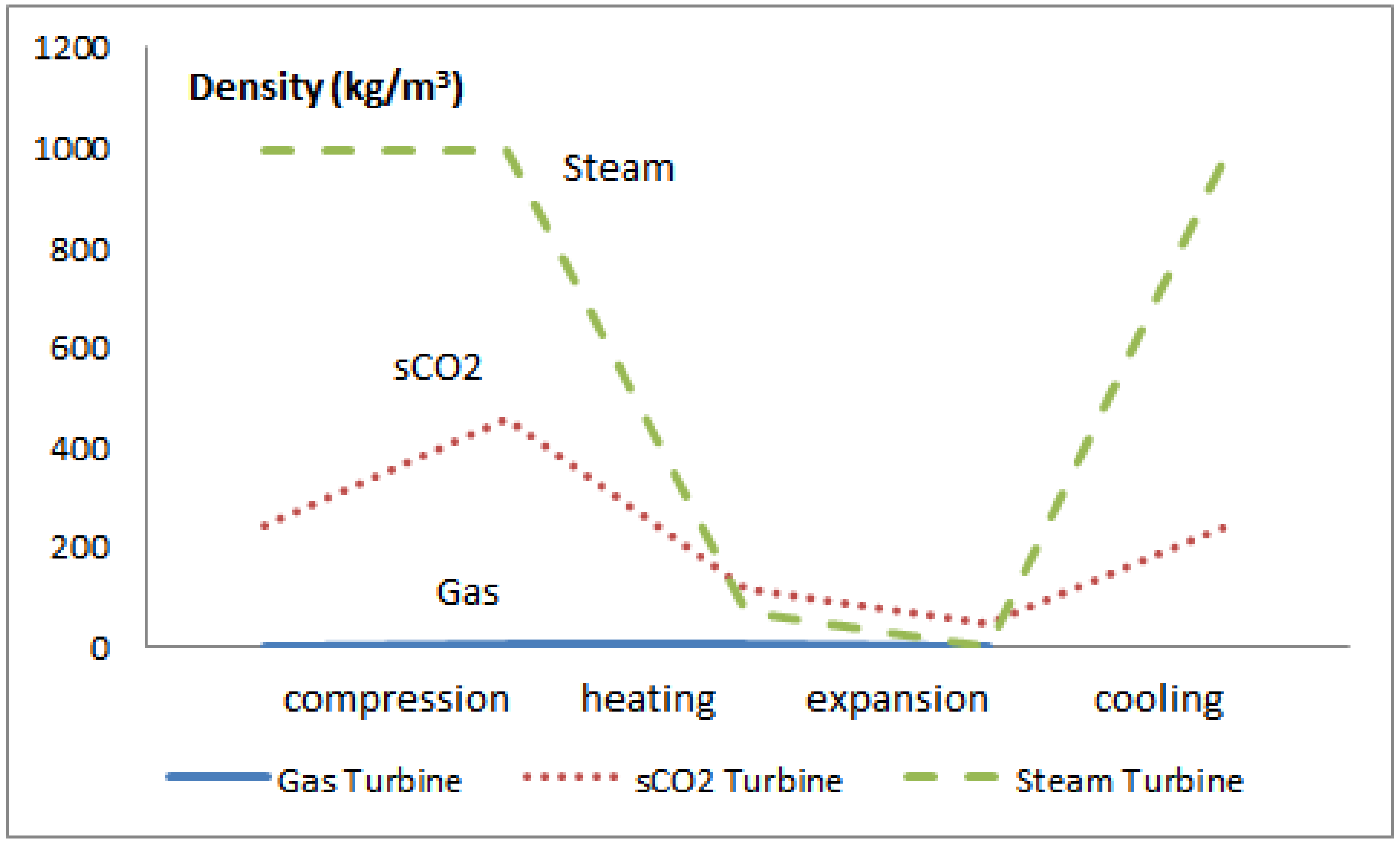


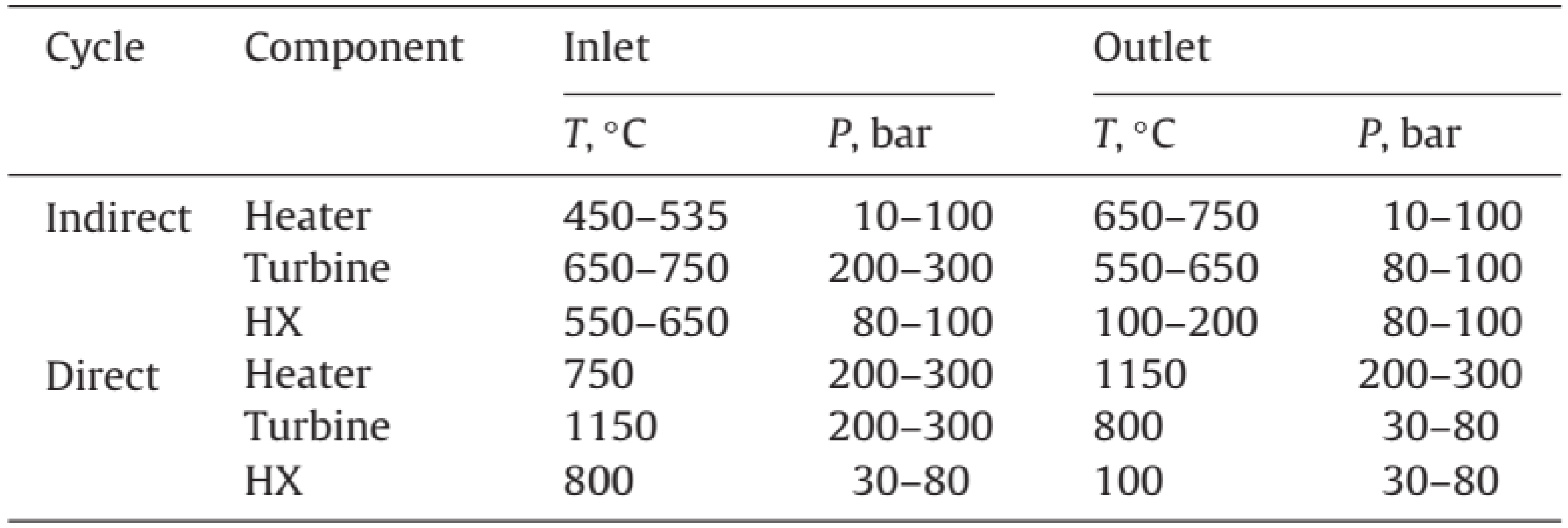
A-USC 760 °C ComTest Turbine

Power Cycle Comparisons









Cycle	Component	Inlet		Outlet	
		T, °C	*P*, bar	*T*, °C	*P*, bar
Indirect	Heater	450–535	10–100	650–750	10–100
	Turbine	650–750	200–300	550–650	80–100
	HX	550–650	80–100	100–200	80–100
Direct	Heater	750	200–300	1150	200–300
	Turbine	1150	200–300	800	30–80
	HX	800	30–80	100	30–80

Operating conditions in indirect- and direct-cycle sCO_2 power systems [Holcomb, 2016]

Materials performance and degradation identified as barrier to commercialization.

sCO_2 Brayton Cycle Materials Options

	COMPONENT	MATERIAL TYPE	SUPPORTING TECH BASE	RISK / RATIONALE
Heat Exchanger	HEX, <1,000F	Austenitic Stainless Steel	Various	High Technology Readiness Level (TRL) for lower pressures
	HEX, >1,000F	Ni-Cr, solid solution strengthened alloys	USC/A-USC Steam	sCO_2 oxidation, Weldable, moderate strength
Turbo-Machinery	Compressor Housing	Steel casting	UK Nuclear Magnox / AGR	High TRL for lower pressures
	Compressor Impeller	(trades incomplete)	Cryo Propellant Turbopump	High TRL, Low temp limits oxidation
	Compressor Rotor	Alloy Steel	Various	High TRL, Low temp limits oxidation
	Seals, Dry Gas	Ceramics / Cermet coating	Process Industries	Accelerated wear in sCO_2
	Turbine Housing	Ni-based casting alloys	A-USC Steam	Low TRL (in development)
	Turbine Disk	Ni-base superalloy	Gas / Power Turbine	Tech Base is shorter life, sCO_2 Oxidation, Creep
	Turbine Blade	High Cr, Ni-base superalloy Ni-base superalloy + Pt-Al	Gas / Power Turbine	Tech base is shorter life , sCO_2 Oxidation, Creep, HCF
	Ducts, <1,000F	Austenitic Stainless Steel	Various	High TRL for lower pressures
	Ducts, >1,000F	High Cr, Ni-base superalloy	USC Steam	Low TRL. Oxidation, Creep., Demonstrated weldability.
Balance-of-Plant	High Temp. Valves	Austenitic/Nickel-based	A-USC Steam	Intermediate TRL, not tested in service, supply chain questionable
	High Temp. Piping	Austenitic/Nickel-based	USC/A-USC Steam	High TRL, but supply chain is not established for many needed components

20 Years of DOE-funded AUSC Materials Research, $90M

- **Higher efficiency for new and existing fossil fuel plants**
  - +25% HHV efficiency improvement over the average U.S. power plants
  - 760˚C/1400˚F steam conditions drives the need to use nickel-based superalloys
- **Minimizing risk for utilities to build A-USC power plants**
  - Close technology gaps leading to commercial scale demonstration
  - Development of fabrication, welding, corrosion/materials database, …
- **Validation of technology applicable to multiple fossil, nuclear, sCO_2, and renewable power generation options**
  - Focusing on development of U.S. supply chain that can produce boiler and turbine components out of AUSC materials
  - Industry partnership under DOE demonstrating supplier readiness for fabricating 760˚C/1400˚F-capable components
- **ASME code case approval for two new alloys:**
  - Inconel ® 740H, CC-2702 (2012)
  - Haynes ® 282, CC-3024 (2021)
- **Fabrication demonstrations:**
  - Welding: DMWs, thick section, overlay
  - Forming: bending, extruding, swaging
  - Casting: flowability, modeling

Component	Method	Primary Alloy(s)	Key Dimensions
Main Steam Pipe/Header + Bends	Extrusion	Inconel ® 740H	25,000 lbs 22 x 3.7 inch
Hot Reheat Pipe/Header + Bends	Extrusion	Inconel ® 740H	25,000 lbs 28 x 1.5 inch
Header Assembly	Welding	740H, H282, stainless	About 14’ x 16’ 16 tube lengths
Membrane Panel	Welding	P92	10’ x 4’
Wye (VIM-ESR-VAR)	Forging	Inconel ® 740H	25,000 lbs
Nozzle Carrier / Shell	Casting	Haynes ® 282	21,000 lbs
Rotor (VIM-ESR-VAR)	Forging	Haynes ® 282	22,000 lbs

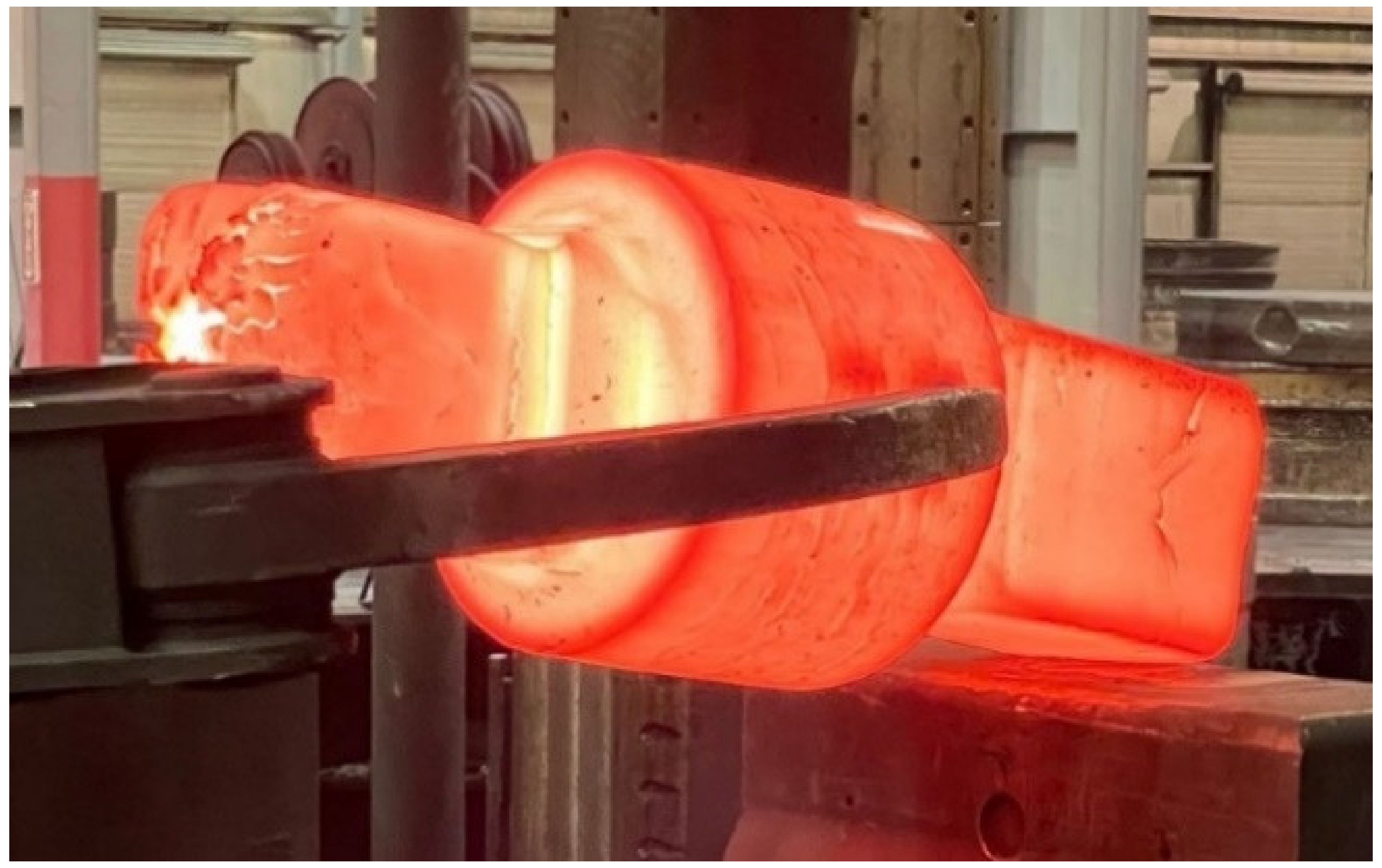
AUSC – Major Achievements in Material Research and Fabrication

Tubing Fabrication Demonstration

In-Plant Corrosion Demonstration

Final Header Assembly

H282 Rotor Forging (Mid-processing)



Header Welding Demonstration

First 740H Pipe Extrusion

H282 Valve Body Casting (after PT)

H282 Nozzle Carrier Casting

sCO_2 Materials Technical Challenges

Current Knowledge

- **Existing materials/mechanical properties**
  - OK for main components (piping, valves, turbomachinery, etc.)
- **Environmental considerations – high temperature sCO_2**
  - Corrosion testing – short-term, coupons, representative temps/pressures, mass gain (vs. depth)

Gaps Remaining/Technical Challenges

- **Availability**
  - Code compliant materials/qualified alloys; design codes
  - Supply chain – in required forms and sizes
- **Environmental considerations – high temperature sCO_2**
  - Longer-term (short-term testing inadequate – breakaway corrosion, intergranular corrosion)
  - Testing under “real” conditions (flow, stress, impurities – H_2O, O_2, others; indirect vs. direct cycles)
  - Reliability of data
  - Mechanical property degradation
- **Performance of actual components/material forms**
  - Thin sections – property differences, effect of geometry
  - Diffusion bonded, brazed, welded joints – corrosion resistance
  - Erosion, fouling of microchannel heat exchangers
  - Thermal fatigue, creep-fatigue interactions, high blade bending loads/temperature + pressure combinations
- **Other challenges and considerations**
  - Cost-effective alloys
  - Higher temperature applications
  - Coatings
  - Non-metallics – degradation of seals via swelling, rapid gas depressurization
  - Leverage previous work – comparison to steam and SCW corrosion, pressure effects

Materials are available…but there are knowledge gaps…efforts are required to complete the picture.

