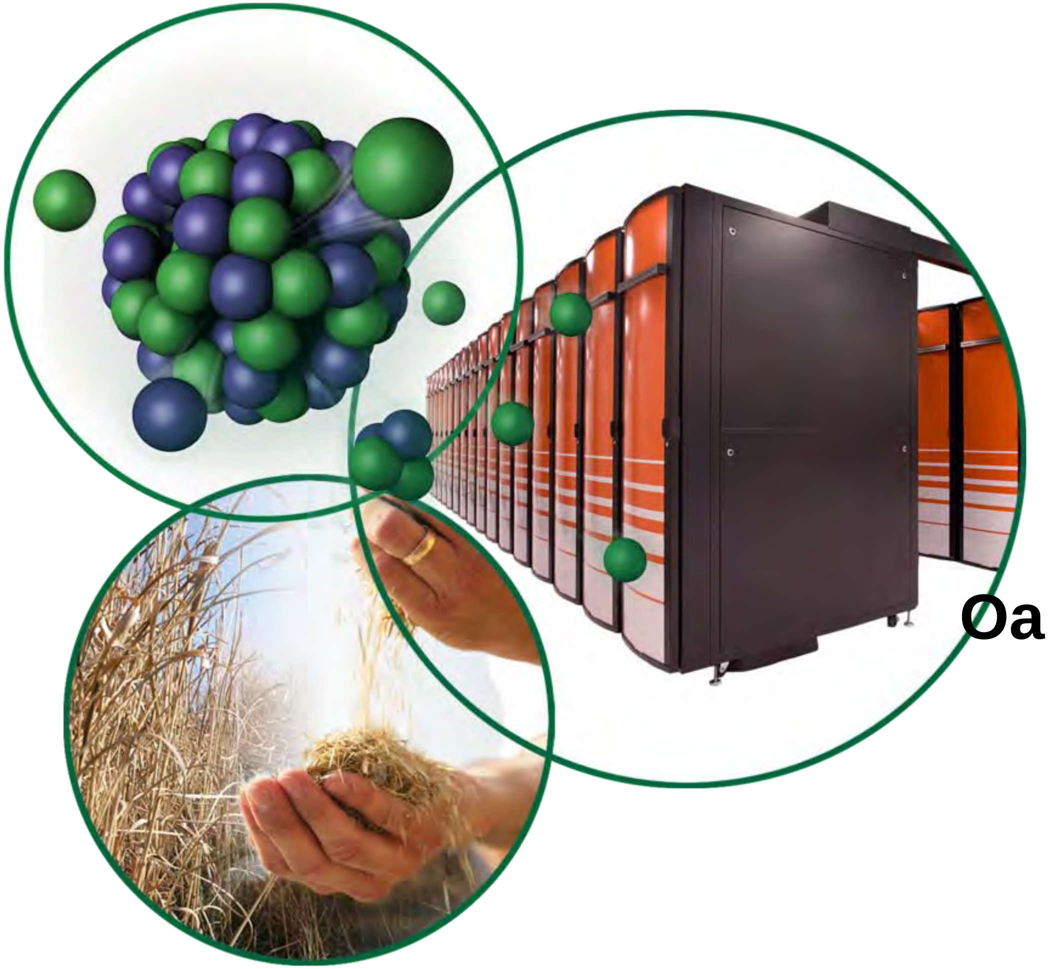
Life Cycle Modeling of Propulsion Materials



Sujit Das

Oak Ridge National Laboratory

May 11, 2011

Project ID: PM034

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Start – Oct. 2008
- Finish – Sept. 2011 & beyond
- 10% Complete for FY11

Budget

- Total project funding
  - $80K (FY'09)
  - $185K (FY'10)
  - $185K (FY'11)

Barriers

- Advanced propulsion materials needed to meet various multi-year Vehicle Technology program goals are several times more expensive than conventional steel – would they be economically viable, energy-efficient, and environmentally friendly when commercialized?
- Specific technology improvements affecting major cost drivers detrimental to technology viability based on upfront costs in light-duty vehicles
- Material viability in most cases determined on the basis of part by part substitution
- Vehicle retail price instead of life cycle cost consideration in light-duty vehicles

Study Objective

- **Life Cycle Energy and Environmental Evaluation of Downsized vs. Lightweight Material Automotive Engines**
- **Energy Benefits of CF8C+ Cast Austenitic Stainless Steel**

