# High Strength, Light-Weight Engines for Heavy Duty Trucks


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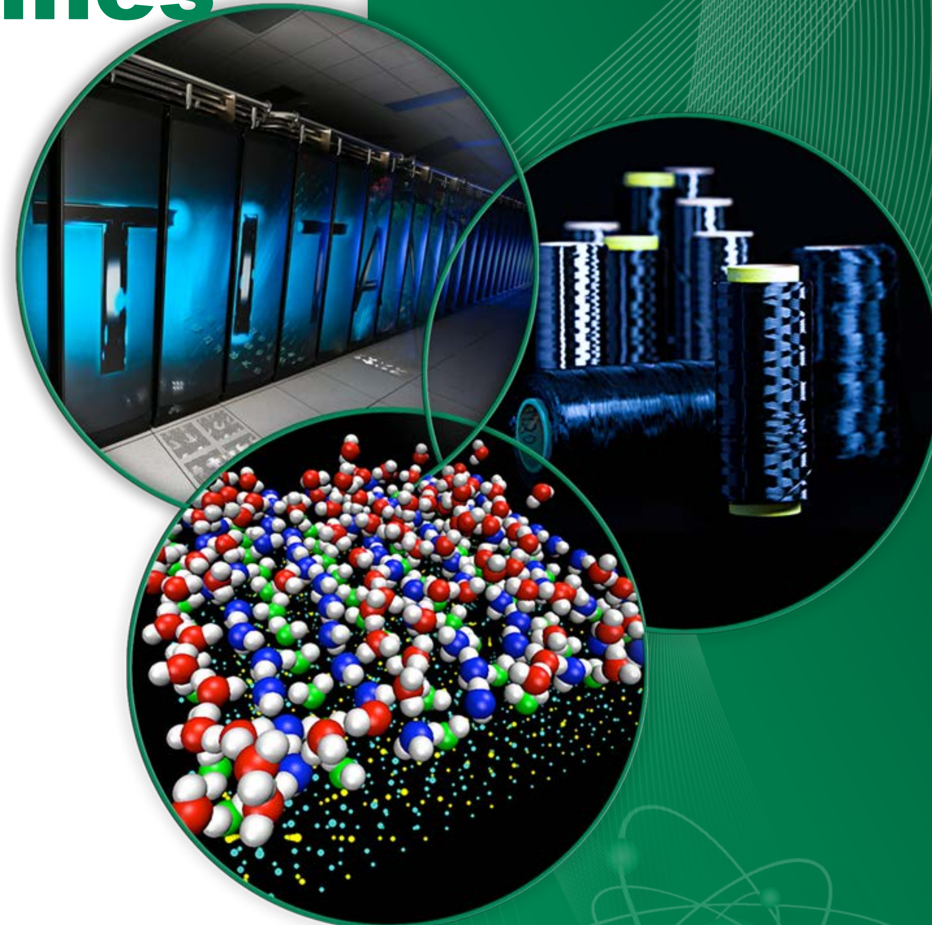

Project ID #PM 063

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# Overview

## Timeline

- Started FY12
- Completion FY17
- 35% Complete

## Budget

- Total project funding:
  50% DOE
  50% Cummins
- FY11:$250K
- FY12:$350K(CRADA start)
- FY13: $100K
- FY14  $200K

## Barriers

1. Changing internal combustion engine combustion regimes
2. Long lead times for materials commercialization
3. Need to reduce the weight in advanced technology vehicles

## Partners/Collaborations

- Interactions/ collaborations:
  - Cummins Inc.

