Modeling Creep-Fatigue-Environment Interactions in Steam Turbine Rotor Materials for Advanced Ultrasupercritical Coal Power Plants

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imagination at work

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High temperature rotor application

HP/RHT Rotor

- High temperature steam
- High stress concentration at bucket connection

→ Creep-fatigue-environment interaction

- **DOE's goal: A-USC 1400F capability (5000 psi steam, 20+years)**
- **Candidate alloy: 282**

Overall goal and tasks of the program

Creep-fatigue-environment interactions of Alloy 282

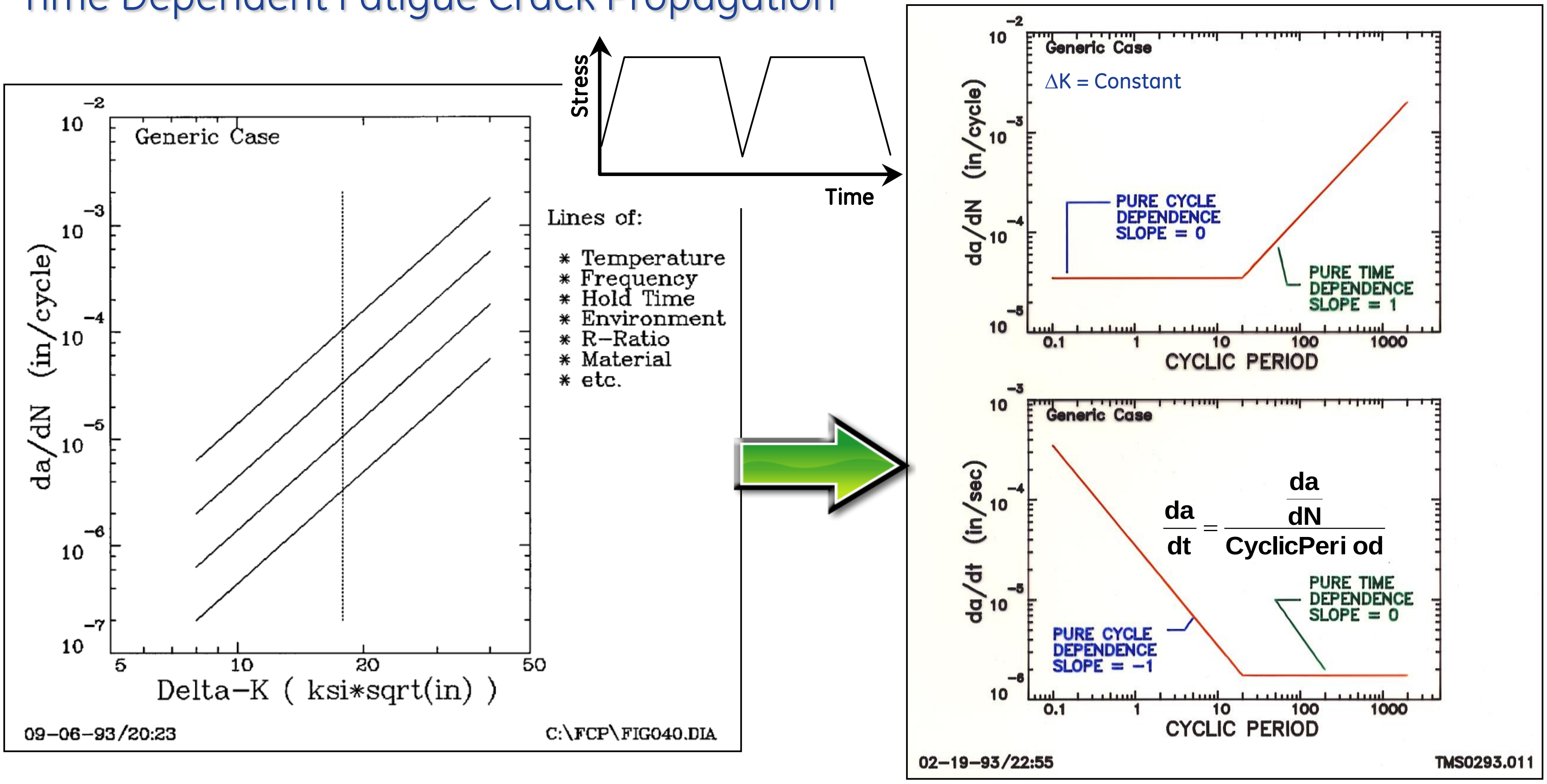
- Fatigue performance in steam and air environment
  - Hold-time fatigue experiment (Task 2)
  - Hold-time fatigue FEM modeling (Task 6)
  - Fundamental understanding at crack tip (Task 2,3)
- Creep performance
  - Creep modeling & prediction (Task 5)
  - Long-term microstructure stability & interaction with defects (Task 4)

Tasks of the program

Creep-fatigue-environment interactions of Alloy 282

- Fatigue performance in steam and air environment
  - **Hold-time fatigue experiment (Task 2)**
    - **Establish relationship between crack growth and LCF for Alloy 282**
    - **Predict LCF behaviors in steam and air**
  - Hold-time fatigue FEM modeling (Task 6)
  - Fundamental understanding at crack tip (Task 2,3)
- Creep performance
  - Creep modeling & prediction (Task 5)
  - Long-term microstructure stability & interaction with defects (Task 4)

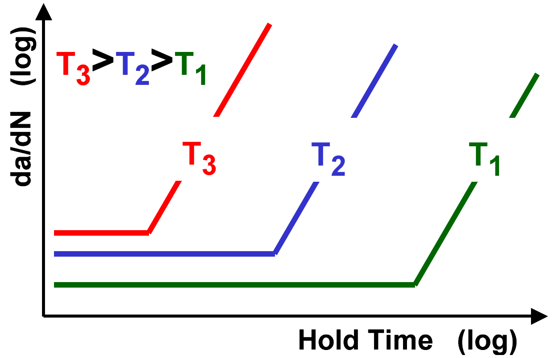
Time Dependent Fatigue Crack Propagation



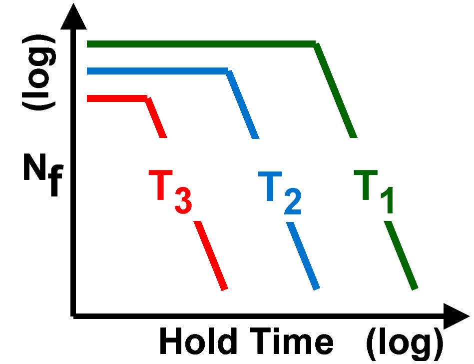
Hold time fatigue can generally be categorized into cycle dependent behavior, time dependent behavior, and in some cases, a combination of the two

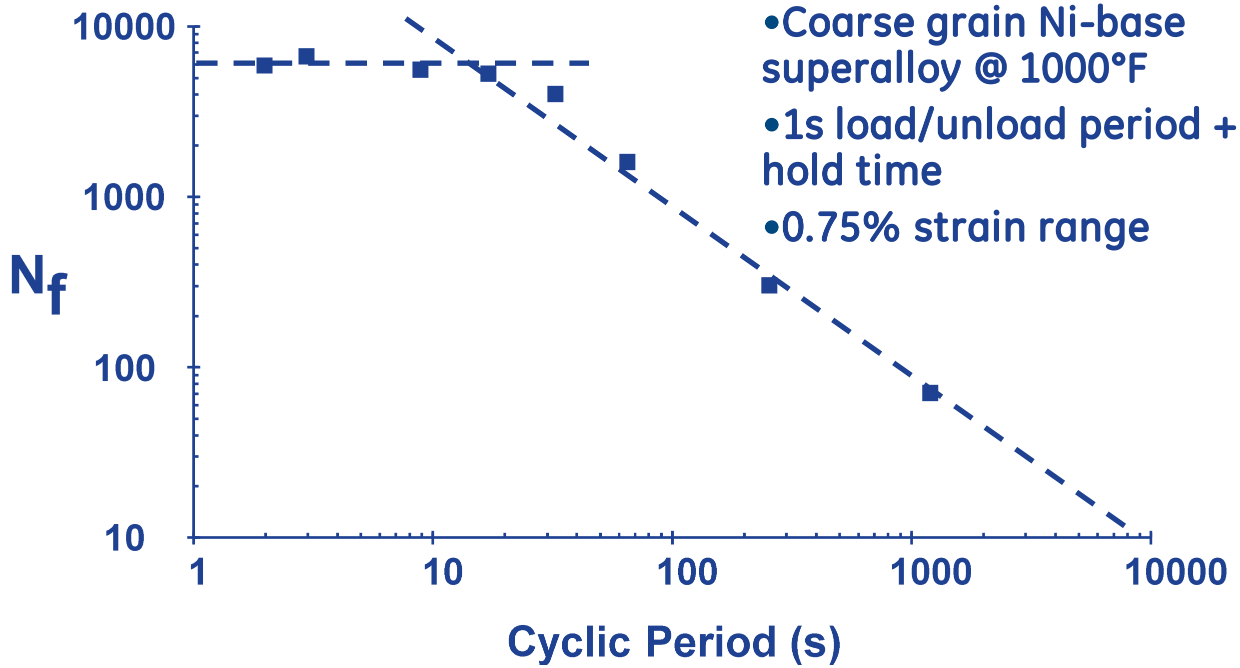
Time-Dependent LCF

If we have crack growth data like this:



Then we expect LCF data to be:





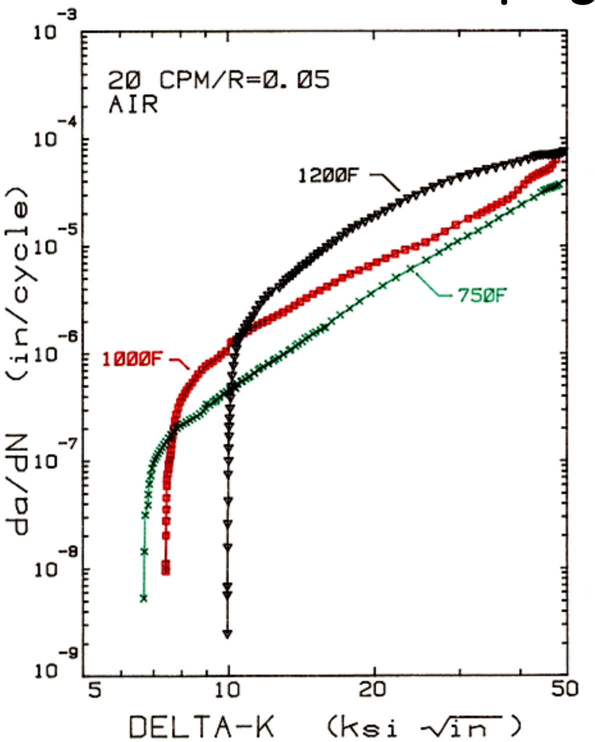
- Coarse grain Ni-base superalloy @ 1000°F
- 1s load/unload period + hold time
- 0.75% strain range

