Low-Mass and High-Efficiency Engine for Medium-Duty Truck Applications

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General Motors

6/23/2022

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Overview

Timeline

Project start date: 10/2019

Project end date: 12/2023

Percent complete: ~55%

Budget

Total project funding

- DOE share $7,007,878
- Non-Federal Share $3,294,329

Funding received in FY21

- $2,807,347

Funding for FY22 planned

- $1,160,427

Barriers/Technical Targets

Combustion Technology

- Advanced gasoline stoichiometric dilute combustion to achieve the target fuel economy requirement & deliver outstanding value to the customer

Materials Technology

- Lightweight, high performance, and low cost

Partners

Oak Ridge National Laboratory

The Ohio State University

Michigan Technological University

ECK Industries Inc

Project lead: General Motors

Relevance

Objective:

Develop a medium duty truck engine, compliant with EPA emission standards, utilizing advanced materials and combustion technologies capable of (relative to 2015 L96 VORTEC 6.0L V8 engine as defined by FOA):

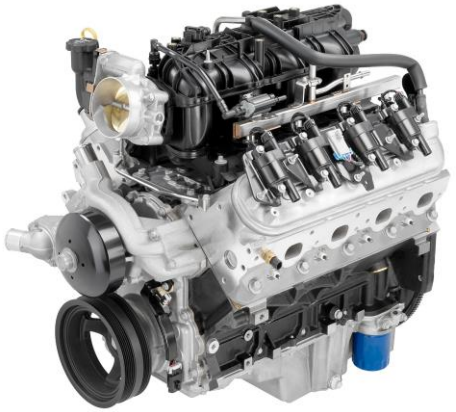
≥10% fuel economy improvement

≥15% engine weight reduction

Impact:

- The integrated R&D of advanced propulsion materials, manufacturing, and combustion strategies can not only expand engine operating efficiency, but also enable lighter weight engines for better performance and fuel economy.
- The technologies developed and demonstrated in this project will help bridge the technology gap between light and medium-duty engines.
- The approach and methodologies developed and implemented in this project can be readily applied to other material/component

Reduce energy usage and CO_2 emissions & increase energy security



2015 L96 6.0L V8 Engine (Baseline)

Chevrolet Silverado 3500HD truck with the baseline engine

Approach

Phase I - Research and Development | **Phase II - Validation and Demonstration**

2020 → 2021 → 2022 → 2023

Key Tasks

Task 1
- ❑ Simulate advanced combustion technology combinations
- ❑ Simulate durability at higher temperature and pressure
- ❑ Choose best combinations

Task 2
- ❑ Proof of concept physical testing using "basis" engine
- ❑ Develop materials and processes for Phase 2 testing on new engine
- ❑ Select technologies for Phase 2 new engine

Task 3
- ❑ Detailed design of new Phase 2 engine
- ❑ Fabricate parts for new engine
- ❑ Verify feasibility of new material and process innovations

Task 4
- ❑ Build and calibrate new engine
- ❑ Verify performance
- ❑ Post test evaluation of parts fabricated by new material and process innovations

Strategy & Work Streams

Fuel Economy Improvement: Simulation & Analysis → Engine Concept Testing

Weight Reduction: Simulation & Analysis → Engine Concept Testing

→ Design & Build Final Solution → Test & Validate Final Solution

Milestones

Month/Year	Description of Milestone or Go/No-Go Decision	Status
March 2022	Proposed medium duty truck engine hardware designed (GM)	Completed
June 2022	Key engine components produced with the developed material & manufacturing solutions (All)	On Schedule
Sept 2022	Thorough process modeling and durability analysis using ICME completed (GM, OSU, ECK)	On Schedule
Dec 2022	Go/No Go Decision #3 - An initial assessment is completed as to the capability of the new concepts to meet or exceed the project targets (All)	On Schedule
March 2023	Final evaluation of material and manufacturing solutions completed (All)	On Schedule
June 2023	Comparison of model predictions with experiment data completed (All)	On Schedule
Sept 2023	Final proposed medium duty truck engine testing completed (GM)	On Schedule
Dec 2023	Final proposed medium-duty truck engine weight evaluated, and vehicle fuel economy simulation completed (All)	On Schedule

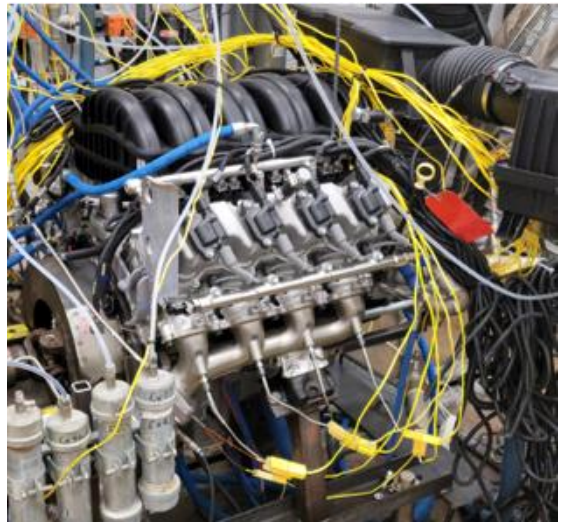
GM – General Motors, ORNL – Oak Ridge National Lab, OSU – Ohio State University, MTU – Michigan Technological University, ECK – Eck Industries Inc

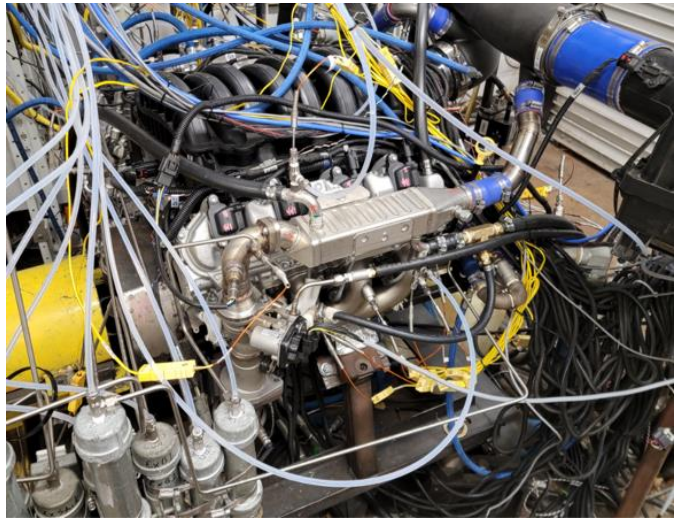
Technical Accomplishments

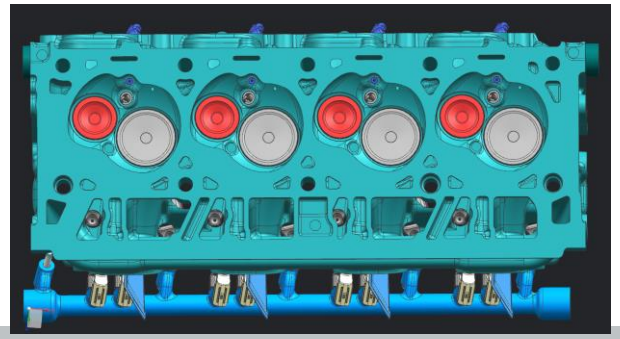
Fuel Economy Improvement TASK 2 - 2021 (Technology Research & Development)

