Advanced Turbomachinery for sCO2 Power Cycles

October 2015 Review

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Advanced Turbomachinery for sCO2 Power Cycles

Description

- Define sCO2 Turbomachinery concepts & applicability to indirectly & directly-heated cycles
  - Indirect / Un-cooled (< 760 deg C)
  - Direct / Cooled (>760 deg C)
  - Identify technology gaps and plans to mature TRL
- Initiate materials compatibility tests

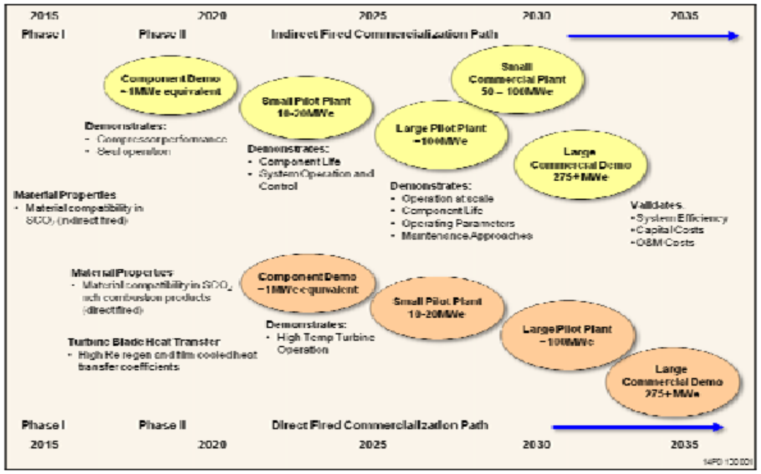
Impact

- Exceed DOE Goals for performance of directly and indirectly heated cycles

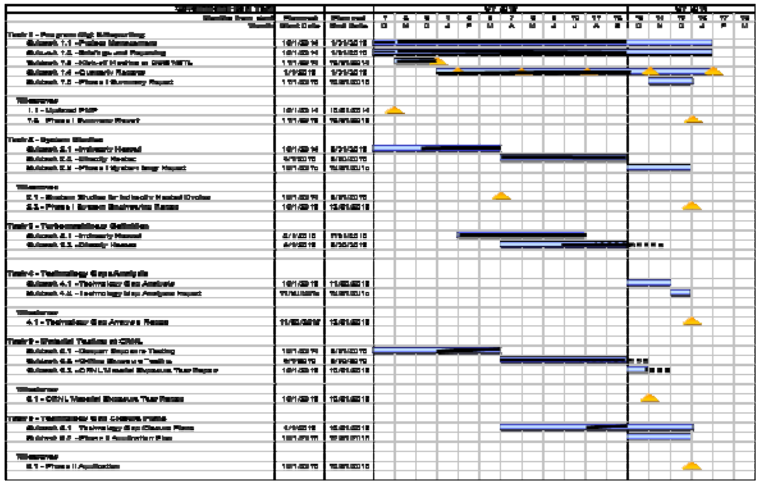
Team Members and Roles

- **GTI** – Lead, sCO2 technology
- **Alstom** – Support sCO2 hardware design and manufacture
- **Duke Energy** – End user insight into market pull for central & distributed generation and co-funding
- **Electric Power Research Institute** – End user insight, review of process and cost modeling
- **Oak Ridge National Laboratory (ORNL)** – Materials compatibility tests (indirect Cycles)

Commercialization Path and Technologies



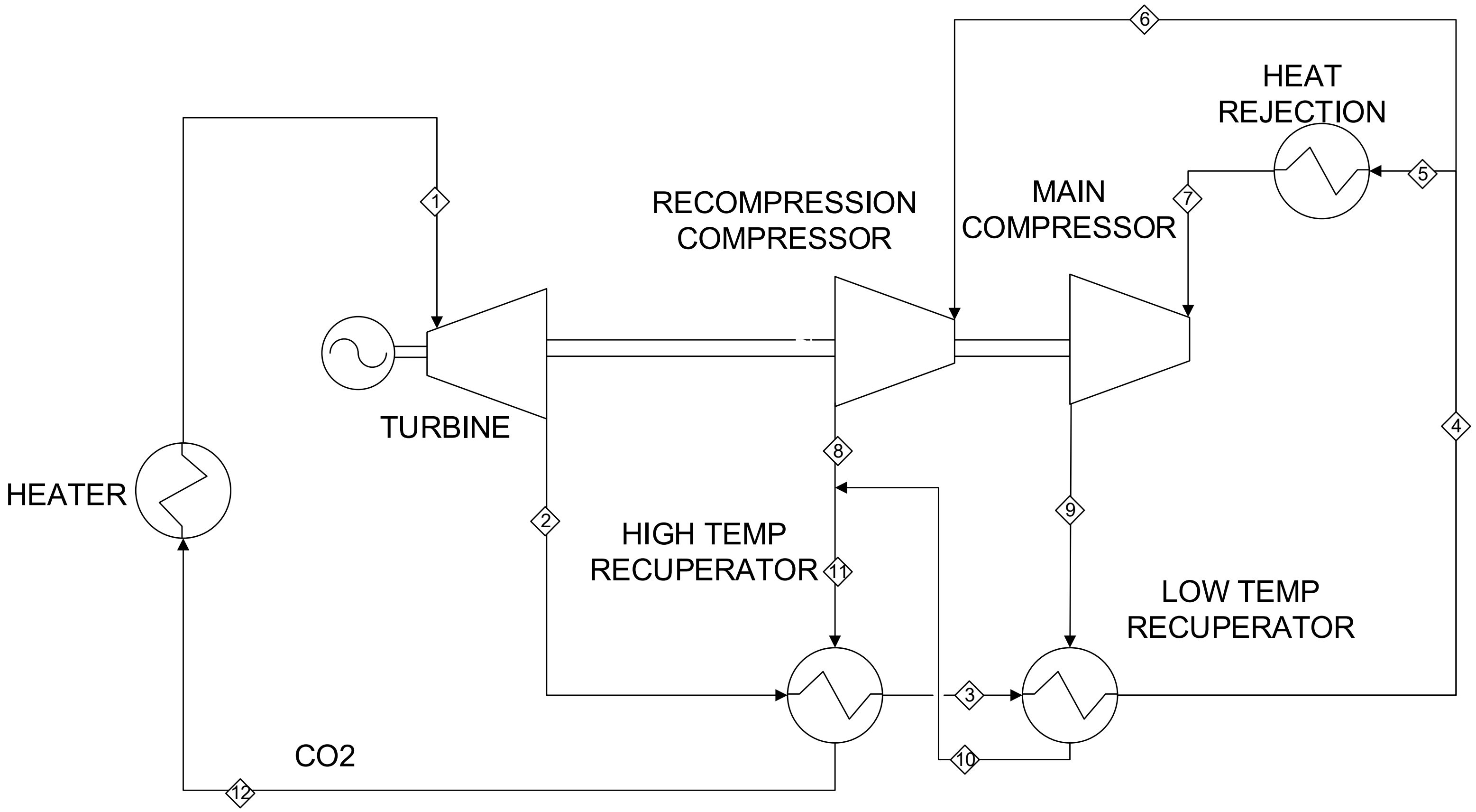
Schedule



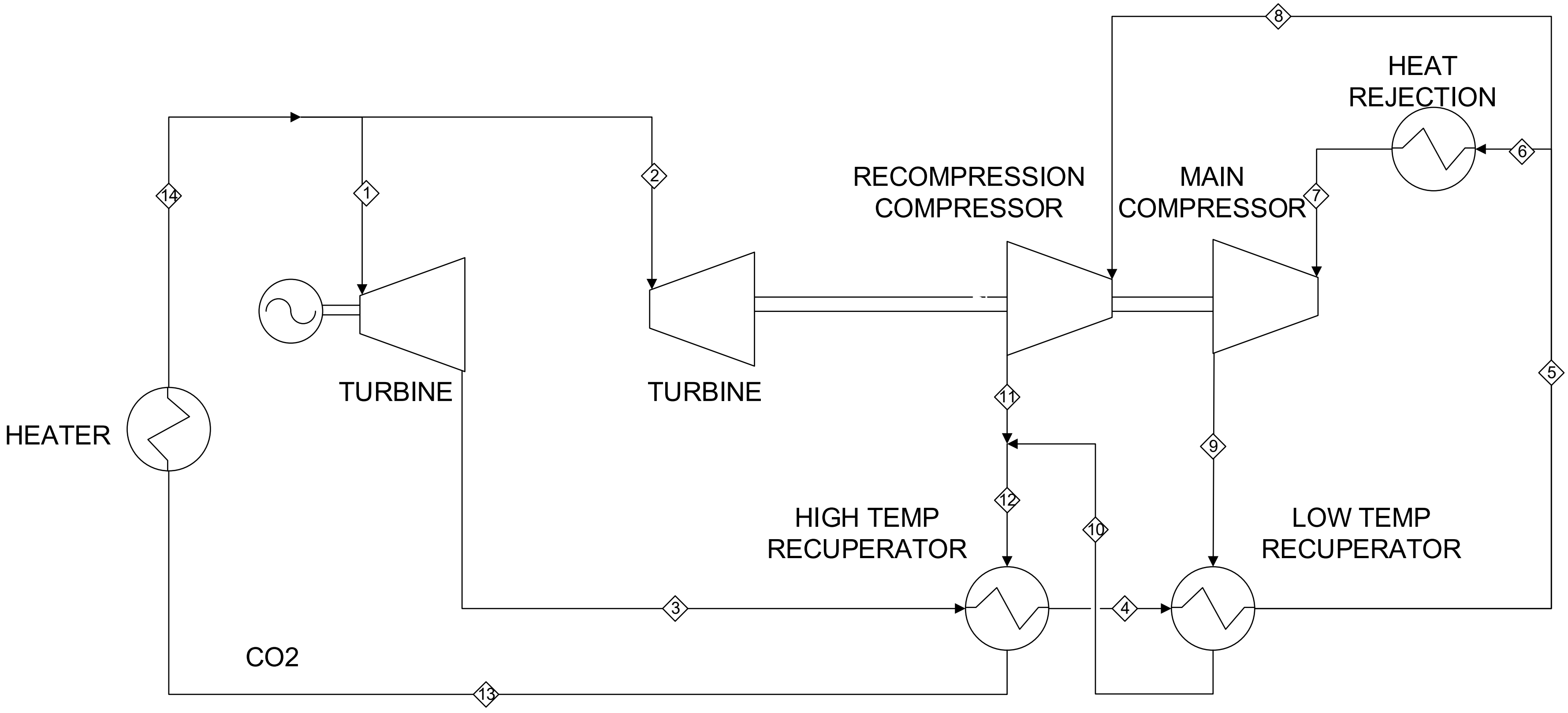
Indirectly Heated Cycles

- 6 Cases were analyzed
  - Turbine Inlet Temperature = 1300°F (705°C)
  - Turbine Inlet Pressure = 4,000 psia (28MPa)
  - Plant Capacity: 10, 25, 50, 100, 250, 550 MWe

