Technical Qualification of New Materials for High Efficiency Coal-Fired Boilers and Other Advanced FE Concepts (aka Haynes® 282® code case) FEAA117 (April 2015 – 12/2019?)

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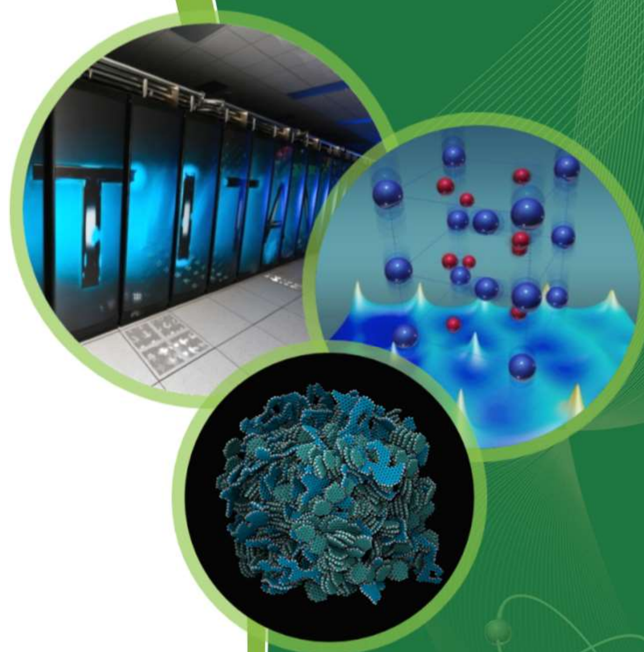

Presentation for 2018 Crosscutting Research Project Review Meeting
April 12, 2018

Acknowledgments

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  - Jessica Robertson, Mike Katcher, Vinay Deodeshmukh
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- Funding from DOE Crosscutting Research Program
  - Support of ComTest/Energy Industries of Ohio
- Legacy funding from DOE EERE (AMO) ARRA (stimulus) funding
  - 24 creep frames rebuilt for CF8C-Plus ASME BPV Code Case

The goal is to code qualify Haynes 282 for A-USC & more

- Objective
  - With Haynes International, deploy Ni-base alloy Haynes® 282® for applications in superheaters, reheaters, and steam delivery pipes, by completing base metal and cross-weld mechanical testing needed for an ASME Boiler and Pressure Vessel Code Case and the associated microstructural analyses needed for assurance of boiler-relevant lifetimes
- Milestones
  - Complete tensile testing of 3 commercial 282 heats (completed 6/30/16)
  - Complete 100,000 h of creep testing (cumulative) (completed 7/31/16)
  - Complete report compiling all 282 tensile and creep results (complete 1/2017)
  - Complete 250,000 h of creep testing (cumulative) (complete 9/2017).
  - Complete all tensile testing on cross-weld specimens (completed 3/31/18).
  - Complete 400,000 h of creep testing (cumulative) (delayed, 6/2018).
  - Complete all base metal creep testing (9/30/18)

Haynes® 282® began full scale production in 2005

- 60 full-scale heats produced in numerous product forms
  - Sheet (0.3-3 mm), plate (4-54 mm), bar, wire, billet and tube
- Largest ingot 20” diameter VIM+ESR
- Produced 225 metric tons (½ million lbs.) ship weight by 2017
- Many aircraft and land based gas turbine engine builders testing worldwide. Applications include combustor rings, combustor liners, turbine cases, fuel nozzles, turbine exhaust cases, exhaust guide vane assemblies, fasteners, sheet and plate fabrications for LBGT hot gas path
- Other markets in test: automotive turbochargers, metallic thermal protection, ultra-supercritical power boilers and steam turbines, etc.

Many commercial developments achieved

- SAE-AMS 5951 specification issued for sheet and plate
- UNS N07208 assigned
- Many evaluations underway worldwide for aero engine and land based gas turbine components
- Selected specific applications
  - Multi-year contract for PW1000 geared turbofan aero engine
  - APU components for the new Airbus A350XWB
  - helicopter gas turbine exhaust guide vane assembly
- Casting developments underway by several alloy foundries

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282 has a unique combination of strength and fabricability

- **Superior creep strength due to:**
  - ✓ Controlled amounts of gamma-prime (γ') forming elements
  - ✓ Controlled amounts of solid solution strengthening elements
- **Superior fabricability due to:**
  - ✓ Relatively low equilibrium γ' volume fraction resulting in slower γ' precipitation kinetics.
  - ✓ Typical issues:
    - Poor hot workability: limited T range due to γ' formation
    - Poor cold formability: insufficient cooling rate from anneal
    - Poor weldability: strain age cracking

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Composition of Several Haynes Gamma-Prime (γ') Strengthened Alloys

Alloy	Ni	Fe	Co	Cr	Mo	Al	Ti	C	γ'
263 alloy	Bal.	0.7*	20	20	6	0.6*	2.4*	0.06*	12
282 alloy	**Bal.**	**1.5***	**10**	**19**	**8.5**	**1.5**	**2.1**	**0.06**	**19**
R-41 alloy	Bal.	5*	11	19	10	1.5	3.1	0.09	24
Waspaloy alloy	Bal.	2*	13.5	19	4.3	1.5	3.0	0.08	27

*maximum

all values are in wt.%

282® alloy has a higher level of solid-solution strengthener (Mo) than Waspaloy or 263 alloy

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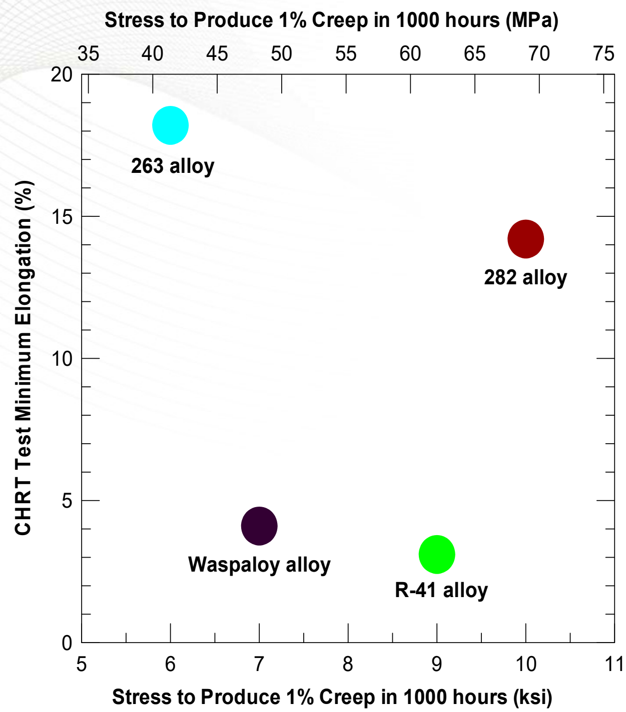
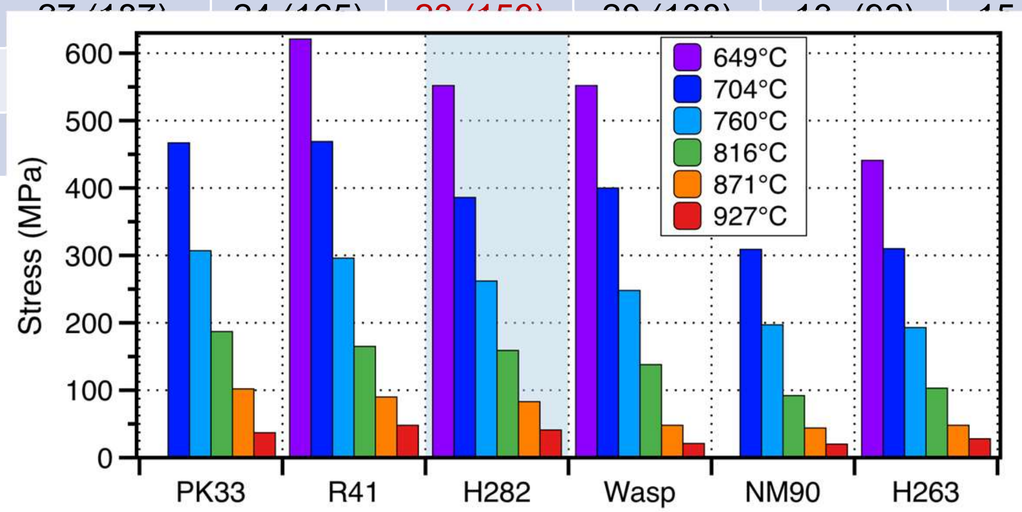
282 has a unique combination of strength and fabricability