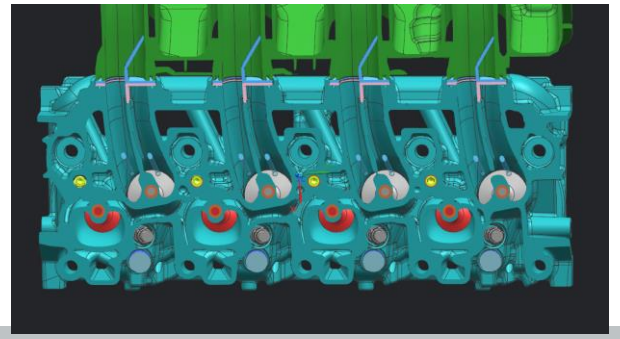
Design and build hardware to further develop TASK1 simulation predictions

- **Combustion system technology hardware to support test cell evaluation**
  - ✓ Advanced combustion system(s)
  - ✓ Advanced EGR dilution systems including E-EGR
  - ✓ Atkinson cycle strategies
  - ✓ Variable induction system strategies
  - ✓ Combustion chamber cooling strategies









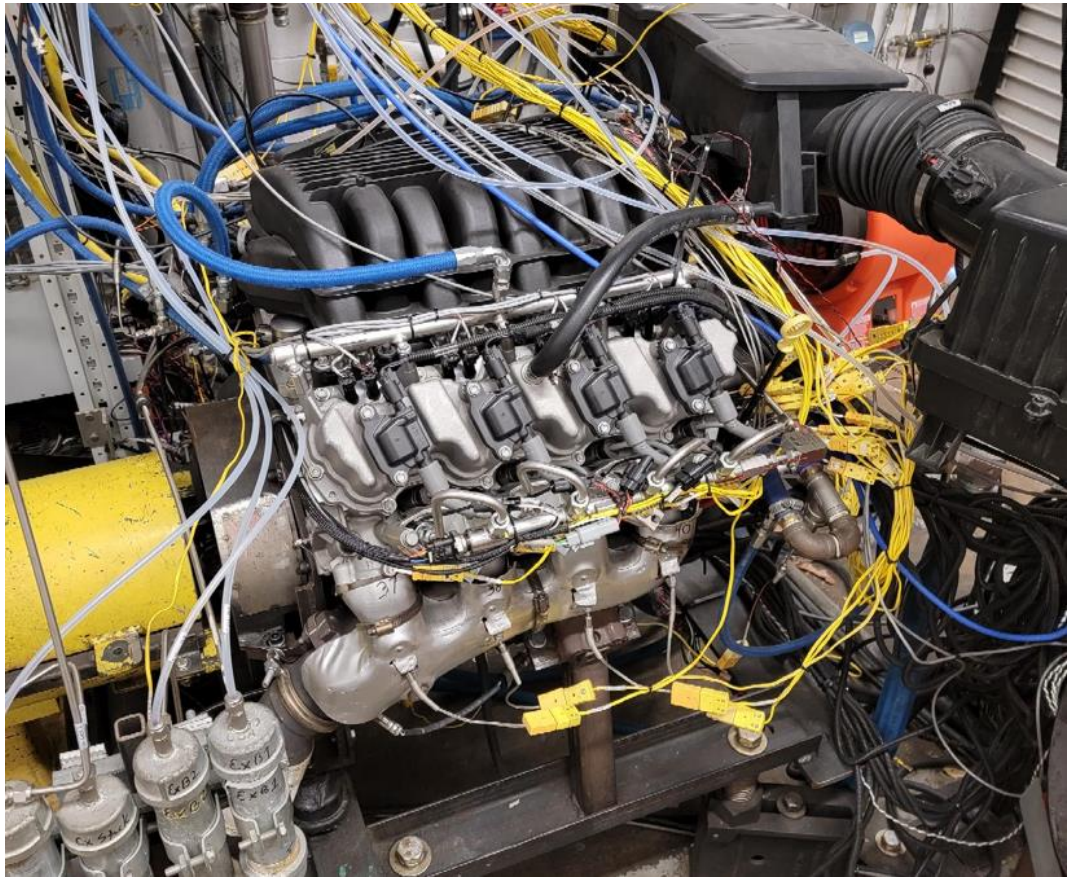
Technical Accomplishments

Fuel Economy Improvement TASK 2 - 2021 (Technology Research & Development)

Design and build hardware to further develop TASK1 simulation predictions

- **Developed combustion system technology hardware to support test cell evaluation**
  - ✓ Advanced fuel systems including “ultra” high pressure DI (1000 BAR)

(NOTE: Testing incomplete at time of presentation submission)



Technical Accomplishments

Fuel Economy Improvement TASK 2 - 2021 (Technology Research & Development)

Design and build hardware to further develop TASK1 simulation predictions

Fuel Economy Improvement Status vs Predicted

Measured Weighted Fuel Economy Improvement	
L96 Baseline	
PHASE1	0.7%
Charge Motion Control Valve (CMCV)	2.8%
E-EGR	1.8%
Full Authority Cylinder Deactivation	1.3%
UHP Direct Fuel Injection	TBD
Passive Pre-chamber Ignition	TBD
TOTAL:	6.6%

Predicted Weighted Fuel Economy Improvement from Simulation	
L96 Baseline	
PHASE1	
PHASE1 + Charge Motion Control Valve	4.4%
E-EGR	4.3%
Full Authority Cylinder Deactivation	1.3%
UHP Direct Fuel Injection	1.8%
Passive Pre-chamber Ignition	2.8%
TOTAL:	14.6%

Technical Accomplishments

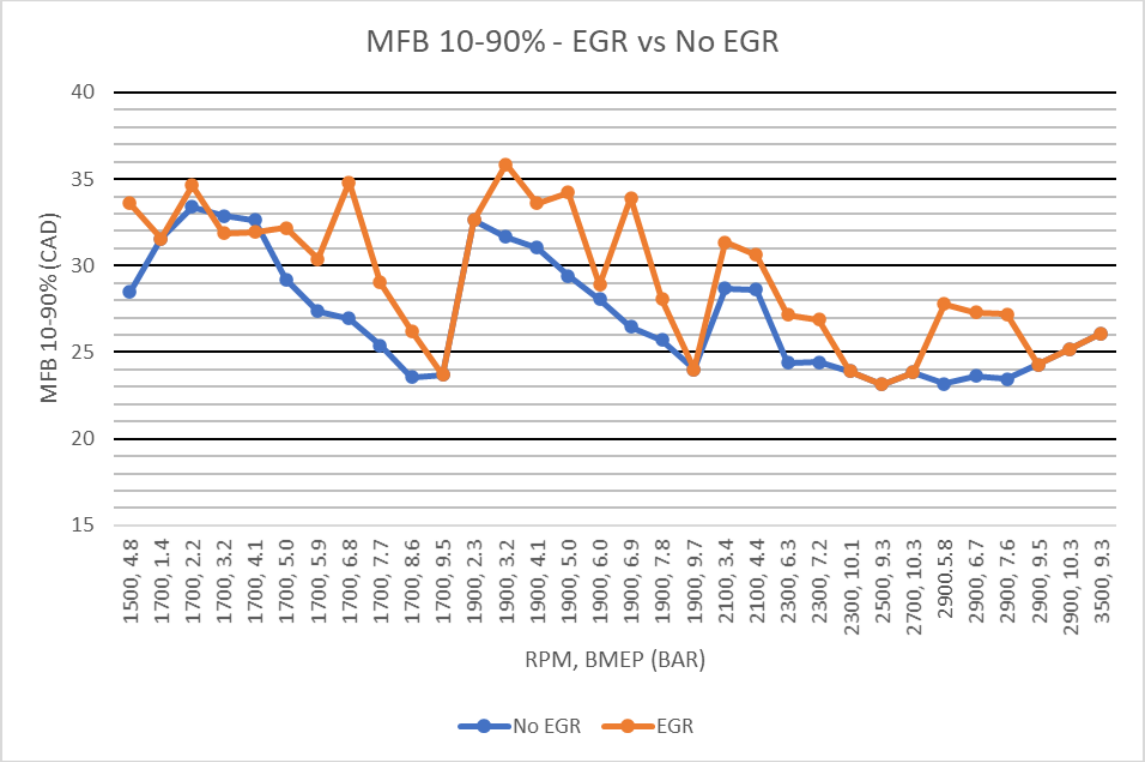
Fuel Economy Improvement TASK 2 - 2021 (Technology Research & Development)

