ARPA-E REMEDY Program

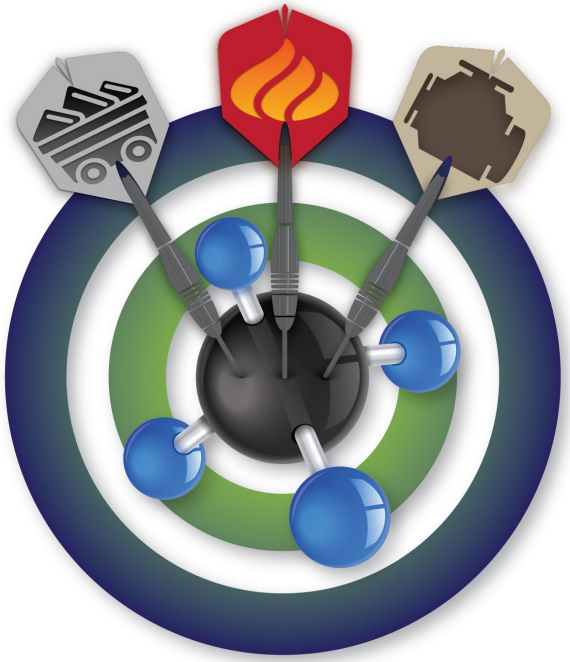
Reducing Emissions of Methane Every Day of the Year

2023 Methane Connects

Jack Lewnard, Program Director

Jack.lewnard@hq.doe.gov

October 5, 2023



Overview

- ARPA-E

- REMEDY overview, performers, and needs
  - Engines
  - Flares
  - VAM

- Beyond REMEDY
  - International
  - EPA
  - DOE
  - National Academies

What is ARPA-E?

The Advanced Research Projects Agency-Energy (ARPA-E) is an agency within the U.S. Department of Energy that:

- Provides **Research and Development funding** for high-risk, high-reward, transformational ideas. FY2023 budget $470 MM.
- Focuses on technologies that could **fundamentally change** the way we get, use and store energy: high impact/high risk
- Accelerates energy innovations that will create a more secure, affordable, and sustainable **American energy future**

REMEDY: Engines, Flares, Coal Mines

- 3 yr, $35MM program, diverse technologies/teams, systems approach, field tests in year 3

- Point source emissions
  - 50,000+ natural gas-fired engines in oil and gas and CHP/electric generation
  - 300,000 flares for oil and gas "routine" operations – not flares "temporarily" burning associated gas
  - ~250 coal mine ventilation shafts

- Program update https://arpa-e.energy.gov/2023-repair-annual-meeting

REMEDY: Two phases with down-select, 36 months, $35MM

Stage 1
12 teams, 12-18 mo.,
$1-2M per team

Lab demonstration with $50/ton CO_2^e levelized cost of carbon and at least 98% methane destruction efficiency

Down-select based on lab demonstration performance and updated Phase 2 scope/schedule

Stage 2
~4-7 teams, 18-24 mo.,
up to $3M per team

Systems-level demonstration in field with $40/ton CO_2^e levelized cost of carbon and at least 99.5% methane destruction efficiency

Additional Metrics: Environmental and Economic

- 85-87% LCA CO_2e reduction
- No adverse environmental impacts
- No Hazardous Air Pollutants (HAPS, i.e., formaldehyde, etc.)

- 87% LCA CO2e reduction
- Meet or exceed New Source Performance Standards
- No HAPS or adverse environmental impacts
  - If technology uses water
    - LCA water use equal or less than CCS
    - Meet or exceed NDES

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CHANGING WHAT'S POSSIBLE

REMEDY Teams Seeking:

- Engines
  - Marquette: Field test site(s), system integrator
- Flares
  - ACT: Field test site, application/commercialization partners
  - U Michigan: Test site(s)
  - U Minnesota: Bakken and Permian test sites
  - Flare methane quantification
    - Verify 99.5% methane destruction efficiency
- VAM
  - PCI: Field test site, system integrator

REMEDY Teams based on Methane Source

Exhaust from Natural Gas-Fired Lean Burn **Engines**

MAHLE

COLORADO STATE UNIVERSITY

MARQUETTE UNIVERSITY

TEXAS A&M UNIVERSITY

Waukesha

INNIO

Flares for Safe Operation of Oil and Gas Facilities

ACT

ADVANCED COOLING TECHNOLOGIES

The Thermal Management Experts | www.1-ACT.com

UNIVERSITY OF MICHIGAN

UNIVERSITY OF MINNESOTA

CIMARRON

CREATING A CLEANER ENVIRONMENT™

Coal Mine Ventilation Air Methane (**VAM**)

JM Johnson Matthey

Inspiring science, enhancing life

MIT Massachusetts Institute of Technology

PCI Precision Combustion, Inc.

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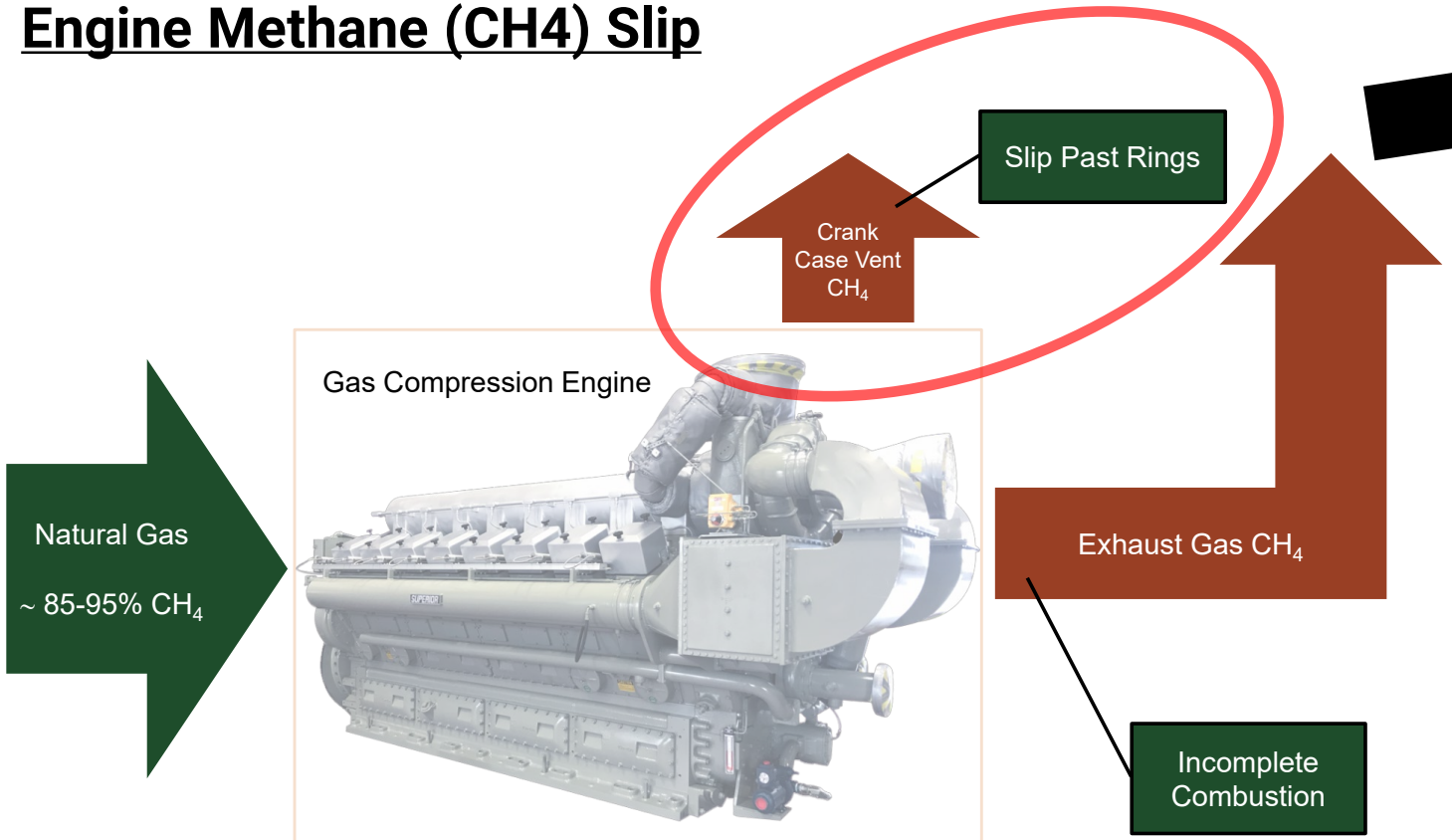
CHANGING WHAT'S POSSIBLE

