Creep Behavior of a New Cast Austenitic Alloy

CF8C-Plus

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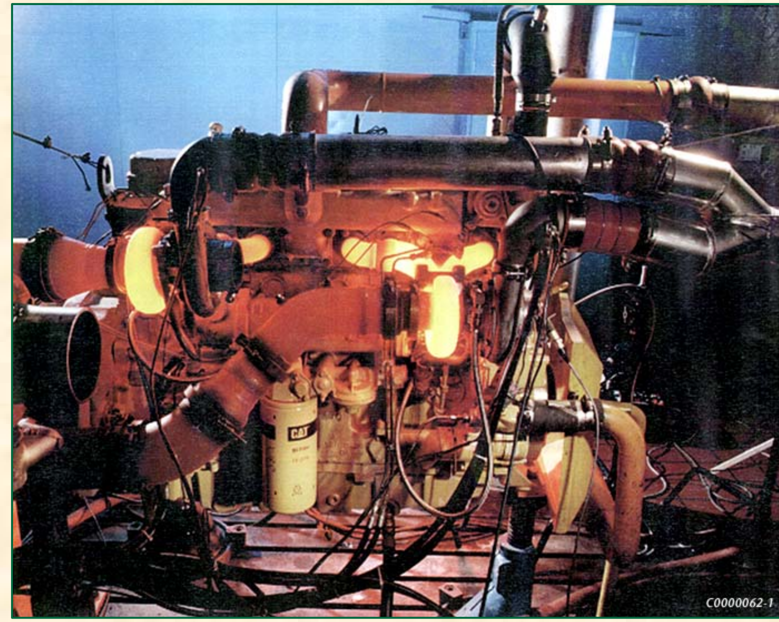
Outline

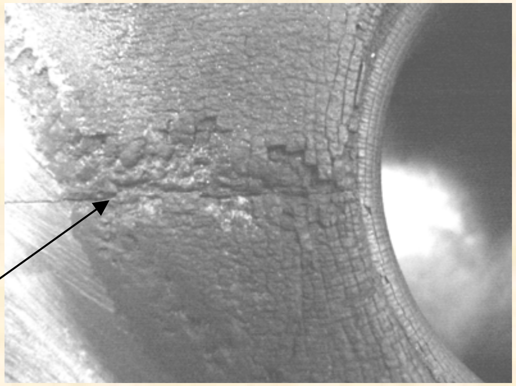
- **Development of CF8C-Plus**
  - **Materials Needs: Cost Effective Performance**
  - **Engineered Microstructure Approach**
  - **Casting Considerations**
- **Creep Behavior**
  - **CF8C vs. CF8C-Plus**
  - **Compared with Alloys of Interest**
- **Additional Mechanical Properties**
- **Current and Future Commercial Interest**
- **Additional Alloy Modifications**

Materials Needs

- **Increased Efficiency of Diesel Engines = Higher Exhaust Temperatures**
  - **Load at Temperature: Creep**
  - **Start-up/Shut-down: Fatigue**
  - **Oxidation**
- **CRADA between ORNL & CAT**
  - **Unacceptable failure rate anticipated by CAT for SiMo Cast Iron applications**
  - **Evaluate New Cast Materials for Diesel Exhaust Manifolds, Turbo-charger housings, and turbine casings**
  - **Cast Stainless Alloy Development**



Turbo Bridge Failure



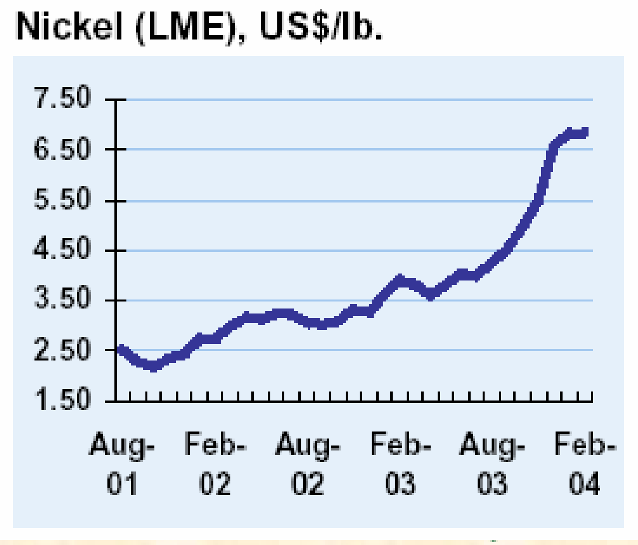
Materials Needs: High Performance Low-Cost Alloy is needed to Replace SiMo Cast Iron

Some Candidate Alloy Compositions (wt%)

- SiMo Cast Iron: Fe-3.45C-4Si-0.6Mo-0.3Mn
- CF8C: Fe-19Cr-10Ni-0.07C-1.0Nb-0.7Mn-1Si
- CN-12: Fe-25Cr-13Ni-0.4C-1Mn-1.7Nb-0.3N-0.15S
- Ni-Resist: Fe-2Cr-35Ni-0.5Mn-5Si-1.9C
- Hitachi 20/20 – Fe-20Cr-20Ni-0.45C-2Nb-3W-1Mn-0.6Si-0.15S

Improving the properties of less expensive alloys without the costly addition of Ni offered the best opportunity