Block Flow Diagram- Single Shaft



Block Flow Diagram- Dual Shaft



Turbomachinery Conceptual Analysis

- Two power plant capacities chosen for turbomachinery layouts: 550 MWe and 10 MWe
- Dual shaft configuration chosen due to slightly higher efficiency and better operational control
- Direct drive required for plants >~250MWe
  - Max output for current state of the art electric motors ~100MW
    - For shaft powers >~40MW rotational speeds limited to near synchronous
      - 1.6 point cycle efficiency penalty for 550MWe plant
  - One option would be to have each of the compressors on a separate shaft, but is unfavorable due to transient concerns
- 10MWe pilot configuration must consider target commercial plant size

Turbomachinery Sizing

- Back-to-back configuration chosen for turbine to help manage axial thrust and reduce blade power bending load
  - Fewest number of stages chosen that still maintained high efficiency to reduce complexity
- Power turbine runs synchronous with the generator
- Compressor turbine runs synchronous with the compressors

Updated Cycle Efficiencies

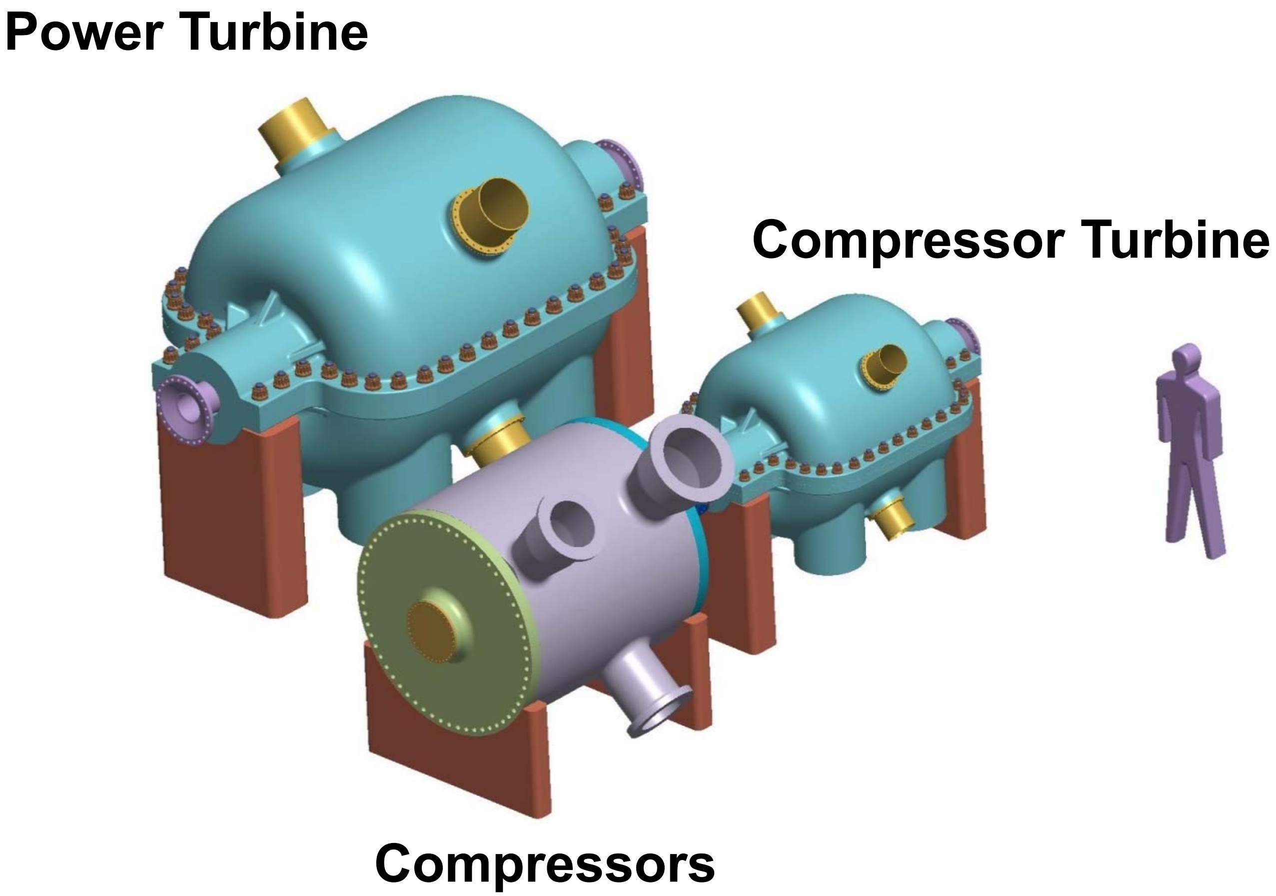
- 550 MWe

Turbine Concept	Turbine (MW)	Turbine Efficiency	Turbine RPM	Main Compressor (MW)	Main Compressor Efficiency	Recycle Compressor (MW)	Recycle Compressor Efficiency	Compressor RPM	Total Power (MW)	Mass Flow Rate (lb/hr)	Cycle Efficiency
Single Shaft	806.5	0.901	3600	102.27	0.781	154.41	0.711	3600	550	33,600,000	51.03%
Dual Shaft	770.83	0.9	3600	89.23	0.85	131.67	0.802	6000	550	32,150,000	52.62%

- 10 MWe

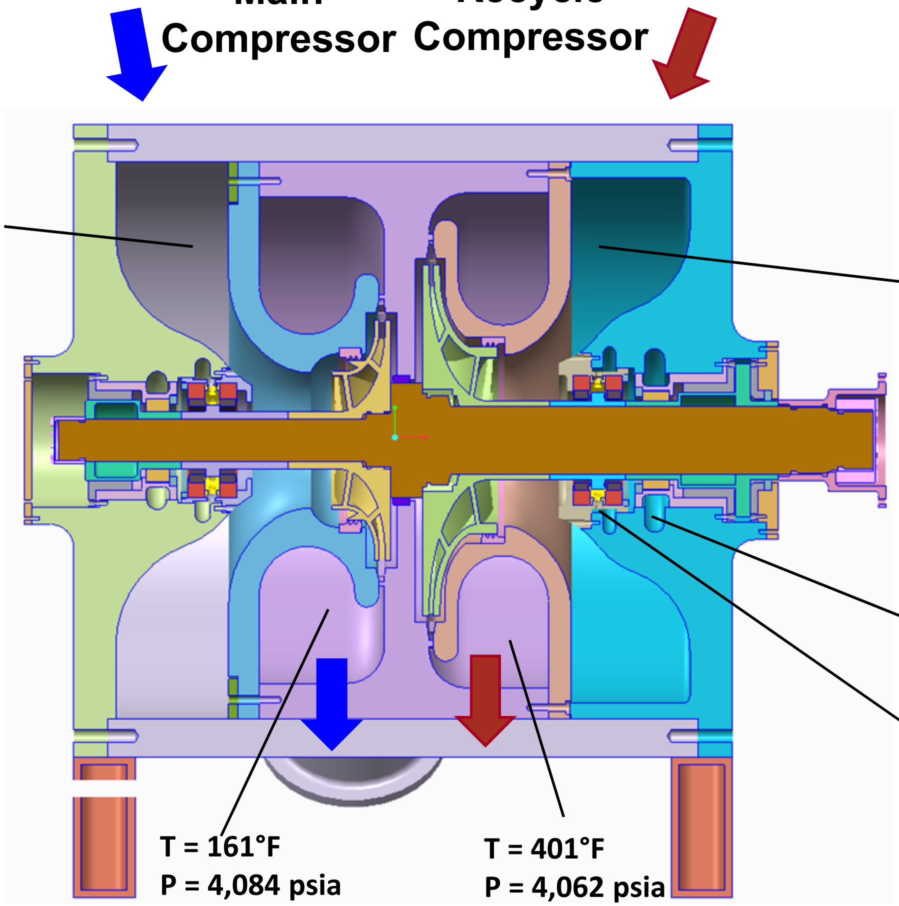
Turbine Concept	Turbine (MW)	Turbine Efficiency	Turbine RPM	Main Compressor (MW)	Main Compressor Efficiency	Recycle Compressor (MW)	Recycle Compressor Efficiency	Compressor RPM	Total Power (MW)	Mass Flow Rate (lb/hr)	Cycle Efficiency
Single Shaft	14.72	0.8585	20000	1.95	0.797	2.79	0.767	39600	10	638,000	48.84%
Dual Shaft	14.67	0.854	25000	1.92	0.798	2.73	0.769	40000	10	663,000	49.83%

