

Pipeline Research Council International, Inc.

GHG SRP

Some CAPSTC Projects and Activities involving
Colorado State University and Texas A&M
University

Dr. Timothy J. Jacobs, Texas A&M University
Dr. Daniel E. Olsen, Colorado State University
Fall 2024 GHG SRP Meeting, Dallas, TX
10/15/2024

Agenda

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AGENDA

- 1) GHG SRP funded Prechamber Roadmap Projects for reducing Methane
- 2) ARPA-E funded projects
- 3) DOE MERP proposals

Prechamber Roadmap Projects to Reduce Methane

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In the beginning. . .

- 1. Around the time PRCI was developing the GHG SRP, certain members of CAPSTC were identifying technological capabilities of pre-combustion chambers (PCCs) to improve emissions, stability, efficiency, and reliability of large-bore, two-stroke integral-compressor engines.**
- 2. PCCs were identified as a key technology enabler for reducing methane from the engines.**
- 3. Thus, a research and technological development roadmap was created in late 2019 that aligned well with the objectives of the GHG SRP. This roadmap is commonly called the “PCC Roadmap.”**

Prechamber Roadmap Projects to Reduce Methane

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Hate to be a spoiler, but. . .

1. Although not yet complete with all the projects, the Roadmap has proven to be widely successful.

1. Twelve independent and unique projects over the course of five years.
2. As many (12) PRCI reports
3. As many (12) unique and publicly available published journal articles and conference papers.
4. About six supported graduate research students
5. Extremely strong and unparalleled collaboration among two universities, several pipeline operators, OEMs, and PRCI.
6. At least two leveraged federally-funded methane-reducing projects, valued at over \$5million.
7. A submitted collaborative proposal with several PRCI-affiliated organizations, valued at over \$5million.

Prechamber Roadmap Projects to Reduce Methane

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- **Prior to the development of a roadmap, a “state of the art” studied was collaboratively conducted among various PRCI-affiliated organizations:**
 - Greg Beshouri, Timothy J. Jacobs, Daniel Olsen, Mark Patterson, “Compendium of Precombustion Chamber Research Needs of Lo-NO_x and Lo-GHG Legacy Engines”, PR-703-19205, PR-702-19204, 2019.
- **Once the compendium had been written, work was started to develop the Roadmap. A workshop with several engaged and available Stakeholders resulted in an action plan for the development of the Roadmap. A key researcher (Dr. Patterson) worked to formally develop the Roadmap which much iterative discussion and consensus building among all invested Stakeholders.**
 - Advanced Engine Technologies Corporation, “Pre-Combustion Chamber Research Road Map”, PRCI CPS-14-05, 2020.

Prechamber Roadmap Projects to Reduce Methane

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Pre Combustion Chamber Research Road Map				
Year: 2020	2021	2022	2023	
Yearly Budgets: \$177 k	\$324.5 k + \$103.25 k	\$45 k + \$289.1 k	\$515 k + \$442.5 k	
CPS-14-05 CFD Study of Prechamber Ignition Mechanisms for GHG Reduction + PCC Road Map	Initial Literature Review: - Feasibility of ideas - State of the art Quenching Study: - Quenching mechanisms in the ring pack - Effect of air manifold temp - Effect of partial or late combustion NOx Study: - NOx chemical mechanisms - Effect of PCC size on ignition and NOx PCC Ignition Mechanisms: - Rich ignition early to seed main chamber with radicals (multiple PCC ignitions) - Thermal mechanisms in PCC Hydrogen: Reactive fuel for PCCs (H2, heavies, radicals, etc) H2 in the pipeline	Late Fuel Injection: - Ignition characteristics - Can we avoid CH₄ in the crevices? PCC Combustion: - Timed fuel pulses - Stoich vs lean combustion - Optimize fuel/air mixing - Premixing fuel/air - Improve combustion eff. - Multi-axis fuel/air swirl - Purge air - Total fuel energy more important than lean vs. stoich? Prechamber Controls: - Available technologies - Which sensors are needed? - New control algorithms? - Closed-loop controls - Skewness of COV? - Feed forward controls Dual or multi-stage prechamber (CFD Feasibility, \$25k?) Follow-on from quenching Need literature review White paper on PCCs vs. open chamber	PCC Thermal Management: - Ceramic liner for PCC - Separate cooling loop for PCC Low Load Optimization: - Optimizing PCC operation for low load - Loading strategies to follow demand - Will we face low load THC regulations Investigate PCC fuel nozzle size Interplay between manufacturing and design (3D printing, etc.) Fuel reforming / H2 case study	Additional ideas / "parking lot" Radicals vs. Flame - Retrofit potential? - Design tradeoffs? Geometric design of PCC to generate radicals thermally Could all of the combustion (or combustion + injection?) happen in the PCC? Extended testing on lean PCCs

Key

Ongoing

Mechanisms

Design

Control

Fueling

Other

Optional / Off Ramp

Notes:

- Budgets for 2021-2023
 - First number is for methane slip
 - Second number is for hydrogen reforming
 - Numbers are totals, not just for PCC research
- All budget numbers are before the 18% PRCI fee
- 2020 ongoing research shown for reference
- "Parking lot" ideas can be added to replace off-ramped projects

Prechamber Roadmap Projects to Reduce Methane

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- **Completed projects and their associated reports:**
 - Mark Patterson, Nelson Xie, Kyle Beurlot, Timothy J. Jacobs, Daniel Olsen, “CFD Study of Prechamber Ignition Mechanisms for GHG Reduction, Contract PR-309-20201, 2020.
 - Kyle Beurlot, Greg Vieira, Taylor Ritchie, Jacob Nowlin, Daniel Olsen, and Timothy Jacobs, “Evaluation of New Ignition Concepts on Large Bore NG Engines for Methane Emissions”, Contract PR-457-21204, 2022.
 - Greg Vieira, Rachel Lorenzen, Daniel B. Olsen, “Methane Abatement from LB NG 2-Stroke Cycle Engines Through In-Cylinder Modifications: H2 Blending Intermediate Final Report”, Contract PR-179-21205, 2023.
 - Jacob Nowlin, Kevin Wallace, Kyle Beurlot, Mark Patterson, Timothy J. Jacobs, “CFD Study of Prechamber NOx Production Mechanisms”, PR-457-21206, 2023.
 - Kyle Beurlot, Mark Patterson, Timothy J. Jacobs, “Effects of Inlet Port Geometry on MCC Mixing Sensitivity Study”, PR-457-22210, 2024.
 - Titilope Banji, Daniel B. Olsen, “Improved In-Cylinder Mixing - Injection Pressure Sensitivity”, Contract PR-179-22207, 2024.