Stress-to-Produce Rupture in 1000 h
ksi (MPa)

Temperature °F (°C)	PK-33 Alloy	R41 Alloy	282 Alloy	Waspaloy	90 Alloy	263 Alloy
1200 (649)	-	90 (621)	80 (552)	80 (552)	-	64 (441)
1300 (704)	68 (467)	68 (469)	56 (386)	58 (400)	45 (309)	45 (310)
1400 (760)	45 (307)	43 (296)	38 (262)	36 (248)	29 (197)	28 (193)
1500 (816)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	(103)
1600 (871)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	(48)
1700 (927)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	(28)



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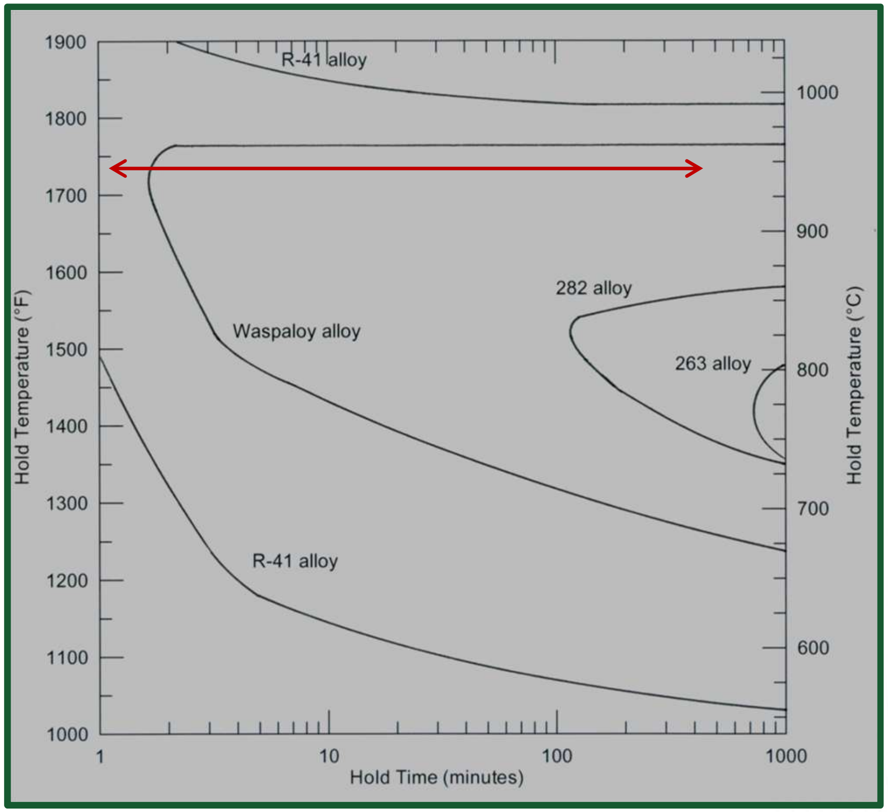
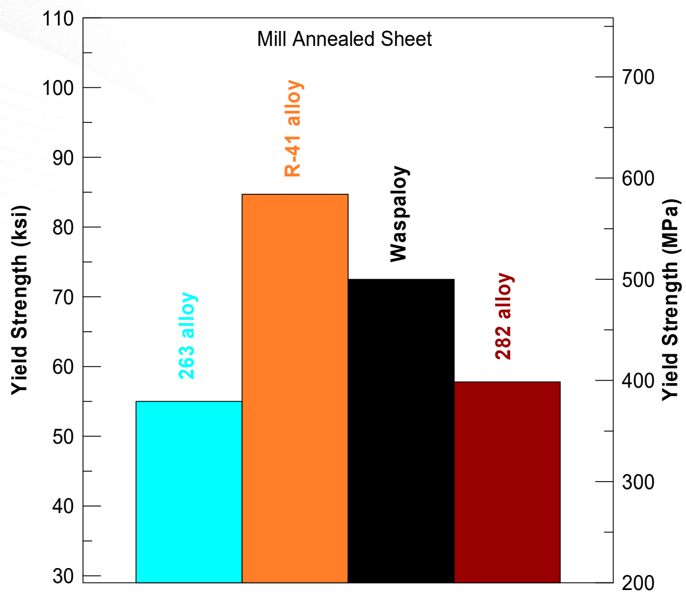
Comparative T-T-H Curves (R_c = 30)



282® alloy hot working range = 1750 - 2150°F (954 - 1177°C)

282® alloy offers an extended hot working range due to slower formation of gamma-prime (γ’) versus Waspaloy or R-41 alloy

282 fabricability due to low as-annealed strength



Mill annealed properties

Form	Hard-ness	Yield Strength		Ultimate Tensile Strength		Elong.
		ksi	MPa	ksi	MPa	%
Sheet	91 Rb	58	398	122	838	56
Plate	94 Rb	57	394	121	831	57

- **282 has low strength in the annealed condition (very little γ' present)**
- **Low strength in the annealed condition is desirable for good formability**

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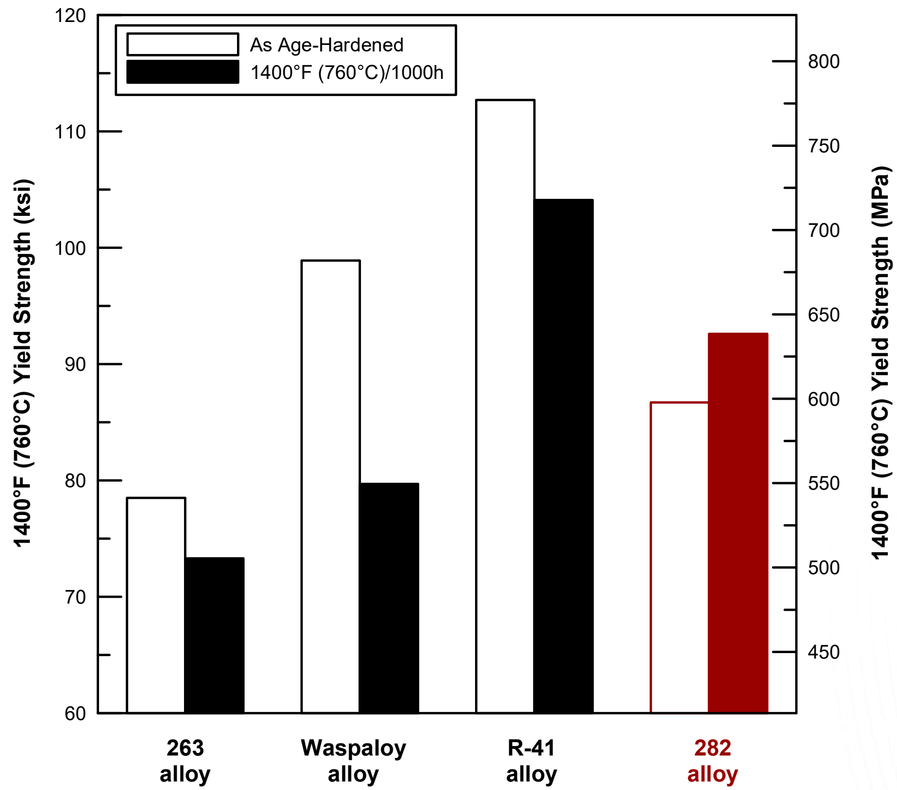
Excellent Retained Strength after Thermal Exposure



Only 282 was found to increase in strength after 1000 h thermal exposure at 1400° F (760° C)