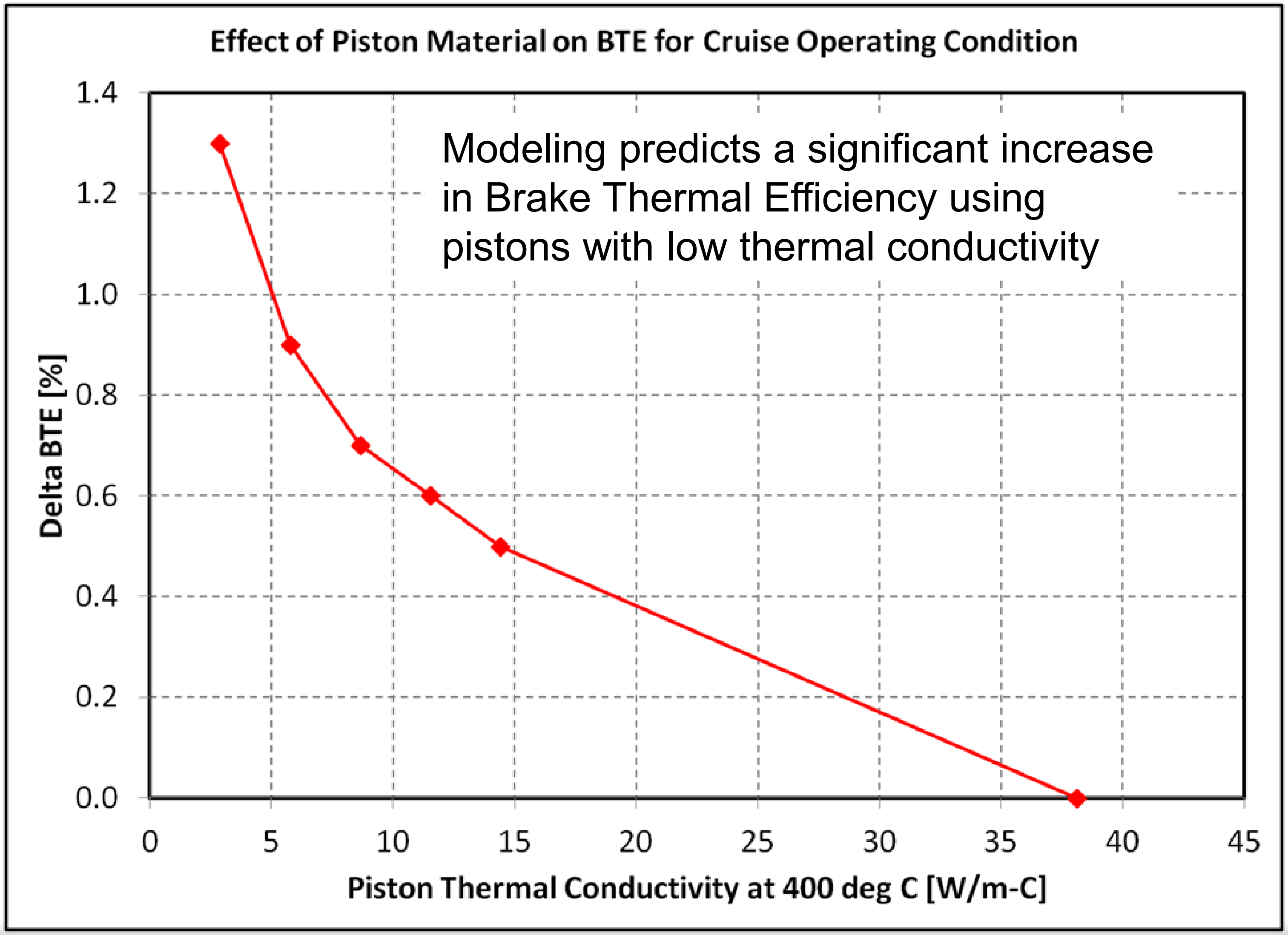
# Relevance: Increased Operating Temperatures are Anticipated in High-Efficiency Engines

- Increased operating temperatures and improved thermal management will enable increases in ***power density*** (greater power output for the same sized engine)
  - Allows engine downsizing (or light-weighting) for the same power output
- Use of thermal insulation to decrease heat loss in certain components to achieve improved efficiency will result in increased temperatures in selected components within the engine
- New materials are needed to allow the engine to reach the efficiency, commercially viable durability, and emission targets

# Relevance: New Materials Are Required to Achieve Improvement in Brake Thermal Efficiency (BTE)

- Cummins Development of high efficiency engine to achieve significant improvements in Brake Thermal Efficiency (BTE)
  - Basic thermodynamics indicates holding the energy in the gas increases pressure, and therefore power, with an equal amount of fuel.
  - Thermal modeling has quantified the possible increase in BTE achieved by decreasing heat losses within the cylinder
  - New piston materials are needed to decrease thermal losses, reduce reciprocating mass, and survive in this higher temperature combustion regime
  - Since greater heat is retained in the combustion gas, new exhaust handling materials are needed to withstand the higher exhaust temperatures between the cylinder and the turbocharger

# Relevance: New Materials Are Required to Achieve Improvement in Brake Thermal Efficiency (BTE)



# Objectives

- Develop/ identify alternate materials systems to enable **pistons** to withstand higher temperatures
  - Develop/identify alternate materials for pistons
  - Develop/identify thermally insulating coatings
  - Develop/identify piston design to decrease heat transfer
  - Modeling indicates that a piston with an effective thermal conductivity of 2W/m °C increases BTE by ~1.5%
- Develop/ identify alternate materials to high SiMo cast iron that would enable an increase in the operating temperatures of **exhaust manifolds**