Prechamber Roadmap Projects to Reduce Methane

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- **Completed projects and their associated reports:**
 - Forrest Pommier, Asa Schwierking, John Frank, Kevin Wallace, Timothy J. Jacobs, “Reduced Cyclic Variability for Improved GHG Emissions, PR-457-22208, 2024.
 - Greg Vieira, Daniel Olsen, “Prechamber Air + Fuel Premixing Proof of Concept: GMV CFD Simulation”, Contract PR-179-22206, 2024.
 - Greg Vieira, Titilope Banji, Daniel B. Olsen, “Methane Abatement from LB NG 2-Stroke Cycle Engines Through In-Cylinder Modifications”, Contract PR-179-21205, 2024.
- **In-Process projects, scheduled for completion by 12/31/2024.**
 - Troy Hreor, Timothy J. Jacobs, et al., “Feasibility Study of the Premixing of Prechamber Fuel and Air to Reduce GHG Emissions, PR-457-22209, *In Process*.
 - Greg Vieira, Daniel Olsen, “Design and Testing of a Multi-Nozzle PCC on a GMV4 LB NG Engine”, Contract PR-179-23204, *In Process*.
 - Max Lunifeld, Kyle Beurlot, Timothy J. Jacobs, et al., “Investigation of Supersonic Prechamber Jets to Reduce GHG Emission,” PR-457-23203, *In Process*.

Prechamber Roadmap Projects to Reduce Methane

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- **Where to from here?**
 - First task to bring closure to the Roadmap is to summarize in a Compendium
 - Consulting contracts with Drs. Olsen and Jacobs to summarize and synthesize the major findings and results from the Roadmap into a Compendium.
 - The Compendium will include results and information from other non-PRCI literature and sources.
 - Importantly, the Compendium will include a Technology Evaluation Gride, using industry-accepted TRLs, to position each PCC technology in context of its level of development.
 - Consulting contractors (Olsen and Jacobs) intend to frame out another Roadmap that builds upon the PCC Roadmap work and identifies new areas of research and development.

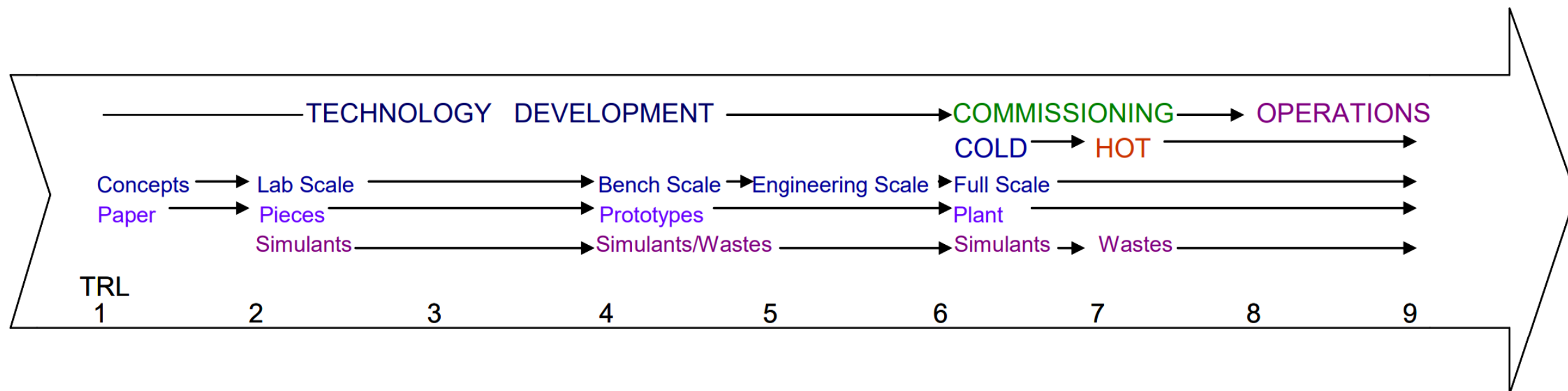
Prechamber Roadmap Projects to Reduce Methane

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Technology	Applicable Contract Number	Evaluation Method (CFD/Experimental)	Emission Reduction	DOE TRL Level
Directional PCCs	PR-309-20201, PR-179-23204	Both, Experiments on-going	99.9% CH ₄ reduction according to CFD	6
Late Cycle HPFI	PR-179-21205	Both	~20% CH ₄ reduction at constant NO _x	9
H ₂ Blending	PR-179-21205	Both	Negligible at constant NO _x	6
PCC Air + Fuel Premixing	PR-179-22206	CFD	Negligible as retrofit to existing OEM PCC	4

Prechamber Roadmap Projects to Reduce Methane

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Prechamber Roadmap Projects to Reduce Methane

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1. **TRL-1. Basic principles observed and reported: Scientific problem or phenomenon identified.** Essential characteristics and behaviors of systems and architectures are identified using mathematical formulations or algorithms. The observation of basic scientific principles or phenomena has been validated through peer-reviewed research. Technology is ready to transition from scientific research to applied research.
2. **TRL-2. Technology concept and/or application formulated: Applied research activity.** Theory and scientific principles are focused on specific application areas to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
3. **TRL-3. Analytical and experimental critical function and/or characteristic proof of concept: Proof of concept validation has been achieved at this level.** Experimental research and development is initiated with analytical and laboratory studies. System/integrated process requirements for the overall system application are well known. Demonstration of technical feasibility using immature prototype implementations are exercised with representative interface inputs to include electrical, mechanical, or controlling elements to validate predictions.
4. **TRL-4. Component and/or process validation in laboratory environment- Alpha prototype (component):** Standalone prototyping implementation and testing in laboratory environment demonstrates the concept. Integration and testing of component technology elements are sufficient to validate feasibility.

