Durable, Impermeable Brazes for Solid Oxide Fuel Cells

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Outline

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  - Problems with Silver-Copper Brazes
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- **Results and Discussions**
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  - Alloy Manufacture and Characterization
  - Braze Interface Engineering
  - Oxide Scale Manufacture and Characterization
  - Accelerated Testing
- **Future Work**

Research Team

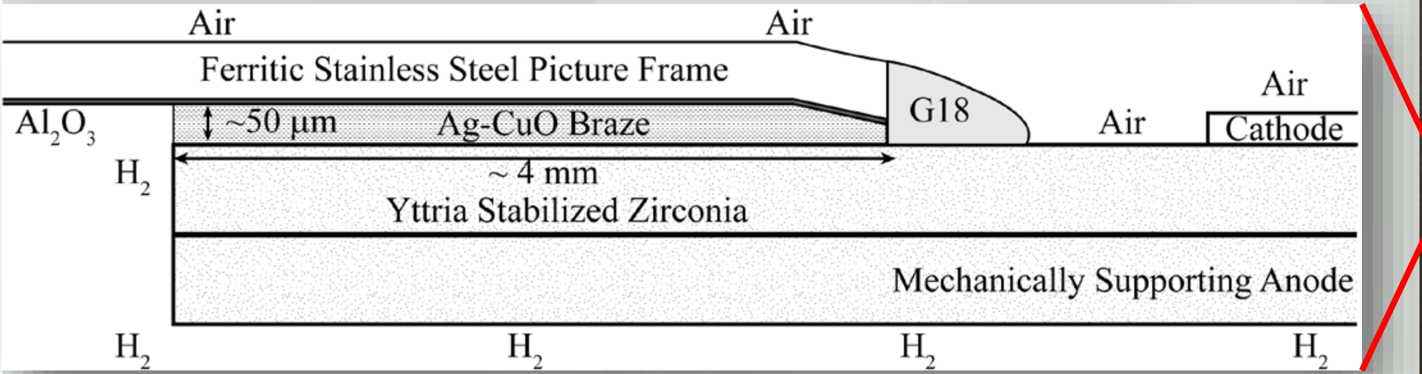
- **MSU:**

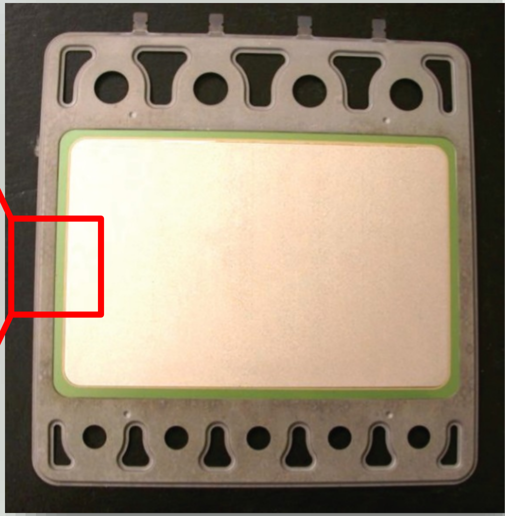
Jason D. Nicholas	PI, SOFC Expertise
Yue Qi	PI, Computational Materials Science Expertise
Thomas R. Bieler	PI, Metallurgy Expertise
Quan Zhou	Graduate Student
Tridip Das	Graduate Student
Yuxi Ma	Graduate Student
Yang Kim	Undergraduate Student

- **Delphi:**
  - Rick Kerr (and his team …)
  - Stephanie Surface
  - Bryan A. Gillispie

- **NETL**
  - Joseph Stoffa

State of the Art Delphi SOFC Joint Schematic





A. J. DeRose et. al. US 7855030 B2, Inhibitor for prevention of braze migration in solid oxide fuel cells

Project Objectives

Design and test new, SOFC-compatible, silver-free brazes forming durable, oxygen and hydrogen impermeable protective surface scales.

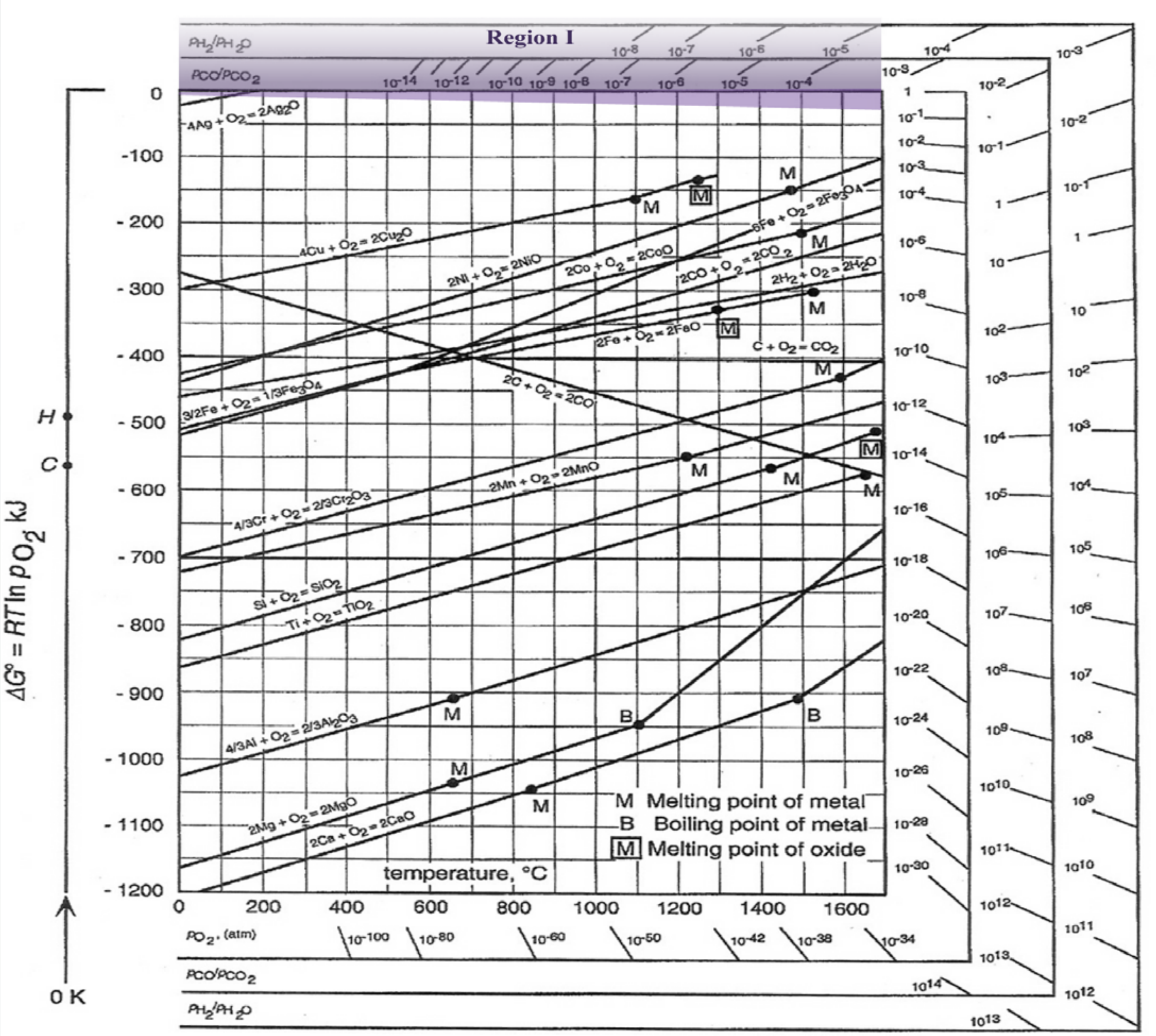
Accomplishments

- Systematic computational evaluation of all ternary combinations of acceptable elements in the periodic table identified some surprising alloys that melt between 900 and 1000˚C , such as those containing refractory metals such as Nb and Ta (Tm for Nb = 2469˚C, Tm for Ta = 3020˚C)