Materials in CO_2 Environments – Before ~2008

Previous Knowledge

- **CO_2 gas-cooled Magnox reactors**
  - Many reactor years of operation
  - Structural material behaviour well-characterized
  - High temperature (650 °C) but low pressure ($< P_c$)
  - Corrosion rates higher during operation
  - Breakaway corrosion caused by exfoliation and nucleation of oxides – mainly influenced by exposure time and/or CO_2 gas pressure
- **Oil and gas industry CO_2 experience**
  - Enhanced oil recovery (EOR), CO_2 transport pipelines
  - Effects of contaminants
  - High pressure (<21 MPa) but low temperature (< 200 °C)
  - Pure, dry – virtually inert < 500 °C
  - Significant corrosion of steels and nickel alloys with ppm H_2O, > 600 °C
  - Austenitic alloys better than ferritic-martensitic steel
  - High levels of Cr and Ni increase corrosion resistance

Materials in CO_2 Environments – 2008-2023

Recent Corrosion and Other Testing

- **Fundamentals (oxidation and carburization)**
  - Mechanisms and scales
- **Testing results**
  - Weight gain, oxidation scales
  - Factors affecting corrosion
    - Temperature, pressure, impurities
    - Materials (alloying, structure, thickness, etc.)
    - Effects of stress
- **Materials selection strategy**
  - Strength and corrosion vs. temperature
- **Recent review paper (Li et al. 2023)**
  - Progress in Materials Science 136 (2023)
  - State of the art overview material degradation in high-temperature supercritical CO_2 environments

sCO_2 Corrosion Fundamentals

CO_2 Corrosion at Elevated Temperatures

- Oxidation

$$xM + yCO_2 = M_xO_y + yCO$$

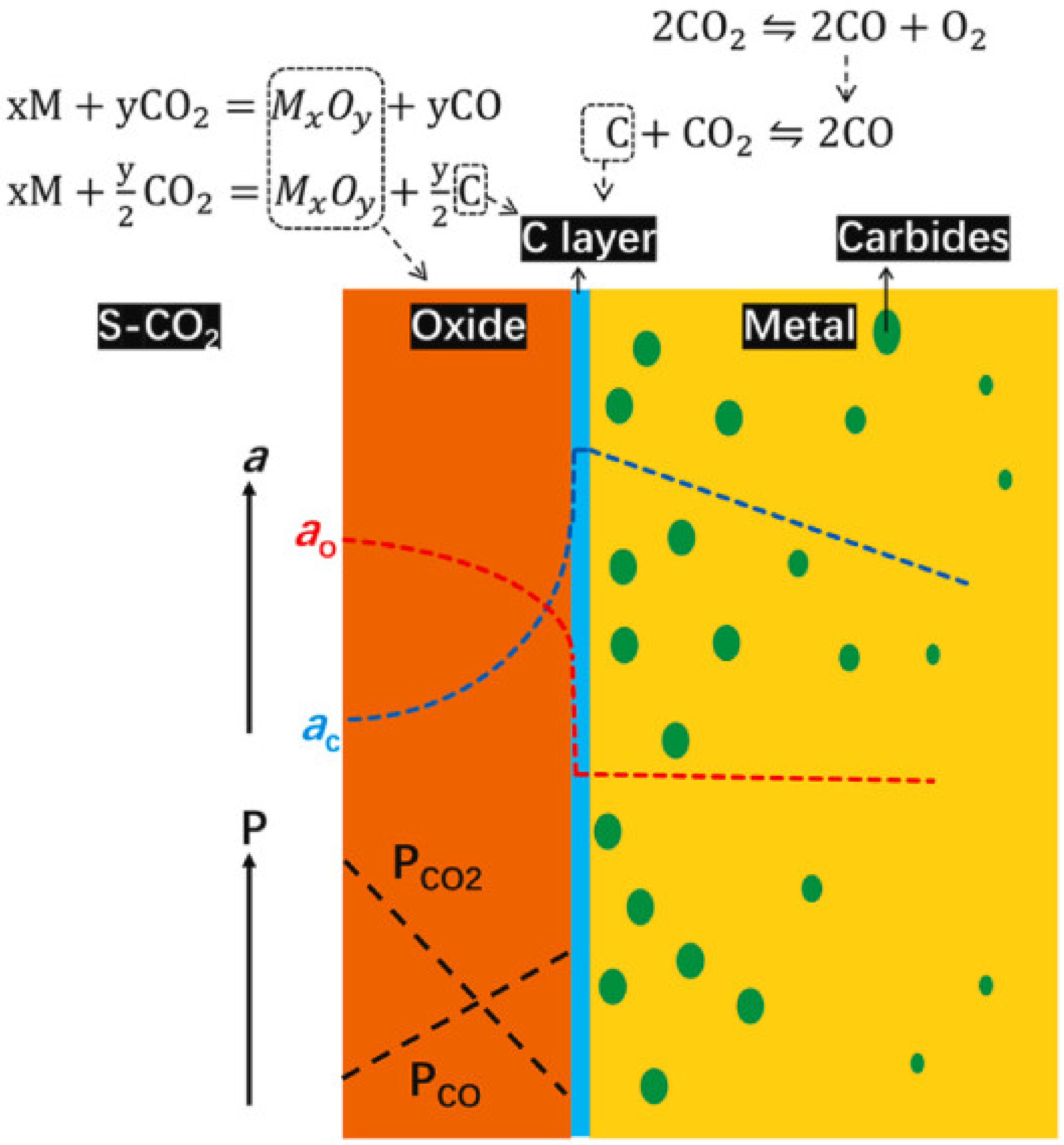
$$xM + (y/2)CO_2 = M_xO_y + (y/2)C$$

  - Oxygen partial pressure high enough to induce oxidation
  - Formation of oxide layer
- Carburization

$$2CO_2 \leftrightarrow 2CO + O_2$$

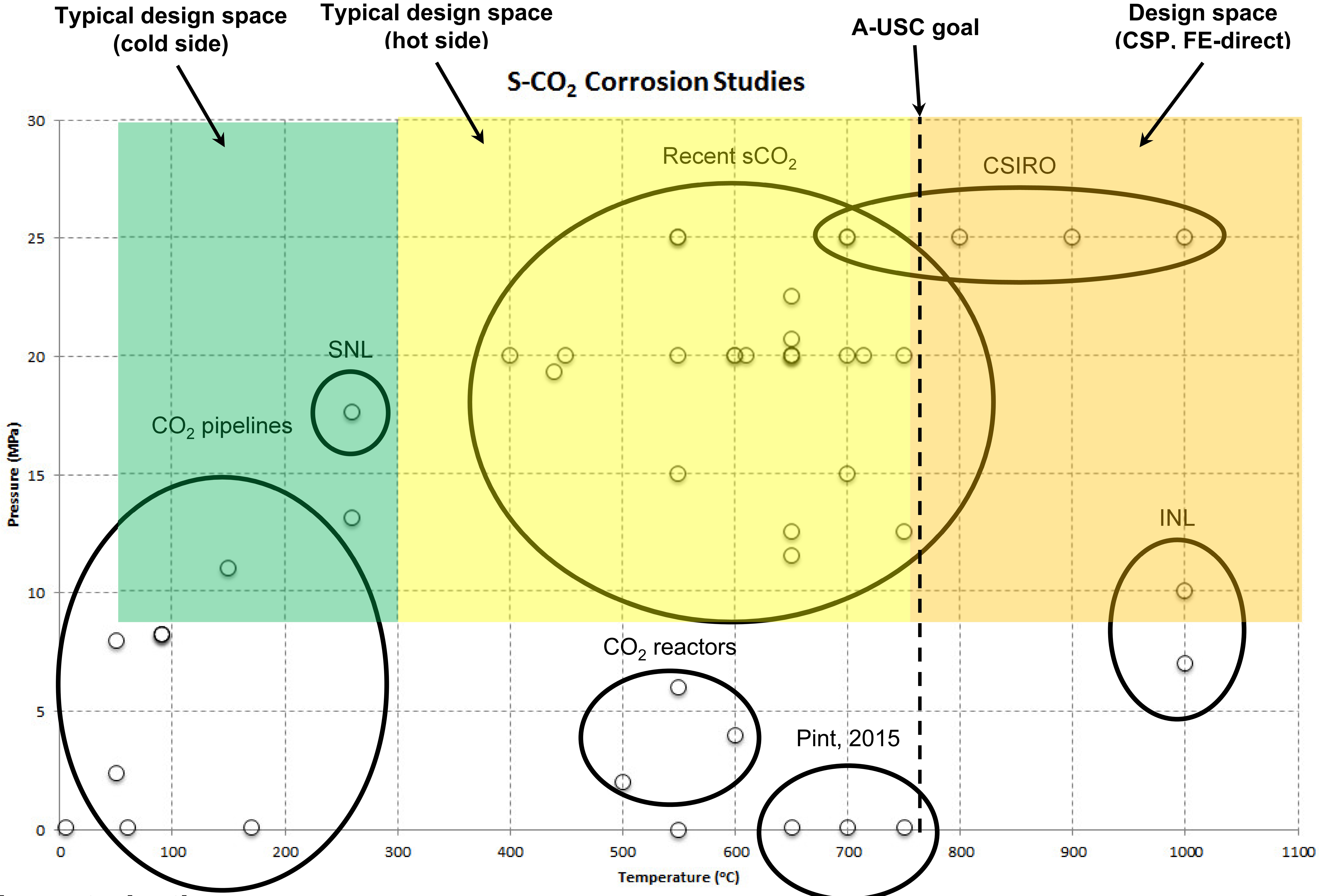
$$2CO_2 \leftrightarrow CO_2 + C$$

  - Penetration of C through the oxide layer
  - Reaction with metallic elements



[Li et al., 2023]

(High Temperature) sCO_2 Corrosion Testing



- **Characterization**
  - Weight gain/corrosion layer thickness
  - Scales/mechanisms
- **Various materials tested (steels (FM, austenitic), nickel alloys)**

sCO_2 Corrosion Testing – Weight Gain

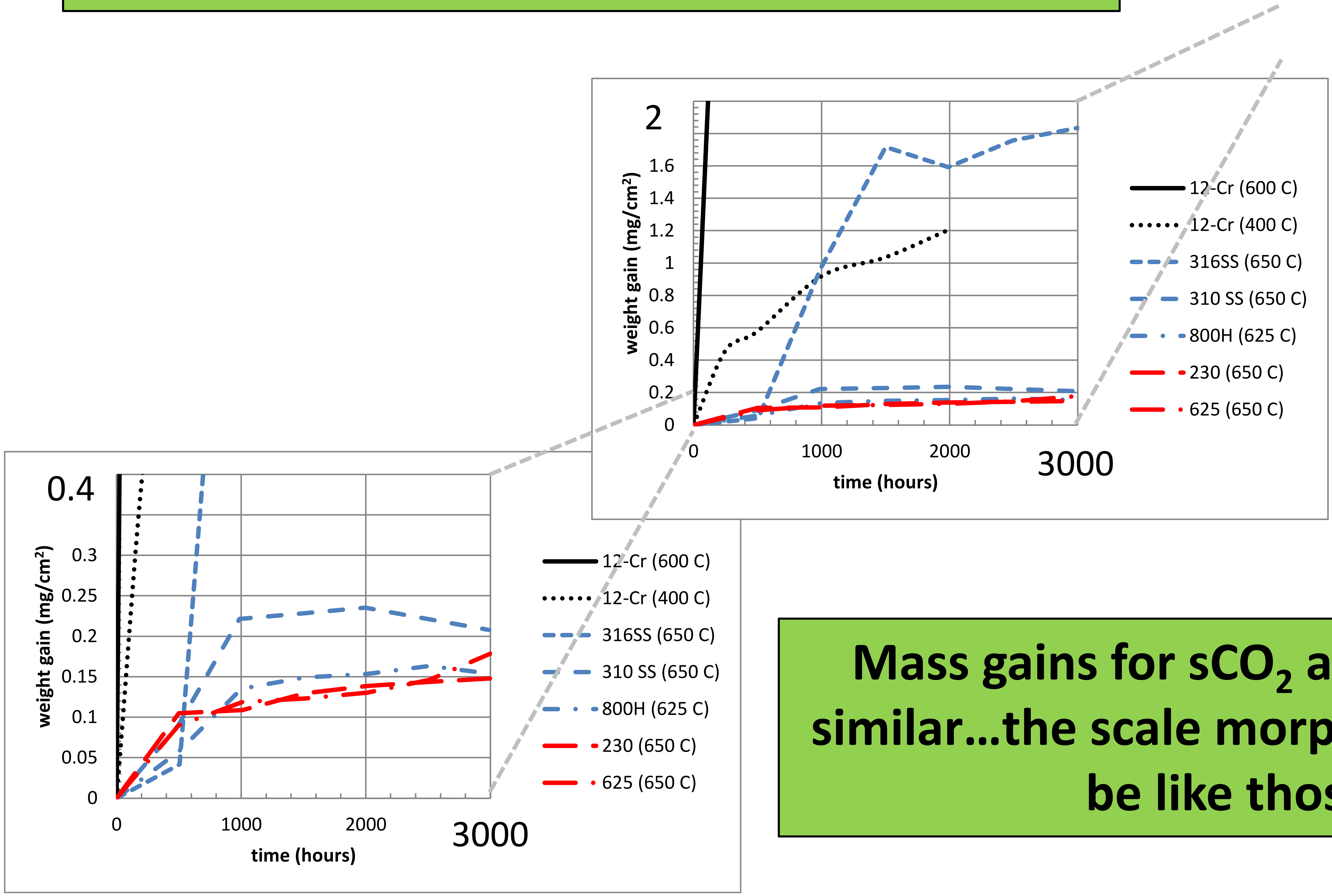
General Weight Gain Trends

FM > austenitic > nickel-base

Fe-Cr (<12% Cr) > Fe-Cr-Ni (>16% Cr) > Ni-Cr-X (>16% Cr)

12

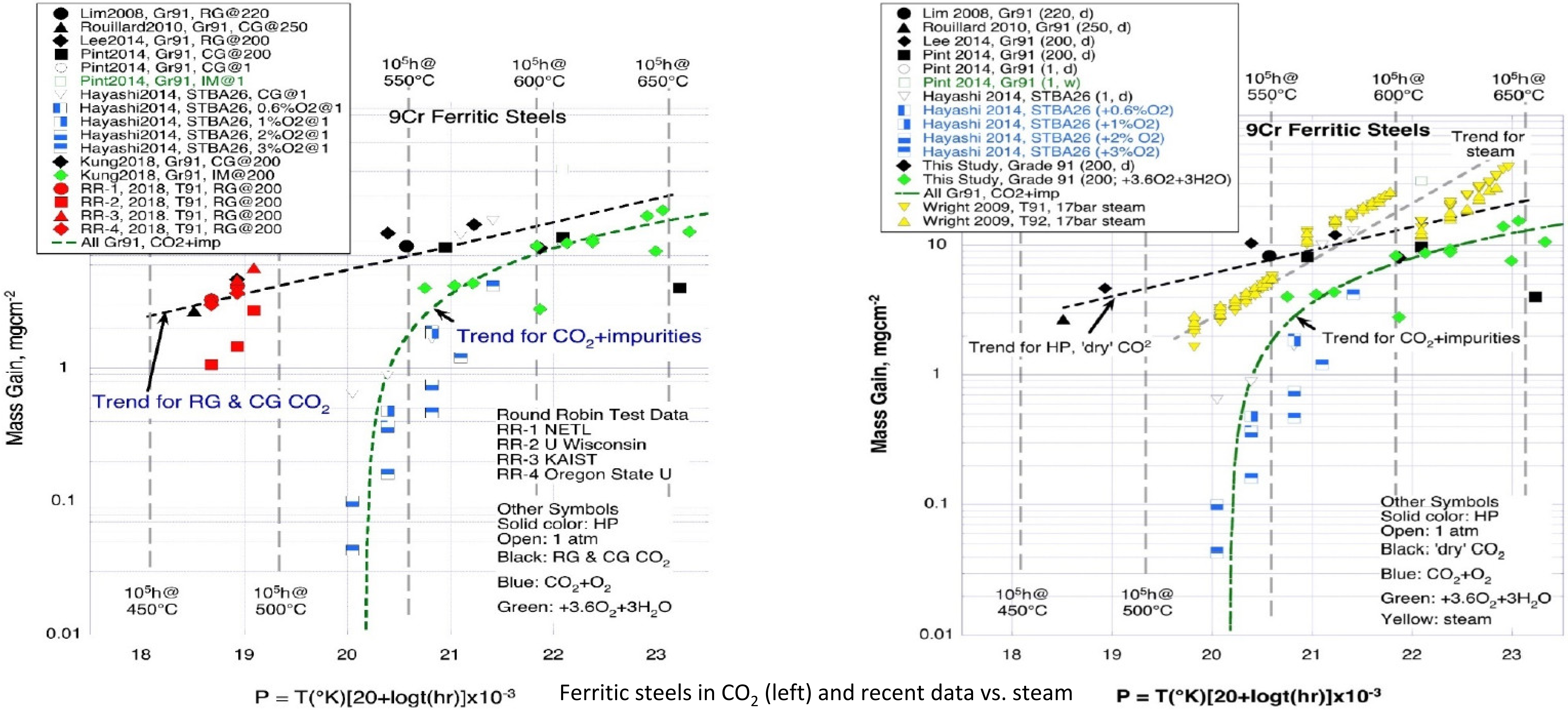
3000



Mass gains for sCO_2 and steam are approx. similar…the scale morphologies in sCO_2 would be like those in steam

sCO_2 Corrosion Testing – Weight Gain

Ferritic-Martensitic Steels



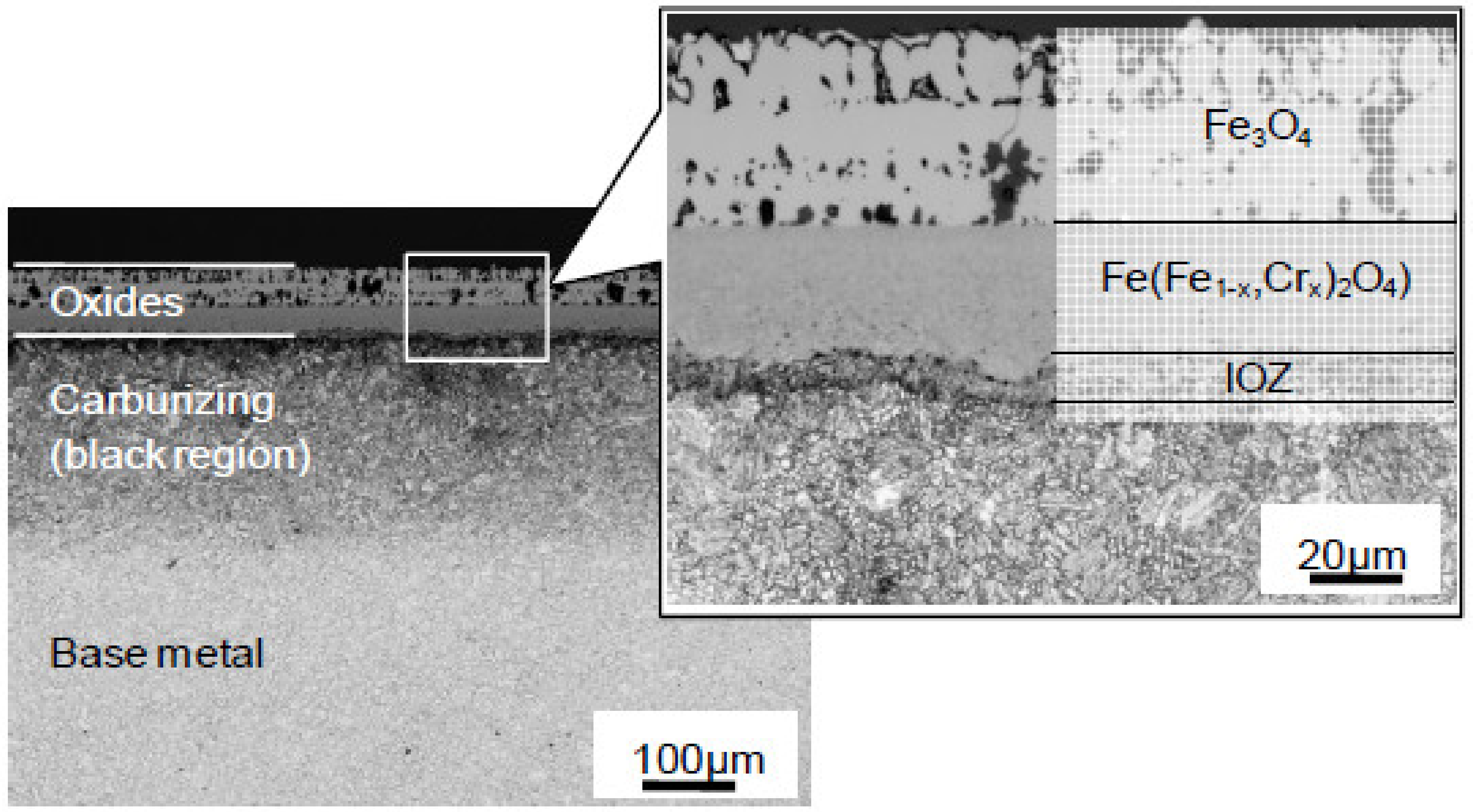
Ferritic steels in CO_2 (left) and recent data vs. steam (right) [Kung, 2018]