Prechamber Roadmap Projects to Reduce Methane

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5. **TRL-5. Component and/or process validation in relevant environment- Beta prototype (component):** Thorough prototype testing of the component/process in relevant environment to the end user is performed. Basic technology elements are integrated with reasonably realistic supporting elements based on available technologies. Prototyping implementations conform to the target environment and interfaces.
6. **TRL-6. System/process model or prototype demonstration in a relevant environment- Beta prototype (system):** Prototyping implementations are partially integrated with existing systems. Engineering feasibility fully demonstrated in actual or high fidelity system applications in an environment relevant to the end user.
7. **TRL-7. System/process prototype demonstration in an operational environment- Integrated pilot (system):** System prototyping demonstration in operational environment. System is at or near full scale (pilot or engineering scale) of the operational system, with most functions available for demonstration and test. The system, component, or process is integrated with collateral and ancillary systems in a near production quality prototype.
8. **TRL-8. Actual system/process completed and qualified through test and demonstration Pre-commercial demonstration:** End of system development. Full-scale system is fully integrated into operational environment with fully operational hardware and software systems. All functionality is tested in simulated and operational scenarios with demonstrated achievement of end-user specifications. Technology is ready to move from development to commercialization.



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ARPA-E REMEDY

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- **Advanced Research Projects Agency – Energy (ARPA-E) launched a program titled “Reducing Emissions of Methane Every Day of the Year”, or REMEDY for short, in 2021.**
 - Both Colorado State University and Texas A&M University submitted successful proposals
 - CSU: “Lean-burn Natural Gas Engine System to Achieve Near-zero Crankcase Methane Emissions from Existing and Future Engine Fleet”
 - Texas A&M: Reducing Emission of Methane through Advanced Radical Kinetics and Adaptive Burning in Large Engines (REMARKABLE)
 - The goal of ARPA-E in general, and especially REMEDY specifically, is to bring technology from TRL 3 – 4 to TRL 6 – 7.
 - Phase I of projects launched in 2022, with Phase II renewal evaluation occurring in 2024.
 - Go/No-Go milestone for transition from Phase I to Phase II involved laboratory demonstration of the technology.
 - Both projects approved for renewal for Phase II
 - Phase II requires field-demonstration of the technology.
 - Teams currently working on engineering the technology for field-engine testing, expected to occur in late 2025.



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DOE MERP

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- **Inflation Reduction Act (IRA) provided new authority under Section 136 of the Clean Air Act to specifically reduce and regulate methane emission from the O&G industry through a new program called Methane Emissions Reduction Program (MERP)**
 - MERP essentially has two elements:
 - Regulatory: managed by EPA
 - Assistive: Mostly managed, particularly the financial aspects, by DOE.
- **IRA provides for up to \$1.36billion in financial and technical assistance to support MERP.**
 - \$350million awarded to states to assist well owners / operators with well plugging.
 - \$850 million available to distribute to proposals under review that “help small oil and natural gas operators reduce methane emissions and transition to available and innovative methane emissions reduction technologies, while also supporting partnerships that improve emissions measurement and provide accurate, transparent data to impacted communities.”

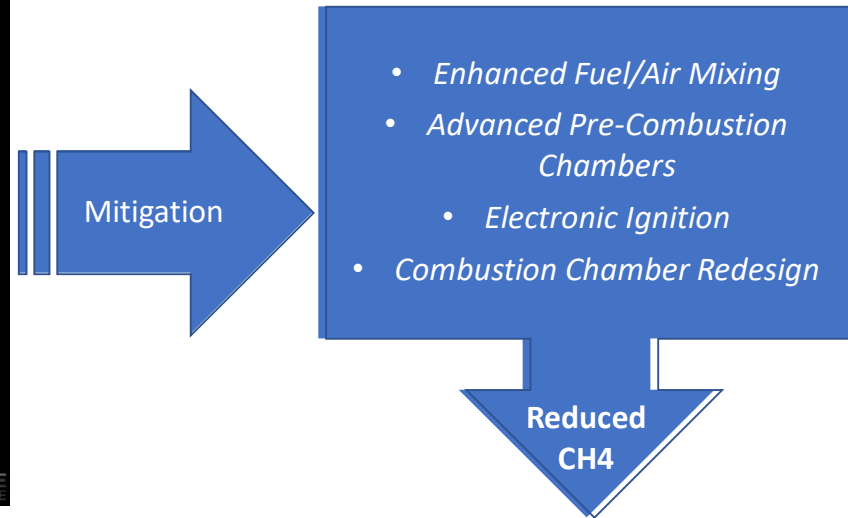
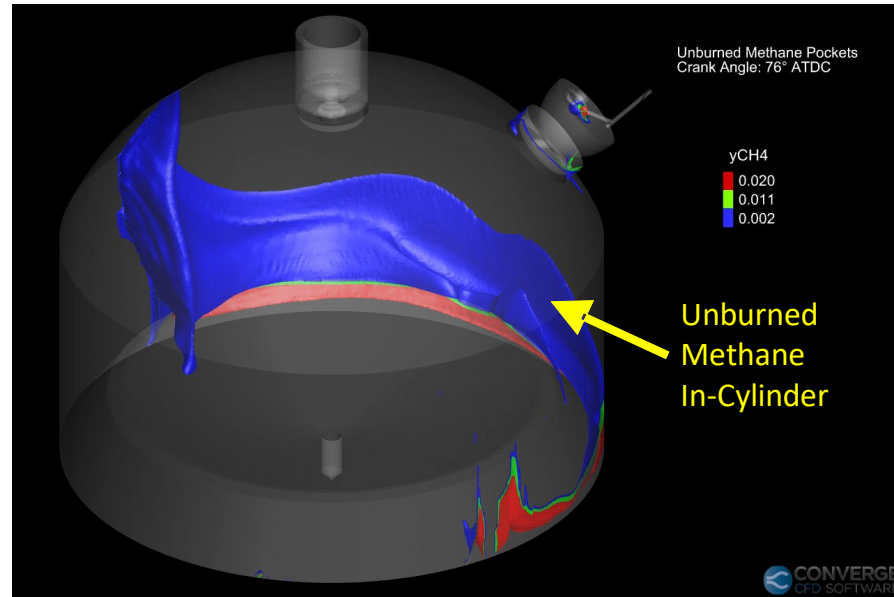
DOE MERP