Indirect Cycle Turbomachinery Concept



550 MWe Plant Compressor – Flow Conditions

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



T = 89°F
P = 1,123 psia
$\dot{m}$ = 21,058,250 lbs/hr

T = 170°F
P = 1,142 psia
$\dot{m}$ = 11,091,750 lbs/hr

Bearing lubricant supply

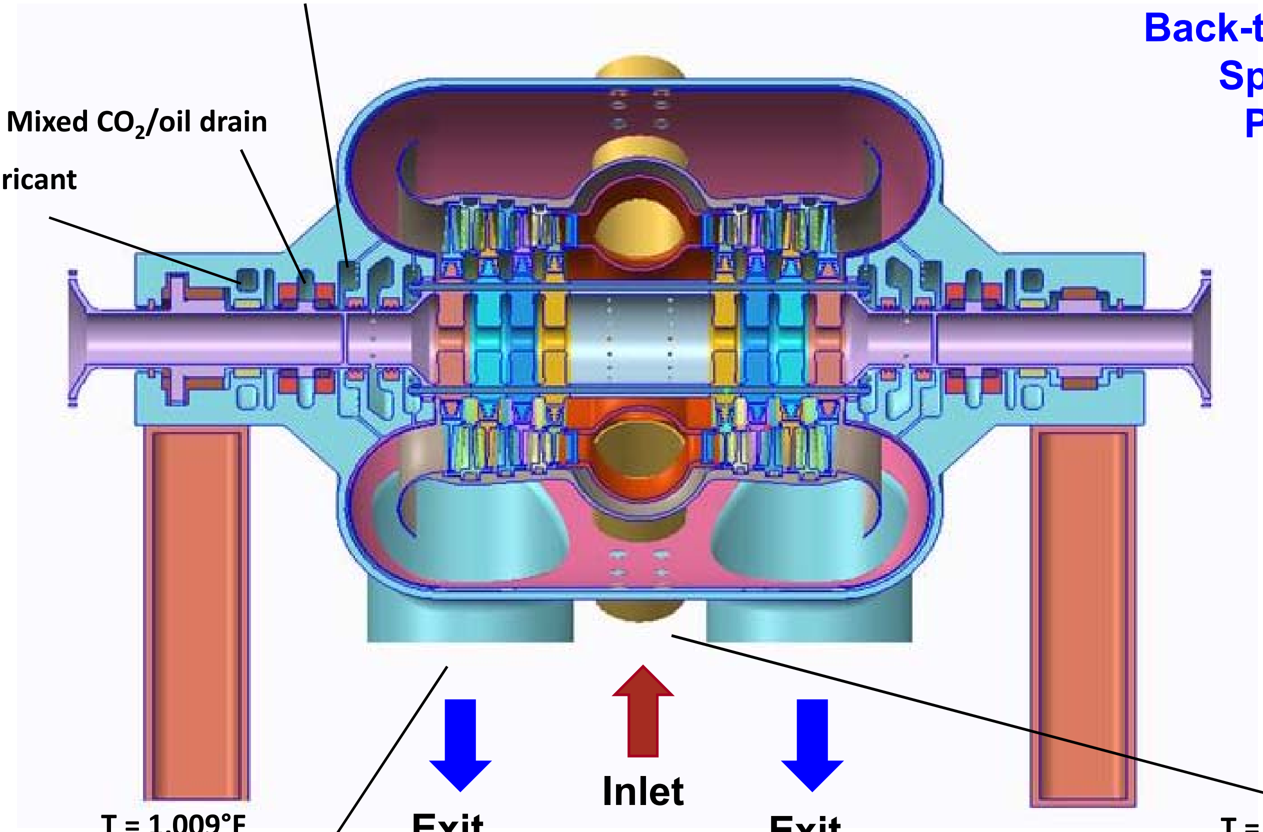
Mixed CO_2/oil drain, atm P

T = 161°F
P = 4,084 psia
$\dot{m}$ = 21,058,250 lbs/hr

T = 401°F
P = 4,062 psia
$\dot{m}$ = 11,091,750 lbs/hr

550 MWe Plant Compressor Turbine – Flow Conditions

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



CO_2 Supply

Mixed CO_2/oil drain

Bearing Lubricant Supply

Exit

Inlet

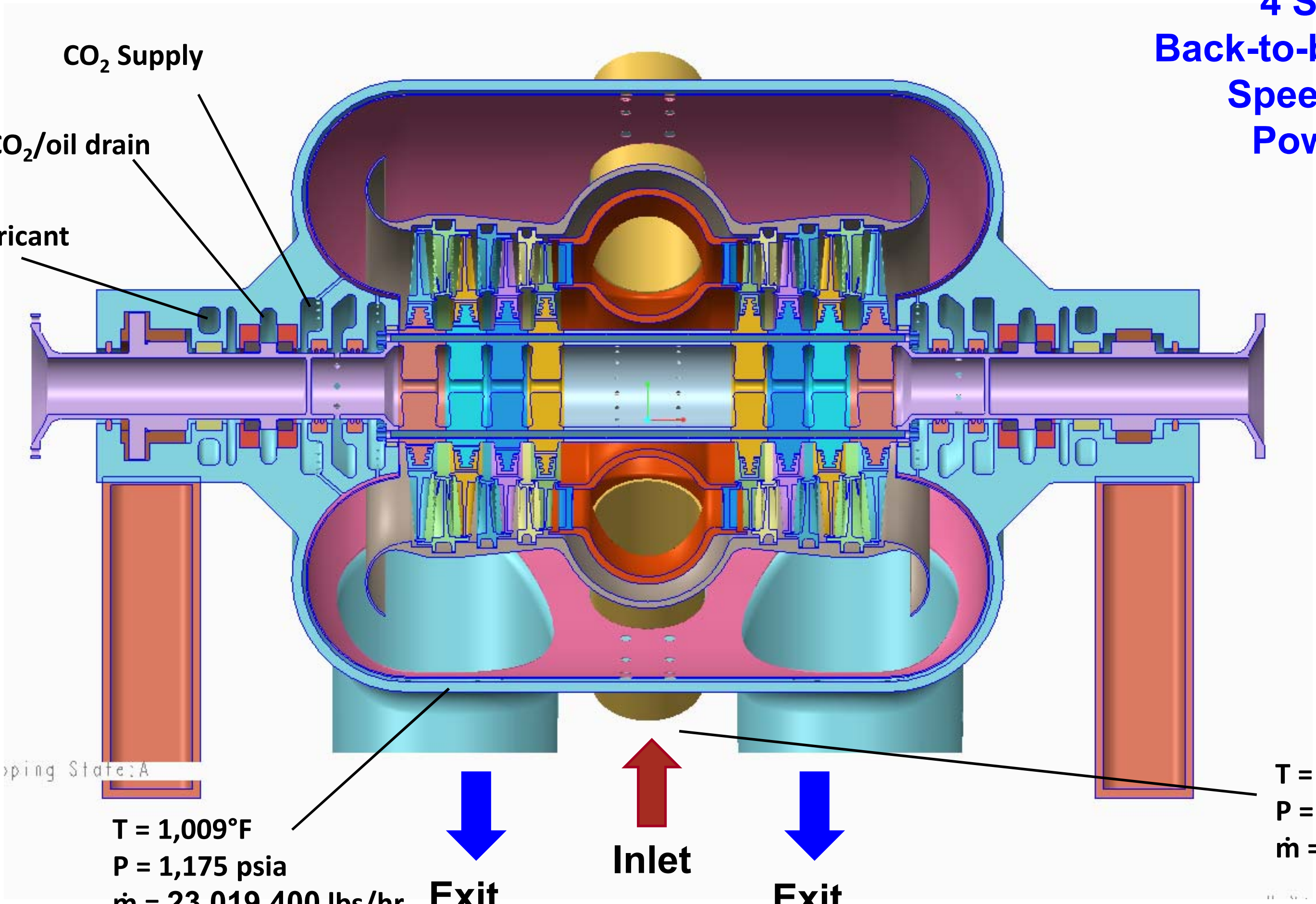
Exit

T = 1,009°F
P = 1,175 psia
