Next Generation, High-Efficiency Boosted Engine Development

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Ford Motor Company

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DE-EE0008878

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2:10 pm EDT
30-Minute

Project Overview

Partners

FEV North America Inc.
Oak Ridge National Lab (ORNL)

Barriers

- Engine efficiency can be improved by increasing the compression ratio (CR). CR is limited by autoignition (knock), heat losses, and unfavorable combustion chamber shapes.
- Dilute stoichiometric combustion offers benefits in engine efficiency but is limited by combustion stability and exhaust gas recirculation (EGR) flow capacity.
- Engine friction, pumping work, and accessory loads must be minimized to improve net efficiency.
- Reducing vehicle mass improves fuel economy but is limited by structural requirements and manufacturing techniques.

Timeline

Project start:	4Q 2019
Project end:	4Q 2022
Percent complete:	45%

Budget

Total project funding: $10M

- DOE share: $7,566,282
  - EERE: $7,416,282
  - FFRDC: $150,000
- Recipient: $2,433,718

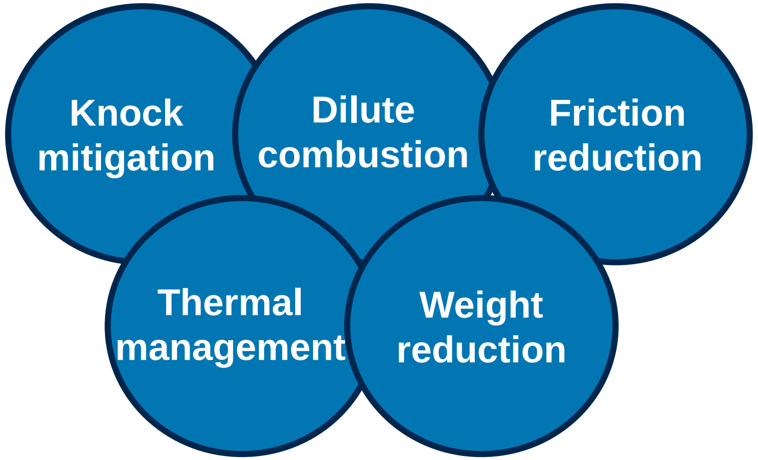
- Budget period 1: $3,972,279
- Budget period 2: $4,716,989
- Budget period 3: $1,310,732

Any proposed future work is subject to change based on funding levels.

Project Relevance

Objective: Design, evaluate, build and test an engine that will achieve 23% fuel economy improvement and 15% weight reduction relative to a 2016MY 3.5L V6 EcoBoost F150 baseline.

Impact: Technologies investigated in this project will reduce CO_2 emissions of the highest production volume powertrains found in light duty vehicles by addressing the following barriers:



Supports the Vehicle Technologies Office (VTO) Advanced Combustion Engines (ACE) Subprogram goals of improving light-duty engine efficiency, reducing mass and hence improving passenger vehicle fuel economy.