Design and build hardware to further develop TASK1 simulation predictions

Conclusions and Next Steps

- Increased combustion speed is required to optimize fuel consumption performance
- Phase 2 engine design progressing to address these opportunities while enabling PCSP evaluation

Measured Combustion Performance



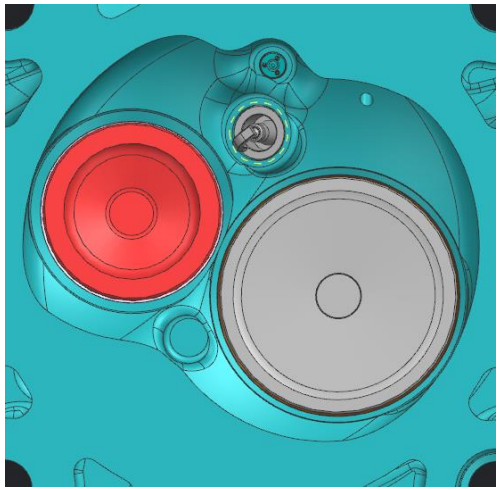
Technical Accomplishments

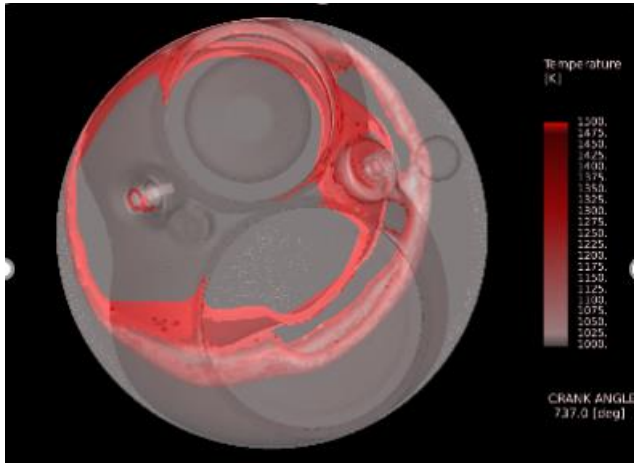
Fuel Economy Improvement TASK 3 - 2022 (Validation and Demonstration)

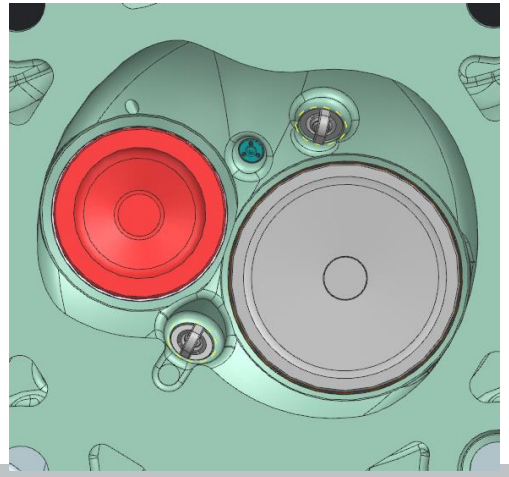
Detailed design of new Phase 2 engine

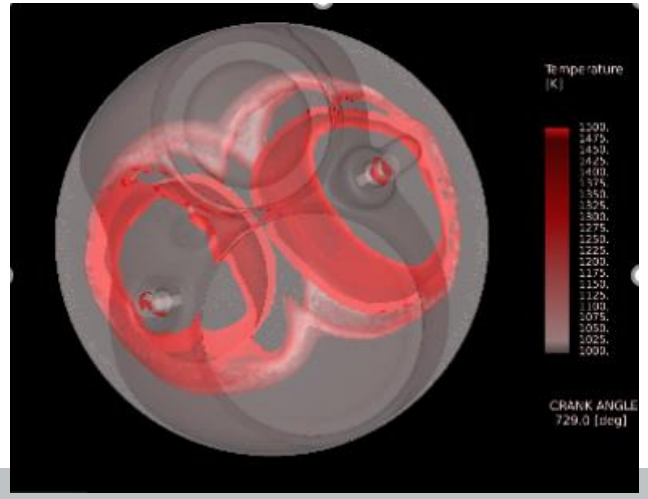
Combustion Analysis Progression

5200 RPM Full Load		Phase1	Phase2
SPKADV	DEG bTDCF	22	20
MFB 0-10%	DEG	23.5	23.2
MFB 10-50%	DEG	11.9	10.4
MFB 50-90%	DEG	25.6	17.1
MFB 10-90%	DEG	37.5	27.5









Technical Accomplishments

Materials and Manufacturing Solutions TASK 2 - 2021 (Technology Research & Development)

- **Mass Reduction Solutions**
  - ✓ New high performance cast aluminum engine block developed to replace iron block, saving mass by 56%
  - ✓ Hollow cast steel and ductile iron crankshafts developed to replace the forged steel crank, saving mass by 3%
  - ✓ Additive manufacturing (AM) aluminum piston with novel alloy developed to replace cast Al, saving mass by 3%
  - ✓ Overall engine mass saving by >20% over L96 baseline engine

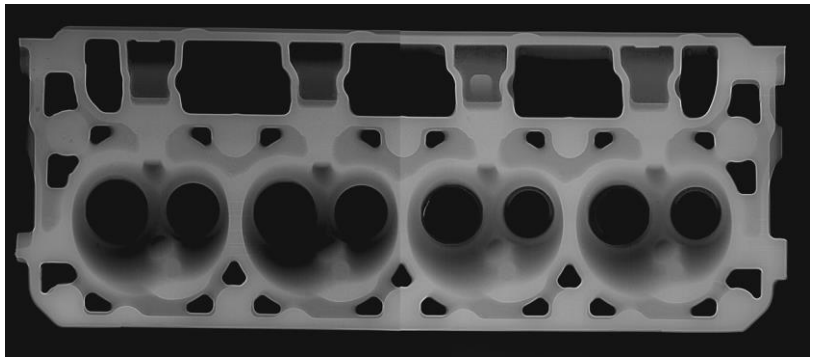
DOE FOA Baseline Engine		Phase 1 - R&D		
Key Parts (Kg)	**L96 6.0L V8 Engine**	**L8T 6.6L V8 Engine**	**DOE L8T 6.6L V8 Engine**	
			Option 1	Option 2
Engine Block	96.95 Cast Iron (250)	108.11 Cast Iron (250)	49.84 (Single Cast Al Block)	47.03 (Split Block = Cast Al+Mg)
Cylinder Head	10.76 Cast Al	11.16 Cast Al	11.16 Cast Al	11.16 Cast Al
Crankshaft	22.86 Ductile Iron	25.77 Forged Steel	25.53 Cast Steel	24.98 Ductile Iron
Piston (Each)	0.48 Cast Al	0.44 Cast Al	0.43 AM Al	0.427 AM Al
Oil Pan & others*	7.21 Multiple materials	7.59 Multiple materials	4.39 Multiple materials	4.39 Multiple materials
Total Engine Weight	**243.1**	**254.9**	**193.1**	**189.7**
Mass Reduction			**-24.2%**	**-25.6%**
			-20.6%	**-22.0%**