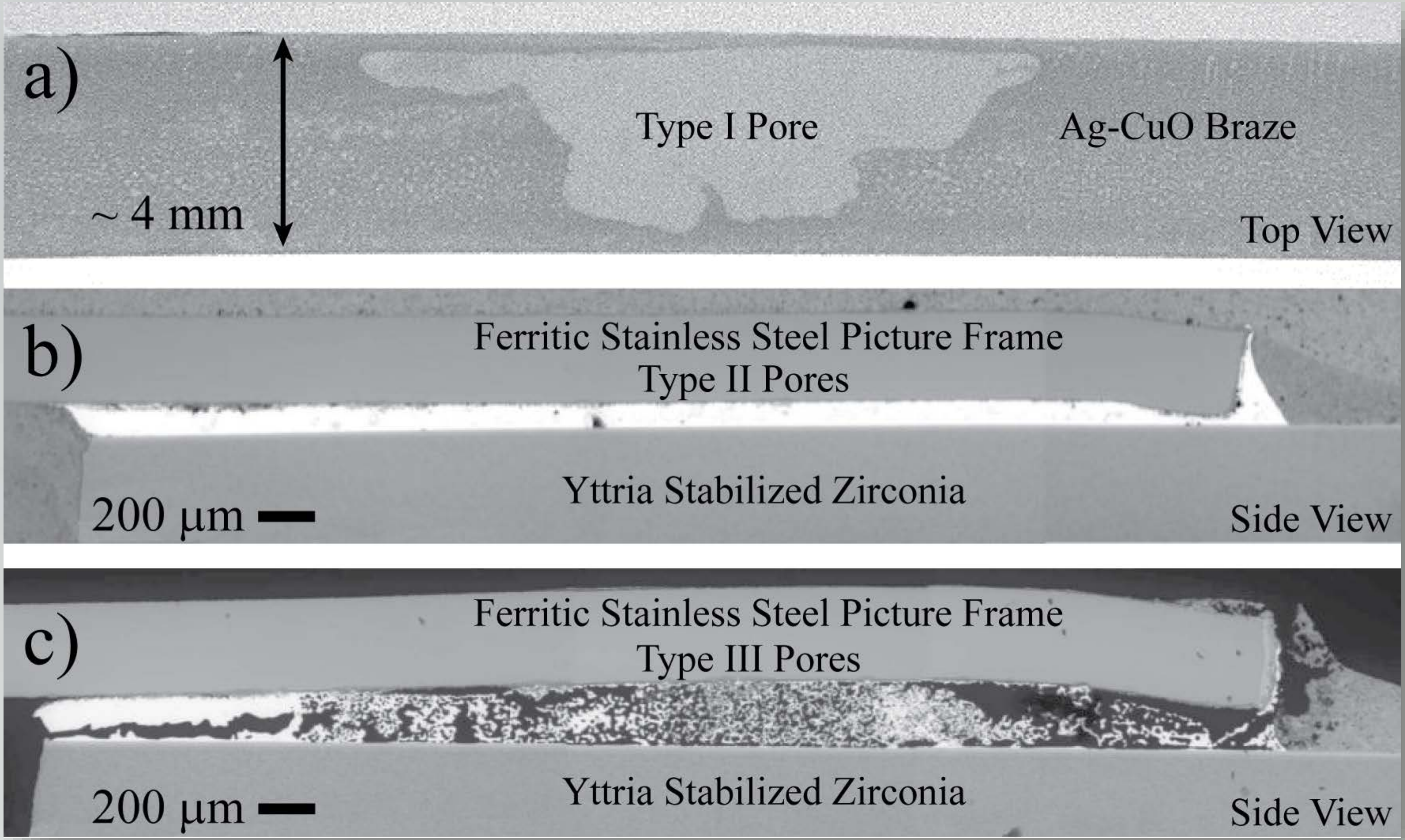
- A new, computationally identified Ta-Ni-Si alloy was shown to have oxidation resistance superior to that BNi2 (one of the most oxidation resistant commercially available Ni superalloys).

- The Ellingham diagrams proved to be a reliable guide for identifying surface-forming oxides.