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- **Proposals for the \$850million were due on August 26, and covered a large array of broad topical areas (known as Areas of Interest, or AOIs):**
 - The AOI of interest to CAPSTC specifically, and perhaps GHG SRP generally was AOI 2a: “Field Deployment of Engine and Compressor Methane Reduction Technologies”
 - Both Colorado State and Texas A&M submitted individual proposals to the effort, with Colorado State being a major partner of the Texas A&M proposal.
 - The Colorado State-led project focuses on methane reduction of 4-stroke engines.
- **Texas A&M Project: “Field Deployment of New Low Methane Technology on Natural Gas Integral Two-Stroke Engines”**
 - Texas A&M (Lead), Cooper Machinery Services, Colorado State University, PRCI, TC Energy, Kinder Morgan

DOE MERP

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• Technological Concept

- Unburned methane effectively exists in pockets within the MCC
- Employing existing technologies developed for Nox-reduction will be redesigned purposefully for reducing methane in the various pockets of the main chamber.

DOE MERP

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- **Technical Goals**

- Redesign existing components to minimize methane emissions
- Most design elements were chosen based on PRCI research
- Hardware:
 - High pressure electronic fuel injectors
 - Multi-nozzle PCCs
 - Electronic ignition
 - High compression ratio pistons and heads
- Test at Cooper, CSU, TC Energy, and Kinder Morgan
 - Design iterations tested at Cooper and CSU
 - Production prototypes tested at TC Energy and Kinder Morgan



DOE MERP

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- **Overall budget: >\$5.1 million**
- **44-month timeline**
- **4 phases:**
 - Research/design/validation
 - Prototype construction and testing
 - Field testing at TC Energy and second partner
 - Report generation
- **Testing partners have the option to buy and continue using final hardware configuration**
- **Goal is sub-5g/bhph methane emissions with a path to “near zero”**

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PCC Roadmap (Additional Slides)

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- **(PR457-22208) Reduced Cyclic Variability for Improved GHG Emissions**
 - Investigating governor control to reduce cyclic variability (particularly misfires) to reduce methane emissions
 - Developed MATLAB tools for analyzing the stochasticity and determinism of in-cylinder pressure measurements
 - Intended to guide development of control strategies and search for misfire root causes
 - Draft report submitted; awaiting voting and feedback.
- **(PR457-22209) Feasibility Study of the Premixing of Prechamber Fuel and Air to Reduce GHG Emissions**
 - Investigate potential benefits/feasibility of premixing fuel and air before injection into the PCC
 - CFD study on AJAX engine, evaluating several different premixed A/F mixtures injected into air-only-charged PCC.
 - Simulations in progress; expect draft final report by July 31, 2024.

PCC Roadmap (Additional Slides)

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- **(PR457-22210) Effects of Inlet Port Geometry on MCC Mixing Sensitivity Study**
 - Investigate the potential CH₄ reduction by improving MCC mixing through better-mated inlet port geometries to advancements in PCC design.
 - CFD study on AJAX engine, evaluating different port geometries and observing changes in mixing and CH₄ reduction.
 - Final report submitted and approved; project complete.
- **(PR457-23203) Investigation of Supersonic Prechamber Jets to Reduce GHG Emission**
 - Investigate potential benefits/feasibility of achieving supersonic jet injection of PCC gases into MCC.
 - The idea supposes that supersonic injection would lead to improved MCC mixing and thus lower CH₄ emissions.
 - Running into substantial computational issues; there is a fix but it requires excessive computational time and compute expense.
 - Either way, expect to have simulation results wrapped up in fall 2024. Project is 40% complete.

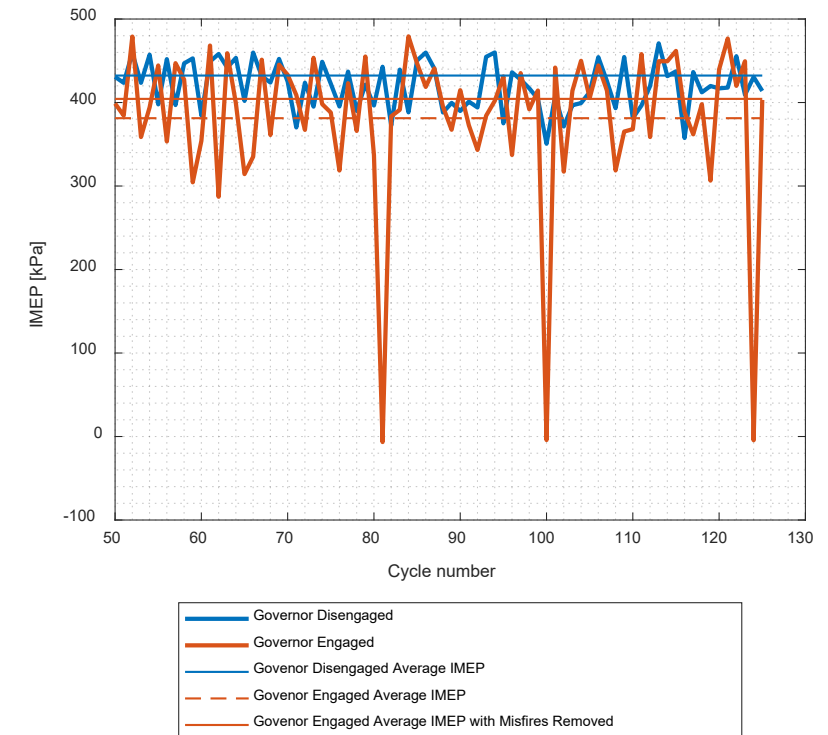
PCC Roadmap (Additional Slides)