Milestones

- **Completed the life cycle energy and environmental evaluation of downsized vs. lightweight material automotive engines (August’10) – Presentation Focus**
- **Completed energy benefits analysis of CF8C+ cast austenitic stainless steel (Sept.’10) – Presentation Focus**
- **Estimate the life cycle cost-effectiveness of necessary materials changes for higher operating temperature and improved efficiency of light-duty internal combustion engines (Sept.’11)**

LCA Approach Used for Energy and Environmental Analysis of Alternative Engine Designs

- Four life cycle stages considered – extraction and materials processing, manufacturing (limited), use, and vehicle disposal
- Focus on engine components and sub-assemblies that are different among three design options representing following share of total engine weight– baseline (58%); downsized (56%); and magnesium lightweight material (54%)
- Baseline engine – 2009 Ford Fusion with the Duratec 3.0 L V6 engine; Downsized – VW Passat or 2008 Mini Cooper S 2.0 L I4 engine
- End-of-life component recycling rate varies by material type: ferrous and aluminum (85%) and magnesium (75%)
- SimaPro LCA software used and new life cycle materials inventory data were developed for the analysis
- Life cycle energy estimate is based on Cumulative Energy Demand method whereas for environmental impacts IPCC GWP 100a and EcoIndicator methods are used

Major Engine Components Considered...

Component	Baseline		Downsized		Lightweight	
	Material Type	Weight (lbs)	Material Type	Weight (lbs)	Material Type	Weight (lbs)
Crankshaft	Steel, MnVS,	45	Steel, MnVS	39	Steel, MnVS	45
Cylinder Block	Aluminum B380, Diecast	60	Aluminum B380, Diecast	48	Magnesium AZ91, Diecast	40
Cylinder Head	Aluminum A319-T5, Sand Cast	61	Aluminum A356-T6, Sand Cast	38	Aluminum A319-T5, Sand Cast	61
Camshafts	Nodular Iron, Cast	10	Nodular Iron, Cast	12	Nodular Iron, Cast	10
Front Cover	Aluminum A380, Diecast	7	Aluminum A380, Diecast	6	Magnesium AZ91, Diecast	5
Intake Manifold	Nylon 6, Inj. Mold	7	Nylon 6, Inj. Mold	3	Nylon 6, Inj. Mold	7
Lower Intake - Upper Plenum	Aluminum A319-T5, Cast	6	-	-	Aluminum A319-T5, Cast	6
Oil Pan	Aluminum A380, Diecast	11	Low Carbon Steel - 1000S	5	Magnesium AZ91, Diecast	7
Turbo Intake Housing	-	-	Aluminum A319-T5, Sand Cast	2	-	-
Turbo Bearing Support	-	-	SiMo Ductile Iron, Sand Cast	4	-	-
Turbo Exhaust Housing	-	-	Ni-Resist Iron, Sand cast	7	-	-
Others	-	152	-	129	-	152
Total	**-**	**360**	**-**	**292**	**-**	**334**

CF8C+ Energy Benefits Estimation Approach

- CF8C+ is a new heat- and corrosion-resistant cast CF8C stainless steel with improved high temperature strength and ductility
- Two specific potential markets considered
  - Automotive (exhaust manifolds, turbochargers)
  - Industrial gas and coal-fired steam turbines (casings/shells components such as valves, steam chests, nozzle box, and cylinders)
- Forecast period (2010-2025)
- Life cycle basis (material manufacturing, part manufacturing, and part use)
- Assumed market penetration rate and anticipated fuel efficiency improvement applied to the latest EIA annual market projections
- Energy benefits estimated annually and cumulatively
- Major driving force behind CF8C+ applications is projected to be its durability and cost-effectiveness – not considered in this analysis