- Larson-Miller plots for comparison
- Mass gain plotted
- CO_2 and recent sCO_2
- Recent sCO_2 and steam

Mass gains for sCO_2 and steam are approx. similar…the scale morphologies in sCO_2 would be like those in steam

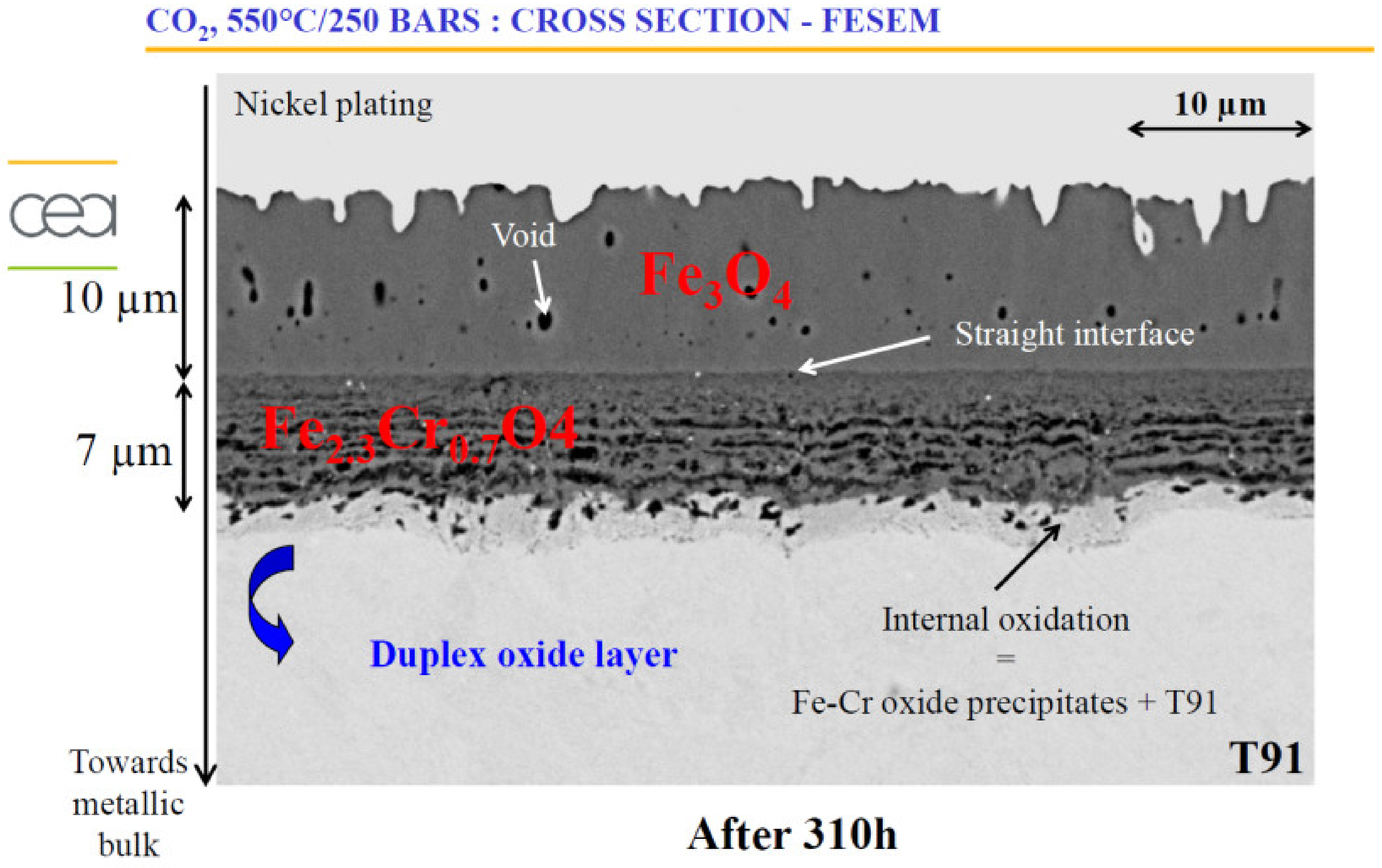
sCO_2 Corrosion Testing – Corrosion Scales

Ferritic-Martensitic Steels



(a) 12Cr-steel, 20MPa 600ºC 1000h

[Furukawa et al., JPES, 2010]



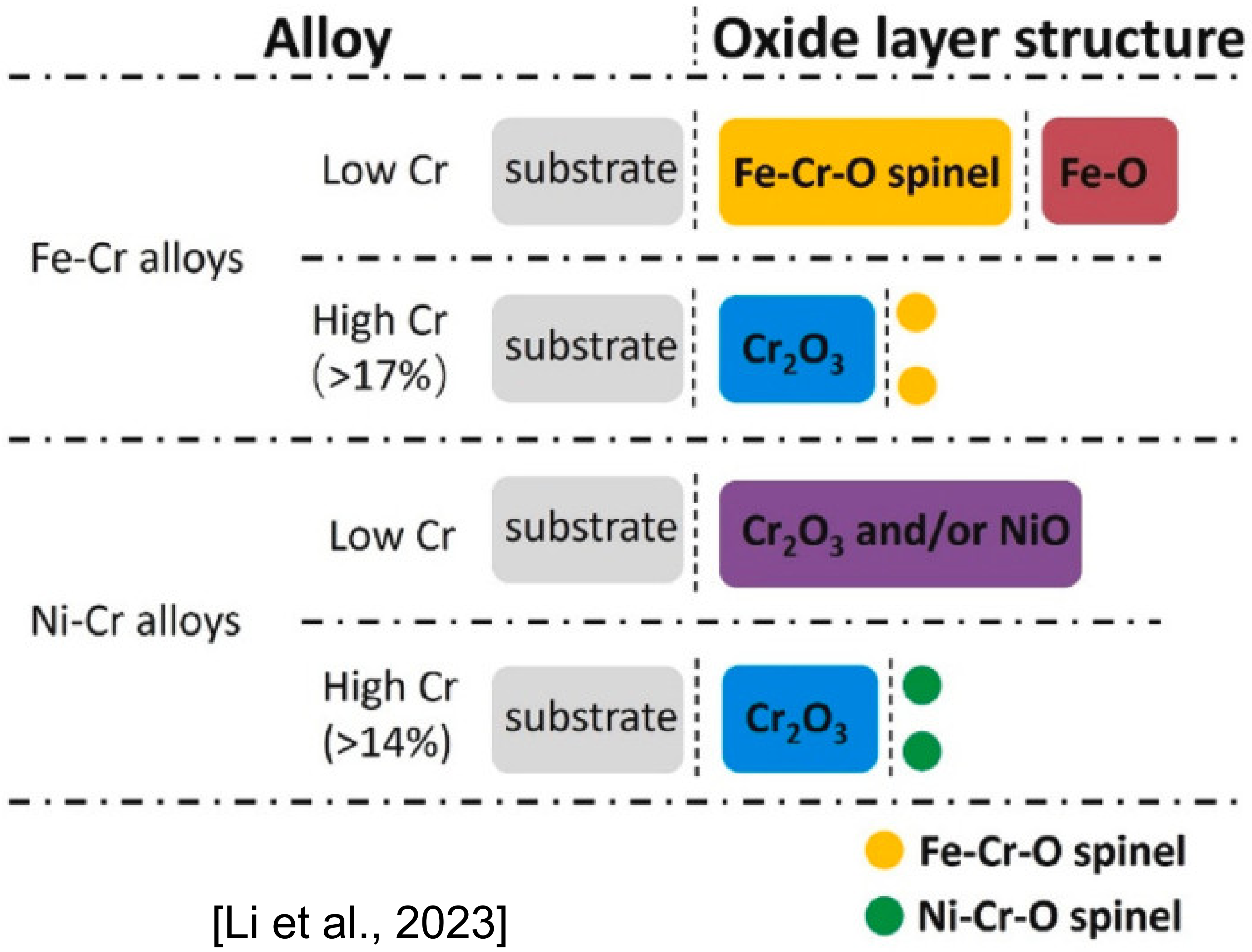
[Rouillard, sCO_2 PCS 2011]

- 12Cr Martensitic steel
- Two successive layers, no breakaway corrosion
  - Outer: Fe oxide, Fe_3O_4
  - Inner: Fe+Cr oxide, $Fe(Fe_{1-x},Cr_x)_2O_4$
- Thin internal oxide zone (IOZ) between base metal and inner layer
- Carburizing observed near surface in base metal
  - Factor in breakaway corrosion, degradation of ductility

- T91 9Cr F-M steel
- Duplex oxide layer
  - Outer: magnetite, Fe_3O_4
  - Inner: spinel, $Fe_{3-x}Cr_xO_4$
- Internal oxidation also
- Extrapolation to 20 years
  - Corrosion layer thickness = 500 µm
- Static tests at 50 °C @ 10 MPa
  - No corrosion observed
- Flowing CO_2
  - Similar oxide scale at 550 °C @ 1 bar (+ outer Fe_2O_3 haematite)

sCO_2 Corrosion Testing – Corrosion Scales

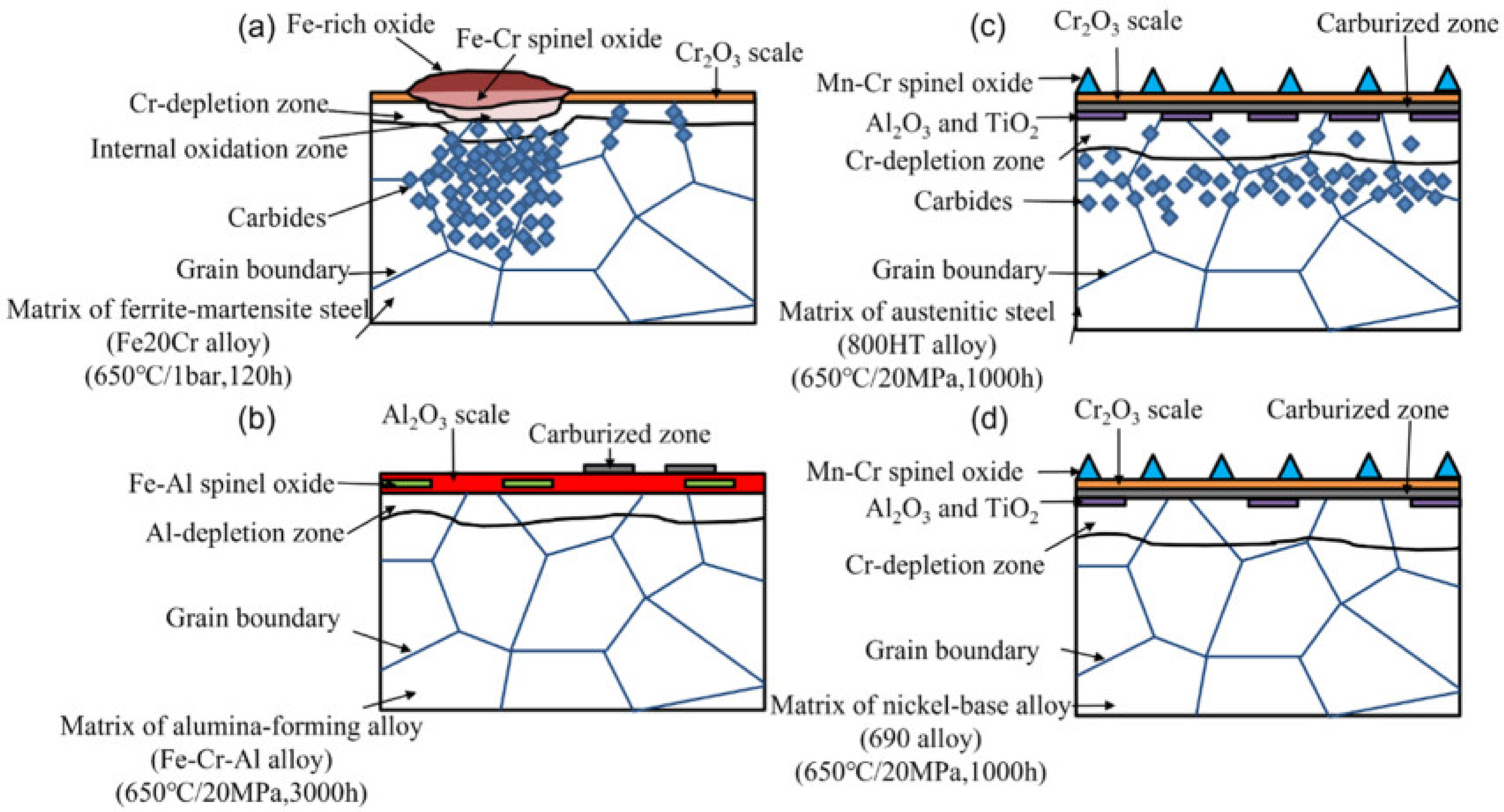
Schematics of Corrosion Scales for Various Alloy Systems



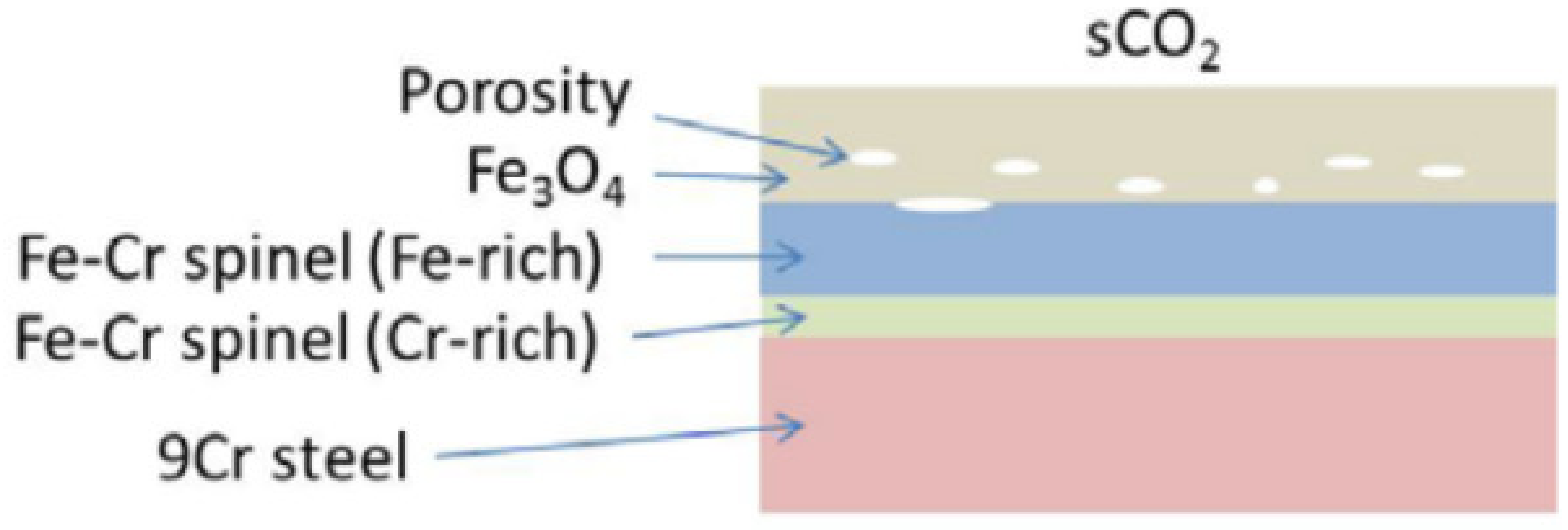
Alloy		Oxide layer structure		
Fe-Cr alloys	Low Cr	substrate	Fe-Cr-O spinel	Fe-O
	High Cr (>17%)	substrate	Cr_2O_3	🟡 🟡
Ni-Cr alloys	Low Cr	substrate	Cr_2O_3 and/or NiO	
	High Cr (>14%)	substrate	Cr_2O_3	🟢 🟢

🟡 Fe-Cr-O spinel
🟢 Ni-Cr-O spinel

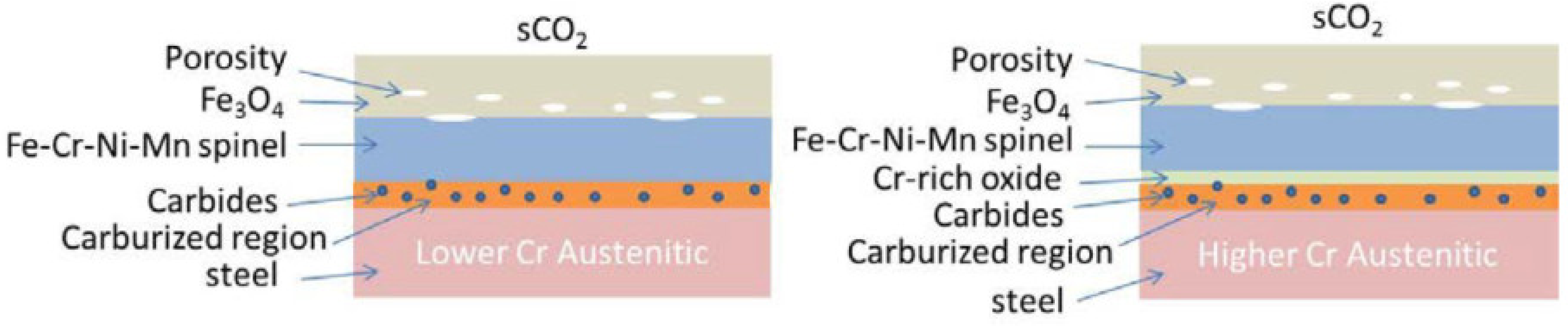
[Li et al., 2023]



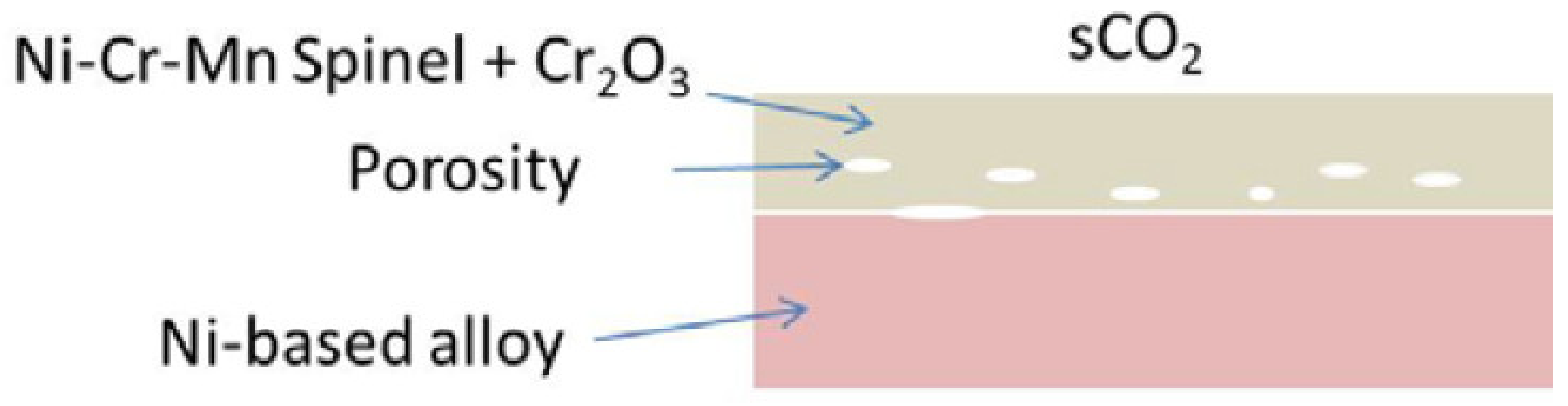
(a) FM steel (b) austenitic steel (c) AFA (d) nickel-base alloy [Yang et al., 2022]