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- **Ajax E-565 single cylinder, two stroke engine used for study**
- **Engine tested at 510 RPM, 520 N-m**
 - 1000 cycles collected for governed and ungoverned operation
 - Premixed fueling method (DI system not functional at time of testing)
- **Results indicate average IMEP is greater for ungoverned operation**
 - Zero misfires occurred during 1000 cycle run
- **Partial-firing and misfire events are significantly higher**
 - High number of slow burning cycles
 - Low peak pressure, but average IMEP for the cycles
 - Oscillatory combustion events for governed operation
 - Poor combustion cycles followed by strong cycles



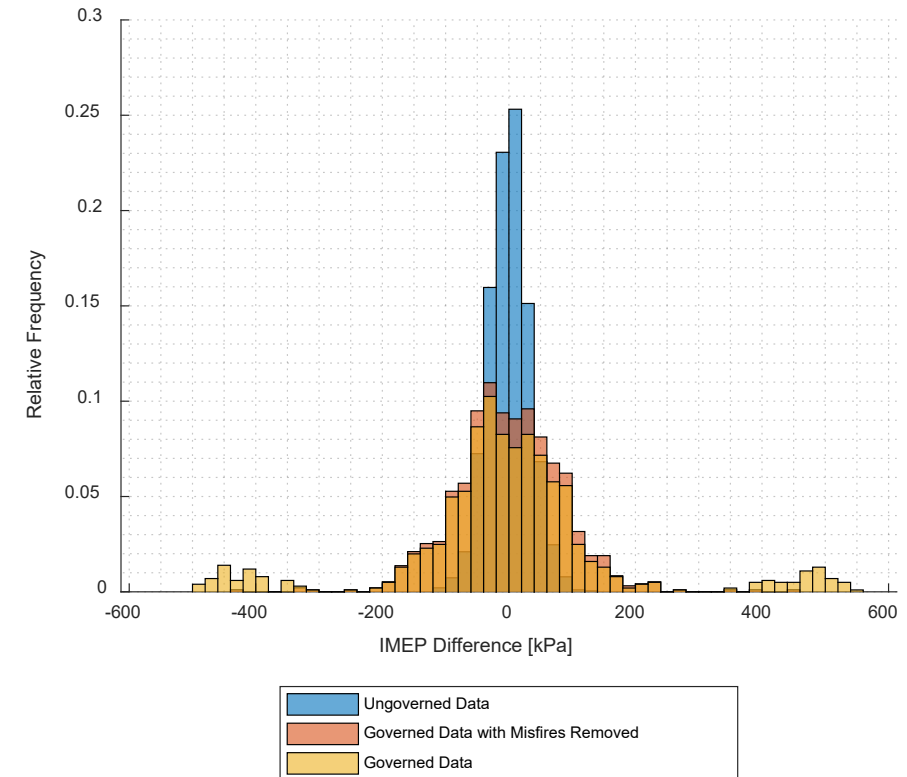
Ajax E-565 at TAMU engine lab



PCC Roadmap (Additional Slides)

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- **Peak in-cylinder pressure in the respective location provide useful insight on a cycle's combustion**
- **Ungoverned operation yields:**
 - Peak pressure: 1400-2200 kPa for healthy cycles with IMEP above 410 kPa
 - Location of peak pressure: 20-35 CAD ATDC
- **Governed operation yields:**
 - Peak pressure: 1100-1900 kPa
 - Location of peak pressure: 26-45 CAD ATDC
- **IMEP differences between cycle i and $i+1$ show contrast between governed and ungoverned operation**
 - Ungoverned standard deviation: 32.21 kPa
 - Governed standard deviation: 84.82 kPa
 - Trimodal response reflects weak partial-fire and misfire events followed by a strong combustion



PCC Roadmap (Additional Slides)

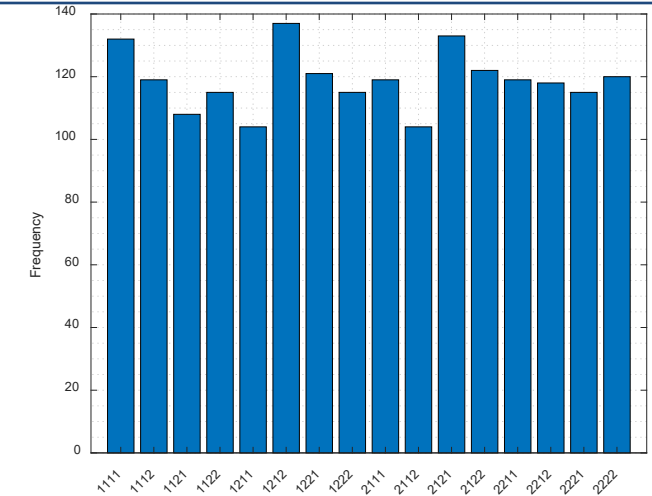
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- A modified form of Shannon entropy is used to determine the stochastic relationship between the sequences