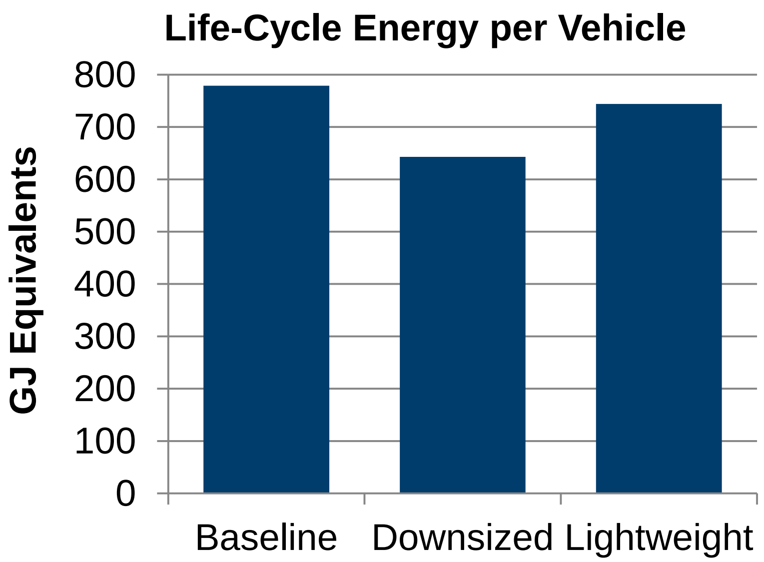
Market Characteristics of CF8C+ Potential Applications

- **Automotive Market**
  - Exhaust manifolds and turbocharger applications in cars and light- and heavy-duty trucks considered explicitly
  - CF8C+ would replace HK30 stainless steel
  - Important turbocharged gasoline engine (GDI) market is projected to grow from 5% in 2009 to 25% in 2014 and 75% in 2025
  - Gasoline engine benefit is limited to its increase in inlet gas temperature capability (1/3rd of NRC estimated turbocharging fuel economy improvement of 6% considered)
  - Only 0.66% fuel economy improvement available in saturated turbocharged diesel engine market
- **Turbine Market**
  - Supercritical and ultra-supercritical steam turbine markets considered -- thermal efficiency increases by 5% with steam temperature increase from 600C to 700C
  - CF8C+ would replace Ni-based superalloys such as Inconel 625
  - Generation-capacity additions may be limited (particularly in steam turbine markets) by slowly growing demand, existing excess capacity, and federal subsidies and state programs for renewables
  - 3200 lbs of CF8C+ in 150 MW steam turbine & 50MW gas turbine; 10,000lbs of CF8C+ in 125 MW combined cycle turbine

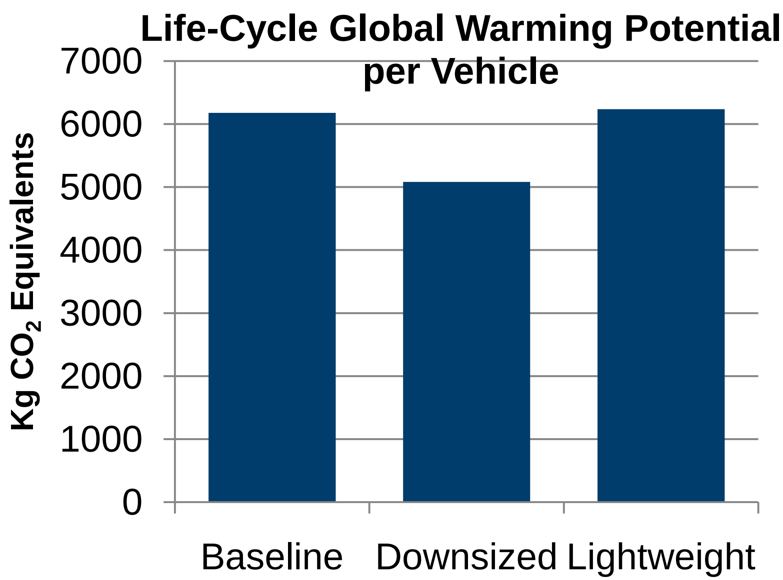
Technical Accomplishments and Progress

- **Life cycle modeling determined the relative energy, GHG emissions, and cost-effectiveness benefits of two competing lightweighting engine design options, i.e., downsized and turbocharged vs. lightweighting using magnesium**
- **CF8C+ has been demonstrated successful in several high-temperature applications, including its cost-effectiveness and so a life cycle energy assessment in potential future markets is consequential**
- **Several analysis levels considered, starting with raw material manufacturing and ending with component use and recycling with due consideration of fuel savings due to lightweighting**

Life Cycle Benefits of Alternative Engine Lightweighting



Life Cycle Stage	Baseline	Downsized	Lightweight
Manufacturing	15	10	18
Fuel Use	775	640	739
Recycling	-11	-7	-13
Total Energy	**779**	**643**	**744**



GHGs	Baseline	Downsized	Lightweight
Carbon Dioxide	5908	4861	5662
Sulfur Hexafluoride	11	13	324
Methane	227	188	216
Remaining substances	32	20	35
Total	**6178**	**5082**	**6237**