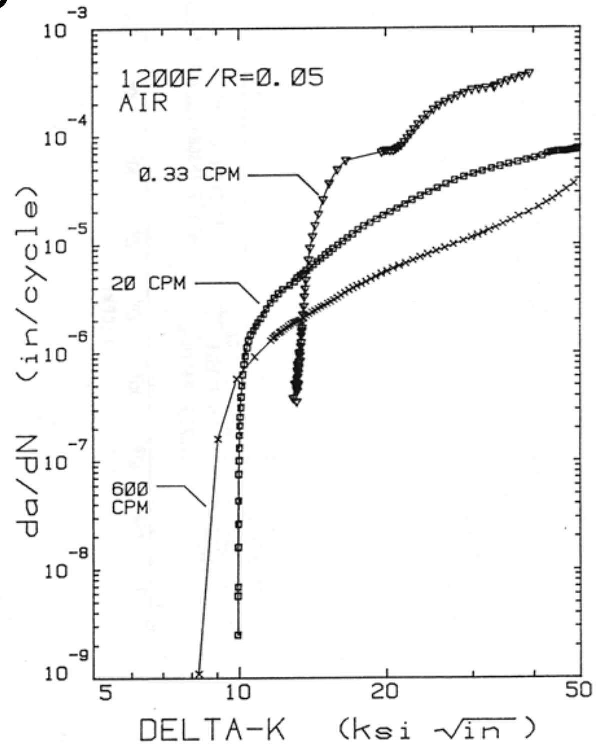
Hold-time effect can manifest itself in LCF as well

imagination at

Time Dependent Fatigue Model: Detailed Approach

Crack Propagation Behavior





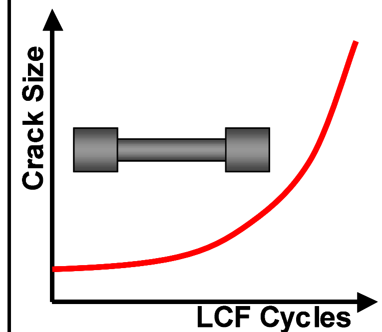
Thresholds get higher as you go to more time dependent conditions (T or ν)

Need to establish:

- Initiation criteria and short crack growth behavior
- Upper bound of time independent and time dependent curves

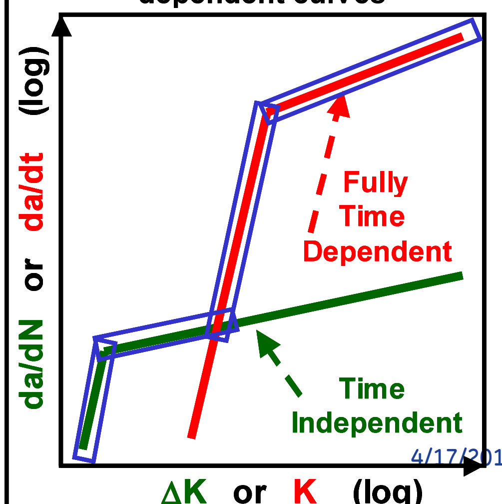
Goal: Calculate smooth bar LCF life by integrating time-independent and time-dependent crack growth curves

Cracks initiate early in smooth bar LCF specimens, and grow systematically throughout life.



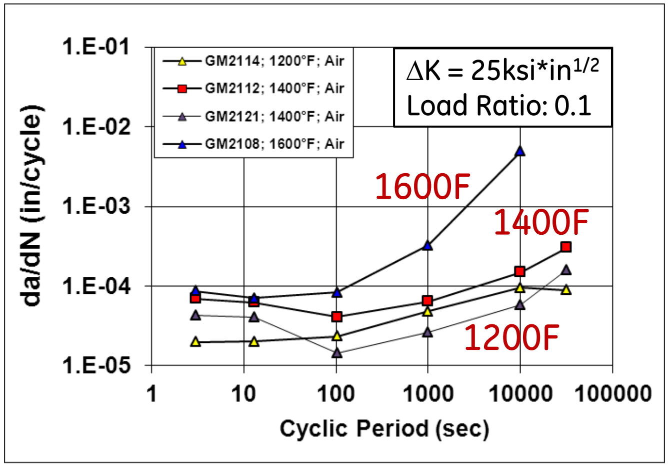
Smooth bar LCF construct

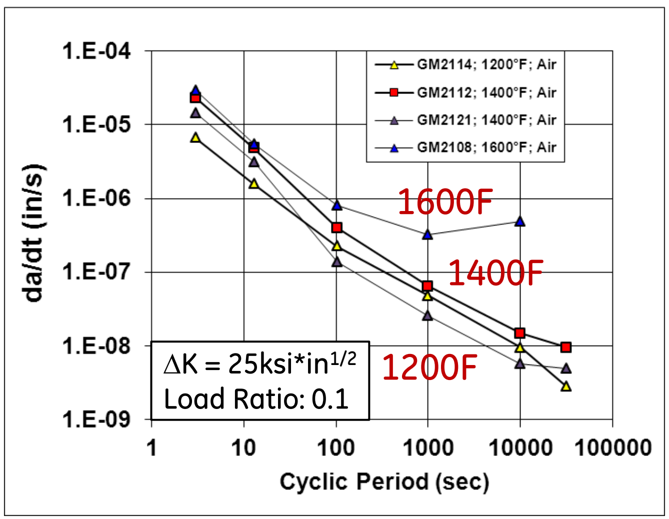
Cracks growing in hold time fatigue follow the upper bound of the time independent and time dependent curves



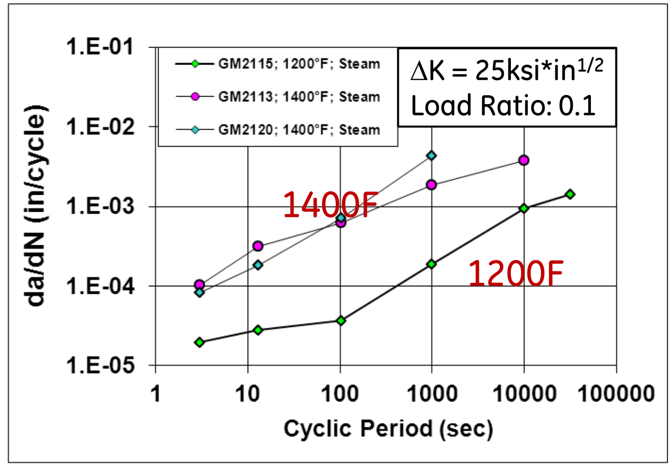
Hold-Time-Sweep Testing

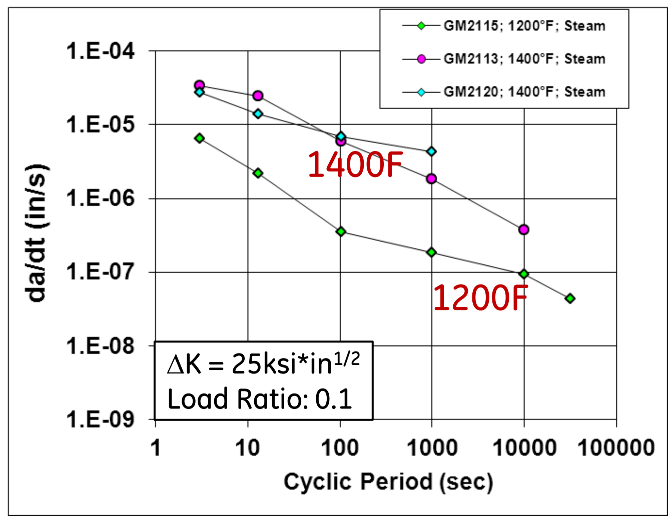
Alloy 282 Air





Alloy 282 Steam



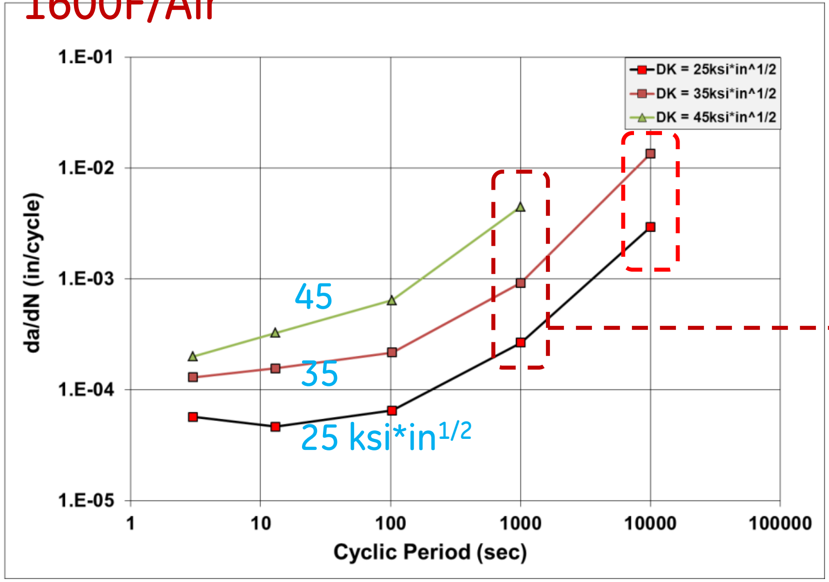


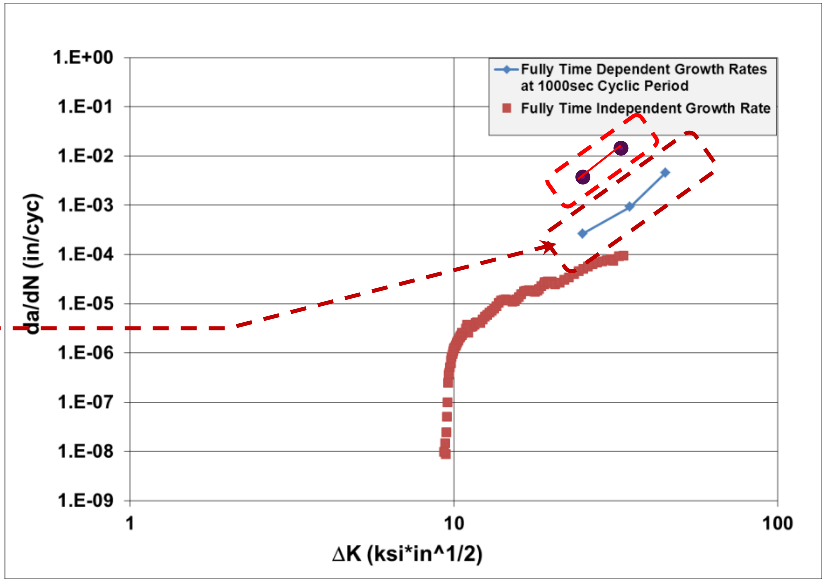
- Effect of <u>steam</u> apparent at 1200°F, for cyclic periods greater than 100 seconds
- Effect of <u>steam</u> apparent at 1400°F, for cyclic periods greater than 3 seconds
- 1600°F <u>air</u> behavior shows fully time dependent crack growth beyond 1000sec cyclic period

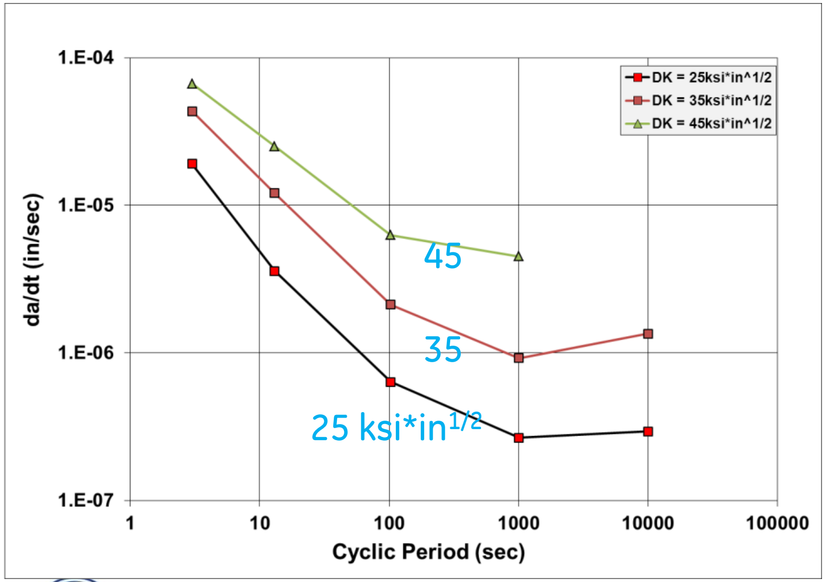
1600°F/Air selected to evaluate the relationship between crack growth and LCF