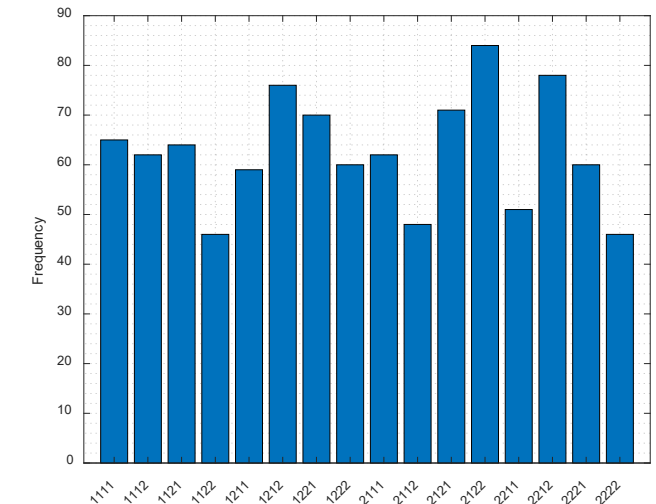
- n_{seq} is the number of sequences measured
- p_k is the probability of the sequence occurring

$$H_s = -\frac{1}{\log(n_{seq})} \sum_k p_k \log(p_k)$$

- A perfectly stochastic data set equals 1
 - Low chance to determine a pattern in the data
- Both data sets indicate highly stochastic behavior
 - Ungoverned: $H_s = 0.9976$
 - Governed: $H_s = 0.9919$
- Given the results, this method does not yield much potential for implementation of a control algorithm



Symbol sequence of IMEP for ungoverned cycles

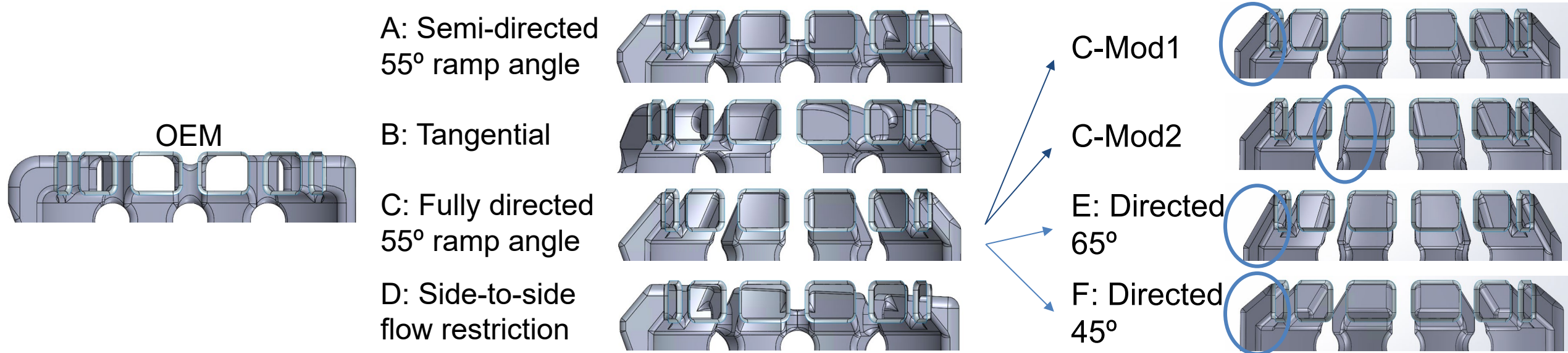


Symbol sequence of IMEP for governed cycles

PCC Roadmap (Additional Slides)

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- Examined 8 new intake manifold concepts intended to improve mixing



- Initial evaluations were carried out for air mass delivery improvements

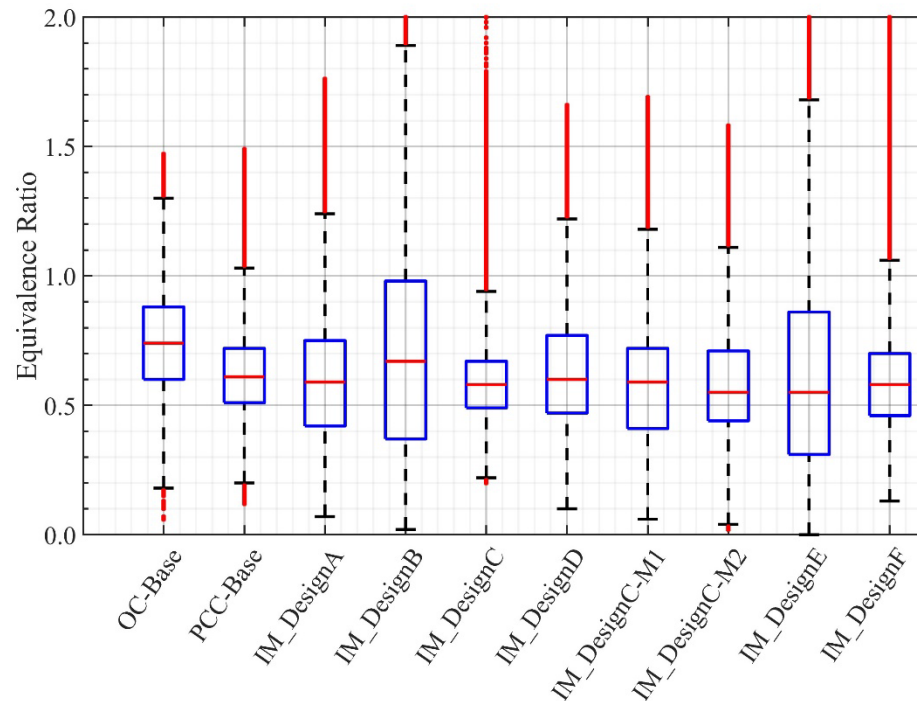
Case	Air Mass Delivered (g, IM to MCC)	Relative to OEM IM
OC-Base	10.69	-1.08%
PCC-Base	10.80	N/A
IM_DesignA	11.26	4.27%
IM_DesignB	9.73	-9.96%
IM_DesignC	11.12	2.90%