Cost-Effectiveness of Engine Lightweighting

Downsizing and Turbocharging

Engine Subsystem	Baseline ($)	Downsized ($)	Increment
Crank Drive	$200	$158	-($42)
Cylinder Block	$272	$279	$7
Cylinder Head	$399	$240	-($159)
Valvetrain	$297	$174	-($123)
Timing Drive	$71	$10	-($61)
Intake	$44	$16	-($28)
Fuel Induction	$55	$140	$85
Exhaust	$354	$327	-($27)
Lubrication	$42	$36	-($6)
Cooling*	-	$42	$42
Induction Air Charging	-	$281	$281
Others	$134	$234	$100
Total	**$1868**	**$1937**	**$69**

Magnesium Substitution

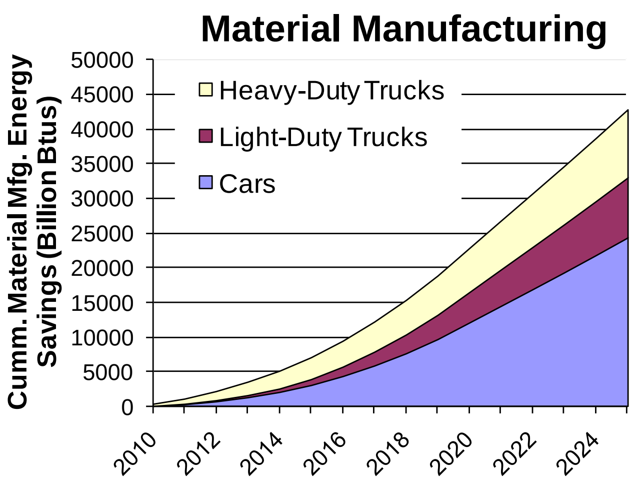
	Mass (lbs)	Cost Premium (per lb)	Incremental Cost
Aluminum	78		
Magnesium	52		
Weight savings	26	$3.89	$101

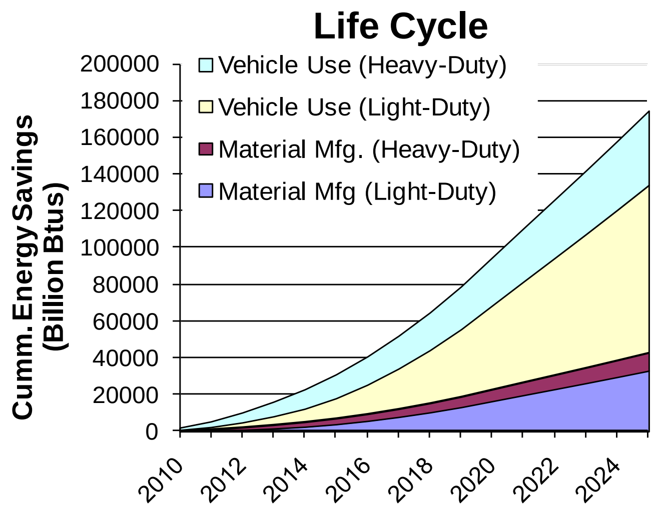
Major Observations re: Engine Alternatives…

- Turbocharging with downsizing offers the most engine lightweighting - 19% engine weight reduction compared to 7% for lightweight material engine
- Aluminum alloys will continue to be the preferred engine material with additional cast iron required for engine turbocharging components
- Fuel economy improvements are projected to be 10-30% for turbocharged and downsized engines compared to 1% for lightweight material engine
- Vehicle use phase dominates the life cycle energy use and emissions; thus, turbocharged and downsized engine provides the most life cycle energy and emissions benefits
- Downsized engine would also be the most cost-effective option. Cost per mpg fuel economy improvement is estimated to be $15.60 compared to $98 for lightweight material engine
- Magnesium use in lightweight material engine results in both higher energy and environmental penalties, the latter particularly because SF6 use continues. Magnesium substitution in engine alone cannot provide the estimated benefits obtained by turbocharged and downsized engines .