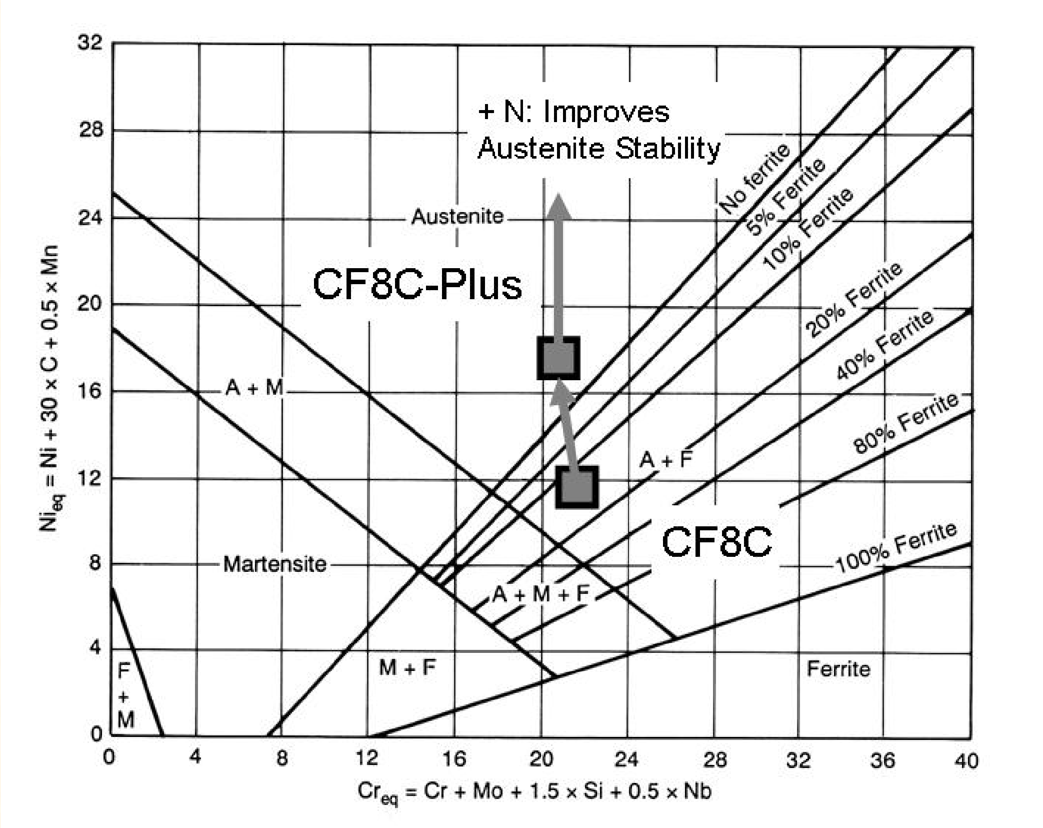
<u>**CF8C-Plus = Best Results**</u>



Engineered Microstructure Approach

- **Austenitic Alloy Design is based on achieving desired microstructure for High-Temperature Strength and Stability**
- **Additions made using ‘alloying rules’ developed using 30+ years of experience at ORNL**
  - **Reactant, Catalytic, Inhibitor, and Interference Effects**
- **Started with base CF8C composition (wrought equivalent = 347 stainless steel)**
- **Desired microstructure and properties were produced during the 1st year of development**
- **500 lb (1100kg) Commercial trials began during 2nd year**

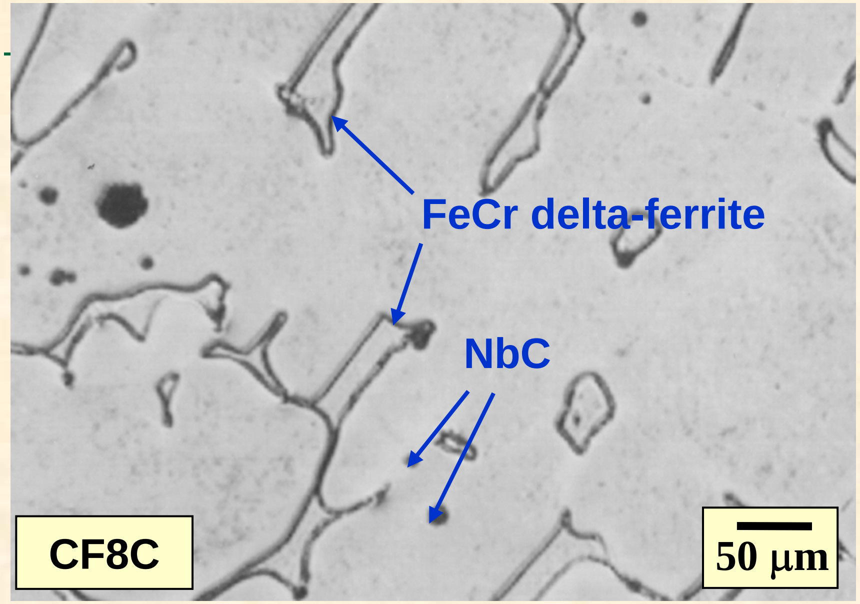
Mn and N Additions can improve CF8C Austenite Stability

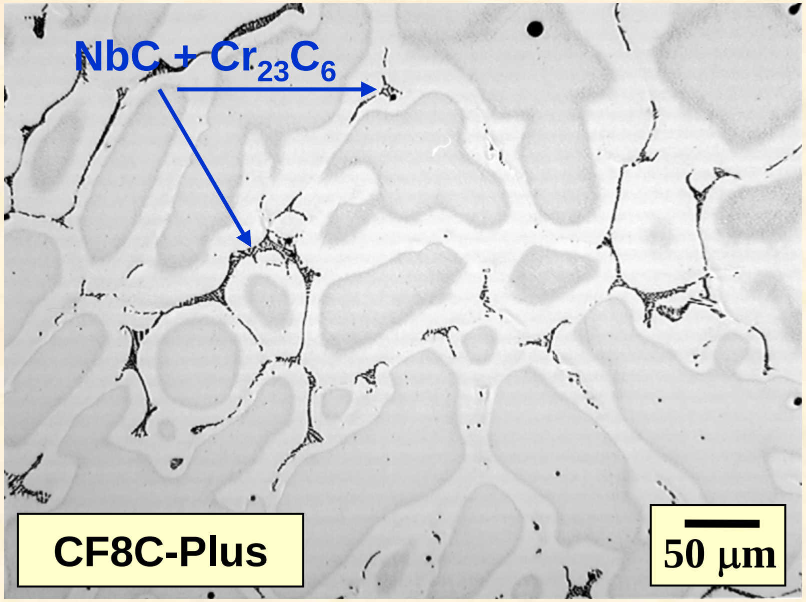


- **Large Costly <u>Additions of Ni are NOT needed</u> for fully austenitic stainless steel**
- **CF8C = 15% Delta Ferrite, CF8C-Plus = 0% Delta Ferrite**

Detrimental Phases can be avoided

- **CF8C**
  - Delta (δ) ferrite → Aging → Sigma (σ) Phase
    - Loss of Ductility & Toughness
    - Weakened Grain Boundaries
- **CF8C-Plus**
  - **No δ-ferrite**
  - Strong Grain Boundaries (mix of MC and $M_{23}C_6$ carbides)
  - Fine stable MC carbide precipitate early during aging