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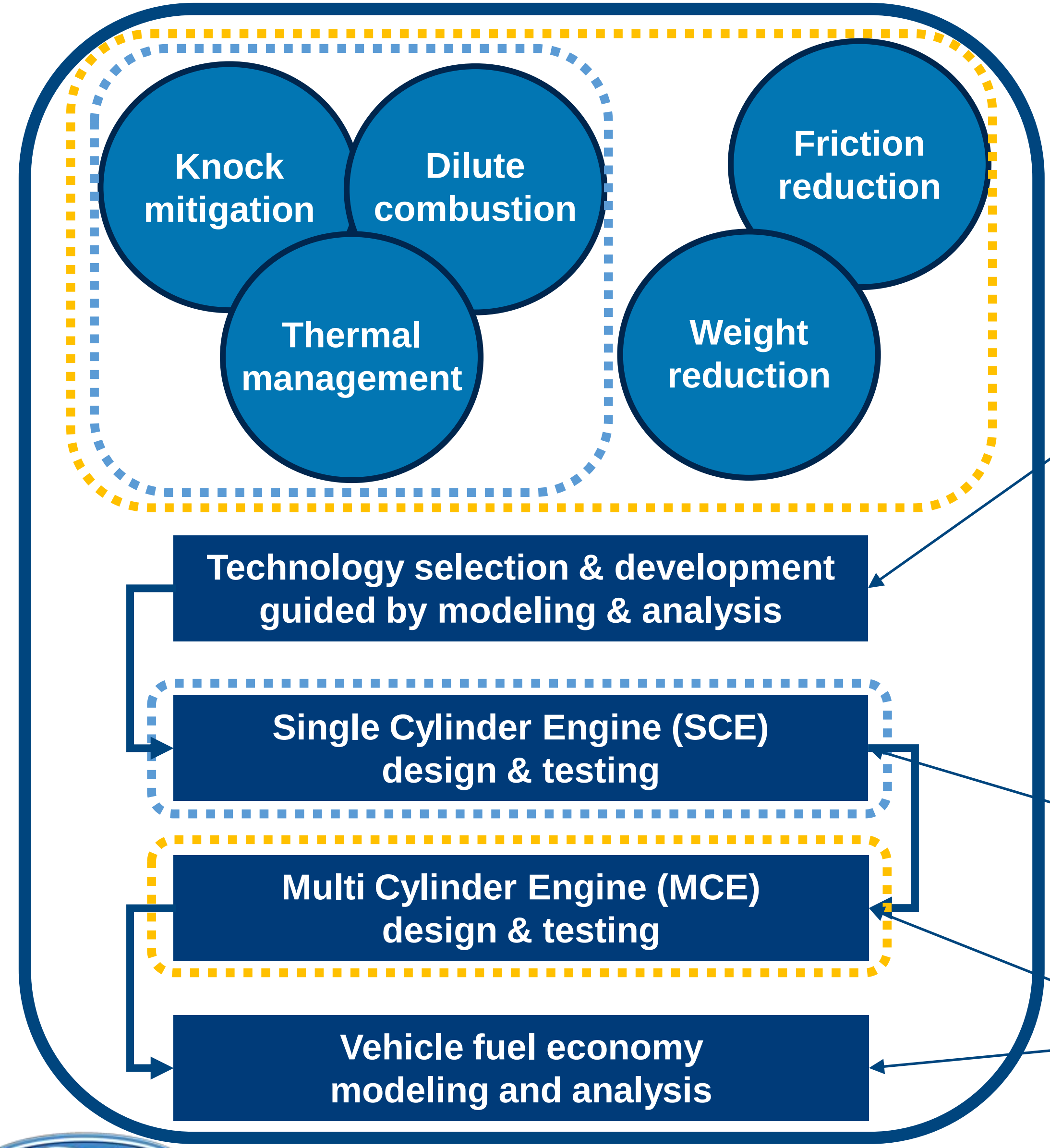
Project Approach



- Extensively leverage analytical tools in the design and evaluation of concepts:
  - Upfront 3D CFD with detailed ignition & combustion modeling designing for extended dilution limits.
  - 1D engine simulations to address performance and knock mitigation requirements.
  - Multi parameter 3D CFD intake port optimization
  - 3D CFD on cylinder head and block water jacket cores to optimize cooling and pressure drop.
  - Critical fastener clamp load assessments to satisfy robustness requirements.
  - Crankshaft material selection based on robustness factor of safety assessments.
  - 1D transient flow and 3D CFD modeling of exhaust gas recirculation (EGR) system for optimized flow capability and compressor robustness.

- Evaluate select combustion system concepts for dilution tolerance, efficiency, and knock resistance using SCEs.

- Acquire dynamometer measurements of MCE fuel consumption and use vehicle simulation model to predict consumption on regulatory drive cycles. Components will be weighed and compared to the target.

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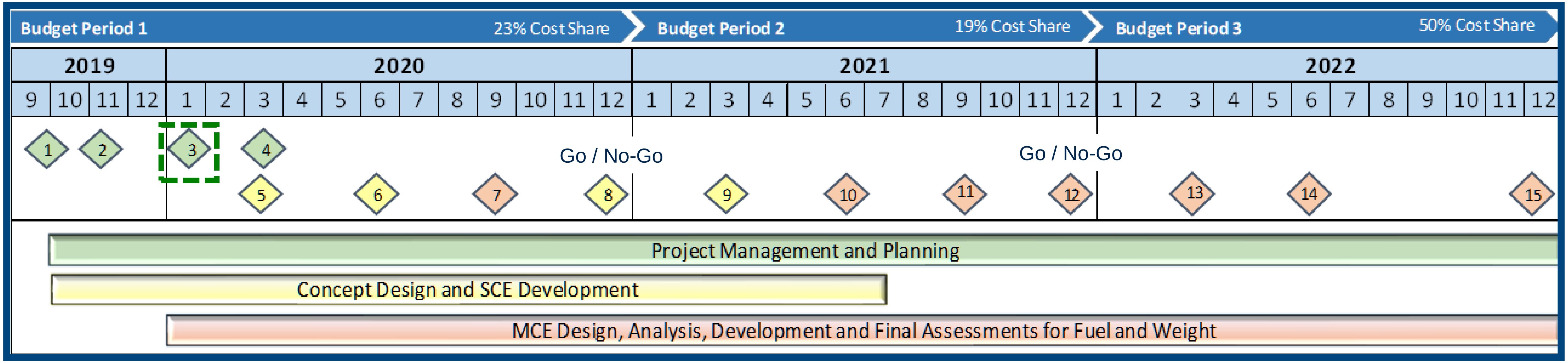
SCE = Single Cylinder Engine
MCE = Multi Cylinder Engine