$\dot{m}$ = 9,130,600 lbs/hr

T = 1,300°F
P = 4,000 psia
$\dot{m}$ = 9,130,600 lbs/hr

550 MWe Plant Generator Turbine – Flow Conditions

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

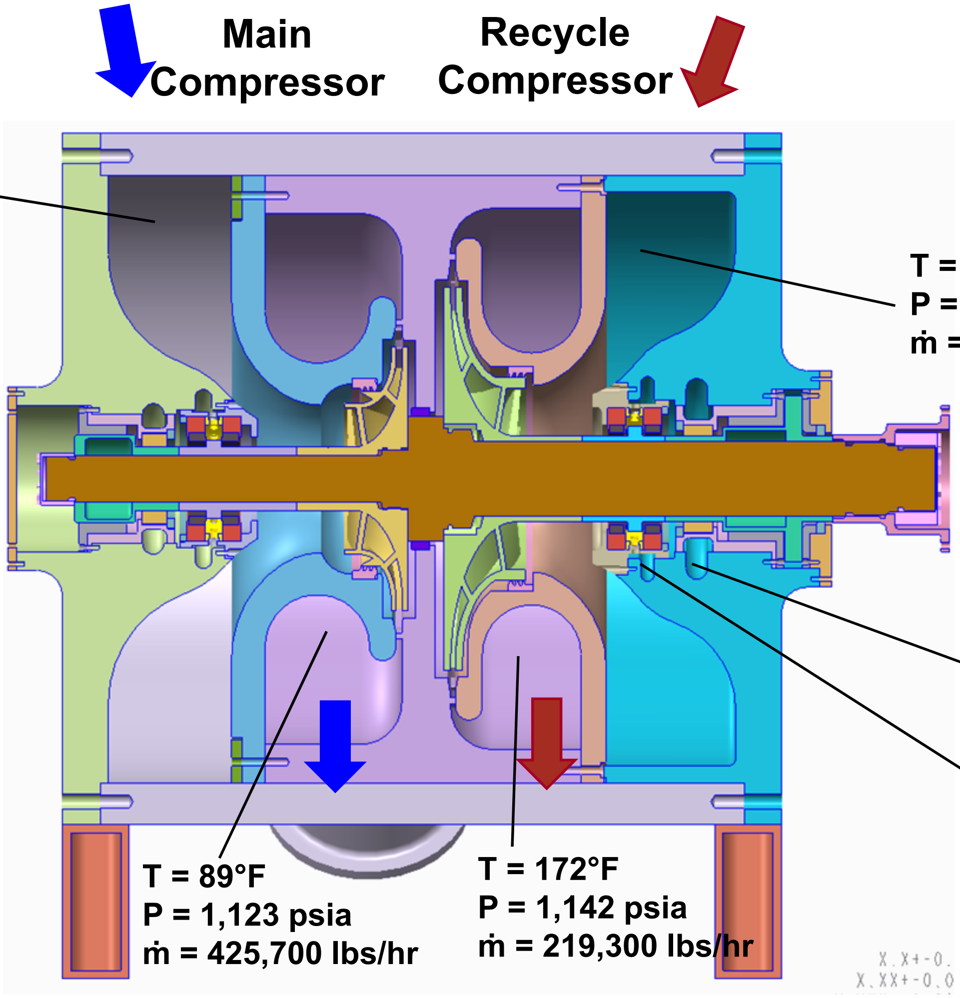


T = 1,009°F
P = 1,175 psia
$\dot{m}$ = 23,019,400 lbs/hr

T = 1,300°F
P = 4,000 psia
$\dot{m}$ = 23,019,400 lbs/hr

10 MWe Plant Compressor – Flow Conditions

Speed = 39,000 RPM
MC Power = 1.9 MW
RC Power = 2.8 MW



Main Compressor

Recycle Compressor

T = 89°F
P = 1,123 psia
ṁ = 425,700 lbs/hr

T = 172°F
P = 1,142 psia
ṁ = 219,300 lbs/hr

T = 89°F
P = 1,123 psia
ṁ = 425,700 lbs/hr

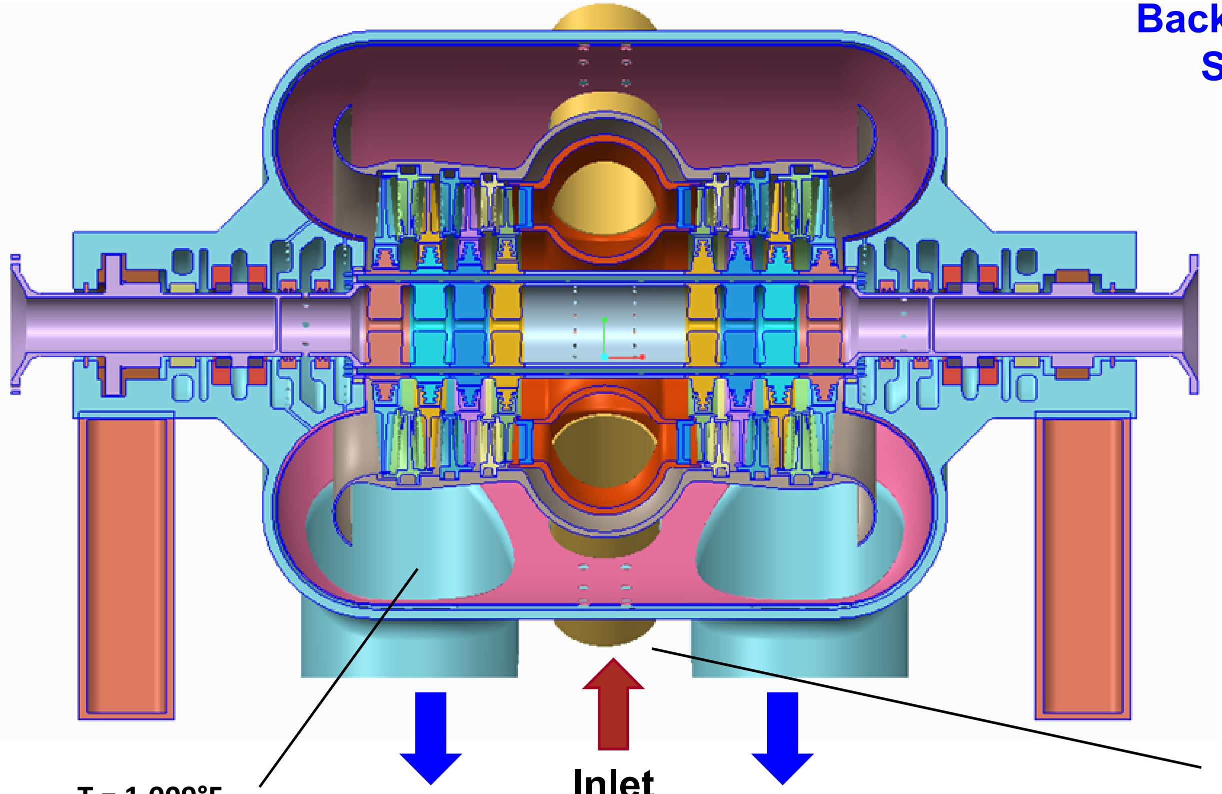
T = 172°F
P = 1,142 psia
ṁ = 219,300 lbs/hr