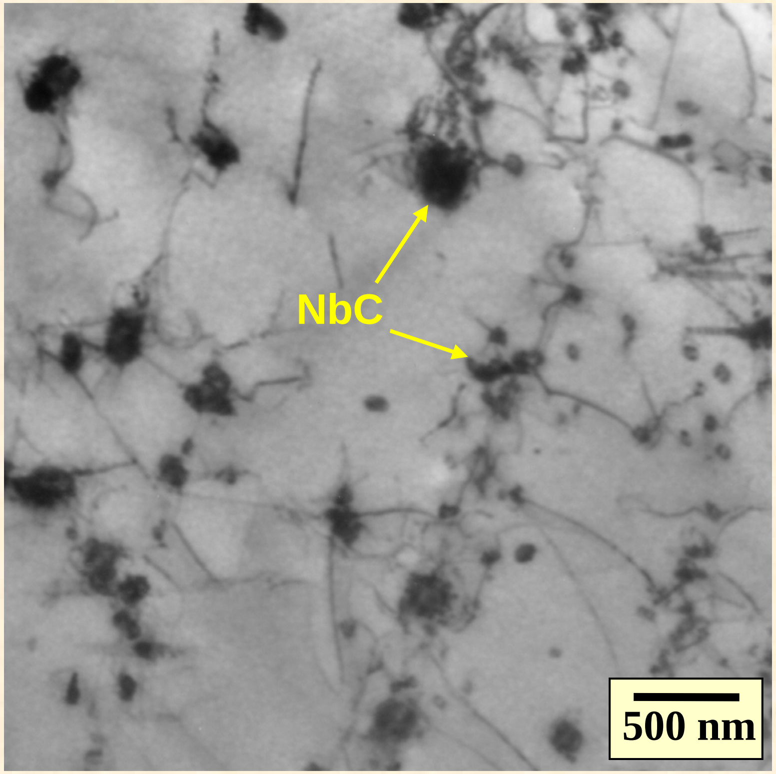


As-cast (Optical metallography, polished and etched) As-cast

Nano-scale Carbide Strengthening

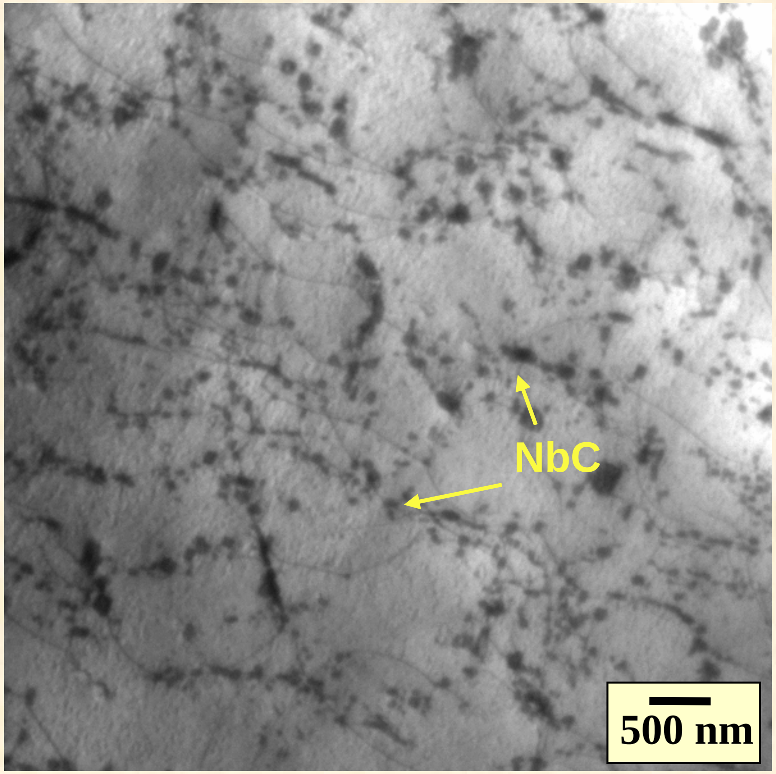
- **CF8C-Plus Has "Super" Creep Resistance at 850°C Because Abundant, <u>Stable</u> Nano-Scale NbC Pin Dislocations**

Commercial, Standard CF8C



Creep Tested 850°C/500 h

CF8C-Plus



Creep Tested 850°C/23,000 h

(TEM, as cast)

Additional Casting Considerations

- **Melt Fluidity:**
  - **CF8C has Si to improve fluidity**
  - **CF8C-Plus has reduced Si, but Mn improves fluidity and shows as good or better melt fluidity compared to CF8C**
- **Hot Tearing:**
  - **CF8C is susceptible to hot tearing**
  - **No hot tears have been observed in any CF8C-Plus castings including components with cross sections ranging from 0.1” (2mm) to 9” (220mm) thick**
- **Post-Casting Heat-Treatment**
  - **CF8C is typically solution annealed after casting to homogenize structure**
  - **CF8C-Plus shows the best properties in the as-cast condition = process cost reduction**
- **Machining**
  - **Machining characteristics of CF8C-Plus are comparable to other austenitic alloys**
- **Welding**
  - **All weld trials have been successful on CF8C-Plus using commercially available weld fillers**

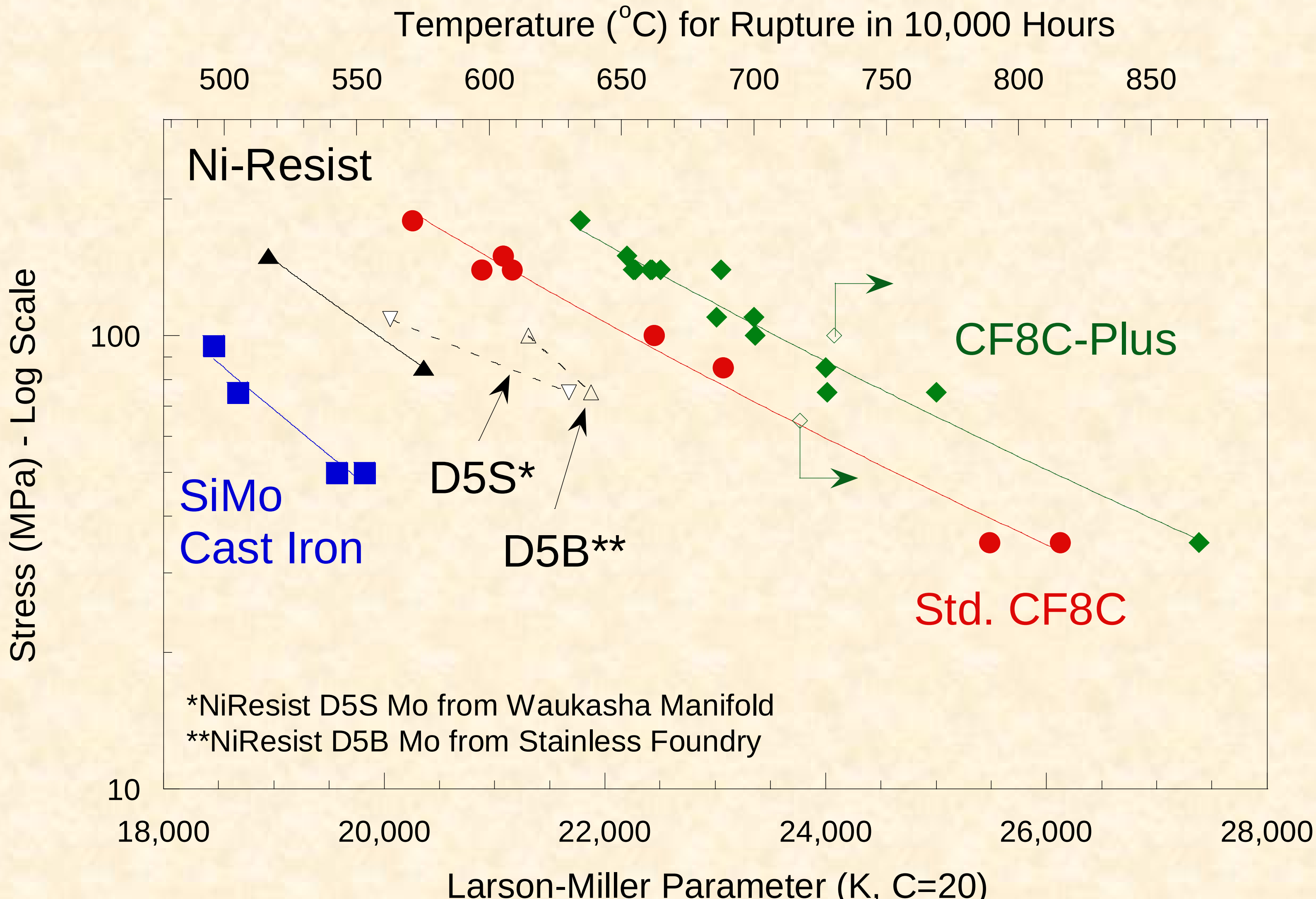
Typical Composition (wt%)