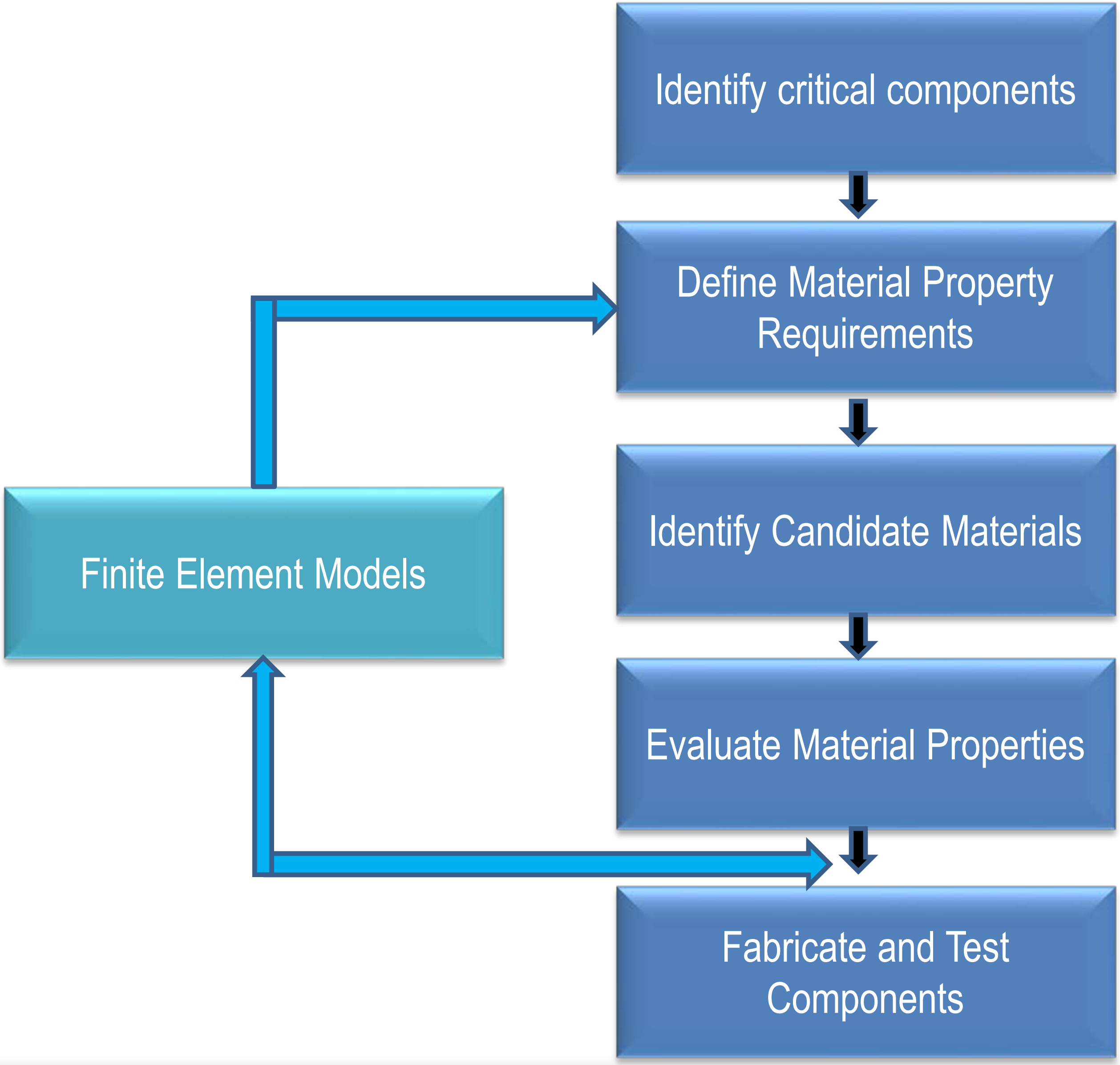
# Milestones

| Month/ Year | Milestone/ Go-No Go Decision | Description | Status |
|---|---|---|---|
| March 2013 | Milestone | Complete oxidation testing up to 5000 hours of representative compositions of high Si-Mo cast iron, D5S, TMA6301, TMA4705, Cast AFA, and a cast austenitic stainless steel with less than 20 wt. % Ni | Complete |
| June 2013 | Milestone | Complete constrained thermal fatigue testing of one composition from each class of alloys at one TMF condition | Complete |
| Sept. 2013 | Milestone | Compile all required property data for finite element modeling for at least two promising alloy composition classes for exhaust manifolds | Complete |
| Sept. 2013 | Go/No-Go | Identify next generation monolithic material choices for higher temperature operation of pistons, with capability of at least 50°C (preferably 100°C) over current design limit | Complete |
| Dec. 2014 | Milestone | Evaluate potential performance of down-selected alloy using finite element model and mechanical and thermal property data | Complete |
| March 2014 | Go/No-Go | Evaluate castability of selected candidate manifold alloy/s | Complete |