Only **Metals** in Region I Won’t Oxidize in Air

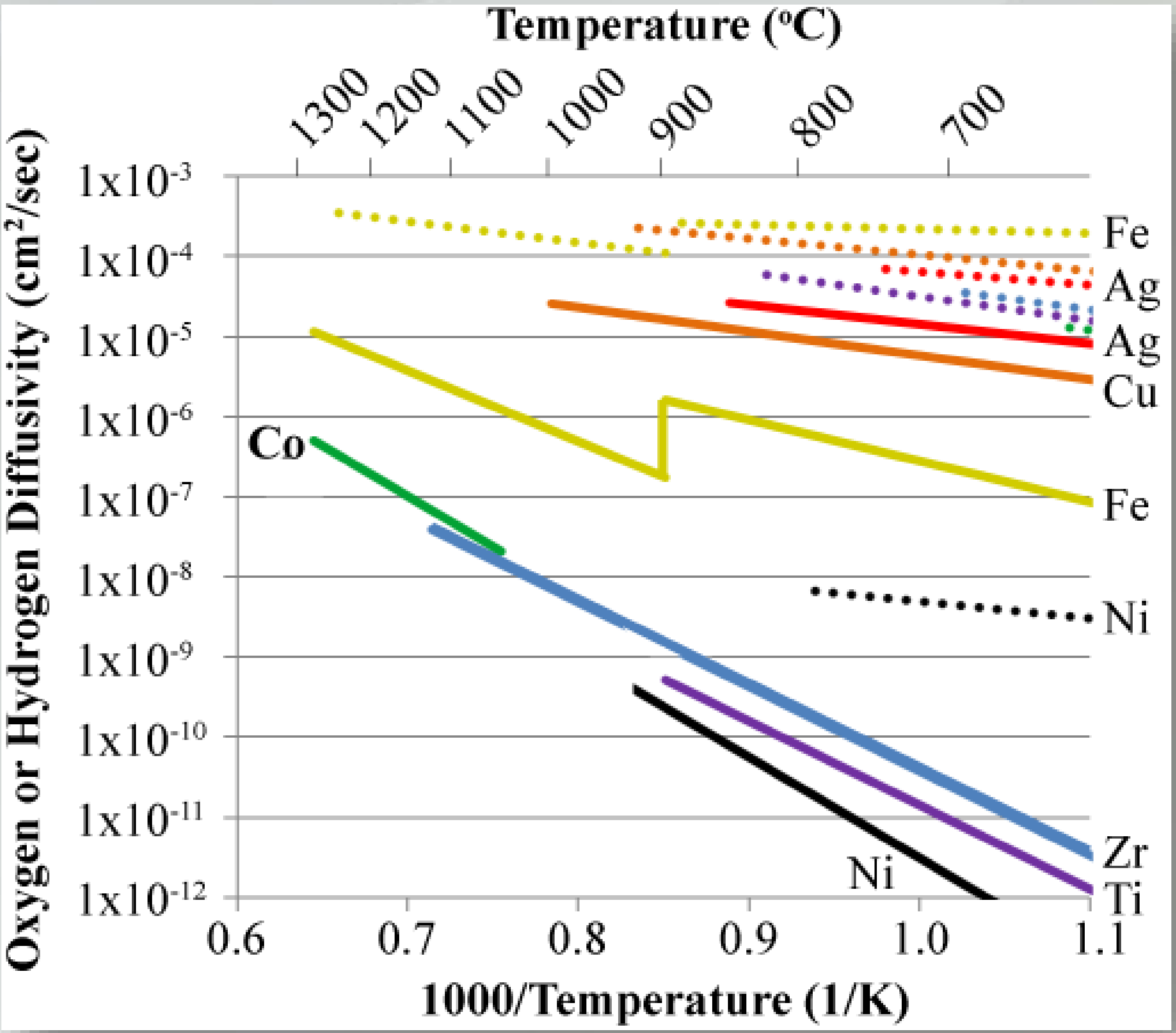


Delphi 97.5%Ag-2.5%Cu Braze Degradation



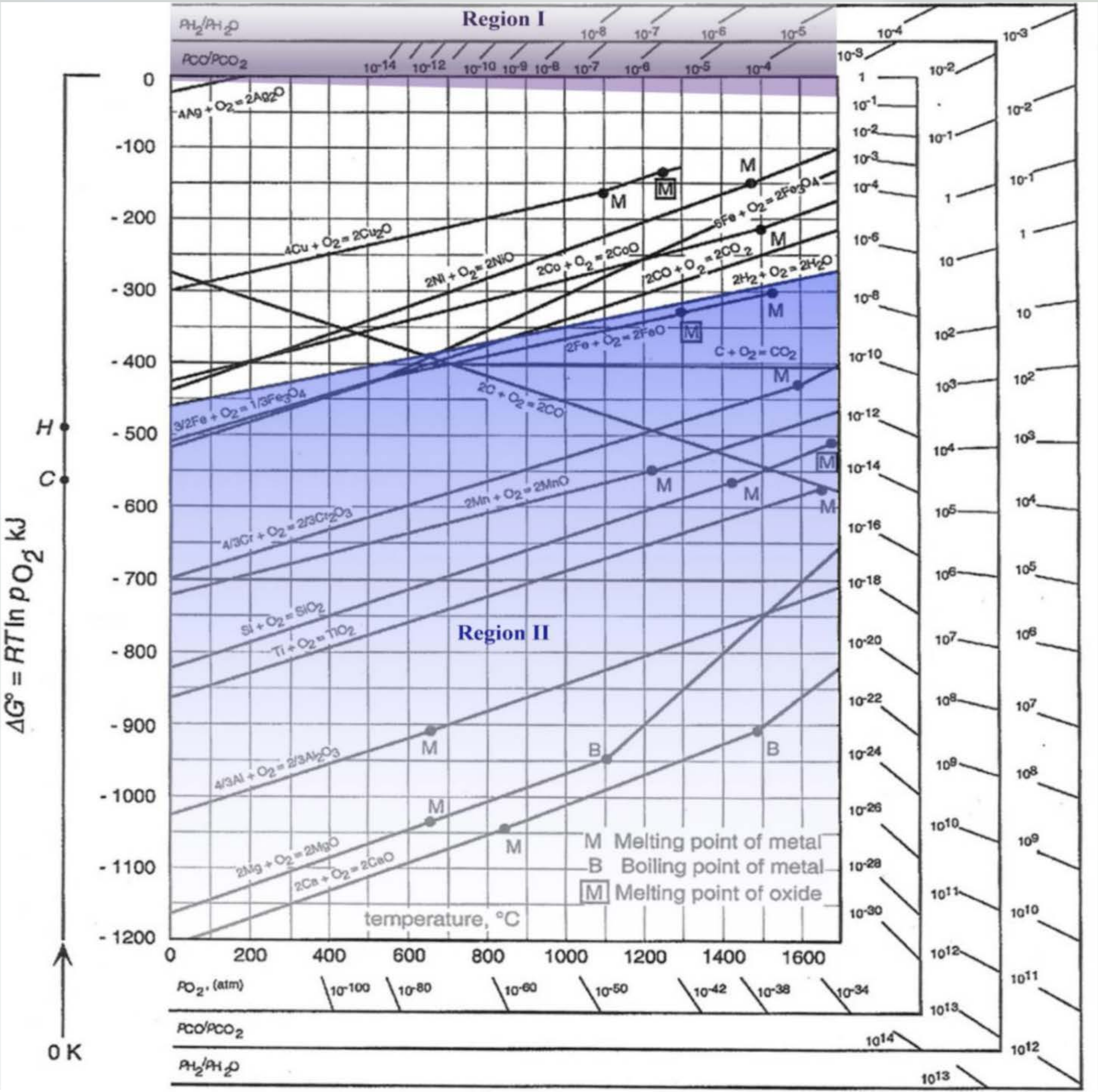
- Type I Pores: Form During Manufacturing
- Type II Pores: Form at Braze Interface due to CuO Reduction
- Type III Pores: Form in Braze due to Water Pocket Formation

Oxygen (Solid) & Hydrogen (Dashed) Diffusivities in Common Metals



Smithells CJ, Gale WF, Totemeier TC. Smithells Metals Reference Book. 8th ed. Boston, MA: Elsevier Butterworth-Heinemann; 2004

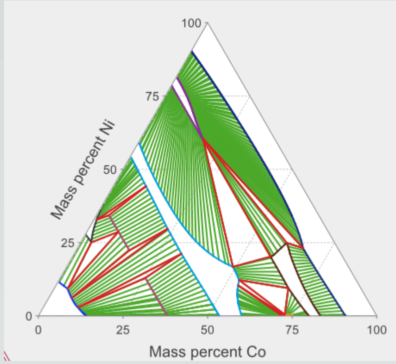
Only Metals in Region II Form Oxide Scales Stable in H_2



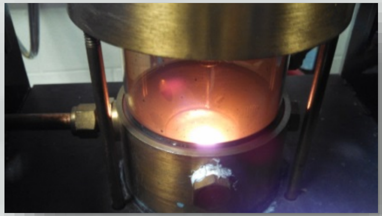
Project Approach Summary

I: Computationally Guided Alloy Composition Search/Design

Phase Diagram Calculations

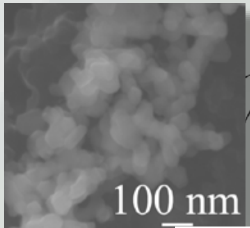


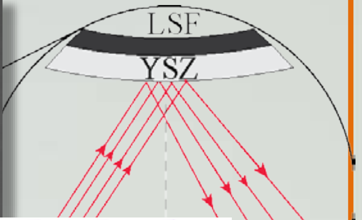
Identify composition with manufacturing compatible liquidus temperature



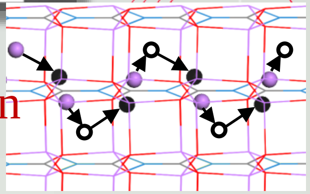
Identify composition forming chemical stable CTE-compatible oxides

II: Oxide Passivation



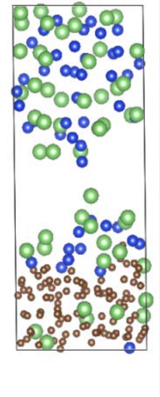


Diffusion

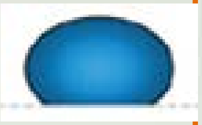


III: Braze Interface Engineering

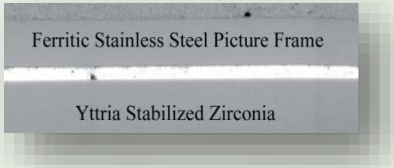
Wsep



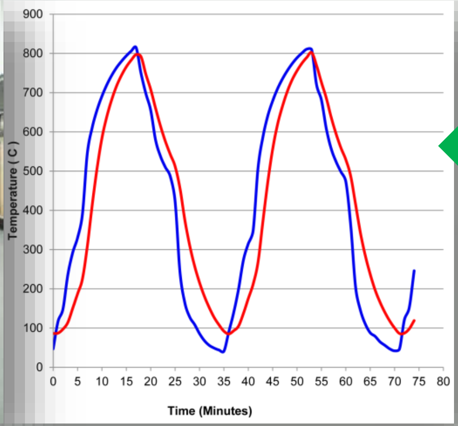
Wetting



Bending tests



IV: Braze Performance under Accelerated SOFC Operating Conditions



Results and Discussions

- Computationally, rational design of alloy compositions
- Experimentally, forming and testing the promising alloy compositions
  - Focus so far
    - Liquidus temperature
    - Solidus temperature
    - Oxidation resistance --- Passivation property

Brazing Element Selection Criteria

- ✓ Elements tend to form solid solutions or solid phase compounds.
  - Noble gases are dropped
- ✓ Should not be radioactive.
  - Polonium onwards (atomic number > 83) elements are dropped
- ✓ Elements should not react to form undesired phases, like brittle phase, liquid or vapor phase.
  - Alkali meatals, Halogens and Chalcogens are dropped.
- ✓ Should not be a good conductor of oxygen or hydrogen ions.
  - Polarizable Lanthanide group is dropped along with Bi.
- ✓ Elements should not have high vapor pressure (≥ 0.1 Torr) at 750°C
  - Alkaline earth metals and semiconducting elements are not considered except Mg as it can form passivating oxide layer with Al and O.
- ✓ Should not be banned element due to toxicity (by REACH-ECHA or US-EPA)
  - Cd, Pb, Tl
- ✓ Should not be in vapor or liquid state at braze operating condition
  - Ga
- ✓ Should not be of high cost (≥ ~$50/gm w.r.t Ag ~ $3/gm)*
  - Re, Pd, Ru, Pt, Au, Os, Ir, Sc, Rh are dropped

Elements List I (13): Ni, Al, Co, Cr, In, Mn, Mo, Nb, Si, Sn, Ta, W, Zn

Elements List II (25): B, C, Mg, Al, Si, V, Cr, Mn, Fe, Co, **Ni**, Cu, Zn, Ga, Nb, Mo, In, Sn, Ta, W, Ti, Y, Zr, Hf, Ag

Criteria Used for Braze Alloy Base Composition From CALPHAD Calculations

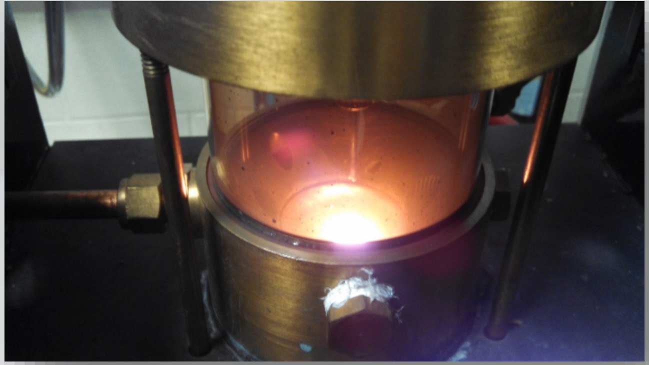
- CALPHAD (Computer Coupling of Phase Diagrams and Thermochemistry) approach implemented in Thermocalc® was used.