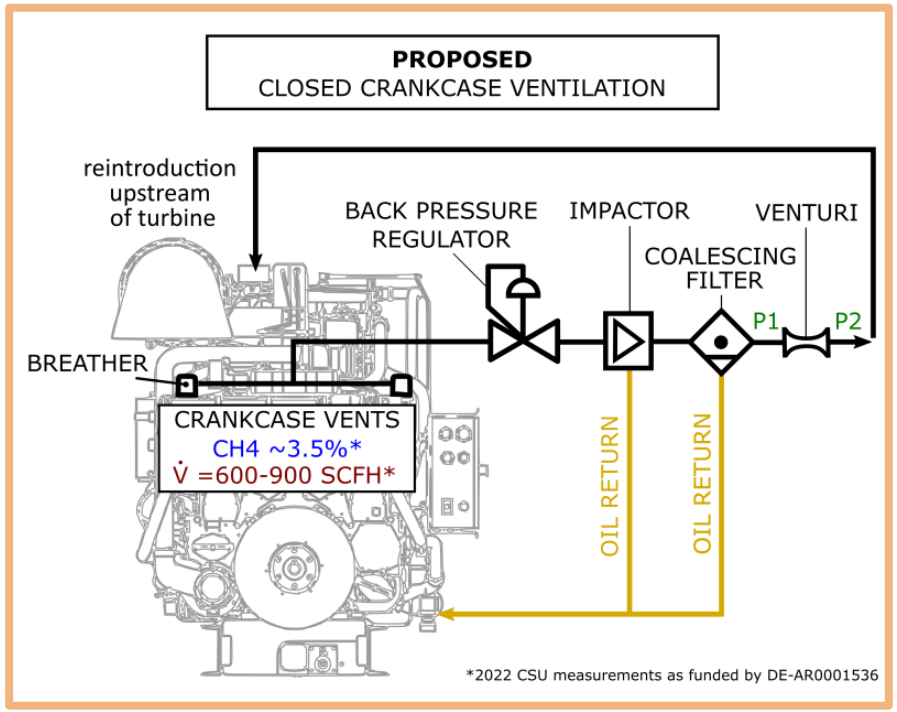
Crankcase Gas Rerouting/ Filtration System to Reduce Crankcase Methane Emissions from Lean-burn NG Engines

CATERPILLAR®

Engine Methane (CH_4) Slip



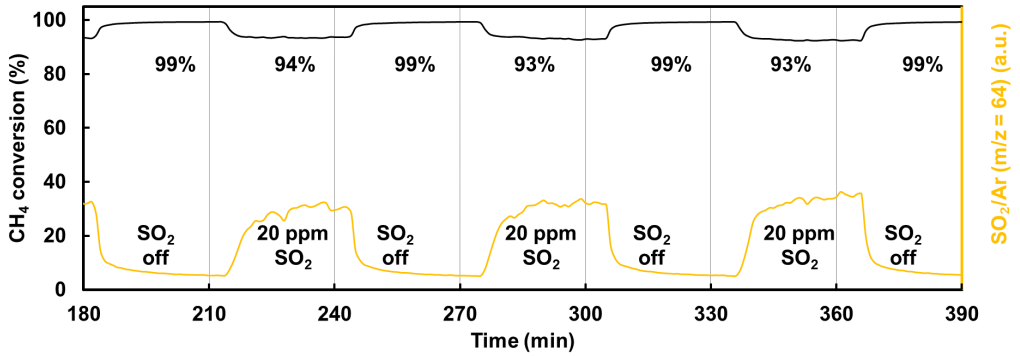
Approximately 10-30% of total methane emissions for lean-burn 4-stroke engines.

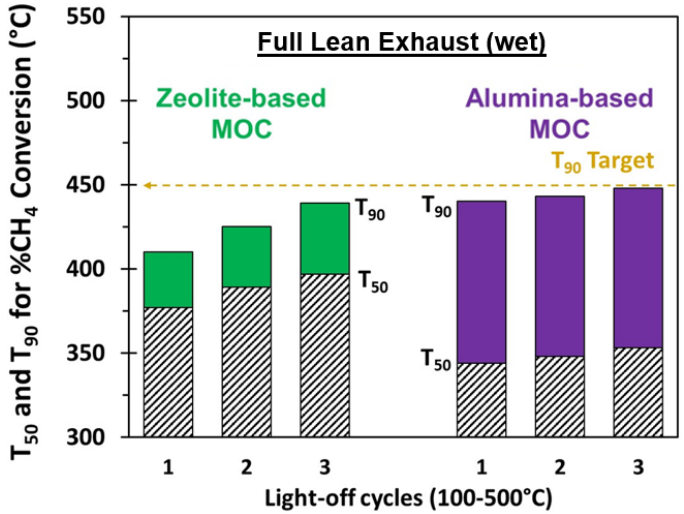


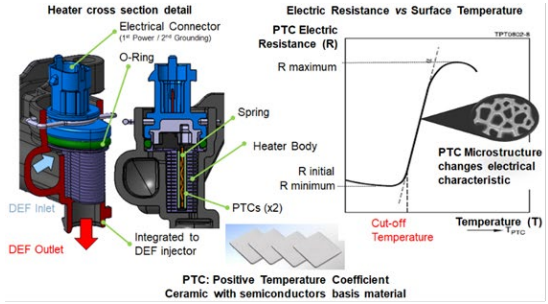
Recent testing of CCG recirculation system showed 95% reduction of crankcase CH4.

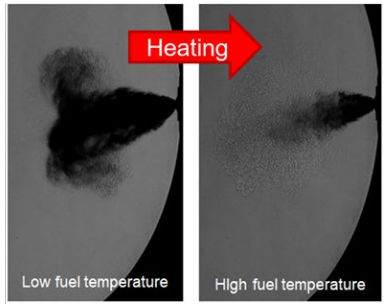
Mahle: Methane Oxidation Catalysts and Heated Urea for Large NG-Fueled Engine

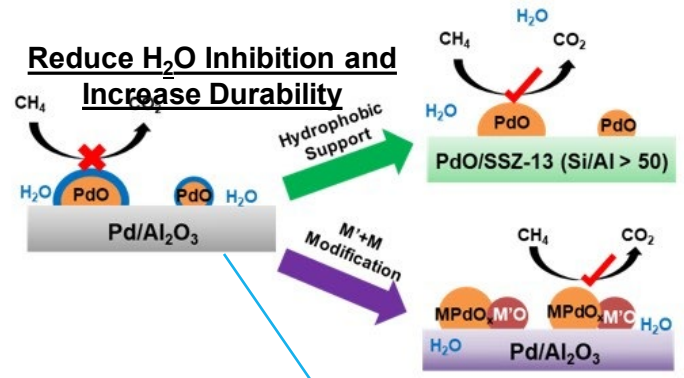
- ARPA-E REMEDY program
  - 3 years, approx. $4m
- Goal: Eliminate methane slip in large lean-burn NG engine exhaust using aftertreatment solution
- Challenge: Methane oxidation catalyst (MOC) compatibility with lean-burn NG engines (Oil&Gas, Marine, etc.):
  - Water inhibition at low exhaust temperatures prevents CH_4 conversion
- Solution: New hydrothermally stable MOC formulation
  - Lower light-off temperatures in high water environments
  - Upstream NO oxidation with heated urea to improve methane selectivity

