



# Influence of CO<sub>2</sub> Purity on the Corrosion of Structural Alloys for Supercritical CO<sub>2</sub> Power Cycles

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Sandia National Laboratories (Livermore, California)

TMS 2018

High Temperature Corrosion of Structural Materials

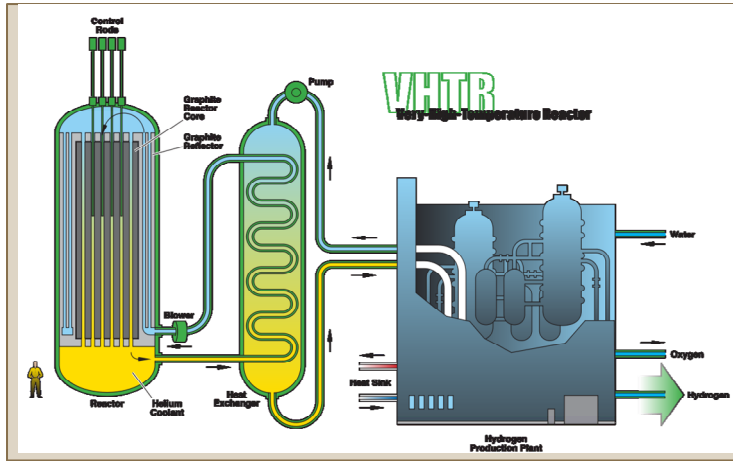
March 14<sup>th</sup> 2018



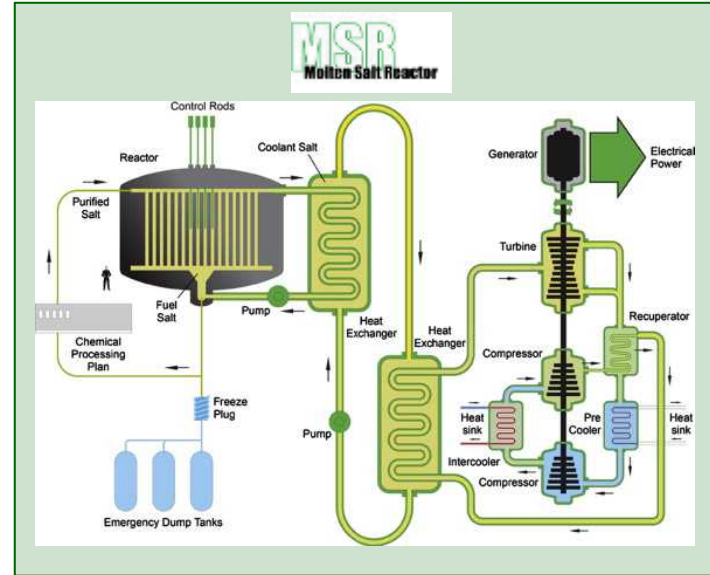
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# Advanced nuclear reactor concepts aim for advances over existing LWRs

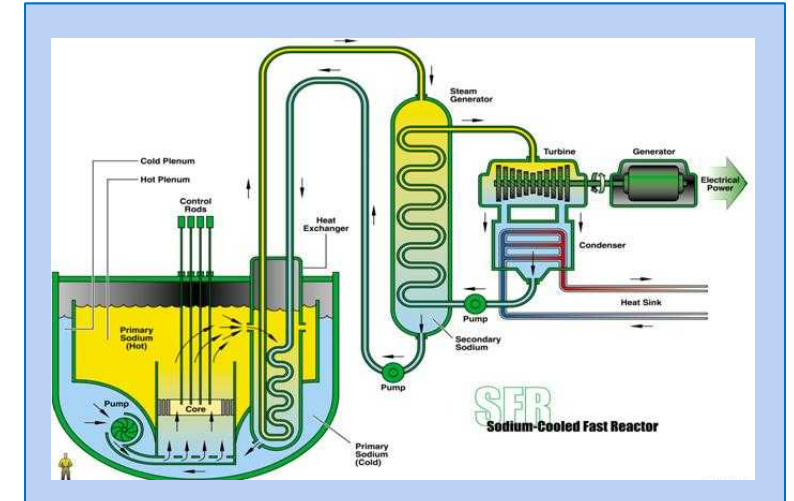
## DOE Advanced Nuclear Reactor Program



Program Lead: INL



Program Lead: ORNL

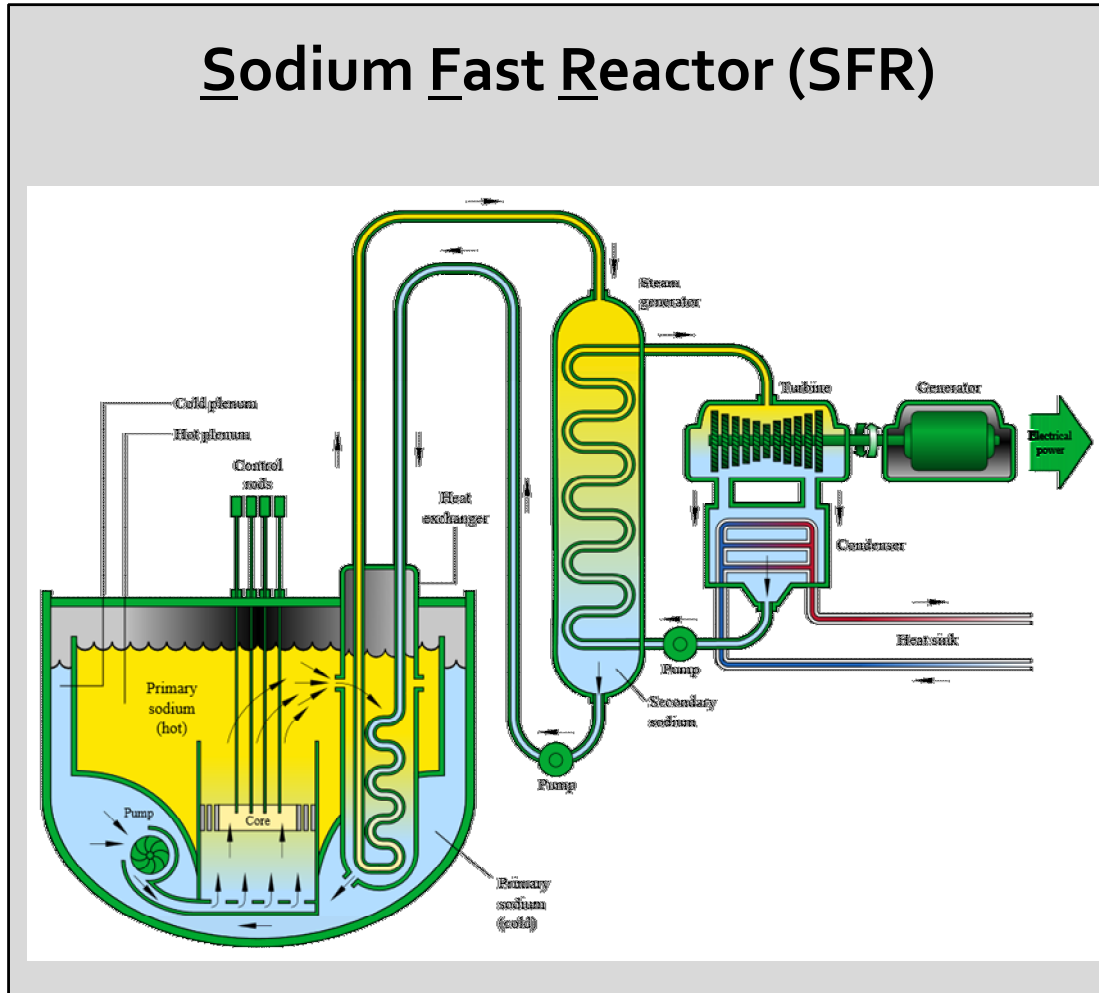


Program Lead: ANL

Advanced reactors are intended to provide advancements in the following areas:

- Sustainability
- Safety
- Reliability
- Economics
- Non-proliferation

## *Sodium Fast Reactor Concept*



### Characteristics:

- Sodium coolant
- 550°C outlet temperature
- High thermal efficiency

Fast reactor concepts are important for meeting sustainability goals

- Efficient resource (fissile material) utilization and generation
- Waste minimization (consumption of LWR actinides)

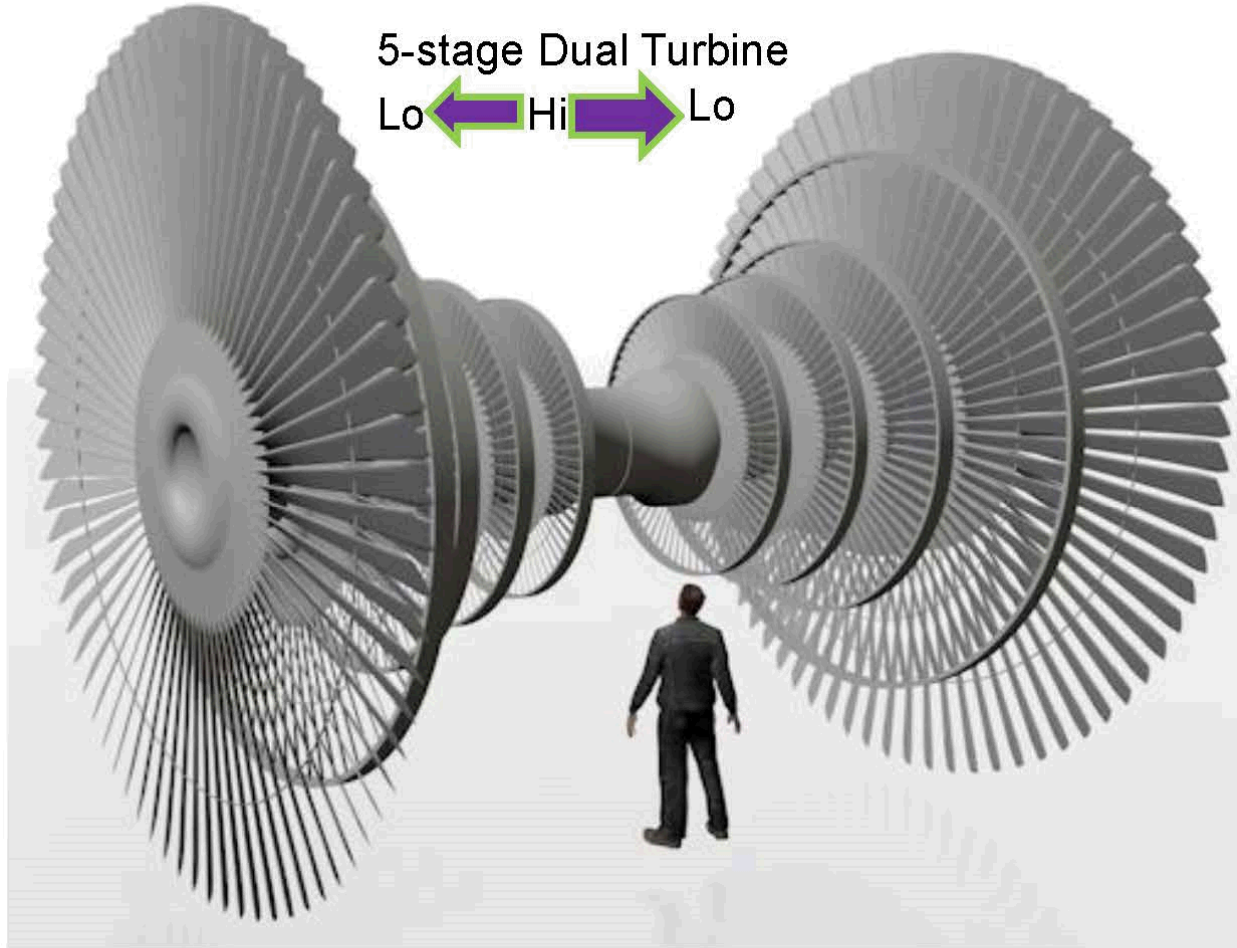
Research program established to develop and integrate a Supercritical CO<sub>2</sub> Energy Conversion System in place of the Conventional Steam Rankine System