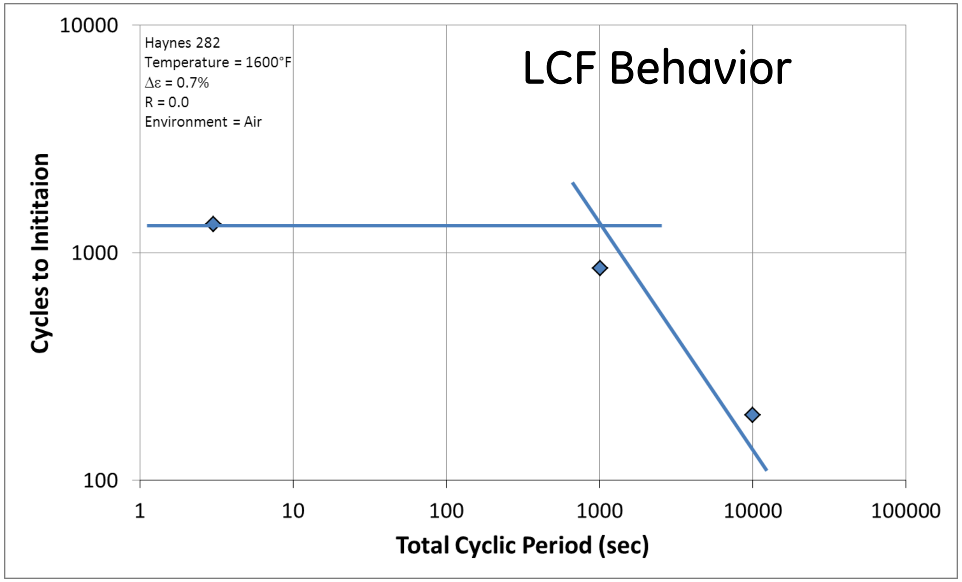
Preliminary Results: Building LCF/FCGR Correlation

1600F/Air









Hold-time effect manifested in Alloy 282 FCGR and LCF behavior

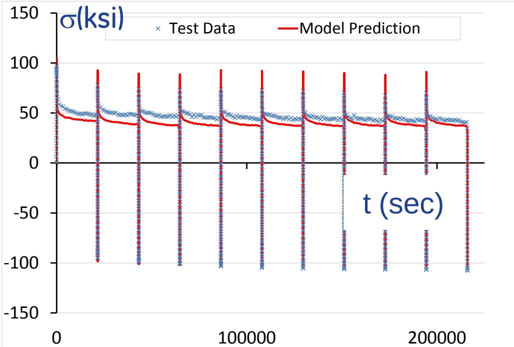
Tasks of the program

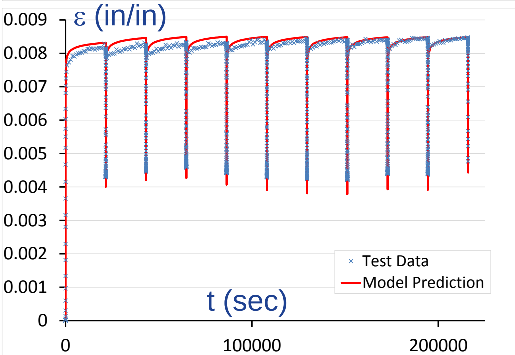
Creep-fatigue-environment interactions of Alloy 282

- Fatigue performance in steam and air environment
  - Hold-time fatigue experiment (Task 2)
  - **Hold-time fatigue FEM modeling (Task 6)**
    - **Calibrate 282 bulk material response for ANSYS**
    - **Predict crack propagation with/without hold-time, different strain ratios**
  - Fundamental understanding at crack tip (Task 2,3)
- Creep performance
  - Creep modeling & prediction (Task 5)
  - Long-term microstructure stability & interaction with defects (Task 4)

Hold-time fatigue FE modeling (Task 6)

Constitutive material modeling

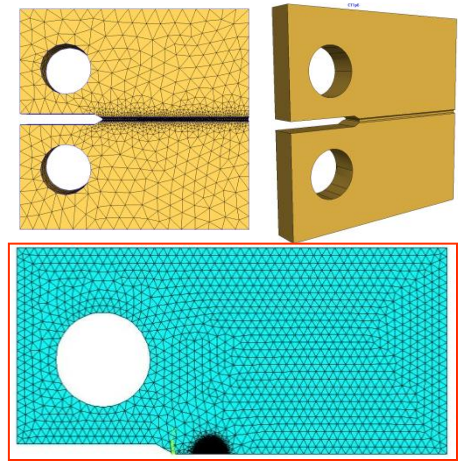




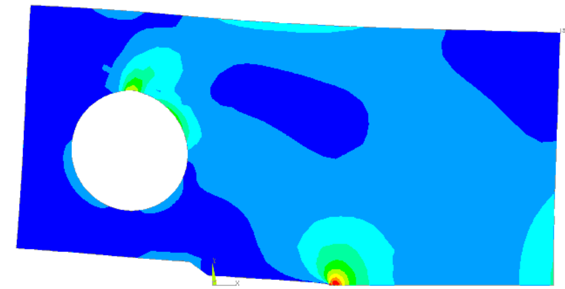
$$\frac{d\underline{\underline{\varepsilon}}}{dt} = f\left(\underline{\underline{\sigma}},\ldots\right)$$

Identify material's cyclic, SPLCF elastic-plastic response

Finite Element simulations

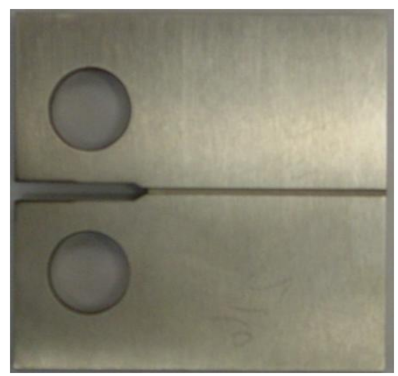


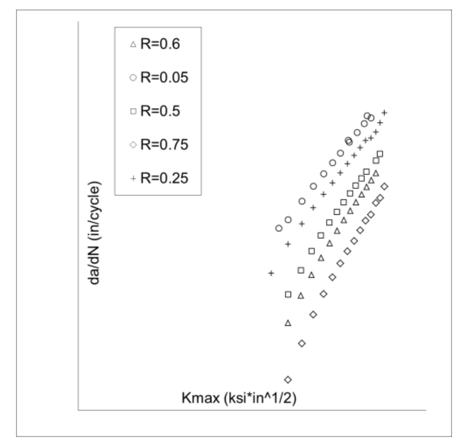
Crack tip plasticity history



$$\frac{d\rho}{dt} = g\left(K_I,\ldots\right)$$

Perform ONE Fatigue Crack Growth Test (CT geometry)





Rate Independent

$$\frac{da}{dt} = \alpha\left|\frac{d\rho}{dt}\right|$$

Rate Dependent

$$\frac{da}{dt} = \alpha\left|\dot{\rho}\right| + \dot{\beta}$$

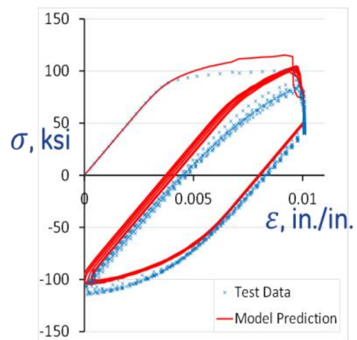
imagination at work

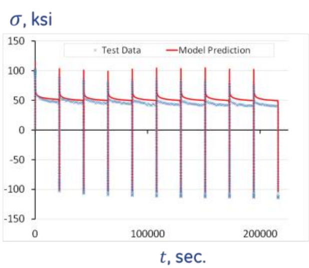
Goal: Predict crack growth rate for different R-ratio conditions, with and without hold time

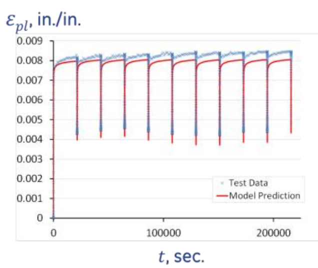
Fatigue and crack propagation FE modeling (Task 6)

Calibrate Chaboche rate-dependent material model in ANSYS

- SPLCF: 4 RB specimens
- 20CPM ramps w/ 6hr holds at max strain
- Strain ranges: [0, 0.0125], [0, 0.01], [0, 0.008], and [0, 0.007]
- Strain ratio: $R = 0$
- 1400F

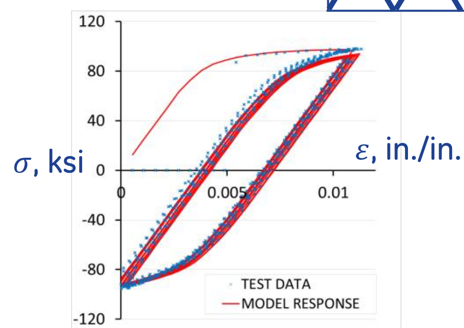


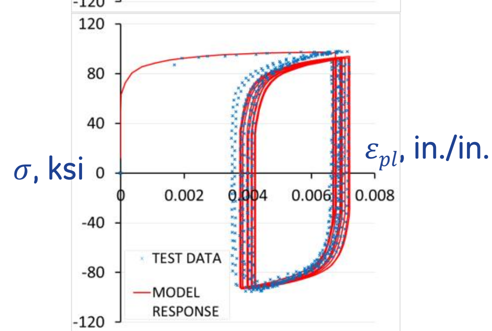




Calibrate Chaboche rate-independent material model in ANSYS

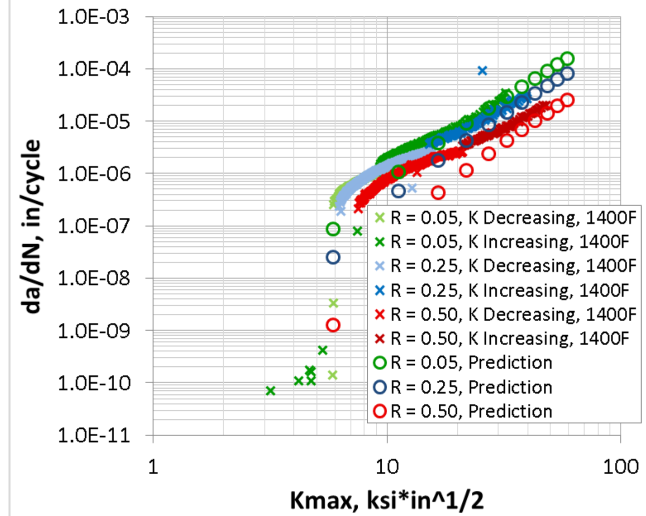
- LCF: 15 RB specimens
- Strain ranges*: [0,0.011], [0,0.0085], [0,0.0065], [0,0.005], [0,0.004]
- Strain ratio: R = 0
- 1400F





Confined crack-tip plasticity model to predict crack growth rate

- FCP: 11 CT specimens
- 20Hz, Environment: Lab air
- K increase and K shed tests
- Load ratio: R = 0.05, 0.25, 0.5, 0.9
- 1200F, 1300F, 1400F
- Crack measurement technique: DC Potential drop (ASTM E647-08)