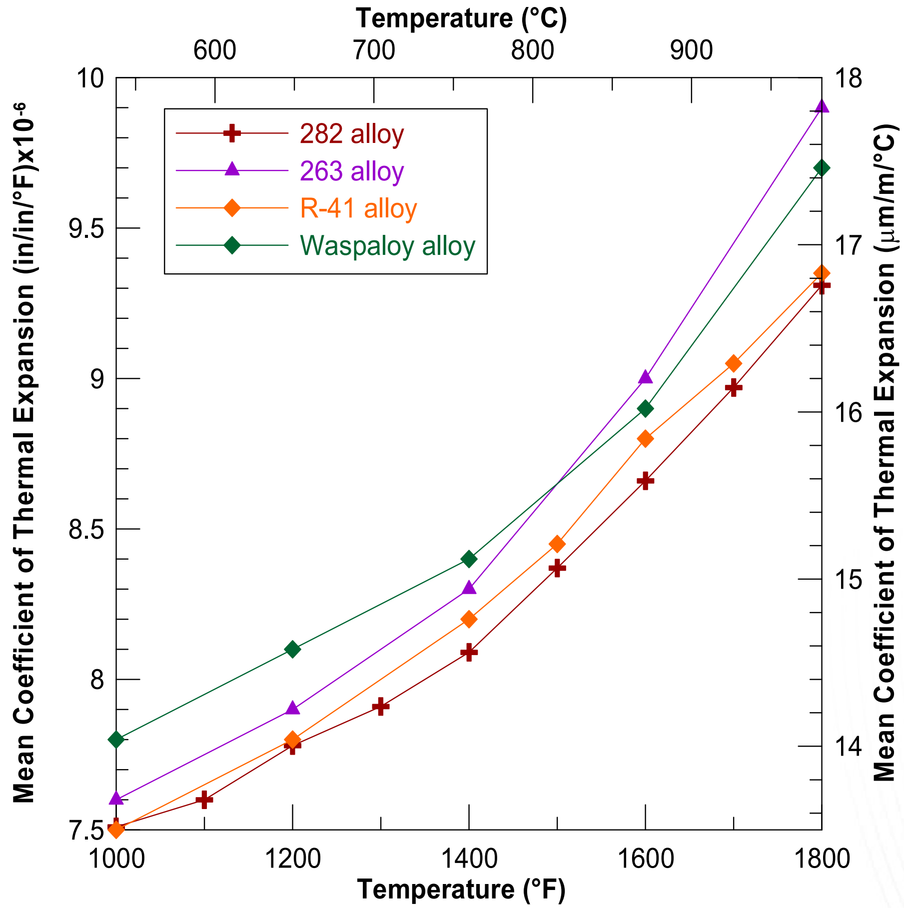
282 also retains high room temperature ductility compared to other gamma-prime (γ') alloys

Thermal Exposure: 1600°F (871°C) for 1000 h

Alloy	RT Tensile Ductility (% elongation to failure)	
	As-Age Hardened*	Age-Hardened* + Thermal Exposure
263	36	41
282	**30**	**23**
Waspaloy	27	13
R-41	22	3

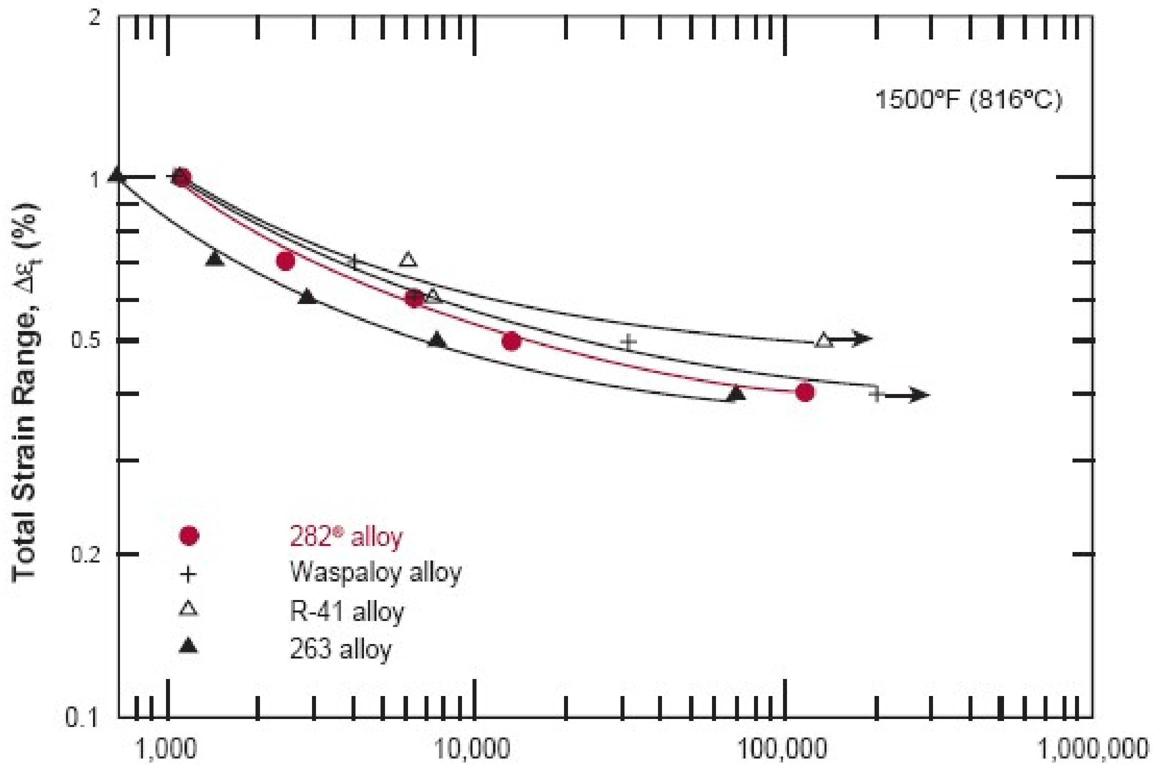
*Age Hardening Treatment: 1850°F (1010°C)/2h/AC + 1450°F (778°C)/8h/AC

282 has lower coefficient of thermal expansion



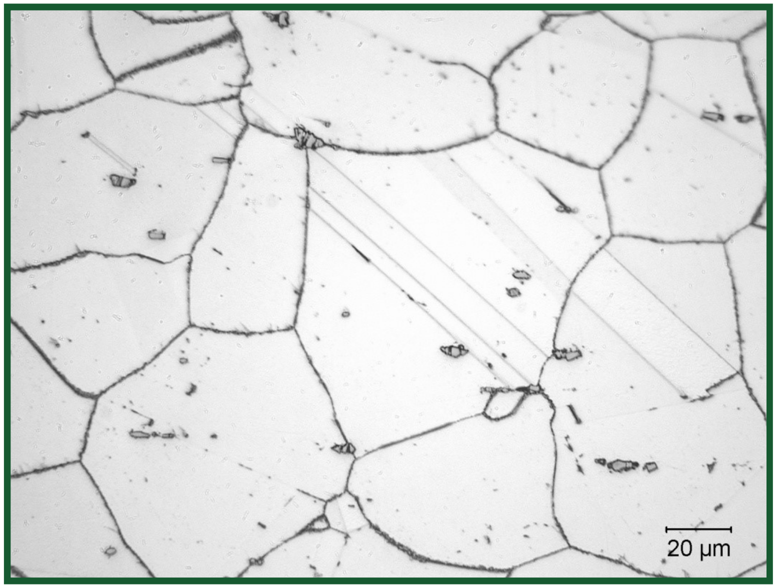
Lower CTE is beneficial for thermal fatigue resistance

282 has comparable low-cycle fatigue life



- LCF resistance of 282 alloy is superior to 263 alloy
- At high strain ranges 282 has similar LCF resistance as Waspaloy and R-41

Example 282 Microstructure in Age Hardened Condition



- Annealing range: 2025 to 2100°F (1107 to 1149°C)
- Age-hardening heat treatment:

  1850°F (1010°C)/2h/AC + 1450°F (788°C)/8h/AC
- Typical grain size: ASTM 4-4½

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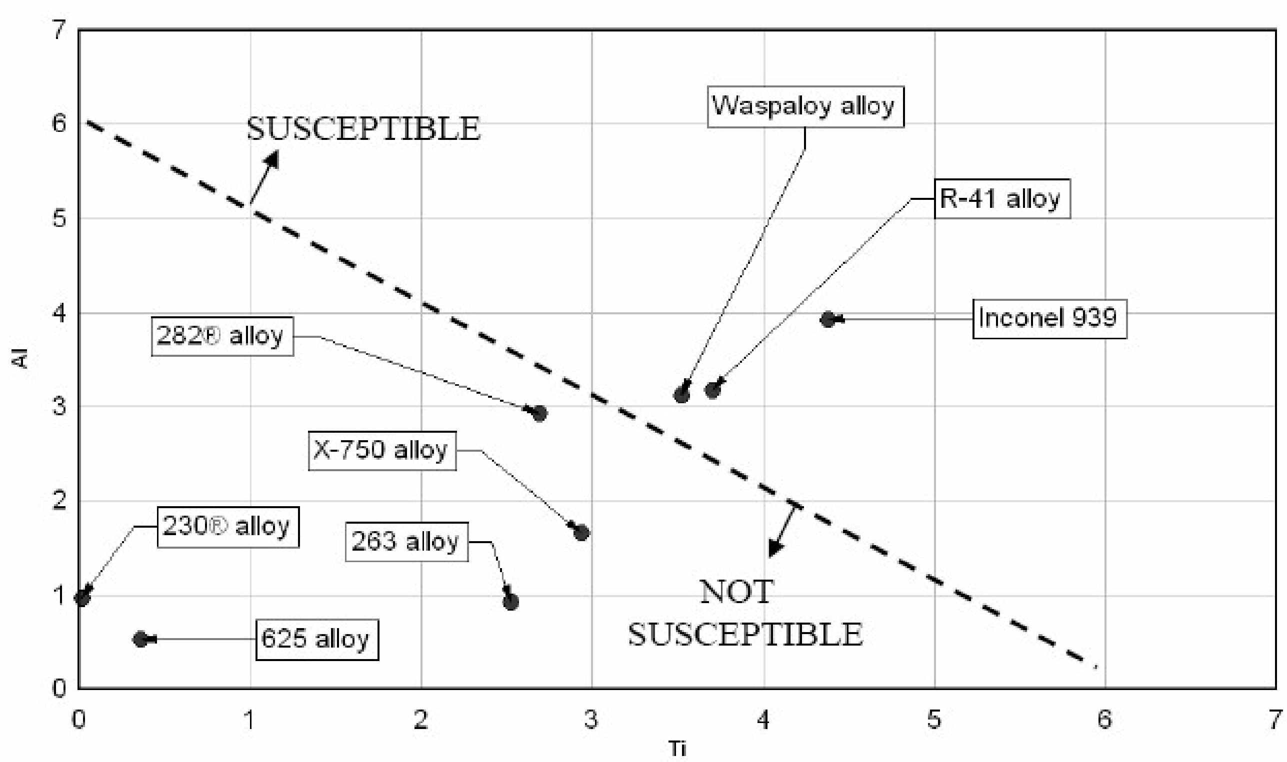
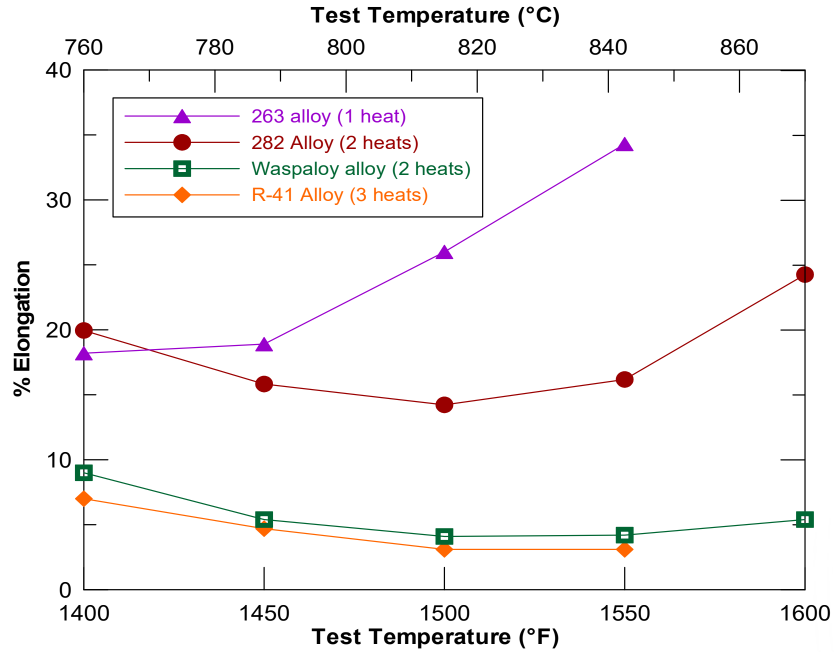
Composition suggests strain-age cracking resistance



Prager & Shira plot (PS Plot) showing susceptibility of nickel based superalloys to strain age cracking / fabrication & weldability problems.

282 has good resistance to strain-age cracking

Controlled heating-rate tensile test



- **The relatively low γ´ volume fraction in 282 results in improved resistance to strain-age cracking**
- **282 approaches the strain-age cracking resistance of 263 alloy and possesses much higher resistance than Waspaloy and R-41 alloys**

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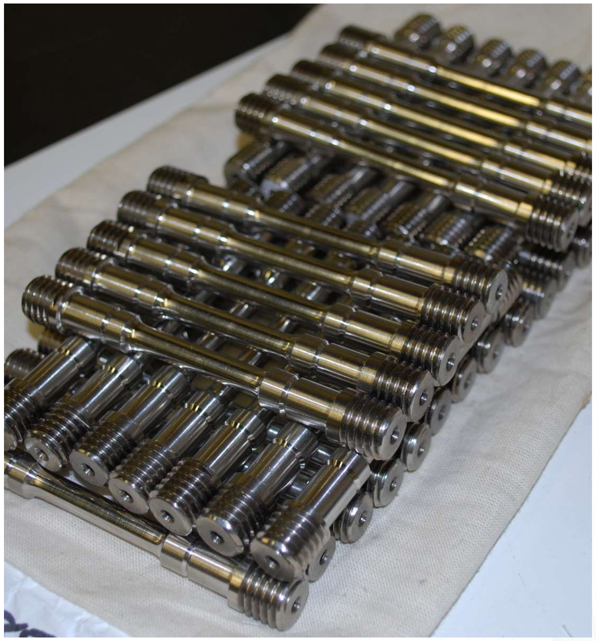
Haynes 282 code case project started in FY15

- Project kicked off April 1, 2015
  - 26,500 h ago
- Creep frames inherited from 2009 ARRA project to deploy CF8C-Plus
  - $600,000 investment in 24 frames (16 with DAQ)
- All 282 specimens supplied to ORNL
  - Part of Haynes International cost share
  - Single age heat treatment (4h at 800°C)
  - Three base metal heats (~60 each)
  - GTA and GMAW cross-weld specimens
  - All weld metal specimens
    - Necessary to use 282 weld wire
- 11 creep tests started by December 2015
  - New grips machined for 282 creep tests
  - Matrix 1100°-1700°F (927°C)
    - 8 frames upgraded to type S TC (Pt/PtRh)
  - Four frames added DAQ
    - Minimum creep rate desired on all creep tests



~525,000 h of creep testing needed on three heats and weld specimens

°F	°C	500h	1400h	4000h	10,000h
1100	593	all	all	all	all
1150	621	1 heat		1 heat	
1200	649	all	all	all	all
1250	677	1 heat		1 heat	
1300	704	all	all	all	all
1350	732	1 heat		1 heat	
1400	760	all	all	all	all
1450	788	1 heat		1 heat	
1500	816	all	all	all	all
1550	843	1 heat		1 heat	
1600	871	all	all	all	all
1650	899	1 heat		1 heat	
1700	927	all	all	all	all

+ one 30,000 h test

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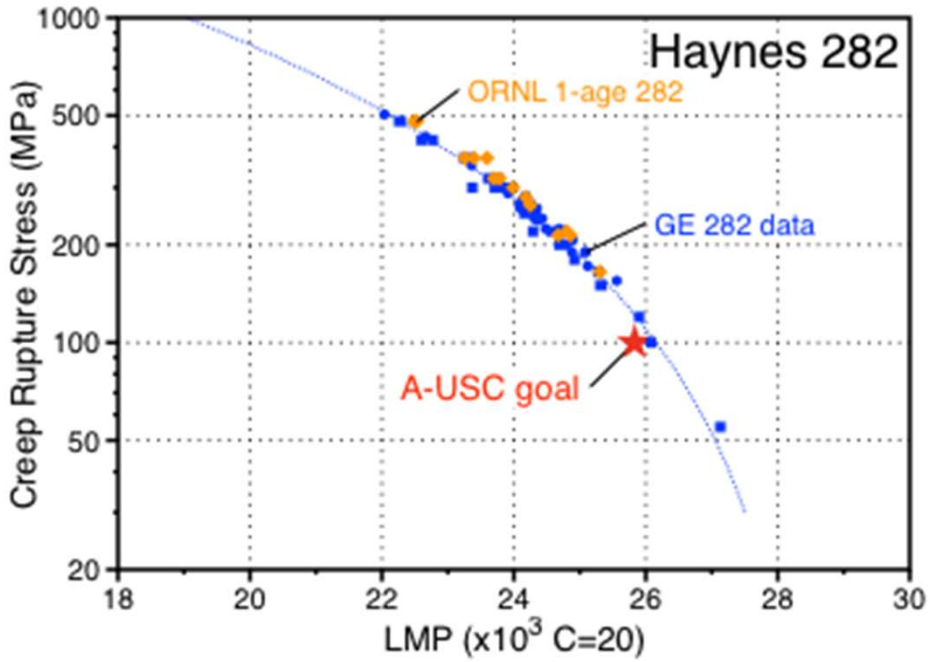
Less creep testing required on GTA + GMAW specimens and only rupture time (use frames without DAQ)