- Sandia is teaming with Argonne to develop this system

# Developing a transformative energy conversion system

## Supercritical CO<sub>2</sub> (sCO<sub>2</sub>) Energy Conversion Systems

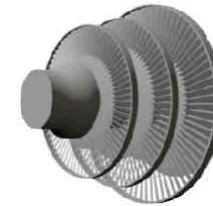
5-stage Dual Turbine  
Lo ← Hi → Lo



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

### Motivation for sCO<sub>2</sub> Energy Conversion Systems

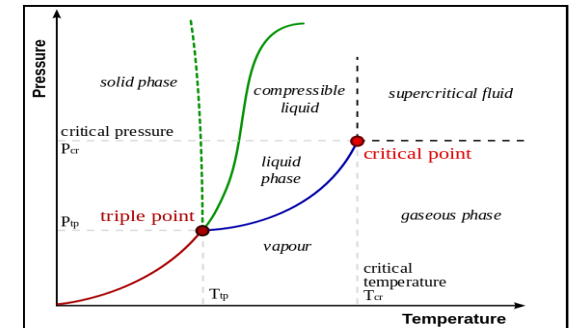
- High Efficiency (>40%)
- Compact Turbomachinery that is easily scalable
- Reduced Cost



3-stage Single Turbine

Hi → Lo

1 meter sCO<sub>2</sub> (300 MWe)  
(Brayton Cycle)



Critical Point for CO<sub>2</sub>:  
31.1°C ( 87.98°F) and 7.39 MPa (1071 psi)

# Distinct challenges exist with materials for sCO<sub>2</sub> EC Systems

## *Focus Areas for sCO<sub>2</sub> Materials Development*

- Two areas identified where materials contributions are critical to the successful development of this technology :

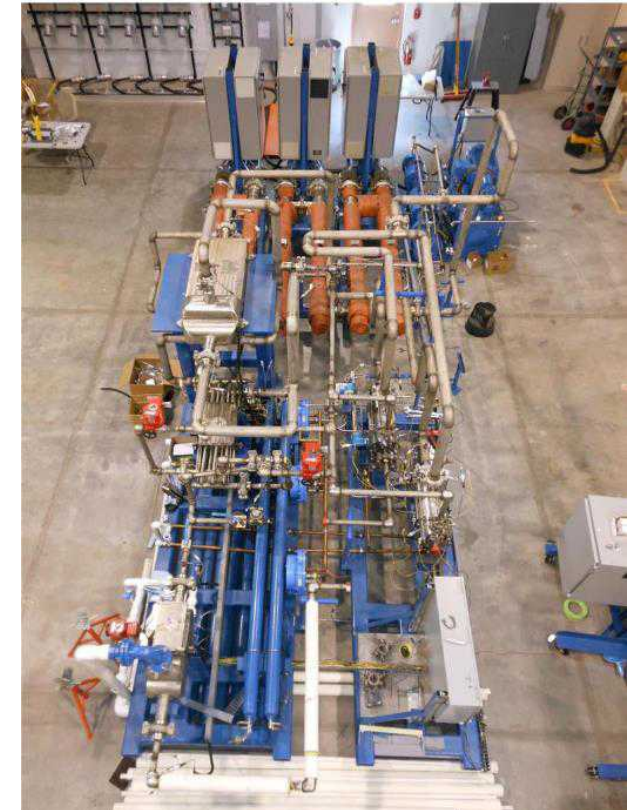
### 1. Alloy Selection for sCO<sub>2</sub> EC Systems

- T<550°C: SFR
- T>550°C: HTGR and MSR

### 2. Materials Support for sCO<sub>2</sub> System Development

- Turbine Degradation
- Bearing Foil Materials (coatings)
- Systems for In-situ Measurement of Materials Corrosion
- sCO<sub>2</sub>/Polymer Interactions

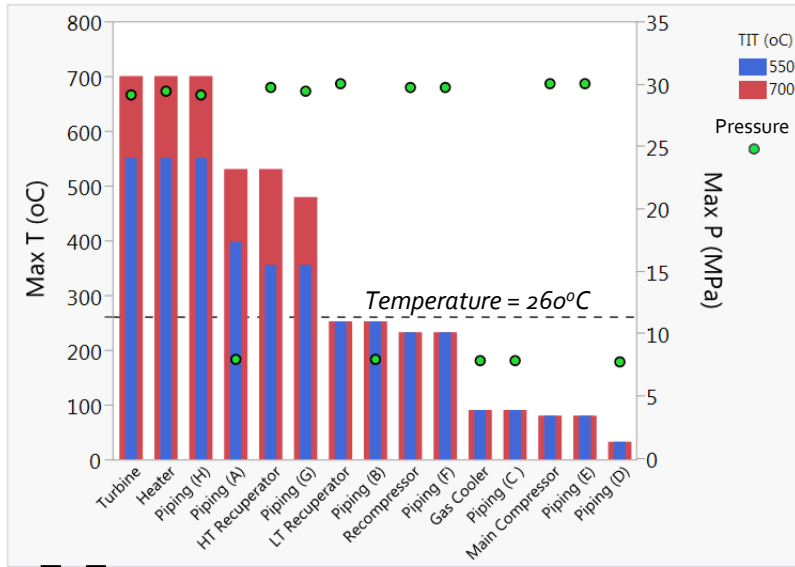
Sandia National Laboratory  
250 kW sCO<sub>2</sub> RCBC



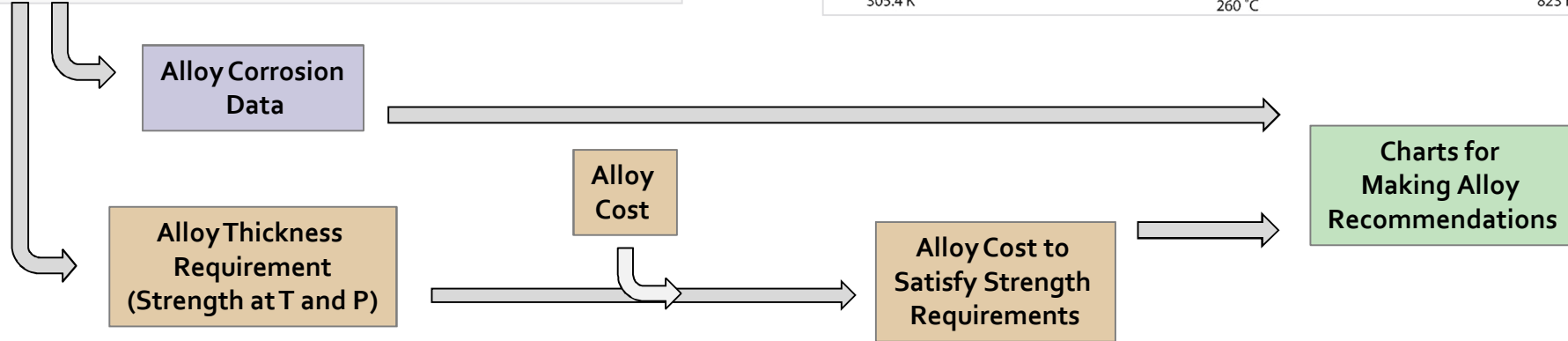
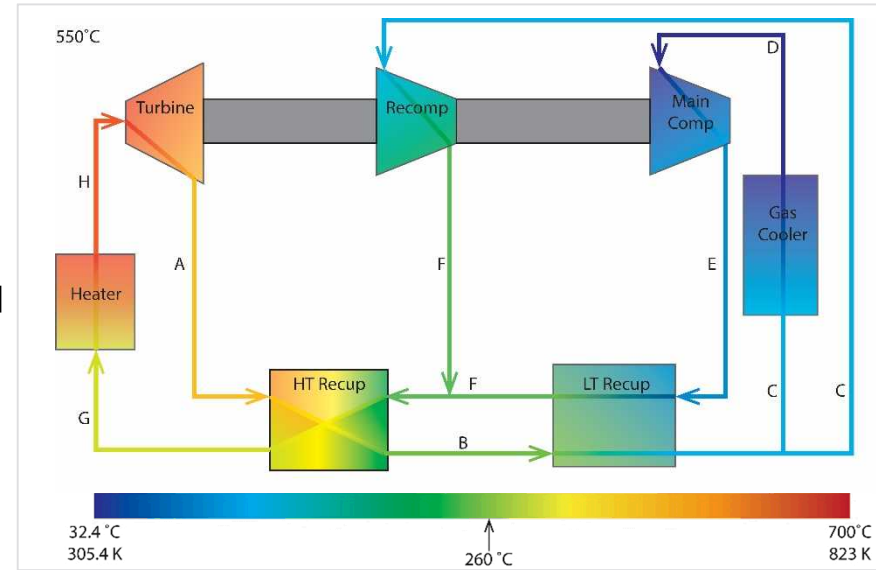
# Informed decision making process used for selecting component alloys