9-Cr steels [Strakey, 2014]



austenitic steels [Strakey, 2014]



nickel-base alloys in sCO_2 [Strakey, 2014]

sCO_2 Corrosion Testing – Factors

- **Temperature**
  - Most important factor – increasing temperature leads to increasing corrosion
  - Parabolic growth breaks down, scale becomes non-protective, breakaway corrosion
  - However, are there any “surprises” at low temperatures
  - Very high temperatures?
    - Coatings, very high temperature materials, cooling schemes
- **Pressure**
  - No “real” consensus
  - As pressure increases, oxidation and carburization increase?
    - Some results show increased weight gain
    - Going from 0.1 to 20 MPa has minimal effect
    - Some results show more protective scale
    - Infiltration of C becomes easier – more carburization?

sCO_2 Corrosion Testing – Factors

- **Impurities**
  - Indirect cycles: ppm levels
  - Direct cycles: % levels
  - Corrosion behaviour expected to change as thermodynamics and kinetics change
  - Various results
- **Alloying**
  - Cr – determines corrosion resistance of alloys – chromia stable oxide, good protection
    - High Cr favours Cr_2O_3
    - Low Cr fails to form continuous scale – less protective, prone to internal corrosion
  - Ni – Ni-base alloys show better carburization resistance than steels
    - Facilitates stable chromia layer
    - Higher solubility of carbides – higher tolerance to C
  - Al – improves corrosion resistance by forming protective alumina layer
    - Higher stability, lower oxidation kinetics, higher resistance to C

sCO$_2$ Corrosion Testing – Factors

- **Component thickness**
  - Must consider tolerance of corrosion-induced thickness loss
    - Due to oxidation and carburization
    - Strength considerations
  - Thicker sections have better corrosion resistance
    - Alloy reservoir
  - Also consider component geometry
- **Welding and joining**
  - Heat affected zone, microstructural changes, segregation of alloying elements
    - Leads to weak points, can affect corrosion and mechanical behaviour of the joints
  - Alloys with poor corrosion resistance will be worse after welding
  - Fe- and Ni-base alloys with high alloying levels may not be so affected
- **Coatings**
  - Application of coatings to protect metal substrate
  - Reduce oxidation and carburization – may allow application of low-alloyed materials

sCO$_2$ Corrosion Testing – Factors

- **Stress-assisted corrosion**
  - Combined effects of mechanical loading/stresses and corrosion will accelerate material degradation leading to early failure
  - Tensile behaviour
    - Increased strength and reduced ductility (carbide precipitation)
    - Fe-alloys more prone to degradation vs. Ni-alloys
  - Creep
    - Not much work done here
  - Stress corrosion cracking
    - Combined effects of chemical and mechanical loading
    - Some work here
      - C-rings
      - Pressurized tubes
  - Fatigue and thermal cycling
    - Limited work

sCO$_2$ Materials Challenges – Availability

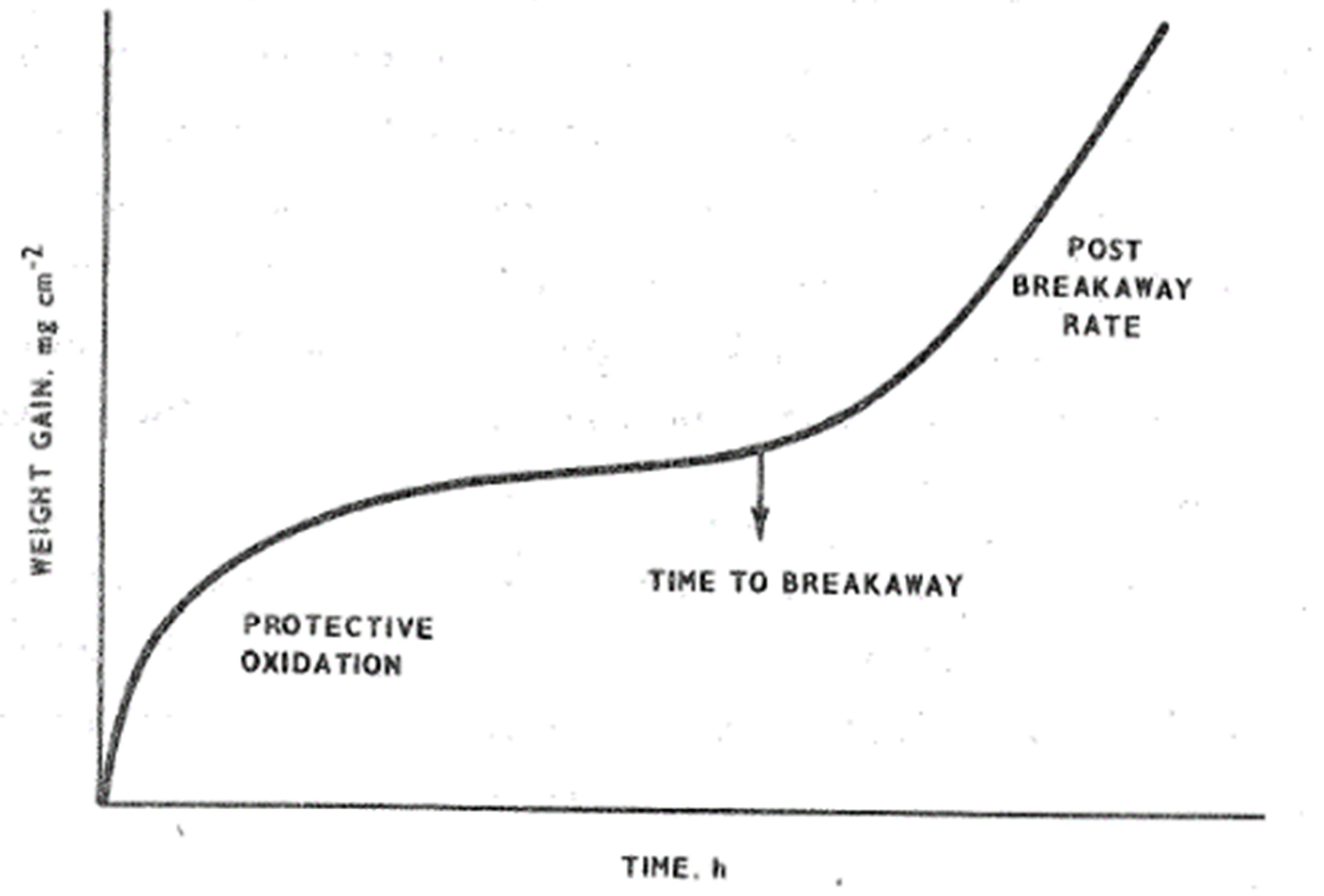
- **Code compliant materials/qualified alloys; design codes**
  - IN740H code case approved
  - Haynes 282 code case approved
  - Design codes for valves, heat exchangers?
- **Supply chain – in required forms and sizes**
  - Market pull to enable capability
  - IN740H for tube, pipe, fittings [deBarbadillo, 2018 and 2022]
    - Tube and pipe available
    - Fittings, etc. not available from stock
  - Various TRL levels
    - Manufacturing mill products (TRL 8, full plant required for TRL 9)
    - Manufacturing components, fabricating systems (TRL 6, moving to 8)
    - Systems (limited experience, TRL 4)

Smallest tube made at Greenville Tube

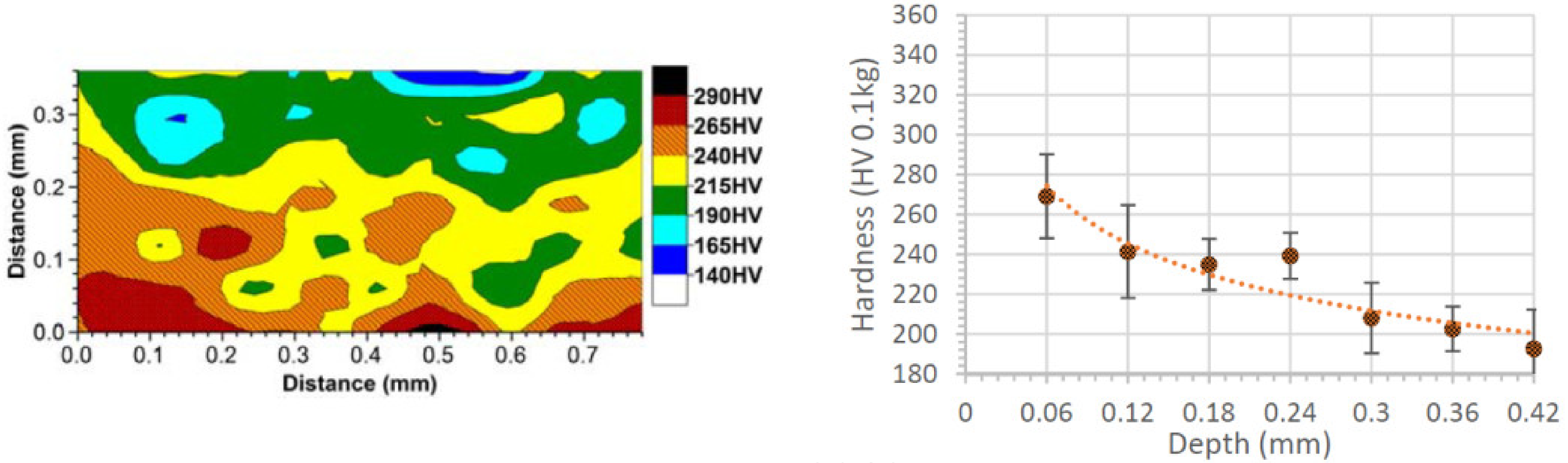
Largest pipe made at Wyman-Gordon

sCO_2 Materials Challenges – Environmental Considerations

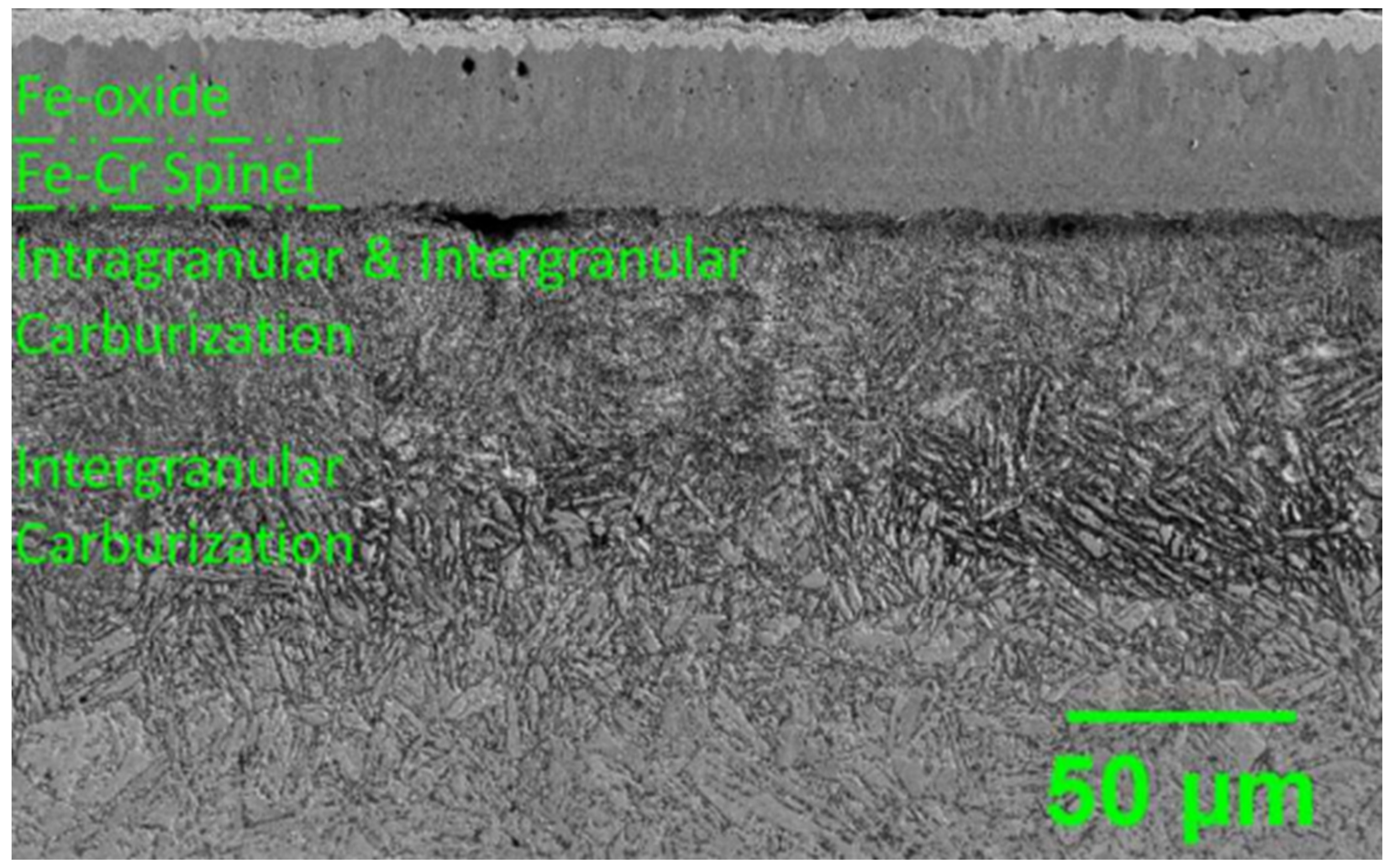
- **Longer-term (short-term testing inadequate – breakaway corrosion, intergranular corrosion)**
  - Currently max test duration in range of 3-6 kh
  - Carburization and internal oxidation leading to breakaway corrosion, exfoliation
    - Issue with ferritic steels
    - Seen in austenitic steels (initial stages, with duplex scales, after exfoliation)
    - Ni-based alloys with high Cr likely to resist
    - Estimate via micro hardness measurements [Kung, 2018] or quantify via Glow Discharge Optical Emission Spectroscopy (GDOES) [Lance, 2018] and [Brittan, 2020]
    - Results in Grade 92 Steel [Brittan, 2020]



[Ferguson, BNES 1974]



[Kung, 2018]

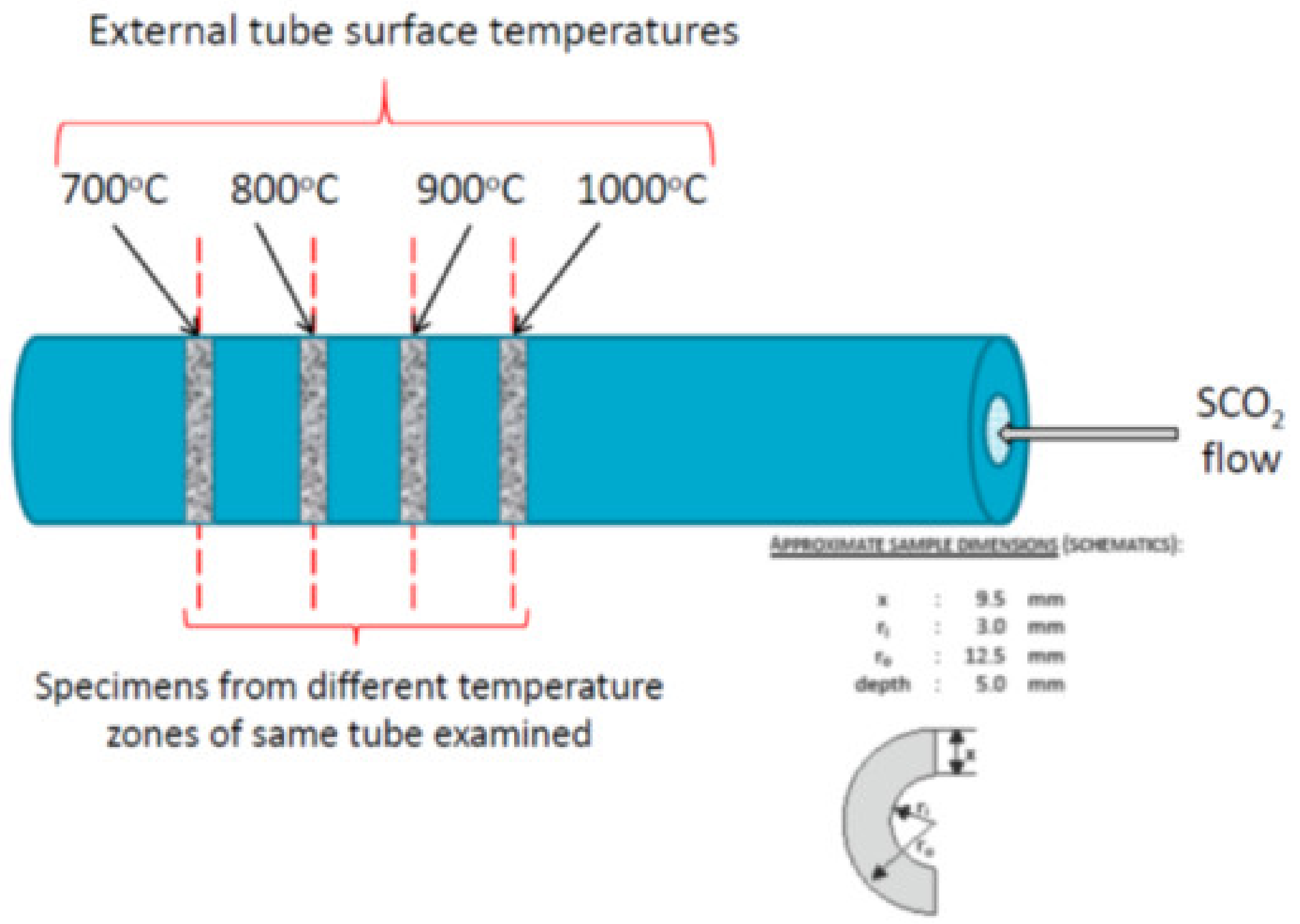


[Brittan, 2020]

