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Progress in Overcoming Materials Challenges with sCO_2 RCBC's

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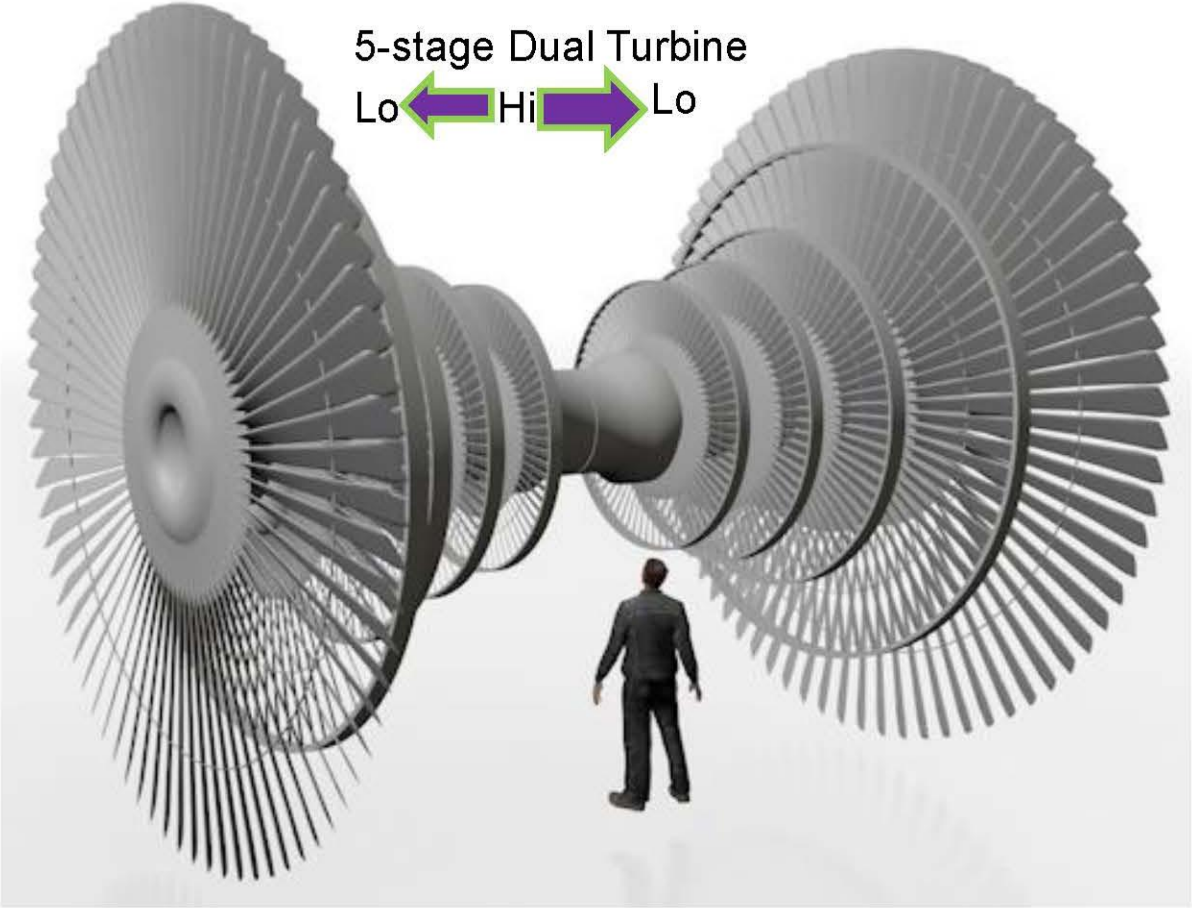
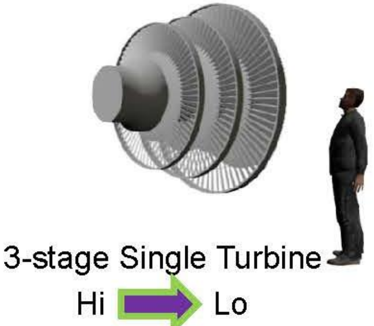
Transformational Energy System



20 meter Steam Turbine (300 MWe)
(Rankine Cycle)

Comparison

- Rankine efficiency is 33%
- Supercritical CO_2 (sCO_2) potential to surpass 40% efficiency
- Greatly reduced cost for sCO_2 compared to the cost of conventional steam Rankine cycle
- sCO_2 compact turbo machinery is easily scalable



1 meter sCO_2 (300 MWe)
(Brayton Cycle)

Origins in SFR Development

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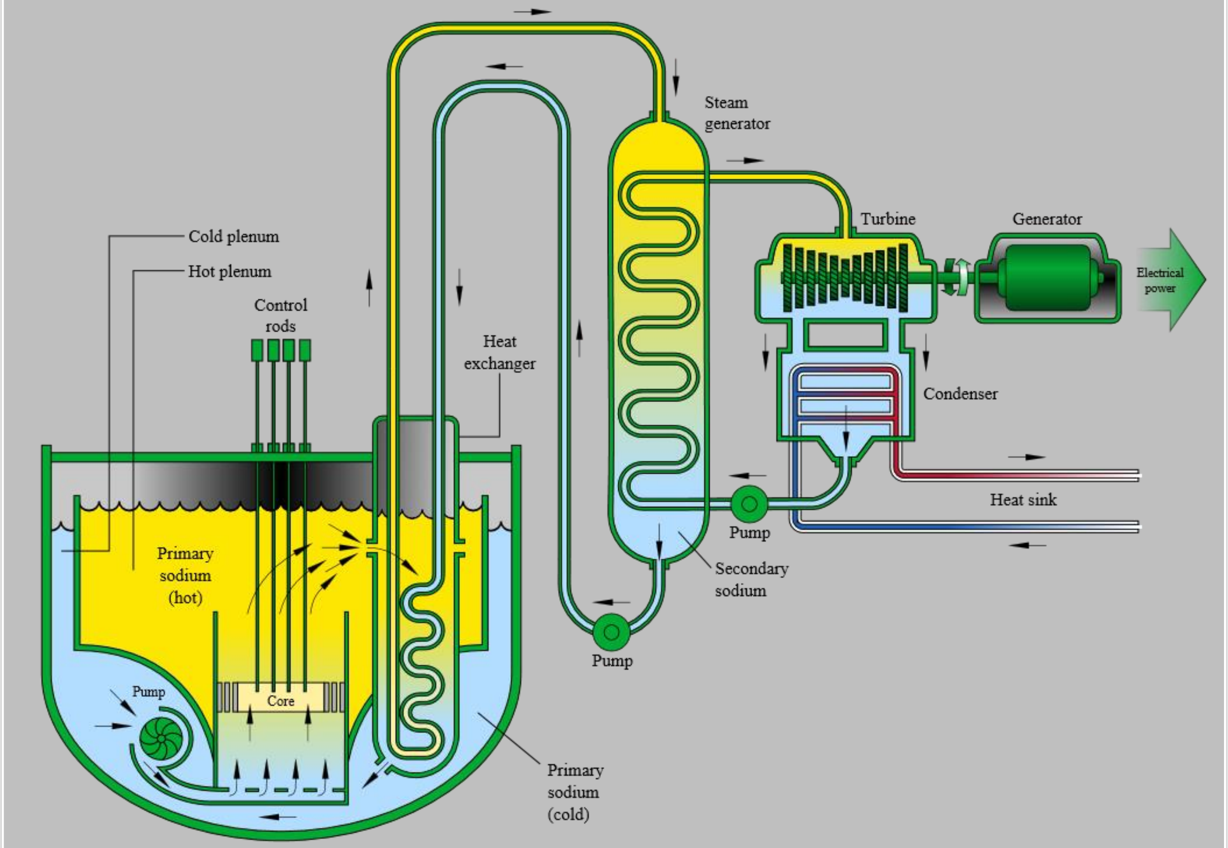
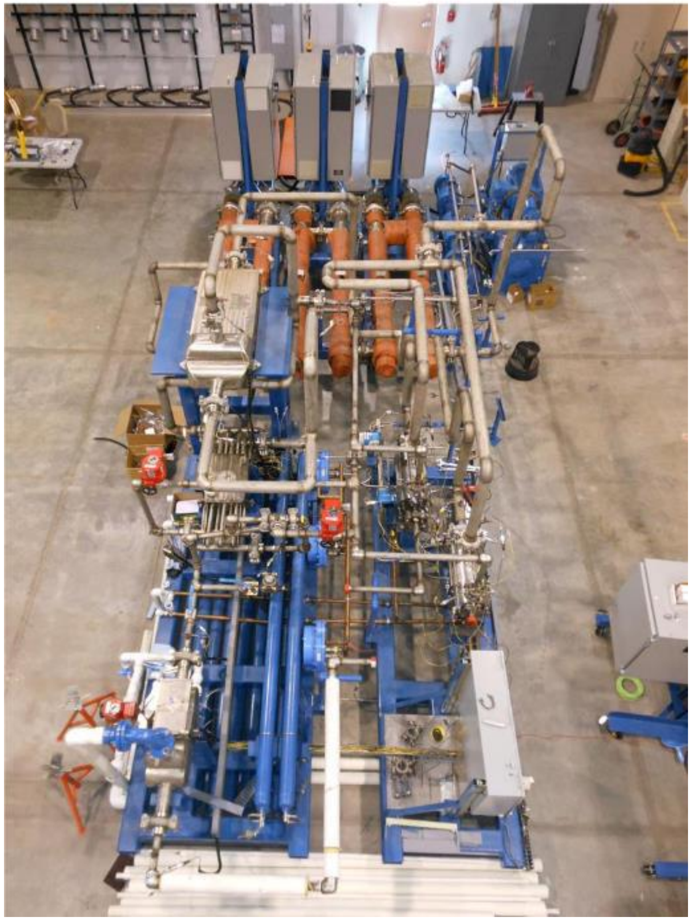
Sodium Fast Reactor (SFR)