## 10 MW SFR Energy Conversion System

Component Exposure Conditions

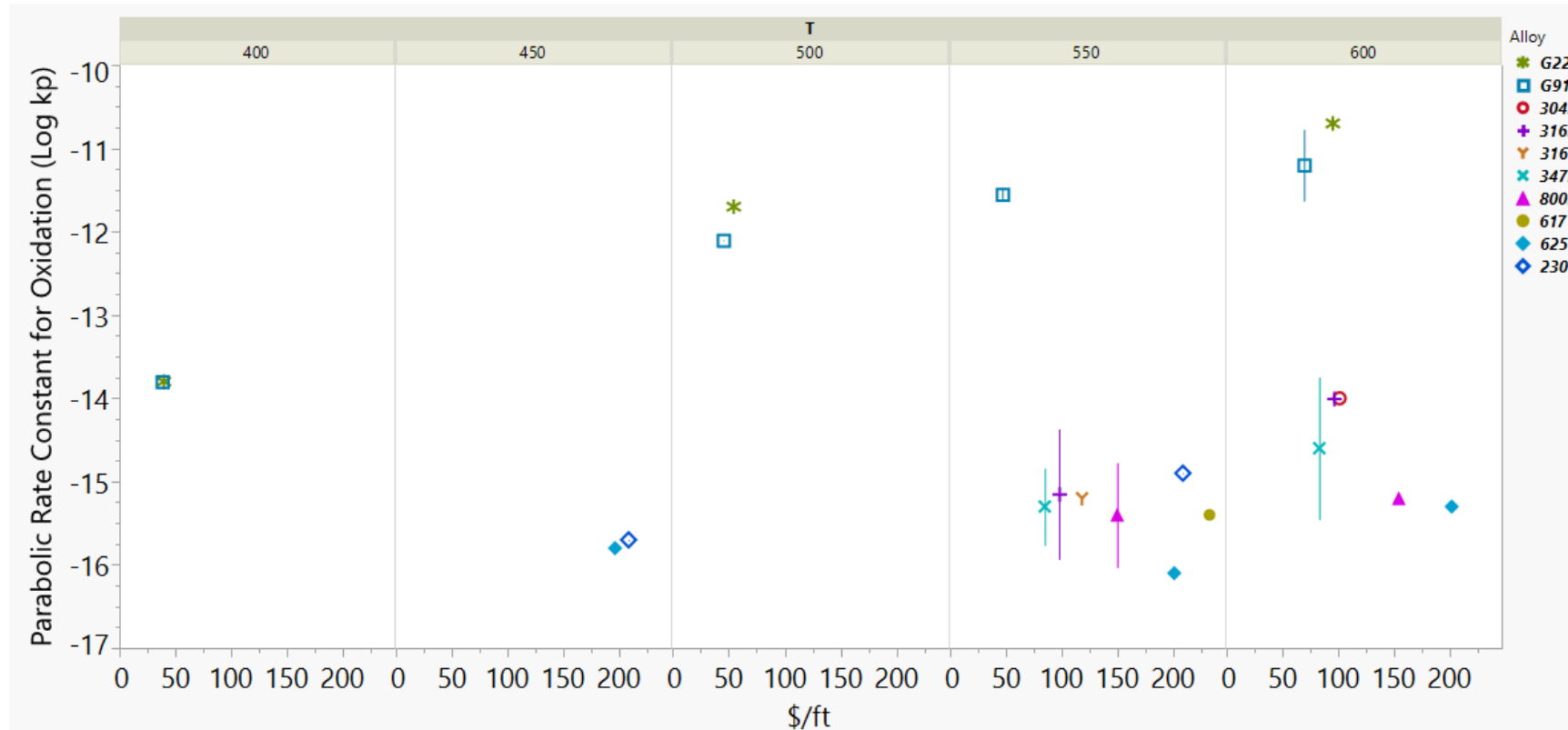


10 MW EC System Design for SFR (550°C)



# Alloys recommendations made using available data – caveats exist

## 10 MW SFR Energy Conversion System Candidate Alloys



### Alloy Recommendations for SFR EC

- Temperatures > 400°C: 347H, 316H, 316L
- Temperatures < 400°C: G22, G91

### Caveats

- Alloy costs calculated using alloy chemistry and market elemental prices
- Only considers surface oxidation and not internal carburization
- All corrosion data collected using RG CO<sub>2</sub> rather than IG CO<sub>2</sub>

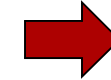
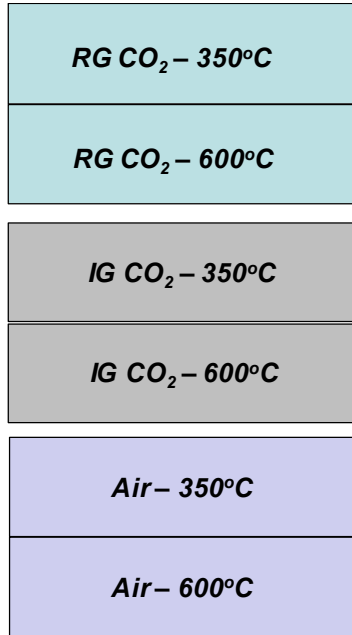
# Evaluating the impact of CO<sub>2</sub> gas chemistry on alloy corrosion

## Corrosion Experimental Overview

### Six - 1000 Hr Tests

#### Alloys

Grade 22  
Grade 91  
304H  
316H  
347H  
800H  
HR120  
617



- **Post-Test Measurements:**
  - ✓ Weight Change
  - ✓ Oxide Microstructures
  - Internal Carburation
  - Metal Loss – Lifetime Predictions

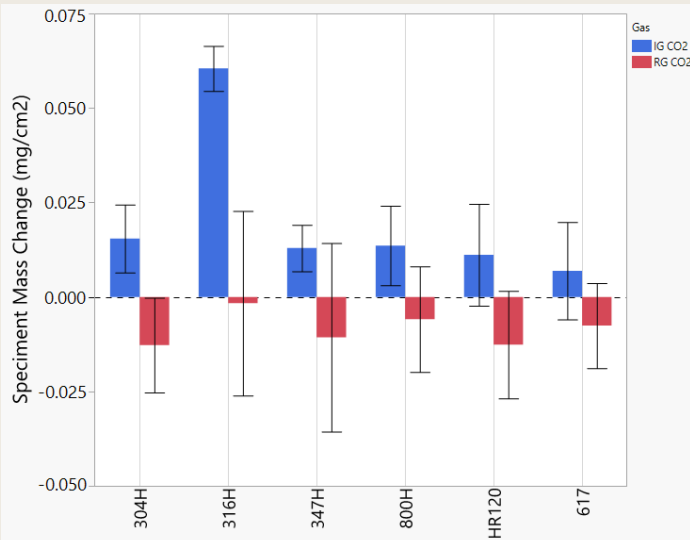
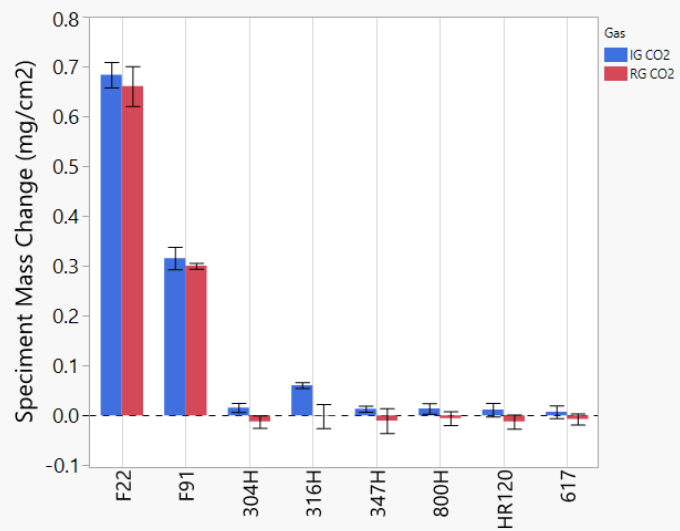
Alloy	Chemical Analysis (Wt %)																			
	Fe	Cr	Ni	Mn	Co	Mo	Si	Al	B	C	Cu	P	S	Ti	W	Nb	N	V	Zr	Ta
F22	98.13	2.19	0.07	0.4	-	0.95	0.2	0.021	0.0001	0.1	0.1	0.008	0.011	0.002	-	0.001	-	0.004	-	-
F91	89.25	8.38	0.18	0.43	-	0.94	0.32	0.011	-	0.1	-	0.02	0.01	0.007	-	0.067	0.063	0.22	0.001	-
304H	70.54	18.16	8.08	1.39	0.32	0.4	0.44	-	-	0.049	0.51	0.032	0.0004	-	-	-	0.081	-	-	-
316H	68.60	16.61	10.26	1.536	0.152	2.006	0.329	-	-	0.041	0.392	0.036	0.001	-	-	0.005	0.0315	-	-	-
347H	68.73	17.24	9.32	1.83	0.45	0.38	0.66	-	-	0.06	0.51	0.028	0.019	-	-	0.74	0.017	-	-	0.02
800H	46.70	20.56	30.6	0.54	0.03	-	0.32	0.52	-	0.07	0.03	0.12	0.0001	0.57	-	-	0.01	-	-	-
HR120	35.48	24.91	37	0.68	0.15	0.27	0.5	0.08	0.002	0.062	0.09	0.012	<0.002	<0.01	<0.1	0.6	0.163	-	-	-
617	0.76	22.63	53.2	0.02	12.33	9.38	0.15	1.15	0.002	0.06	0.05	-	0.001	0.27	-	-	-	-	-	-

CO <sub>2</sub> Grade	Gas Chemical Analysis						
	CO <sub>2</sub> (%)	CO (ppm)	H <sub>2</sub> (ppm)	N <sub>2</sub> (ppm)	O <sub>2</sub> (ppm)	CH <sub>4</sub> (ppm)	H <sub>2</sub> O (ppm)
RG	> 99.999	0.012	0.005	1.070	<b>0.040</b>	0.153	< 0.02
IG	> 99.980	< 0.010	0.040	35.370	<b>11.110</b>	0.430	<b>0.53</b>

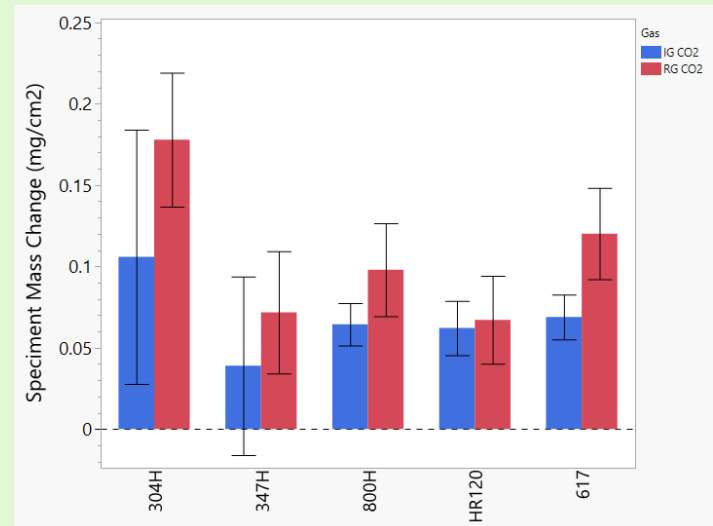
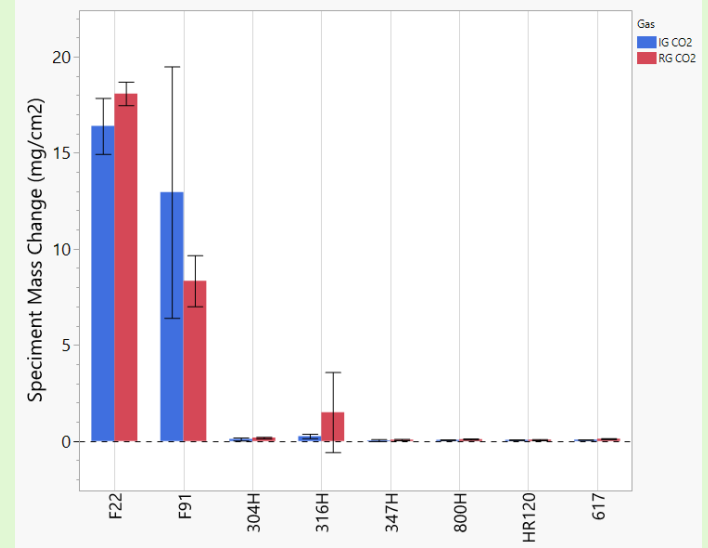
# After the ferritic alloys, 316H is the most susceptible to corrosion in CO<sub>2</sub>