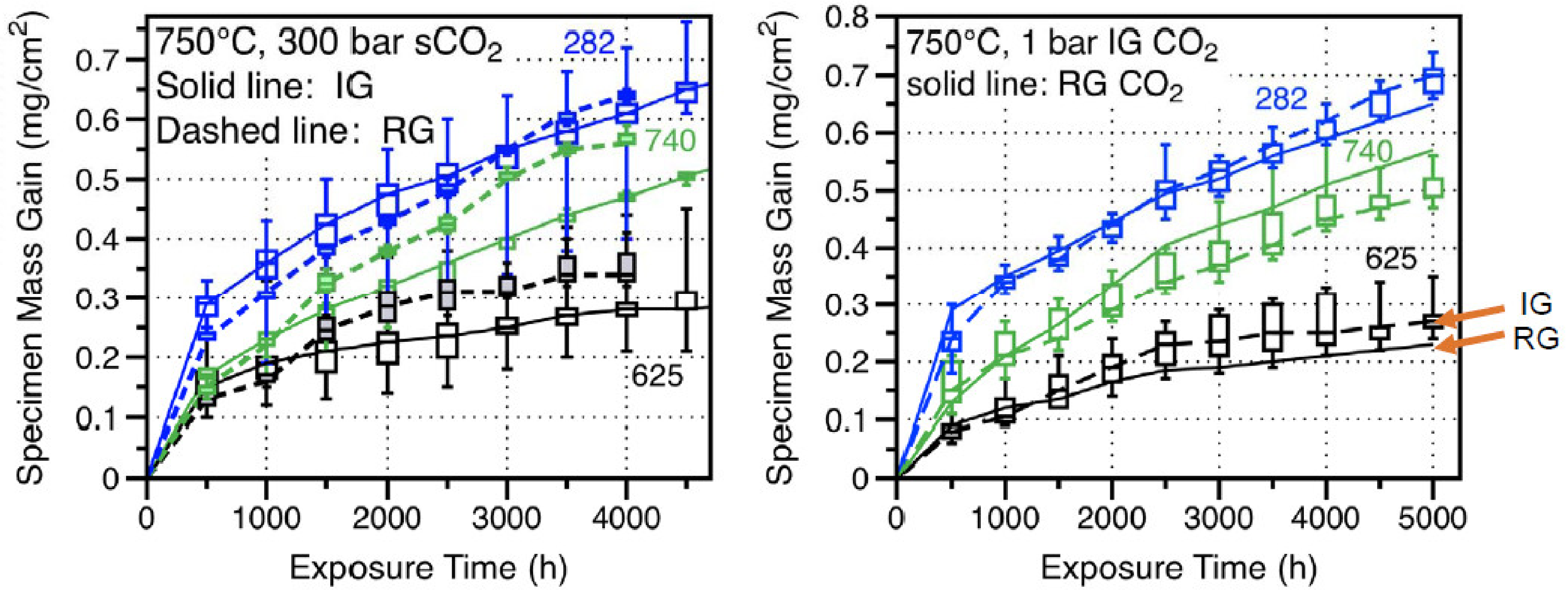
sCO_2 Materials Challenges – Environmental Considerations

- **Testing under “real” conditions (flow, stress, impurities – H_2O, O_2, others; indirect vs. direct cycles)**
  - GTI/Oak Ridge National Laboratory
    - C-ring testing (stressed material) in sCO_2 (750 °C, 20 MPa,500-1000 hours)
    - Various materials (housing, disk, blade) [Keiser, 2016+2017]
      - No SCC seen
  - CSIRO
    - Pressure vessel as test specimen (stressed material)
  - Various labs examining effects of impurities
    - CO_2 composition (RG vs IG)
      - Not much difference
    - Open cycle conditions
    - [Shingledecker, 2016], [Kung, 2018], [Lolla, 2018], [Pint, 2018], [Tylczak, 2018], [Walker, 2018], [Pint, 2019]

[Keiser, sCO_2 PCS 2016]



[CSIRO]

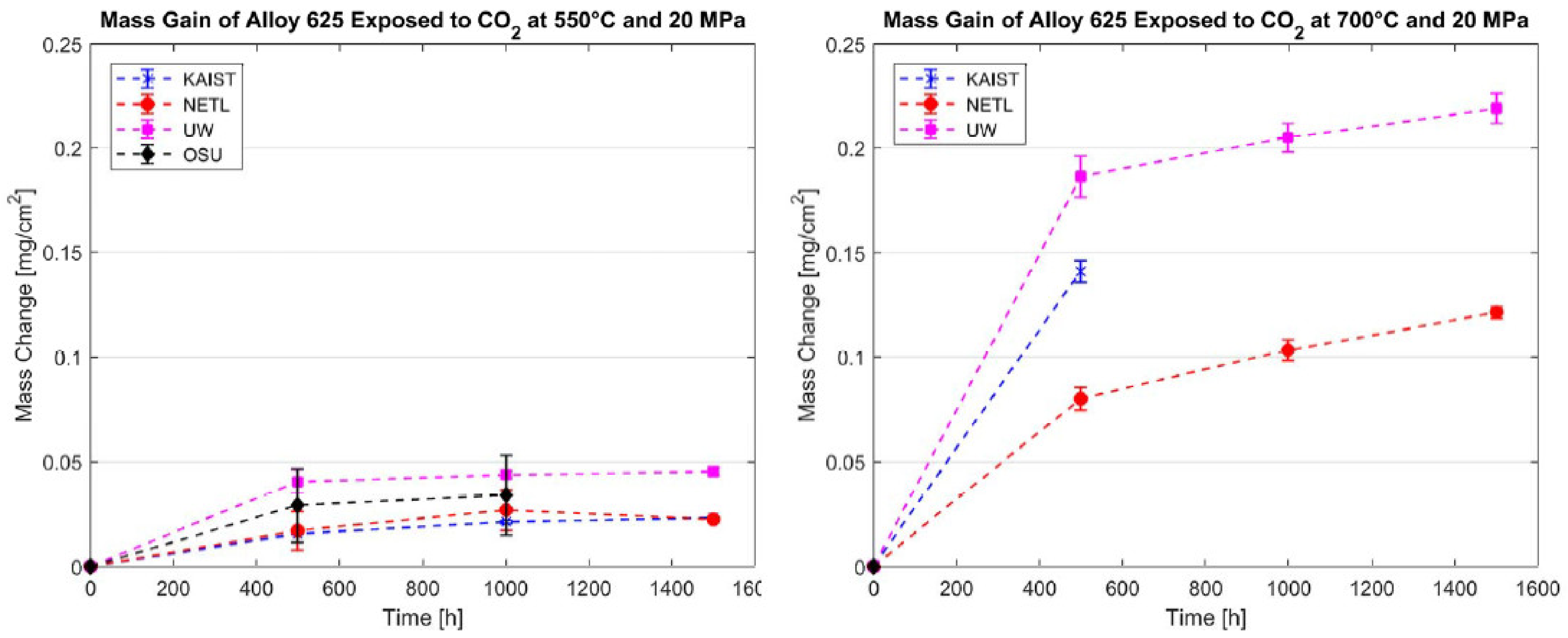


[Pint, 2018]

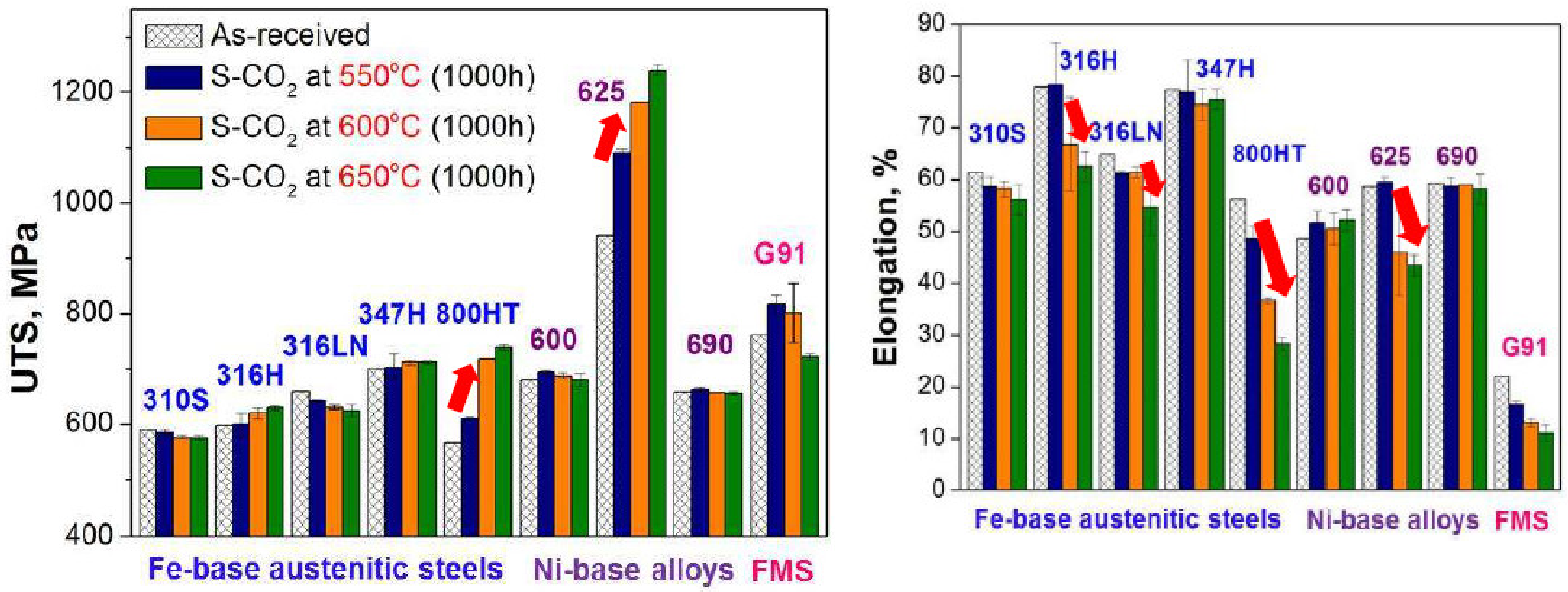
sCO_2 Materials Challenges – Environmental Considerations

- **Reliability of data**
  - Round Robin Testing and Fundamental Modeling (US DOE Nuclear Energy University Programs)
  - Various test facilities, but previously no formal test program to validate data consistency
  - Comparable and reproducible results desired
  - Lead: OSU, Collaborators: UofW-Madison, ORNL, NETL, Carleton University, KAIST, EPRI
  - Initial results [Tucker, 2018] +/- consistent
  - Recent results [Zanganeh, 2022]
- **Mechanical property degradation**
  - Compact tension specimens exposed, study subsequent fatigue crack growth [Holcomb, 2016]
  - Evaluate effects of sCO_2 exposure on tensile properties [Pint, 2016] and [Jang, 2014]
  - Ex-situ fatigue response after sCO_2 exposure [Rozman, 2018]
  - In-situ environmentally induced cracking [Teeter, 2018]
  - Effect of sCO_2 on steel ductility [Pint, 2021]
  - Degradation of steels in CO_2 [Rozman, 2022]

Organization	Maximum Temperature	Maximum Pressure	Chamber Volume	Flow rate (mL/min)	Autoclave Material
OSU	800°C	26 MPa	1235 cm^3	0-24	Haynes 230
UW (2 systems)	750°C	25 MPa	900 cm^3 (combined)	0-24	Inconel 625
	760°C	38 MPa		0-24	Haynes 282
ORNL	850°C	30 MPa	1400 cm^3	0-24	Haynes 282
NETL	800°C	28 MPa	1040 cm^3	0-24	Haynes 230
Carleton	750°C	25 MPa	1150 cm^3	0-250	Inconel 625
KAIST	700°C	25 MPa	1077 cm^3	0-24	Inconel 625



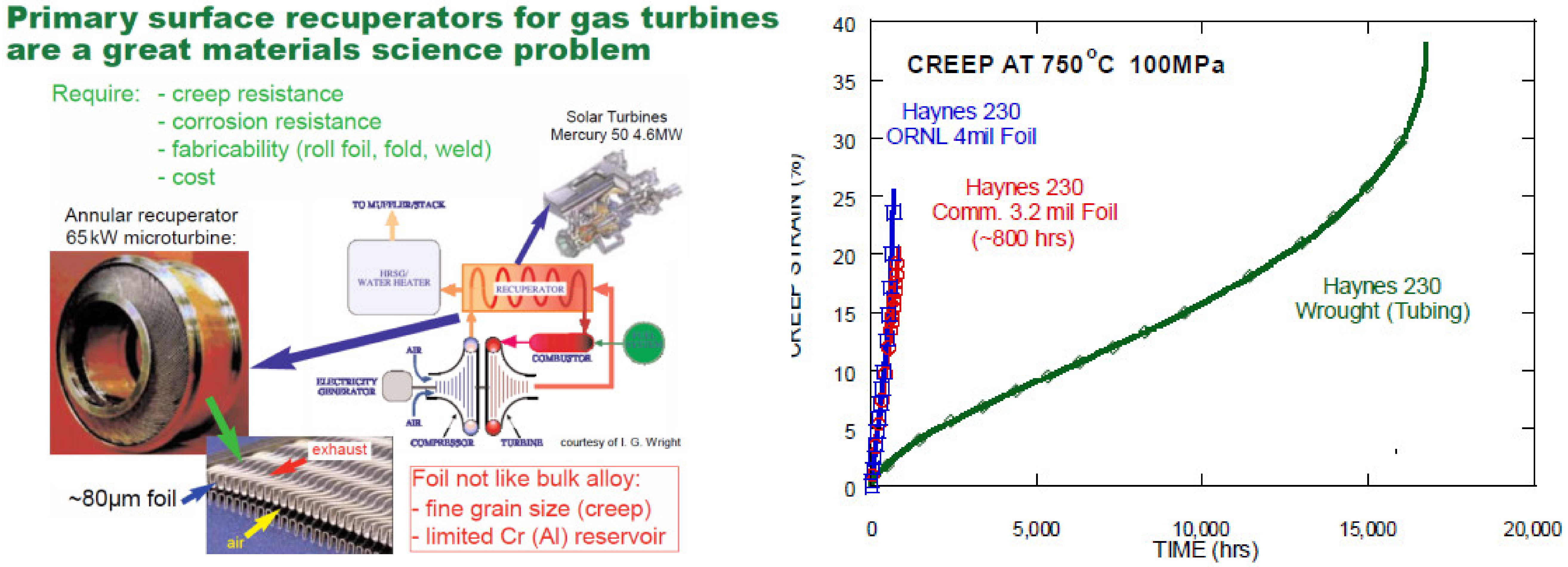
[Tucker, 2018]



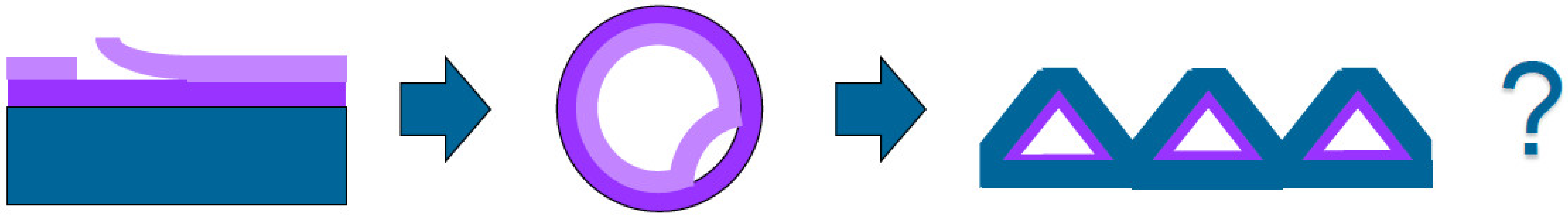
[Jang, sCO_2 PCS 2014]

sCO_2 Materials Challenges – Performance of Actual Components/Material Forms

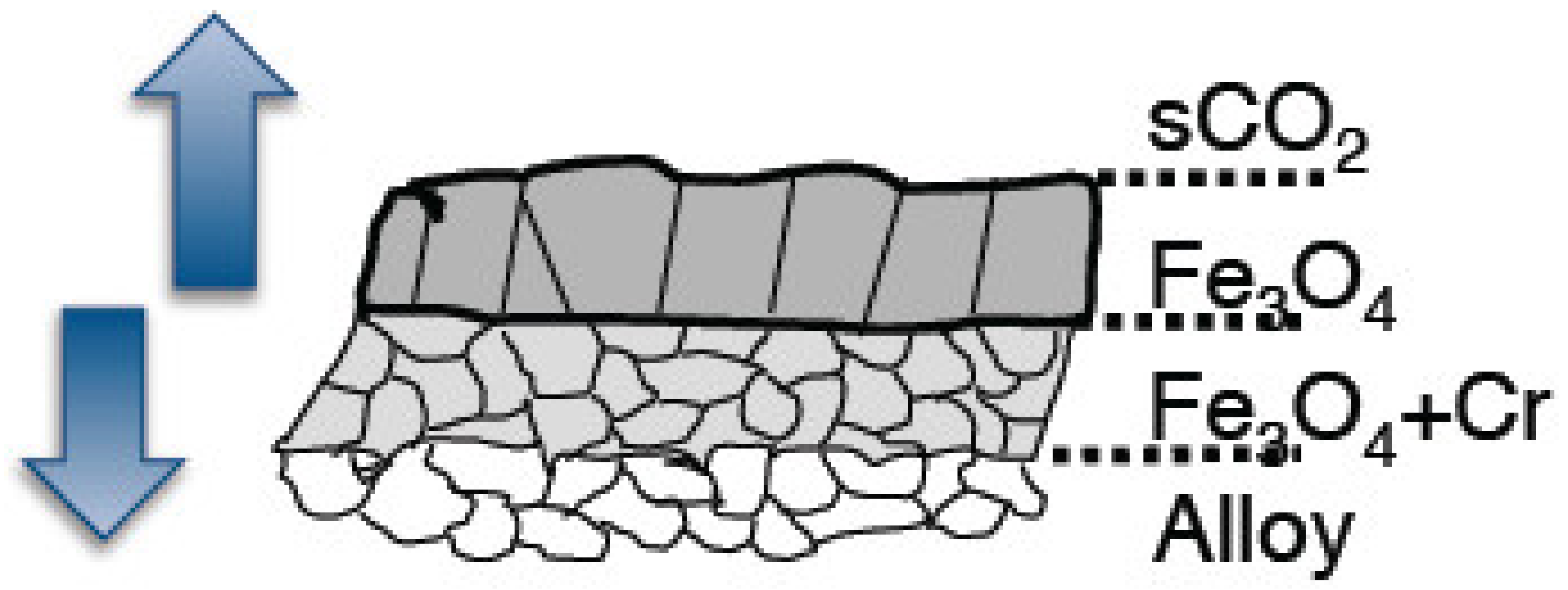
- **Thin sections – property differences, effect of geometry**
  - Creep debit for thin sections [Pint, 2016]
  - Microstructure and creep of 740H sheet [Shingledecker, 2022]
  - Oxide thickness not extent of damage [Pint, 2016]
  - Heat flux, stress from complex geometries [Kung 2016]
- **Diffusion bonded, brazed, welded joints – corrosion resistance**
  - Performance of welded 740H and 282 [Brittan, 2018] and Grade 92 [Brittan, 2020]
  - Weldment cracking of sCO_2 heater [Shingledecker, 2022]
- **Erosion, fouling of microchannel heat exchangers**
  - Is erosion a real problem – fluid or debris, exfoliation? [Fleming, 2014], [He, 2018]
  - Oxide scale itself may cause blockage [Sabau, 2016]
- **Thermal fatigue, creep-fatigue interactions, high blade bending loads/temperature + pressure combinations**