°F	°C	1,000h	2,500h	4,500h	6,000h
1100	593	all	all	all	all
1150	621				
1200	649				
1250	677				
1300	704	all	all	all	all
1350	732				
1400	760				
1450	788				
1500	816	all	all	all	all
1550	843				
1600	871				
1650	899				
1700	927	all	all	all	all

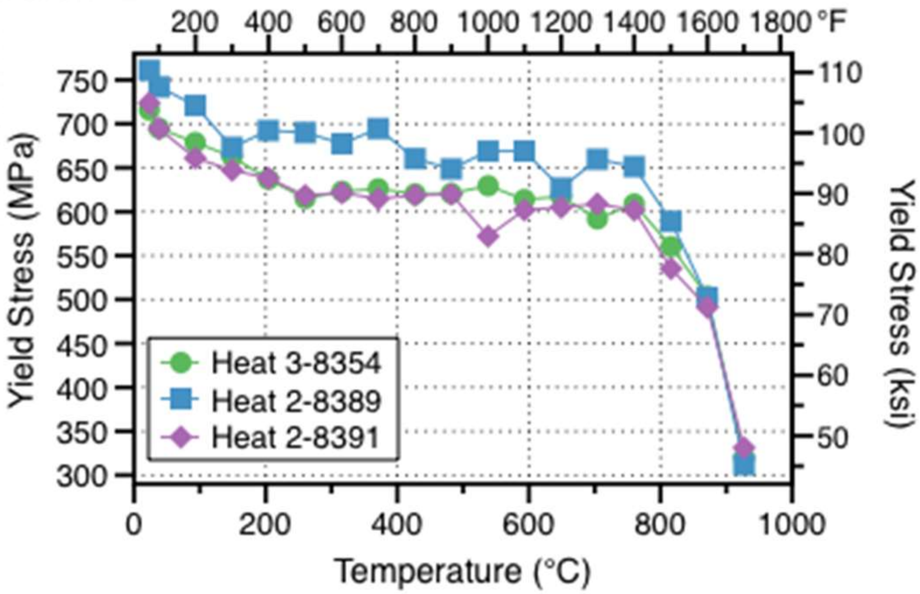
Only 8 all weld-metal tests required

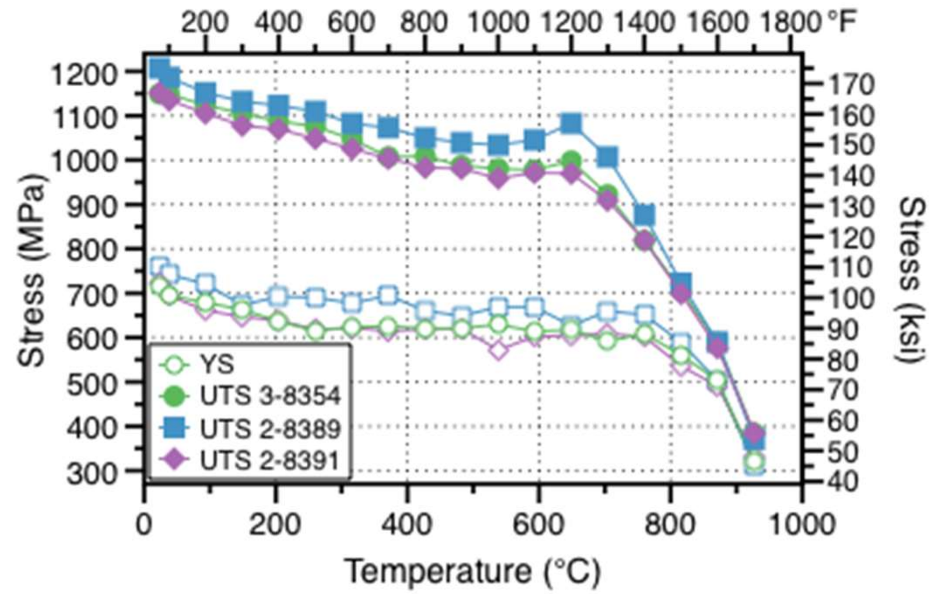
Prior double-aged 282 creep data was not applicable

- Single-aged treatment preferred by boiler community
  - 4h at 800°C selected
- Some data were available from ORNL and GE
  - Some just rupture time
- Decision was made to start over with new test matrix to 927°C (1700°F)
  - Allow use to 871°C (1600°F)



Base metal tensile testing finished in 2016





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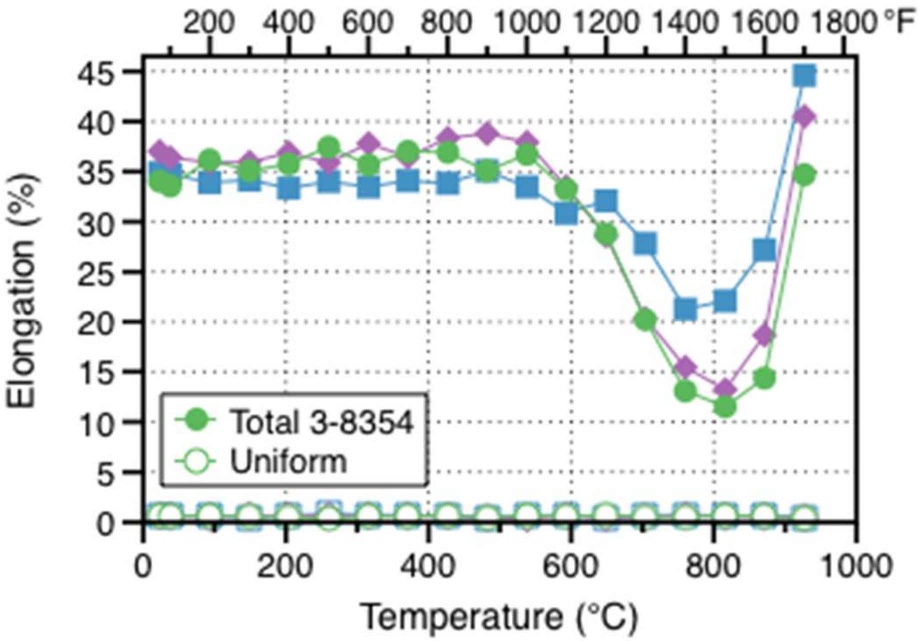
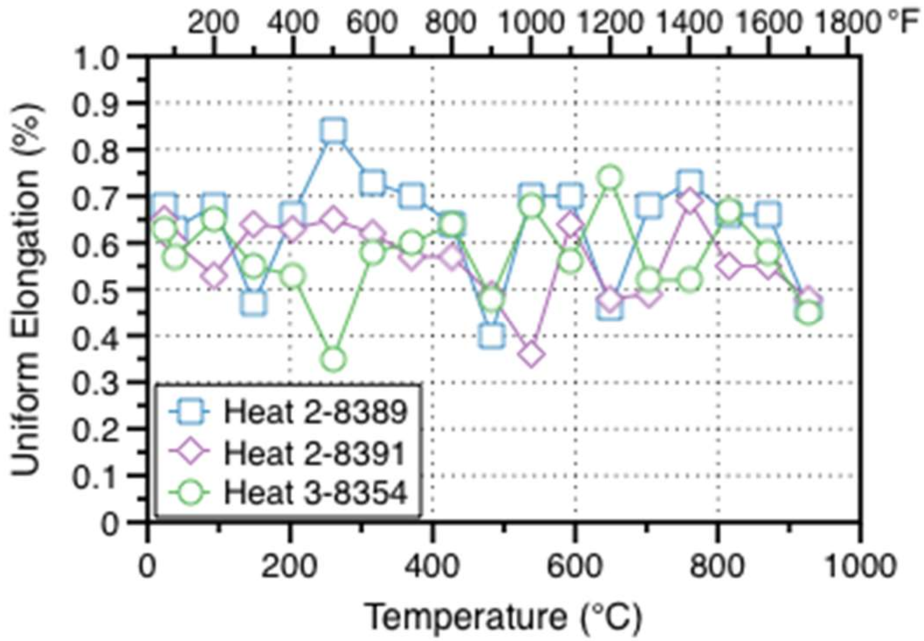
Base metal tensile testing finished in 2016