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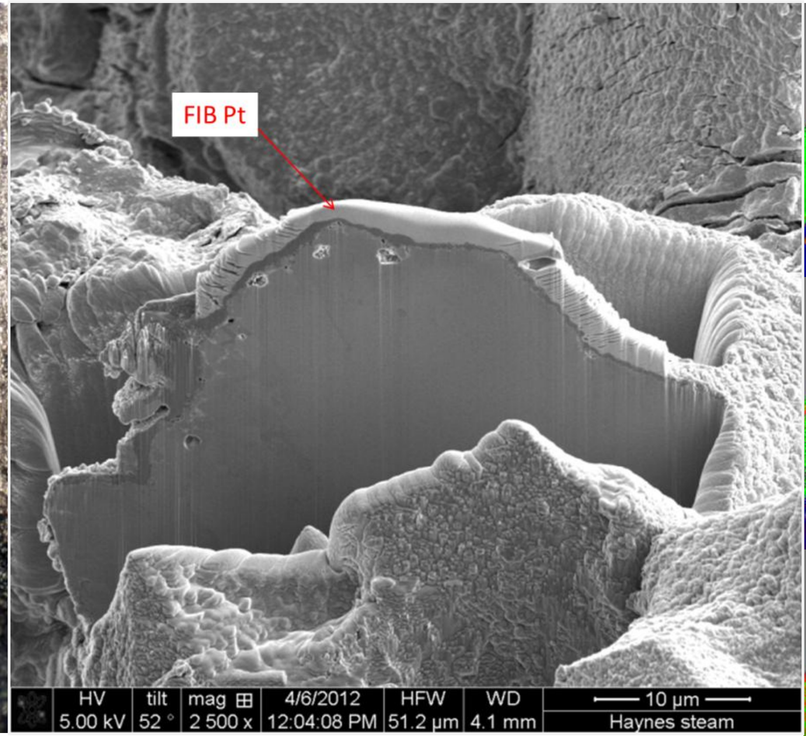
Calibrate model and predict crack growth

Tasks of the program

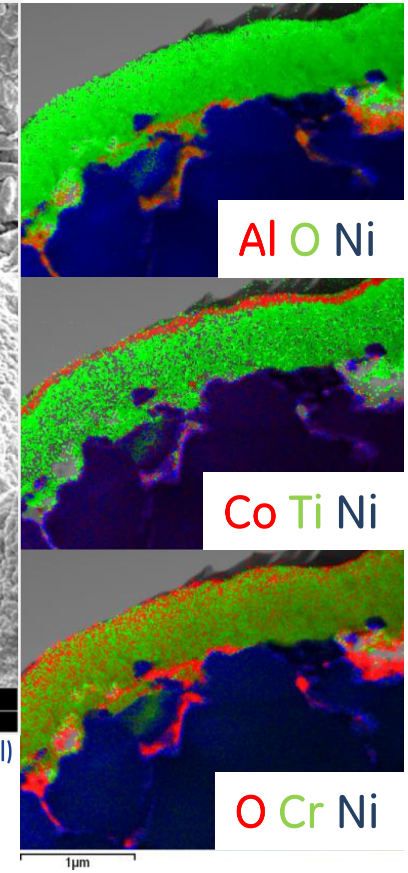
Creep-fatigue-environment interactions of Alloy 282

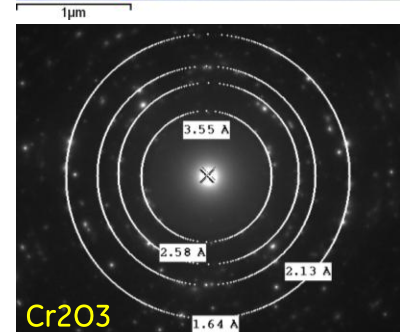
- Fatigue performance in steam and air environment
  - Hold-time fatigue experiment (Task 2)
  - Hold-time fatigue FEM modeling (Task 6)
  - **Fundamental understanding at crack tip (Task 2,3)**
    - **FIB/TEM: oxidation characteristics in air & steam**
    - **Ab initio/atomistic:**
      - **Oxidation-crack tip interaction, controlling mechanisms to hold-time effect**
      - **Oxygen diffusivities, energetics & kinetics (input to Tasks 4,6)**
- Creep performance
  - Creep modeling & prediction (Task 5)
  - Long-term microstructure stability & interaction with defects (Task 4)

Crack-tip characterization (Task 2), ab initio/atomic modeling (Task 3)



(Courtesy D Ellis, E Hall)





FIB/Lift-out at crack front from <u>1400F steam</u> specimen

- α-Al2O3 filled surface cracks
- Very thin Co-rich oxide at surface
- Bulk of Cr2O3 with lesser Ti

Ab initio/atomic modeling is pursuing:

- Crack tip oxide formation
- Oxygen diffusion in Cr2O3 and paths along GBs & interfaces

Provide microscopic mechanisms and parameters to high-level models

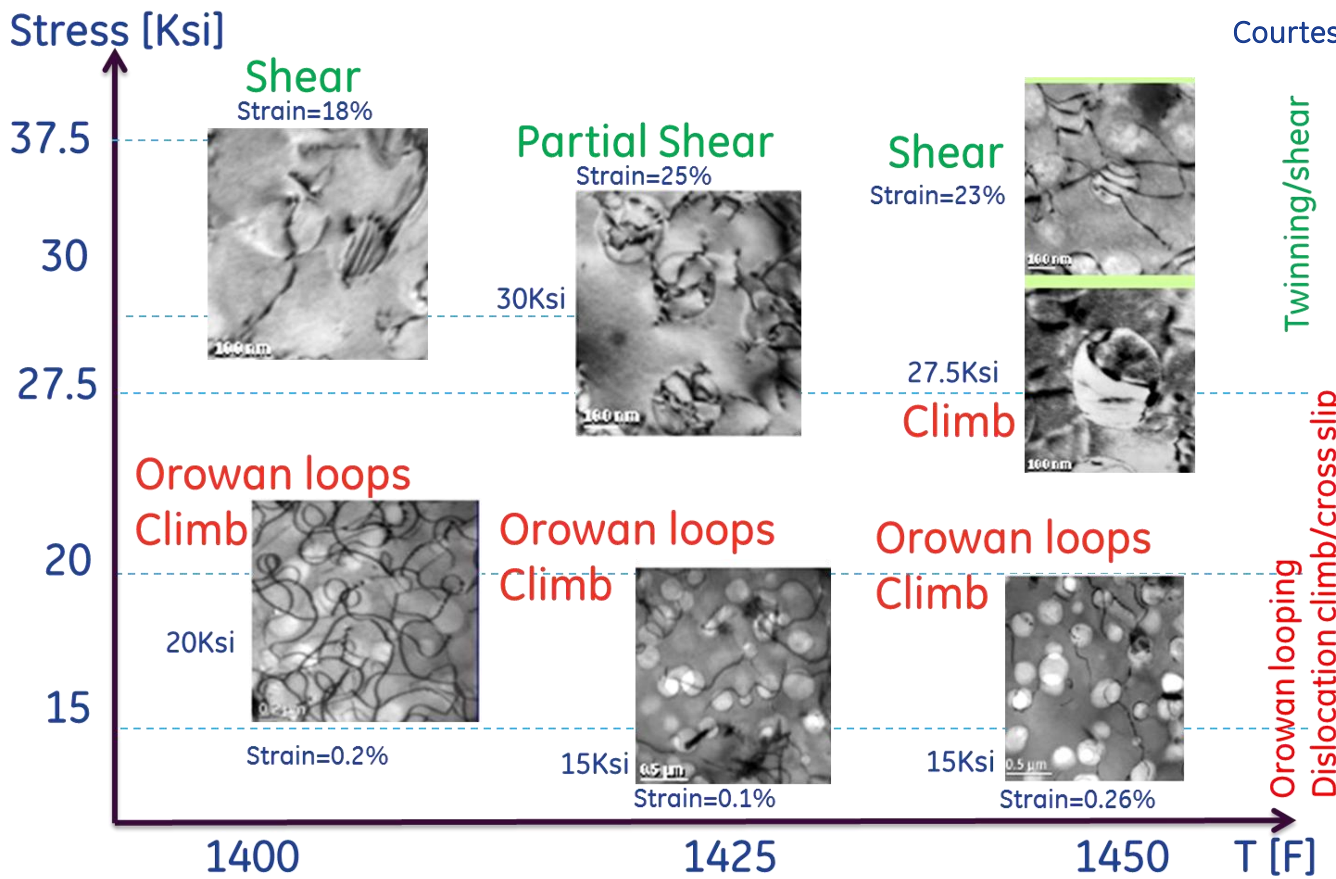
Tasks of the program

Creep-fatigue-environment interactions of Alloy 282

- Fatigue performance in steam and air environment
  - Hold-time fatigue experiment (Task 2)
  - Hold-time fatigue FEM modeling (Task 6)
  - Fundamental understanding at crack tip (Task 2,3)
- Creep performance
  - **Creep modeling & prediction (Task 5)**
    - **Microstructure-based constitutive model**
    - **Creep curve simulation and present shortcoming**
  - Long-term microstructure stability & interaction with defects (Task 4)

Alloy 282 creep mechanism understanding (Task 5)

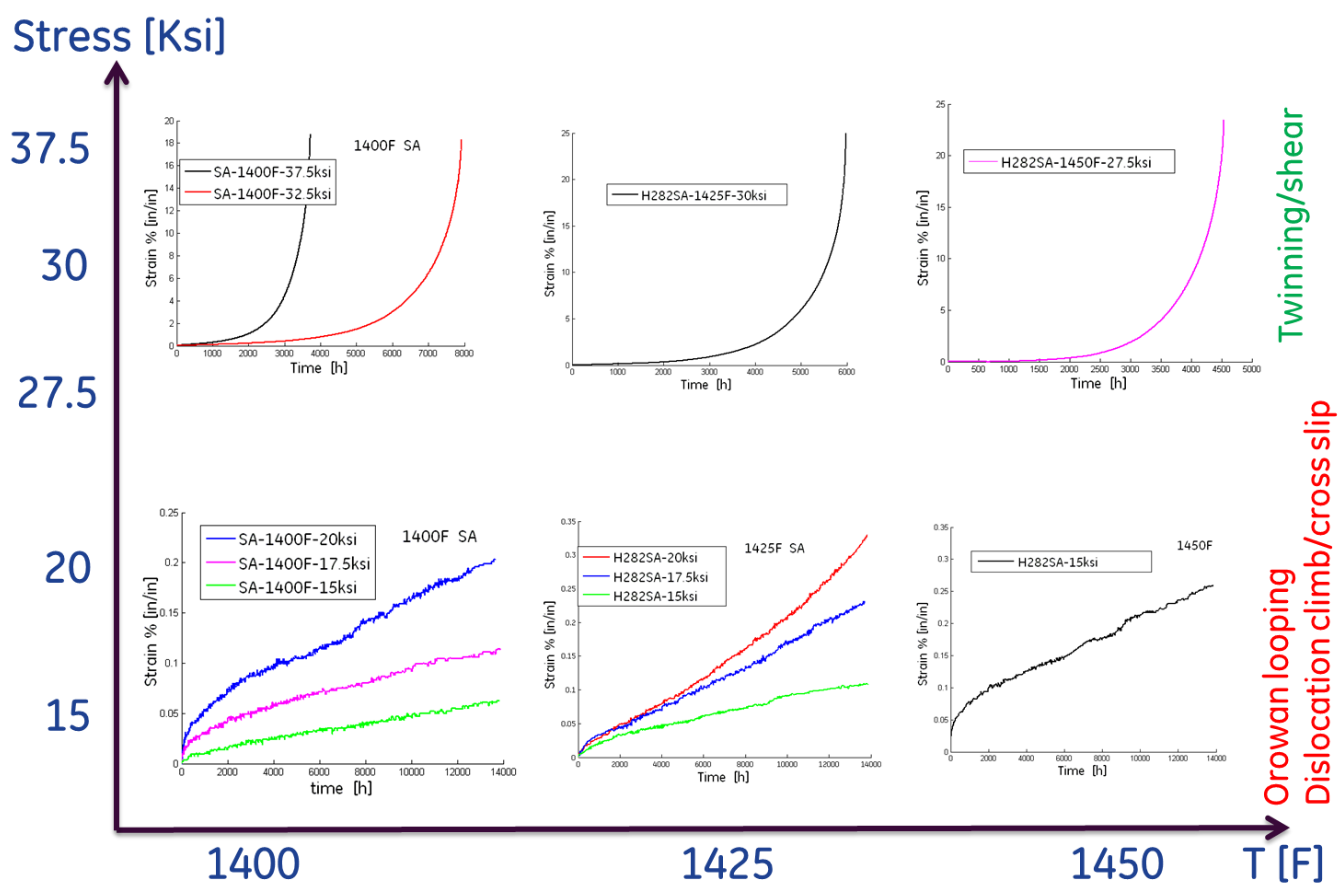
Courtesy M Karadge



- Low stress: dislocation looping & climb,
- Higher stress: γ' shearing
- Microtwinning at very low stress, low temperature