Project Milestones



#	Date	Event / Milestone	%
1	10/01/19	Conditional award effective	100
2	11/13/19	DOE on-site kick-off	100
3	01/27/20	Definitized DOE award executed	100
4	03/16/20	FEV sub-contract executed, purchase order issued	100
5	03/31/20	SCE assumptions, targets & hard points defined	100
6	06/30/20	SCE hardware frozen, 3-plug and pre-chamber	100
7	09/30/20	Composite oil pan concept selected	100
8	12/31/20	Analytical assessment of combustion metrics	100

#	Date	Event / Milestone	%
9	03/31/21	SCE development complete & MCE ignition selected	75
10	06/30/21	MCE design frozen	50
11	09/30/21	MCE hardware procurement	10
12	12/31/21	Analytical assessment of SCE & MCE design vs. targets	10
13	03/31/22	MCE built, install and debug complete	0
14	06/30/22	Initial fuel consumption map complete	0
15	12/31/22	Final assessment of vehicle fuel economy & engine weight	0

Hardware delays, shutdowns and facility access limitations due to COVID 19 have had an impact on the SCE development testing.

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Accomplishments and Progress – Two SCEs Developed

Dilute combustion

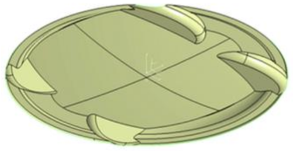
Knock mitigation

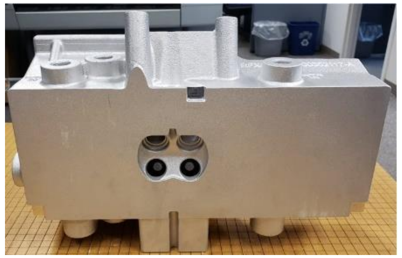
SCE Common Elements

Cylinder bore diameter:	84 mm	Main chamber fuel:	Port fuel injection (PFI) and side direct injection (DI)
Stroke:	112 mm	Exhaust event duration & timing:	245°, Closing 25° after top dead center
Compression ratio:	14.0:1	Intake event duration / timing:	Hydraulic continuously variable valve lift

3-Plug SCE

- Charge motion via tumble intake port with valve masking
- All parts designed, analyzed, and procured
- Engine assembled, installed, and debugged
- Test plan finalized and testing has started





Active Pre-Chamber SCE

- Charge motion via tumble intake port, no valve masking
- All parts designed, analyzed, and procured
- Engine assembled, installation in progress

SCE have been analyzed, designed, built, and are ready to test. These engines will evaluate the combustion system concepts for dilution tolerance, efficiency, and knock resistance.

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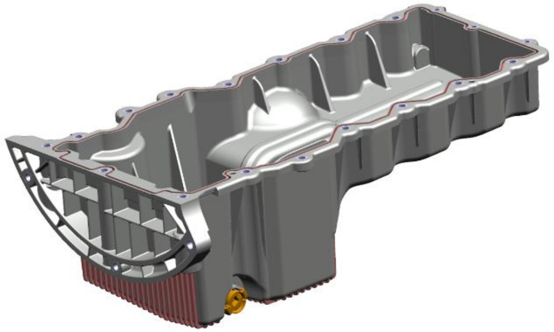
SCE = Single Cylinder Engine