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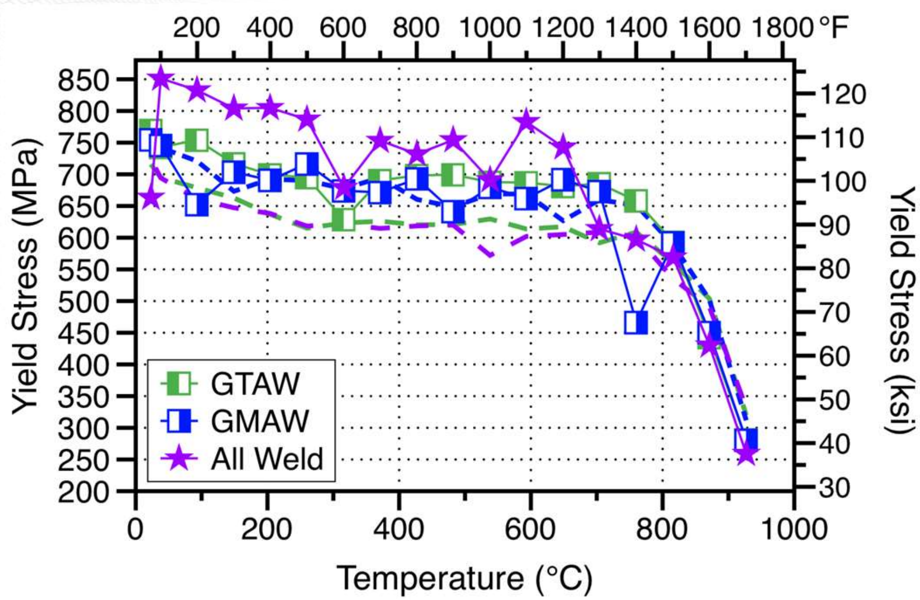
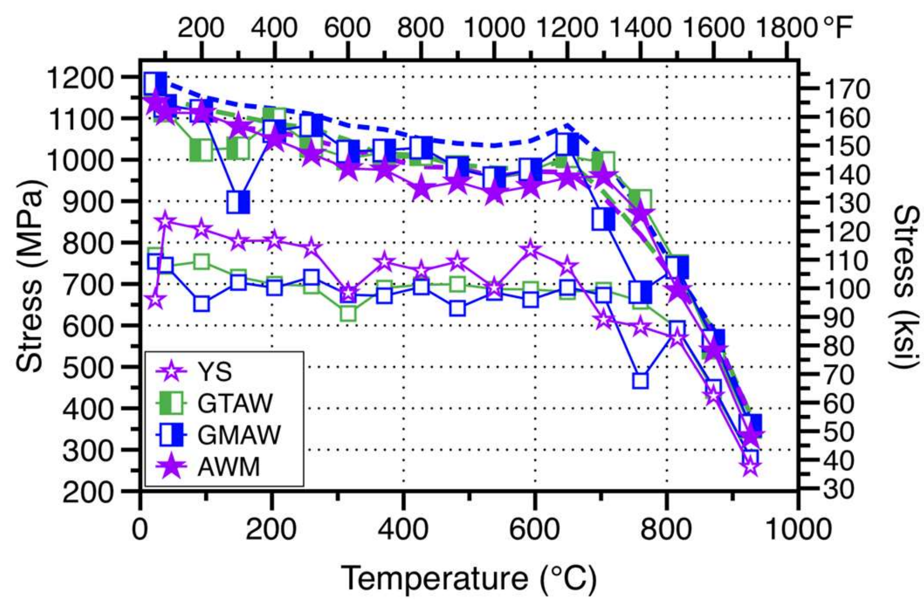
Yield and ultimate stress: similar for weld specimens

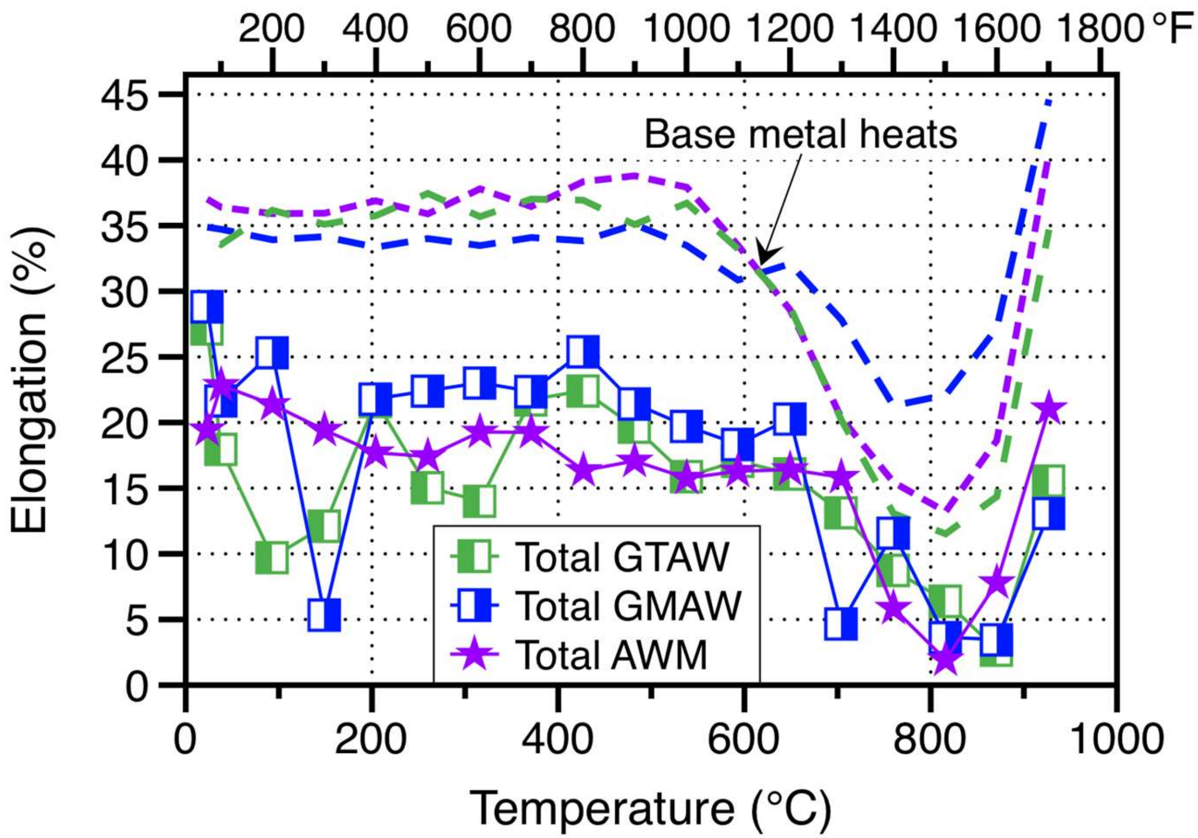




GTAW 538°C (1000°F)

GMAW 149°C (300°F)