Bearing lubricant supply

Mixed CO_2/oil drain, atm P

10 MWe Plant Compressor Turbine – Flow Conditions

4 Stage Turbine
Back-to-back configuration
Speed = 39,000 RPM
Power = 4.7 MW



T = 1,009°F
P = 1,175 psia
ṁ = 208,335 lbs/hr

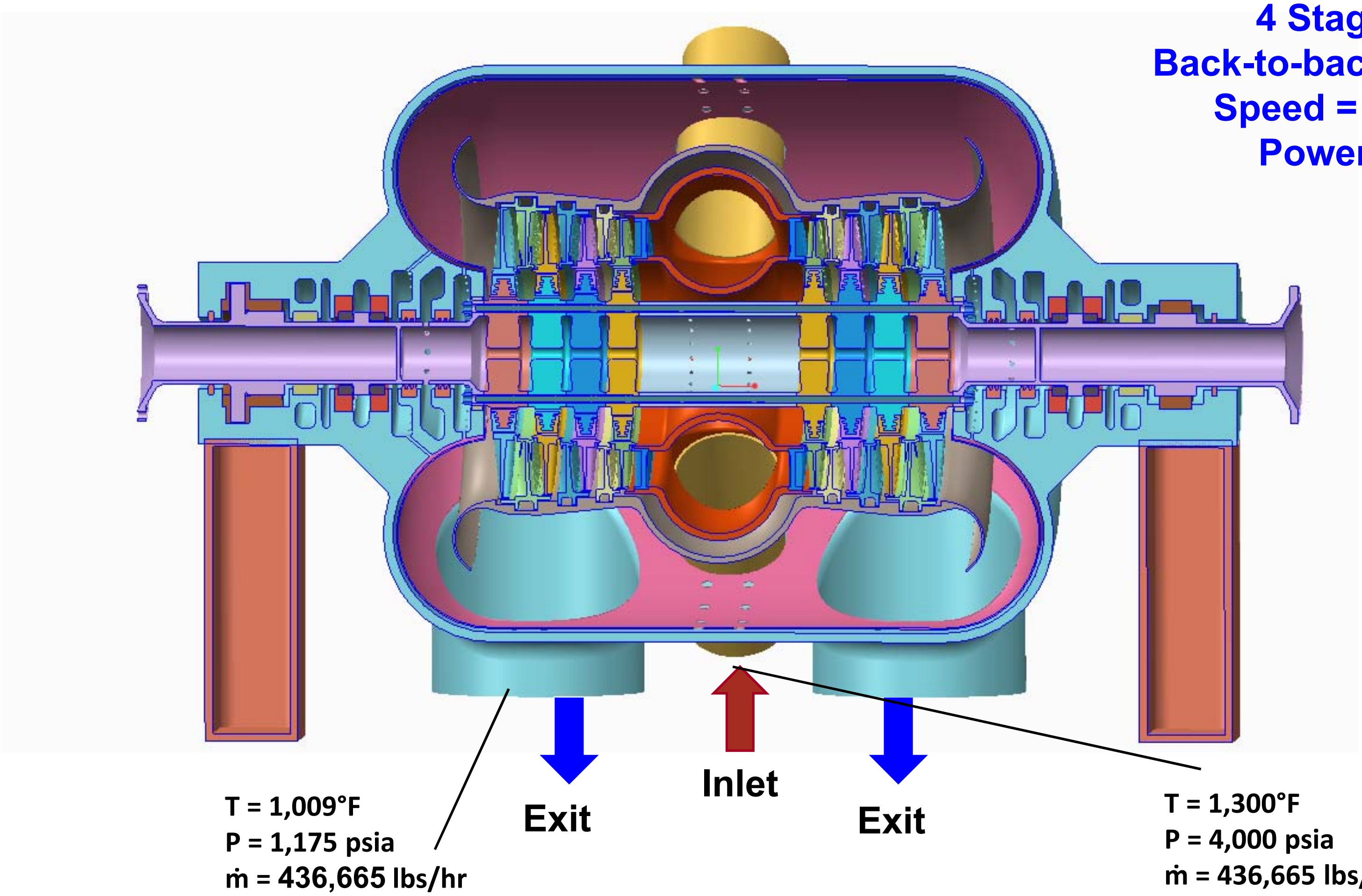
Exit

Inlet

Exit

T = 1,300°F
P = 4,000 psia
ṁ = 208,335 lbs/hr

10 MWe Plant Generator Turbine – Flow Conditions



4 Stage Turbine
Back-to-back configuration
Speed = 25,000 RPM
Power = 10 MW

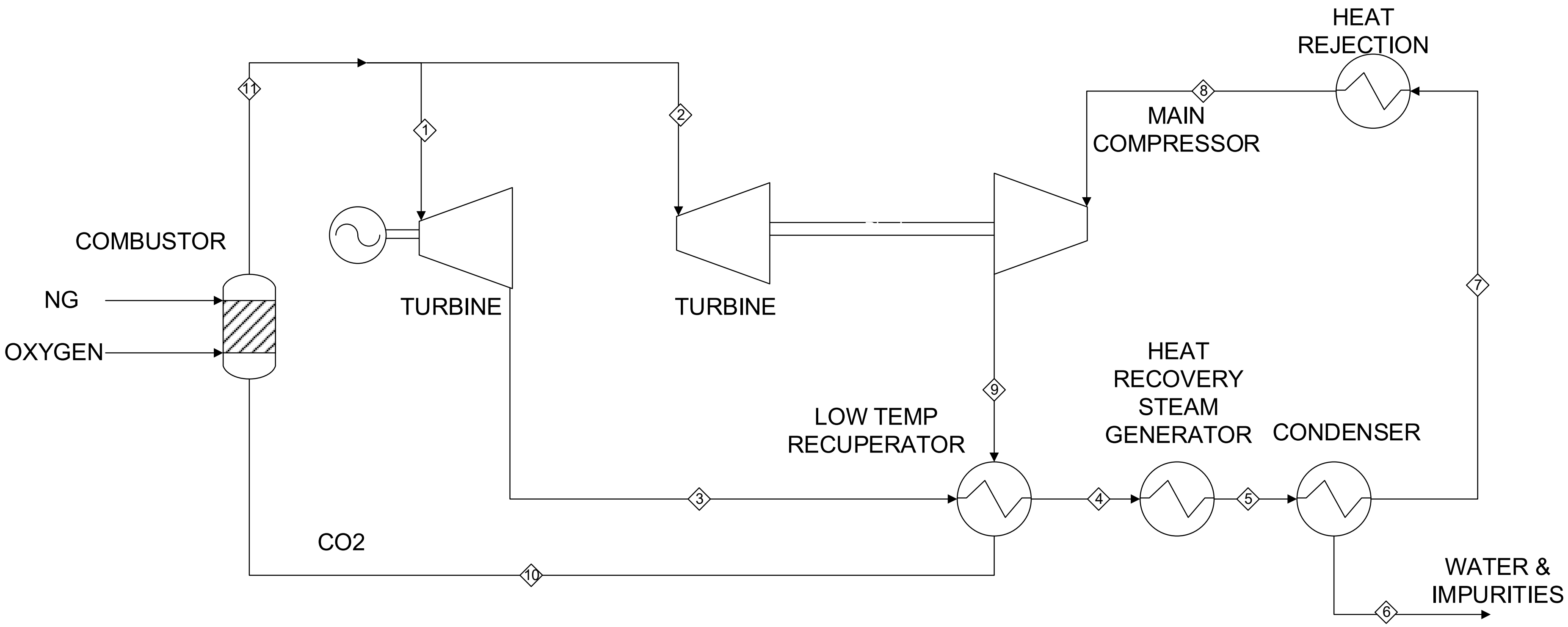
T = 1,009°F
P = 1,175 psia
ṁ = 436,665 lbs/hr

T = 1,300°F
P = 4,000 psia
ṁ = 436,665 lbs/hr

Directly Heated Cycles

- 6 cases were analyzed:
  1. Fuel: NG, Coolant: H2O
  2. Fuel: Syngas (91% H2), Coolant: H2O
  3. Fuel: Syngas (39% H2), Coolant: H2O
  4. Fuel: NG, Coolant: CO2
  5. Fuel: NG, Coolant: CO2, alternate cooling scheme with regen coolant as separate closed loop
  6. Fuel: Syngas (39% H2), Coolant: CO2
- Both NG and syngas were evaluated to determine compatibility with NGCC and IGCC (with and without capture) plants

Directly Heated Cycle Block Flow Diagram



Turbomachinery Conceptual Analysis

- NG with CO_2 as coolant was chosen for turbomachinery evaluation
- Dual shaft configuration chosen due to slightly higher efficiency and better operational control
- Straight through flow configuration chosen to maintain high turbine efficiency

Direct Cycle Turbomachinery Sizing

Compressor Turbine

- Total Power = 173 MW
- Mean Diameter = 35 in
- RPM: 4900
- Efficiency: 86.4%
- 8 stages
- Film cooling 1st stage vane only
- Regen cooling first 5 stage vanes and blades

Generator Turbine

- Total Power = 497 MW
- Mean Diameter = 55 in
- RPM: 3600
- Efficiency: 88.8%
- 8 stages
- Film cooling 1st stage vane only
- Regen cooling first 5 stage vanes and blades

Main Compressor

- Total Power = 173 MW
- 2 stages
- Efficiency: 83.6%
- RPM: 4900

CO_2 Compressor

- Off the shelf reciprocal compressor

Updated Cycle Efficiencies

- Turbomachinery sizing performed for Case 5 only (in blue below). Those efficiencies were applied to other cases

Fuel	Coolant	SCOT PWR Turbine (MW)	SCOT PWR Turbine Efficiency	SCOT PWR Turbine RPM	SCOT CMPR Turbine (MW)	SCOT CMPR Turbine Efficiency	SCOT CMPR Turbine RPM	Steam Turbine (MW)	Steam Cycle Efficiency	Main Compressor (MW)	Main Compressor Efficiency	Main Compressor RPM	Auxiliary Loads (MW)	Heat Input (MW)	Total Power (MW)	Mass Flow Rate (lb/hr)	Cycle Efficiency	Plant Efficiency
NG	Steam	484	88.8%	3600	154	86.4%	4900	167	36.0%	154	83.6%	4900	256	846	549	8,329,825	76.90%	64.89%
Syngas - 91% H_2	Steam	561	88.8%	3600	174	86.4%	4900	211	36.5%	174	83.6%	4900	397	1310	549	9,378,270	76.35%	41.91%
Syngas - 39% H_2	Steam	537	88.8%	3600	166	86.4%	4900	190	37.5%	166	83.6%	4900	344	1190	549	9,200,275	76.97%	46.17%
NG	CO_2	490	88.8%	3600	171	86.4%	4900	158	36.5%	171	83.6%	4900	269	853	549	8,519,099	75.91%	64.40%
NG	CO_2 (sep loop)	494	88.8%	3600	173	86.4%	4900	153	36.0%	173	83.6%	4900	269	853	550	8,586,366	75.86%	64.51%
Sygnas - 39% H_2	CO_2 (sep loop)	537	88.8%	3600	191	86.4%	4900	179	37.5%	191	83.6%	4900	356	1194	551	9,414,349	76.99%	46.17%

Materials Selection

Three classes of materials identified for evaluation with unique fabrication, service and performance requirements:

Machined Castings for Turbine Housings

- Weight not a design driver for land-based cycles
- Lower cost material candidates may be an option

Turbine Disk Alloys

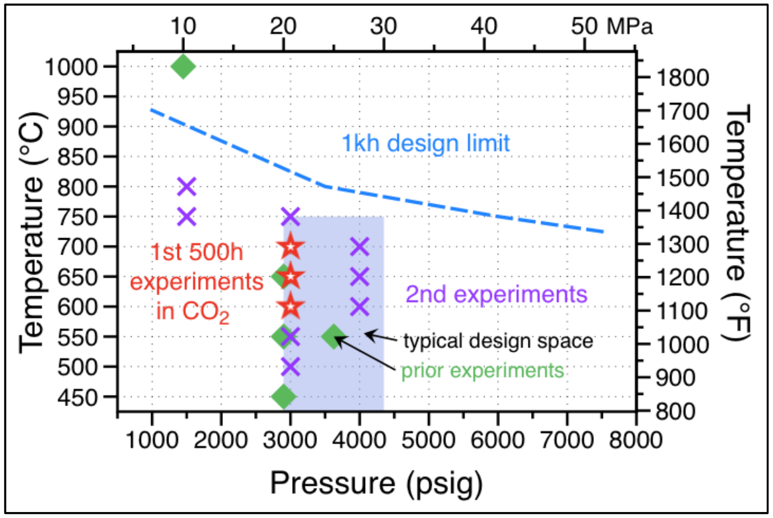
- High-temp strength, creep and fatigue resistance required
- Wrought superalloys traditional candidate for T > 0.5Tm (~1400F)
- Ni-Cr alloys show superior resistance in sCO_2 to Fe-Cr
- Some SCOT studies preferred uncooled turbine configurations

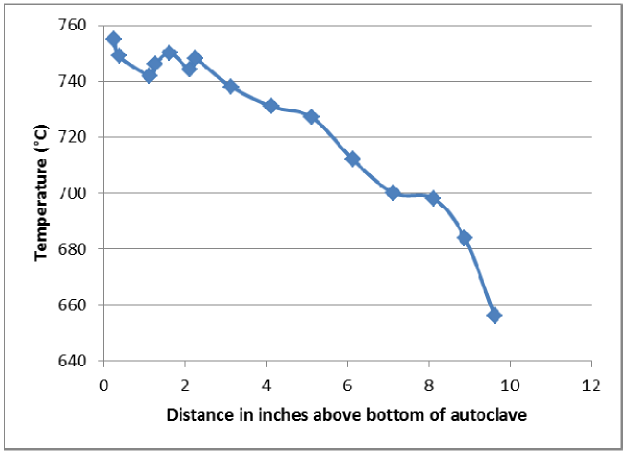
Blade Alloys

- Similar to turbine disk alloys
- Creep, fatigue and oxidation resistance prime requirements
- Uncooled configurations eliminate coatings, improve reliability
- Single-crystal superalloys meet need if sCO_2 resistant