## Alloy Specimen Mass Changes

350°C – 1000 hrs



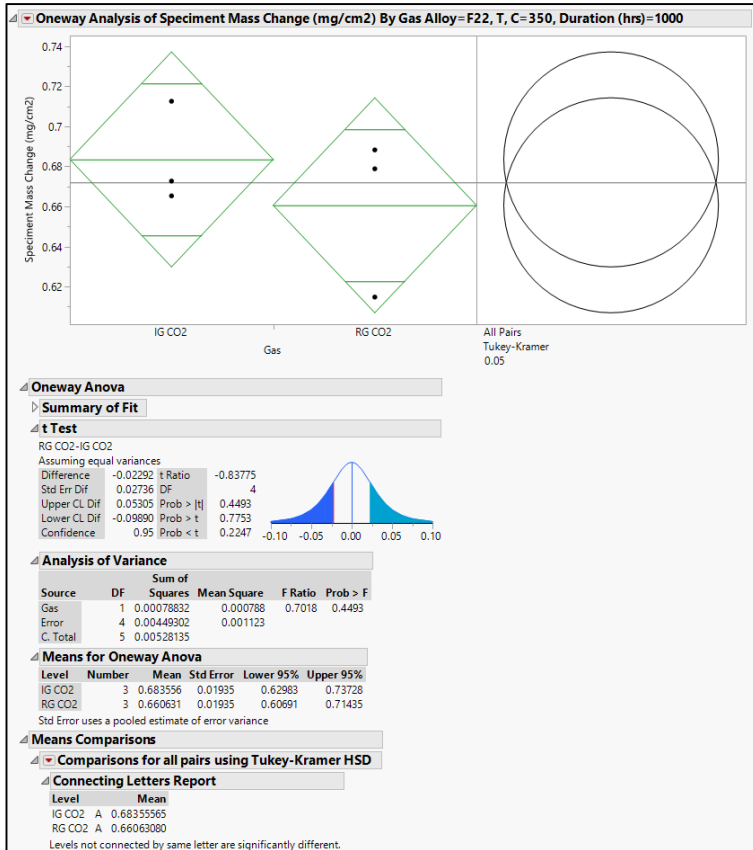
600°C – 1000 hrs



# Gas chemistry (RG vs IG CO<sub>2</sub>) has very little influence on alloy corrosion

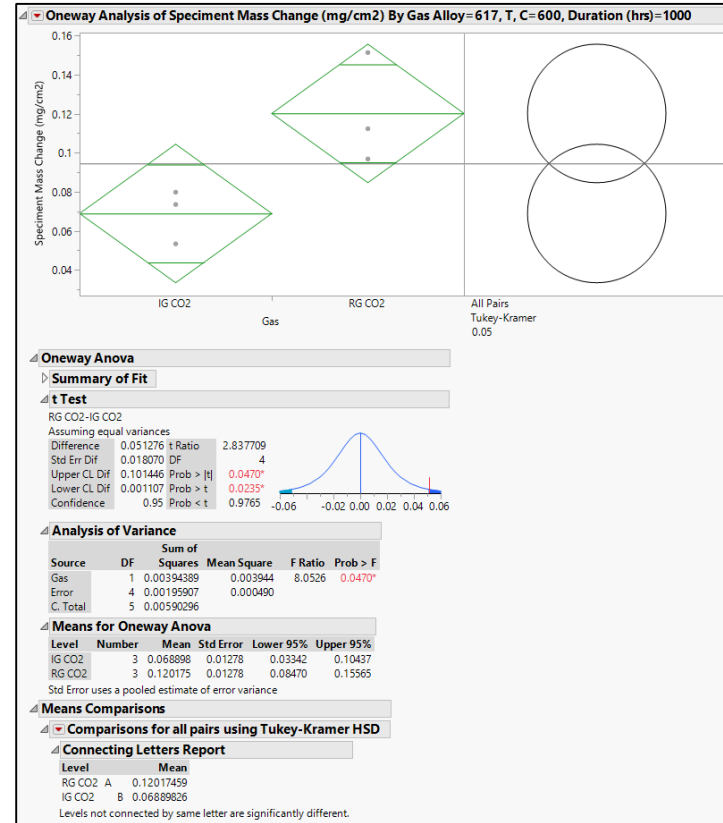
## Statistical Analysis for Different Gas Chemistries

### Statistically Significant Difference Does Not Exist



Comparing weight gain data for F22 at 350°C in RG and IG CO<sub>2</sub>

### Statistically Significant Difference Does Exist



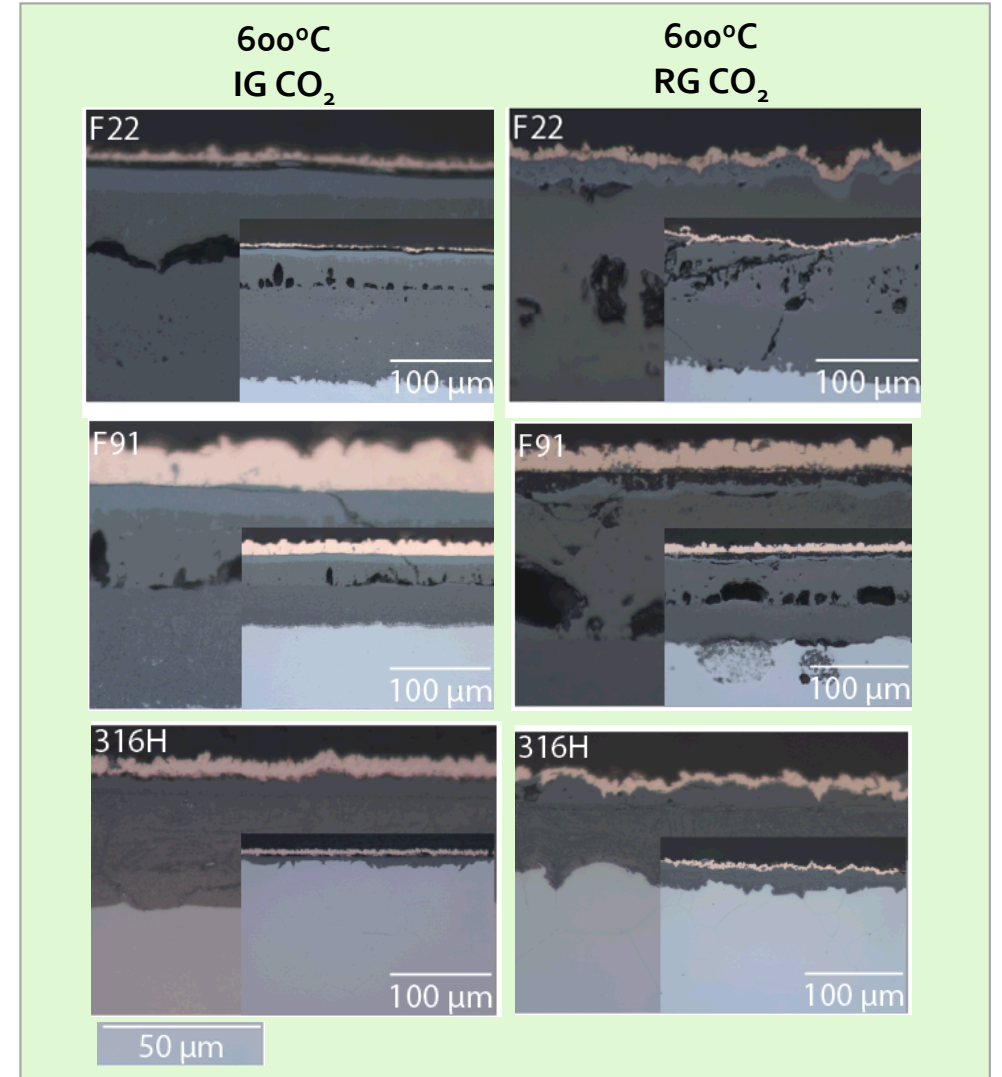
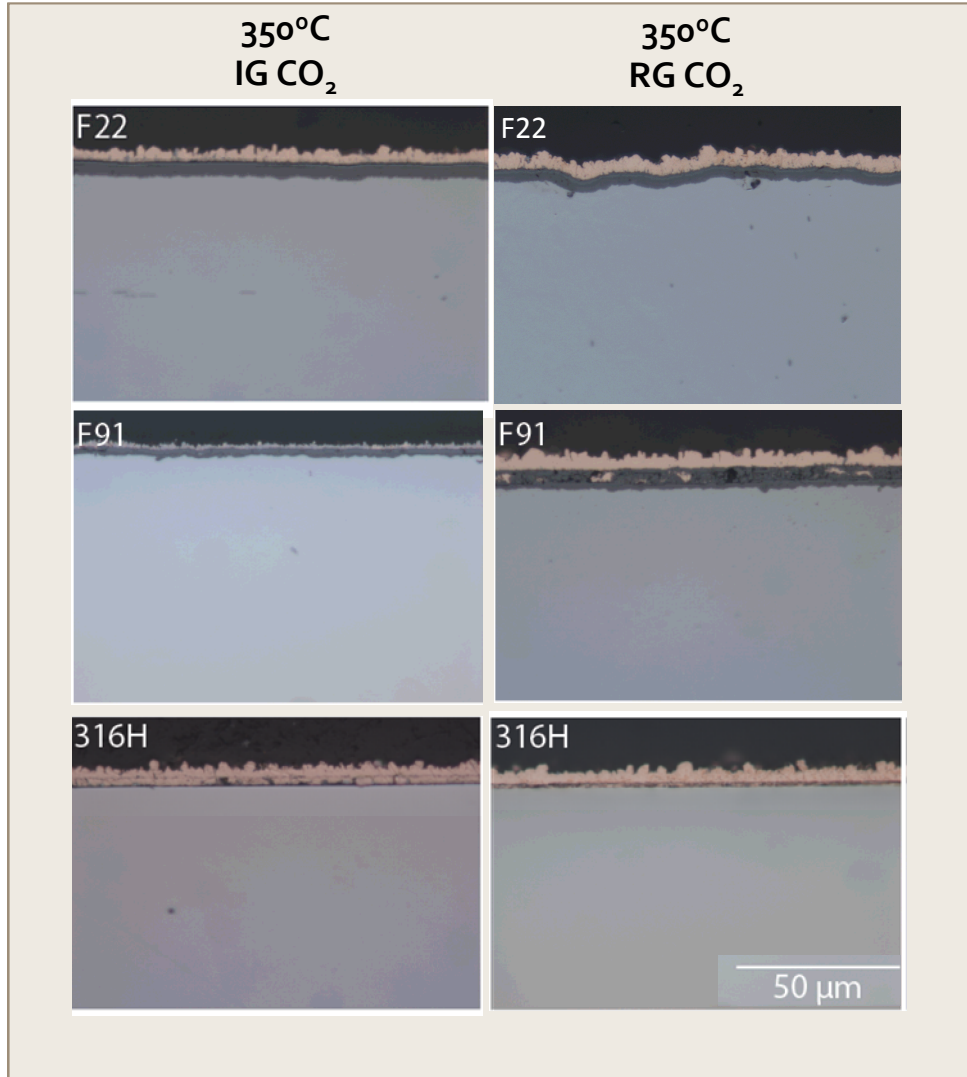
Comparing weight gain data for 617 at 600°C in RG and IG CO<sub>2</sub>