* others - pickup tube assembly, oil pan cover, and block valley cover

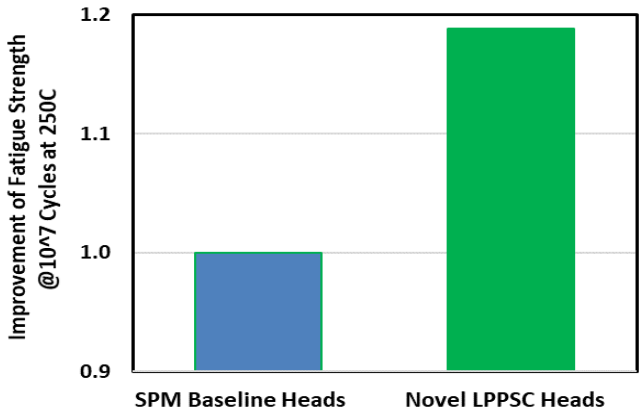
Technical Accomplishments

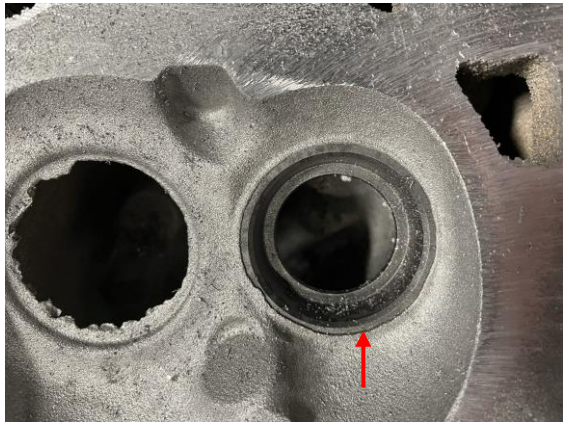
Materials and Manufacturing Solutions TASK 2 - 2021 (Technology Research & Development)

- **Cast Al Cylinder Head**
  - ✓ Novel LPPSC process developed by ECK and GM for high quality head with the improved mechanical properties (near 20% improvement)
  - ✓ Cast-in-place valve seats designed & successfully cast in the LPPSC head at ECK with the technologies developed from the comprehensive lab-scale overcast studies at OSU
  - ✓ New cylinder head alloys (ACMZ) evaluated and down-selected by ORNL

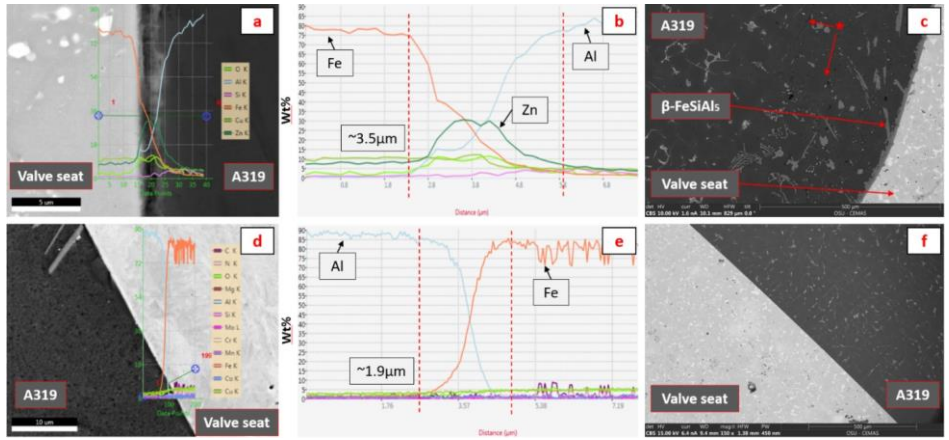


X-ray CT showing good quality of LPPSC head





Cast-in-place exhaust valve seat

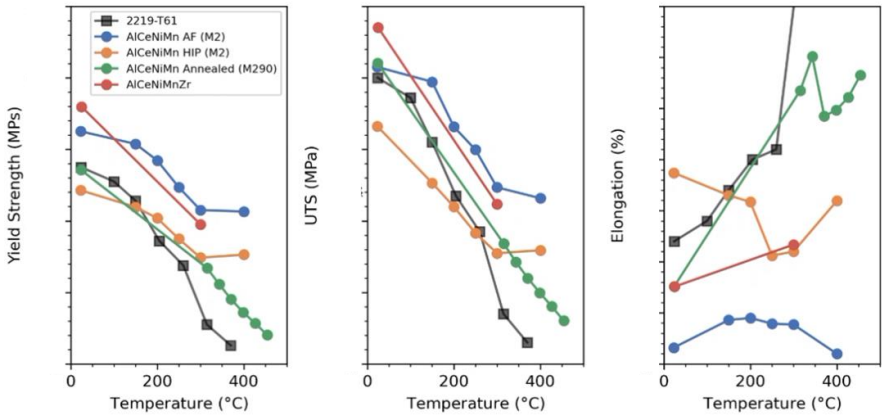


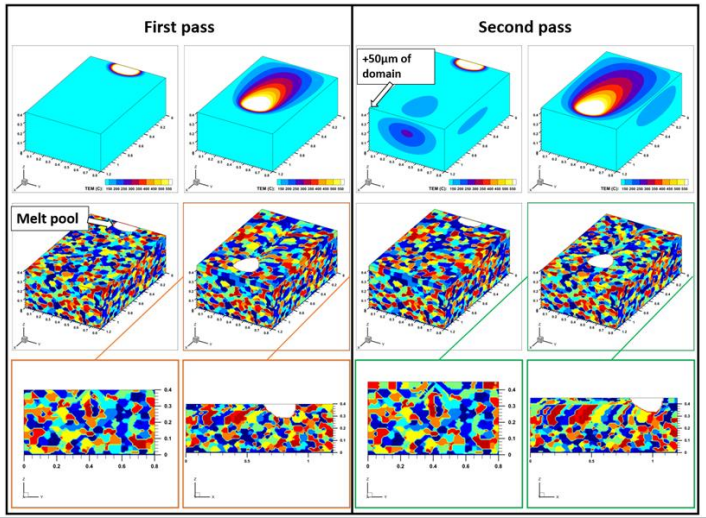
a, b) Zn-plated; c) Al-Fin coated; d,e,f) Sample w/o coating

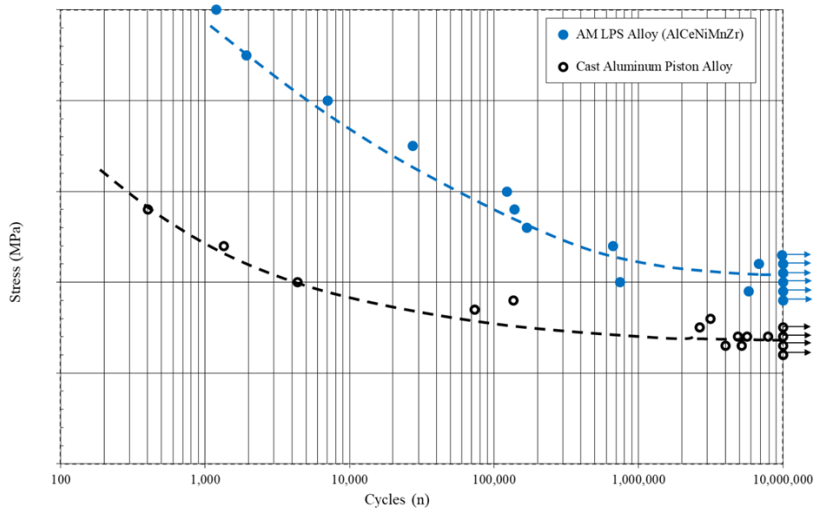
Technical Accomplishments

Materials and Manufacturing Solutions TASK 2 - 2021 (Technology Research & Development)