| June 2014 | Milestone | Identify materials issues related to fabrication of multi-material pistons via additive manufacturing | On Track |
| Sept. 2014 | Milestone | Fabricate and evaluate microstructures and thermal properties of multi-material composites on steel | On Track |

# Approach

- Evaluate existing component design, materials, and manufacturing processes using finite element modeling
  - Calculate component temperature and stress exposure conditions
  - Identify materials requirements for critical components
- Down-select candidate materials and perform materials testing
  - Identify initial materials microstructure and property characterization matrix
  - Select/develop candidate alloys and associated manufacturing process to satisfy the materials property and manufacturing needs
- Modify design, fabricate and test prototype component:
  - Down-select new materials based on assessment of properties of candidate materials
  - Fabricate components, evaluate their performance, and compare with requirements

# Approach Flow-Chart



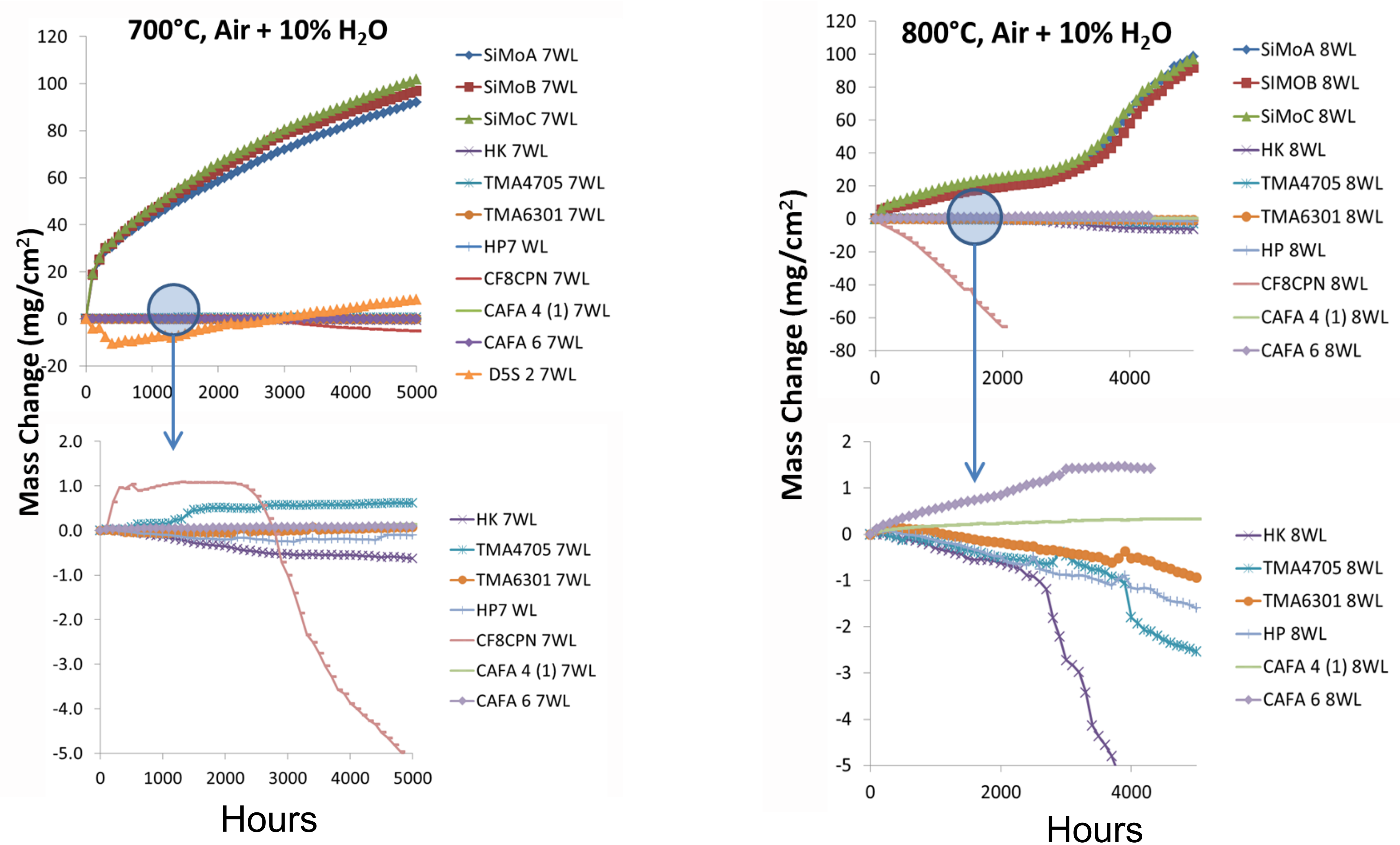
# Identified the Critical Property Requirements for Components