Sandia is a Leader in sCO_2 System Development

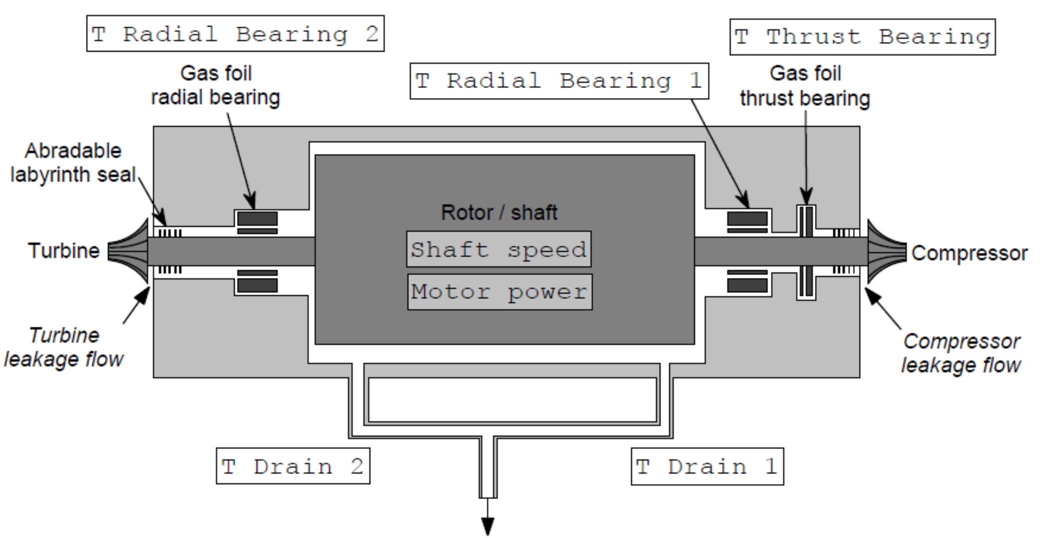
- **Component Development with Manufacturers**
- **Component Testing Platforms**
- **System Testing and Integration**
- **System Economics Modelling**
- **Materials Development**