Total elongation lower for cross-weld and all weld specimens



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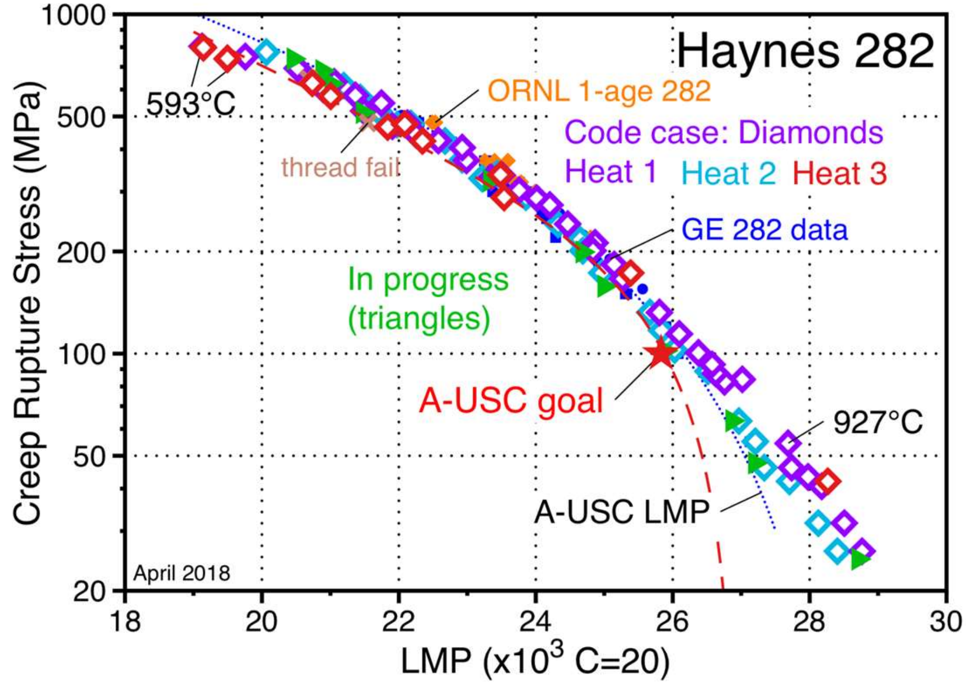
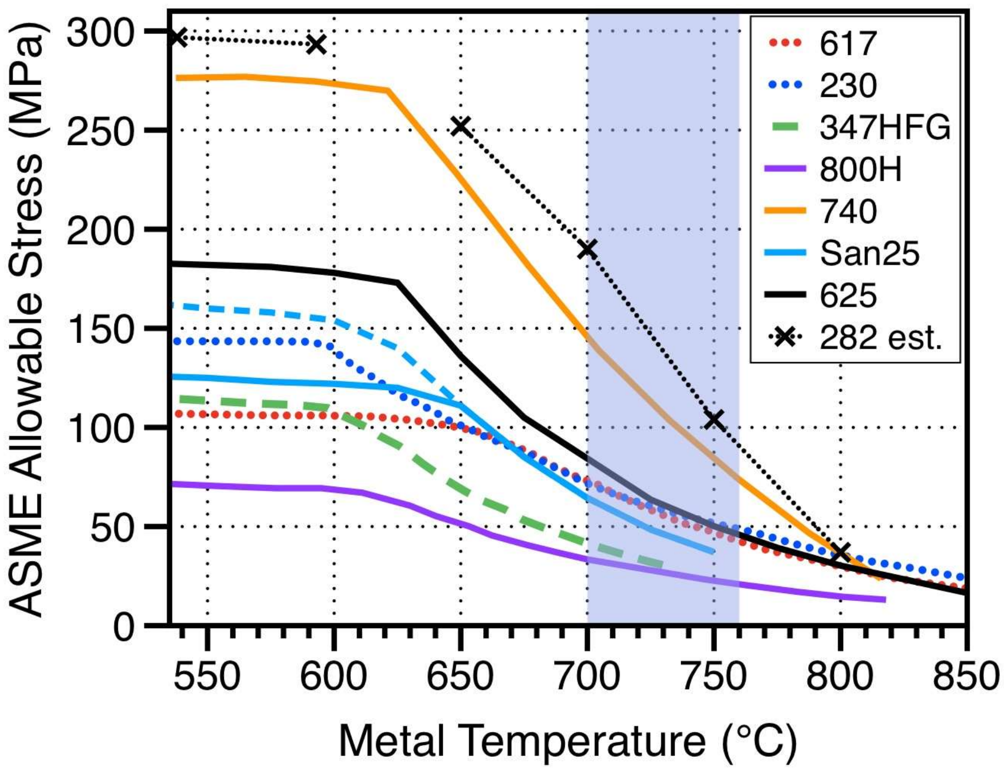
Project continues to progress after 36+ months

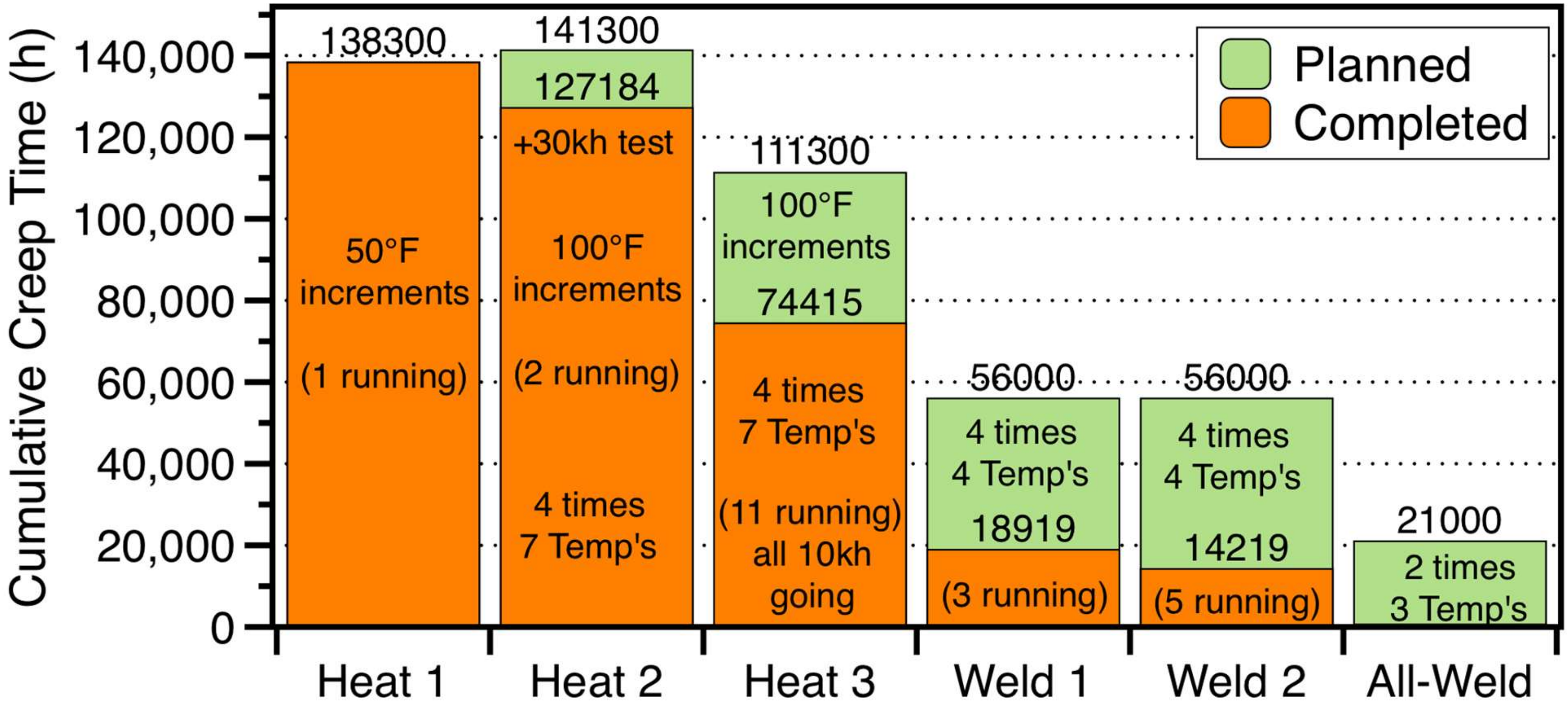
- Primarily base metal tested
  - Weld specimens filling open frames
- 108 tests started
  - 89 failed (3 in threads)
  - 19 in progress
  - >373,000 h completed
  - 71% complete
    - Heat 1 is 99% complete (39 of 40 done)
    - Heat 2 is 90% complete (27 of 29 done)
- Weldments only need rupture time
  - Using 4 frames without DAQ
  - Only 6 failures to date