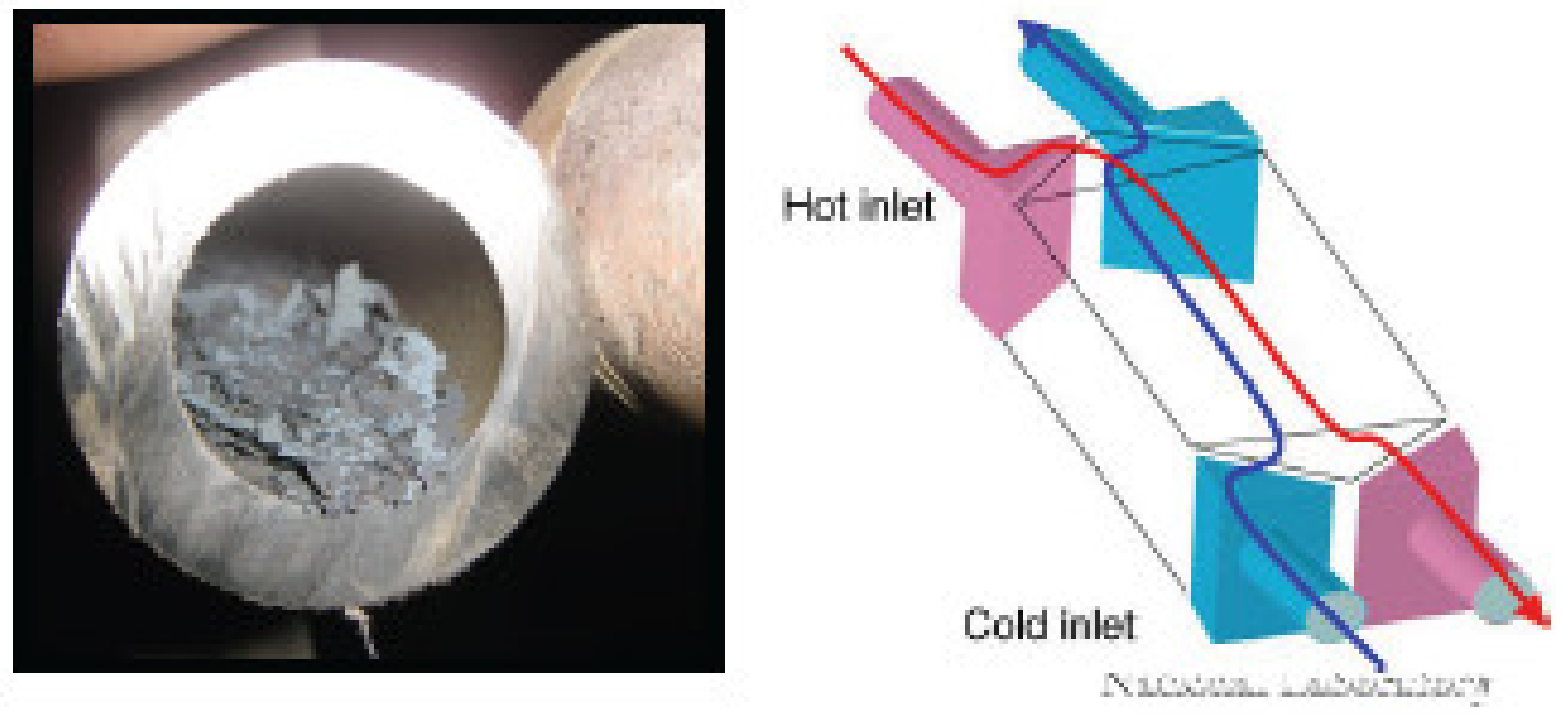


[Pint, 2015]



[Kung, sCO_2 PCS 2016]

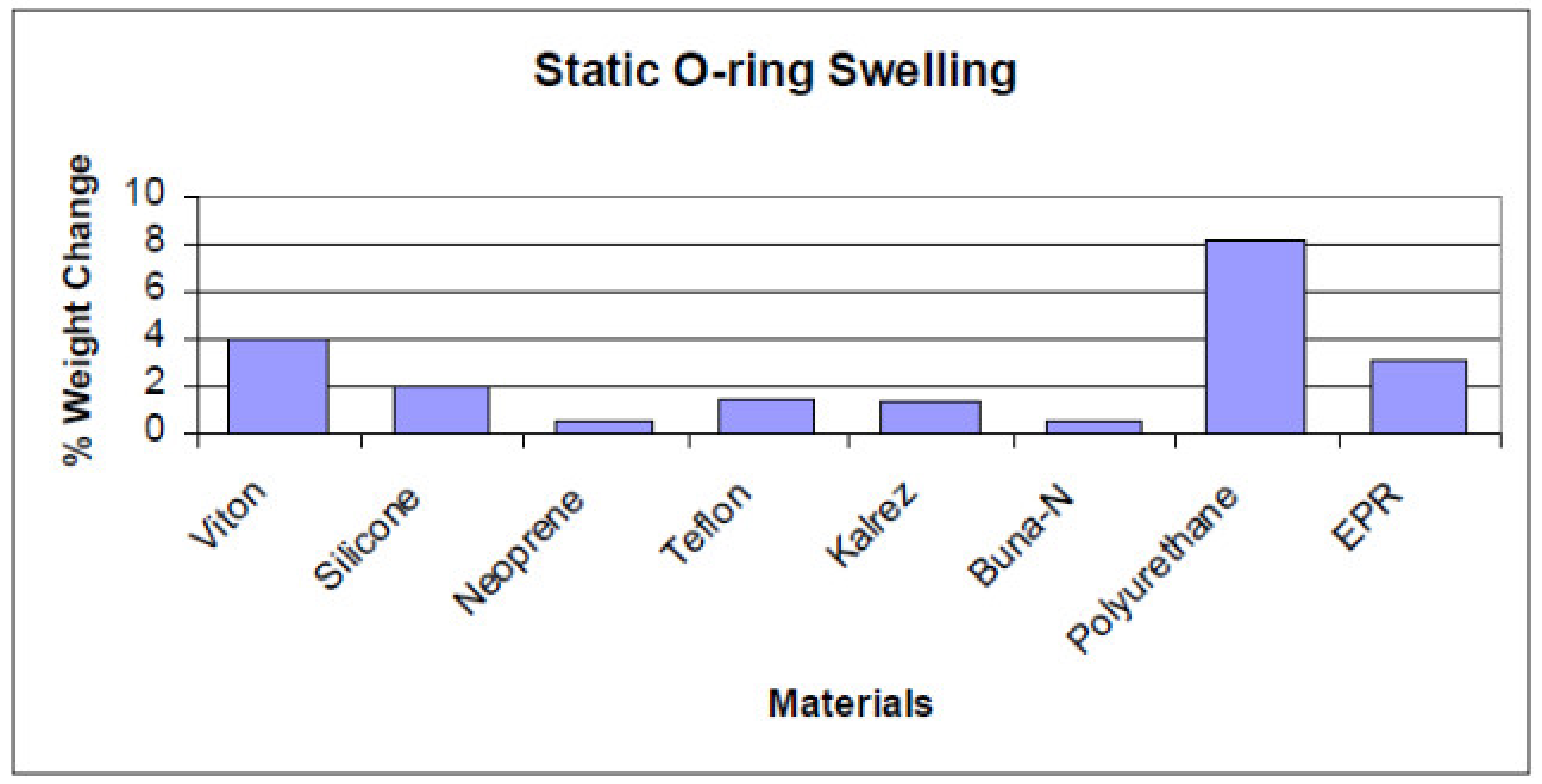




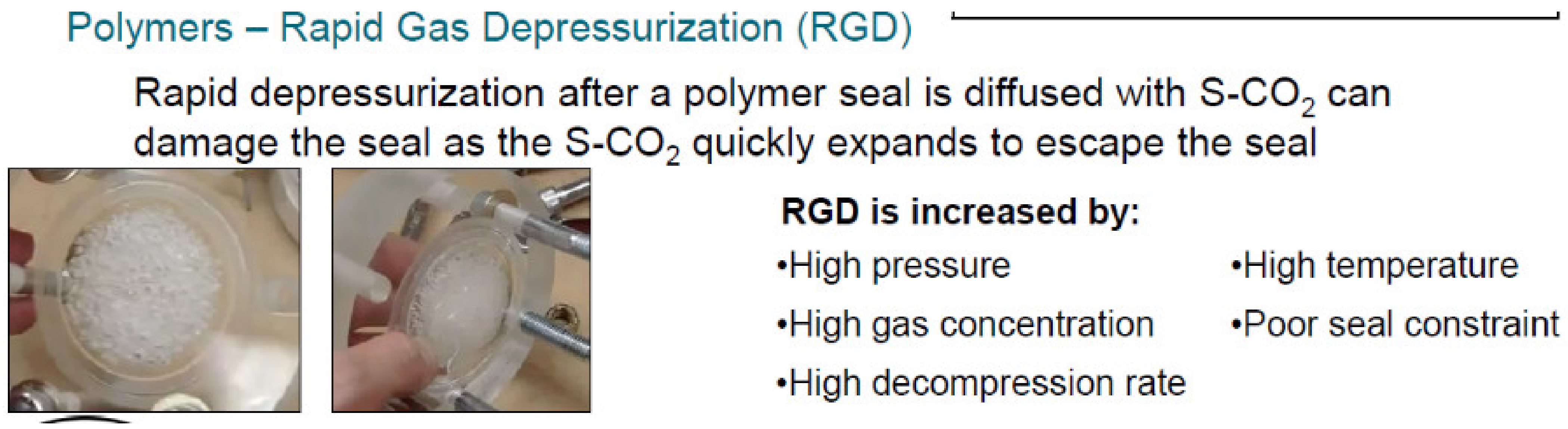
[Sabau, sCO_2 PCS 2016]

sCO_2 Materials Challenges – Other Considerations

- **Cost-effective alloys**
  - Steels for direct-fired [Oleksak, 2022]
- **Higher-temperature applications**
  - SiC piping [Neiderer, 2022] and [Barringer, 2022]
  - Material options [Pint, 2022]
- **Coatings**
  - Allow use of lower-cost alloys or push corrosion limit of material
- **Non-metallics – degradation of seals via swelling, rapid gas depressurization**
  - [Tunnison, 2009] and oil and gas studies
- **Compatibility of polymers**
  - [Menon, 2022]
- **Leverage previous work – comparison to steam and SCW corrosion, pressure effects (testing in CO_2)**
  - Extend ORNL/EPRI exfoliation model for steam to sCO_2 [Sabau, 2016], [Kung, 2018]
    - Exfoliation of oxide scales on boiler tubes
    - Predicts scale failure and loss based on evolution of oxide
  - Little pressure effect seen in sCO_2 – low pressure CO_2 testing OK?



[Tunnison, 2015]



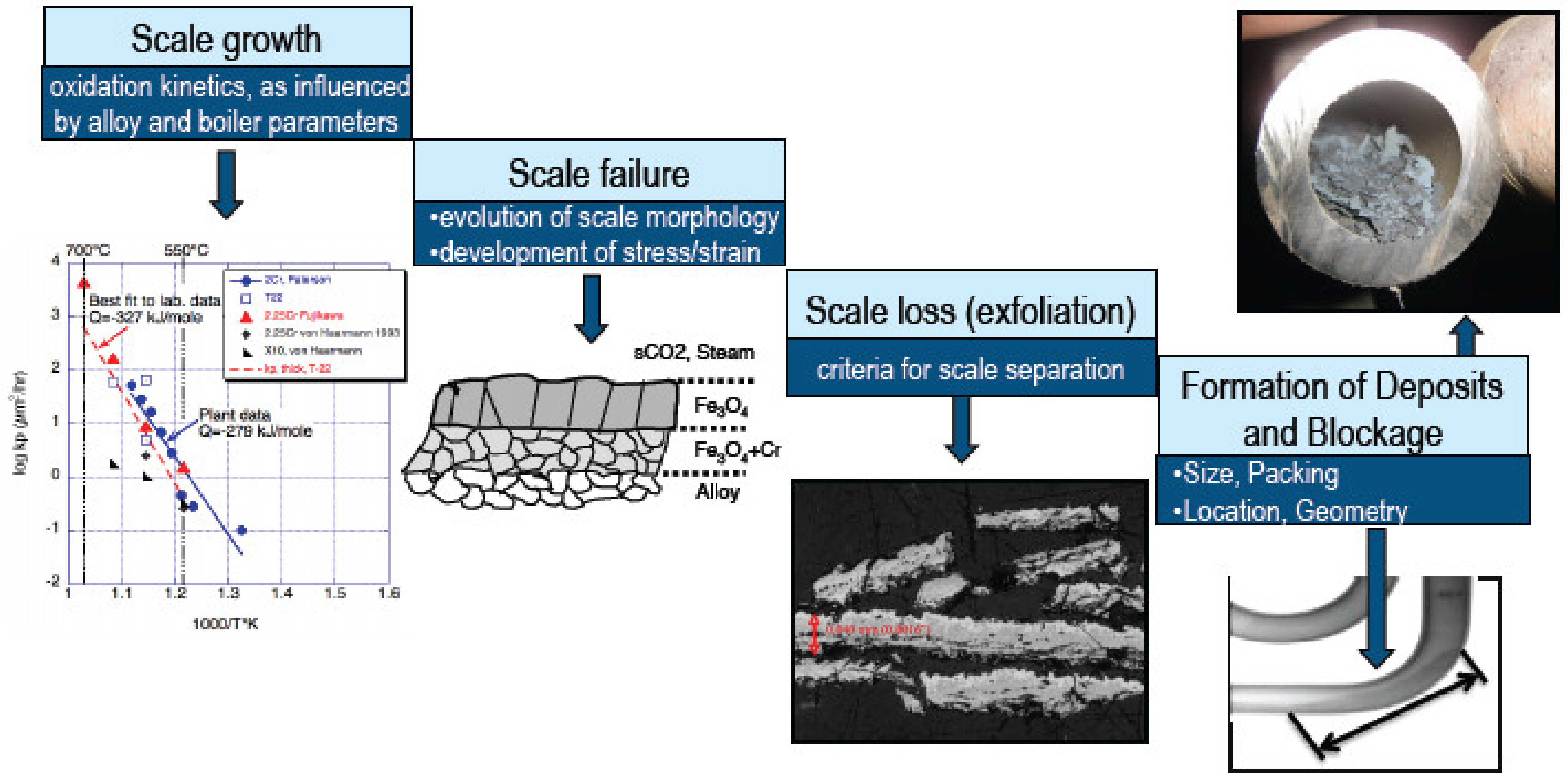
Polymers – Rapid Gas Depressurization (RGD)

Rapid depressurization after a polymer seal is diffused with S-CO_2 can damage the seal as the S-CO_2 quickly expands to escape the seal

RGD is increased by:

- High pressure
- High gas concentration
- High decompression rate
- High temperature
- Poor seal constraint

[sCO2 Fundamentals Tutorial, 2013]



[Sabau, sCO_2 PCS 2016]

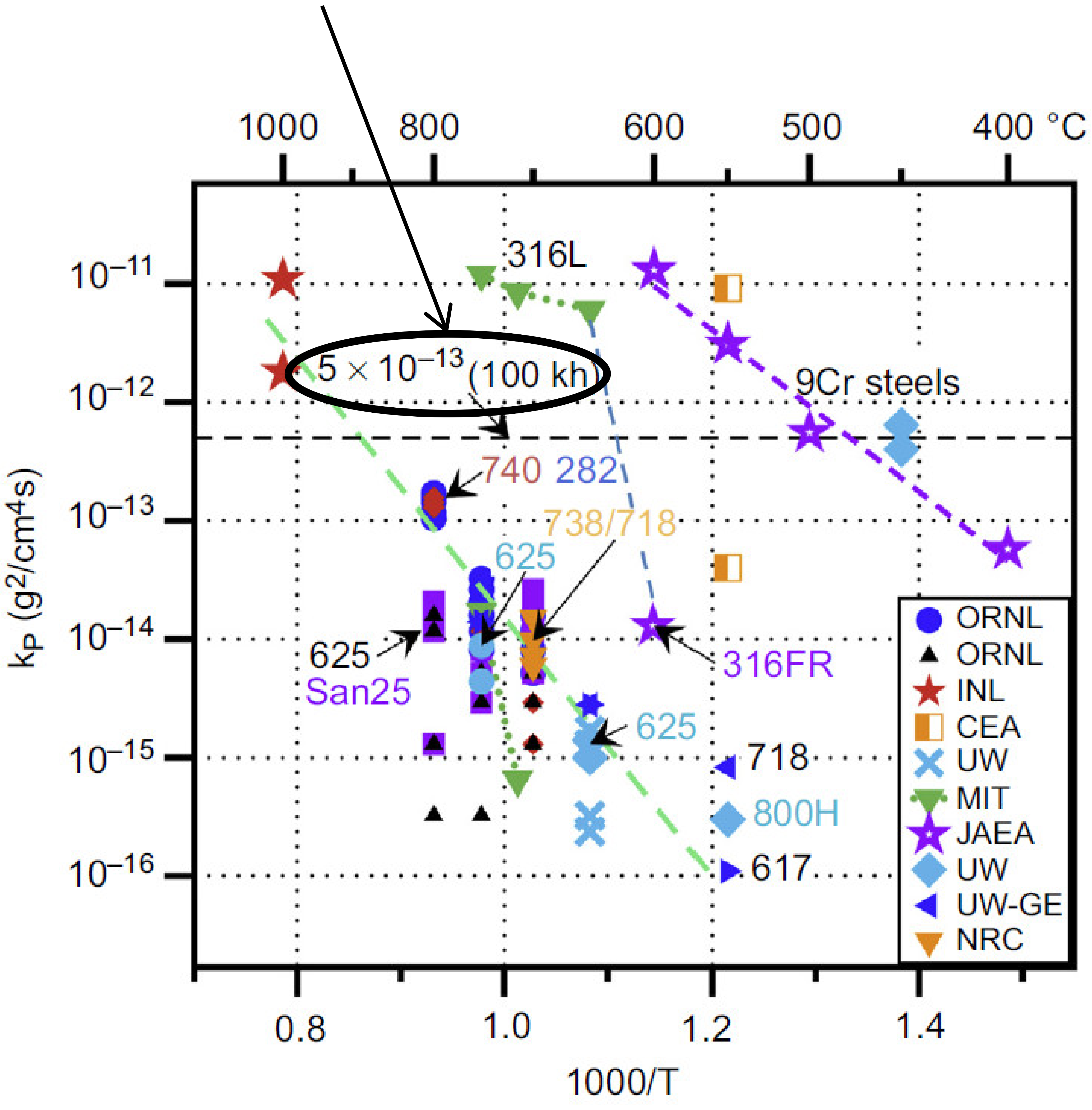
Summary of Main Findings

- **Alloys with high Cr and Ni, and Ti and Al more corrosion resistant**
  - Build a stable, tight oxide layer that resists corrosion
- **Alloys with low Cr levels less corrosion resistant**
  - Build a duplex layer with that does not resist corrosion as well
- **In general, decreasing corrosion resistance:**