Oak Ridge National Laboratory
Supercritical CO_2 Autoclave

Facility commissioned 1Q 2015



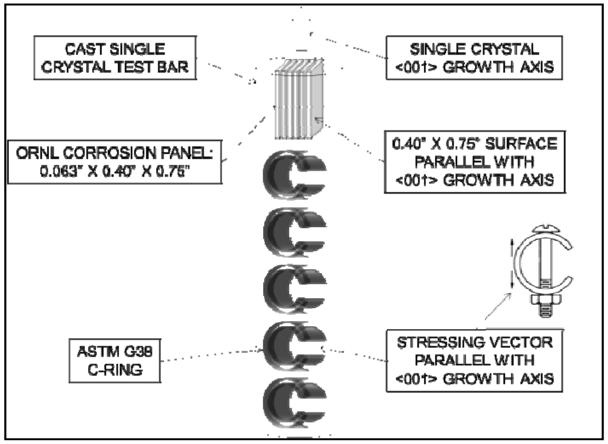


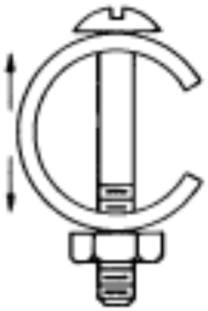
Ref: Bruce Pint, ORNL, 4-14-2014
Jim Keiser, ORNL, 6-04-2015

Pre-Stressed Exposures

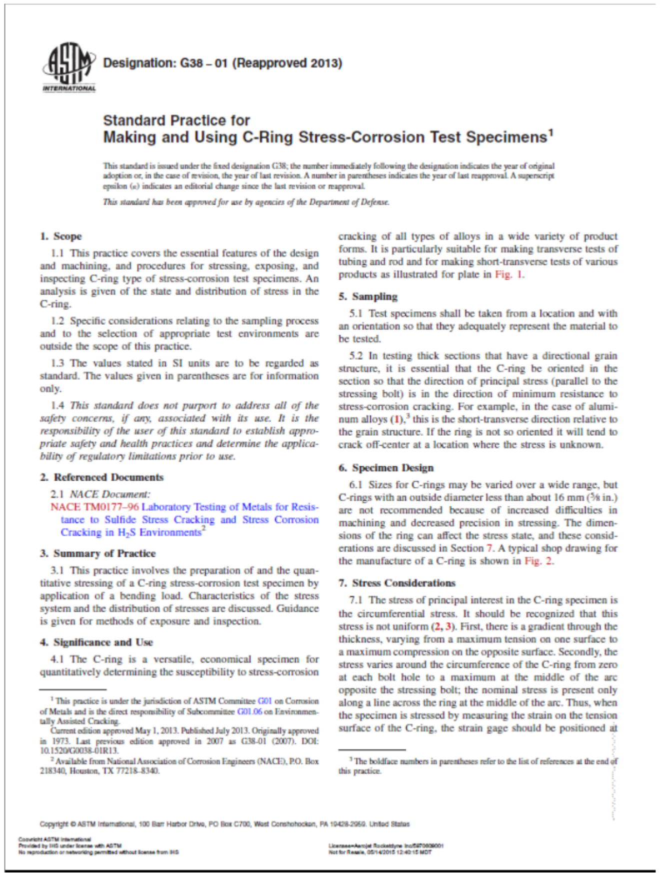
ASTM G38:
Standard Practice for Making & Using C-Ring Stress-Corrosion Test Specimens

- **Relatively simple, self-contained sample**
- **Compact – fits in small spaces**
- **Minimal tooling required**
- **Standard sample**
- **Established calculation methods**





COMPACT SIZE PERMITS FAB FROM SINGLE CRYSTAL TEST BARS



Designation: G38 – 01 (Reapproved 2013)

Standard Practice for Making and Using C-Ring Stress-Corrosion Test Specimens[1]

This standard is issued under the fixed designation G38; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This practice covers the essential features of the design and machining, and procedures for stressing, exposing, and inspecting C-ring type of stress-corrosion test specimens. An analysis is given of the state and distribution of stress in the C-ring.

1.2 Specific considerations relating to the sampling process and to the selection of appropriate test environments are outside the scope of this practice.

1.3 The values stated in SI units are to be regarded as standard. The values given in parentheses are for information only.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *NACE Document:*

NACE TM0177–96 Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking and Stress Corrosion Cracking in H_2S Environments[2]

3. Summary of Practice

3.1 This practice involves the preparation of and the quantitative stressing of a C-ring stress-corrosion test specimen by application of a bending load. Characteristics of the stress system and the distribution of stresses are discussed. Guidance is given for methods of exposure and inspection.

4. Significance and Use

4.1 The C-ring is a versatile, economical specimen for quantitatively determining the susceptibility to stress-corrosion cracking of all types of alloys in a wide variety of product forms. It is particularly suitable for making transverse tests of tubing and rod and for making short-transverse tests of various products as illustrated for plate in Fig. 1.

5. Sampling

5.1 Test specimens shall be taken from a location and with an orientation so that they adequately represent the material to be tested.

5.2 In testing thick sections that have a directional grain structure, it is essential that the C-ring be oriented in the section so that the direction of principal stress (parallel to the stressing bolt) is in the direction of minimum resistance to stress-corrosion cracking. For example, in the case of aluminum alloys (1),[3] this is the short-transverse direction relative to the grain structure. If the ring is not so oriented it will tend to crack off-center at a location where the stress is unknown.

6. Specimen Design

6.1 Sizes for C-rings may be varied over a wide range, but C-rings with an outside diameter less than about 16 mm (⅝ in.) are not recommended because of increased difficulties in machining and decreased precision in stressing. The dimensions of the ring can affect the stress state, and these considerations are discussed in Section 7. A typical shop drawing for the manufacture of a C-ring is shown in Fig. 2.

7. Stress Considerations

7.1 The stress of principal interest in the C-ring specimen is the circumferential stress. It should be recognized that this stress is not uniform (2, 3). First, there is a gradient through the thickness, varying from a maximum tension on one surface to a maximum compression on the opposite surface. Secondly, the stress varies around the circumference of the C-ring from zero at each bolt hole to a maximum at the middle of the arc opposite the stressing bolt; the nominal stress is present only along a line across the ring at the middle of the arc. Thus, when the specimen is stressed by measuring the strain on the tension surface of the C-ring, the strain gage should be positioned at

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[1] This practice is under the jurisdiction of ASTM Committee G01 on Corrosion of Metals and is the direct responsibility of Subcommittee G01.06 on Environmentally Assisted Cracking.

Current edition approved May 1, 2013. Published July 2013. Originally approved in 1973. Last previous edition approved in 2007 as G38-01 (2007). DOI: 10.1520/G0038-01R13.

[2] Available from National Association of Corrosion Engineers (NACE), P.O. Box 218340, Houston, TX 77218-8340.

[3] The boldface numbers in parentheses refer to the list of references at the end of this practice.

Materials Candidates & Test Status

All samples machined by Metal Samples Company, Munford, AL

SCOT Component	Material	Flat Panel Samples MSC Material	C-Rings MSC Material	C-Rings AR Material
Housing	HK40	🟩 10	🟨 3	
Housing	HK50	🟩 10		
Housing	CAFA7			🟨 3
Housing	DAFA30			🟥 3
Housing	Haynes 282 (cast)			🟥 3
Disk	Waspaloy	🟩 10	🟨 3	
Disk	Udimet Alloy 720	🟩 10		
Disk	Alloy 718	🟩 10	🟥 3	
Disk	Alloy A-286	🟩 10		
Disk	Astroloy	(10)		
Disk	Rene 41	🟩 10		
Blade	CMSX-4			🟨 3
Blade	CMSX-8			🟥 3
Blade	PWA 1483			🟨 3
Blade	Rene N4			🟨 3

LEGEND

🟩 **FIRST EXPOSURE: SAMPLE ANALYSIS COMPLETE**

🟨 **SECOND EXPOSURE: SAMPLE ANALYSIS INITIATED**

🟥 **THIRD EXPOSURE: RUN COMPLETE 10-28-2015**

Matrix size limited by several constraints:

- Sample prep costs for full matrix exceeded budget
- Excessive temperature variation in autoclave limits test volume
- Post test characterization cost limits sample analysis