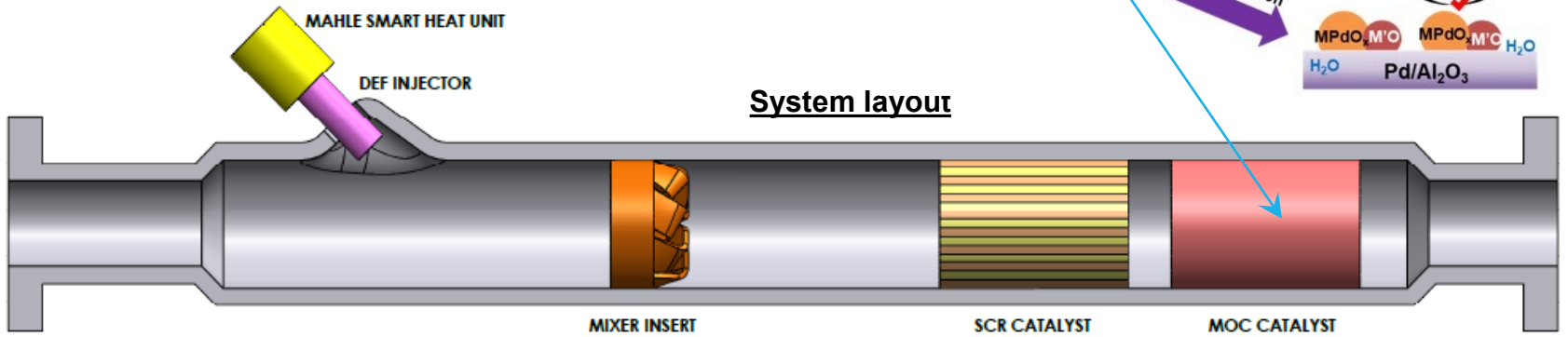












INNIO: Ultra Low Methane Slip Reciprocating Engine

Jim Zurlo, Principal Investigator James.Zurlo@innio.com

Technology Summary

- New piston, and other components that dramatically reduces crevice volumes
- Weight optimization of large-bore steel piston to achieve same reciprocating mass as current aluminum piston
- Cost neutral/weight neutral package that is intended to be used in new production, and for fleet upgrades of existing engines

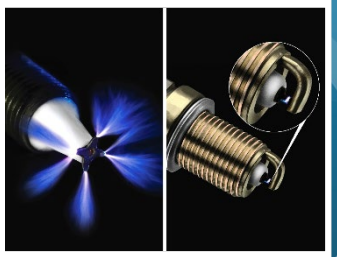
Technology Impact

Through optimization of the piston and other components, the unburned in-cylinder **methane slip is reduced by 80%.** This results in a **20% reduction in CO2e** vs current engine

Progress

- All new components meet design goals
- All prototype components procured
- Emissions testing to start soon

Texas A&M: Reducing Emission of Methane through Advanced Radical Kinetics and Adaptive Burning in Large Engines (REMARKABLE)

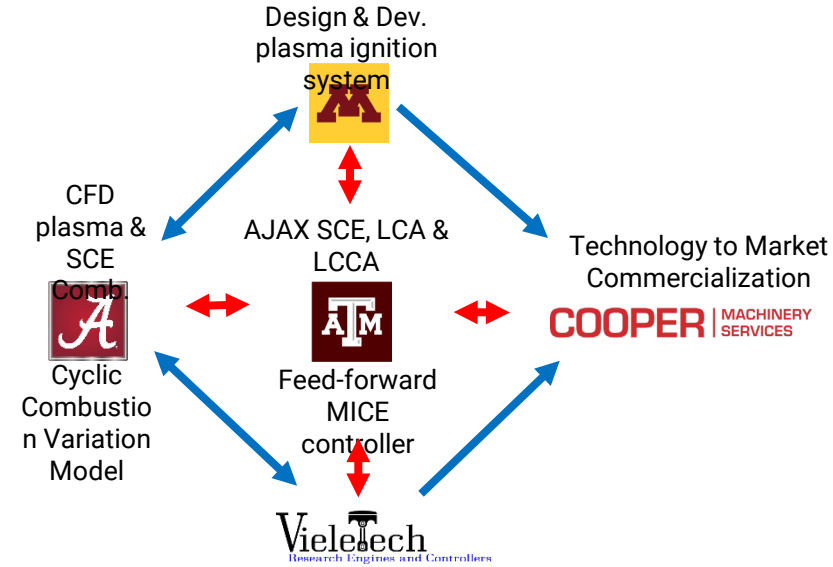


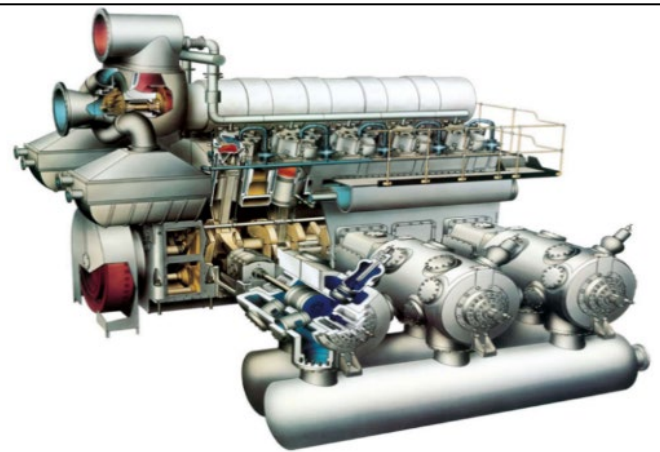
- Summary: Deliver a model-based feed-forward combustion control system to predict and mitigate partial-fire and misfire cycles and a field-tested, prototype plasma ignition system that results in rapid self-sustaining combustion

Project Status:

- Texas A&M has collected data on test engine and provided data to Alabama for initial development of feedback controller
- Minnesota has begun testing plasma ignition in their combustion vessel for precombustion chambers
- Vieletech is continuing to develop engine control hardware
- Texas A&M will soon finish engine upgrades in preparation for plasma ignition system handoff from Minnesota for installation on test engine

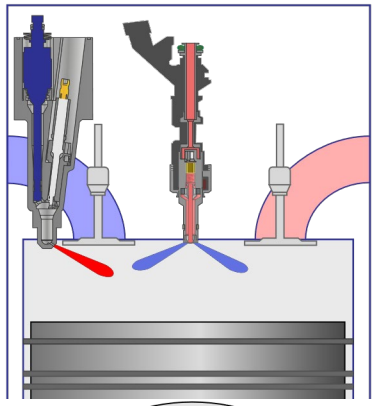
Team Coordination:

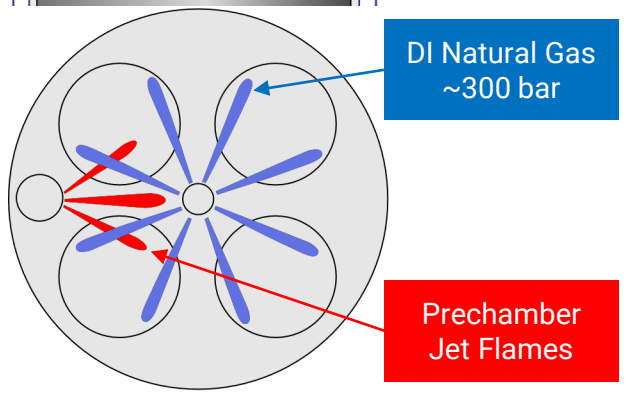


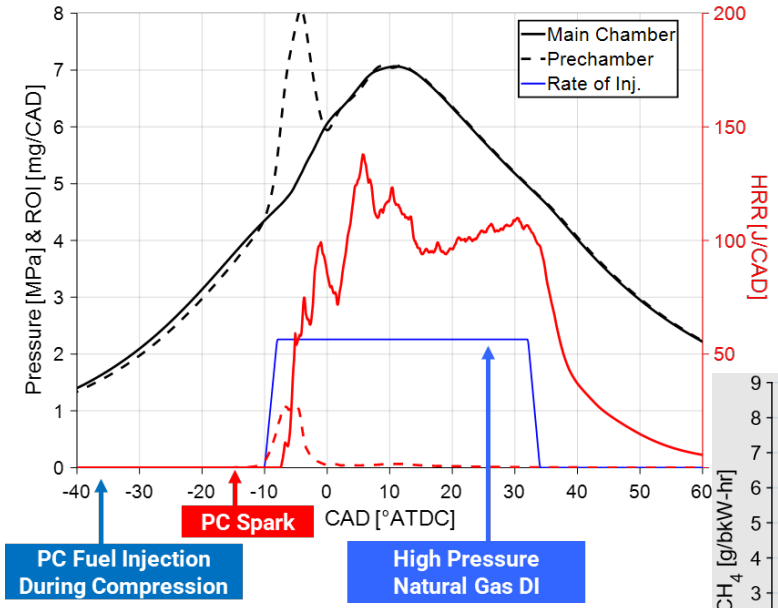


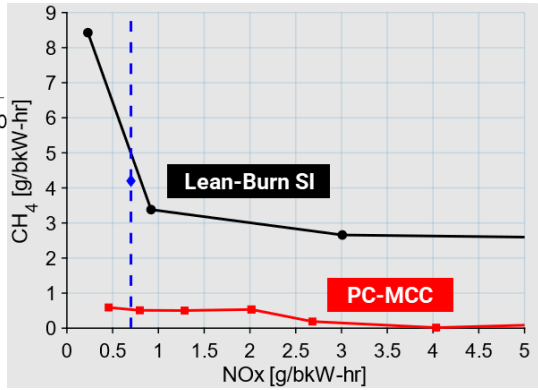
Marquette: Prechamber Enabled Mixing Controlled Combustion (MCC) of Natural Gas

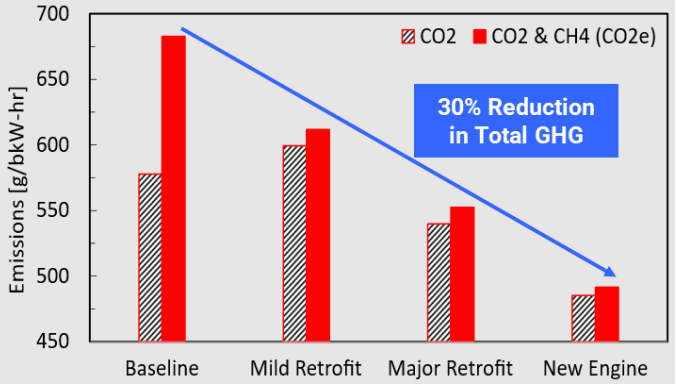
- **Active prechamber igniter for Direct Injected Natural Gas**
- **Non-premixed, Mix[illegible]**
  - Eliminates classic CH_4 slip sources – Crevices & Blow-thru
  - Removed Knock Limitation → Increase Efficiency
  - Tolerant to a very wide range of gas qualities (Methane #)
- **Applicable to 2-stroke and 4-stroke engines**
- **~10x reduction in CH4 slip emissions at equal NOx emissions**
- **Transformational reduction in CH_4 emissions from NG engines & fuel agnostic tech. for future low carbon engines (Ammonia, Hydrogen, etc.)**











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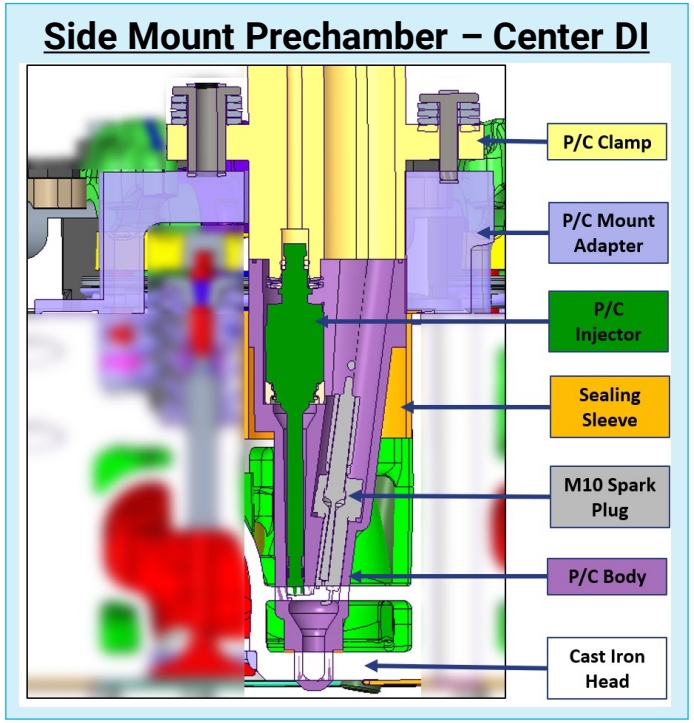
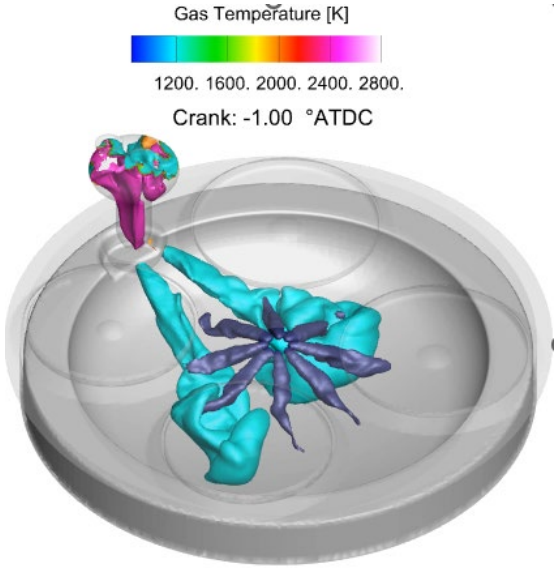
Marquette: Prechamber Enabled Mixing Controlled Combustion (MCC) of Natural Gas

- **Single-Cylinder Engine Laboratory Testing**
  - Starting in November 2023
  - 4-stroke diesel engine converted to Natural Gas
- **Interested in Field Testing Partners for Phase 2**
  - Planning & Execution Begins in Spring 2024
  - Testing Approximately Spring 2025
  - Interest in platforms that have high methane slip, and ample room in the cylinder head
  - 2-Stroke engines could be great candidates
  - 4-Stroke engines are also very welcome





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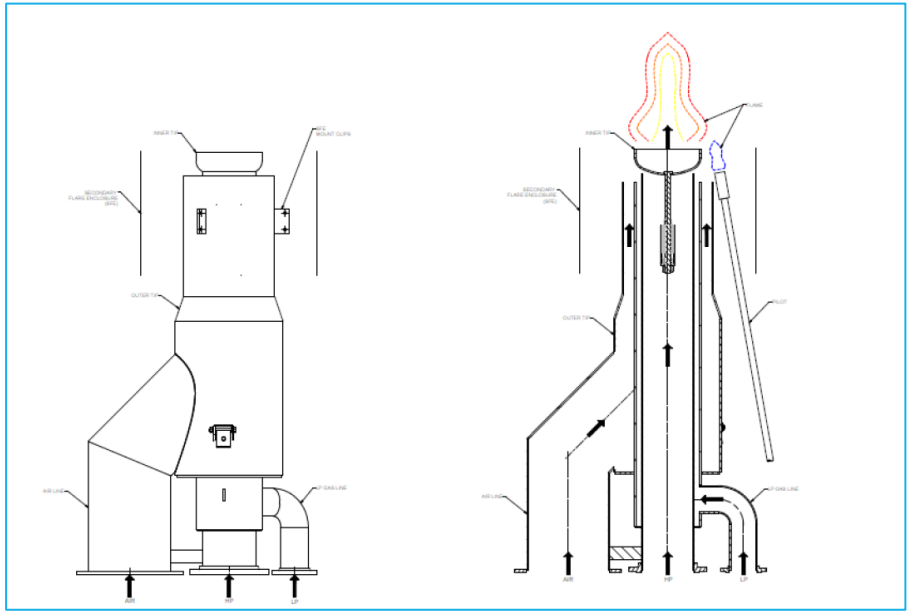
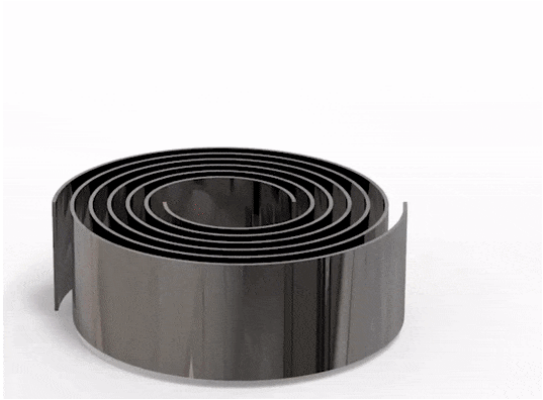
CIMARRON
CREATING A CLEANER ENVIRONMENT™