| Component | Critical material properties of interest |
| --- | --- |
| Exhaust Manifold | **Thermo-physical properties**: Thermal expansion coefficient, specific heat, density, elastic modulus, thermal conductivity<br>**Mechanical properties**: Room temperature strength, Constrained thermal fatigue strength, elevated temperature strength, high temperature fatigue strength, and creep strength<br>**Other Properties**: Oxidation resistance, microstructural stability at high temperatures, and the ability to cast in complex shapes. |
| Piston | **Thermo-physical properties:** Thermal conductivity, density, thermal expansion and specific heat.<br>**Mechanical Properties**: Constrained thermal fatigue strength, high temperature strength, and high temperature fatigue strength<br>**Other Properties**: Oxidation resistance |

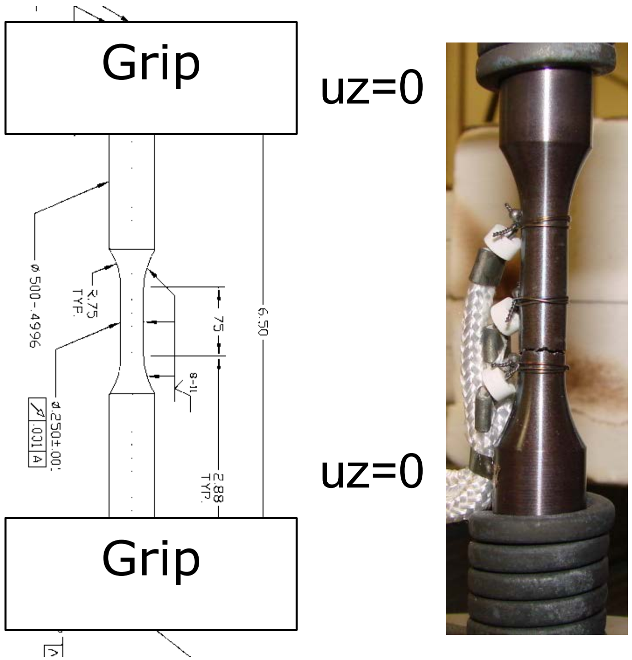
# Potential Alternate Candidate Alloys For Exhaust Manifolds Have Been Down-selected