- **Additive Manufacturing (AM) Pistons**
  - ✓ Novel Al-Ce based alloy and AM process developed by ORNL for quality pistons through alloy development and process optimization
  - ✓ Superior mechanical properties of AM Al-Ce based alloy piston over the cast Al piston
  - ✓ ICME tools developed at OSU & GM to model defects and microstructure in AM and cast aluminum pistons using Cellular Automaton (CA) approach

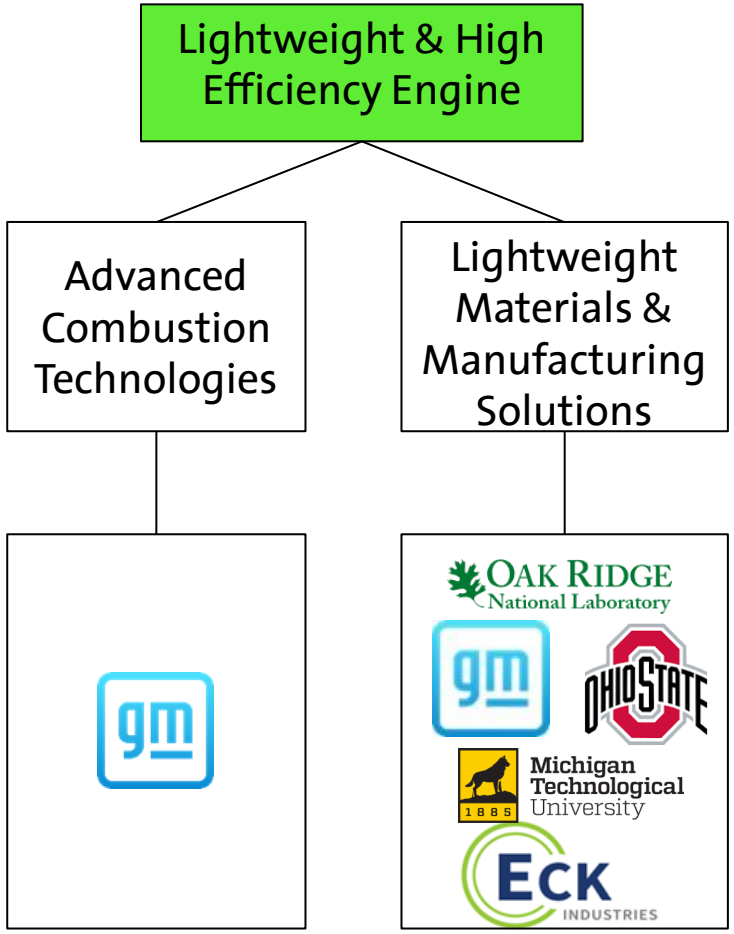






Collaborations and Coordination

GM - Q. Wang, E. Keating, (prime) S. Campbell	Develop combustion technologies and high integrity low mass solutions; design, build and test new engine; CAE analysis, Virtual Casting, Project management
ORNL - A. Shyam, A. Haynes, (CRADA) A. Plotkowski, J. Simpson	Develop high strength high temperature Al alloys for head, block and piston & AM process for piston
OSU - A. Luo, M. Moodispaw (sub)	Develop overcasting technology for head valve seats, lightweight high entropy alloy (HEA), and computer simulation of defects in AM piston.
MTU - P. Sanders, S. Anderson (sub)	Develop cast steel and ductile iron alloys and casting technology for high performance crankshaft
ECK - D. Weiss, D. Hoefert (sub)	Develop novel casting technologies to cast high quality Al blocks and heads, cast-in-place inserts, casting simulation



Remaining Challenges and Barriers

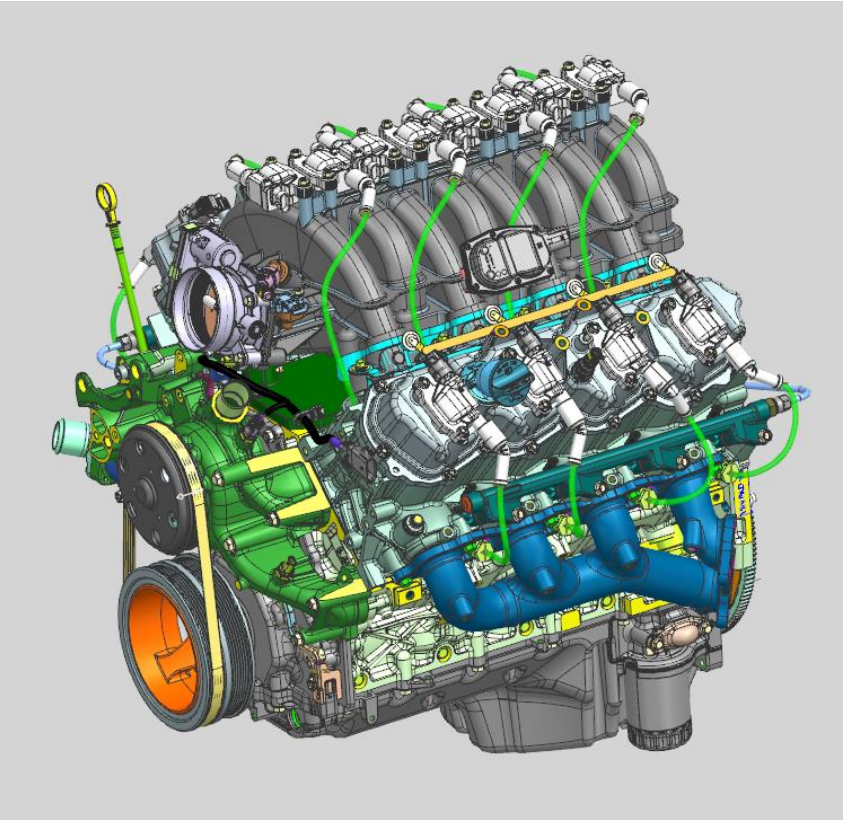
- The advanced gasoline stoichiometric dilute engine concept is required to achieve the target fuel economy while delivering outstanding value to the customer.
- Peak cylinder pressure is expected to increase by up to 50% with 10% fuel economy improvement, which poses high demand in properties for key combustion components (block, head, crank and piston).
- Significant improvement of mechanical properties, particularly fatigue, has been seen in specimens machined from the AM pistons. The unique roughness of non-machined AM piston surfaces may pose some challenging in dyno test.
- Novel LPPSC has been developed for both cast aluminum heads and blocks. More work is needed to determine whether the new process minimizes or even eliminates porosity.
- Cast steel cranks initially made with the chill-less printed sand casting have shown equivalent LCF properties compared to the forged steel cranks but lower HCF strengths due to the presence of micro shrinkage porosity. It is hoping to eliminate the micro porosity through new gating/riser system design and the use of chills.