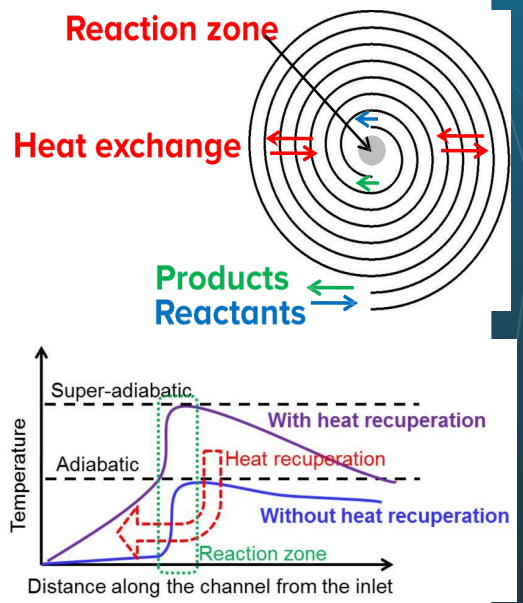
- 1. DreamDuo flare
- 2. Hybrid Flare
- 3. DRE-Max
- 4. Computer Vision
- 5. Methane DRE Measurement

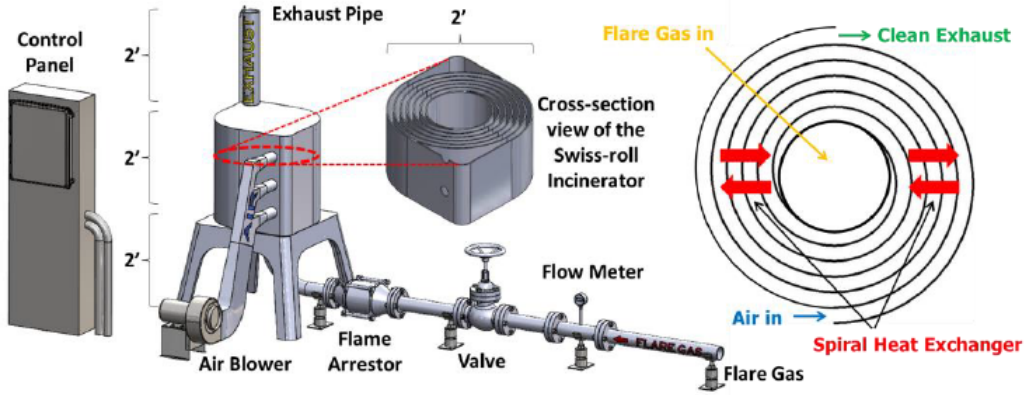


ACT: SWISS-ROLL COMBUSTOR

- Center combustion zone surrounded by spiral heat exchanger
  - Effectively recuperate heat to ensure high reaction temperature
- **High destruction efficiency throughout the wide flow range and compositions**
- Completely **enclosed combustion (no visible flame)** with a wide flammability (ultra-lean to ultra-rich)
- **99.9%+** methane DRE**; ultra-low NOx** emissions
- Clean premixed combustion for a very low heating value flare gas (< 40 BTU/SCF) **without supplementary fuel**
- **Compact** size
- **Applications**
  - Methane mitigation from small and marginal wells
  - Pipeline blowdown operations
  - Incinerate hydrocarbon and chemical storage tank vent fumes







ACT Looking For…

- Partners for field testing
  - small or marginal wells
  - tank vapors
- Collaborators on complementary technologies
  - lean and ultra-lean combustion of low BTU/SCF gases
  - fuel reforming
- Pipeline O&M Companies
- Oilfield Service Providers

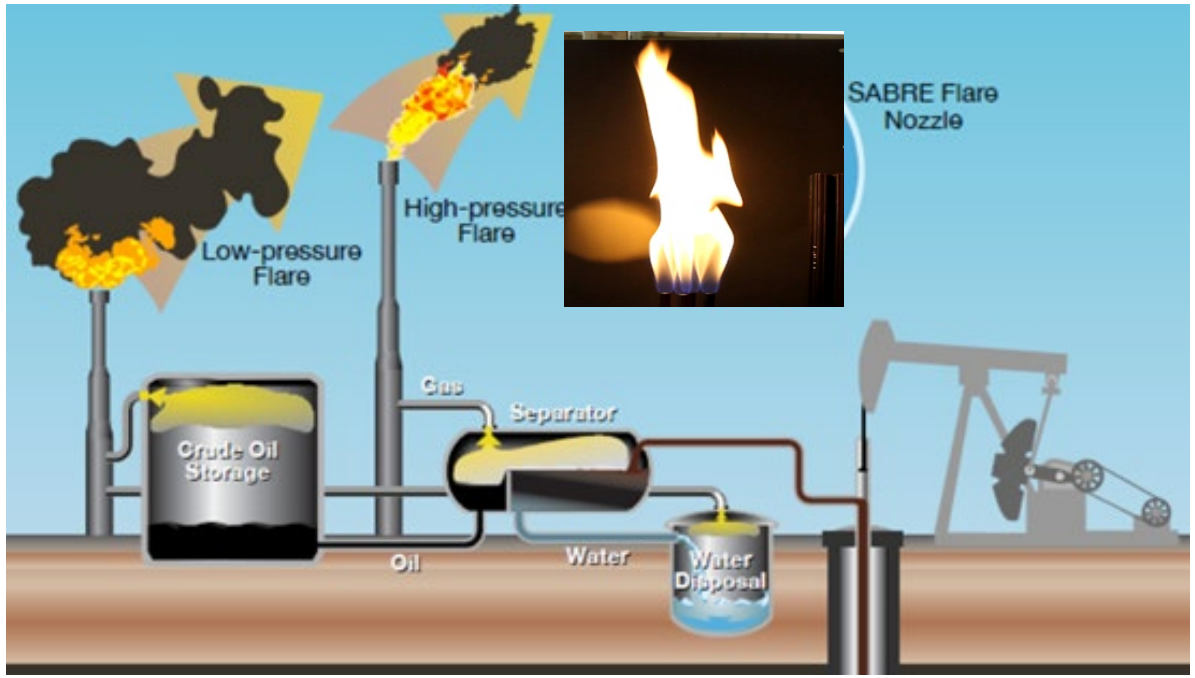
U Michigan SABRE Field Test Site(s)