Dislocation climb-bypass is the main observation at low stresses

Creep experiment



Courtesy R Oruganti

- Historical test data 1375~1450F, 15,000-40,000 psi
- New testing aimed at low stresses ≤ 15,000 psi

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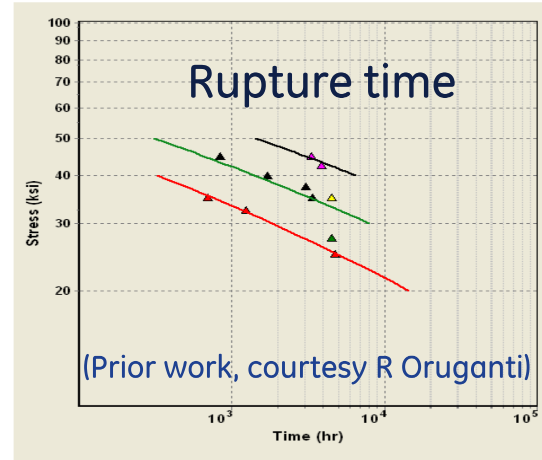
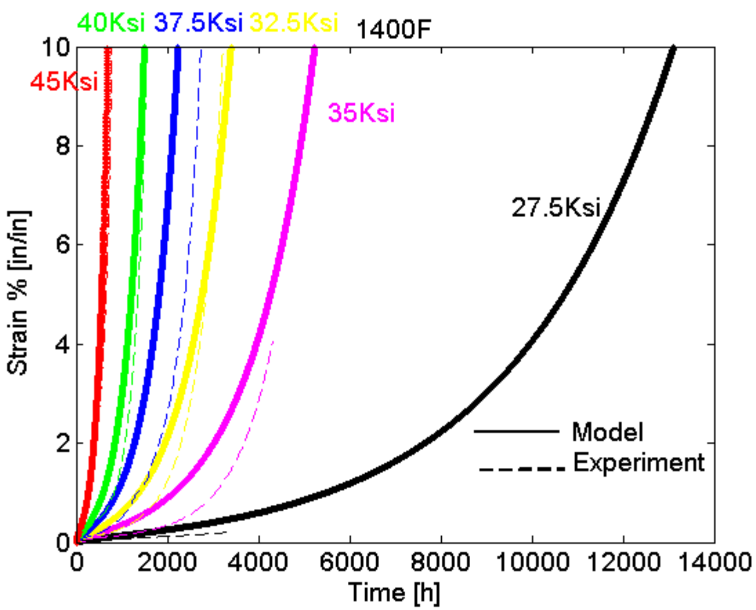
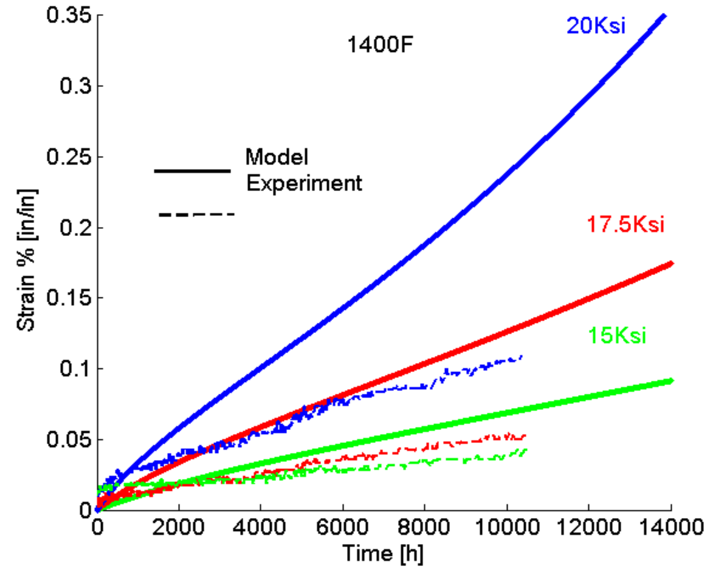
Modeling creep curves

- Current model (Oruganti, 2011) fits rupture times of Alloy 282 at different temperatures
- Does not fit well at low stress regime

  → current focus







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Constitutive creep models

Empirical power law

$$\dot{\epsilon} \sim A\sigma^n \exp\left(-\frac{Q}{RT}\right)$$

Microstructure based constitutive model of Dyson (climb-bypass)

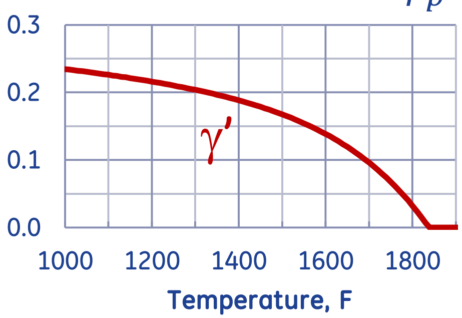
$$\dot{\epsilon} \sim A' \exp\left(-\frac{Q}{RT}\right) \sinh\left(-\frac{\sigma\Omega}{RT}\right)$$

Back stress: $\sigma \rightarrow \sigma - \sigma_B$

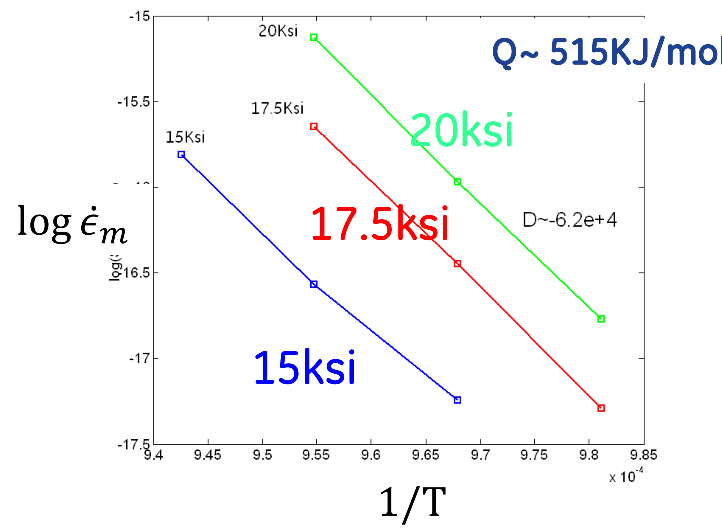
Activation volume: $\Omega \sim \lambda_p b^2$

Prefactor: $A' \sim \rho b (b/r_p)\ \phi_p \lambda_p / \bar{M}$

Volume fraction ϕ_p



Cond	Stress [Ksi]	Temper [F]	Min. strain rate [10^{-7}/s]
SA	17.5	1375	0.31
	20	1375	0.52
	15	1400	0.32
	17.5	1400	0.72
	20	1400	1.16
	15	1425	0.63
	17.5	1425	1.60
	20	1425	2.70
	15	1450	1.36



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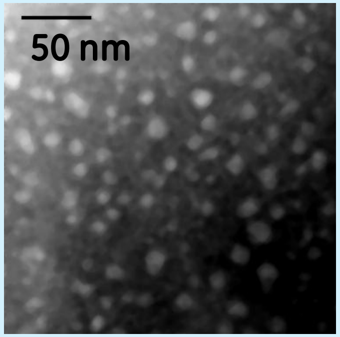
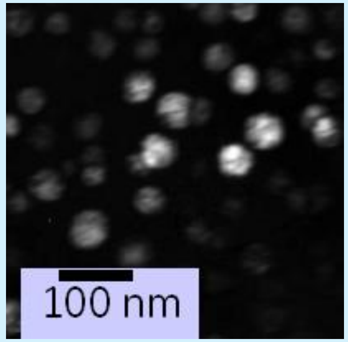
Model creep strain curve with microstructure evolution

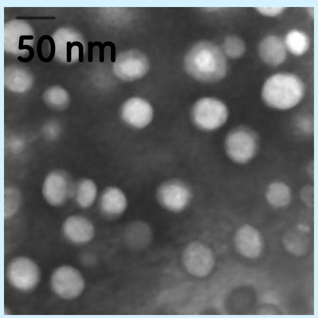
Microstructure dependence



Solution Annealed



PA = SA + 8h @ 1450°F

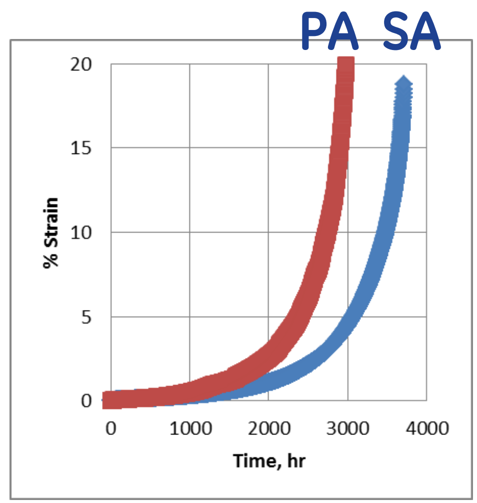


OA = PA + 250h @ 1425°F

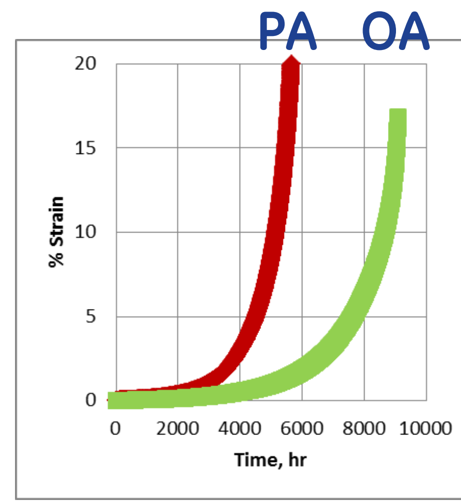
Cond.	γ′ (nm)
SA	5-15
PA	20-50
OA	40-70

Courtesy Jeff Hawk

Creep strain vs. time curves



1400F, 37.5ksi



1425F, 27.5ksi

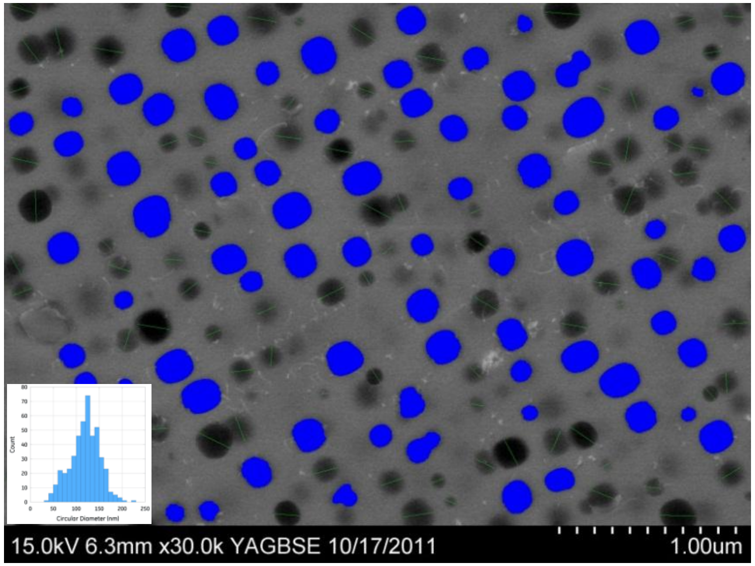
→ more plots

Tasks of the program

Creep-fatigue-environment interactions of Alloy 282

- Fatigue performance in steam and air environment
  - Hold-time fatigue experiment (Task 2)
  - Hold-time fatigue FEM modeling (Task 6)
  - Fundamental understanding at crack tip (Task 2,3)
- Creep performance
  - Creep modeling & prediction (Task 5)
  - **Long-term microstructure stability & interaction with defects (Task 4)**
    - **Precipitate size (coarsening)**
    - **Precipitate spatial distribution & inter-particle spacing**
    - **Precipitate-dislocation interactions**