Nickel **Ni-Cr-X** **Cr>16%**	**Austenitic** **Fe-Cr-Ni** **Cr>16%**	**FM** **Fe-Cr** **Cr<12%**
IN625	800H	12Cr
IN617	AL6-XN	HCM12A
Haynes 230	316SS	NF616
IN718	310SS	T91
IN738		

- **Increased corrosion with temperature**
- **Not much (if any) pressure effect**

~metric for <100 µm oxide in 100 kh



[Pint and Brese, 2017]

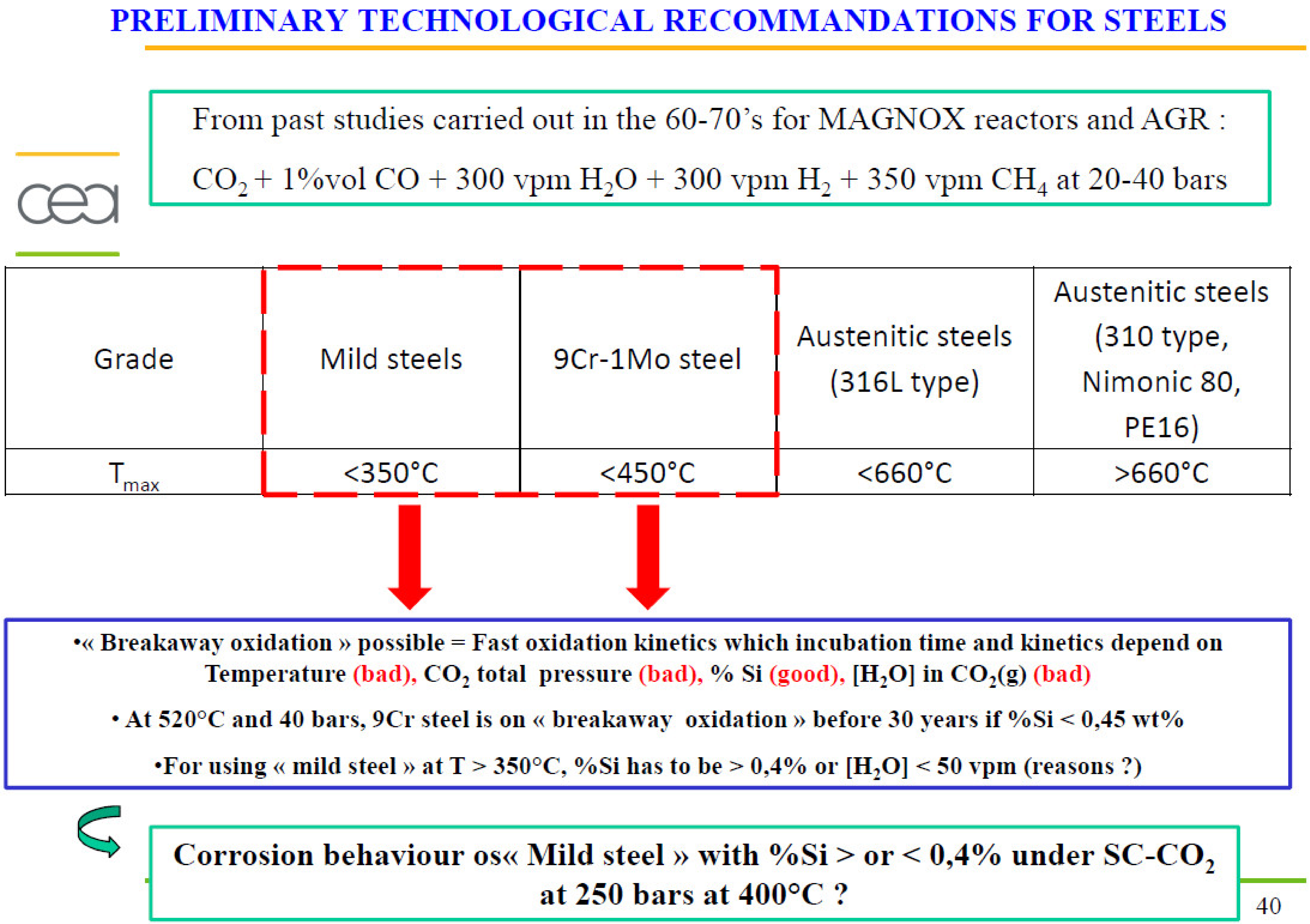
Materials Selection

- **Key step in design**
- **Poor choices?**
  - Failure, increased cost
- **Best material?**
  - Properties to provide necessary service performance
  - Processing of material into finished components
- **Selection process**
  - Analysis of material requirements (translate service and environmental conditions into required material properties)
  - Screen candidate materials (compare needed properties with databases)
  - Select candidate material(s) (analyze candidates – trade-offs, value analysis, cost-benefit, etc.)
  - Develop design data (testing, pilots, etc.)

Materials Selection

- **Piping/casing/heat exchangers**
  - Governed by ASME B&PV Code, Piping Codes, Material Standards
  - Code approved materials, allowable stresses
  - Compatibility – corrosion allowance
- **Turbines/compressors/shafts**
  - More flexibility
  - Lots of materials available
  - OEM designs
  - Compatibility
- **Other components**
  - Seals
  - Bearings
  - Electrical components
  - Etc.

Materials Selection – Strength and Corrosion



PRELIMINARY TECHNOLOGICAL RECOMMANDATIONS FOR STEELS

From past studies carried out in the 60-70's for MAGNOX reactors and AGR :

CO_2 + 1%vol CO + 300 vpm H_2O + 300 vpm H_2 + 350 vpm CH_4 at 20-40 bars

Grade	Mild steels	9Cr-1Mo steel	Austenitic steels (316L type)	Austenitic steels (310 type, Nimonic 80, PE16)
T_{max}	<350°C	<450°C	<660°C	>660°C

•« Breakaway oxidation » possible = Fast oxidation kinetics which incubation time and kinetics depend on Temperature (bad), CO_2 total pressure (bad), % Si (good), [H_2O] in CO_2(g) (bad)

• At 520°C and 40 bars, 9Cr steel is on « breakaway oxidation » before 30 years if %Si < 0,45 wt%

•For using « mild steel » at T > 350°C, %Si has to be > 0,4% or [H_2O] < 50 vpm (reasons ?)

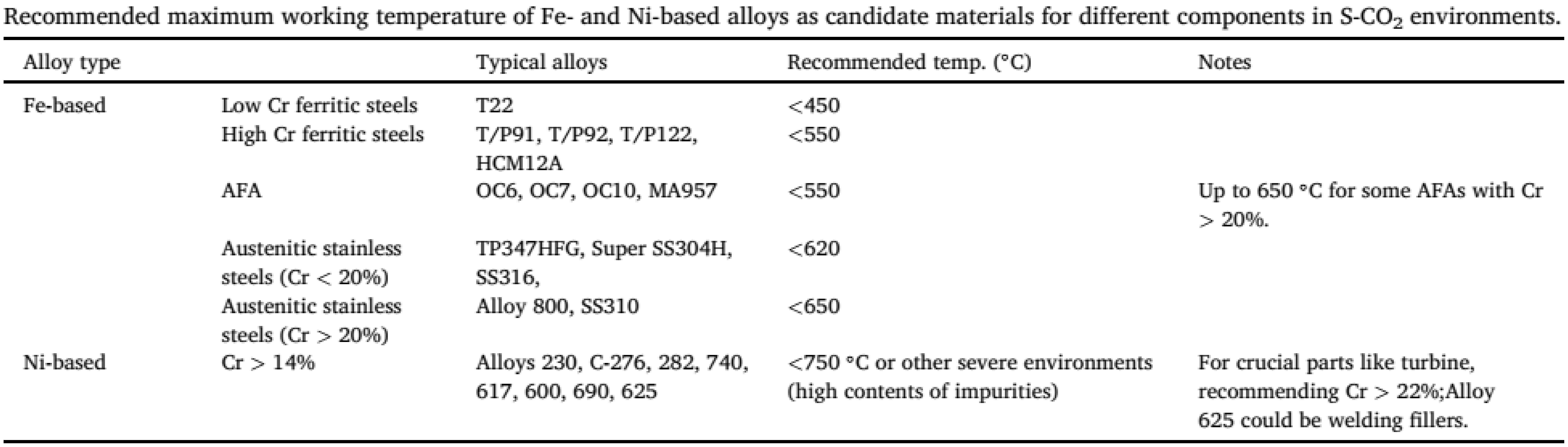
Corrosion behaviour os« Mild steel » with %Si > or < 0,4% under SC-CO_2 at 250 bars at 400°C ?

[Rouillard, sCO_2 PCS 2011]

Materials Selection – Strength and Corrosion

- **Existing data from other high-temperature systems, and sCO_2 work are valuable**
  - Air-sCO_2 – corrosion generally same for corrosion resistant alloys, corrosion worse in sCO_2 for less corrosion resistant alloys
  - Steam-sCO_2 – results generally applicable to sCO_2
  - SCW-sCO_2 – SCW usually more corrosive
- **ASME codes – temperature limits based on allowable mechanical strength**
  - 100,000 hr creep rupture at 100 MPa
- **Corrosion effects?**

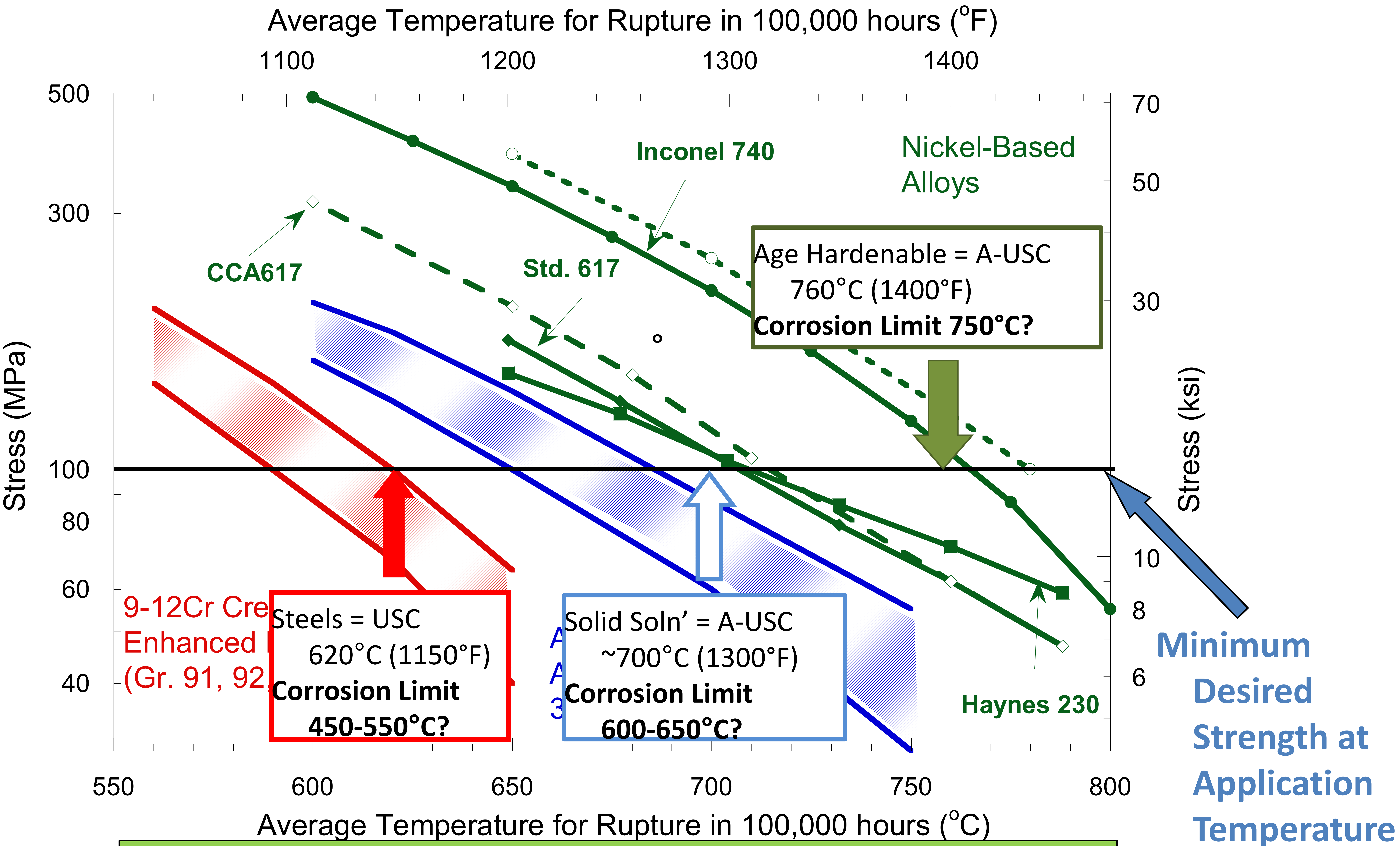
[Li et al., 2023]



Recommended maximum working temperature of Fe- and Ni-based alloys as candidate materials for different components in S-CO_2 environments.

Alloy type		Typical alloys	Recommended temp. (°C)	Notes
Fe-based	Low Cr ferritic steels	T22	<450	
	High Cr ferritic steels	T/P91, T/P92, T/P122, HCM12A	<550	
	AFA	OC6, OC7, OC10, MA957	<550	Up to 650 °C for some AFAs with Cr > 20%.
	Austenitic stainless steels (Cr < 20%)	TP347HFG, Super SS304H, SS316,	<620	
	Austenitic stainless steels (Cr > 20%)	Alloy 800, SS310	<650	
Ni-based	Cr > 14%	Alloys 230, C-276, 282, 740, 617, 600, 690, 625	<750 °C or other severe environments (high contents of impurities)	For crucial parts like turbine, recommending Cr > 22%;Alloy 625 could be welding fillers.

Materials Selection – Strength and Corrosion



Age Hardenable = A-USC
760°C (1400°F)
Corrosion Limit 750°C?

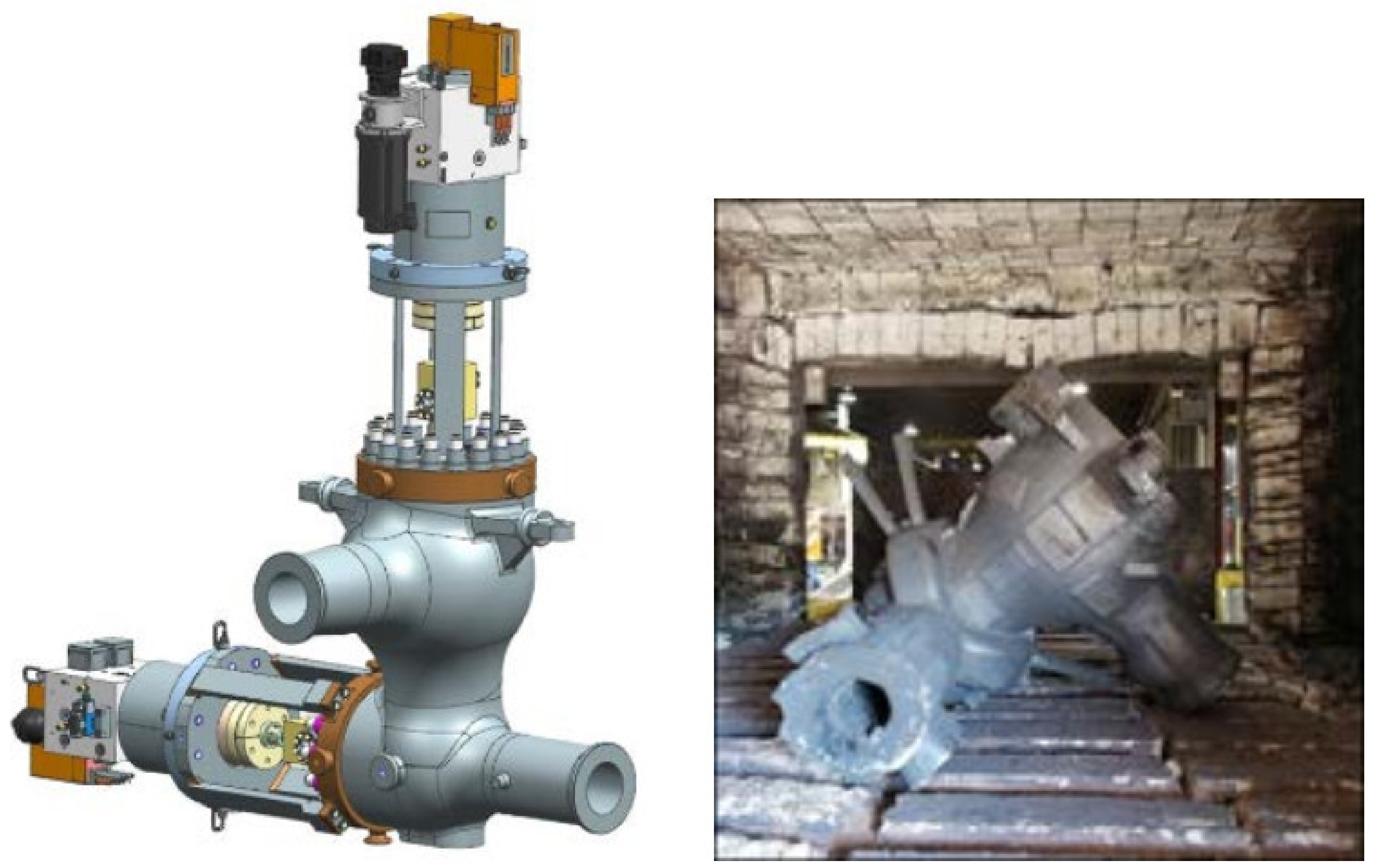
Steels = USC
620°C (1150°F)
Corrosion Limit
450-550°C?