First Exposure – Panel Data

Panels exposed to 99.995% sCO$_2$ at ORNL: 500 hrs at 2900 psig and 750°C

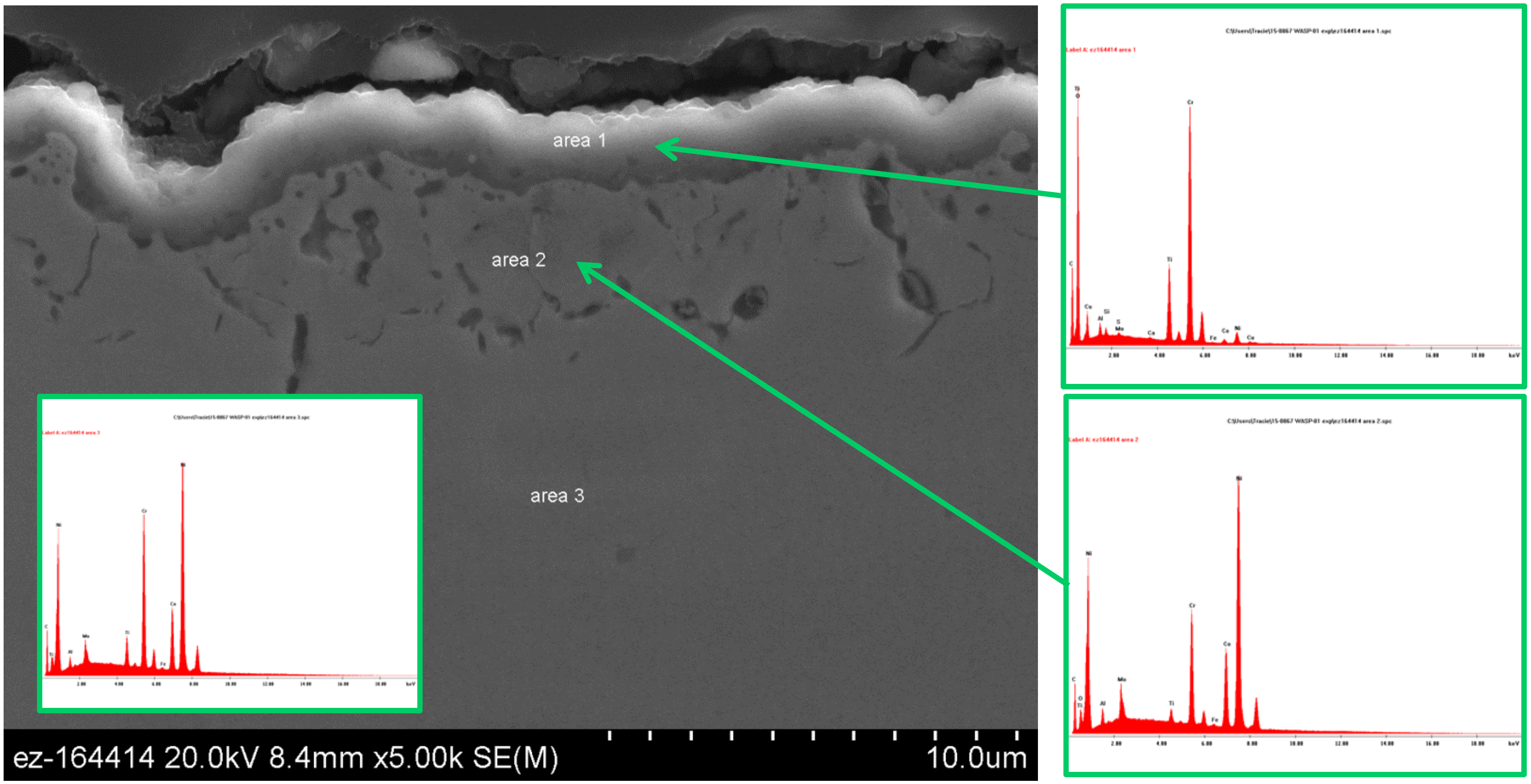
- Weight change recorded; samples selected for optical, SEM examination
- All positive weight change (surface oxide growth)
    - A286 eliminated due to high oxidation rate
    - One housing candidate (HK40) selected for examination
    - Two disk candidates with lowest oxidation rate (718, Waspaloy) selected
- Microstructural examination show some subsurface oxidation effects

Alloy	Sample 1 (mg/cm2)	Sample 2 (mg/cm2)	Sample 3 (mg/cm2)
HK40	0.49	0.49	0.56
HK50	0.41	0.32	0.28
Udimet 720	0.53	0.55	0.55
Waspaloy	0.40	0.34	0.37
Rene 41	0.55	0.54	0.56
A-286	11.27	17.70	17.88
Alloy 718	0.28	0.27	0.34

Waspaloy Panels

Waspaloy Microstructure (SEM with EDS analysis):

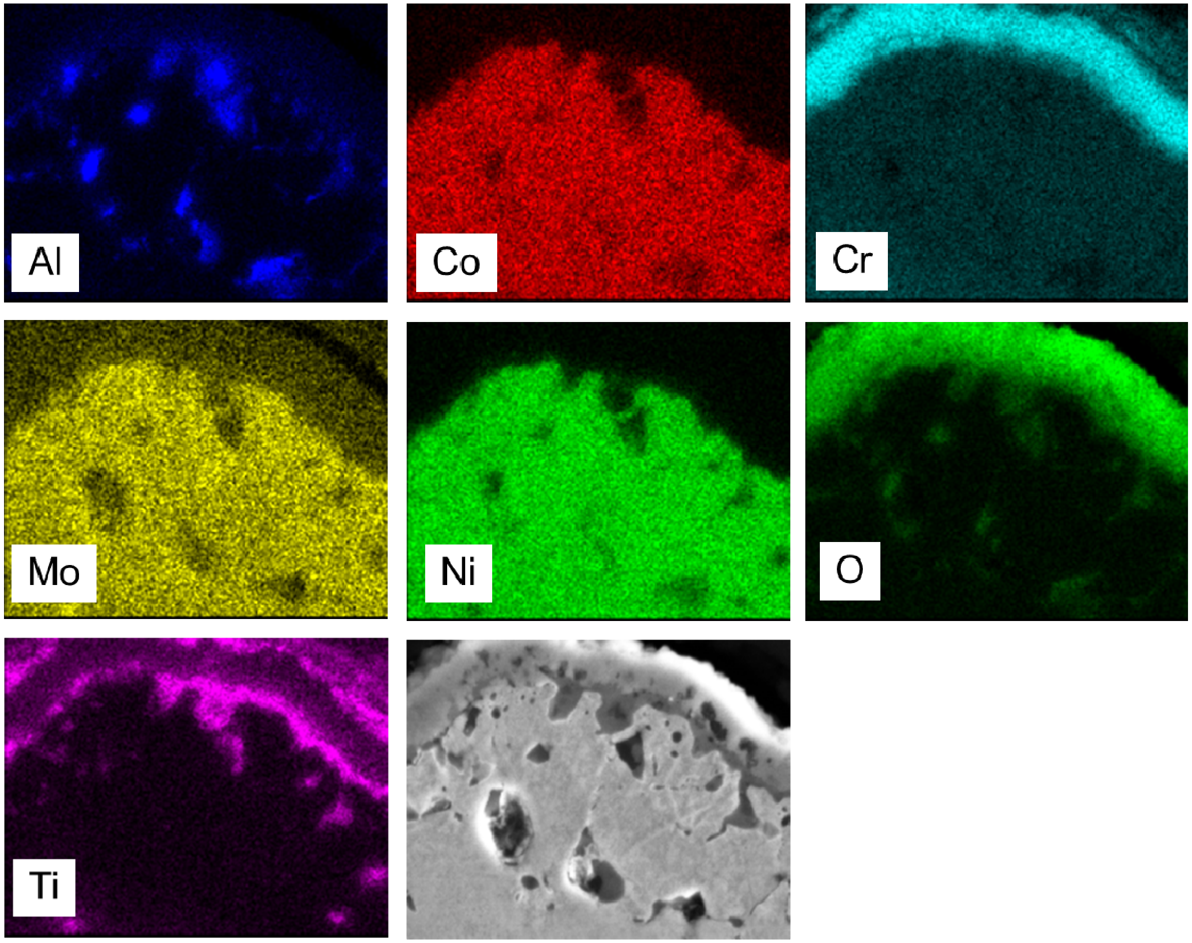
- Surface oxide (area 1) high in Cr, O
- Subsurface zone (area 2) depleted in Cr, Ti with oxide penetration (~5 microns)
- Parent metal (area 3) showing baseline composition



Waspaloy Panels

Waspaloy Microstructure (Microprobe X-Ray maps):

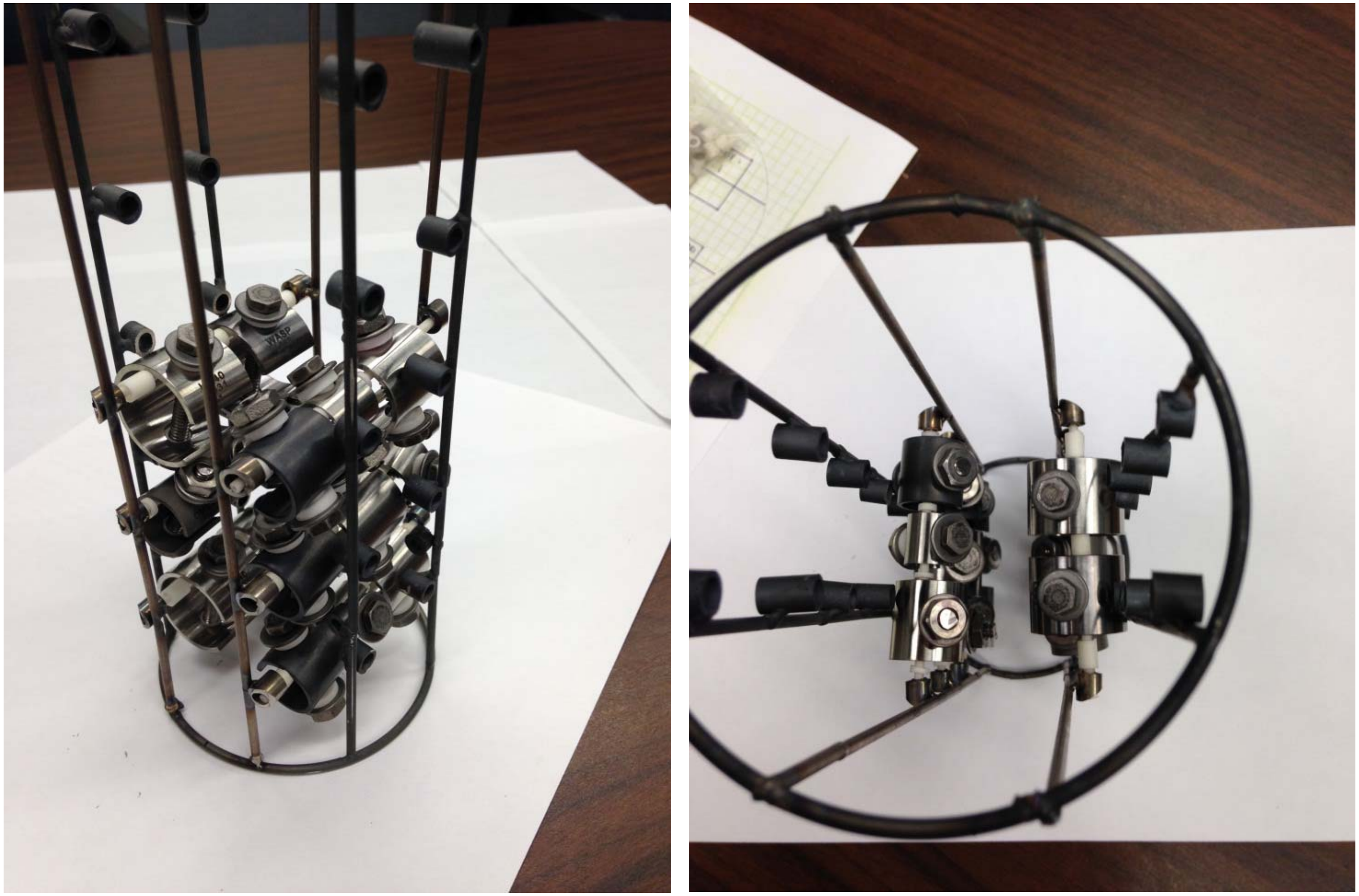
- **Surface oxide (~2 microns) high in Cr, O with Ti enriched intermediate layer**
- **Subsurface zone with O penetration (~5 microns) associated with Al, some Ti**