Case	Air Mass Delivered (g, IM to MCC)	Relative to OEM IM
IM_DesignD	10.07	-6.75%
IM_DesignC-M1	11.10	2.72%
IM_DesignC-M2	11.09	2.64%
IM_DesignE	9.90	-8.34%
IM_DesignF	11.21	3.77%

PCC Roadmap (Additional Slides)

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- Attempted to quantify mixing quality by binning all cells according to equivalence ratio
- All cases showed relatively strong skew as a consequence of overall lean ERs
 - IQR largely replaces the concept of SD for skewed data
 - Smaller IQR (range between 25th and 75th percentile) means middle 50% of data is tighter

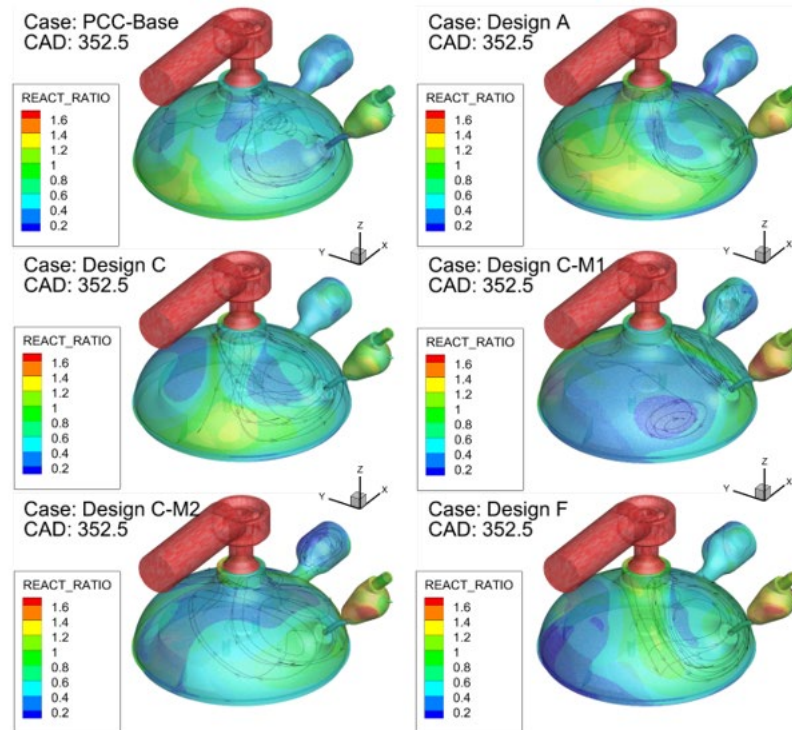


Case	IQR (25 th to 75 th)	Range 15 th to 85 th	Outlier Limits (Low/High)	Rank (By IQR)
IM_DesignC	0.18	0.30	0.22/0.94	1
PCC-Base	0.21	0.32	0.20/1.03	2
IM_DesignF	0.24	0.36	0.13/1.06	3
IM_DesignC-M2	0.27	0.39	0.04/1.11	4
OC-Base	0.28	0.49	0.18/1.30	5
IM_DesignD	0.30	0.45	0.10/1.22	6
IM_DesignC-M1	0.31	0.46	0.06/1.18	7
IM_DesignA	0.33	0.52	0.07/1.24	8
IM_DesignE	0.55	0.83	0.00/1.68	9
IM_DesignB	0.61	0.90	0.02/1.89	10

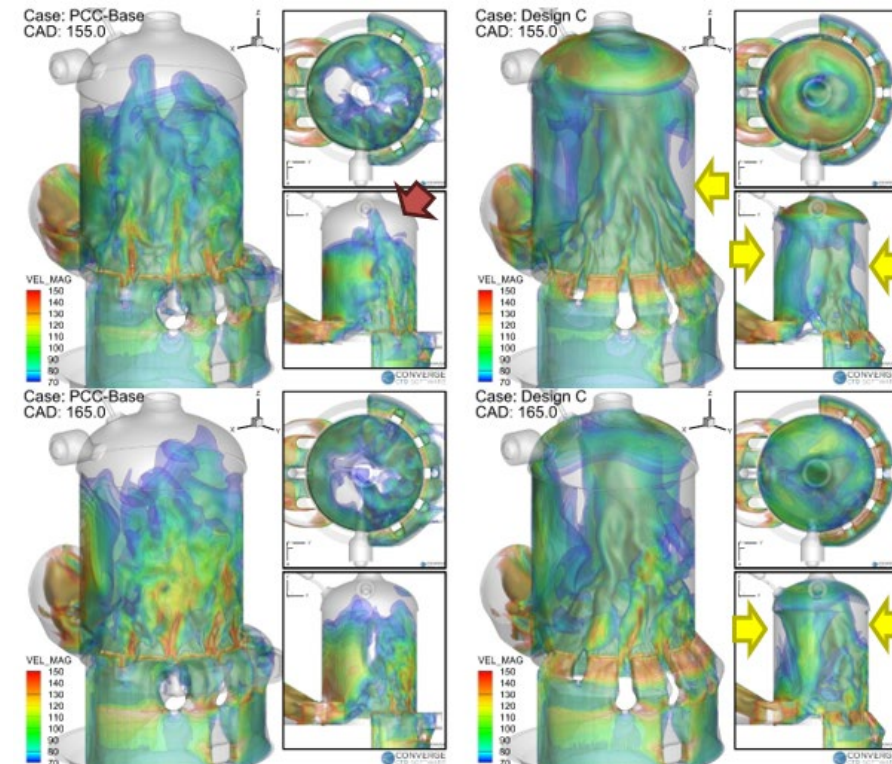
PCC Roadmap (Additional Slides)

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- (Left) Examining stratification in the MCC just before spark timing (352.5CAD)
- (Right) Comparing differences in how the different designs change the flow field
- Examined mechanisms preventing methane oxidation as well as NOx production



Comparison of MCC stratification just before spark (352.8CAD)