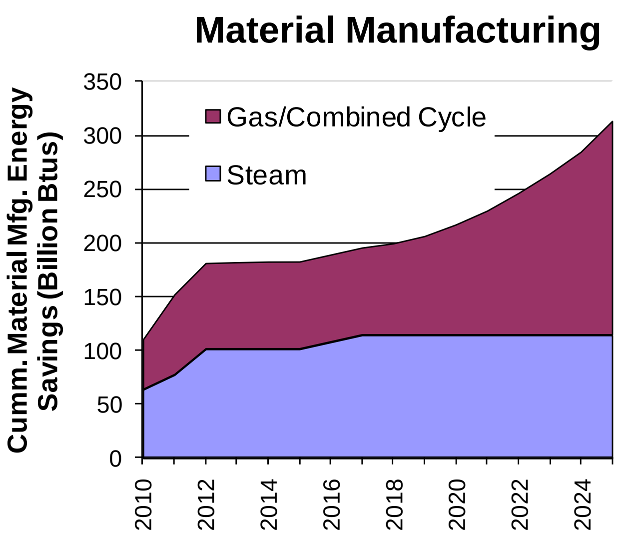
Projected CF8C+ Cumulative Energy Benefits

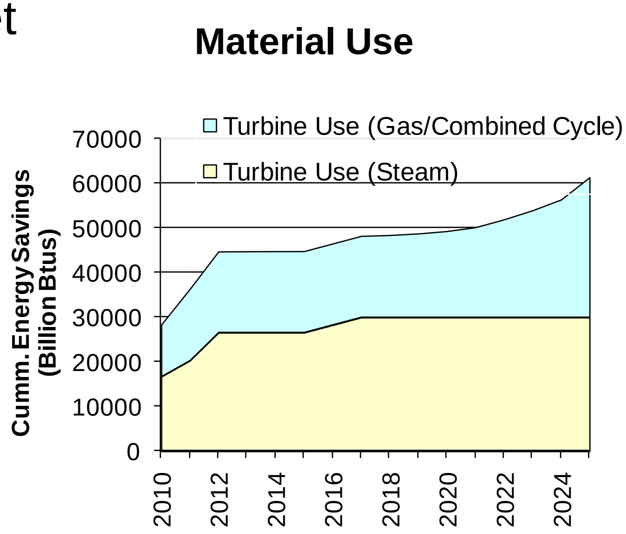
Automotive Market





Turbine Market





CF8C+ Energy Benefits -- Summary

Year	Automotive	Turbine	Total
2015	31	45	76
2020	94	49	143
2025	174	62	236

Note: Trillion Btus (unit)

- Projected energy benefits are estimated to be significantly higher in automotive market
- Total cumulative energy benefits by 2025 are estimated to be about 50% of 2006 total manufacturing energy use in transportation equipment
- Durability and cost-effectiveness would dictate early CF8C+ commercialization
- Potential energy benefits would significantly grow as other high temperature application industries are identified

Proposed Future Work

- **Life cycle impacts of alternative materials and materials-processing techniques that enable development of higher-efficiency conventional powertrains for ground transportation**
- **Viability of advanced propulsion materials in advanced powertrains such as hybrids and fuel cell vehicles**
- **Life cycle analyses considering economic, energy, and environmental impacts of advanced propulsion materials' manufacturing technologies with an emphasis on aluminum, magnesium, titanium, and ceramics**
- **Advanced propulsion materials' potential in heavy-duty vehicles**

Collaborations

- **Honeywell Turbo Technologies – identification of market and energy savings potential of CF8C+ in automotive market**
- **Siemens – turbine manufacturer**
- **MetalTek International – high alloy casting components manufacturer**
- **FEV Inc. – turbocharged and diesel automotive engine manufacturer**
- **University of Tennessee, Knoxville, TN – life cycle analysis of alternative lightweight engine designs**
- **Several high alloy raw material and component manufacturing suppliers**

Summary

- The turbocharged and downsized engine is the preferred lightweighting option from both energy and cost perspectives.
- Engine lightweighting by using magnesium allows only 1% engine weight reduction, thereby insignificant fuel economy improvements. In addition, its cost premium and potential environmental penalties need to be addressed.
- Energy savings from advanced propulsion materials must be examined not only on the basis of material manufacturing, but also in specific component applications to capture the major share of lightweighting benefits
- Advanced propulsion materials such as CF8C+ would provide significant energy savings in applications such as automotive and turbine (particularly gas) markets replacing heat- and corrosion-resistant stainless steel or nickel-base superalloys
- In both cases of downsized turbocharged engine and CF8C+ use in two selected potential markets, energy savings can be achieved at the material/component manufacturing step itself.
- Lower energy requirements would result in a decrease in life cycle GHG emissions, about 18% in case of downsized turbocharged engine.