Proposed Future Work in FY22

TASK 3 (Validation and Demonstration)

Design, build and initial development testing of proposed medium duty truck engine capable of meeting both fuel economy improvement and mass reduction requirements

- **Task 3.1. Design and Build Engines to Facilitate Test Cell Evaluation of Proposed Medium Duty Truck Solution Incorporating Components**
  - ❑ Design and acquire engine rotating and reciprocating system hardware
  - ❑ Design and acquire valvetrain system hardware
  - ❑ Design and acquire induction and exhaust system hardware
  - ❑ Design and acquire fuel system hardware
  - ❑ Design and acquire cooling system hardware
  - ❑ Design and acquire remaining engine hardware
  - ❑ Incorporate components produced in Task 3.2
  - ❑ Assemble 3 development engines



Proposed Future Work in FY22

TASK 3 (Validation and Demonstration)

Design, build and initial development testing of proposed medium duty truck engine capable of meeting both fuel economy improvement and mass reduction requirements

- **Task 3.2. Demonstration of the Highest Payoff Materials and Manufacturing Solutions for Key Engine Components for the Proposed Medium Duty Truck Engine**
  - ❑ Produce high quality cylinder heads with the highest payoff material and manufacturing solutions
  - ❑ Produce high quality engine blocks with the highest payoff material and manufacturing solutions
  - ❑ Produce high quality AM pistons using the selected AM material and optimized process solutions
  - ❑ Produce high quality crankshafts with the highest payoff material and casting process solution
  - ❑ Perform through process modeling and durability analysis using ICME approach
- **Task 3.3. Test Cell Evaluation of Advanced Combustion Technologies and Weight Reduction Techniques Using Current Equivalent Architecture GM Development Engine**
  - ❑ Install engine in test cell and complete run-in testing
  - ❑ Execute initial engine calibration procedures
  - ❑ Conduct engine testing to establish initial performance to fuel economy and emissions targets

Summary

- Hardware to evaluate advanced combustion technologies was designed and built using our current equivalent architecture V8 development engine.
- Substantial test cell evaluation of advanced combustion technologies was completed showing promising fuel economy improvement as expected.
- Advanced material and manufacturing solutions for mass saving and performance have been developed and evaluated for the key engine components such as head, block, piston and crankshaft.
- Through R&D in phase 1, advanced combustion and material technologies have been evaluated and down-selected for the phase 2 new engine development.
- Remaining challenges and barriers for the phase 2 engine development have been identified together with future work plans to address the challenges to be able to achieve the FOA target fuel economy and mass reduction requirements in compliance with EPA emission standards.

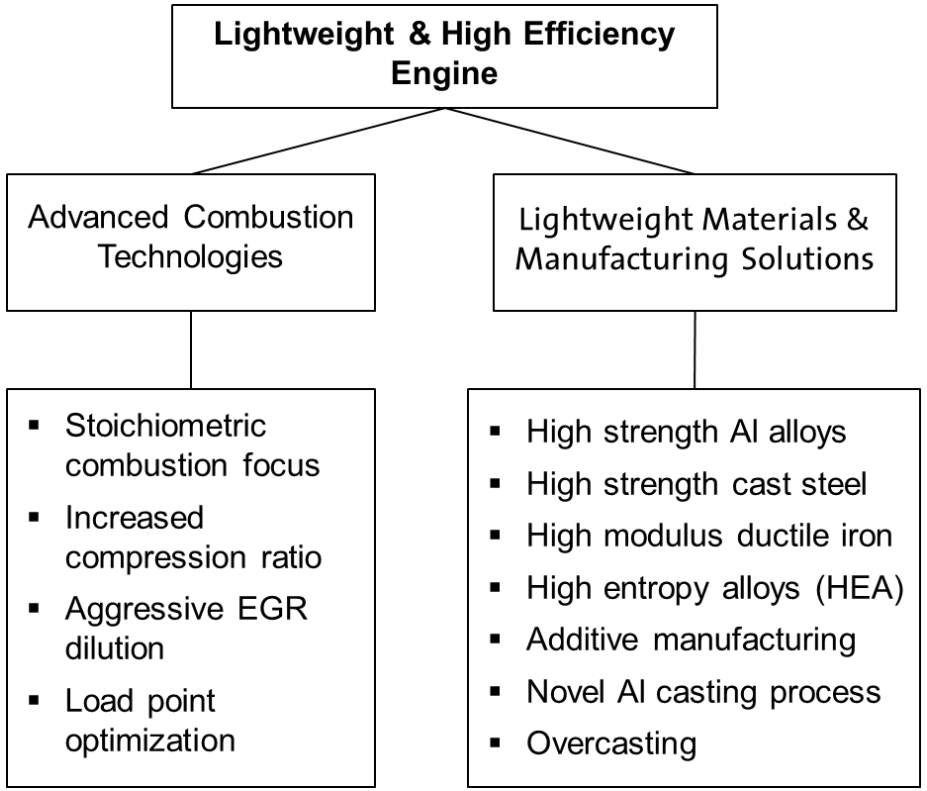
Responses to Previous Year Reviewers' Comments

- **"Question on the baseline for this project. A greater than 10% improvement in fuel economy compared to a 2015 engine seemed rather weak. Current Corporate Average Fuel Economy (CAFE) regulations require approximately 3.7% reductions every year, and this is already a 2015 engine so lots of improvements can be readily made. The reviewer suggested raising the goal to perhaps a 25% improvement."**
  - ✓ Response: The choice of a 2015 engine baseline was defined by the FOA.
- **"Why the project team chose the ultra-high pressure (P) injection at 1,000 bar and suggested also adding 600 and 800 bar to see if there is any significant improvement versus cost"**
  - ✓ Response: Our ultra-high pressure fuel system is specified at 1,000 BAR maximum fuel pressure. This pressure is required to overcome cylinder pressure and promote good air-fuel mixing for the very late, compression stroke fuel injection strategy we are investigating. Reduced fuel pressures are possible with this system for evaluation using alternate injection strategies.
- **"It was interesting to note that all of the outside collaborations were on the Lightweight Materials & Manufacturing Solutions part of the project. Why did not the advanced Combustion Technologies part of the project have collaborators?"**
  - ✓ Response: We feel that we have a clear understanding of the technologies selected for evaluation in support of the 10% fuel economy improvement objective.

Technical Back-Up Slides

Approach for Phase 2

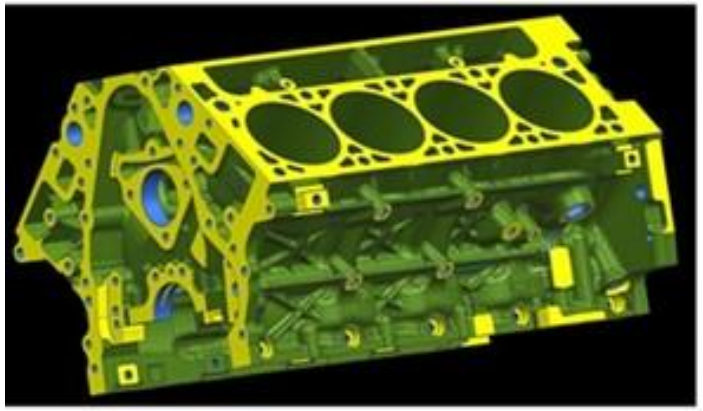
- In Phase 2, the final engine architecture will be designed by integrating the advanced combustion and materials technologies evaluated and down-selected numerically and experimentally in Phase 1. The final engine test will verify engine weight reduction and performance to the FOA objectives.
- The final engine design will also integrate with other research or deployment projects within the pertinent VTO subprogram. (https://www.energy.gov/eere/vehicles/annual-progressreports)
  - Advanced combustion engines (i.e. ace121, ace127, ace 133, etc.)
  - Propulsion materials (I.1.A, I.1.B, I.1.C, I.2.C, etc.) for cylinder heads & cast steel crankshaft
  - Lightweight materials (II.2.D, II.3.D, etc.) and LightMAT project (novel casting process development)
- CAD, CAE and ICME tools will be continuously used to accelerate phase 2 engine development, reduce risk, and enable tailored properties that lead to cost effective mass reduction.