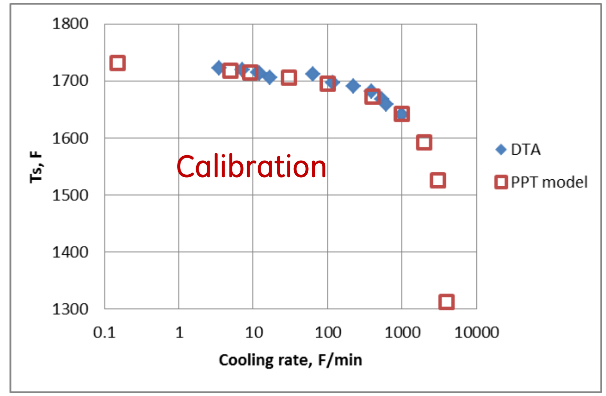
Microstructure modeling (Task 4)



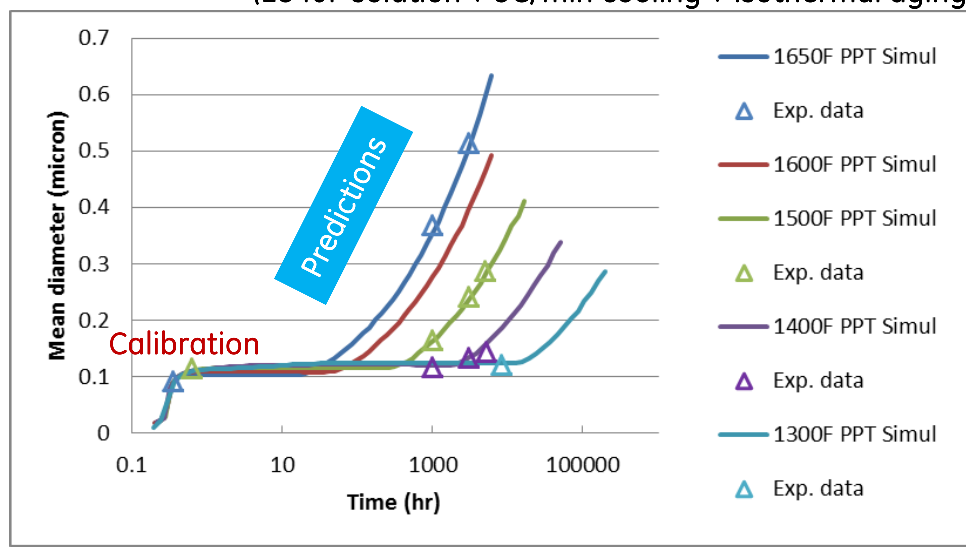
Courtesy Ian Spinelli

- Precipitate (γ') strengthening
- Size and inter-spacing distributions
- Long-term (>20yr) γ' stability

- **Precipitation (Langer-Schwartz) model**
- γ' nucleation, growth, coarsening
- Calibrated to short-term data



(1840F solution + 5C/min cooling + isothermal aging)

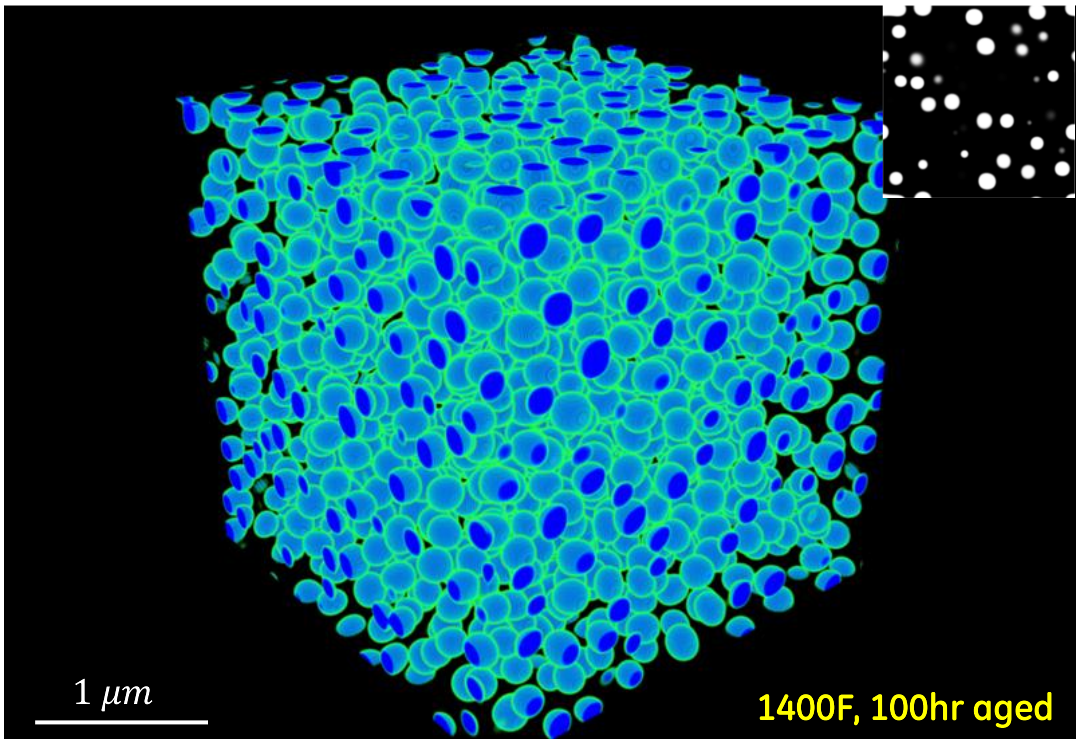


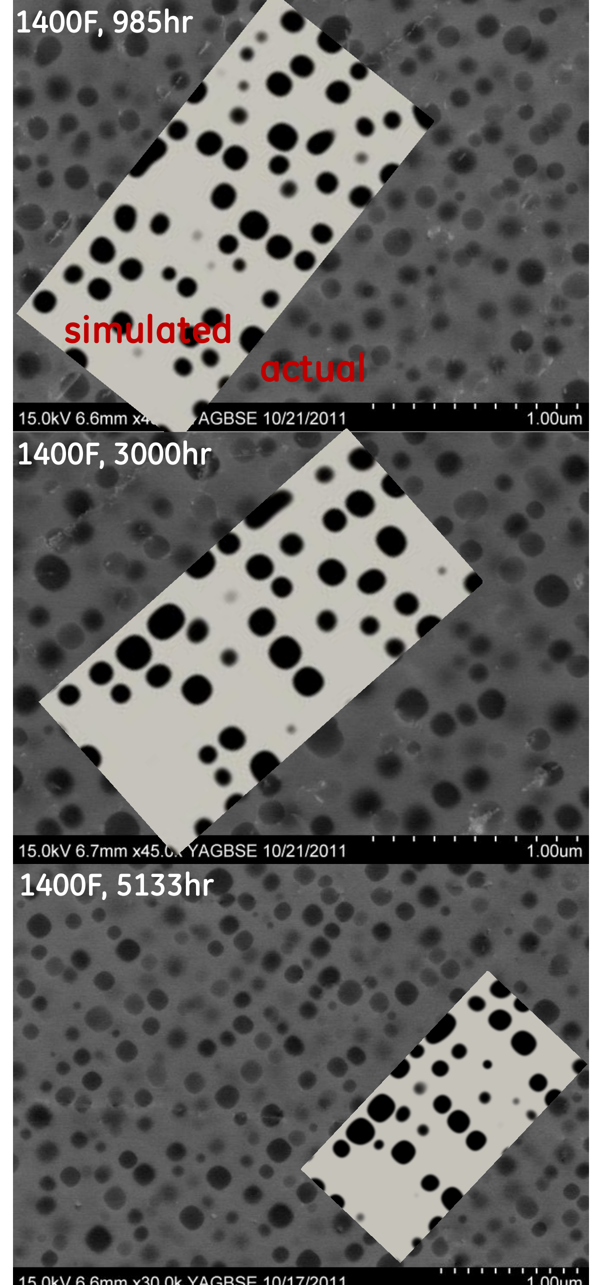
imagination at work

Can predict long-term precipitate size (coarsening)

Microstructure modeling (Task 4)

- **Phase field model**, nucleation, growth and coarsening
- Actual heat treatment (cooling, aging)
- Length scale: $2\mu m$ box
- GPU accelerated, 50:1 time ratio at 1400F