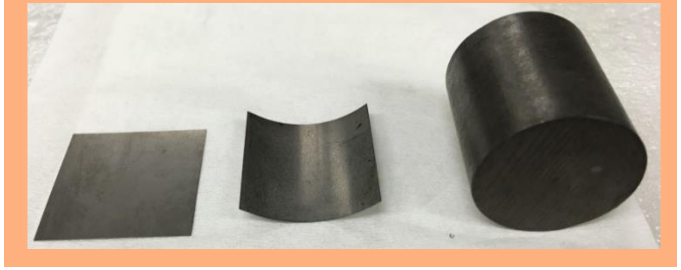
250 kW sCO_2 RCBC



Materials Issues for sCO_2 Systems

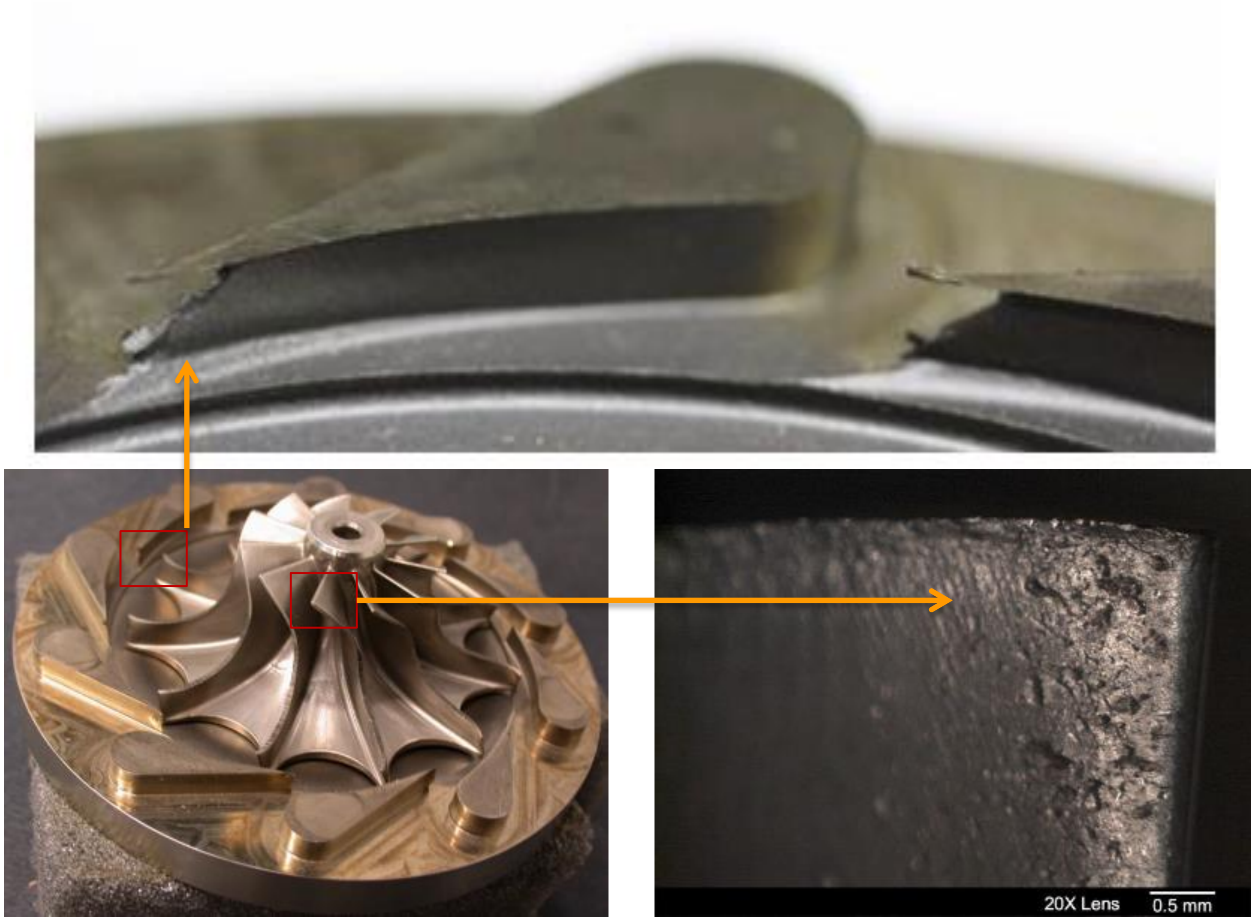
Gas Foil Bearing Behavior in CO_2





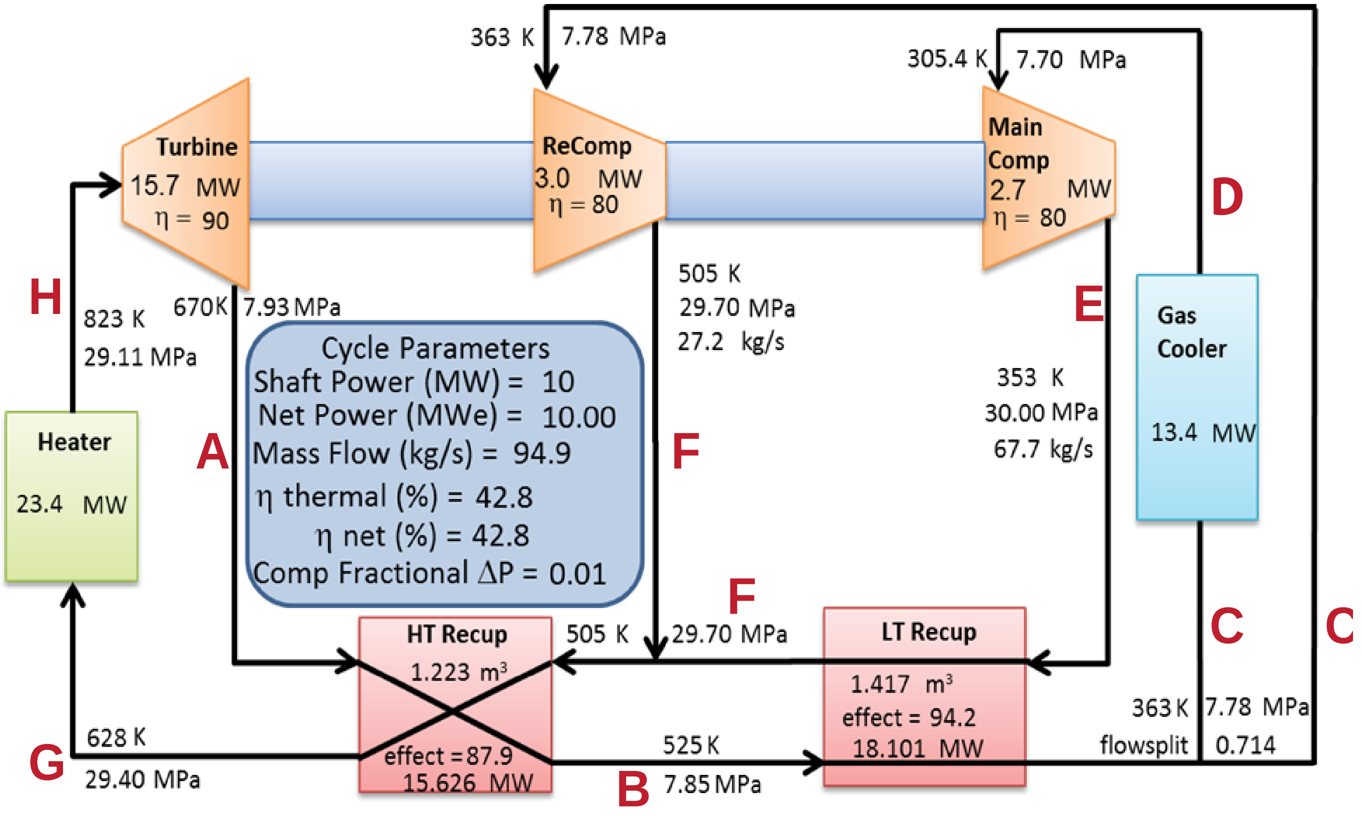
Materials Issues for sCO_2 Systems

Understanding and Resolving Turbine Degradation



Materials Issues for sCO_2 Systems

Identifying Material Options for 550°C, 10 MW System Components



Cycle Parameters

Shaft Power (MW) = 10

Net Power (MWe) = 10.00

Mass Flow (kg/s) = 94.9

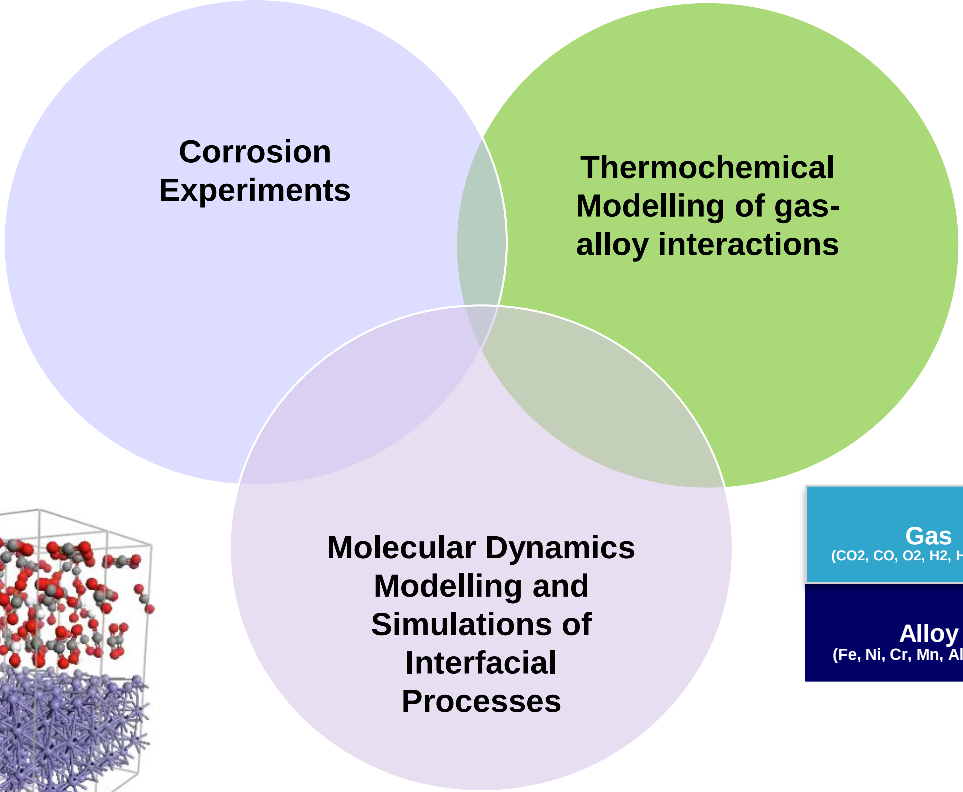
η thermal (%) = 42.8

η net (%) = 42.8

Comp Fractional ΔP = 0.01

Materials Issues for sCO_2 Systems

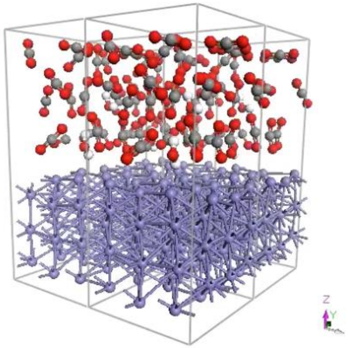
Understanding the Influence of Gas Chemistry on Alloy Corrosion

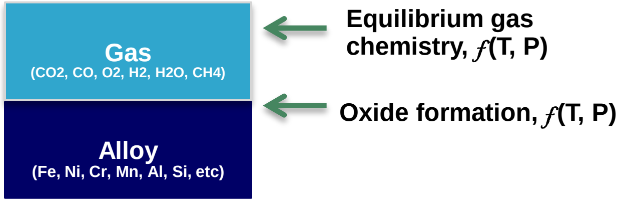


Corrosion Experiments

Thermochemical Modelling of gas-alloy interactions

Molecular Dynamics Modelling and Simulations of Interfacial Processes





Gas
(CO_2, CO, O_2, H_2, H_2O, CH_4)

Alloy
(Fe, Ni, Cr, Mn, Al, Si, etc)

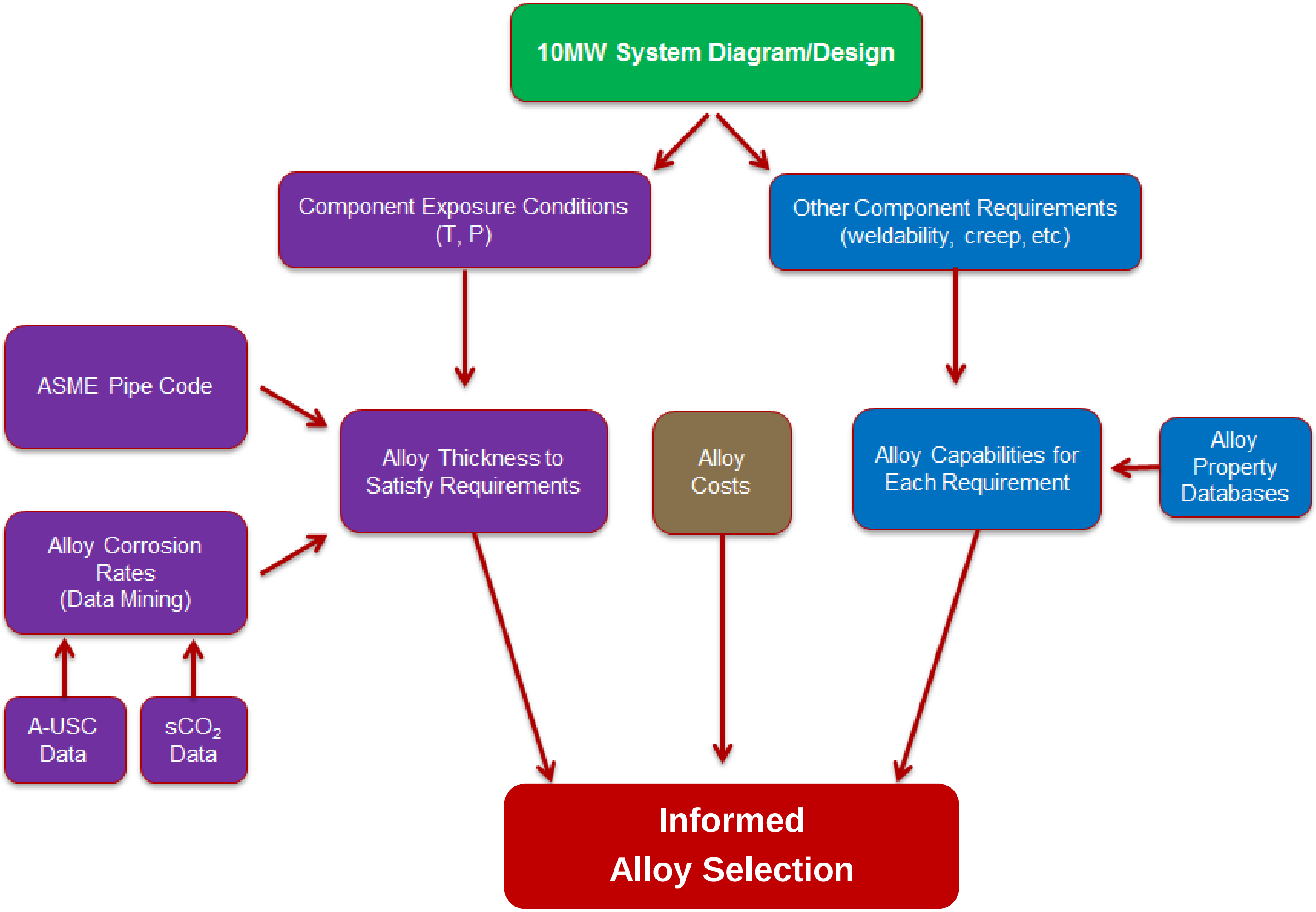
Equilibrium gas chemistry, f(T, P)