### Statistical Analysis Summary of Alloy Weight Change Differences for RG and IG CO<sub>2</sub>

Alloy	350°C		600°C	
	500 hrs	1000 hrs	500 hrs	1000 hrs
F22	IG = RG	IG = RG	IG = RG	IG = RG
F91	IG = RG	IG = RG	IG = RG	IG = RG
304H	IG = RG	IG = RG	IG = RG	IG = RG
316H	IG > RG	IG > RG	IG = RG	IG = RG
347H	IG = RG	IG = RG	RG > IG	IG = RG
800H	IG = RG	IG = RG	IG = RG	IG = RG
HR120	IG = RG	IG = RG	IG = RG	IG = RG
617	IG = RG	IG = RG	IG = RG	RG > IG

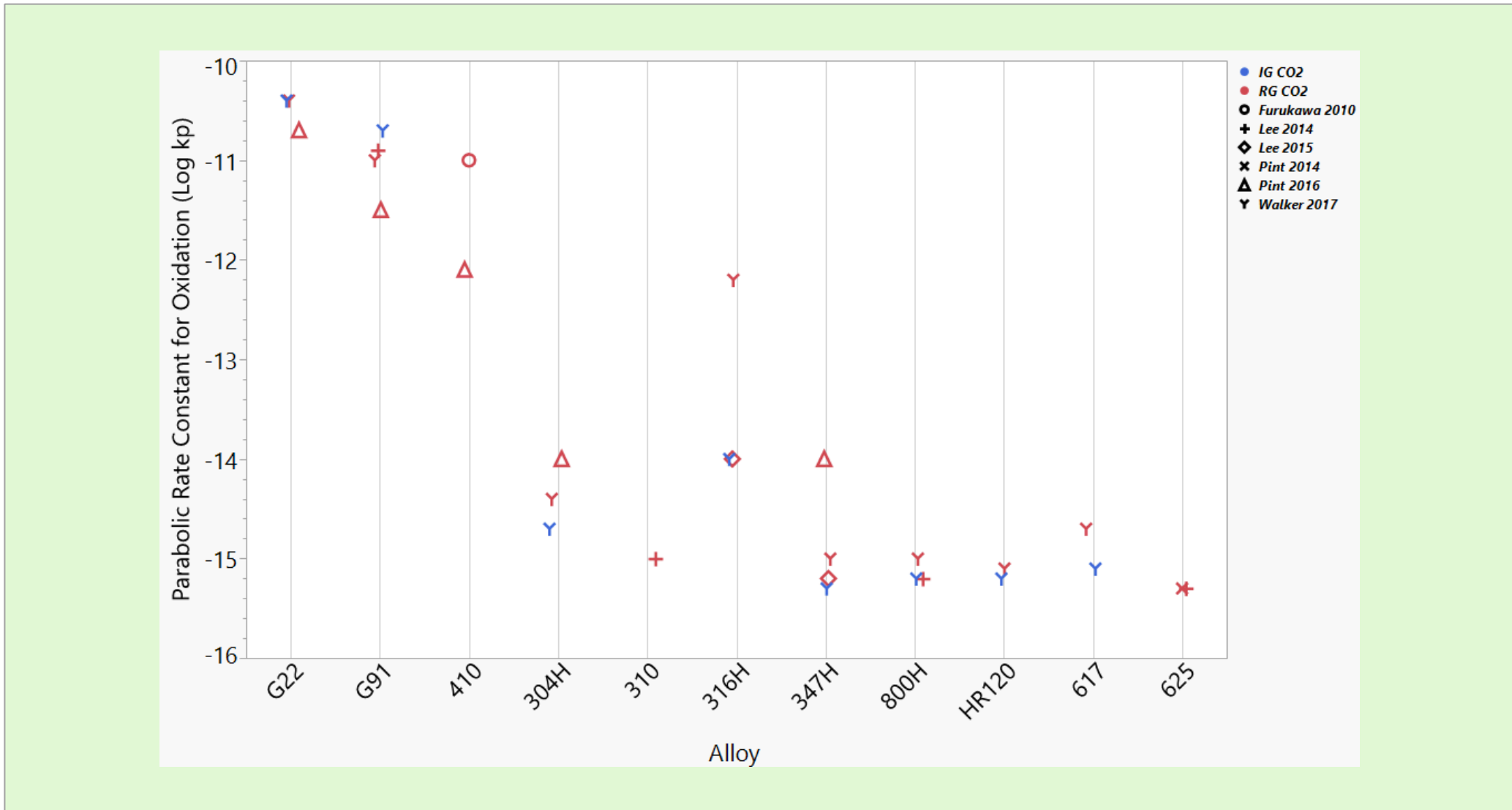
# Gas chemistry (RG vs IG CO<sub>2</sub>) has very little influence on surface oxide

## *Alloy Specimen Oxide Microstructures*



# Valuable observations in comparing to results from other researchers

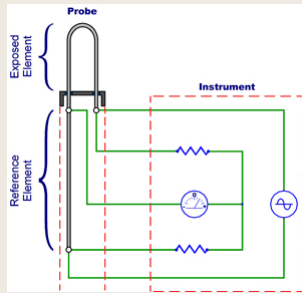
Comparison with Prior Results at 600°C



## In-situ Alloy Corrosion Monitoring

### *in-situ* Carbon Dioxide Corrosion Monitoring

- ER is a simple, robust technique that measures Electrical Resistance across a metallic element
- As the element increases in resistance due to corrosion this is correlated to a loss in the element thickness



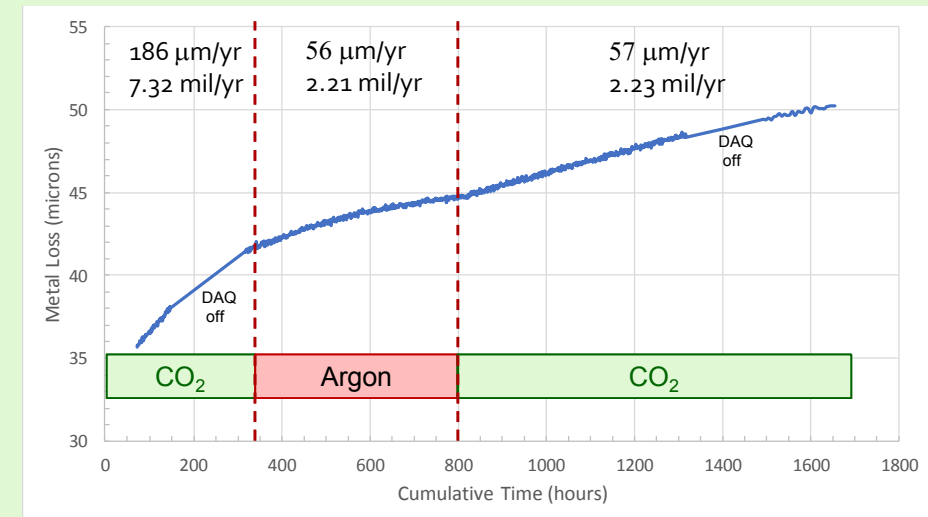
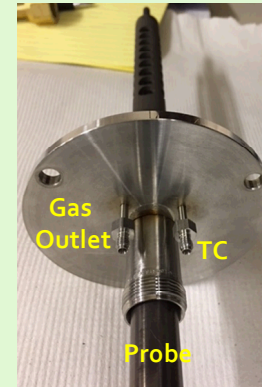
$$R_{probe} = \rho \frac{L}{A}$$



- Photo of 316L ER device with heat shield removed
- Reference element is internal to the device
- Pressure rated to 1500 psi
- Probe life = 10 mils metal loss

- Systems are currently being built where alloy selections are made with limited data
- Capability for real time monitoring of component alloy corrosion in these systems is extremely valuable:
  - Reduces risk for system developers
  - Provides the opportunity to piggyback learning for material behavior in these systems

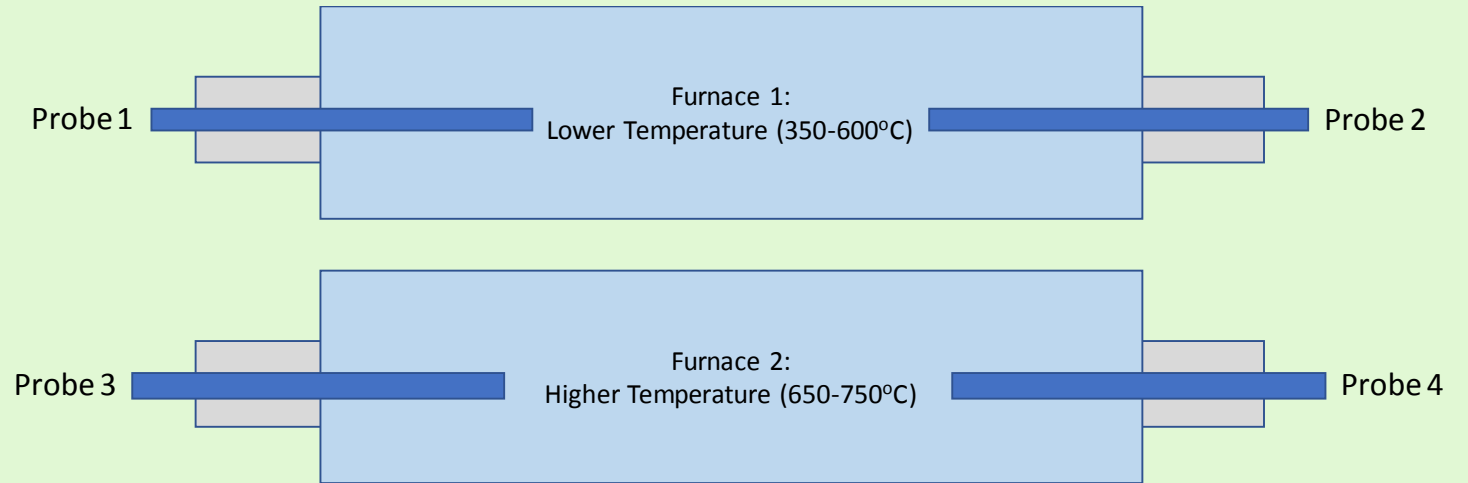
### Shake down results over 1600 hours of continuous testing at 650°C in RG CO<sub>2</sub>



1 mil = 25.4 microns

# Validation of in-situ corrosion monitoring with alloy witness coupons

## *In-situ Alloy Corrosion Monitoring – Next Steps*



- Run probes of 2 different alloys in two separate temperature ranges in CO<sub>2</sub>
- Long duration tests up to 1500 hours
- Witness coupons (3) of each alloy included for extraction at 500 hour intervals (500hrs, 1000hrs, and 1500hrs)
- Lower T Candidates: 9Cr-1Mo (grade 91), 316, 304, 310, 347H
- Higher T Candidates: 800H, HR120, 617, 625, 230, 740H