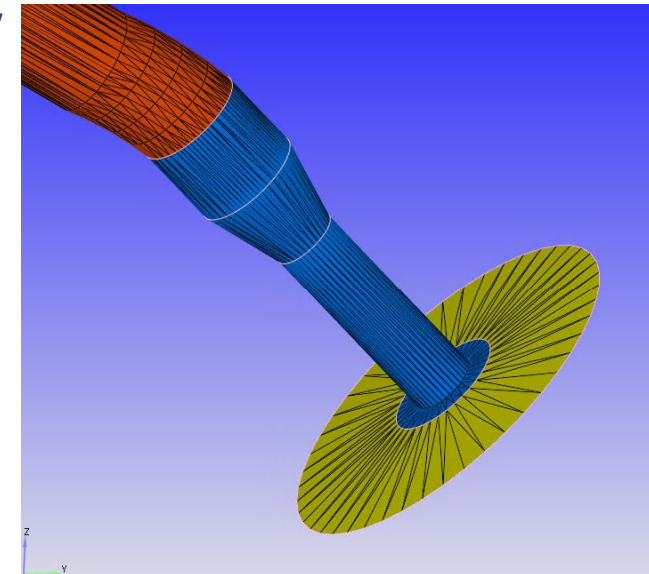
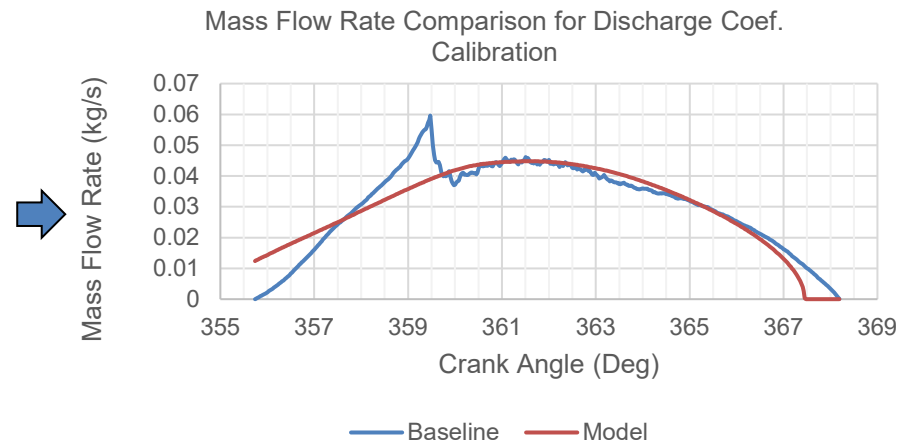
Comparison of flow field changes from the PCC baseline and Design C

PCC Roadmap (Additional Slides)

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- Modified prechambered baseline model from previous PRCI work to accept altered nozzles
- Used baseline data to create a mass flow rate model to help predict desired sonic nozzle diameters as a first pass
 - Collected baseline parameters ($\dot{m}$, P , T , A , γ and R) and calibrated C_d
 - Designed 6 sonic nozzles to test
 - Different nozzles provide different durations of sonic/ss flow

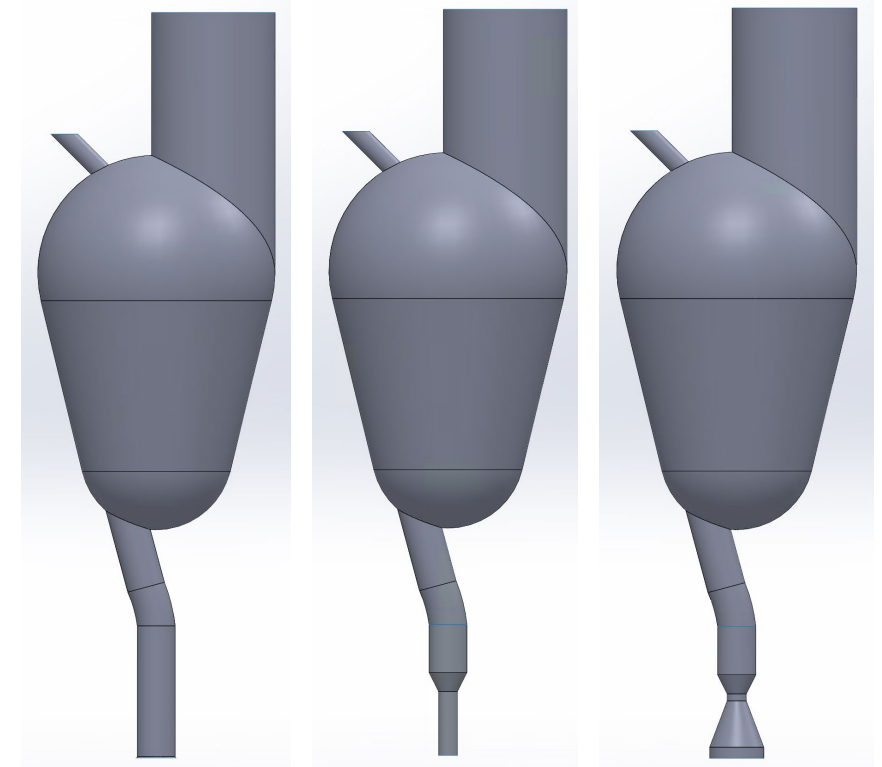
$$\dot{m}_e = C_D P_{PCC} A_e M_e \sqrt{\frac{\gamma}{RT_{PCC}}} \left[1 + \left(\frac{\gamma - 1}{2} \right) M_e^2 \right]^{\frac{\gamma + 1}{2(1 - \gamma)}}$$



PCC Roadmap (Additional Slides)

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- Full set of 6 sonic and 6 supersonic nozzles have been created
- Modified nozzles impair scavenging of PCC, leading to rich conditions
 - Solution: Map condition of baseline PCC to modified PCCs
 - Allows for each of the PCCs to have similar conditions
 - Provides control over parameters such as pressure, temperature, species, etc.



Example Stock, Sonic, and SS
Nozzle Concepts