Oxide formation, f(T, P)

Materials Issues for sCO_2 Systems

- Identifying gas foil bearing behavior in CO_2
- Understanding and resolving turbine degradation
- Identifying materials options for 10 MW RCBC system components
- Understanding the influence of gas chemistry on alloy corrosion

Component Materials Selection



10MW System Diagram/Design

Component Exposure Conditions (T, P)

Other Component Requirements (weldability, creep, etc)

ASME Pipe Code

Alloy Thickness to Satisfy Requirements

Alloy Costs

Alloy Capabilities for Each Requirement

Alloy Property Databases

Alloy Corrosion Rates (Data Mining)

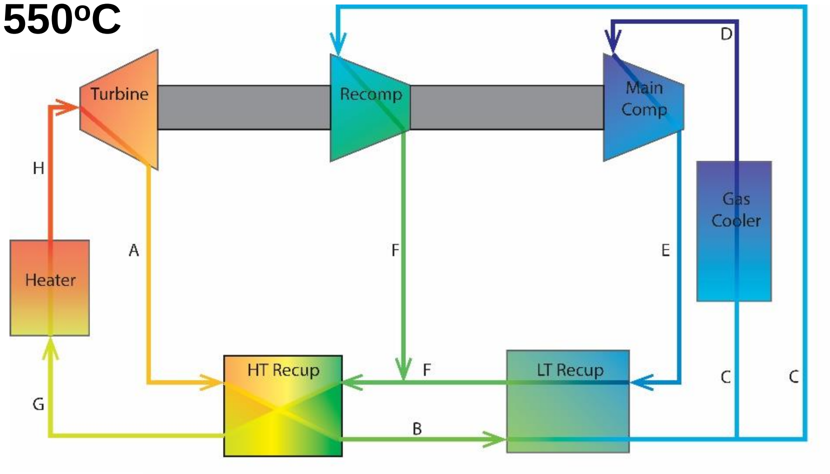
A-USC Data

sCO_2 Data

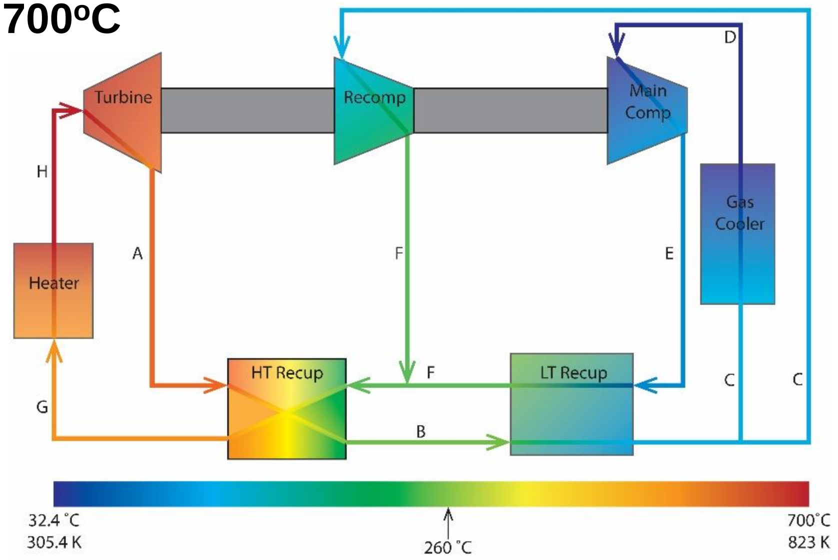
Informed Alloy Selection

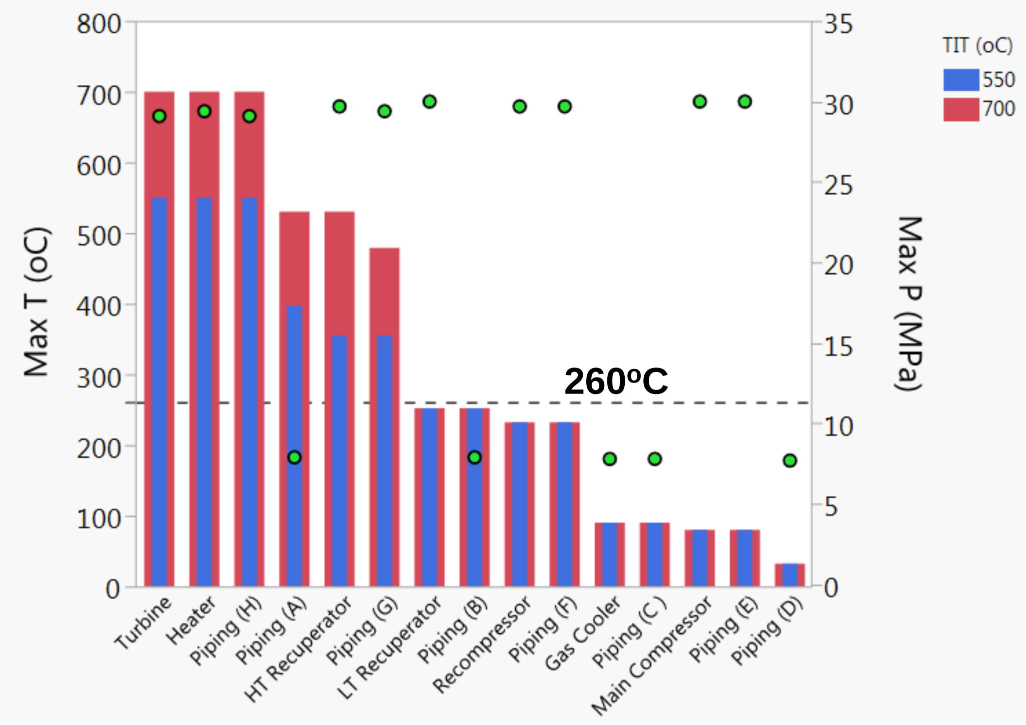
Component Exposure Conditions

550ºC



700ºC





Identifying Candidate Alloys

Alloy	Category	Code Qualifications					Raw Material Cost ($/Lb)
		(Y, N)	ASME B31.1		BPVC		
			Category	Max T (°C)	Category	Max T (°C)	
API 5L	Carbon Steel	Y	Seamless Pipe and Tube (X65)	427			$0.91
Grade 22	Ferritic	Y	Seamless Pipe and Tube (P22, T22, FP22)	593			$1.04
Grade 91	Ferritic	Y	Seamless Pipe and Tube (P91, T91)	649			$1.30
410	Ferritic	Y	Seamless Pipe and Tube (TP410)	371			$1.23
E-Brite	Ferritic	Y	Seamless Pipe and Tube (TPXM-27)	343			$1.75
304H	Austenitic	Y	Seamless Pipe and Tube (TP304H)	816			$1.75
310S	Austenitic	N					$2.37
310H	Austenitic	Y	Seamless Pipe and Tube (TP310H)	816			$2.37
316L	Austenitic	Y	Seamless Pipe and Tube (TP316L)	816			$1.83
316H	Austenitic	Y	Seamless Pipe and Tube (TP316H)	816			$1.83
316FR	Austenitic	N					$1.83
316LN	Austenitic	N					$1.83
316	Austenitic	Y	Seamless Pipe and Tube (TP316)	649			$1.83
347H	Austenitic	Y	Seamless Pipe and Tube (TP347H)	816			$1.82
347HFG	Austenitic	N					$1.82
AL-6XN	Super-Austenitic	Y	Seamless Pipe and Tube (N08367)	427			$2.77
800H	Super-Austenitic	Y	Seamless Pipe and Tube (N08367)	816			$2.64
600	Ni-Base Chromia-Forming	Y	Seamless Pipe and Tube (N06600)	649			$4.18
617	Ni-Base Chromia-Forming	Y	Seamless Pipe and Tube (N06617)	816			$5.38
625	Ni-Base Chromia-Forming	Y	Seamless Pipe and Tube (N06625)	649			$5.60
690	Ni-Base Chromia-Forming	Y			BPVC, Sec II, Part D	650	$4.04
230	Ni-Base Chromia-Forming	Y			BPVC, Sec II, Part D	900	$5.86
282	Ni-Base Chromia-Forming	N					$5.17
PE16	Ni-Base Chromia-Forming	N					$3.43
718	Ni-Base Chromia-Forming	N					$5.29
740	Ni-Base Chromia-Forming	N					$6.27
740H	Ni-Base Chromia-Forming	Y			BPVC, Code Case 2702-1	800	$6.18
HR120	Ni-Base Chromia-Forming	Y			BPVC, Sec II, Part D	900	$4.01
214	Ni-Base Alumina-Forming	N					$4.17
247	Ni-Base Alumina-Forming	N					$9.06