Database	Description
TCNI7	Ni based alloys and superalloy solutions database
TCOX5	Thermo-Calc Software Metal Oxide solutions database
TCSLD2	TCS solder alloy solutions database
TTTI3	Titanium based database (didn't purchase)
PURE5	Scientific Group Thermodata Europe Pure Elements database
PSUB	TCS public substances database
PBIN	TCS public binary alloys database
PKP	Kaufman binary alloys database

- Binary and ternary phase diagram was computed to identify alloy compositions with
  a) the liquidus temperature of the braze below1000°C (maximum 1050°C)
  b) the solidus temperature of the braze above 900°C (minimum 850°C)

Alloy Manufacturing and Characterization

99.99% Pure Metals

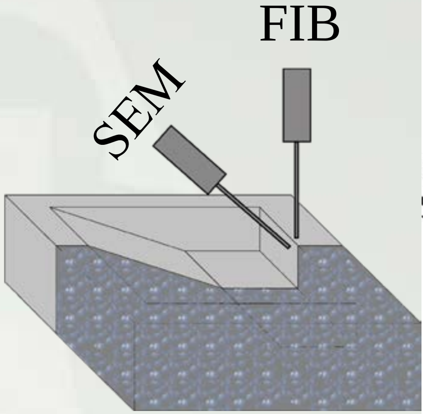


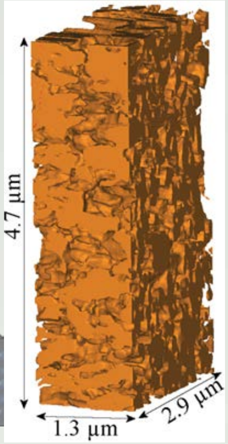
Arc Melting Multicomponent Metals

44%Ni-44%Ti-12%Co

TGA-DSC Testing

Dilatometry Testing

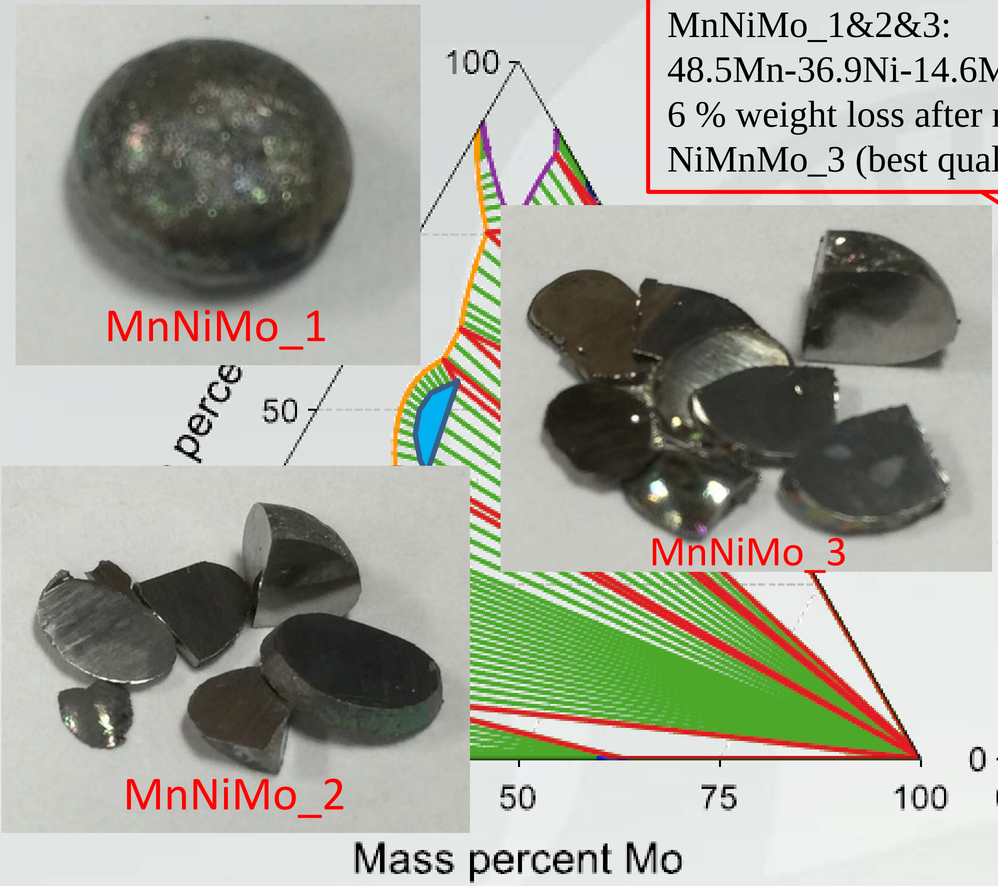




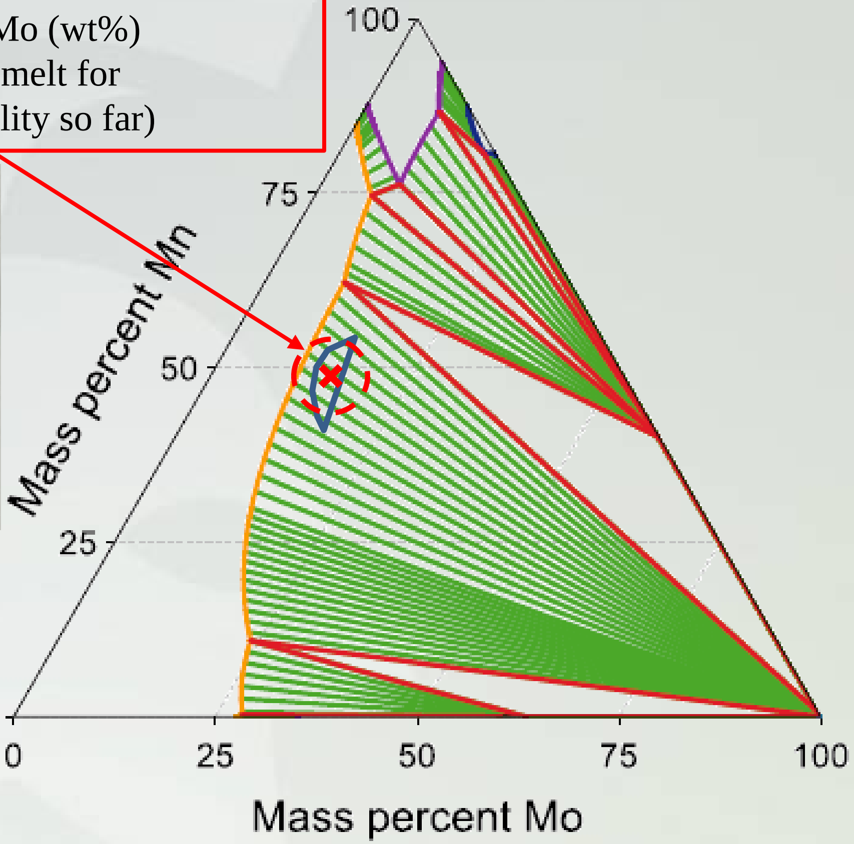
Wetting Studies, XPS, etc.