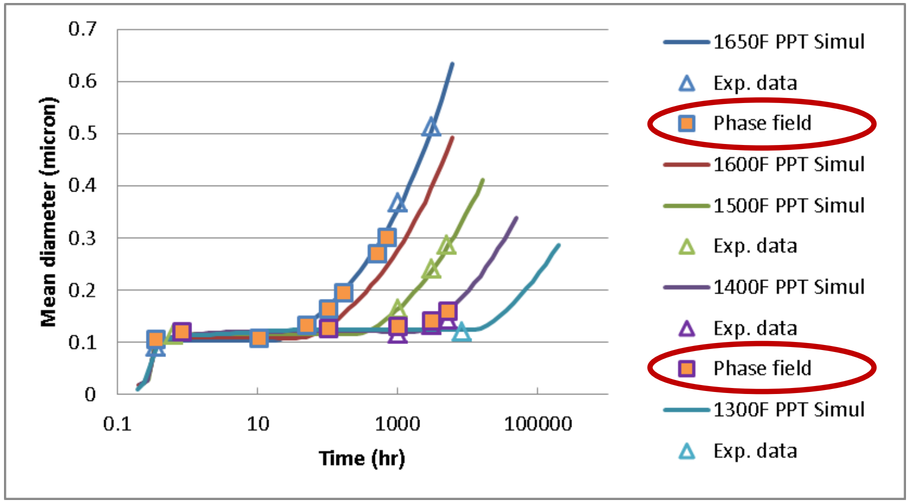


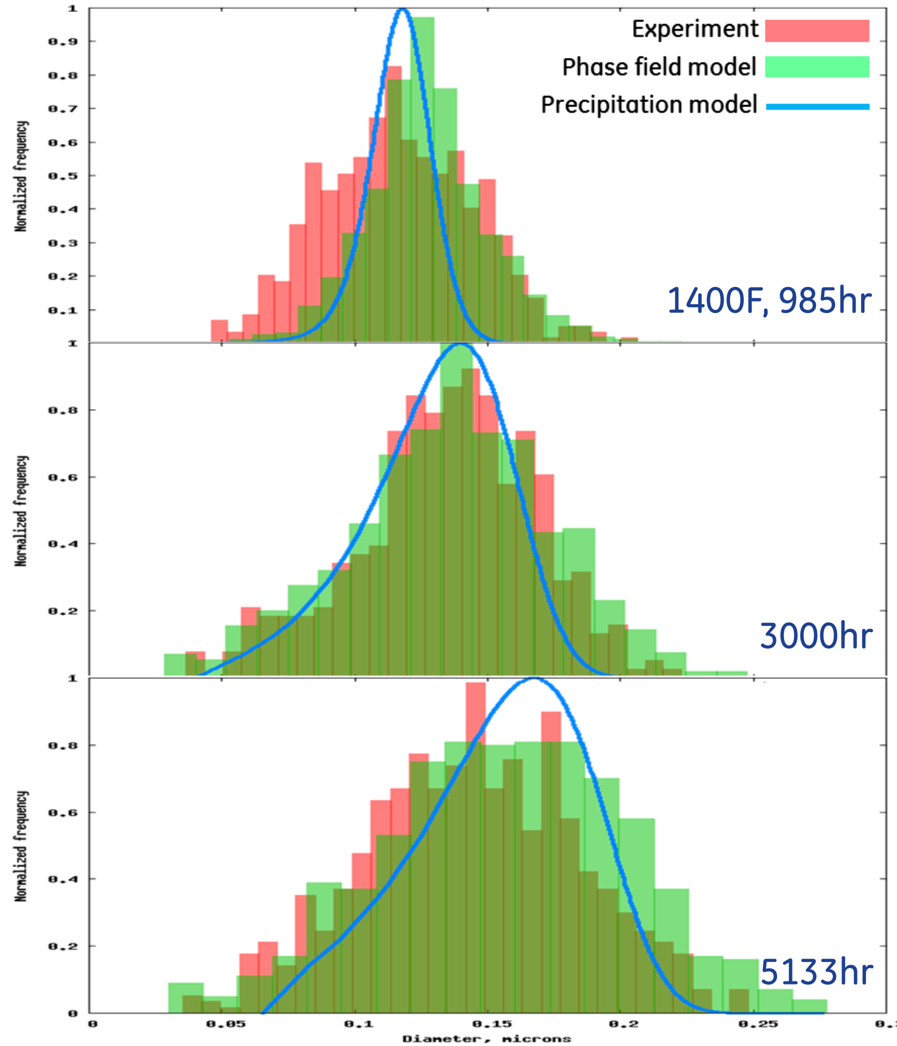
imagination at work

Can predict long-term precipitate spatial distribution

Microstructure modeling (Task 4)

- Use same parameters of precipitation model
- No additional calibration

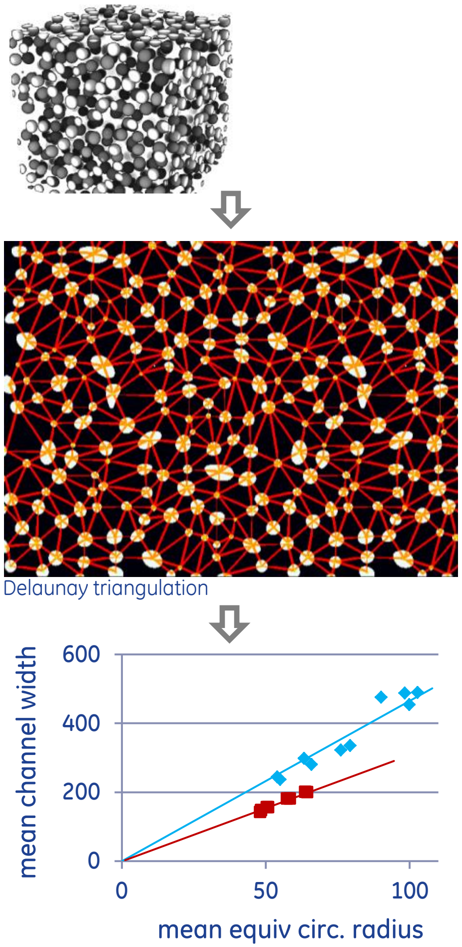




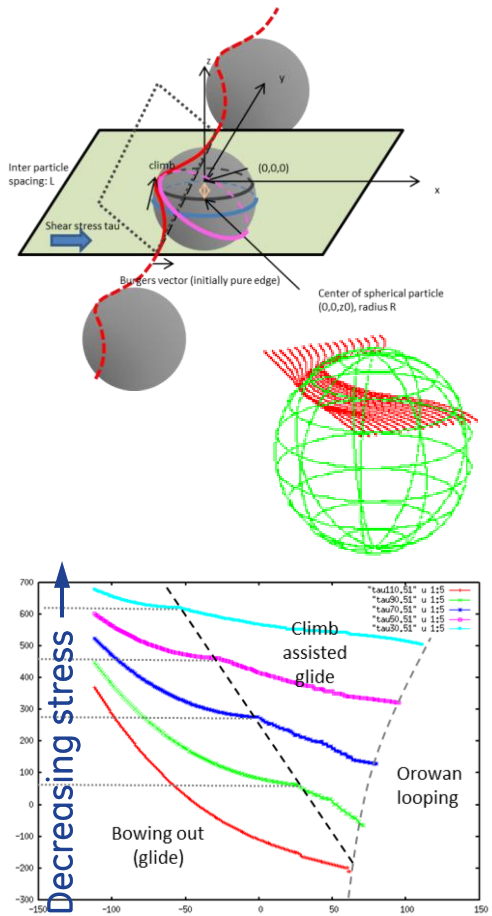
Validate statistical distributions

Microstructure-dislocation interactions (Task 4)

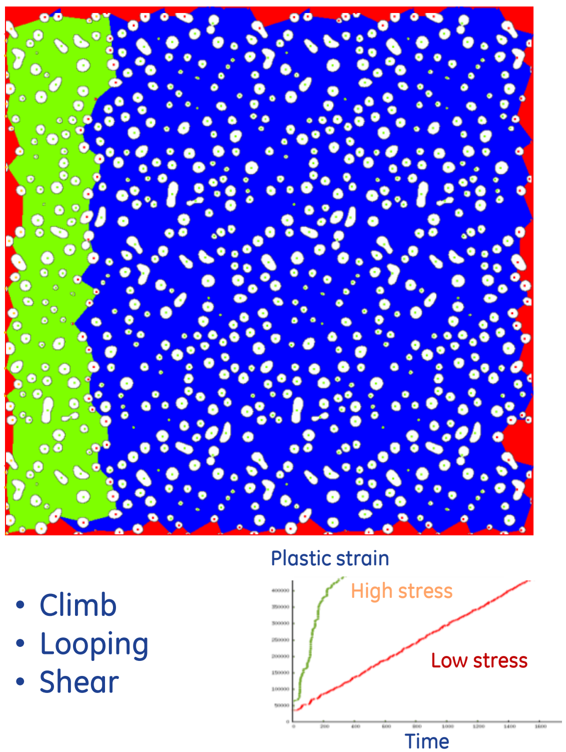
⇨ Creep model:
Back stress, microstructure dependence



Mean γ′ size,
Inter-particle spacing



Dislocation climb-
bypass (one particle)



- Climb
- Looping
- Shear

Many-particle,
spatial distribution

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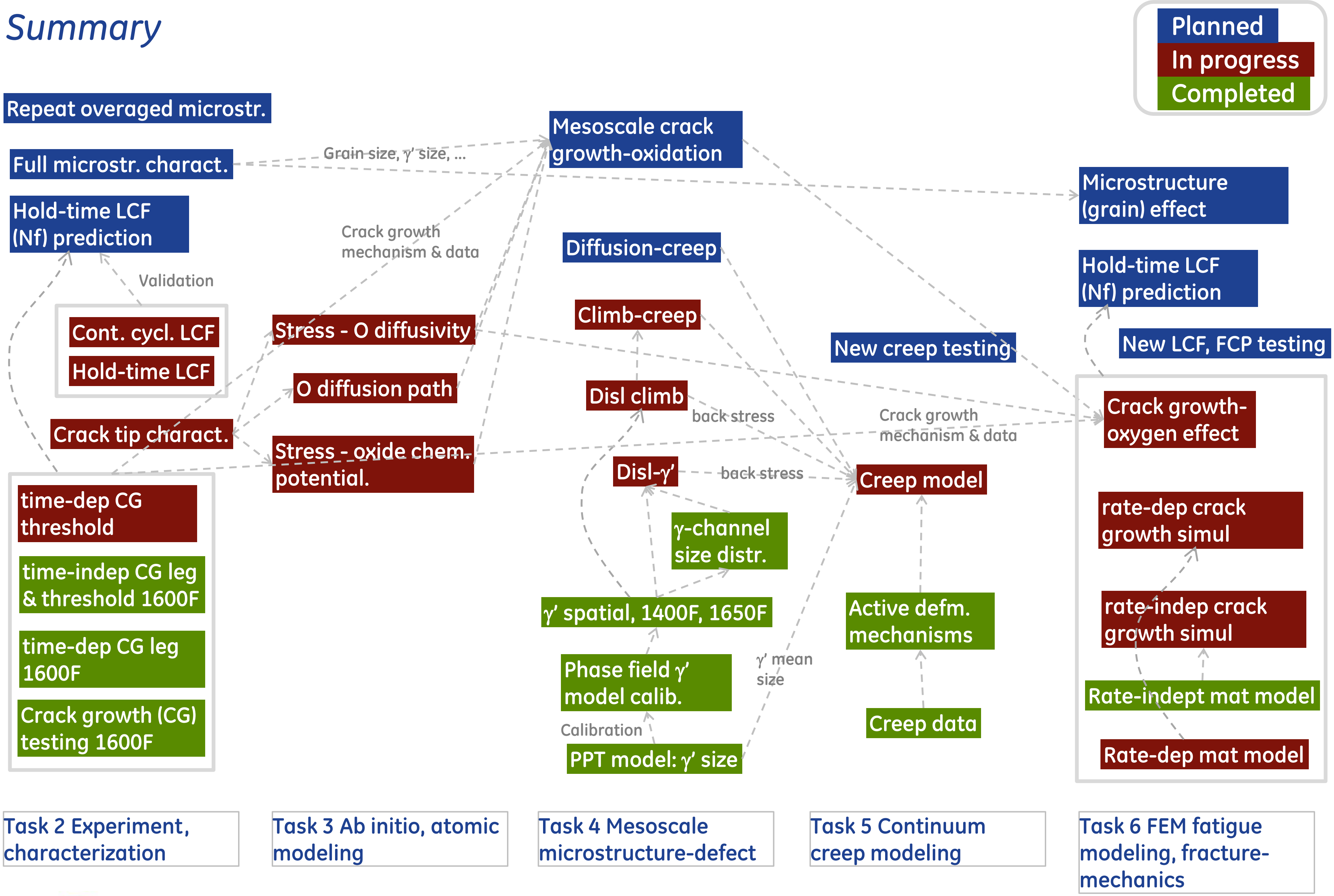
Develop means to incorporate microstructure (evolution) into constitutive creep model

Summary

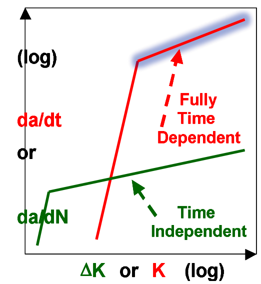

Planned
In progress
Completed
Repeat overaged microstr.
Full microstr. charact.
Grain size, γ' size, ...
Mesoscale crack growth-oxidation
Microstructure (grain) effect
Hold-time LCF (Nf) prediction
Crack growth mechanism & data
Diffusion-creep
Validation
Cont. cycl. LCF
Hold-time LCF
Stress - O diffusivity
Climb-creep
New creep testing
Hold-time LCF (Nf) prediction
New LCF, FCP testing
O diffusion path
Disl climb
back stress
Crack growth mechanism & data
Crack growth-oxygen effect
Crack tip charact.
Stress - oxide chem. potential.
Disl-γ'
back stress
Creep model
time-dep CG threshold
rate-dep crack growth simul
γ-channel size distr.
time-indep CG leg & threshold 1600F
γ' spatial, 1400F, 1650F
Active defm. mechanisms
rate-indep crack growth simul
time-dep CG leg 1600F
Phase field γ' model calib.
γ' mean size
Rate-indept mat model
Crack growth (CG) testing 1600F
Calibration
Creep data
PPT model: γ' size
Rate-dep mat model
Task 2 Experiment, characterization
Task 3 Ab initio, atomic modeling
Task 4 Mesoscale microstructure-defect
Task 5 Continuum creep modeling
Task 6 FEM fatigue modeling, fracture-mechanics