- ✓ **Corrosion Data**
- ✓ **Code Qualified**

Elements	Raw Material Price July 2016 ($/Lb)
Nickel	$4.65
Cobalt	$11.67
Molybdenum	$6.99
Copper	$2.20
Niobium	$34.00
Iron	$0.90
Chromium	$3.78
Tungsten	$13.00
Titanium	$1.15
Manganese	$0.75
Hafnium	$75.00
Tantalum	$59.88
Vanadium	$8.77
Aluminum	$0.75

Alloy Cost to Satisfy Strength Requirements

Minimum wall thickness calculation (Equation 7 in B31.1-2014):

$$t_m = \frac{PD_o}{2(SE + Py)} + \mathrm{A}$$

t_m: Minimum wall thickness (inches)

P: Internal pressure (ksi) - **used 4.35ksi (30 Mpa)**

D_o: Outer diameter (inches) - **used 4 inches**

S: Allowable stress given as function of temperature (ksi) - **used values in code**

E: Weld joint efficiencty - **used 1 (assumed seamless pipe no welds)**

y: used values from table 104.1.2

A: Additional thickness (corrosion allowance, etc.)

Cost of alloy per 1 ft length that satisfies the ASME code strength requirements:

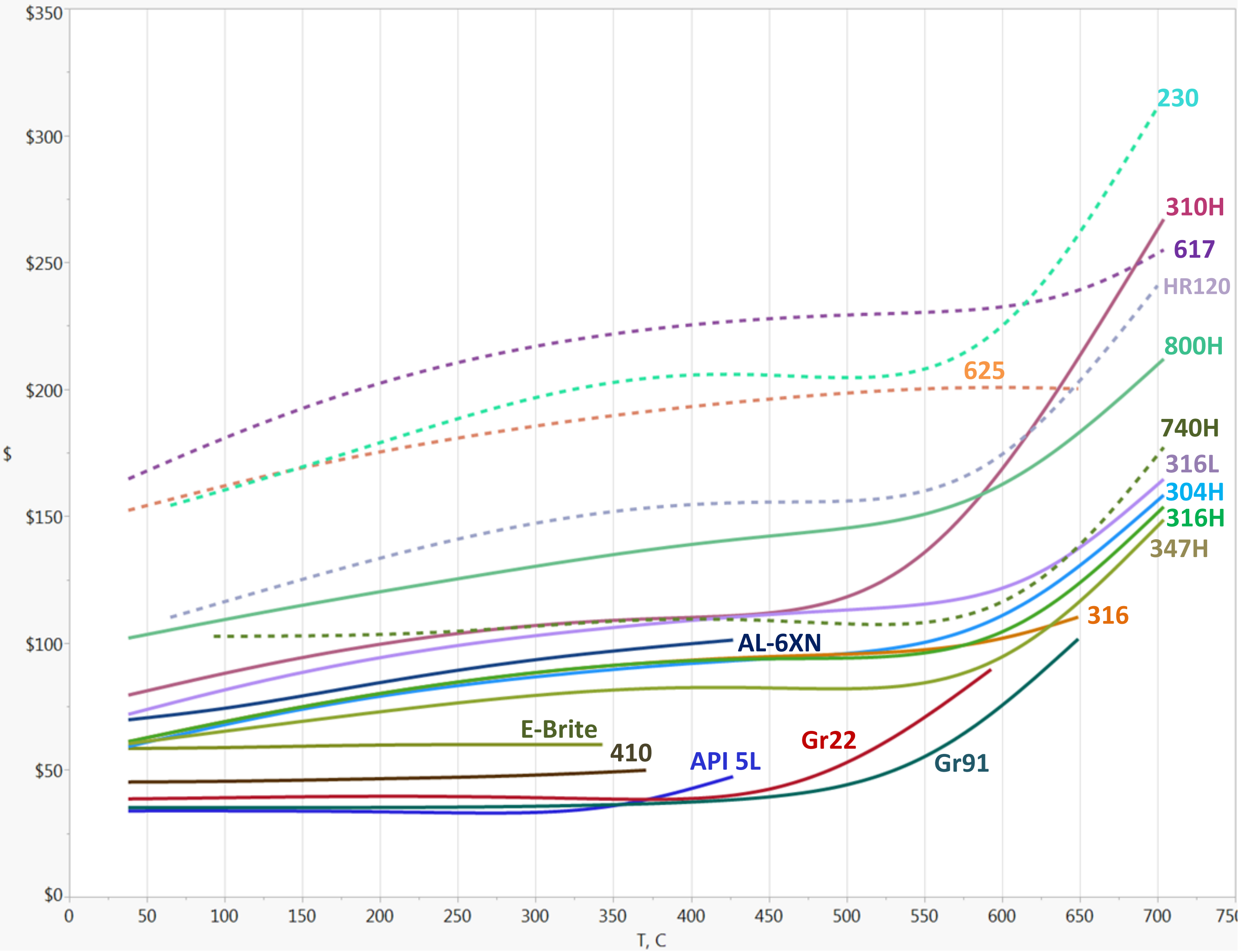
$$Cost\ (\$) = \frac{\pi \times 12in \times [D_o{}^2 - (D_o - t_m)^2]}{1728\ in^3/ft^3} \times \rho_{\text{alloy}} \times \text{Cost}_{\text{alloy}}$$

t_m: Minimum wall thickness (inches)

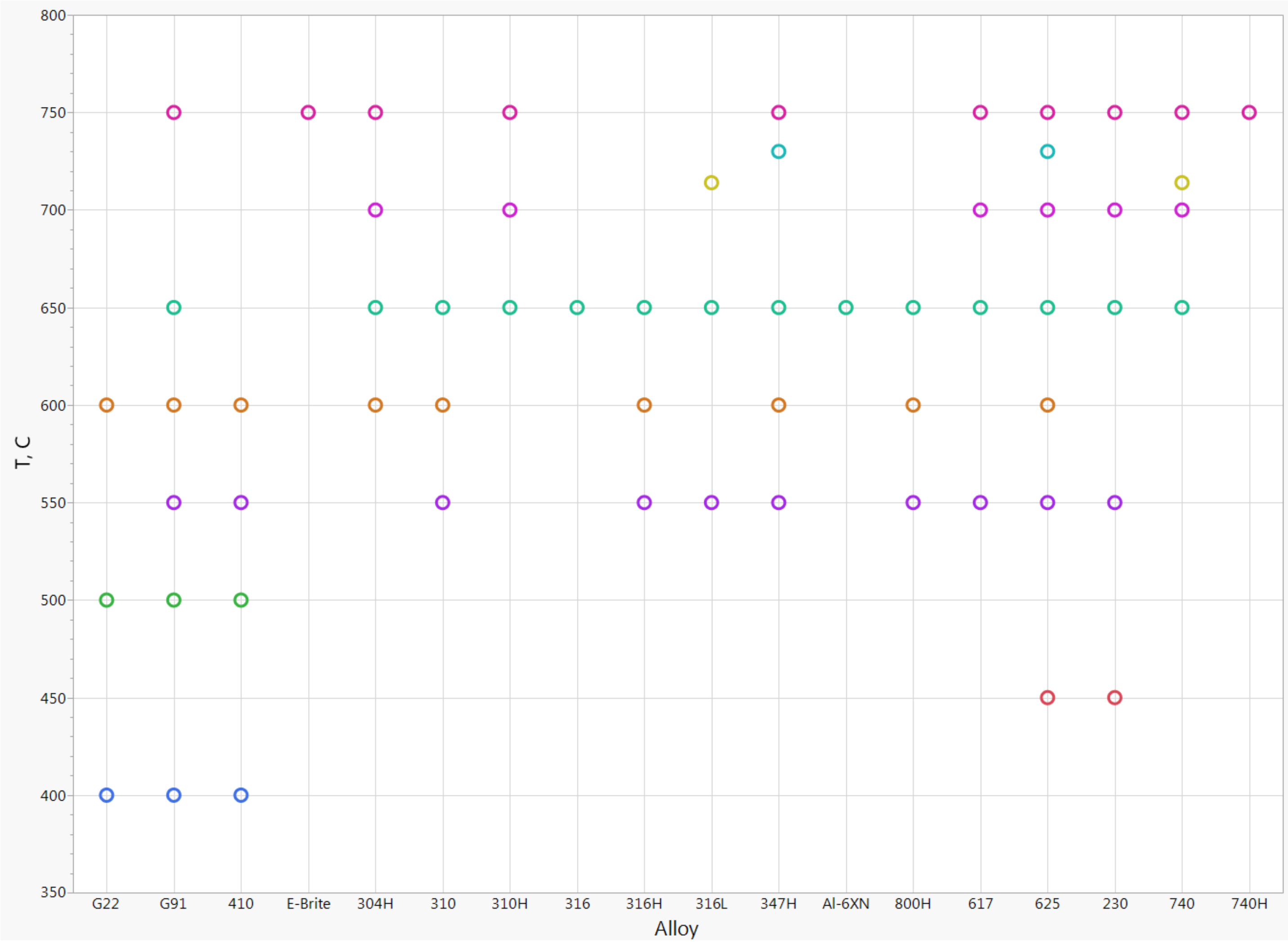
ρ_{alloy}: density of alloy in units of lbs/ft^3