	Cr	Ni	Fe	Mn	Mo	Nb	C	Si	Other
CF8C	19.0	**10.0**	Bal.	<1	0.3	0.80	0.07	1.0	
CF8C-Plus	19.0	**12.5**	Bal.	**4.0**	0.3	0.80	0.10	**0.5**	**0.25N**
SiMo			Bal.	0.3	0.6		3.45	4.0	
Ni-Resist	2.0	**35.0**	Bal.	0.5			1.90	5.0	

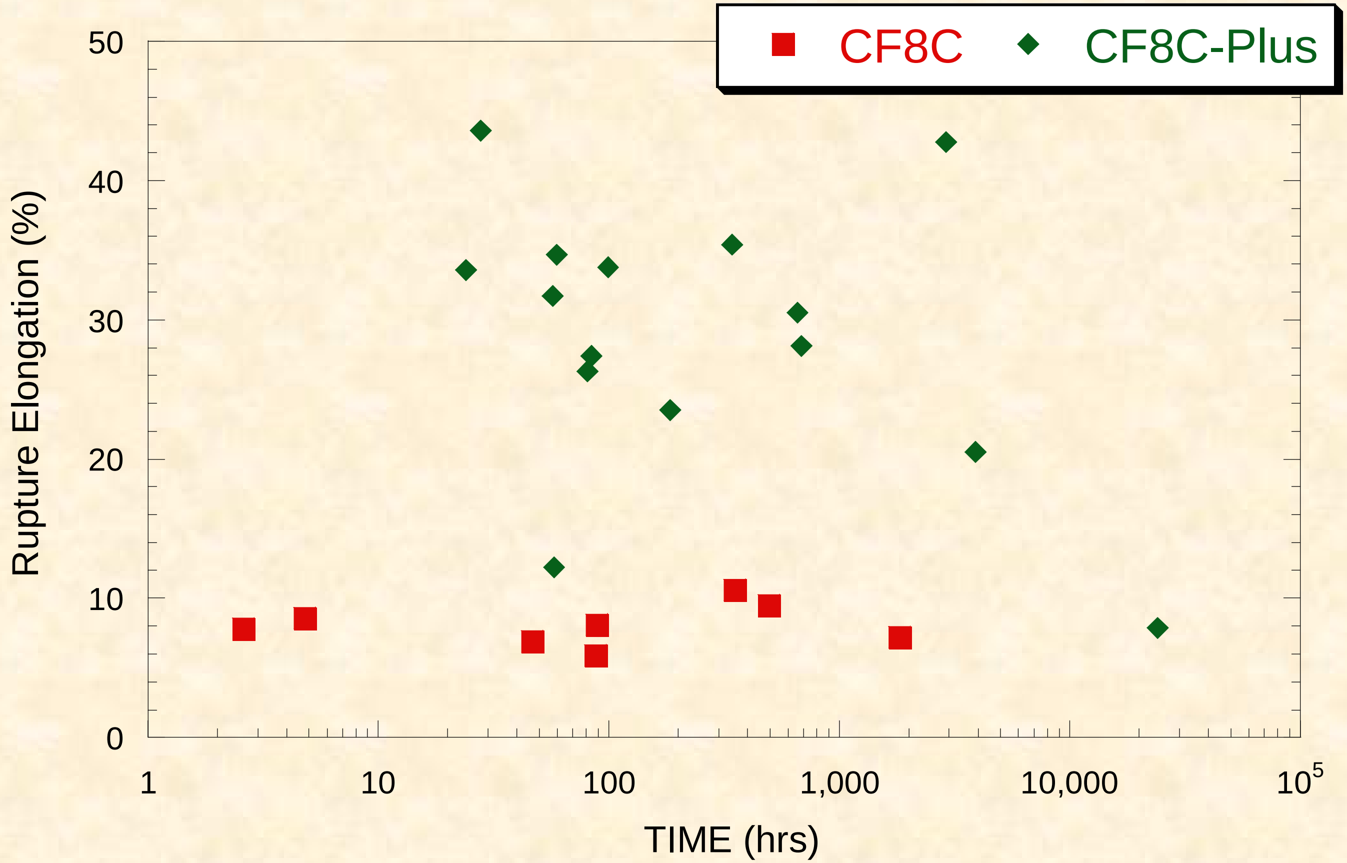
SiMo Cast Iron = Current Alloy of Choice for Diesel Applications

NiResist = Austenitic Iron used in some applications in place of cast iron (good casting properties – many variants)

CF8C-Plus has much greater creep strength compared to current materials and shows large improvements compared to CF8C



CF8C-Plus has improved creep strength & ductility compared to CF8C



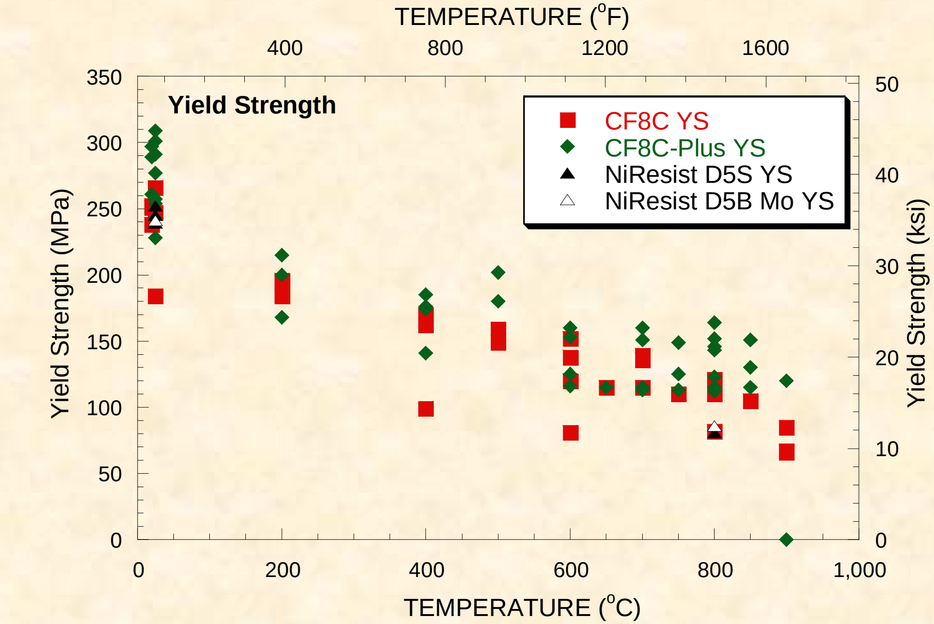
Creep-Rupture Ductility for CF8C and CF8C-Plus tested at 650 to 850C and 35 to 180 MPa