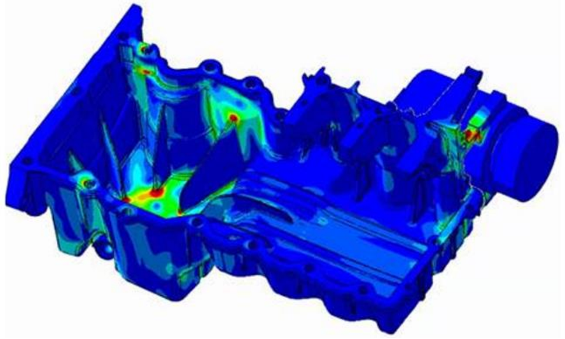
Accomplishments and Progress – Composite Materials

Weight reduction

Composite structural oil pan

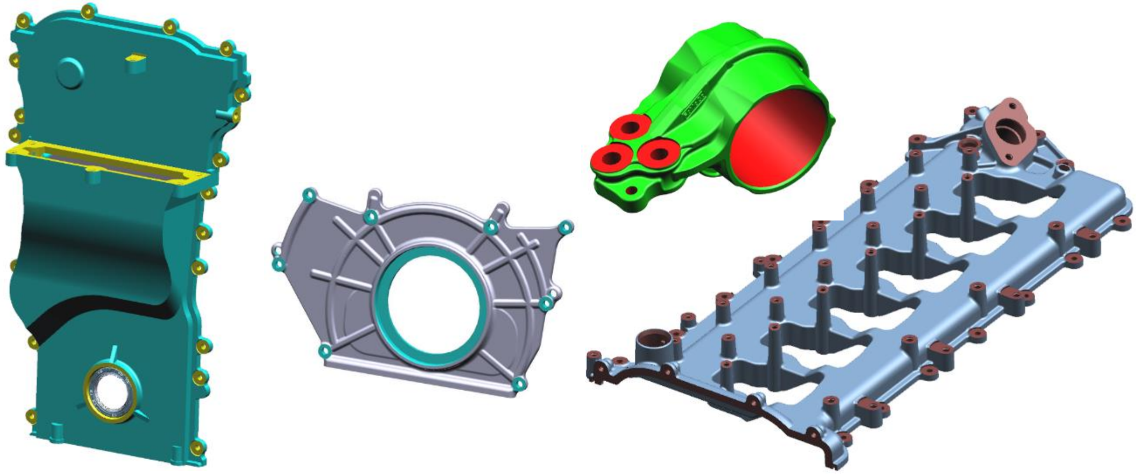
- Collaboration with Oak Ridge National Labs to design, develop, manufacture and test oil pans as a demonstration component
- 43% mass reduction relative to an aluminum oil pan
- Compression molding selected after evaluating multiple processes for manufacturability, cost, durability, material properties and sealing
- A glass / carbon fiber hybrid material is being evaluated
- Pan needs to support A/C compressor and 6 quarts of oil
- FEA to evaluate design and range of material properties





Additional Weight Opportunities Under Consideration

Component	% mass reduction
Composite front cover	30-40
Rear seal retainer	35-40
Composite engine mount	20
Magnesium valve cover	20-25



Use of composites and other light-weight materials is being incorporated into engine component designs when possible

FEA = Finite Element Analysis

Any proposed future work is subject to change based on funding levels.

Accomplishments and Progress – Completed analytical work

Dilute combustion

Knock mitigation

Structural FEA
1-D flow simulations

Component design and packaging

Port & chamber geometry

3-D multi parameter port optimization

FEV

Ford

Pre-chamber layout, volume, nozzle area, initial injection timing and targeting guided by 1-D modeling

1st pre-chamber design

Airpath & exhaust geometry

1-D Engine model

Iterate based on results

Pressure & temperature boundary conditions. EGR flow capability.

3-D ignition and combustion modeling at 4 key operating points.
Pre-chamber air/fuel timing, targeting, mixing, flame propagation, and main chamber energy transfer optimization. Feedback based on burn rate, stability, and efficiency.