Thermo-Calc (TCNI7) Computed Ni-Mn-Mo Ternary Phase Diagram

MnNiMo_1&2&3:
48.5Mn-36.9Ni-14.6Mo (wt%)
6 % weight loss after melt for
NiMnMo_3 (best quality so far)



1000°C



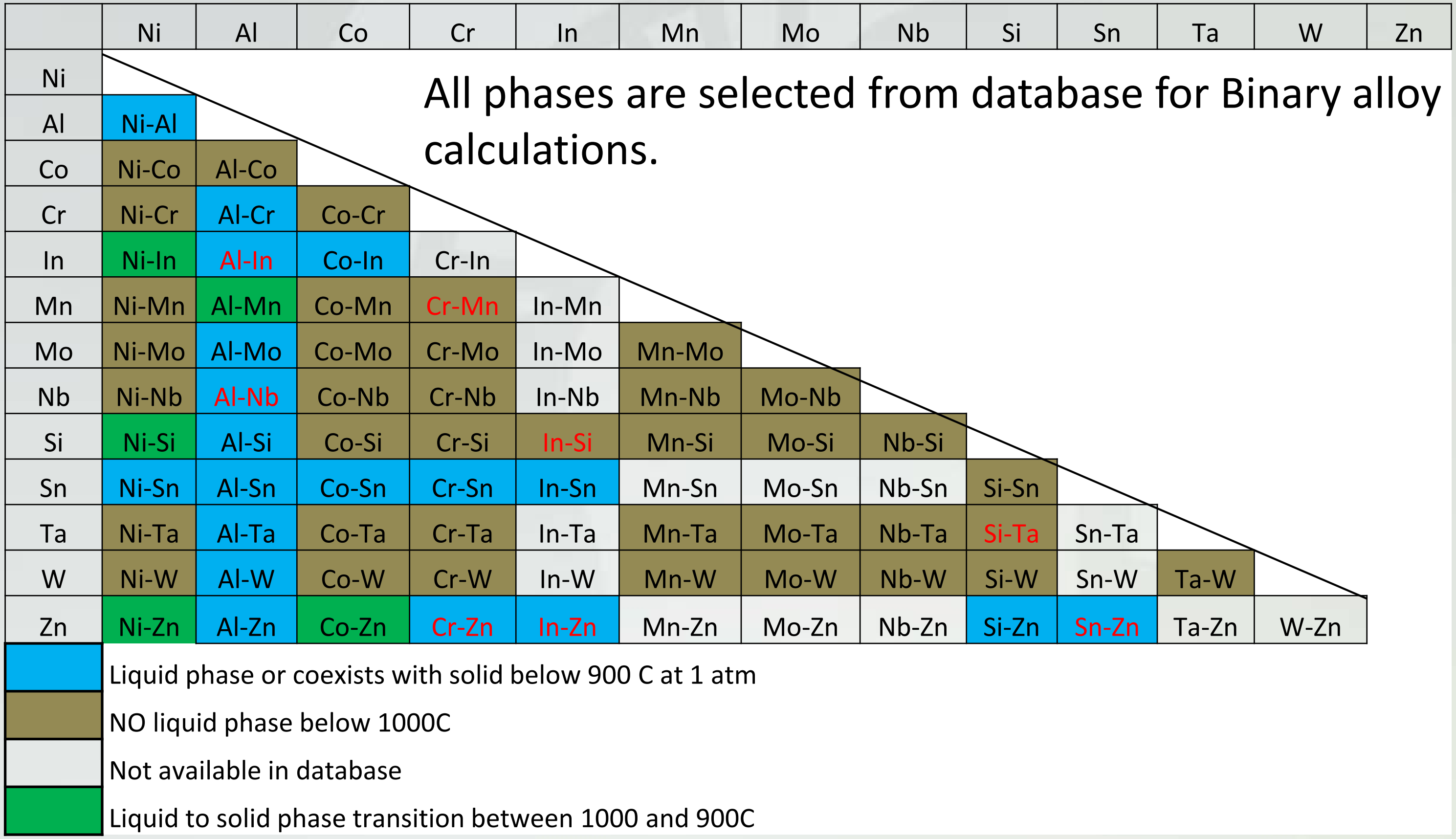
900°C

🟦 Shows the liquid phase.

List of Possible Binary Alloys from Selected Elements

Elements selected (13): Ni, Al, Co, Cr, In, Mn, Mo, Nb, Si, Sn, Ta, W, Zn

Possible binary alloys from above list: $^{13}C_2 = 78$



All phases are selected from database for Binary alloy calculations.

	Ni	Al	Co	Cr	In	Mn	Mo	Nb	Si	Sn	Ta	W	Zn
Ni													
Al	🟦 Ni-Al												
Co	🟫 Ni-Co	🟫 Al-Co											
Cr	🟫 Ni-Cr	🟦 Al-Cr	🟫 Co-Cr										
In	🟩 Ni-In	🟦 Al-In	🟦 Co-In	⬜ Cr-In									
Mn	🟫 Ni-Mn	🟩 Al-Mn	🟫 Co-Mn	🟫 Cr-Mn	⬜ In-Mn								
Mo	🟫 Ni-Mo	🟦 Al-Mo	🟫 Co-Mo	🟫 Cr-Mo	⬜ In-Mo	🟫 Mn-Mo							
Nb	🟫 Ni-Nb	🟦 Al-Nb	🟫 Co-Nb	🟫 Cr-Nb	⬜ In-Nb	🟫 Mn-Nb	🟫 Mo-Nb						
Si	🟩 Ni-Si	🟦 Al-Si	🟫 Co-Si	🟫 Cr-Si	🟫 In-Si	🟫 Mn-Si	🟫 Mo-Si	🟫 Nb-Si					
Sn	🟦 Ni-Sn	🟦 Al-Sn	🟦 Co-Sn	🟦 Cr-Sn	🟦 In-Sn	⬜ Mn-Sn	⬜ Mo-Sn	⬜ Nb-Sn	🟫 Si-Sn				
Ta	🟫 Ni-Ta	🟦 Al-Ta	🟫 Co-Ta	🟫 Cr-Ta	⬜ In-Ta	🟫 Mn-Ta	🟫 Mo-Ta	🟫 Nb-Ta	🟫 Si-Ta	⬜ Sn-Ta			
W	🟫 Ni-W	🟦 Al-W	🟫 Co-W	🟫 Cr-W	⬜ In-W	🟫 Mn-W	🟫 Mo-W	🟫 Nb-W	🟫 Si-W	⬜ Sn-W	🟫 Ta-W		
Zn	🟩 Ni-Zn	🟦 Al-Zn	🟩 Co-Zn	🟦 Cr-Zn	🟦 In-Zn	⬜ Mn-Zn	⬜ Mo-Zn	⬜ Nb-Zn	🟦 Si-Zn	🟦 Sn-Zn	⬜ Ta-Zn	⬜ W-Zn	

🟦 Liquid phase or coexists with solid below 900 C at 1 atm
🟫 NO liquid phase below 1000C
⬜ Not available in database
🟩 Liquid to solid phase transition between 1000 and 900C

Ni-In, Ni-Si, Ni-Zn and Co-Zn have eutectic reaction in binary phase diagram

List of Possible Ni-containing Ternary Alloys from Selected Elements

Elements selected (13): **Ni**, Al, Co, Cr, In, Mn, Mo, Nb, Si, Sn, Ta, W, Zn

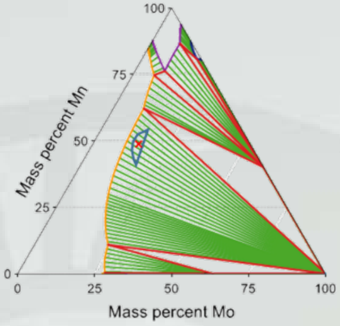
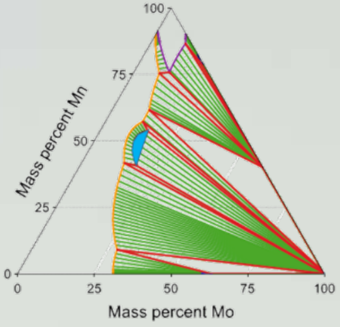
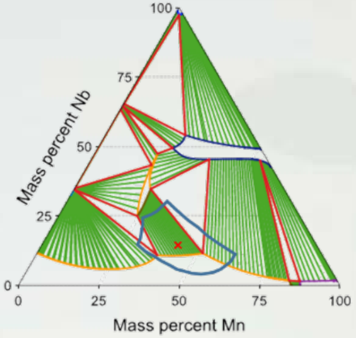
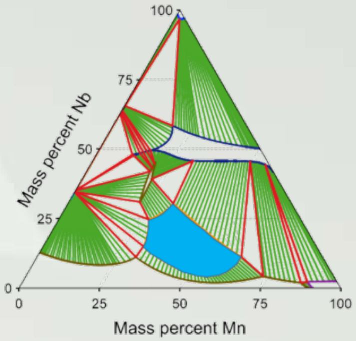
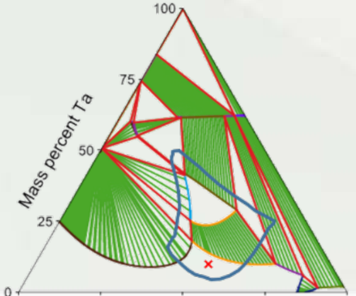
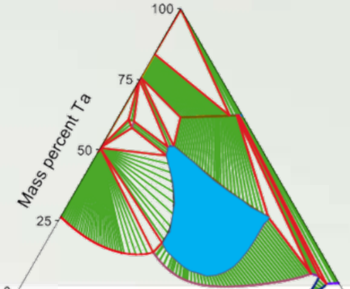
Possible ternary alloys from above list with Ni base: $^{12}C_2 = 66$