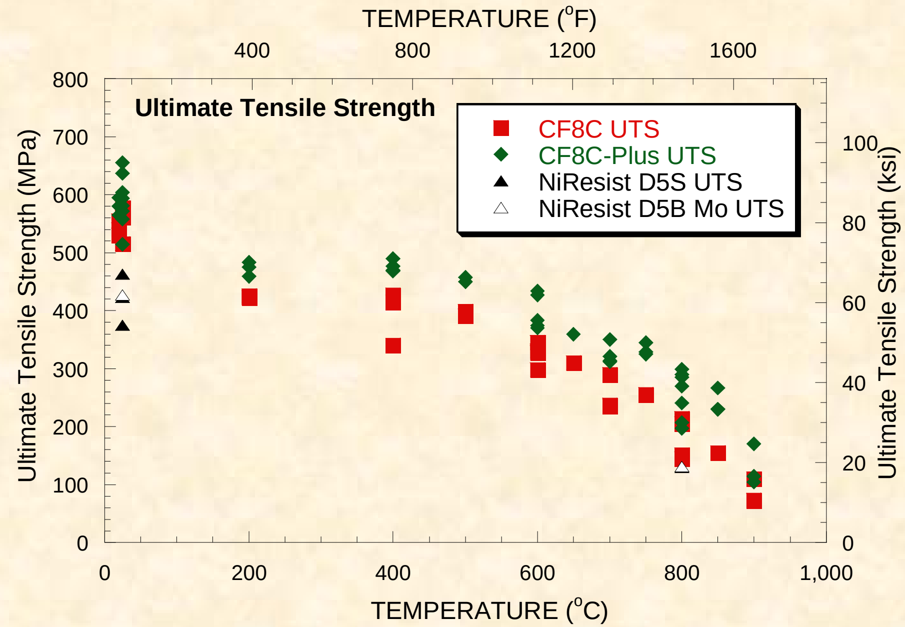
Reasons for Creep Strength Improvement

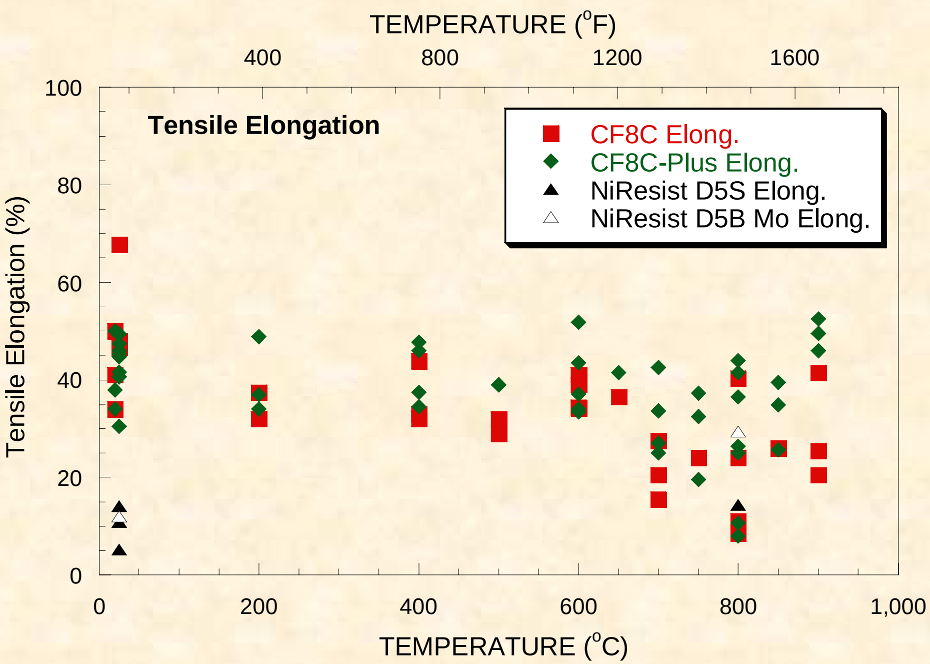
- Fully Austenitic Structure
- Elimination of Deleterious Phases (sigma)
- N Solid Solution Strengthening
- Synergistic Effect of Mn and N
  - Mn improves the solubility of N in austenite
  - Mn and N alter MC carbide precipitate structure
    - Stacking Fault – Partial Dislocation precipitation mechanism (Silcock and Tunstall)
    - Rejection of Mn and N at NbC interface
    - Solidification differences between CF8C and CF8C-Plus

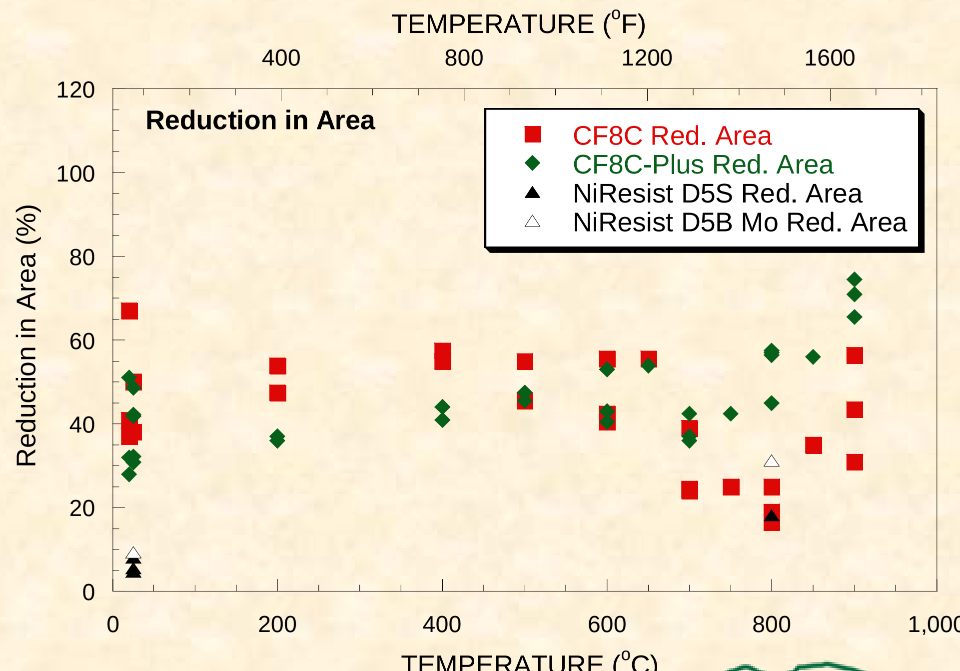
CF8C-Plus shows improved Mechanical Properties compared to CF8C for:

- **Yield Strength at Temperature**
- **Tensile Strength at Temperature**
- **Tensile Ductility at Temperature**
- **Low Cycle Fatigue Resistance at 650 to 850C**
- **Thermal-Mechanical Fatigue**