Second Exposure – C-Ring Summary

Material	*Ring Geometry Inputs, inches*			*Rupture Stress Fraction, %*	*Test Stress psi*	*Installed Deflection at RT, inches*
	2a	*h*	*W*			
CMSX-4	0.675	0.0540	0.675	100	143000	
	0.675	0.0540	0.675	**95**	135850	**0.0319**
	0.675	0.0540	0.675	**85**	121550	**0.0287**
	0.675	0.0540	0.675	**75**	107250	**0.0254**
PWA 1483	0.500	0.0400	0.500	100	104000	
	0.500	0.0400	0.500	**95**	98800	**0.0170**
	0.500	0.0400	0.500	**85**	88400	**0.0152**
	0.500	0.0400	0.500	**75**	78000	**0.0135**
Rene N4	0.675	0.0540	0.675	100	122000	
	0.675	0.0540	0.675	**95**	115900	**0.0253**
	0.675	0.0540	0.675	**85**	103700	**0.0227**
	0.675	0.0540	0.675	**75**	91500	**0.0201**
Waspaloy	1.000	0.0625	0.750	100	54000	
	1.000	0.0625	0.750	**95**	51300	**0.0125**
HK40	1.000	0.0625	0.750	100	14000	
	1.000	0.0625	0.750	**95**	13300	**0.0019**
	1.000	0.0625	0.750	**85**	11900	**0.0015**
	1.000	0.0625	0.750	**75**	10500	**0.0010**
CAFA7	0.750	0.0600	0.750	100	20000	
	0.750	0.0600	0.750	**95**	19000	**0.0015**
	0.750	0.0600	0.750	**85**	17000	**0.0011**
	0.750	0.0600	0.750	**75**	15000	**0.0008**

Second Exposure – C-Rings, Pre-Test

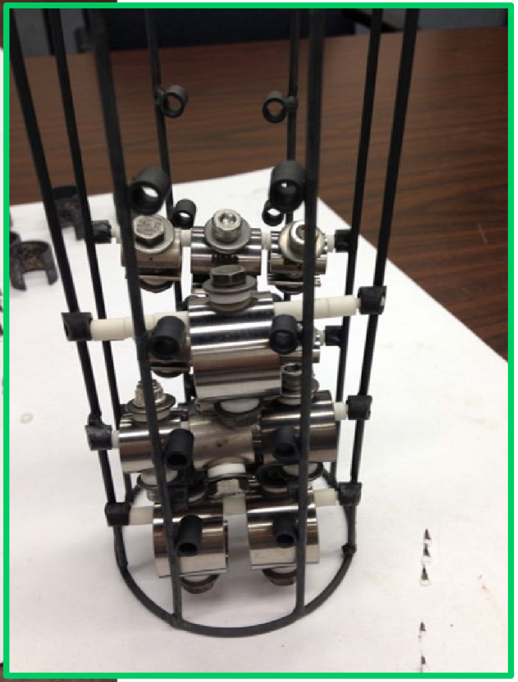


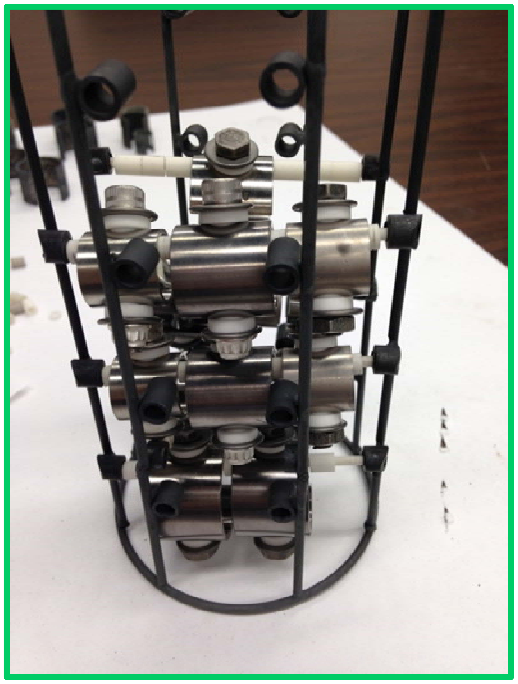
Second Exposure – C-Rings, Post-Test

NOTE FLAKING OXIDE ON HK40 RINGS
(CORRELATES WITH PANEL METALLOGRAPHY)

Third Exposure – C-Rings, Pre-Test

- Exposure initiated : 10-07-2015
- Exposure complete: 10-28-2015
- Disassembly and measurement imminent
- Detailed analysis plan TBD

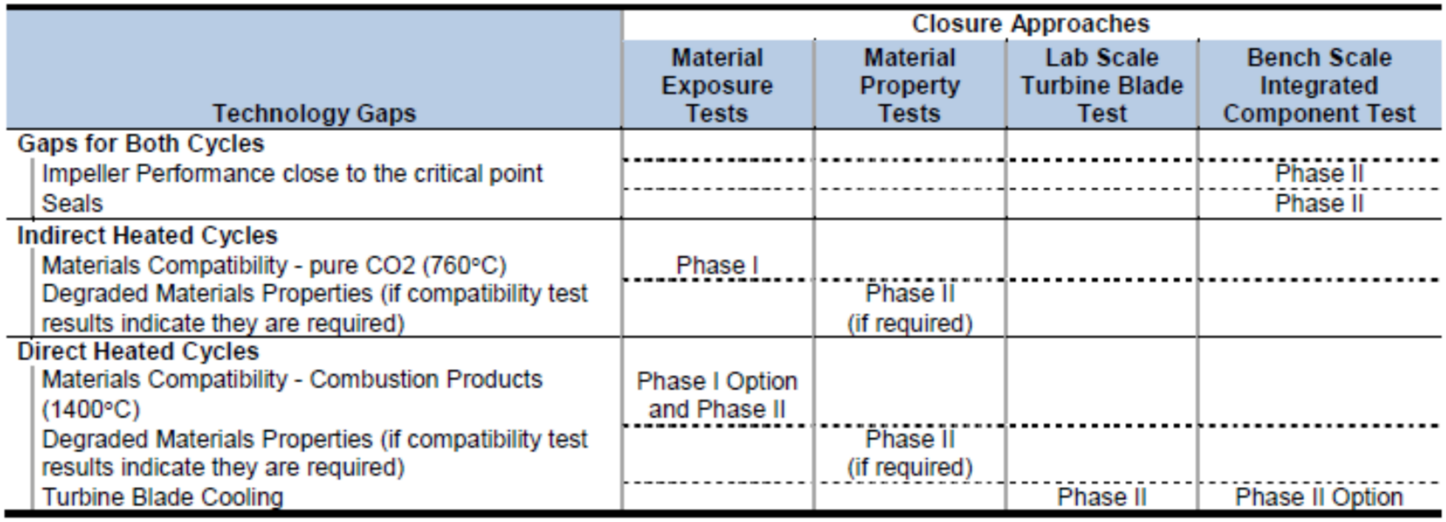




Summary & Future Work

- Three sCO_2 500 hr exposures complete at 750°C and 2900 psig
- Panels show surface oxidation and some oxide penetration
- All C-Rings need post-exposure characterization
- Anticipated results:
  - Ranking of alloys within groups for resistance to sCO_2 effects
  - Insight into potential for alloy embrittlement in sCO_2 environments

Potential Phase II Plan (Task 6)



Technology Gaps	Closure Approaches			
	Material Exposure Tests	Material Property Tests	Lab Scale Turbine Blade Test	Bench Scale Integrated Component Test
Gaps for Both Cycles				
Impeller Performance close to the critical point				Phase II
Seals				Phase II
Indirect Heated Cycles				
Materials Compatibility - pure CO2 (760°C)	Phase I			
Degraded Materials Properties (if compatibility test results indicate they are required)		Phase II (if required)		
Direct Heated Cycles				
Materials Compatibility - Combustion Products (1400°C)	Phase I Option and Phase II			
Degraded Materials Properties (if compatibility test results indicate they are required)		Phase II (if required)		
Turbine Blade Cooling			Phase II	Phase II Option

- Based on the system cycle analysis, the turbomachinery trades and the technology gap assessment, a Phase II plan will be developed
- Potential program plan for Phase II includes a bench scale integrated component test (compressor and turbine)

Questions?

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