$\text{Cost}_{\text{alloy}}$: cost per lb of alloy based on raw material prices

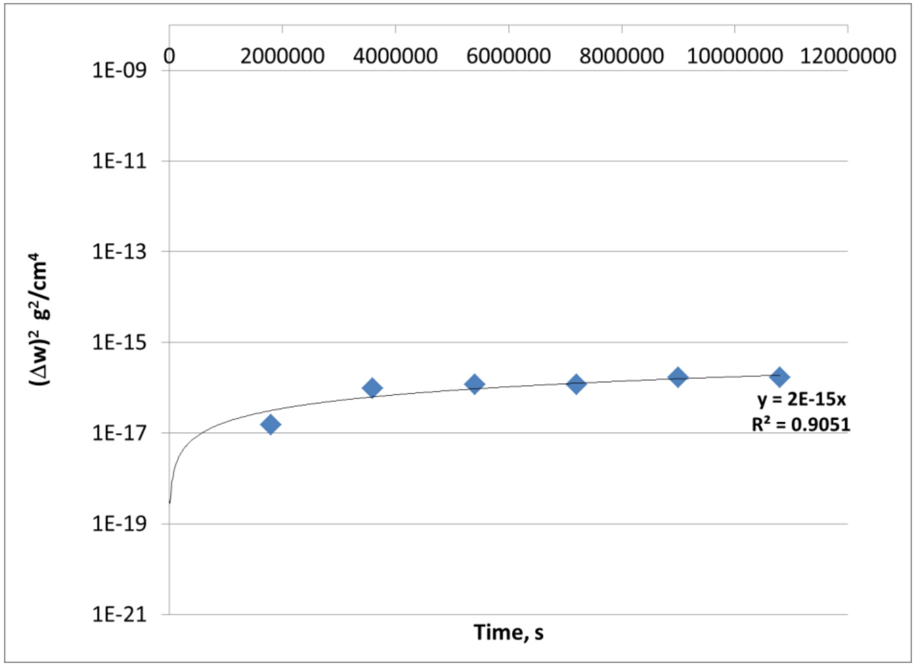
Alloy Costs ($/ft) to Satisfy Strength Requirements



Available Alloy Corrosion Data (400-750ºC, RG sCO_2, 200-250 bar)



Approach for Comparing Alloy Corrosion Rates



Parabolic fit to Cao's (2012) experimental data for 800H at 650^oC

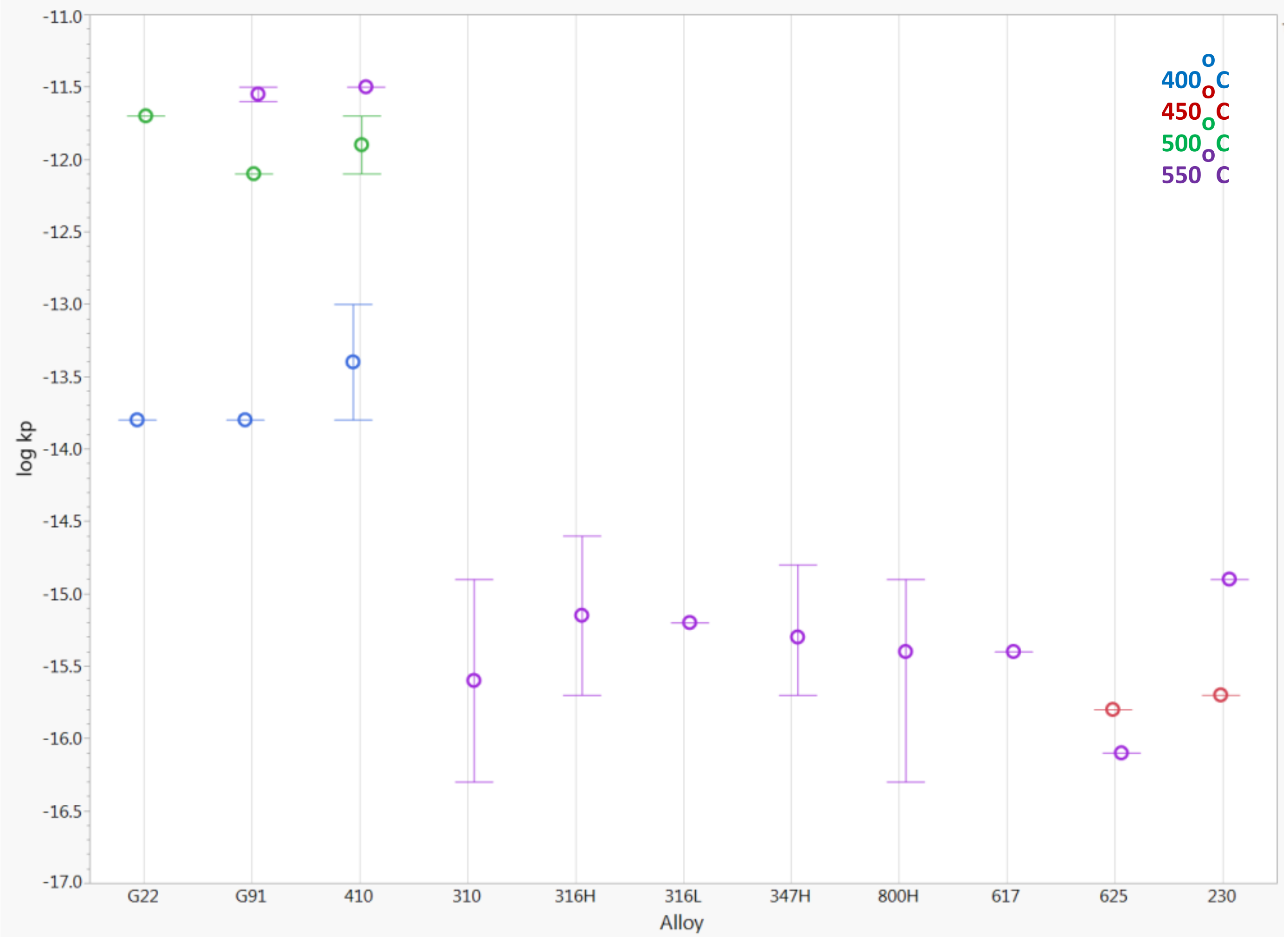
Assuming parabolic oxidation kinetics, the parabolic rate constant (k_p) can be calculated for each set of data