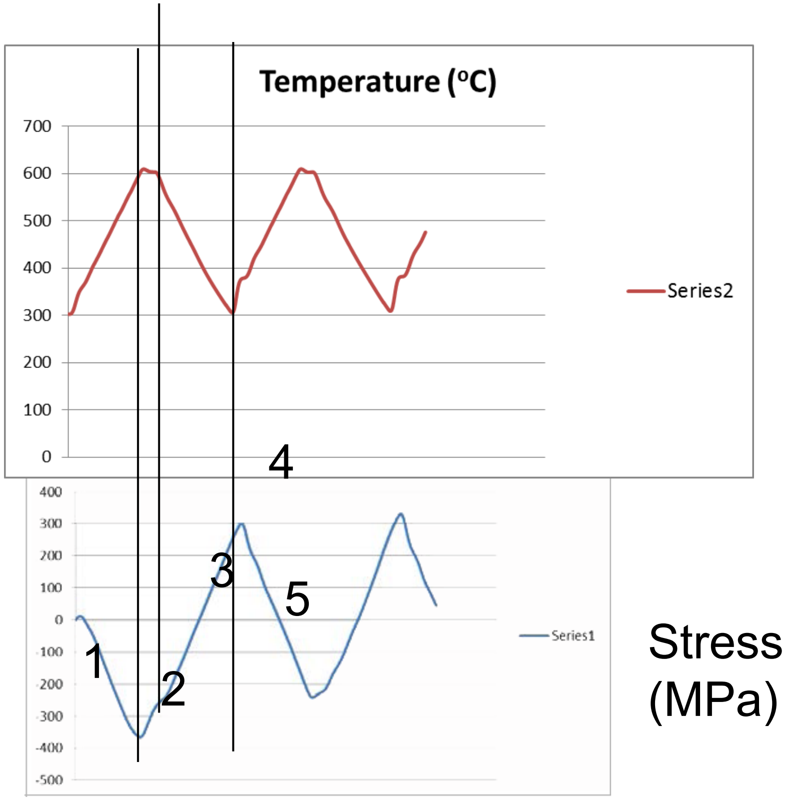
| Alloy | Type of Alloy | Fe | Cr | Ni | Mn | Mo | Nb | W | Si | C | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| High SiMo Cast Iron | Nodular ferritic cast iron | Bal. | | | 0.3 | 0.6 | | | 4.0 | 3.45 | Baseline alloys |
| D5S | Nodular austenitic cast iron | Bal. | 2 | 35 | 0.5 | | | | 5 | 1.9 | High performance cast iron |
| Cast CF8C+ (ORNL Patent) | Cast Austenitic | Bal. | 19 | 12.5 | 4.0 | 0.3 | 0.8 | 0 | 0.5 | 0.1 | 0.25N<br>Low Ni, cost, chromia forming alloy |
| TMA 4705 (ORNL Patent) Nominal | Cast austenitic | Bal. | 26 | 23.5 | 0.6 | 0.47 | 0.35 | 0.28 | 1.33 | 0.6 | Intermediate Ni, chromia forming alloy |
| TMA 6301 (ORNL Patent) Nominal | Cast austenitic | Bal. | 24 | 34.2 | 1.0 | 0.02 | 0.41 | 0.35 | 1.22 | 0.43 | Higher Ni, chromia forming alloy |
| HK30 | Cast austenitic | Bal. | 25 | 20 | | | | | | 0.3 | Standard grade |
| Cast AFA (ORNL patent) | Alumina-forming Cast austenitic | Bal. | 14 | 25 | 2 | 2 | 1 | 1 | 1 | 0.45 | Arc casting data only, Al 3.5 C:0.2-0.5 |

# Accelerated Oxidation Testing at 650-800°C of Candidate Exhaust Manifold Alloys in Air + 10% Water Vapor Demonstrates Advantages of Stainless Steels