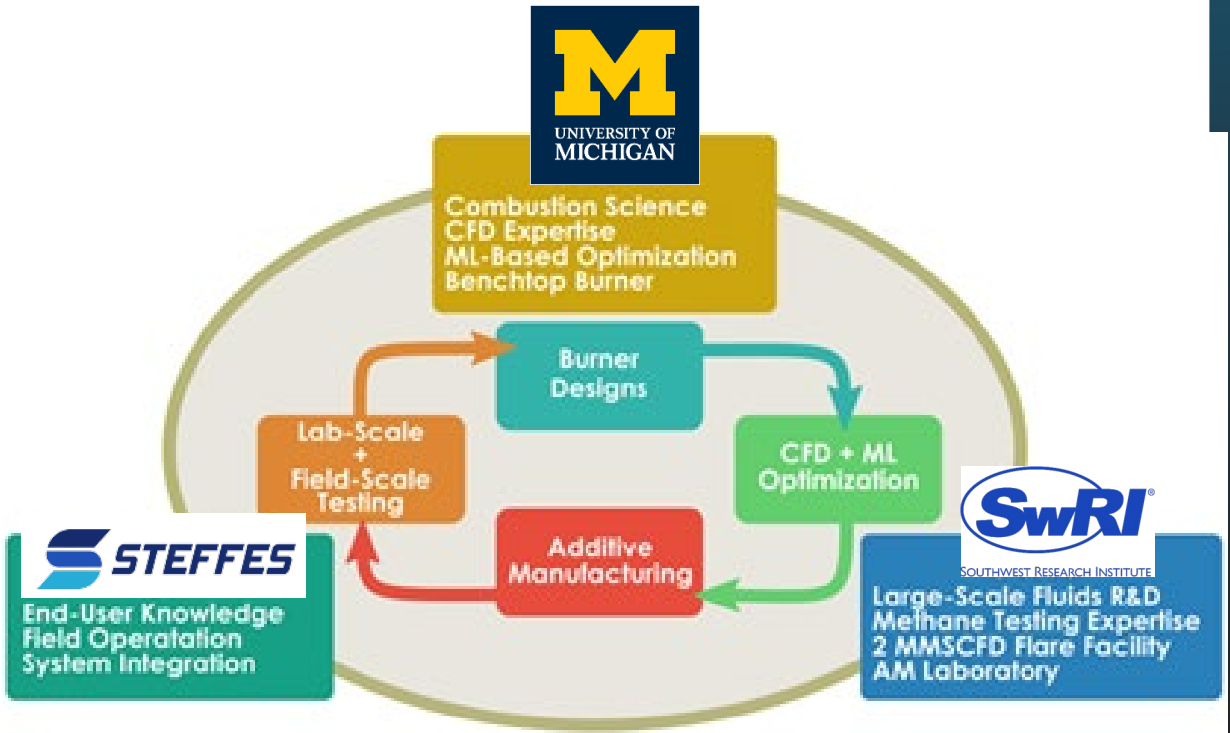
Project will cover instrumentation and testing costs.

- Measure composition, flow for flare streams
- Test new hardware to improve flare performance

Margaret Wooldridge mswool@umich.edu

Project vision: Improved flare-tip burner design enabled by advances in modeling, optimization and additive manufacturing will reduce methane emissions using realistic flare conditions experienced in the field.





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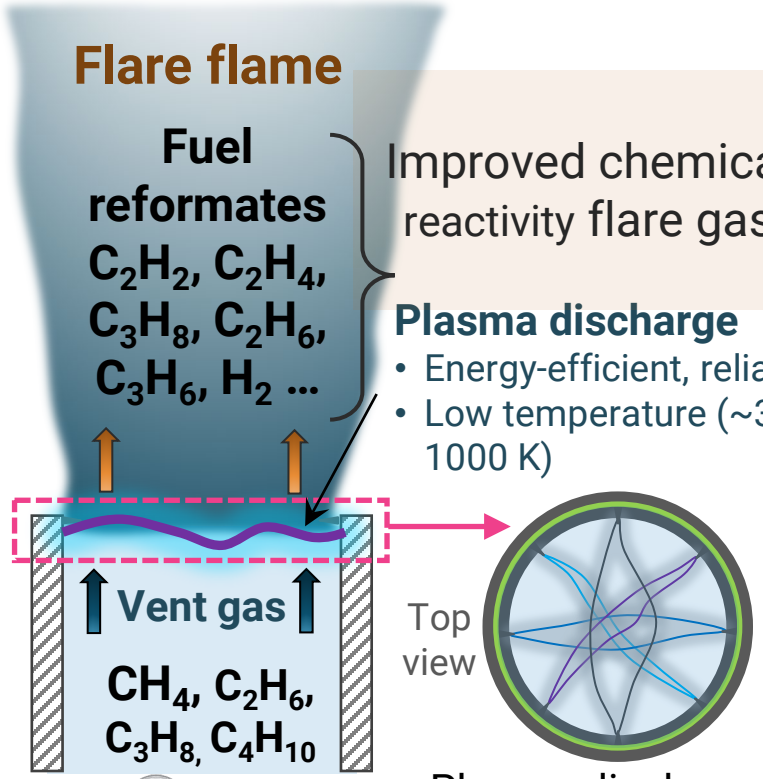
Spectrum
ENVIRONMENTAL SOLUTIONS

Minnesota: Enhancing Methane Flare Destruction Efficiency through Non-Thermal Plasma-Assisted *In-Situ* Reforming

- Low-temperature plasma discharges in flare vent gases enhance chemical reactivity, enabling improved burning characteristics resulting increased flare efficiency, reduced methane emissions
- Plasma enables ignition and flame stabilization



Plasma discharges in vent gas

We are seeking potential operators to assess our plasma hardware in Permian and Bakken

PI: Prof. Sayan Biswas
Email: biswas@umn.edu

Custom 'PlasmaFlareCleaner' retrofits on existing flares

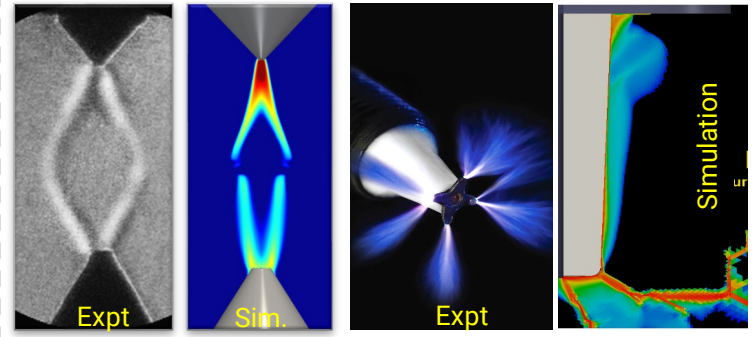
The Team

University of Minnesota

Barr Engineering

John Zink Hamworthy Combustion

Low-temperature plasma discharges



Biswas et al.

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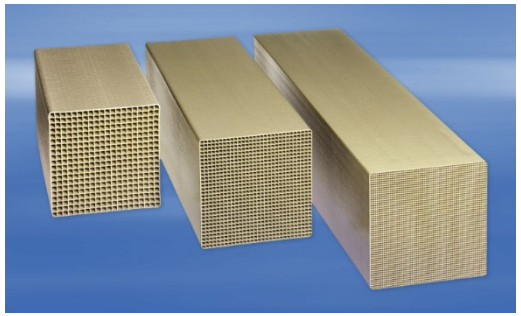
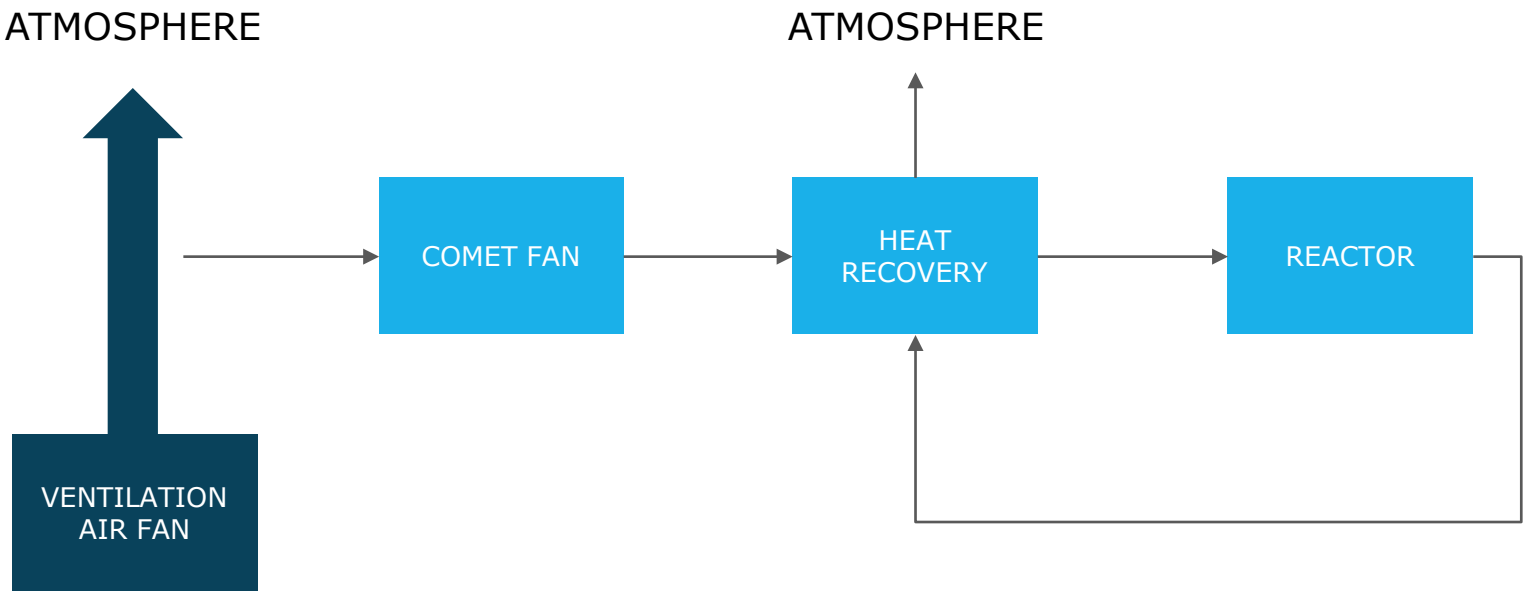
Johnson Matthey
Catalytic Oxidation of Methane – COMET™