Pre-chamber combustion system designed based on modeling & analysis

MCE = Multi Cylinder Engine
FEA = Finite Element Analysis

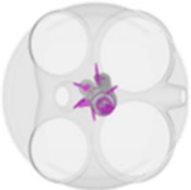
Accomplishments and Progress – Results

Dilute combustion

Thermal management

Analytical assessment of dilution tolerance

- **Pre-chamber body, nozzle plate, fuel & air targeting all optimized for dilute combustion**



Diameter A

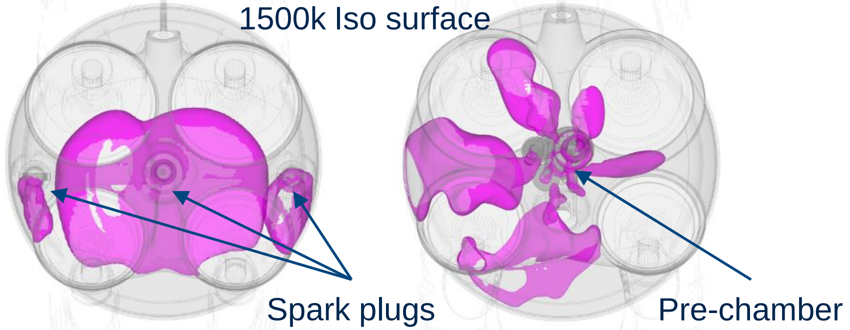
Diameter B

Diameter C

- **1500 rpm, mid torque: Active pre-chamber extends dilution limit by ~10% EGR**

3 plug 30% EGR

Pre-chamber 40% EGR



SCE evaluation of low heat capacity coatings

- **Low conductivity & low heat capacity. Surface ‘follows’ gas temperature.**
- **Multiple coatings evaluated analytically, one selected and applied to SCE piston and valves.**
- **Result: ~1% relative improvement in thermal efficiency due to reduced heat losses offset by a 2.2° degradation in knock limited combustion phasing and a 0.24% penalty due to increased hydrocarbon emissions.**

Coated piston & valves

Active pre-chamber enables higher EGR rates and is better at mitigating knock

MCE moving forward with active pre-chamber & without in-cylinder thermal coatings.

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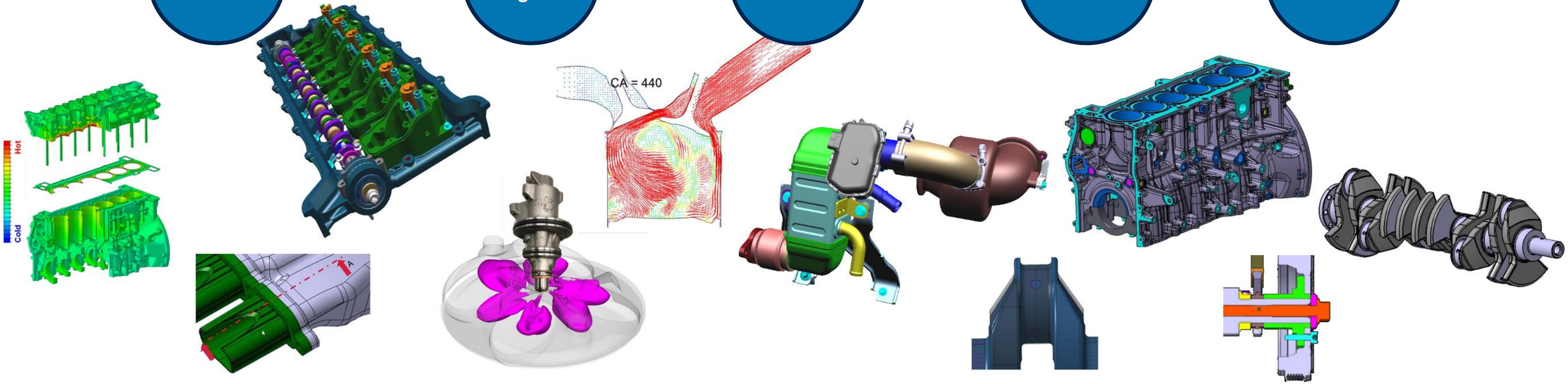
MCE = Multi Cylinder Engine

Accomplishments and Progress – MCE Development

- There has been a Major focus this period on MCE component design supporting the fuel economy and weight targets
- Over 1,300 parts required for each dynamometer engine build
- Numerous Ford first and industry leading technologies incorporated into the design necessary to achieve 23% fuel economy improvement and 15% weight reduction

Thermal management | **Knock mitigation** | **Dilute combustion** | **Weight reduction** | **Friction reduction**



MCE design nearly completed. Part orders are being placed.