Solid Soln' = A-USC
~700°C (1300°F)
Corrosion Limit
600-650°C?

Minimum Desired Strength at Application Temperature

Where are the temperature cut-offs for different materials when corrosion is considered? [Pint, 2022]

10 MW$_e$ STEP Facility and Materials

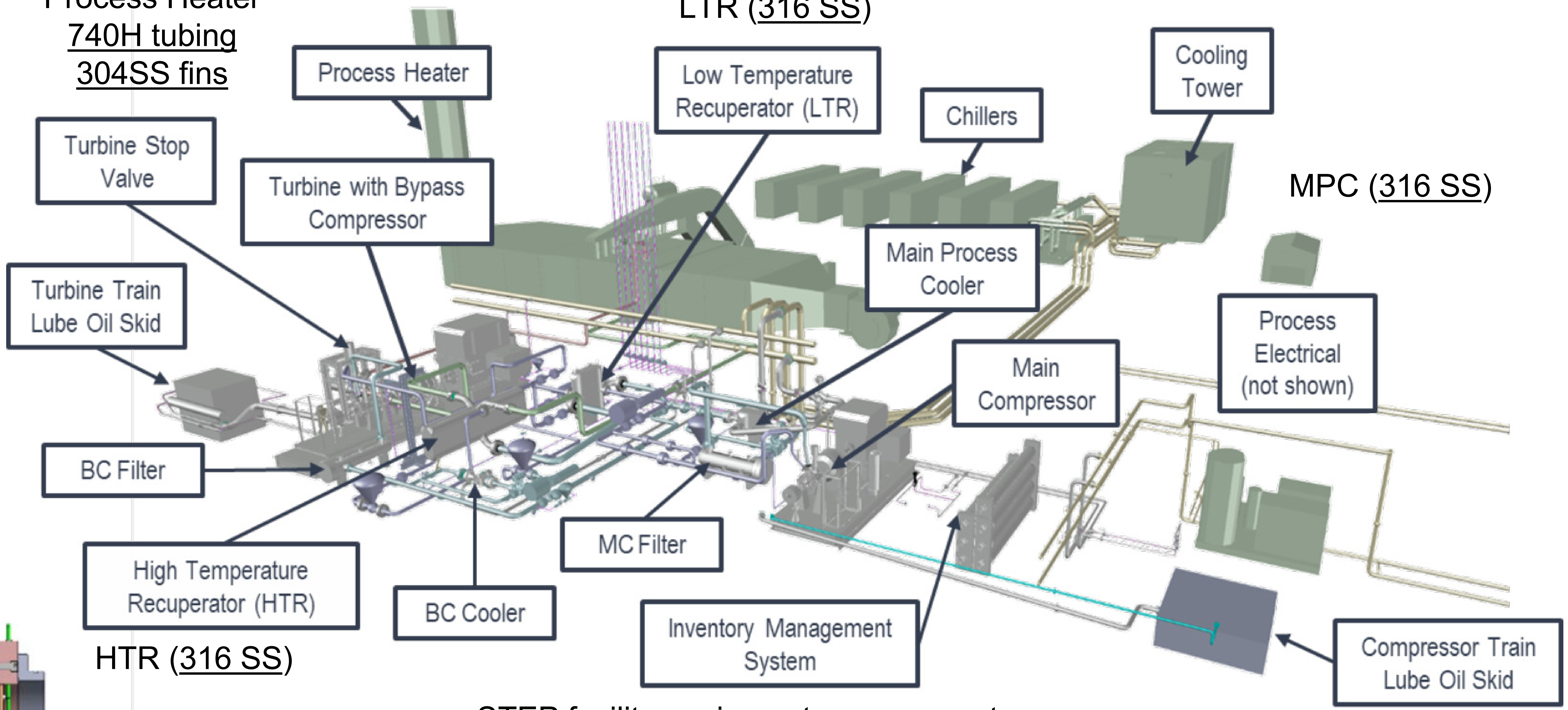


Turbine Stop Valve (Haynes 282)
Alternate valve from 316SS

Process Heater
740H tubing
304SS fins

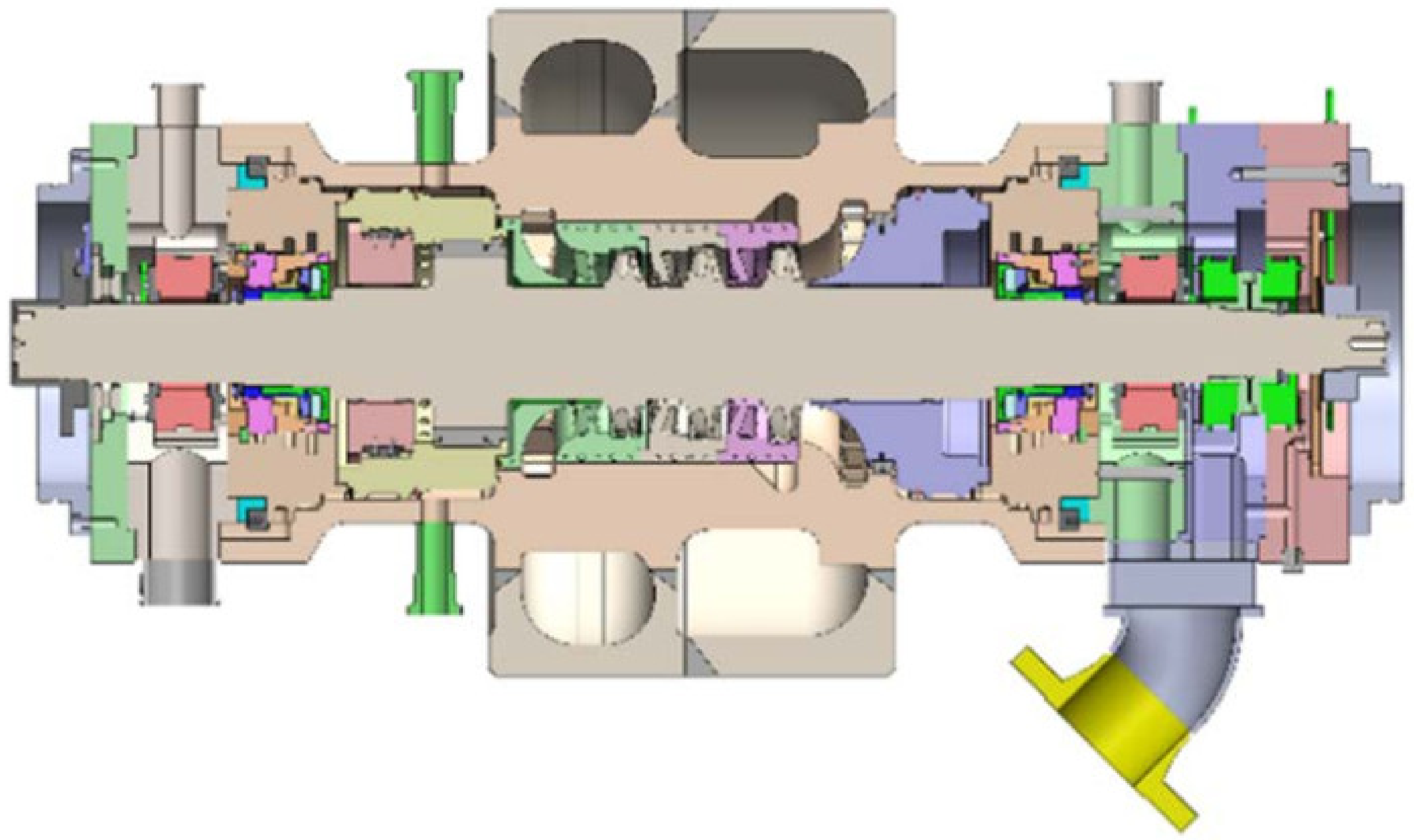
LTR (316 SS)

MPC (316 SS)

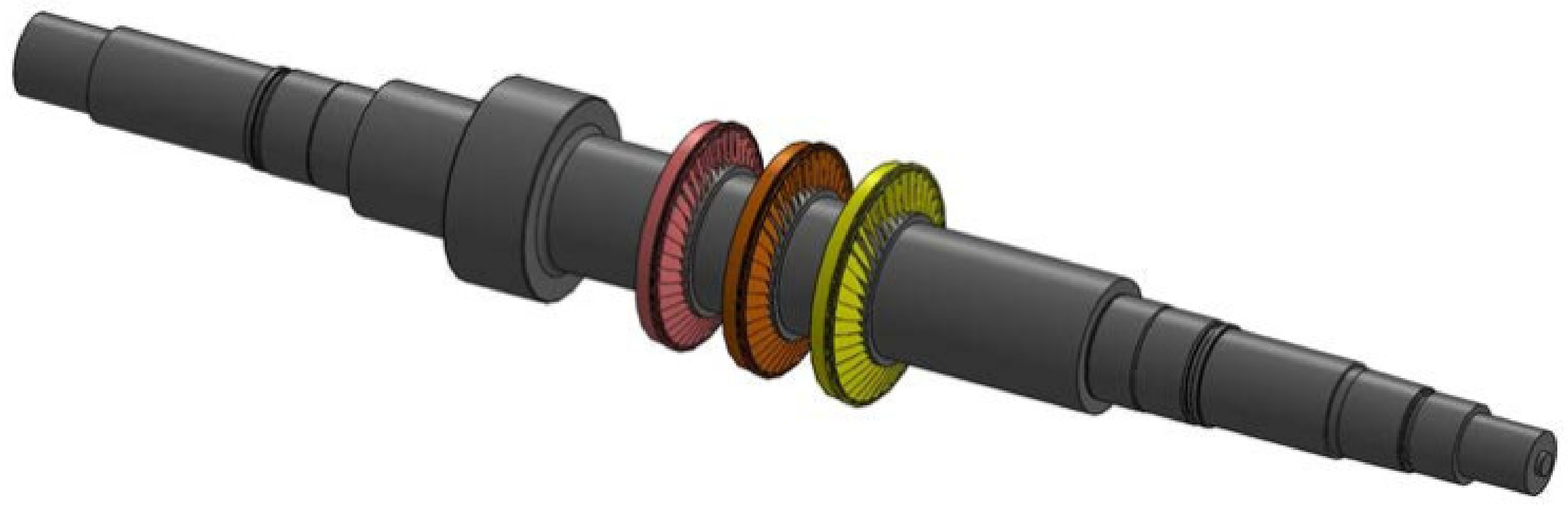


HTR (316 SS)

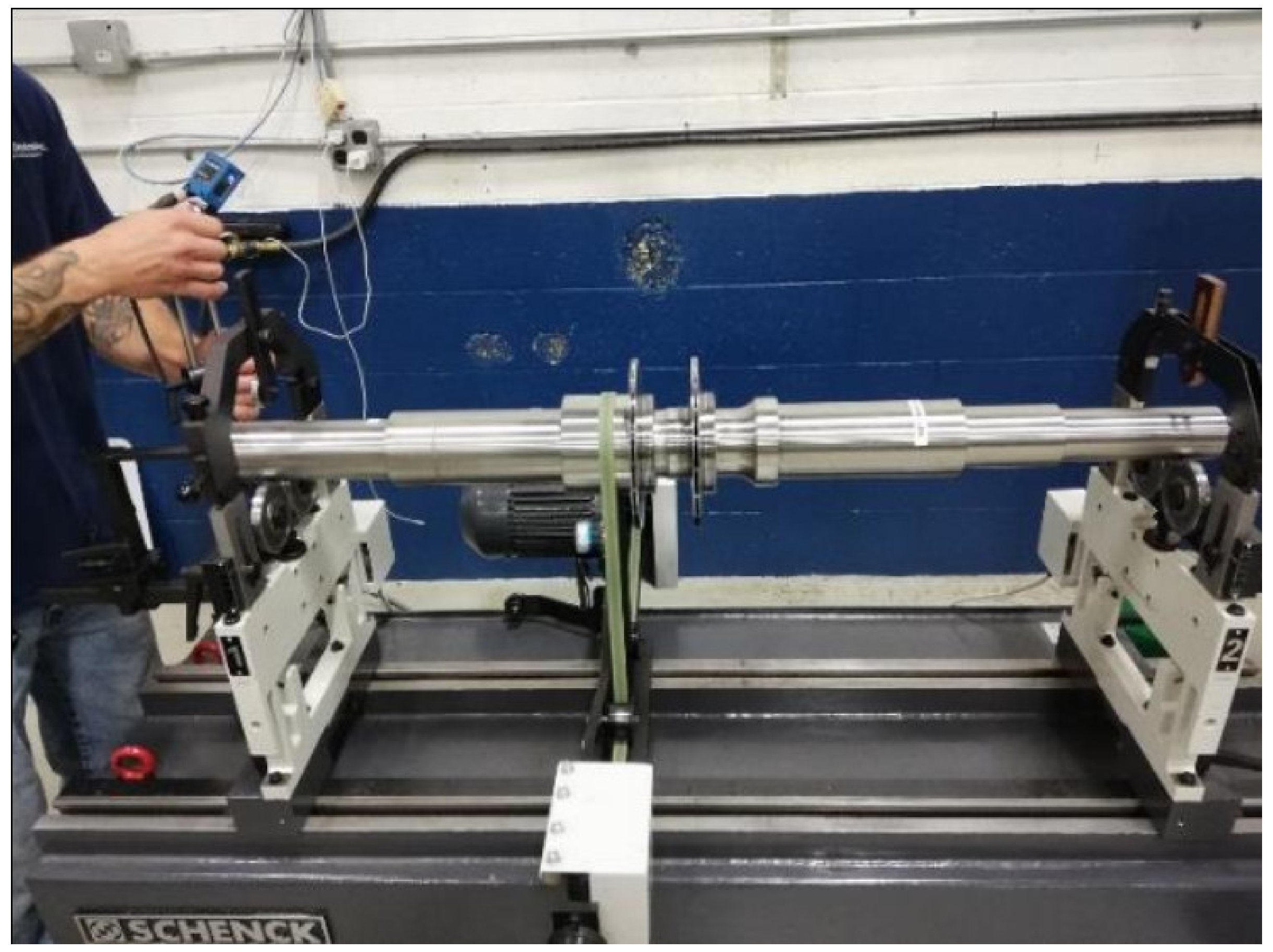
STEP facility equipment arrangement



Turbine Casing IN625

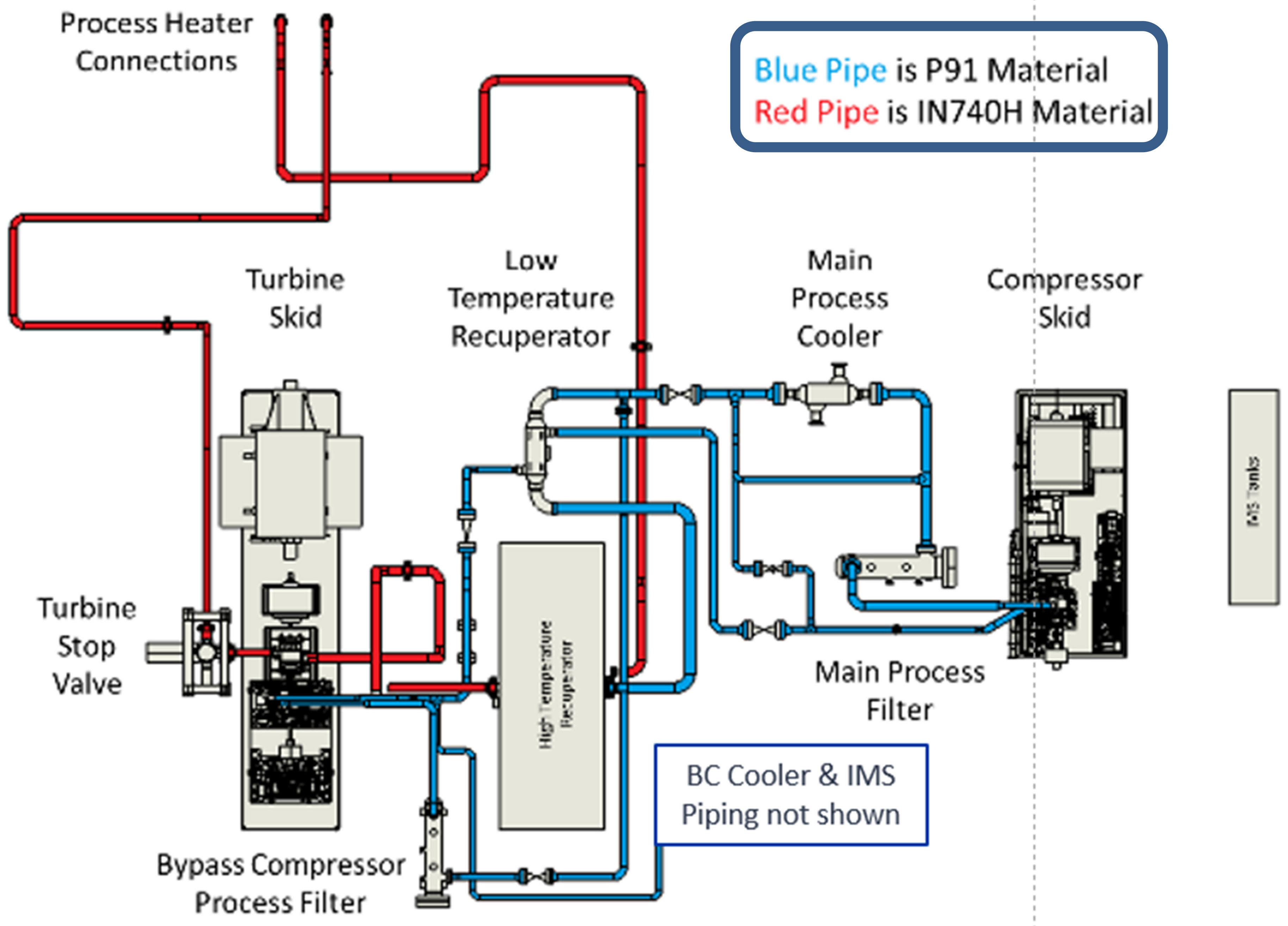


STEP turbine rotor (monolithic Nimonic 105 rotor, EDMed)



STEP bypass compressor rotor (monolithic)

[Marion, 2021] and [Lariviere, 2019]



Piping Layout (P91 and IN740H)

Lessons to be Learned from STEP?

- **Previous loops**
  - Sandia National Laboratories
    - Piping, erosion
  - Naval Nuclear Laboratory
    - Erosion
  - Others?
- **STEP**
  - Materials availability, processing, fabrication
  - Compatibility with service environment
  - Operation under “real” conditions – flow, stress, etc.
  - Failures – failures modes, analysis

Thank You!

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