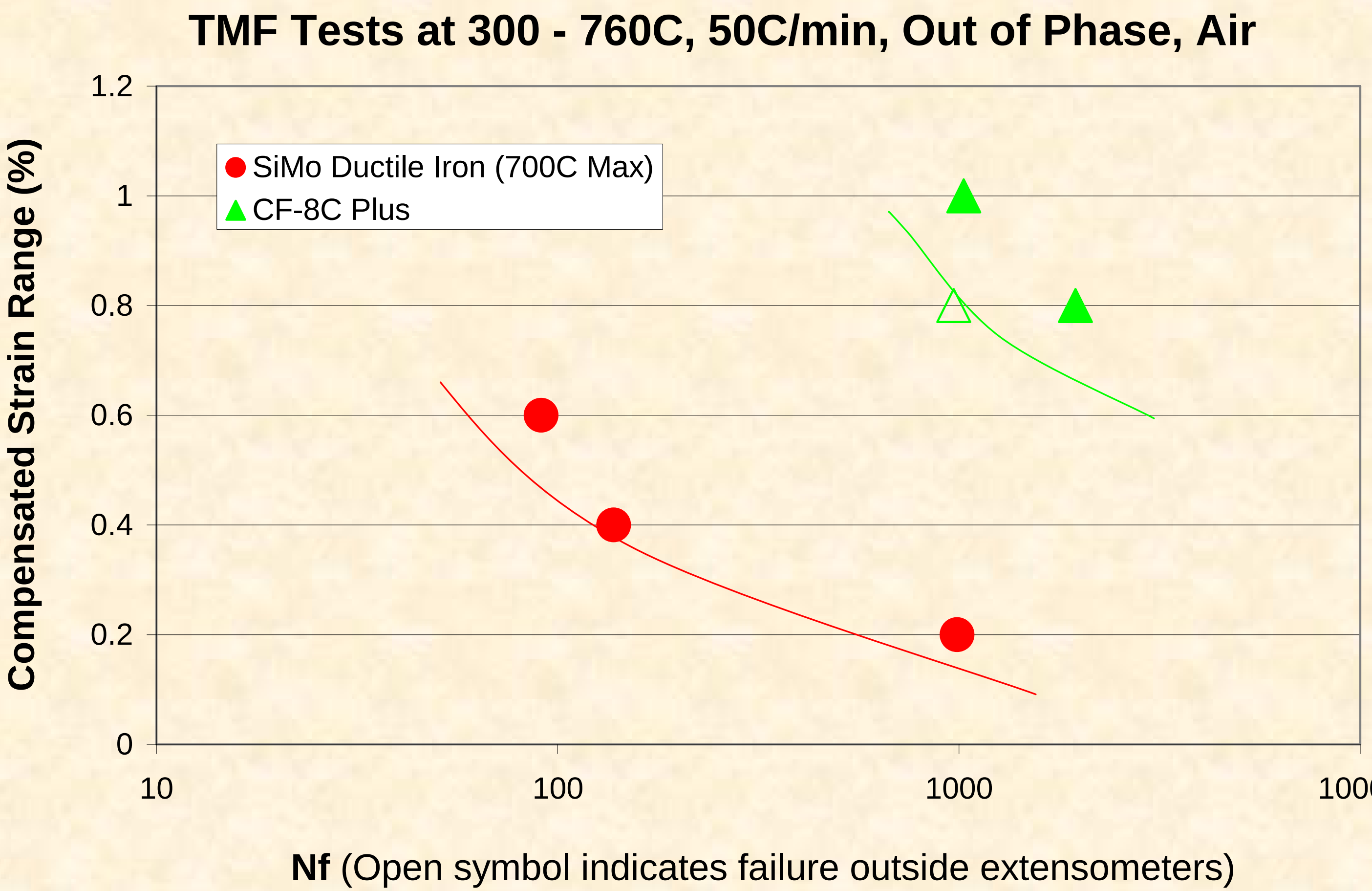

Yield Strength
CF8C YS
CF8C-Plus YS
NiResist D5S YS
NiResist D5B Mo YS
Yield Strength (MPa)
Yield Strength (ksi)
TEMPERATURE (°C)
TEMPERATURE (°F)


Ultimate Tensile Strength
CF8C UTS
CF8C-Plus UTS
NiResist D5S UTS
NiResist D5B Mo UTS
Ultimate Tensile Strength (MPa)
Ultimate Tensile Strength (ksi)
TEMPERATURE (°C)
TEMPERATURE (°F)

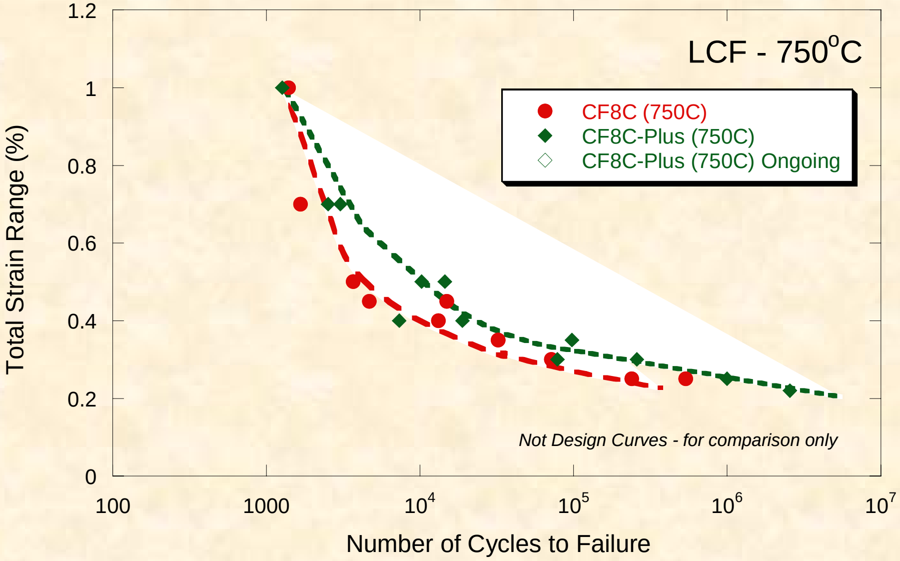

Tensile Elongation
CF8C Elong.
CF8C-Plus Elong.
NiResist D5S Elong.
NiResist D5B Mo Elong.
Tensile Elongation (%)
TEMPERATURE (°C)
TEMPERATURE (°F)