Safe, simple and reliable once through design



*Example of monolith catalyst

*Example of potential scalability of a system



- Continuous flow
- Scalable Modular Design
- <600ºC oxidation
- No NOx
- Low 0.1mol% methane
- >99.5% conversion
- Low maintenance
- Option for power generation

In partnership with:

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CONSOL ENERGY FUEL THE WORLD FOR A BETTER TOMORROW

OAK RIDGE National Laboratory

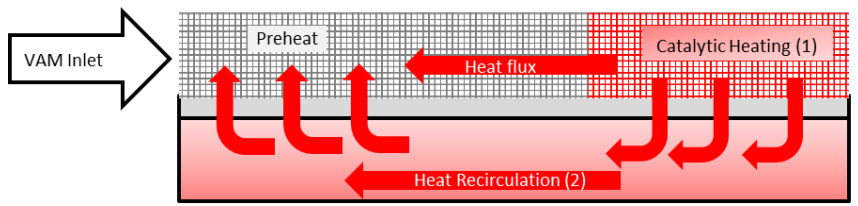
Modular Catalytic System for VAM Oxidation

Benjamin Baird, Subir Roychoudhury, Hani A.E. Hawa (Precision Combustion, Inc.)

Methane oxidation over wide range of inlet compositions @ low operating temperatures w/o external heat

High & low CH_4 concentrations

Process-intensified, modular, oxidation system for VAM



Readily deployed systems

Approach

High Efficiency, Flameless, Methane Oxidation reactor (1)

- High surface area, short contact time, low thermal mass reactor
- Minimize methane oxidation temperature via catalysts

Heat Retention & Recirculation (2)

- Passively capture oxidation exotherm
- Recycle heat to preheat inlet (regenerative)
- Storage & passive heat transfer via features integral to reactor

Features

- **High surface area, short contact time, contaminant tolerant reactor**
- **Advanced architecture to maximize heat flux & surface area**
- **Thermally conserved design to minimize system components**
- **Potential to eliminate supplementary heating**
- **Readily scalable modular design**
- **Sized to fit in mobile ISO container**

Technical Status

De-risk at single-brick

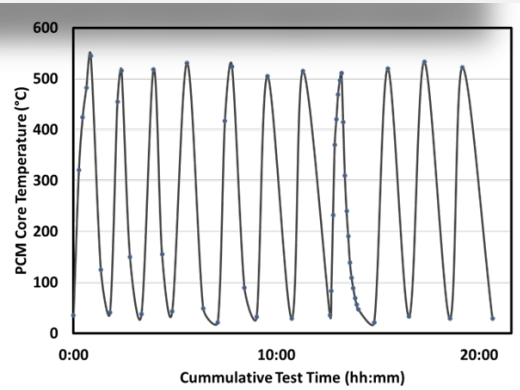
- >98% CH_4 conversion @ <500°C
- Low pressure drop
- Durability, thermal cycle tolerance confirmed

Optimize cost

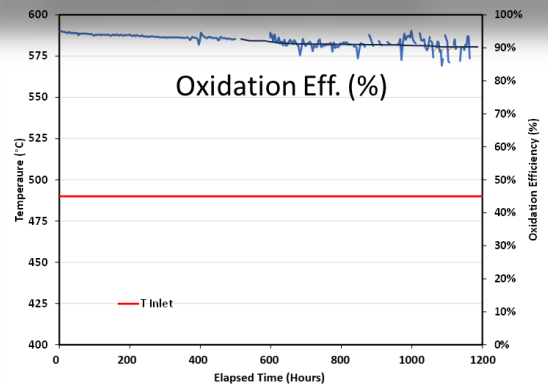
- On track for <$40/ton CO_2e

Pilot scale system demonstration

- Full-scale system, component design ongoing



Thermal cycling tolerance



Exp data indicated potential for long-term durability (>98% CH_4 oxidation w. 1% CH_4 in air)

Commercialization

Revenue from

- Carbon credits
- Methane mitigation from:
  - coal, trona, high wall mines, bleeder wells

OPEX/CAPEX

- Manufacturing innovations for low CAPEX
- Design innovations for low OPEX

Fielding

- HAZOP & MSHA compliance ongoing
- Packaging, ruggedization for difficult terrain
- Seeking partnerships
- Field installation evaluation ongoing

About PCI: Privately-held small business (~50 employees; 14 Ph.D.'s); Solutions for: *Power Gen, Syngas/H_2 production, Air-cleaning, Energy*

Concept → Advanced Prototypes → Fielded Systems

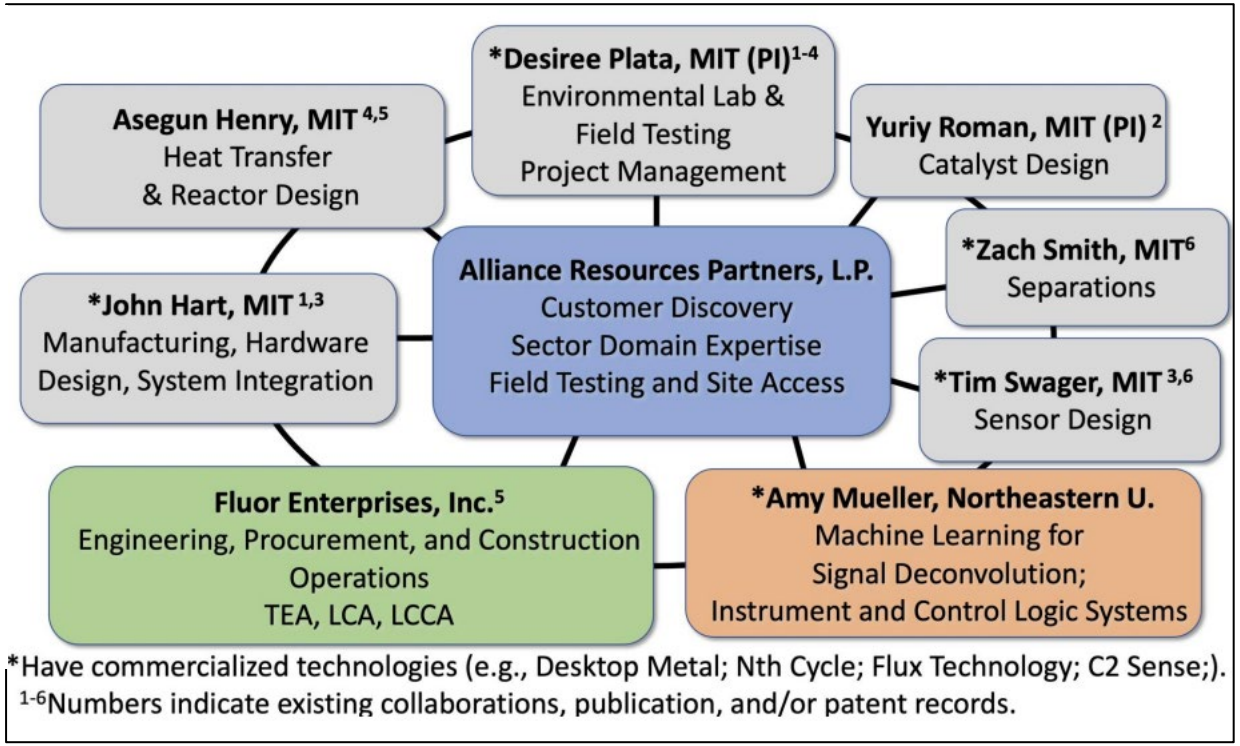
Contact: *Tony Anderson (Business Dev.); Hani A.E. Hawa (PM); Phone: 203-287-3700; Email: aanderson@precision-combustion.com; hhawa@precision-combustion.com; www.precision-combustion.com*