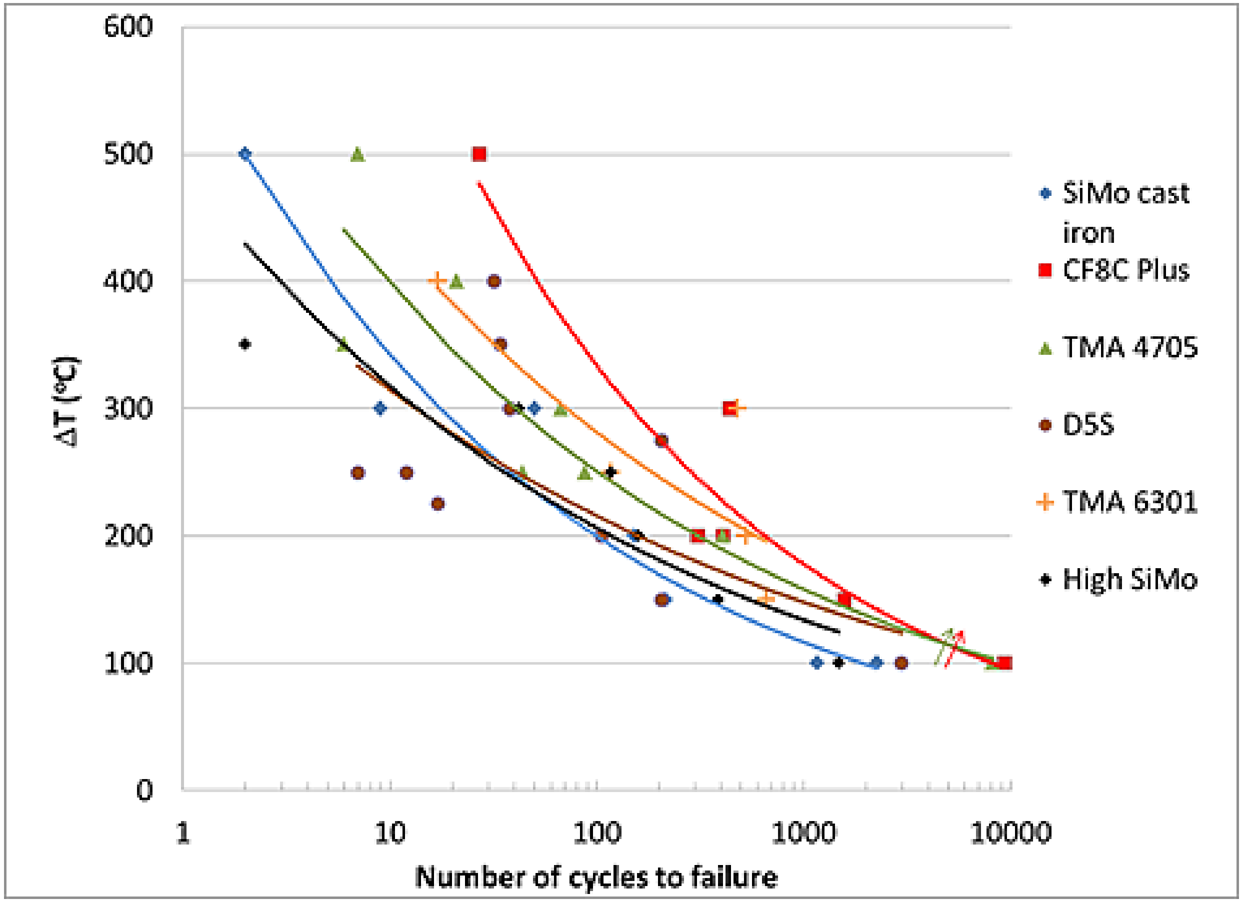
# New Constrained Thermal Fatigue Test System Has Been Developed




1 – heating leads to compressive thermal stresses (αΔTE)
2 – compressive stress relaxation (creep) at maximum temperature hold
3 – cooling to minimum temperature leads to tensile thermal stresses
4 – fatigue hardening or softening curve is dictated by ΔT and Tmax
5 – repeat the decrease in stresses due to heating

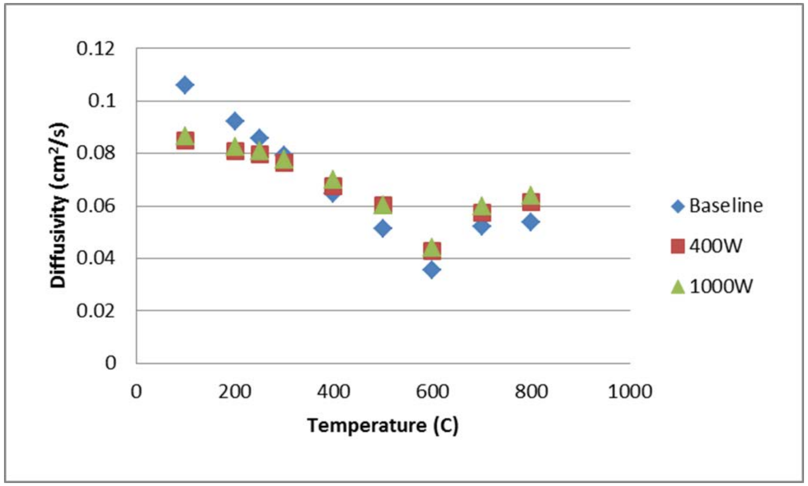
# CF8C+ Shows Best Constrained Thermal Fatigue Properties