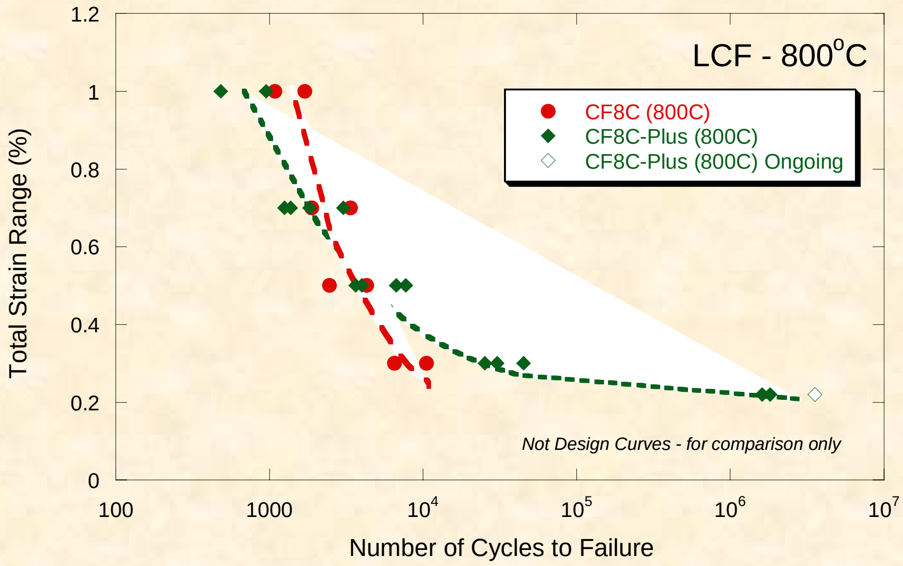

Reduction in Area
CF8C Red. Area
CF8C-Plus Red. Area
NiResist D5S Red. Area
NiResist D5B Mo Red. Area
Reduction in Area (%)
TEMPERATURE (°C)
TEMPERATURE (°F)

CF8C-Plus show a dramatic improvement over SiMo Cast Iron in Thermal Mechanical Fatigue (TMF)



CF8C-Plus shows improved Low-Cycle Fatigue (LCF) Resistance over CF8C

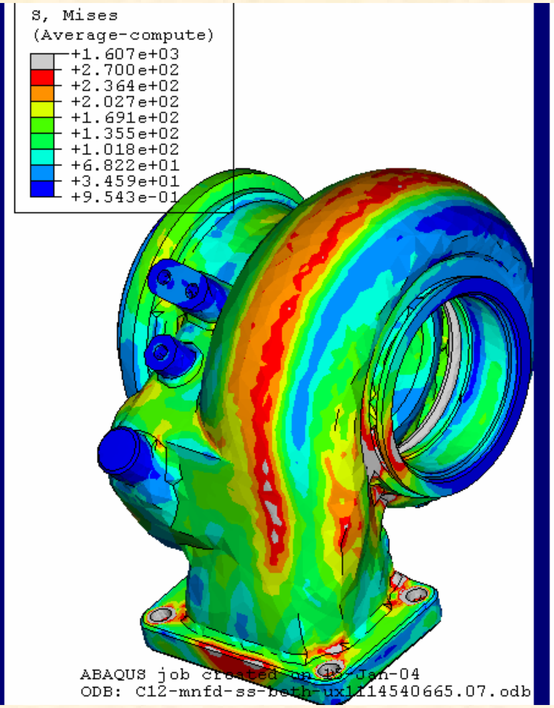


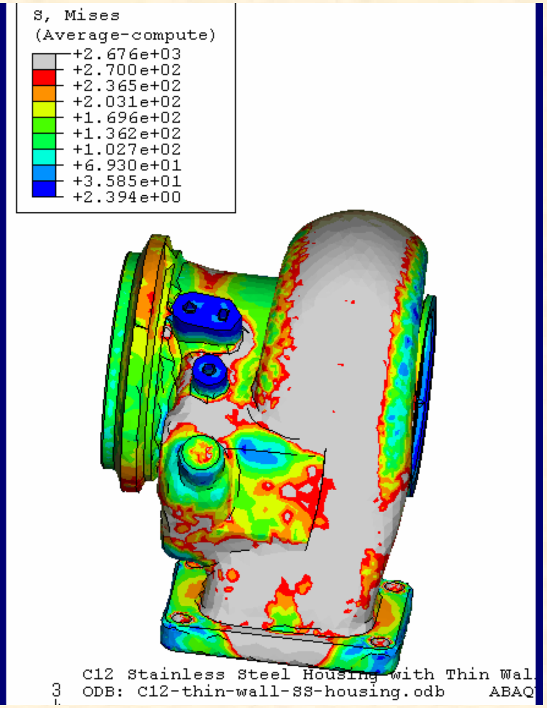


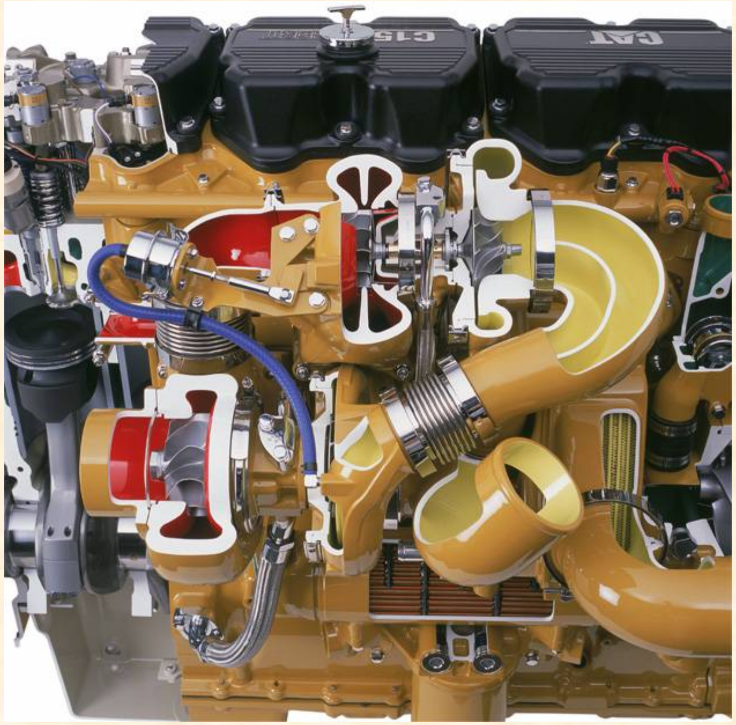
- **Low Cycle Fatigue (LCF) test results at 750 and 800C show CF8C-Plus approaches endurance limit at higher strain ranges**
- **Slow strain rate and creep-fatigue studies ongoing**

Commercial Interest Within CAT: Redesign and Replacement of SiMo Cast Iron

- **Potential for use in turbocharger housings and exhaust manifolds across the board as emissions requirements lead to increased exhaust temperatures.**