Backup slides

Time Dependent Fatigue Model: Detailed Approach

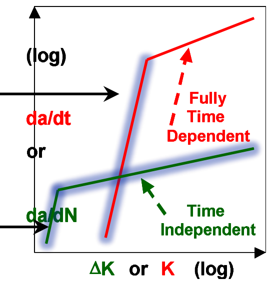
Phase 1: Hold Time Sweep

- Establish fully time dependent crack growth rates at four temperatures, three stress levels
- Establish critical cyclic period (for transition to fully time dependent behavior) at four temperatures, three stress levels



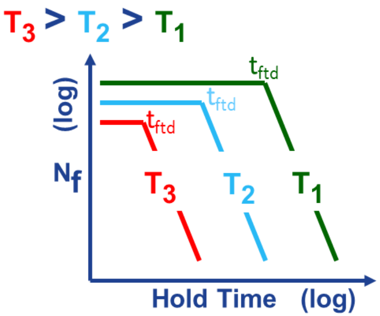
Phase 2: FCP and HTFCP

- Establish hold time crack propagation threshold at four temperatures
- Establish continuous cycling FCP data at four temperatures



Phase 3: LCF

- Establish fully time independent (20cpm) LCF lives at four temperatures
- Establish fully time dependent LCF lives at three temperatures, three hold times
- Construct N_f vs. hold time curves at three temperatures, one strain level



Goal: Calculate smooth bar LCF life by integrating time-independent and time-dependent crack growth curves

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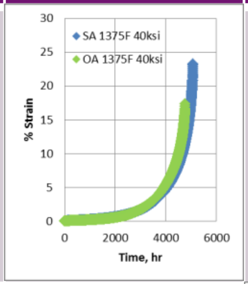
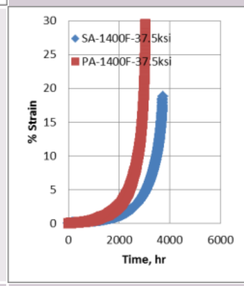
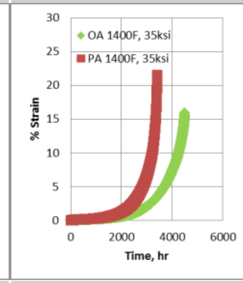
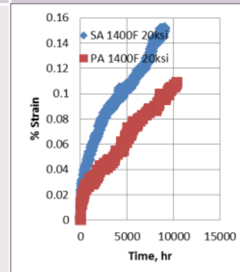
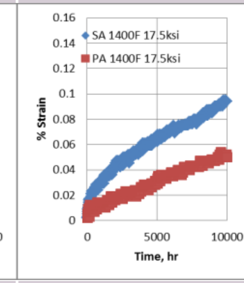
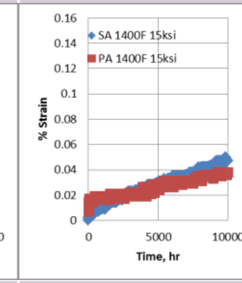
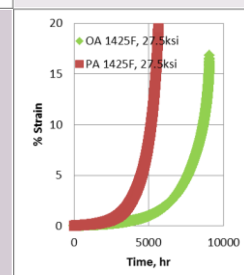
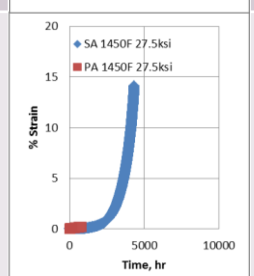
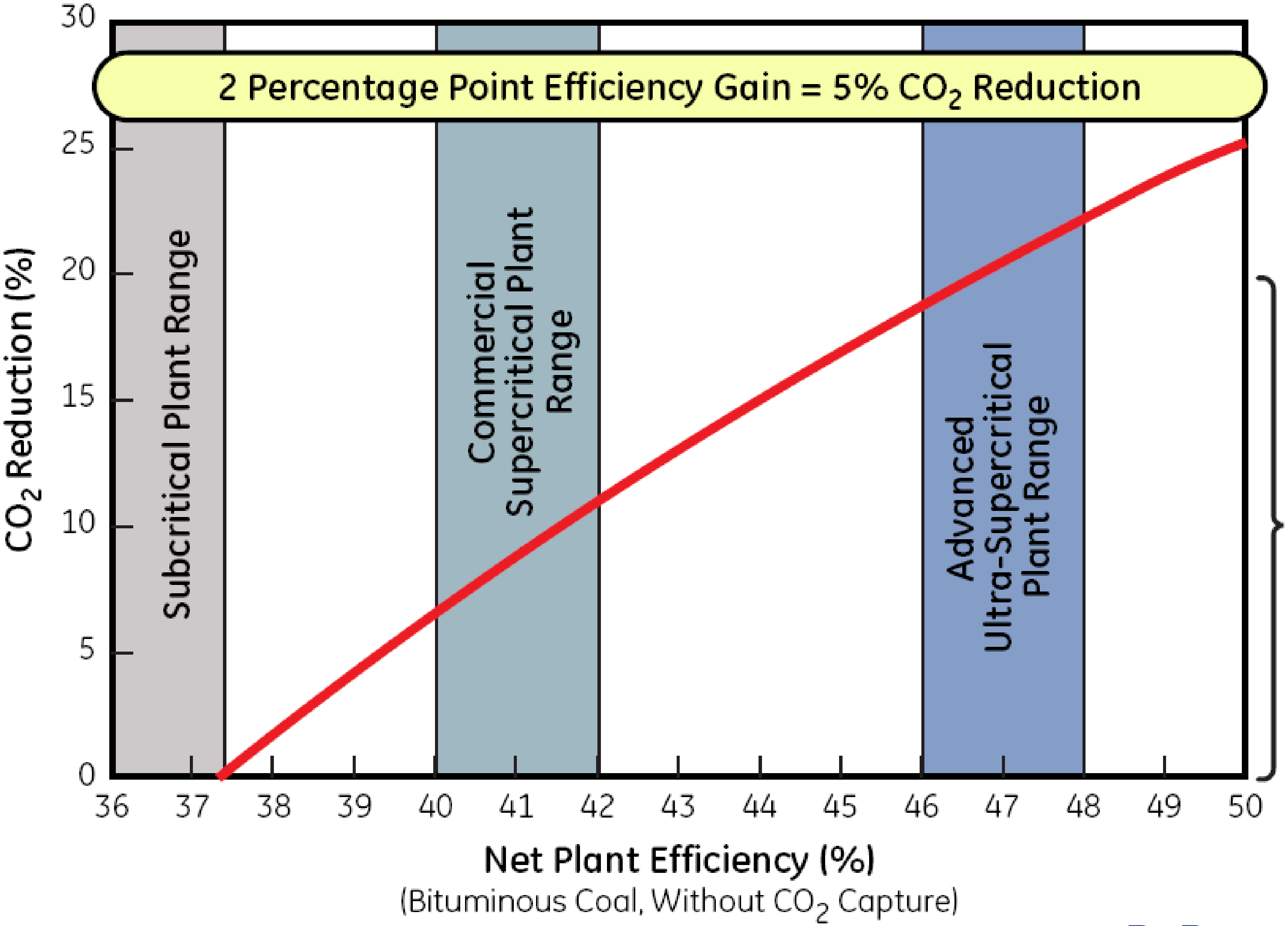
	40ksi	37.5	35	27.5	20	17.5	15
1375F							
1400F							
1425F							
1450F	SA PA OA						

→ back

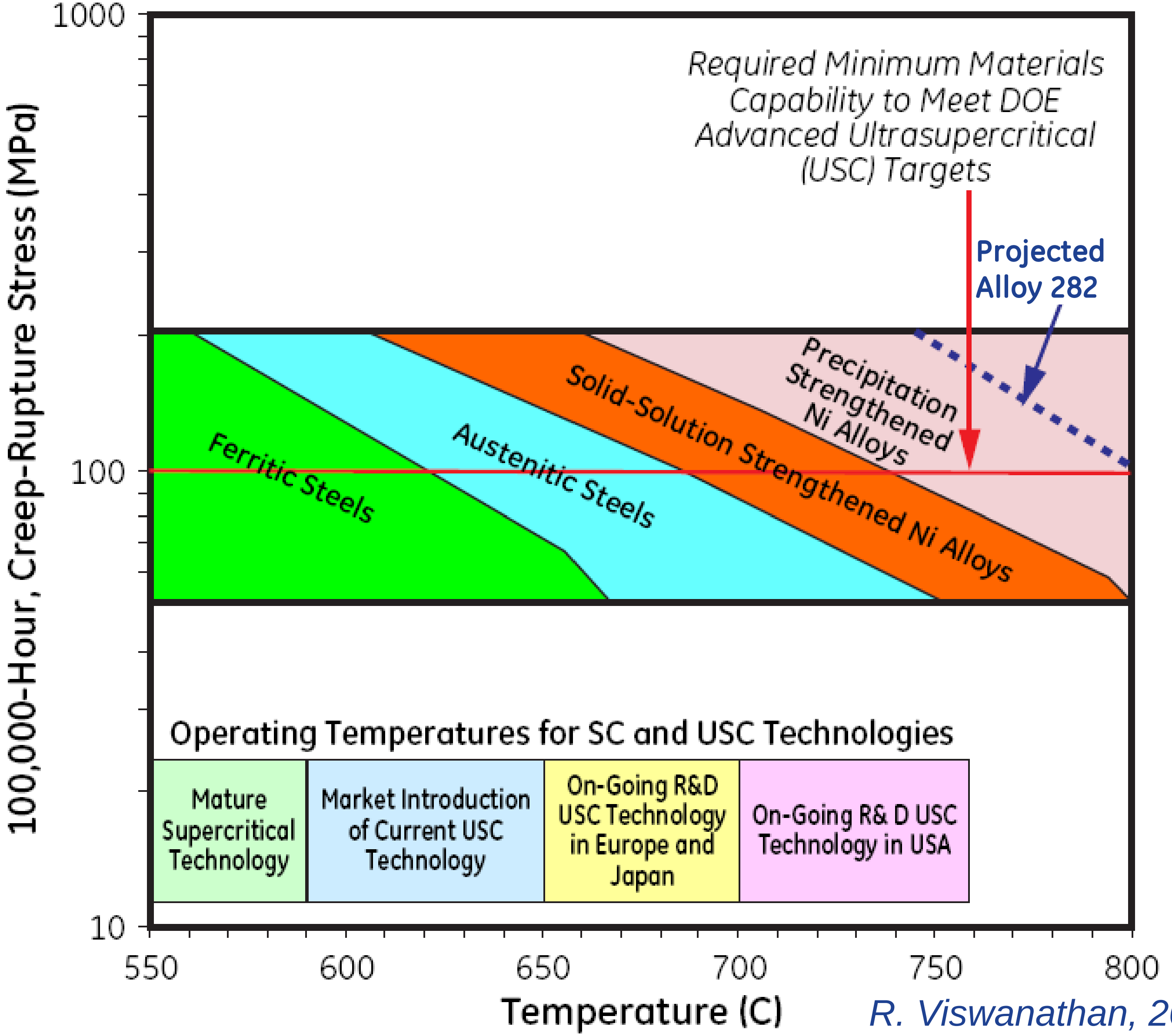
Advanced Ultra-Supercritical Steam Turbine



20% reduction in CO_2 corresponds with similar reductions (per MWh) in consumables including coal and limestone (reducing front-end equipment size), flue gas volume (reducing back-end and emission control equipment size), and overall emissions, water use, and waste generation

R. Romanosky, 2010

A-USC Rotor Materials



R. Viswanathan, 2007, 2009

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