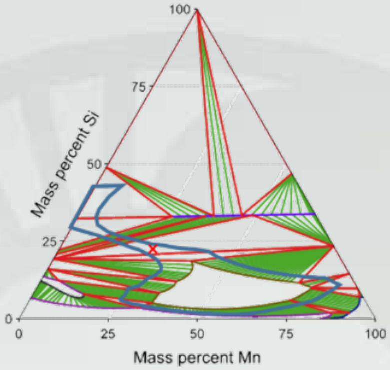
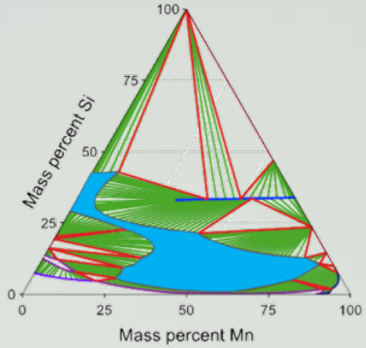
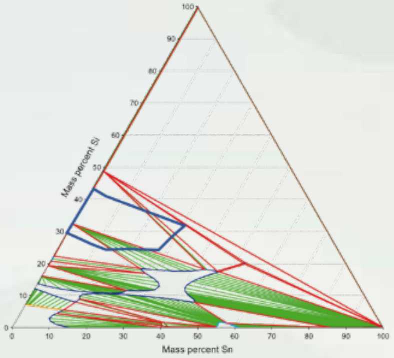
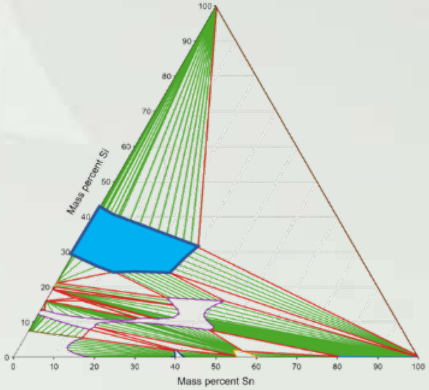
Ni	Al	Co	Cr	In	Mn	Mo	Nb	Si	Sn	Ta	W	Zn
Al												
Co	🟦 Ni-Al-Co											
Cr	🟦 Ni-Al-Cr	🟫 Ni-Co-Cr										
In	🟦 Ni-Al-In	🟦 Ni-Co-In	⬜ Ni-Cr-In									
Mn	🟦 Ni-Al-Mn	🟫 Ni-Co-Mn	🟫 Ni-Cr-Mn	⬜ Ni-In-Mn								
Mo	🟦 Ni-Al-Mo	🟫 Ni-Co-Mo	🟫 Ni-Cr-Mo	⬜ Ni-In-Mo	🟩 Ni-Mn-Mo							
Nb	🟫 Ni-Al-Nb	🟫 Ni-Co-Nb	🟫 Ni-Cr-Nb	⬜ Ni-In-Nb	🟩 Ni-Mn-Nb	🟫 Ni-Mo-Nb						
Si	🟦 Ni-Al-Si	🟫 Ni-Co-Si	🟩 Ni-Cr-Si	🟦 Ni-In-Si	🟩 Ni-Mn-Si	🟫 Ni-Mo-Si	🟦 Ni-Nb-Si					
Sn	🟦 Ni-Al-Sn	🟦 Ni-Co-Sn	⬜ Ni-Cr-Sn	🟦 Ni-In-Sn	⬜ Ni-Mn-Sn	⬜ Ni-Mo-Sn	⬜ Ni-Nb-Sn	🟩 Ni-Si-Sn				
Ta	🟦 Ni-Al-Ta	🟫 Ni-Co-Ta	🟫 Ni-Cr-Ta	⬜ Ni-In-Ta	🟩 Ni-Mn-Ta	🟫 Ni-Mo-Ta	🟫 Ni-Nb-Ta	🟩 Ni-Si-Ta	⬜ Ni-Sn-Ta			
W	🟦 Ni-Al-W	🟫 Ni-Co-W	🟫 Ni-Cr-W	⬜ Ni-In-W	🟫 Ni-Mn-W	🟫 Ni-Mo-W	🟫 Ni-Nb-W	🟫 Ni-Si-W	⬜ Ni-Sn-W	🟫 Ni-Ta-W		
Zn	🟦 Ni-Al-Zn	🟦 Ni-Co-Zn	⬜ Ni-Cr-Zn	🟦 Ni-In-Zn	⬜ Ni-Mn-Zn	⬜ Ni-Mo-Zn	⬜ Ni-Nb-Zn	🟦 Ni-Si-Zn	🟦 Ni-Sn-Zn	⬜ Ni-Ta-Zn	⬜ Ni-W-Zn	

🟦	Liquid phase or coexists with solid below 900 C at 1 atm
🟫	NO liquid phase below 1000C
⬜	Not available in database
🟩	Liquid to solid phase transition between 1015 and 900C

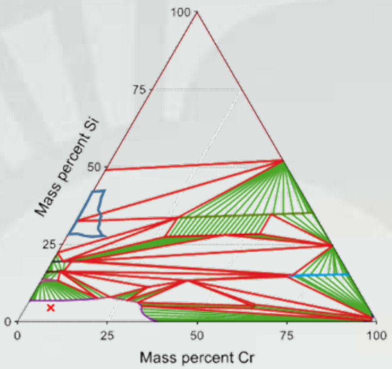
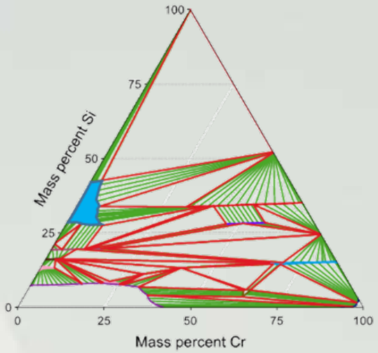
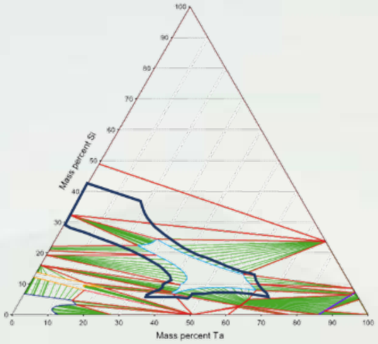
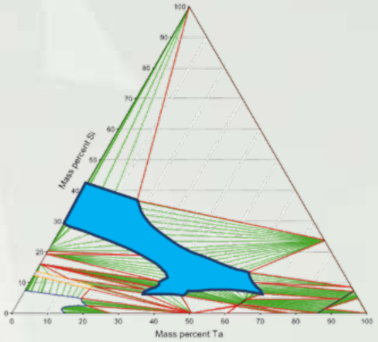
The 7 alloys systems can be further categorized into two systems:

NiSi(Cr,Sn,Ta,Mn) & **NiMn(Mo,Nb,Ta,Si)**

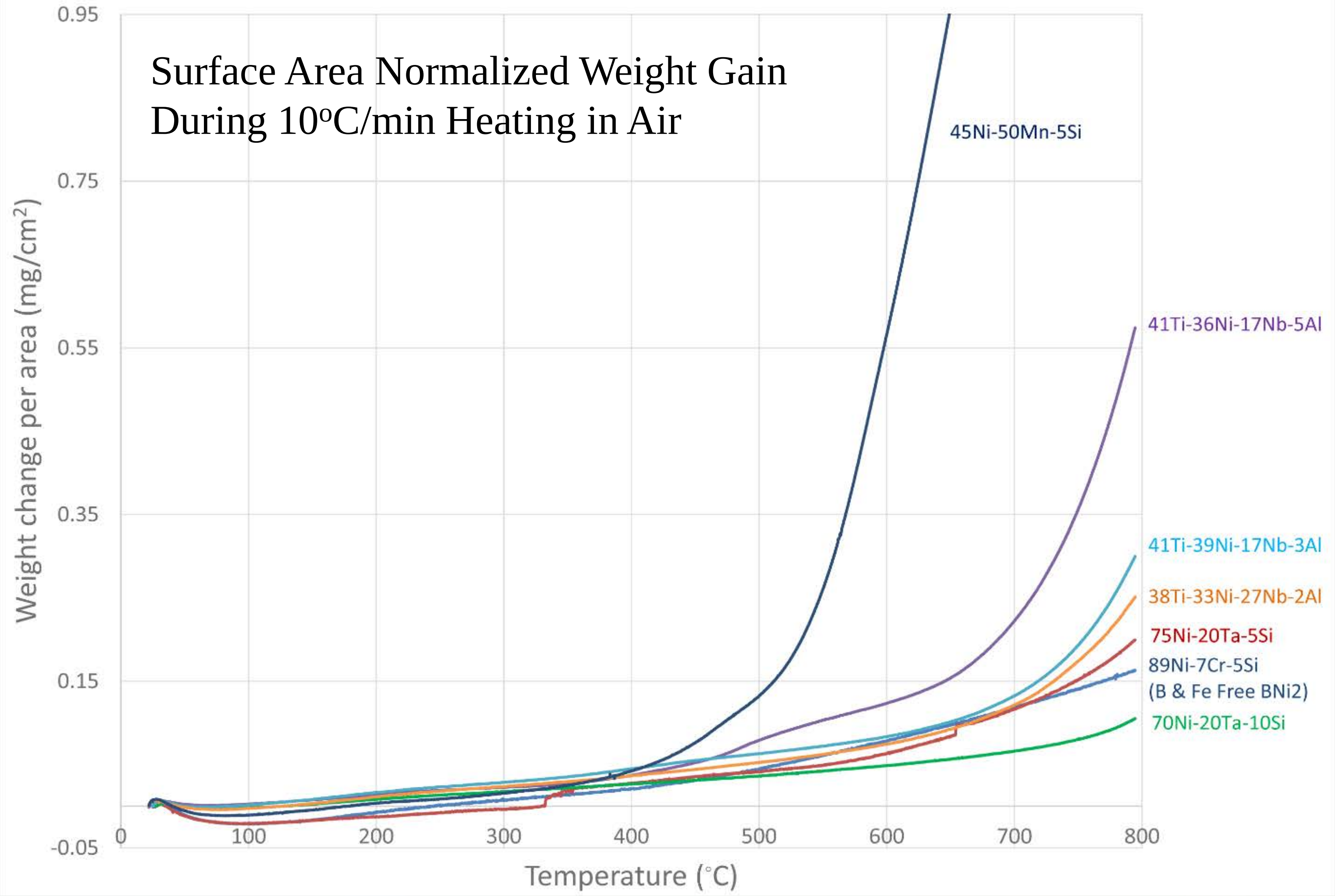
Tested Compostions	Characterization Results	900°C Ternary Phase Diagram	1000°C Ternary Phase Diagram
49Mn36Ni-15Mo	- Poor Oxidation Resistance	Ni-Mn-Mo 	Ni-Mn-Mo 
41Ni-43Mn-15Nb	- Poor Oxidation Resistance	Ni-Mn-Nb 	Ni-Mn-Nb 
37Ni-52Mn-11Ta	- Poor Oxidation Resistance	Ni-Mn-Ta 	Ni-Mn-Ta 

Tested Compostions	Characterization Results	900°C Ternary Phase Diagram	1000°C Ternary Phase Diagram
45Ni-50Mn-5Si	• Poor Oxidation Resistance • Brittle	Ni-Mn-Si  	Ni-Mn-Si 
52Ni-26Mn-22Si	• So Brittle it Disintegrated During Fabrication		
Untested because the high (>25%) Si content required to produce alloys with desirable melting properties suggest that these alloys are likely brittle due to silicide formation		Ni-Sn-Si  	Ni-Sn-Si 

Promising systems to pursue

Tested Compostions	Characterization Results	900°C Ternary Phase Diagram	1000°C Ternary Phase Diagram
89Ni-7Cr-5Si (Fe-Free & B-Free BNi2) BNi2:14.0-Cr, 4.0-Si, 3.1-B, 0.02-P, 78.88-Ni	• Excellent Oxidation Resistance • Ductile	Ni-Cr-Si 	Ni-Cr-Si 
75Ni-20Ta-5Si	• Good Oxidation Resistance • Ductile	Ni-Ta-Si 	Ni-Ta-Si 
Possible Optimal Composition			
70Ni-20Ta-10Si	• Excellent Oxidation Resistance • Brittle		

Ta-Ni-Si An Oxidation Resistance Superior to BNi2



Surface Area Normalized Weight Gain
During 10°C/min Heating in Air

Conclusion and Accomplishments

- Systematic computational evaluation of all ternary combinations of acceptable elements in the periodic table identified some surprising alloys that melt between 900 and 1000˚C , such as those containing refractory metals such as Nb and Ta (Tm for Nb = 2469˚C, Tm for Ta = 3020˚C)

- A new, computationally identified Ta-Ni-Si alloy was shown to have oxidation resistance superior to that BNi2 (one of the most oxidation resistant commercially available Ni superalloys).

- The Ellingham diagrams proved to be a reliable guide for identifying surface-forming oxides.

On going

- 25x25 combinations have been tested, more alloys systems and compositions will be tested.

Braze Alloy Design Criteria and Evaluation Methods

Design Parameter	Target Values	Justification	97.5Ag-2.5CuO Values
Liquidus Temperature (T_L)	900°C $\leq T_L \leq$ 1015°C	So the braze is solid during SOFC operation & does not alter the microstructure of previously made layers	**912°C**
Linear Coefficient of Thermal Expansion (CTE)	7 ppm/K ≤25-750°C CTE≤ 16 ppm/K	To prevent surface oxide spallation. 25-750°C YSZ CTE=9 ppm/K [11]. 25-750°C 441 Steel CTE=12ppm/K [11].	*~21 ppm/K [12]* *Non-passivating, spallation-prone CuO forms on the surface in air [13]*
Ductility	≥3%	So the braze can withstand YSZ-441 thermal expansion mismatch stress	**Sufficient [18], but unknown**
Vapor Pressure	750°C Vapor Pressure $<1\text{x}10^{-8}$ torr	To ensure that volatilization does not degrade the braze or the protective oxide	*Ag 750°C Vapor Pressure in Air = $1\text{x}10^{-5}$ torr [19]*

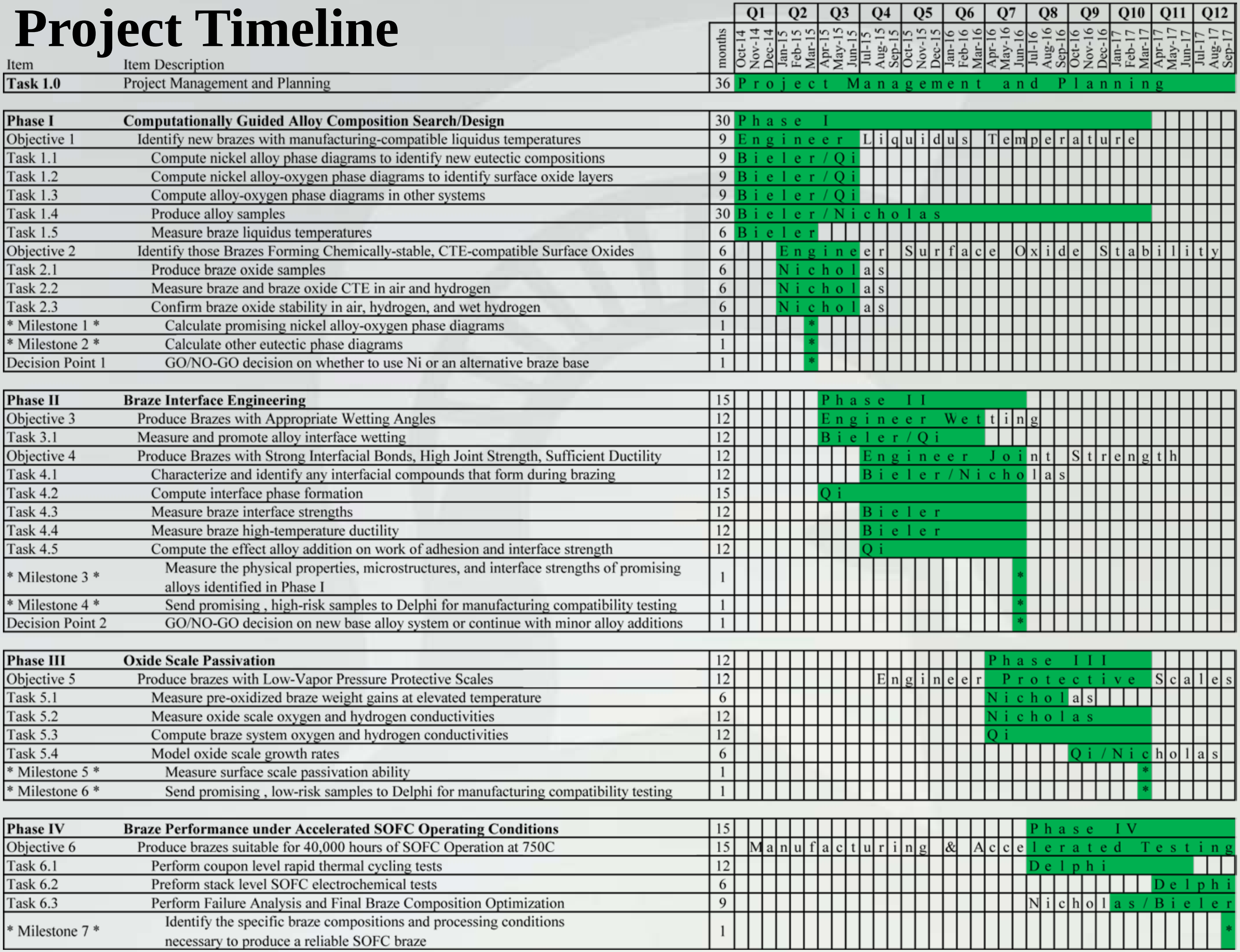
Braze Interface Design Criteria and Evaluation Methods