Estimates of 282 stress allowables are being generated



Project is 71% complete, 34 creep tests remain to start



3 x 6,000h tests remain to start
6 x 4500 h tests remain to start

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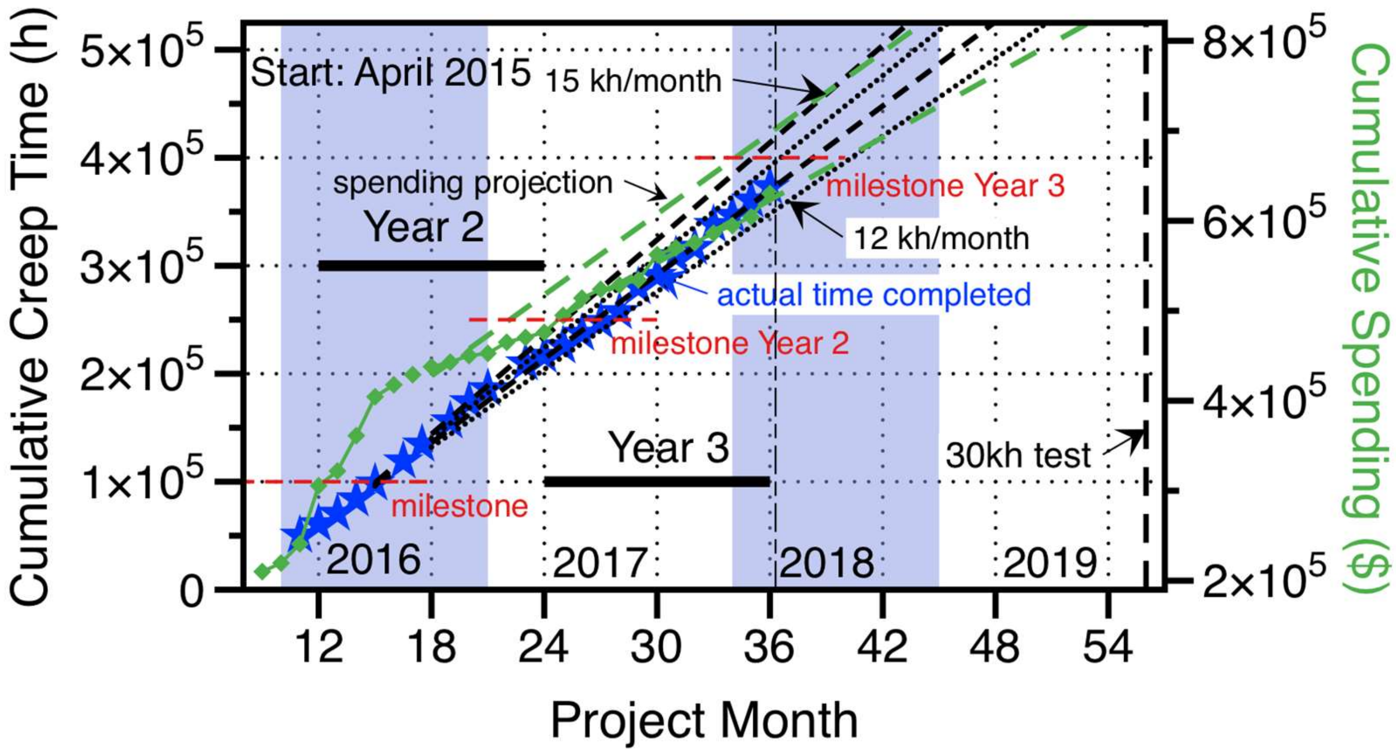
Most creep testing will be complete by early 2019



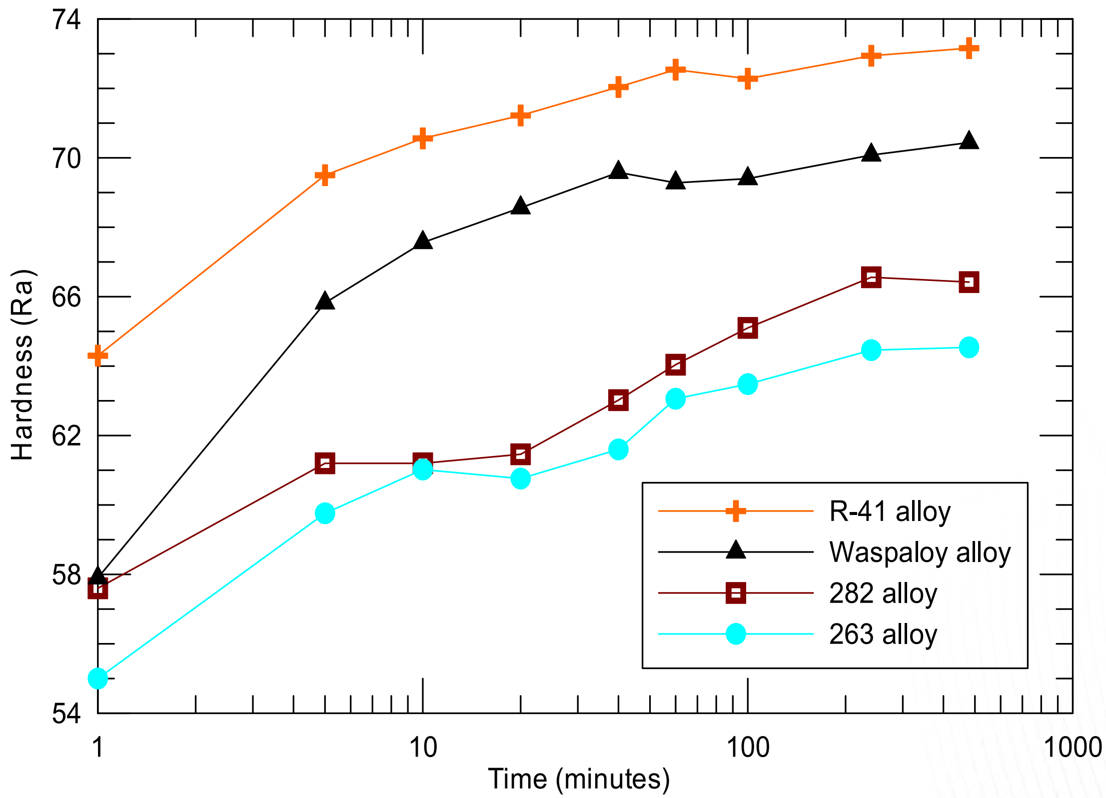
30,000 h test not scheduled to fail until late 2019
Highly dependent on productivity and tests not running long (2 now over time)
Spending going well

About 1 year away from project completion

- Project is on-budget and on-schedule for 2019 completion
  - Averaged >13,000 h of creep testing/month in past 12 months
  - Trying to keep at least 20 frames running with minimal down time
  - Should complete cumulative 400,000 h creep milestone in ~2 months
- Tensile testing of cross-weld and all weld metal specimens were completed recently
- Haynes International will assemble data for ASME review
- If budget allows, crept microstructure will be characterized

Backup slides

Aging Kinetics at 1500°F (816°C)



282® alloy does not require rapid cooling rates after annealing due to slower formation of gamma-prime (γ’) versus Waspaloy or R-41

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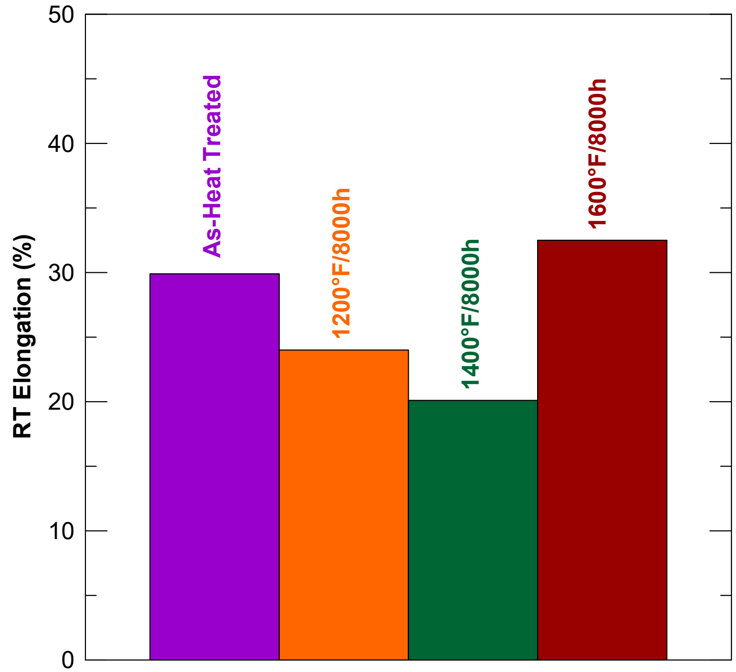
Conclusions about Haynes 282

- HAYNES® 282® alloy offers the unique combination of high creep strength to 871°C/1600°F and fabricability
  - Better creep strength than Waspaloy, almost as good as René 41
  - Better fatigue resistance than alloy 263
  - Higher temperature capability than 718 or 718 Plus
  - Easier to fabricate than Waspaloy or René 41
- Excellent thermal stability and low thermal expansion
- Easy availability in a broad variety of product forms and sizes

Effect of Thermal Exposure on the Room-Temperature Ductility of HAYNES 282 Alloy



The ductility of 282 alloy remains greater than 20% even after thermal exposures as long as 16,000 hours

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