Technical Accomplishments

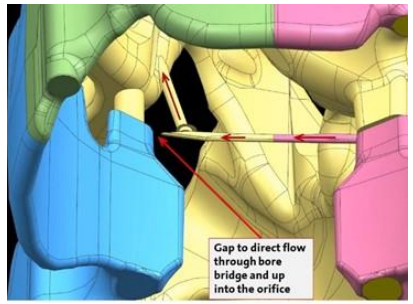
Materials and Manufacturing Solutions TASK 2 - 2021 (Technology Research & Development)

- **Cast Aluminum Engine Block**
  - ✓ New cast aluminum engine block designed at GM using CAD, CAE and ICME tools
  - ✓ Novel low pressure precision sand casting (LPPSC) process developed and optimized
  - ✓ Special sawcut and orifice geometry proposed and simulated to decrease block interbore temperature by 50°C
  - ✓ Novel cambore and bulkhead chills developed to enhance local material properties
  - ✓ New cast aluminum alloy developed and down-selected

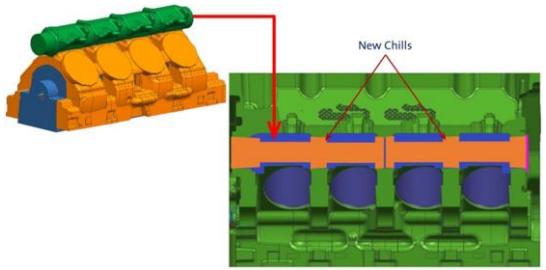


V8 cast aluminum block developed

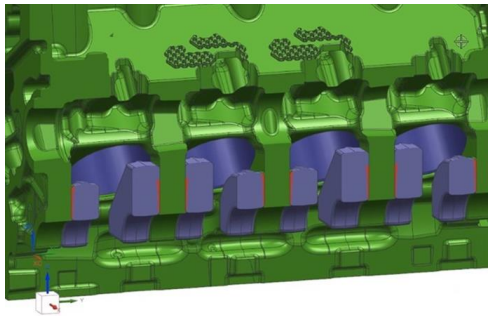
LPPSC cast aluminum block tooling



Special sawcut & orifice



New cambore chill



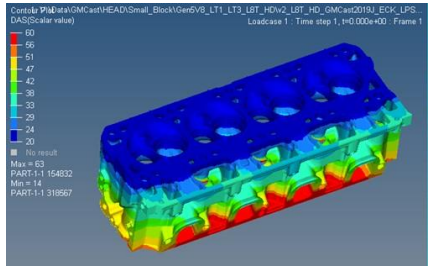
Raised bulkhead chills

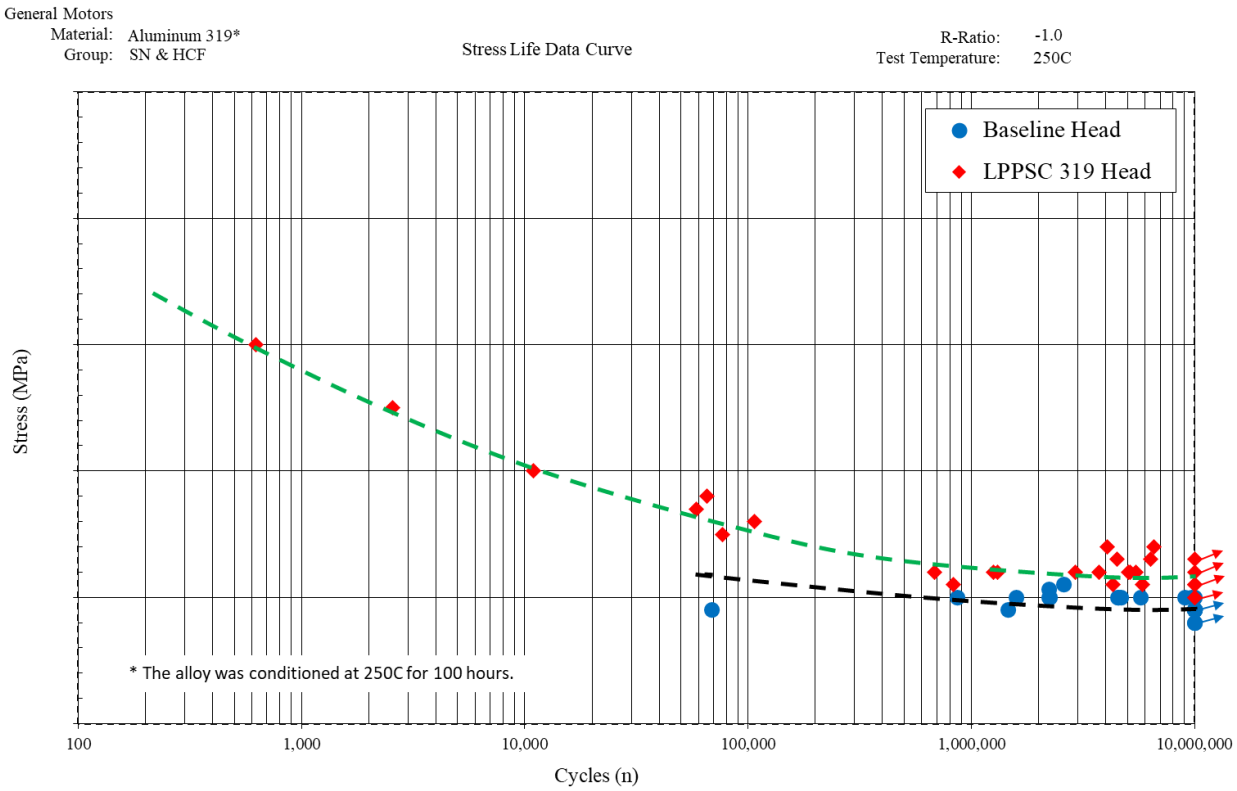
Technical Accomplishments

Materials and Manufacturing Solutions TASK 2 - 2021 (Technology Research & Development)

High Performance Cast Aluminum Cylinder Head Development

- **Novel Casting Process**
  - ✓ Low pressure precision sand casting (LPPSC) developed by ECK and GM
  - ✓ Optimal gating system/tooling design and process achieved with ICME tools
  - ✓ Effective deckface chill in LPPSC and helium gas application further reduced DAS in the high-loading deckface
  - ✓ Fatigue property improved notably in comparison with baseline process