$$k_p = \frac{(\Delta m)^2}{2t}$$

Log k_p values are used as a corrosion rate comparison between alloys

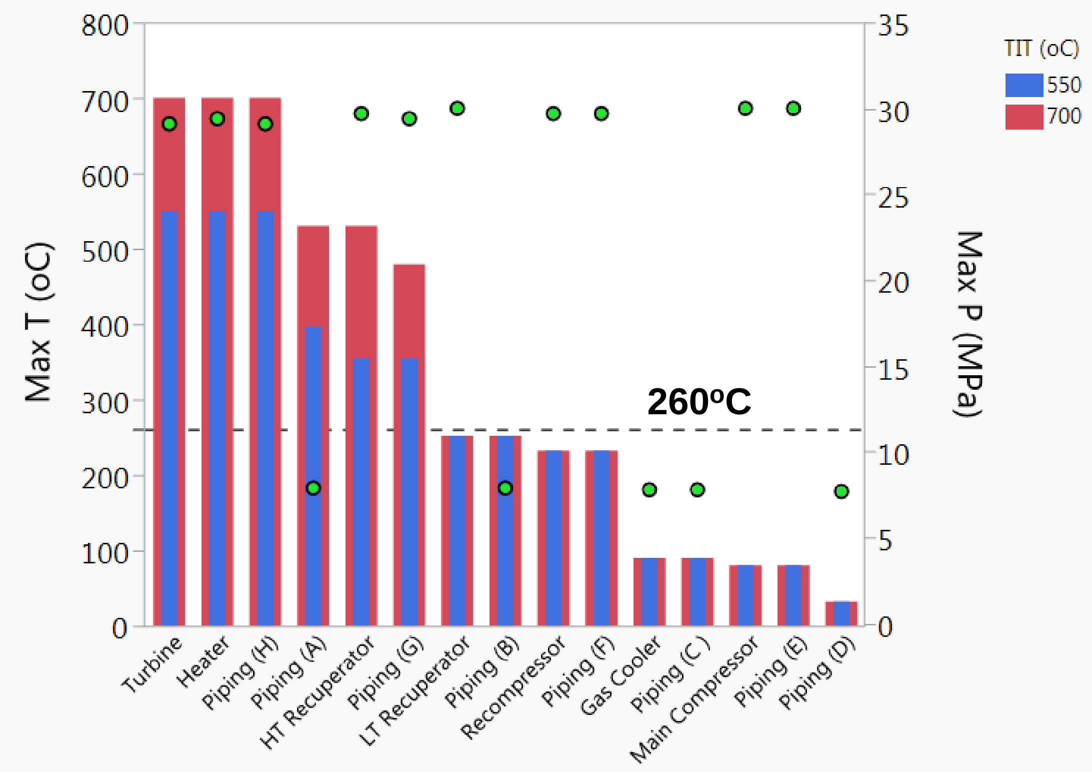
Unable to accurately relate this back to alloy thickness requirements, which would be preferred

Comparing Alloy Corrosion Rates (400 – 550°C)



Comparing Alloy Corrosion Rates (600 – 700°C)

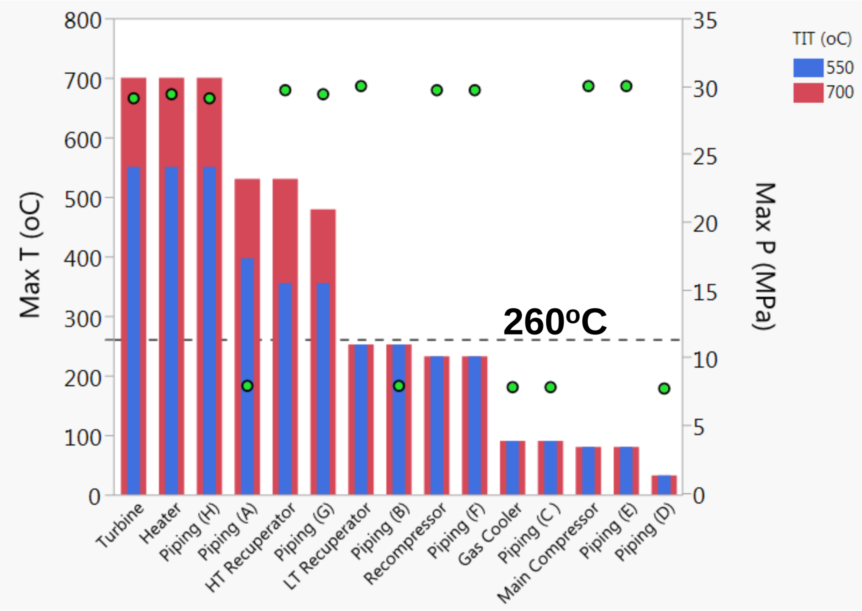
Alloy Selection for Components Based on Analysis



550ºC TIT

- Components @ < 400ºC:
  - Gr91 alloy recommended based on cost comparison
  - Corrosion rate comparison not available to 347H, 316H, etc. due to no data at these lower T's
- Components @ 550ºC:
  - 347H alloy recommended
  - Significantly lower corrosion rate than Gr91 (4 orders of magnitude) at moderately increased $ ($75 vs $50 per ft)
  - Similar corrosion rate to 316 alloys, but at lower $

Alloy Selection for Components Based on Analysis



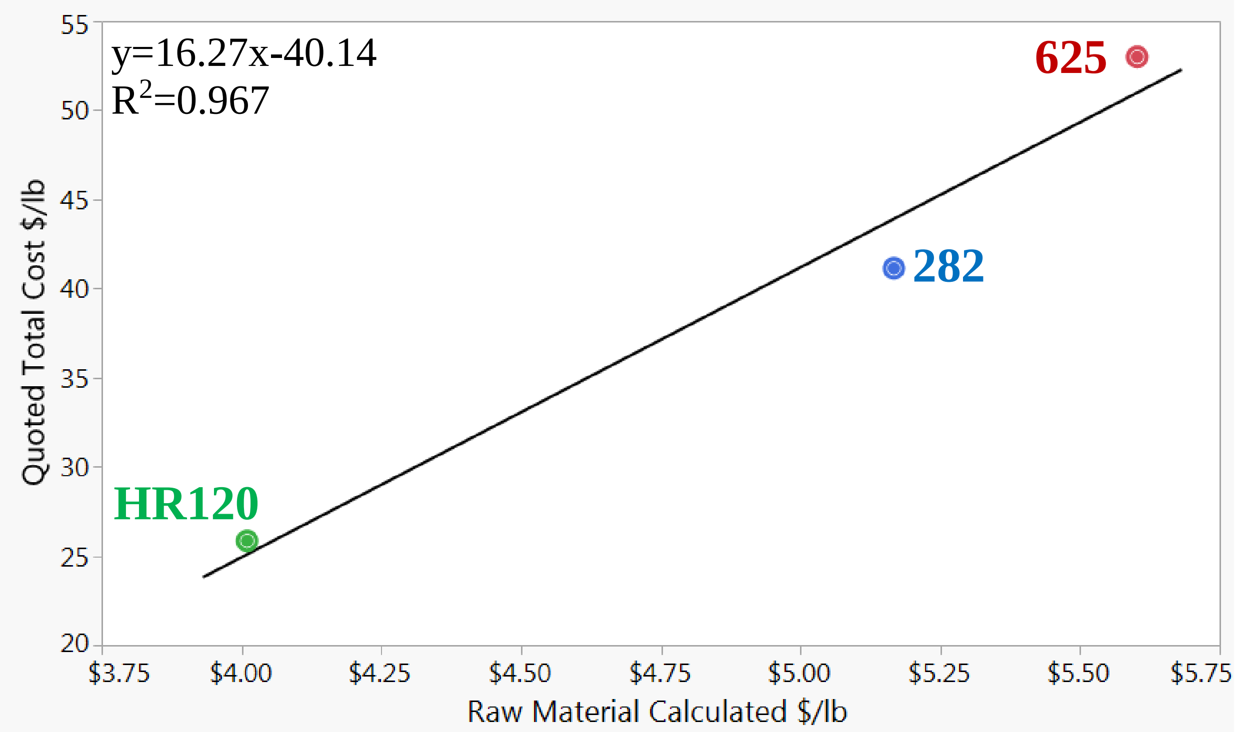
700ºC TIT

- Components @ < 260ºC:
  - Gr91 alloy recommended based on cost comparison and expected low corrosion rate (no data at these T's)
- Components @ 500-525ºC:
  - 347H alloy recommended
  - Same reasons as for 550ºC system components
- Components @ 700ºC:
  - 740H alloy is recommended
  - 740H has $50/ft higher cost than 347H, but has significantly lower corrosion rate (2 orders of magnitude at 650ºC)
  - Corrosion data at 700ºC is available for 740H, but not for 347H

Summary and Next Steps

- **Systems level approach has been used to make informed alloy recommendations for 10MW RCBC components (550^{o}C and 700^{o}C TIT)**
- **Analyses revealed gaps where corrosion data is needed**
  - **Ex: 700^{o}C for 347H, and <400^{o}C for Gr91 alloy**
- **Future work is needed that incorporates other critical items into this process for alloy selection (manufacturability, weldability, etc.)**