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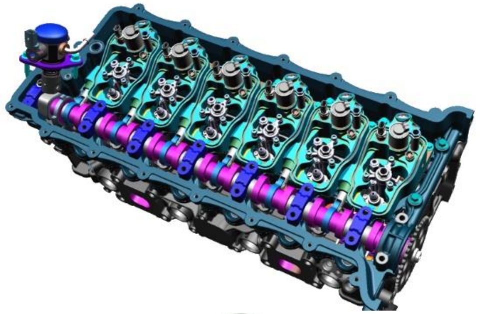
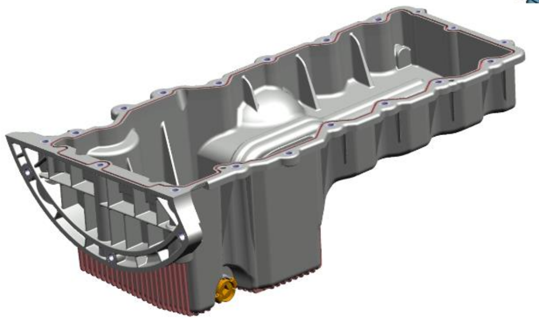
MCE = Multi Cylinder Engine

Accomplishments and Progress – Weight

Weight reduction

Assembly	Weight delta [kg]	
Upper end: • Head, valvetrain • Exhaust manifold • Cam cover	-21	
Block / sealing • Block • Head bolts • Front cover, rear seal carrier • Oil pan	-4	
Cranktrain • **Crankshaft, damper** • Connecting rods • Piston assemblies	+11	
As-installed • Exhaust & catalysts • Battery	-16	% Reduction*
Total	-30	17%





*status of listed parts only

**Designs achieved significant weight savings on major components.
Weight gain expected with EGR & cooling systems. Workstreams ongoing.**

Response to Previous Year Reviewers' Comments

- *'I expect the collaboration to be quite good given the definition of the partner tasks. It looks like there hasn't been a ton of joint work to date, but that tasks that involve the partnerships are starting up so we should see a lot more as we go towards the next review.'*
  - *Response: Correct, the Ford team began work on the project immediately upon notification of the award. Work with the partners was not initiated until after the contract was definitized. With FEV, an agreement to all award flow-down terms and a purchase order were necessary. As a result, work at FEV started about one month prior to the 2020 AMR presentation slides being turned in.*
- *'…the proposed new technologies on the engine would increase the challenge of meeting the weight reduction goal…It would be helpful if the future work can address this outstanding issue.'*
  - *Response: Going from a V6 to an I6, improved manufacturing techniques, and lightweight materials all provide weight saving opportunities but trade-offs to the weight have been made to push the engine efficiency and develop engine technologies that are not currently used in high-volume production applications. It may be possible to meet the fuel economy targets without some of the added technologies. A reduced set may be considered for meeting both the efficiency and weight targets.*
- *What is the criteria for engine concept selection between the 3-spark plug and pre-chamber? Are cost and reliability the determining factors if performance is equivalent?*
  - *Response: Analytically there is a burn rate and dilution tolerance benefit for the pre-chamber as well as a knock benefit. To mitigate risks associated with the pre-chamber, the MCE has been designed to accommodate either a spark plug or a pre-chamber ignition system.*

MCE = Multi Cylinder Engine

Collaboration and Coordination with Other Institutions

Industry Subrecipient Project Partner

- Co-design / co-development of pre-chamber
- Intake air system design / development
- EGR system design / development
- Piston design / development
- Lubrication system design / development
- Design support for various components

DOE VTO National Laboratory Partner

- Co-design / development of composite structural oil pan
- Material selection, tool development, part production

More than 20 additional companies are engaged in developing prototype components. Greatly expanding the knowledge base leveraged to successfully complete the project.

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Remaining Challenges and Barriers

- **The technologies added to achieve the engine efficiency goals have increased the challenge of meeting the weight reduction target. Mitigating actions:**
  - **Exploring additional composite parts (front cover, mounts, cam cover).**
  - **Performing additional weight optimization on the crankshaft.**
  - **Exploring if a de-contented version of the engine would meet the fuel economy goal.**
- **Several issues have delayed SCE testing including: COVID related manpower shortages, facility issues, hardware damage. Mitigating actions:**
  - **Leveraging additional analytical resources to compensate for the lack of experimental results.**
  - **Used surrogate 3 plug engine to evaluate dilution tolerance, knock mitigation, and temperature swing coating.**
  - **Protecting the MCE design for pre-chamber and central spark plug.**
- **Approximately 7000 parts will be procured for the MCE builds. A delay in any critical component will put the timing at risk.**

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Proposed Future Research

- **Budget Period 2 – Component Development & SCE Testing** **Jan. 2021 – Dec. 2021**
  - SCE Dynamometer Testing
    - » Evaluate two SCE combustion system concepts for dilution tolerance, burn rate, efficiency, and knock resistance relative to the project objectives.
  - MCE Design and build
    - » Complete MCE component analysis and design while balancing trade-offs associated with functionality, robustness, package, weight and cost.
    - » Procure all hardware for MCE builds.
    - » Initiate MCE builds and dynamometer palletization process.