## *Summary and Overview of Future Work*

- **Concerns with Existing Data:**

- Alloy corrosion data has predominantly been obtained using research grade CO<sub>2</sub>, while the lower purity industrial grade CO<sub>2</sub> will be used in a real system
- There is very limited alloy corrosion data available at lower temperatures relevant for sodium fast reactor (SFR) energy conversion system applications
- Alloy corrosion investigations have primarily considered surface oxidation and not internal carburization
- Structural alloy corrosion has only been evaluated in terms of sample weight gain, rather than by the more useful metric of metal loss

- **Achievements through recent research:**

- Long duration (1000-hour) corrosion data has been obtained for 8 alloys at two temperatures relevant to an SFR EC system (350°C and 600°C) in both RG and IG CO<sub>2</sub>
- Statistical analysis of alloy weight change data indicates very little change in alloy corrosion behavior for these two temperatures between RG and IG gases
- Comparison of recent results to others at higher pressures indicate minimal influence of pressure on corrosion in CO<sub>2</sub>
- A recent lab shakedown test has demonstrated significant potential for ER in-situ corrosion probes in CO<sub>2</sub> systems

- **Overview of Future Work:**

- Complete analyses for alloy internal carburization using nanoindentation hardness techniques
- Complete analyses for alloy metal loss through chemical cleaning study (calculate alloy lifetimes)
- Evaluate/develop *in-situ* corrosion monitoring technology for sCO<sub>2</sub> EC systems

# Acknowledgements

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Sal Golub (DOE)  
Alan Kruizenga (Kairos Power)  
Gary Rochau  
Amanda Dodd

# Questions?

# Backup Slides

**Table 2. Corrosion Sample Dimensions**

<b>Alloy</b>	<b>Diameter (in)</b>	<b>Thickness (in)</b>
<b>F22</b>	0.47	0.063
<b>F91</b>	1.25	0.063
<b>304H</b>	0.47	0.188
<b>316H</b>	0.47	0.125
<b>347H</b>	0.47	0.040
<b>800H</b>	0.50	0.063
<b>HR120</b>	0.47	0.063
<b>617</b>	0.61	0.063

**Table 3. Chemical Analysis for CO<sub>2</sub> Gases**

<b>T, °C</b>	<b>CO<sub>2</sub> Grade</b>	<b>Gas Chemical Analysis</b>						
		<b>CO<sub>2</sub> (%)</b>	<b>CO (ppm)</b>	<b>H<sub>2</sub> (ppm)</b>	<b>N<sub>2</sub> (ppm)</b>	<b>O<sub>2</sub> (ppm)</b>	<b>CH<sub>4</sub> (ppm)</b>	<b>H<sub>2</sub>O (ppm)</b>
600	RG	> 99.999	0.054	0.021	3.097	0.110	0.355	< 0.02
350	RG	> 99.999	0.012	0.005	1.070	0.040	0.153	< 0.02
600	IG	> 99.98	< 0.010	0.040	35.370	11.110	0.430	0.53
350	IG	< /= 99.98	< 0.010	0.040	> 80	> 60	0.420	0.81

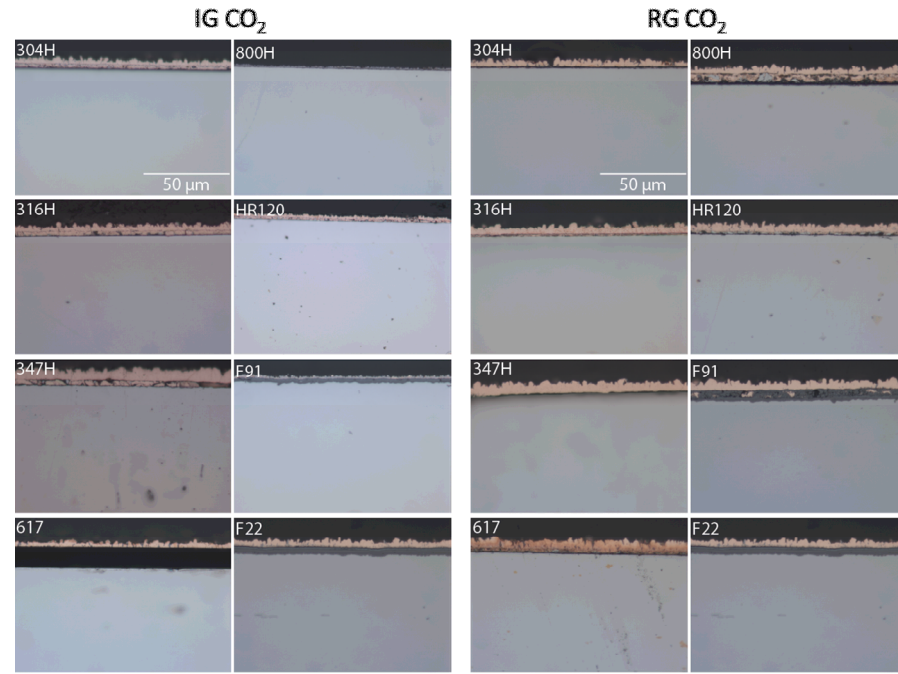
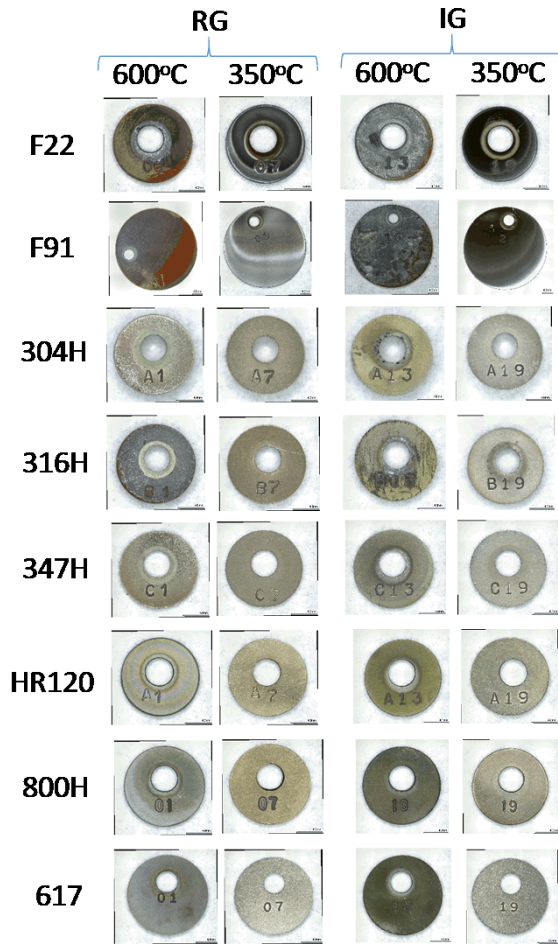


Figure 15. Polished cross-sections of each alloy in IG and RG CO<sub>2</sub> at 350°C for 1000h

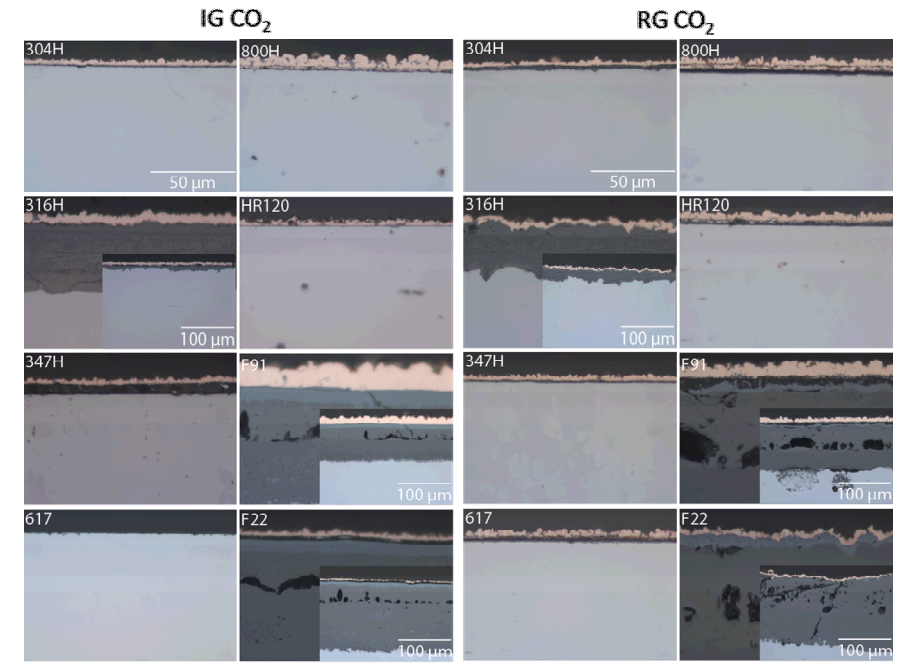


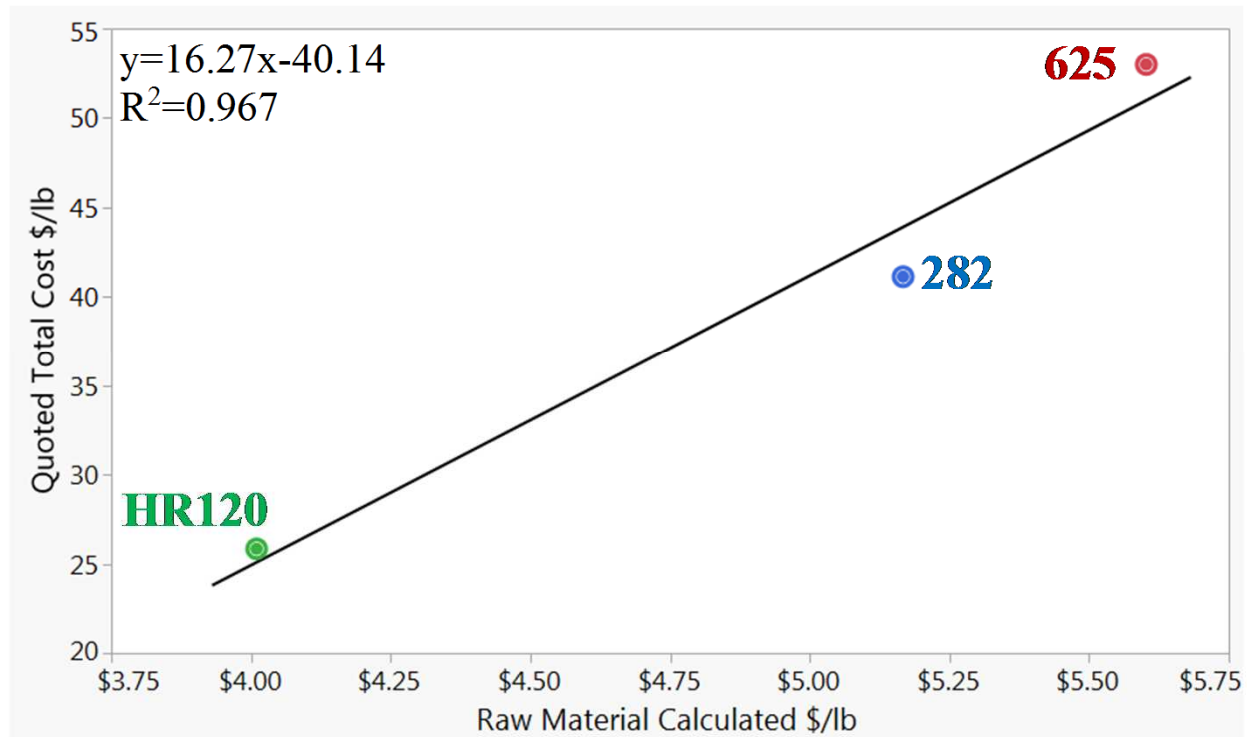
Figure 16. Polished cross-sections of each alloy in IG and RG CO<sub>2</sub> at 600°C for 1000h