Backup Slides



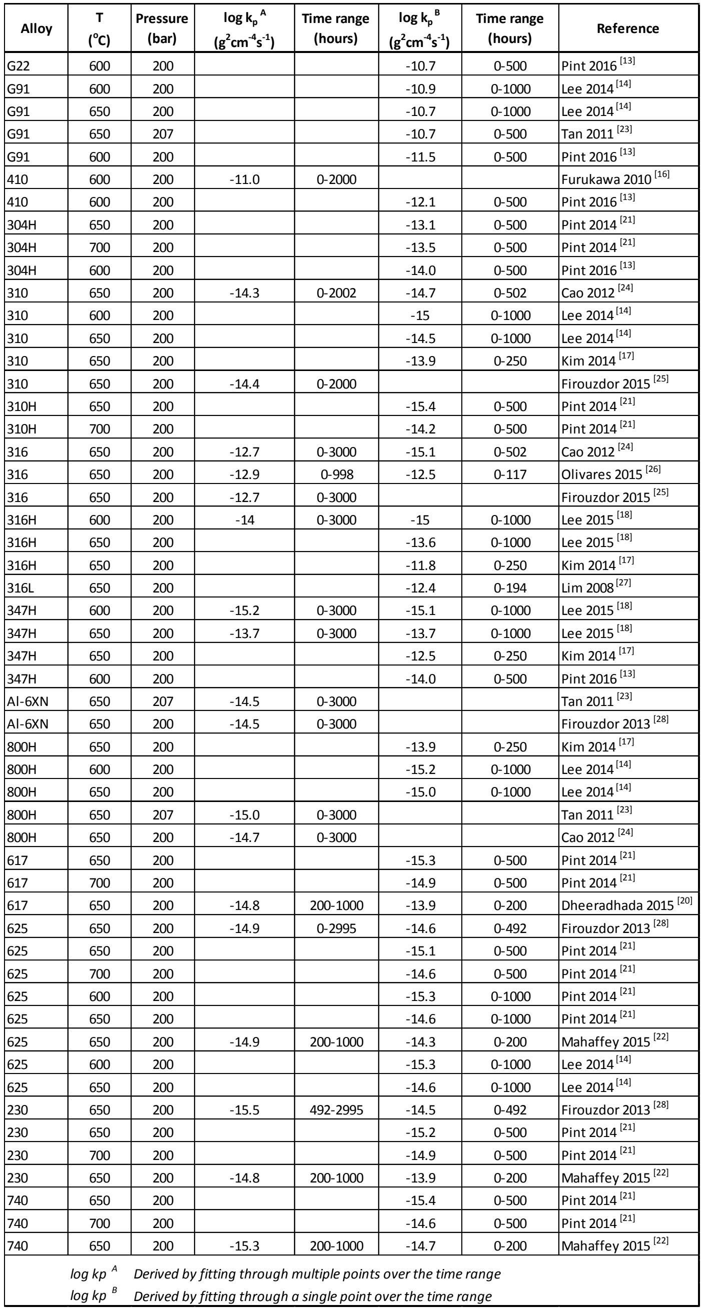
For 3 inch – Schedule 160 pipe

Alloy	T (^{o}C)	Pressure (bar)	log k_p^{A} ($g^2cm^{-4}s^{-1}$)	Time range (hours)	log k_p^{B} ($g^2cm^{-4}s^{-1}$)	Time range (hours)	Reference
G22	400	200			-13.8	0-500	Pint 2016 [13]
G22	500	200			-11.7	0-500	Pint 2016 [13]
G91	550	200			-11.6	0-1000	Lee 2014 [14]
G91	550	250			-11.5	0-310	Rouillard 2011 [15]
G91	400	200			-13.8	0-500	Pint 2016 [13]
G91	500	200			-12.1	0-500	Pint 2016 [13]
410	400	200	-13.0	0-2000			Furukawa 2010 [16]
410	500	200	-11.7	0-2000			Furukawa 2010 [16]
410	550	200	-11.5	0-2000			Furukawa 2010 [16]
410	400	200			-13.8	0-500	Pint 2016 [13]
410	500	200			-12.1	0-500	Pint 2016 [13]
310	550	200			-16.3	0-1000	Lee 2014 [14]
310	550	200			-14.9	0-250	Kim 2014 [17]
316H	550	200	-14.6	0-3000	-15.8	0-1000	Lee 2015 [18]
316H	550	200			-15.7	0-250	Kim 2014 [17]
316L	550	250			-15.2	0-310	Rouillard 2011 [15]
347H	550	200	-15.4	0-3000	-15.7	0-1000	Lee 2015 [18]
347H	550	200			-14.8	0-250	Kim 2014 [17]
347H	550	200	-15.7	0-1000			Mahaffey 2014 [19]
800H	550	200			-14.9	0-250	Kim 2014 [17]
800H	550	200			-16.3	0-1000	Lee 2014 [14]
800H	550	250			-15.1	0-310	Rouillard 2011 [15]
800H	550	200	-15.3	0-1000			Mahaffey 2014 [19]
617	550	200	-15.4	0-1000	-15.1	0-200	Dheeradhada 2015 [20]
625	550	200			-16.1	0-1000	Pint 2014 [21]
625	450	200	-15.8	200-1000	-17	0-200	Mahaffey 2015 [22]
625	550	200	-16.1	200-1000	-15.2	0-200	Mahaffey 2015 [22]
625	550	200			-16.1	0-1000	Lee 2014 [14]
230	450	200	-15.7	200-1000	-16.8	0-200	Mahaffey 2015 [22]
230	550	200	-14.9	0-1000	-15	0-200	Mahaffey 2015 [22]

log kp [A] *Derived by fitting through multiple points over the time range*

log kp [B] *Derived by fitting through a single point over the time range*

400 to 550 ^{o}C



Alloy	T (°C)	Pressure (bar)	log k_p ^{A} ($g^2cm^{-4}s^{-1}$)	Time range (hours)	log k_p ^{B} ($g^2cm^{-4}s^{-1}$)	Time range (hours)	Reference
G22	600	200			-10.7	0-500	Pint 2016 [13]
G91	600	200			-10.9	0-1000	Lee 2014 [14]
G91	650	200			-10.7	0-1000	Lee 2014 [14]
G91	650	207			-10.7	0-500	Tan 2011 [23]
G91	600	200			-11.5	0-500	Pint 2016 [13]
410	600	200	-11.0	0-2000			Furukawa 2010 [16]
410	600	200			-12.1	0-500	Pint 2016 [13]
304H	650	200			-13.1	0-500	Pint 2014 [21]
304H	700	200			-13.5	0-500	Pint 2014 [21]
304H	600	200			-14.0	0-500	Pint 2016 [13]
310	650	200	-14.3	0-2002	-14.7	0-502	Cao 2012 [24]
310	600	200			-15	0-1000	Lee 2014 [14]
310	650	200			-14.5	0-1000	Lee 2014 [14]
310	650	200			-13.9	0-250	Kim 2014 [17]
310	650	200	-14.4	0-2000			Firouzdor 2015 [25]
310H	650	200			-15.4	0-500	Pint 2014 [21]
310H	700	200			-14.2	0-500	Pint 2014 [21]
316	650	200	-12.7	0-3000	-15.1	0-502	Cao 2012 [24]
316	650	200	-12.9	0-998	-12.5	0-117	Olivares 2015 [26]
316	650	200	-12.7	0-3000			Firouzdor 2015 [25]
316H	600	200	-14	0-3000	-15	0-1000	Lee 2015 [18]
316H	650	200			-13.6	0-1000	Lee 2015 [18]
316H	650	200			-11.8	0-250	Kim 2014 [17]
316L	650	200			-12.4	0-194	Lim 2008 [27]
347H	600	200	-15.2	0-3000	-15.1	0-1000	Lee 2015 [18]
347H	650	200	-13.7	0-3000	-13.7	0-1000	Lee 2015 [18]
347H	650	200			-12.5	0-250	Kim 2014 [17]
347H	600	200			-14.0	0-500	Pint 2016 [13]
Al-6XN	650	207	-14.5	0-3000			Tan 2011 [23]
Al-6XN	650	200	-14.5	0-3000			Firouzdor 2013 [28]
800H	650	200			-13.9	0-250	Kim 2014 [17]
800H	600	200			-15.2	0-1000	Lee 2014 [14]
800H	650	200			-15.0	0-1000	Lee 2014 [14]
800H	650	207	-15.0	0-3000			Tan 2011 [23]
800H	650	200	-14.7	0-3000			Cao 2012 [24]
617	650	200			-15.3	0-500	Pint 2014 [21]
617	700	200			-14.9	0-500	Pint 2014 [21]
617	650	200	-14.8	200-1000	-13.9	0-200	Dheeradhada 2015 [20]
625	650	200	-14.9	0-2995	-14.6	0-492	Firouzdor 2013 [28]
625	650	200			-15.1	0-500	Pint 2014 [21]
625	700	200			-14.6	0-500	Pint 2014 [21]
625	600	200			-15.3	0-1000	Pint 2014 [21]
625	650	200			-14.6	0-1000	Pint 2014 [21]
625	650	200	-14.9	200-1000	-14.3	0-200	Mahaffey 2015 [22]
625	600	200			-15.3	0-1000	Lee 2014 [14]
625	650	200			-14.6	0-1000	Lee 2014 [14]
230	650	200	-15.5	492-2995	-14.5	0-492	Firouzdor 2013 [28]
230	650	200			-15.2	0-500	Pint 2014 [21]
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740	650	200			-15.4	0-500	Pint 2014 [21]
740	700	200			-14.6	0-500	Pint 2014 [21]
740	650	200	-15.3	200-1000	-14.7	0-200	Mahaffey 2015 [22]

log kp ^{A} *Derived by fitting through multiple points over the time range*
log kp ^{B} *Derived by fitting through a single point over the time range*

600 to 700 °C