Design Parameter	Target Values	Justification	97.5Ag-2.5CuO Values
Wetting Angle (θ)	$0^{o} \leq \theta \leq 30^{\circ}$	To ensure that the braze spreads through the joint during manufacturing	*45^{o}[14]. Causes Type I pores to form in the braze*
Metallurgical Bonding with Al_2O_3	Interdiffusion or new phase formation	To promote good, active brazing with the Al_2O_3 coating on the ferritic stainless steel	**$CuAl_2O_4$[15] or $CuAlO_2$ [14]**
Metallurgical Bonding with YSZ	Interdiffusion or new phase formation	To promote good, active brazing with the YSZ	**Interdiffusion or a Y-Cu-O phase [16, 17]**
Braze Joint Strength (σ_B)	$\sigma_B > 120$ MPa	So the braze can accommodate YSZ-441 CTE mismatch stress	**220 MPa [14]**

Braze Oxide Design Criteria and Evaluation Methods

Design Parameter	Target Values	Justification	97.5Ag-2.5CuO Values
Alloy Oxygen and Hydrogen Conductivities ($\sigma_{O_2}, \sigma_{H_2}$)	$\sigma_{O_2} < 1\text{x}10^{-8}$ S/cm $\sigma_{H_2} < 1\text{x}10^{-8}$ S/cm	If no surface oxide forms, the braze should have a low oxygen conductivity to prevent Type III pores.	**Ag stable above 160°C in air [20]** *$\sigma_{O_2} = 2\text{x}10^{-4}$ S/cm at 750°C [8] promoting Type III pores [10].*
Braze Oxide Oxygen and Hydrogen Surface Exchange Coefficients (k_{O_2}, k_{H_2})	$k_{O_2} < 1\text{x}10^{-8}$ cm/sec $k_{H_2} < 1\text{x}10^{-8}$ cm/sec	If a surface oxide forms, the oxide should have a low oxygen surface exchange coefficient to prevent Type III pores and to ensure a ductile metal braze core remains.	*Only a reducible CuO scale is present above ~150°C*
Stability over 40,000 hours of SOFC Operation	Retention of all design parameter target values	To ensure reliable SOFC operation	*Does not last past 10,000 hours of SOFC operation [18]*

Project Timeline



			Q1			Q2			Q3			Q4			Q5			Q6			Q7			Q8			Q9			Q10			Q11			Q12		
Item	Item Description	months	Oct-14	Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	May-15	Jun-15	Jul-15	Aug-15	Sep-15	Oct-15	Nov-15	Dec-15	Jan-16	Feb-16	Mar-16	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Oct-16	Nov-16	Dec-16	Jan-17	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17	Sep-17
Task 1.0	Project Management and Planning	36	Project Management and Planning	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Phase I	**Computationally Guided Alloy Composition Search/Design**	30	Phase I	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
Objective 1	Identify new brazes with manufacturing-compatible liquidus temperatures	9	Engineer Liquidus Temperature	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																											
Task 1.1	Compute nickel alloy phase diagrams to identify new eutectic compositions	9	Bieler/Qi	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																											
Task 1.2	Compute nickel alloy-oxygen phase diagrams to identify surface oxide layers	9	Bieler/Qi	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																											
Task 1.3	Compute alloy-oxygen phase diagrams in other systems	9	Bieler/Qi	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																											
Task 1.4	Produce alloy samples	30	Bieler/Nicholas	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
Task 1.5	Measure braze liquidus temperatures	6	Bieler	🟩	🟩	🟩	🟩	🟩																														
Objective 2	Identify those Brazes Forming Chemically-stable, CTE-compatible Surface Oxides	6				Engineer Surface Oxide Stability	🟩	🟩	🟩	🟩	🟩																											
Task 2.1	Produce braze oxide samples	6				Nicholas	🟩	🟩	🟩	🟩	🟩																											
Task 2.2	Measure braze and braze oxide CTE in air and hydrogen	6				Nicholas	🟩	🟩	🟩	🟩	🟩																											
Task 2.3	Confirm braze oxide stability in air, hydrogen, and wet hydrogen	6				Nicholas	🟩	🟩	🟩	🟩	🟩																											
* Milestone 1 *	Calculate promising nickel alloy-oxygen phase diagrams	1						*																														
* Milestone 2 *	Calculate other eutectic phase diagrams	1						*																														
Decision Point 1	GO/NO-GO decision on whether to use Ni or an alternative braze base	1						*																														
Phase II	**Braze Interface Engineering**	15							Phase II	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩															
Objective 3	Produce Brazes with Appropriate Wetting Angles	12							Engineer Wetting	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																		
Task 3.1	Measure and promote alloy interface wetting	12							Bieler/Qi	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																		
Objective 4	Produce Brazes with Strong Interfacial Bonds, High Joint Strength, Sufficient Ductility	12										Engineer Joint Strength	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩															
Task 4.1	Characterize and identify any interfacial compounds that form during brazing	12										Bieler/Nicholas	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩															
Task 4.2	Compute interface phase formation	15							Qi	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩															
Task 4.3	Measure braze interface strengths	12										Bieler	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩															
Task 4.4	Measure braze high-temperature ductility	12										Bieler	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩															
Task 4.5	Compute the effect alloy addition on work of adhesion and interface strength	12										Qi	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩															
* Milestone 3 *	Measure the physical properties, microstructures, and interface strengths of promising alloys identified in Phase I	1																					*															
* Milestone 4 *	Send promising , high-risk samples to Delphi for manufacturing compatibility testing	1																					*															
Decision Point 2	GO/NO-GO decision on new base alloy system or continue with minor alloy additions	1																					*															
Phase III	**Oxide Scale Passivation**	12																			Phase III	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
Objective 5	Produce brazes with Low-Vapor Pressure Protective Scales	12											Engineer Protective Scales								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
Task 5.1	Measure pre-oxidized braze weight gains at elevated temperature	6																			Nicholas	🟩	🟩	🟩	🟩	🟩												
Task 5.2	Measure oxide scale oxygen and hydrogen conductivities	12																			Nicholas	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
Task 5.3	Compute braze system oxygen and hydrogen conductivities	12																			Qi	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
Task 5.4	Model oxide scale growth rates	6																									Qi/Nicholas	🟩	🟩	🟩	🟩	🟩						
* Milestone 5 *	Measure surface scale passivation ability	1																														*						
* Milestone 6 *	Send promising , low-risk samples to Delphi for manufacturing compatibility testing	1																														*						
Phase IV	**Braze Performance under Accelerated SOFC Operating Conditions**	15																						Phase IV	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Objective 6	Produce brazes suitable for 40,000 hours of SOFC Operation at 750C	15		Manufacturing & Accelerated Testing																				🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Task 6.1	Perform coupon level rapid thermal cycling tests	12																						Delphi	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩			
Task 6.2	Preform stack level SOFC electrochemical tests	6																															Delphi	🟩	🟩	🟩	🟩	🟩
Task 6.3	Perform Failure Analysis and Final Braze Composition Optimization	9																						Nicholas/Bieler						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
* Milestone 7 *	Identify the specific braze compositions and processing conditions necessary to produce a reliable SOFC braze	1																																				*

Questions?

Thanks for your Attention!