# 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



For 3 inch – Schedule 160 pipe

# Alloy Cost to Satisfy Strength Requirements

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

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

$t_m$ : 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 efficiency - **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:

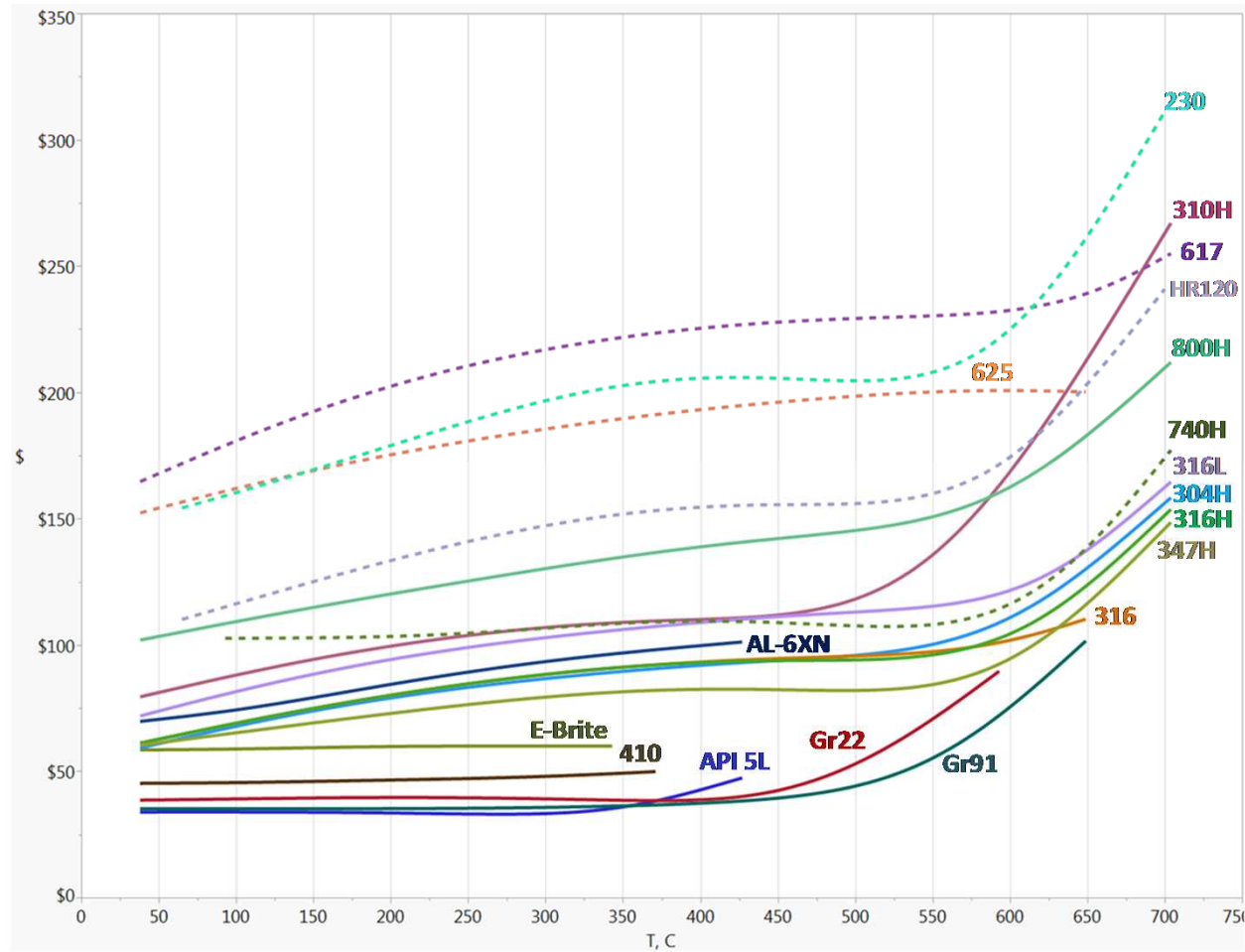
$$\text{Cost (\$)} = \frac{\pi \times 12 \text{in} \times [D_o^2 - (D_o - t_m)^2]}{1728 \text{in}^3/\text{ft}^3} \times \rho_{\text{alloy}} \times \text{Cost}_{\text{alloy}}$$

$t_m$ : Minimum wall thickness (inches)

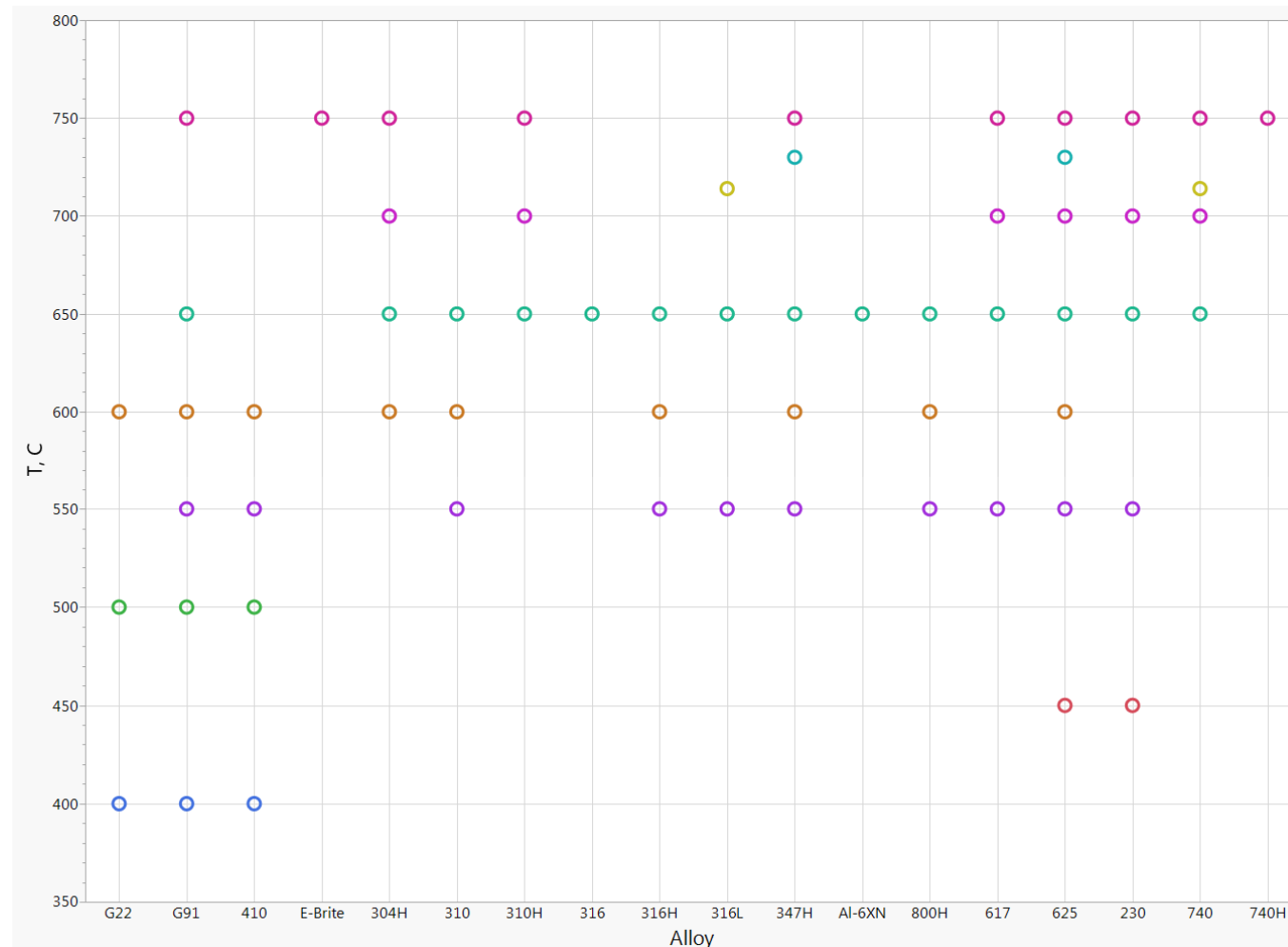
$\rho_{\text{alloy}}$ : density of alloy in units of lbs/ft<sup>3</sup>

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

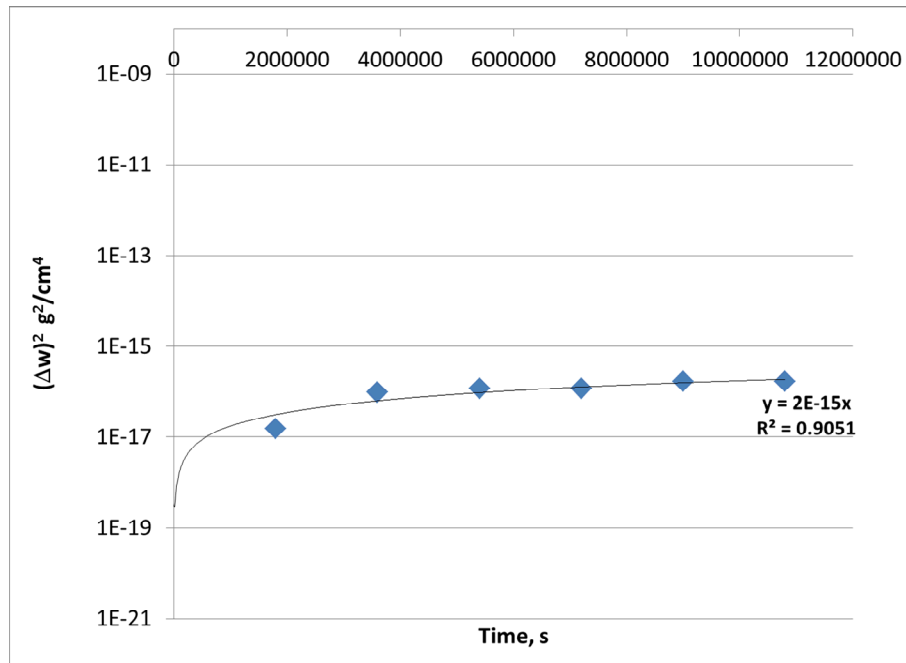
# Alloy Costs (\$/ft) to Satisfy Strength Requirements