PCI: Potential Partnerships

- **Mine Equipment/Facility System Integrator**
  - Pilot scale demonstrations under examination
  - Transition of Pilot to Full-Scale also under examination
  - Ruggedization to mine environment
  - Application dependent economic analysis
- **Carbon Credits**
  - Regulation and quantification/verification standards
  - Sale of credits

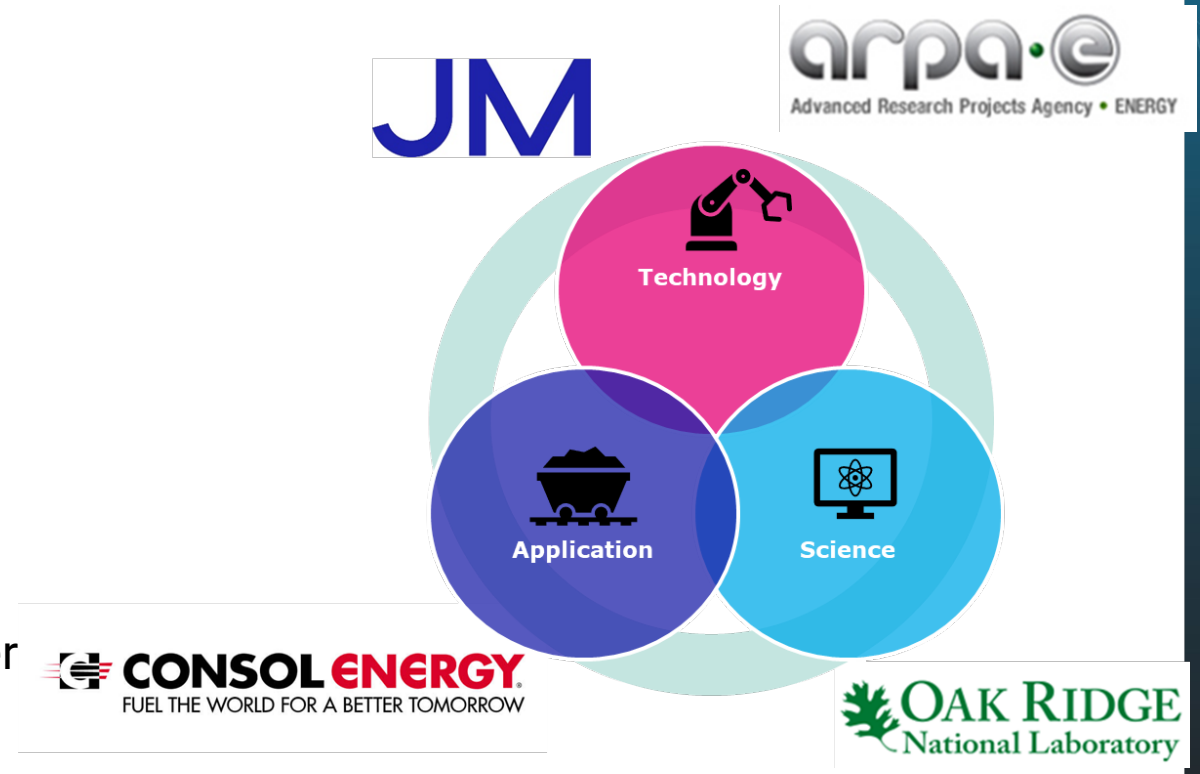
MIT: VAMCO

- Advantage over state-of-the-art:
  - Low-temperature, low-cost, low-level methane performance offers potentially significant advantages with respect to safety and cost
- Goal:
  - Towards an integrated system for destruction of sub-flammable methane via Earth-abundant, low-cost catalysts in high-flow reactors
  - <$50/ton CO2e; >87% GHG savings
- Follow on:
  - Non-dilutive funding for commercial entity for methane abatement technologies
  - Field demonstration at 100k CFM



Next Step

- Currently in TRL 5
- FTU demonstration by end 2024
- Catalyst design and optimization complete
- Site selection complete
- Fabrication of Field Test Unit (FTU) in progress
- Open to project developers who are interested in partner



Needed: Flare Emission Quantification

- We **urgently** need instrumentation to:
  - measure emissions from existing flares (inventorying and financial incentives)
  - assess new “low emission” flare technology
  - Verifiable for emission reporting and credits

- Many candidate tools for the job
  - Airborne/drone sensing
  - Passive or Active FTIR (single path)
  - Imaging based: VISR Mantis (multispectral), Telops (hyperspectral)
  - Differential Absorption LiDAR (DIAL)

- **Can any distinguish >98% efficiency?**
- **Hard to say, especially for “black boxes”**

What needs to happen?

We are designing a **new research program** to

1. **Define the problem** (what are we actually trying to measure?)
2. **Categorize techniques** (what should be used for what?)
3. **Assess existing and emerging instrumentation** (rigorously and transparently)
4. **Develop testing protocols** (defensible accuracy, CFD digital twins, verification and validation, Bayesian statistics)

What do we want from you?

Great foundational work, including:

- **FlareNet** (Canada, 2016-2022):
  how to we measure emissions from upstream flaring?
- **ARPA-e REMEDY** (USA, 2021-2024):
  develop new low-emission flaring technologies

- But more needs to happen...

- **Follow-on funding to support US-based research (e.g., DOE)**
- **Industry technology demonstration/field test partners**
- **International partnerships (World Bank, PTAC, etc.)**

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arpa·e
CHANGING WHAT'S POSSIBLE

EPA Office of Air and Radiation

- Voluntary Programs
  - Public-private partnerships for sharing best practices, expertise
    - Oil and Gas (#1)
      - Natural Gas Star
      - Methane Challenge
    - LMOP (Landfill, #3)
    - AGSTAR (manure, #4)
    - CMOP (Coal mines, #5)
  - https://www.epa.gov/gmi/sector-based-epa-methane-partnership-programs

- Secretariat for Global Methane Initiative
  - Global public-private partnership for methane-to-energy projects, reduce emissions from oil and gas, biogas, and coal mines

DOE Fossil Energy Carbon Management

- Methane Mitigation Strategies

  - Monitoring/quantification
    - $47MM/22 projects – engines, tanks, basin-level/supply chain
    - https://www.energy.gov/fecm/project-selections-foa-2616-innovative-methane-measurement-monitoring-and-mitigation

  - Associated gas conversion to eliminate flaring
    - 10 projects, producing H_2, carbon, fuels, etc

  - METEC upgrades
    - Site for testing methane detection/quantification tools

National Academy: Atmospheric Methane Removal Workshop

- Atmospheric Methane Removal: Needs, Challenges, and Opportunities,
  - October 17-18, DC
  - In-person and virtual options

- Information gathered during the workshop will be used to inform the National Academies' *Committee on Atmospheric Methane Removal: Development of a Research Agenda*