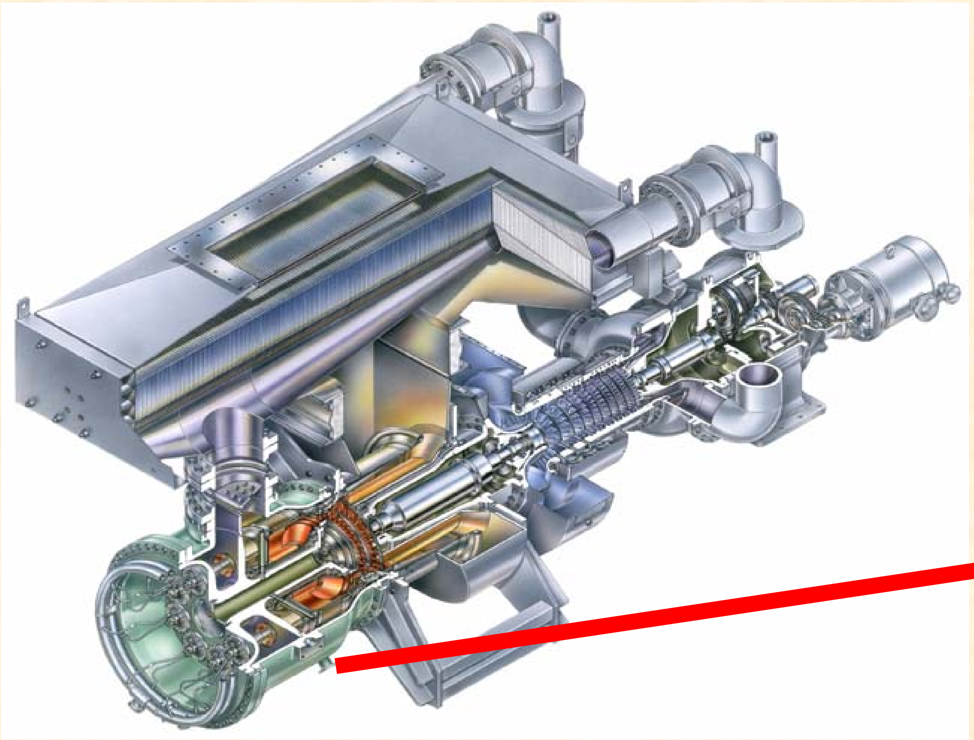


Prototype Parts Being Produced

Commercial Applications – Direct Replacement of NiResist for Natural Gas Reciprocating Engines at Reduced Cost *(Cost of CF8C-Plus = 80% of NiResist)*

80 lb (180kg) static sand-cast CF8C-Plus exhaust component cast by Stainless Foundry and Engineering, Inc.

Solar Turbines Mercury 50 gas turbine application: CF8C Upgrade



Solar Turbines 4.6 MW Mercury 50 recuperated low NO_x gas turbine engine

6,700 lb (14,800 kg) CF8C-Plus end-cover cast by MetalTek

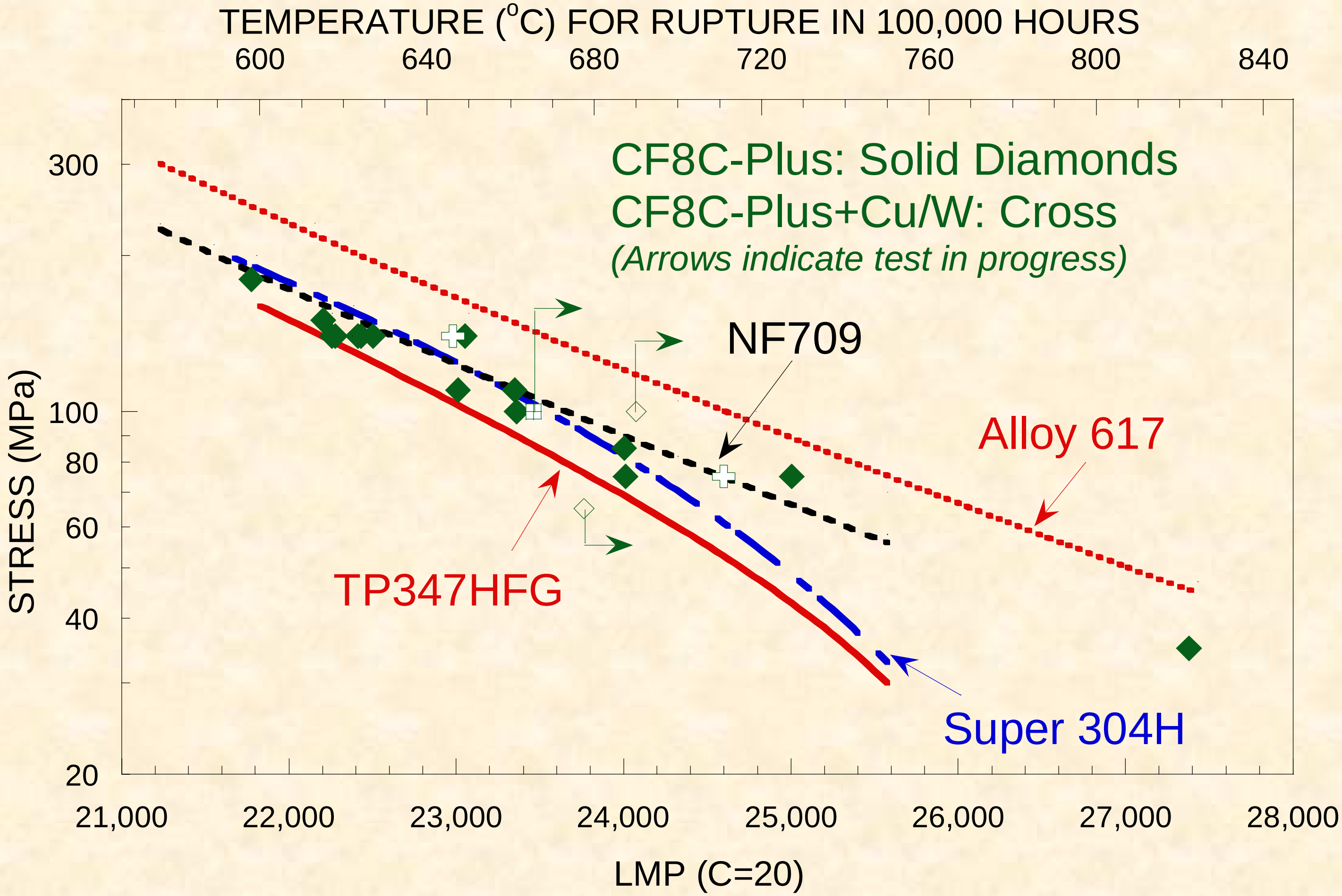
Centrifugally cast CF8C-Plus steel tubes for a global petrochemical company technology application

21,000 lbs (46,000kg) of Thin Wall Tubing Produced by MetalTek

Commercialization Summary

- Good high temperature strength, castability, and cost are driving applications of CF8C-Plus inside and outside of Caterpillar
- Trial licensees: MetalTek International, Wollaston Alloys, and Stainless Foundry & Engineering
- Over 30,000 lb of CF8C-Plus steel have been melted to date
  - Static and centrifugal castings
  - No Casting Defects or difficulties encountered
  - Casting sizes/weights range from 0.5 to 7,000 lbs with thin and thick walls
- Additional Alloy Modifications are being examined to:
  - Maximize Creep Strength: Cu and W
  - Improve corrosion resistance in steam/water vapor
- Potential for High-Temperature Plant applications such as USC turbine casings

Creep strength of CF8C-Plus compared to wrought austenitics and Ni-based alloys



Creep Strength and potential for further alloy modifications at low cost is driving additional interest including high-temperature plant applications