- **Budget Period 3 – MCE Development and Vehicle Simulation** **Jan. 2022 – Dec. 2022**
  - Complete MCE builds. Install and debug engines in the dynamometer test cells.
  - Conduct experimental fuel economy optimization at key operating points to provide emissions and fuel consumption data to support vehicle level fuel economy modeling.
  - Complete engine weight improvement assessment against the 15% target.
  - Complete vehicle fuel economy improvement assessment against the 23% target.

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Summary

- SCE hardware design, fabrication, and assembly are now complete. Both engines have been installed into an engine dynamometer test cell.
- An active pre-chamber ignition system has been selected as the prime path for the MCE due to enhanced dilution tolerance and knock mitigation.
- Extensive design work has been completed for the MCE and orders are being placed for components targeting delivery Q4 of 2021.

Technical Backup Slides

Estimated Fuel Economy Benefits From Project Proposal

Proposed Actions	Baseline	% FE Improvement	Comments
13:1–15:1 CR	10:1	6-8	Requires significant knock mitigation. Airpath thermal mgt., split and optimized cooling system, miller valve events, lube system optimization for piston cooling, high conductivity valve seats and guides
35-50% Cooled EGR	0%	2-5	Requires advanced ignition (active pre-chamber, multi-plug or other unconventional ignition technologies) and boost system improvements
B/S opt: 0.72-0.82	1.06	1.0-2.0	Efficiency / CR enabler, likely requires architecture changes
CVVL	Ti-VCT	2.5-3.5	Enables Miller and transient fuel economy
Stop-Start	-	3.0-4.0	
Down speeding	6 speed	2.0-4.0	10 speed transmission in place of 8 speed
Temperature swing coatings	-	1-2	Reduced heat losses with less intake charge heating
Friction reduction	base	1-2	Form hone, high porosity PTWA with mirror finish, roller bearings, variable displacement oil pump, offset crank, advanced cooling strategy, split and optimized flow paths.
Fast warm-up	base	0.2	Advanced cooling system
Weight reduction		1	Weight reduction achieved through architecture change, composite materials, and additive manufacturing largely offset by adding EGR system and upgrading the boost system.
Engine upsizing	base	-1.7	Increased displacement to offset lower power density
Total		~23	

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Estimated Engine Weight Walk From Project Proposal

Proposed Actions	% Weight Reduction	Comments
Engine architecture	5.2	Shift from a “V” to an “I” architecture
Advanced materials	2.7	Carbon fiber compression-molded oil pan, composite carbon fiber compression-molded front cover (not included), additive hollow titanium connecting rods (not included), composite engine mounts (not included), composite rear seal carrier (not included)
Exhaust manifolds	3.6	Eliminate two cast steel manifolds and integrate into the cylinder head
Single bank aftertreatment	3.5	Reduced number of catalysts bricks, cans and sensors.
Optimized cylinder head	1.2	Use indirect additive manufacturing to optimize head for weight
CVVL	1.3	Delete (2) intake cams and valvetrain hardware
Optimized cylinder block	0.8	Use indirect additive manufacturing to optimize block for weight. (not included in prototype)
PTWA	1.2	Replace (6) cast iron bore liners with plasma transfer wire arc (PTWA) coating
Battery optimization	3.4	Replace 12V flooded / wet cell lead acid with Li-ion 12V starter battery
EGR system	-3.3	Baseline does not have an EGR system so there is a weight increase for hardware (valve, cooler, tubes, sensors, and wiring)
Engine thermal actions	-1.8	Additional piston cooling jets, valves and sensors to manage the advanced cooling system, liquid cooled CAC – dry weight
Long stroke	-2.7	Deck height increase up to 20mm
Net Weight Savings	**15.1**	

Weight reduction actions total 22.9%

Weight additions total 7.8%

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