# Available Alloy Corrosion Data (400-750°C, RG sCO<sub>2</sub>, 200-250 bar)



# Approach for Comparing Alloy Corrosion Rates



*Parabolic fit to Cao's (2012) experimental data for 800H at 650°C*

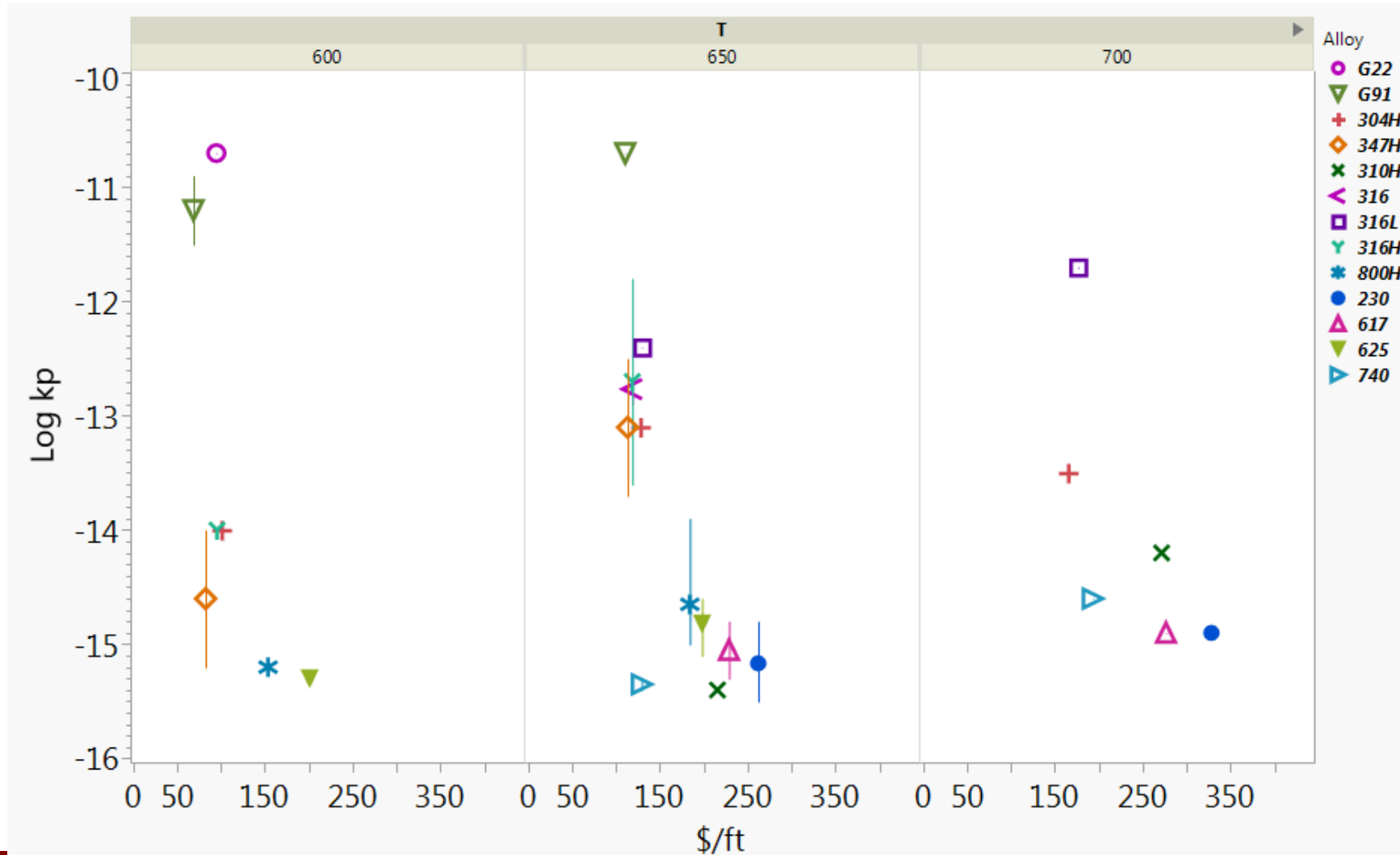
Assuming parabolic oxidation kinetics, the parabolic rate constant ( $k_p$ ) can be calculated for each set of data

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

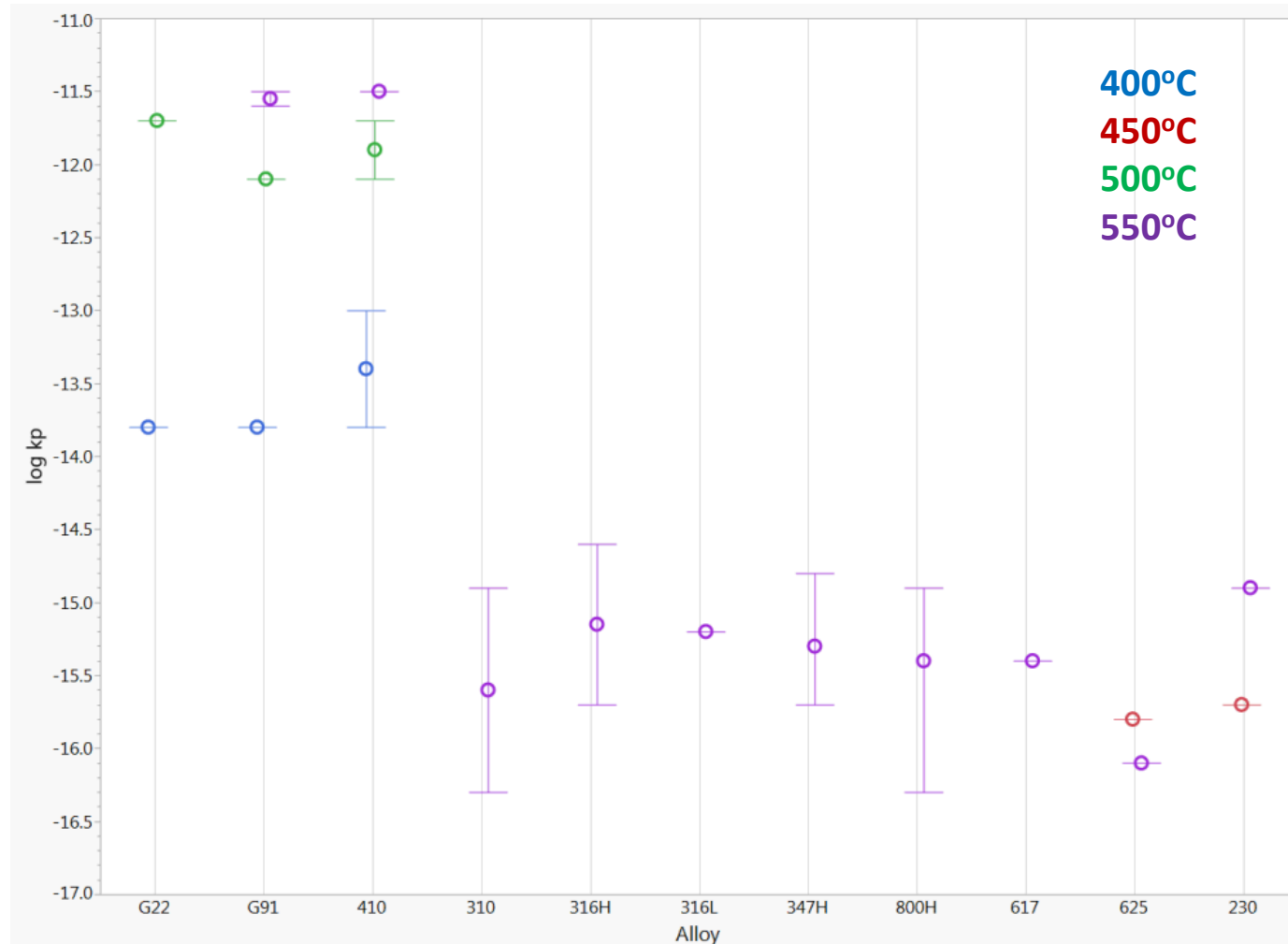
Log  $k_p$  values are used as a corrosion rate comparison between alloys

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

# Comparing Alloy Corrosion Rates (600 – 700°C)



# Comparing Alloy Corrosion Rates (400 – 550°C)



# Comparing Alloy Corrosion Rates (600 – 700°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	400	200			-13.8	0-500	Pint 2016 <sup>[13]</sup>
G22	500	200			-11.7	0-500	Pint 2016 <sup>[13]</sup>
G91	550	200			-11.6	0-1000	Lee 2014 <sup>[14]</sup>
G91	550	250			-11.5	0-310	Rouillard 2011 <sup>[15]</sup>
G91	400	200			-13.8	0-500	Pint 2016 <sup>[13]</sup>
G91	500	200			-12.1	0-500	Pint 2016 <sup>[13]</sup>
410	400	200	-13.0	0-2000			Furukawa 2010 <sup>[16]</sup>
410	500	200	-11.7	0-2000			Furukawa 2010 <sup>[16]</sup>
410	550	200	-11.5	0-2000			Furukawa 2010 <sup>[16]</sup>
410	400	200			-13.8	0-500	Pint 2016 <sup>[13]</sup>
410	500	200			-12.1	0-500	Pint 2016 <sup>[13]</sup>
310	550	200			-16.3	0-1000	Lee 2014 <sup>[14]</sup>
310	550	200			-14.9	0-250	Kim 2014 <sup>[17]</sup>
316H	550	200	-14.6	0-3000	-15.8	0-1000	Lee 2015 <sup>[18]</sup>
316H	550	200			-15.7	0-250	Kim 2014 <sup>[17]</sup>
316L	550	250			-15.2	0-310	Rouillard 2011 <sup>[15]</sup>
347H	550	200	-15.4	0-3000	-15.7	0-1000	Lee 2015 <sup>[18]</sup>
347H	550	200			-14.8	0-250	Kim 2014 <sup>[17]</sup>
347H	550	200	-15.7	0-1000			Mahaffey 2014 <sup>[19]</sup>
800H	550	200			-14.9	0-250	Kim 2014 <sup>[17]</sup>
800H	550	200			-16.3	0-1000	Lee 2014 <sup>[14]</sup>
800H	550	250			-15.1	0-310	Rouillard 2011 <sup>[15]</sup>
800H	550	200	-15.3	0-1000			Mahaffey 2014 <sup>[19]</sup>
617	550	200	-15.4	0-1000	-15.1	0-200	Dheeradhada 2015 <sup>[20]</sup>
625	550	200			-16.1	0-1000	Pint 2014 <sup>[21]</sup>
625	450	200	-15.8	200-1000	-17	0-200	Mahaffey 2015 <sup>[22]</sup>
625	550	200	-16.1	200-1000	-15.2	0-200	Mahaffey 2015 <sup>[22]</sup>
625	550	200			-16.1	0-1000	Lee 2014 <sup>[14]</sup>
230	450	200	-15.7	200-1000	-16.8	0-200	Mahaffey 2015 <sup>[22]</sup>
230	550	200	-14.9	0-1000	-15	0-200	Mahaffey 2015 <sup>[22]</sup>

$\log k_p^A$  Derived by fitting through multiple points over the time range

$\log k_p^B$  Derived by fitting through a single point over the time range

# 400 to 550°C

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

600 to  
700°C

log k<sub>p</sub><sup>A</sup> Derived by fitting through multiple points over the time range

log k<sub>p</sub><sup>B</sup> Derived by fitting through a single point over the time range