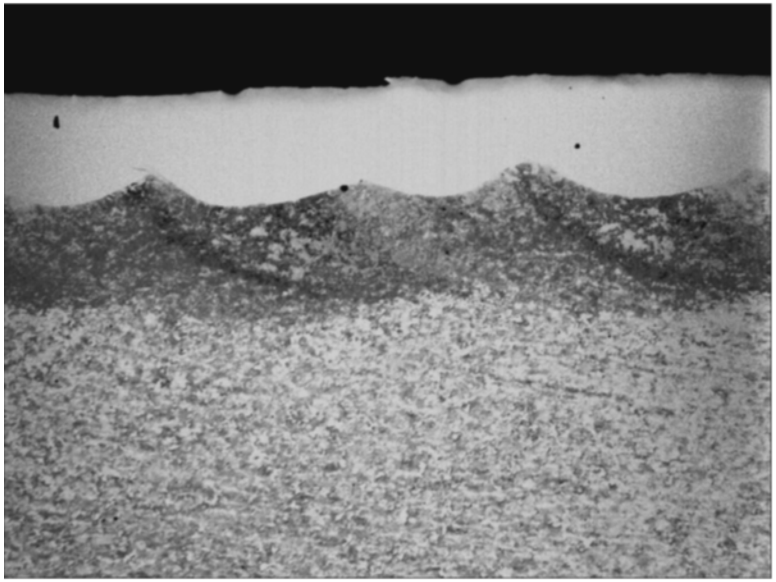


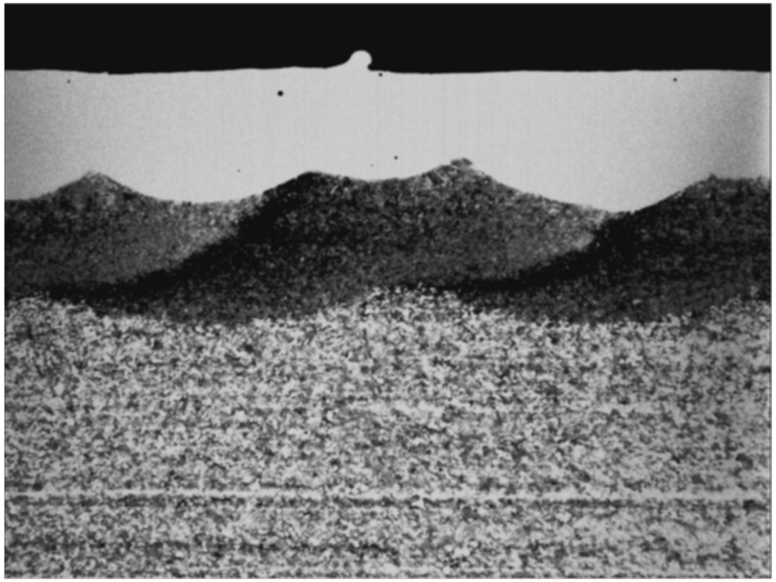

**CF8C+ has been downselected for casting prototype exhaust manifold due to best combination of properties and castability**

# Pistons Have Been Coated to Reduce Thermal Diffusivity

- Alloy 625 coatings were applied to 4140 steels at ORNL using laser-based technique
  - 25% decrease in thermal diffusivity was observed up to 300ºC





Laser power: 400 Watt 200µm

1000 Watt

# Response To Reviewer's Comments

- Project was not reviewed last year

# Barriers

- Technical barriers of importance
  - Finite element modeling tools can only be used as a general guide for the design of exhaust manifolds
    - Temperatures and stresses are higher than those experienced previously
    - New materials have very different mechanical properties compared to cast iron, the material for which the models have been validated
  - Limited foundries are capable of successfully melting and pouring CF8C+ to cast exhaust manifolds
    - Guidance for foundry practices provided by ORNL
  - Standard Lab scale tests to simulate thermal cycling of pistons are not available
    - Temperature and thermal cycles experienced by the piston are difficult to characterize accurately and need to be approximated using models

# Future Work (FY14)

- An exhaust manifold will be cast using CF8C+ at a commercial foundry with previous experience and integrity and materials properties will be evaluated
- Feasibility of additive manufacturing of multi-material pistons will be evaluated
- Effect of alternate thermal barrier coatings on thermal properties of steel substrates will be evaluated
- Durability of thermal barrier coatings on piston materials in the presence of thermal cycling will be evaluated

# Summary

- **Relevance:** Increased operating temperatures and improved thermal management will enable increases in ***power density*** (greater power output for the same sized engine) and allow engine downsizing
- **Approach/Strategy:**. New materials that have the potential to increase the temperature capabilities of pistons and exhaust manifolds will be identified. Components will be fabricated and tested.
- **Accomplishments:** One potential candidate (CF8C+) for exhaust manifolds has been identified based upon its oxidation resistance and constrained thermal fatigue properties. Thermal barrier coatings have been fabricated and feasibility to reduce thermal diffusivity in pistons has been demonstrated.
- **Collaborations:** This is a CRADA with Cummins
- **Proposed Future Work:** Prototype exhaust manifold will be cast, materials properties will be characterized, followed by engine testing. Fabrication routes for pistons including additive manufacturing and associated materials issues will be evaluated to enable a path towards low thermal conductivity pistons.