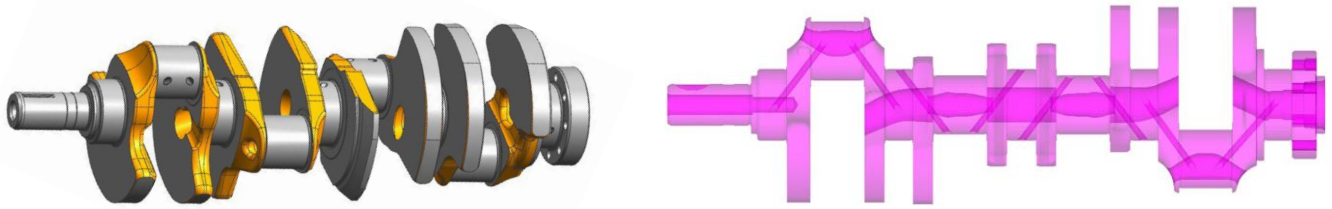




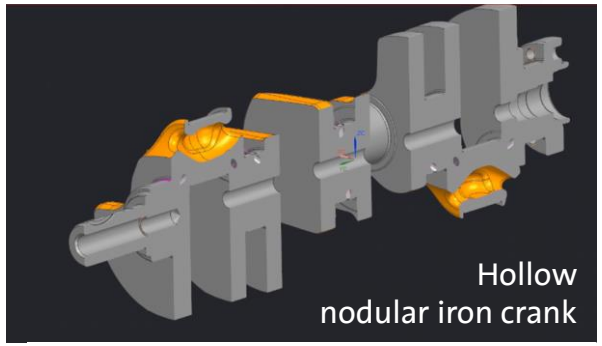
Technical Accomplishments

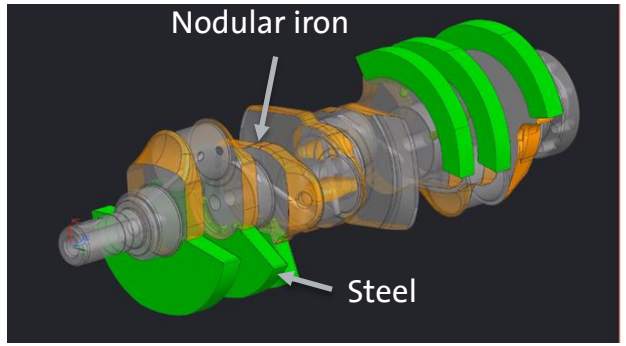
Materials and Manufacturing Solutions TASK 2 - 2021 (Technology Research & Development)

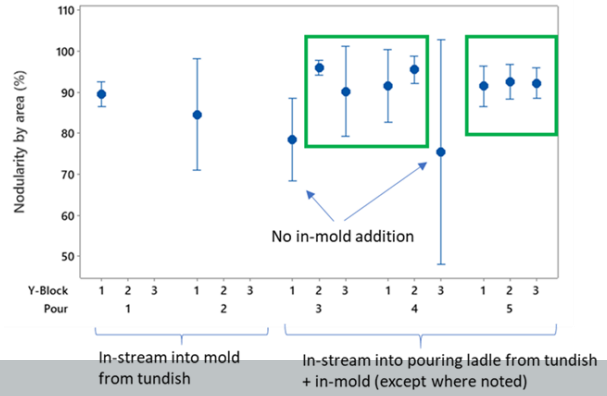
- **Cast Steel and Nodular Iron Cranks**
  - ✓ New hollow cast steel V8 crank developed to replace the forged steel crank, saving mass by 240g.
  - ✓ New hollow high-performance nodular iron V8 developed, saving mass by 791g compared with the forged steel crank
  - ✓ Nodular iron/steel hybrid crank designed, saving mass by 377g
  - ✓ High modulus and high strength nodular irons developed by MTU and GM, showing good graphite nodularity with the combined use of in-stream and in-mold ultraseed-Ce inoculant.

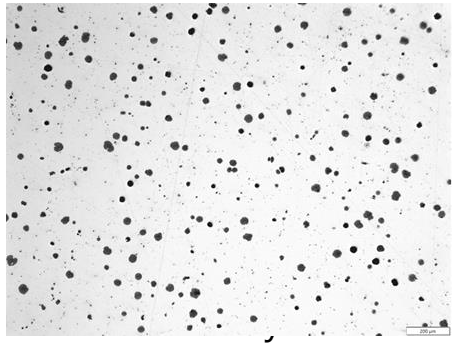


Hollow cast steel crank









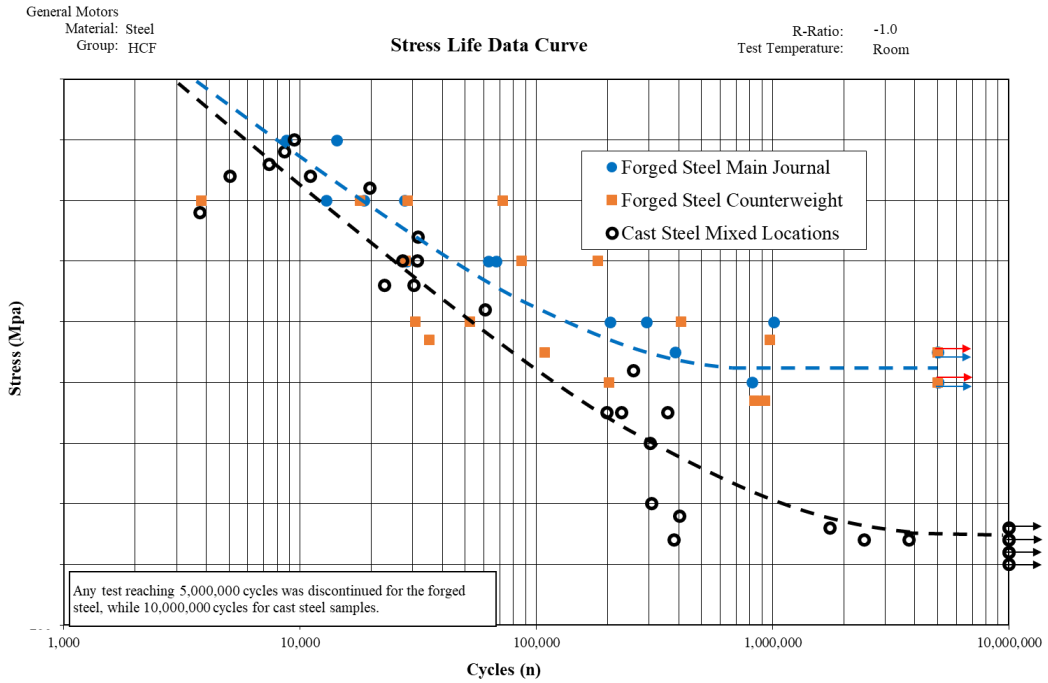
Graphite in Low CE Nodular Iron

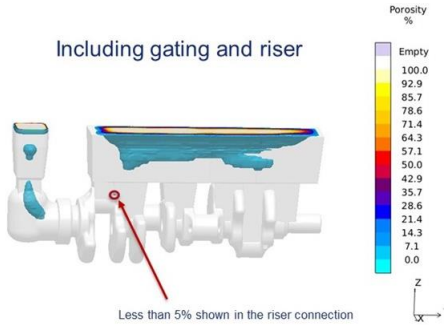
Technical Accomplishments

Materials and Manufacturing Solutions TASK 2 - 2021 (Technology Research & Development)

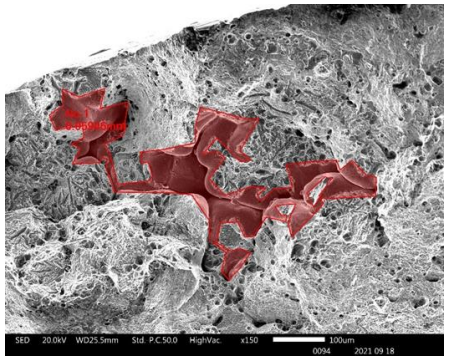
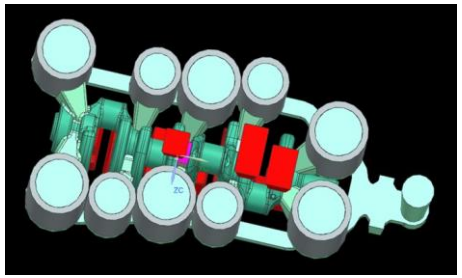
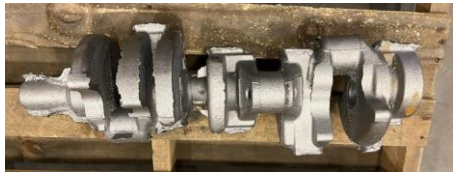
High Performance Cast Steel Crank Development

- **Early Gating/Riser Design**





Micro shrinkage seen in the sample reduced HCF



- **Novel Gating/Riser Design**