Compressor and Pump Station Research

DOT/PRCI Pipeline R&D Forum

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Sam L. Clowney
El Paso Pipeline Group

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Role of Compressor & Pump Stations

- **Force natural gas or liquids along the pipeline (to overcome friction losses)**
  - More than 1600 compressor stations on interstate gas pipelines
    - Stations spaced ~50-75 miles apart
- **~15 MM Horsepower in gas service**
  - ~ 5700 Reciprocating engines
    - 9 MM HP – Large-bore, slow speed units driving reciprocating compressors
  - ~ 1100 Gas turbines
    - 6 MM HP - drive centrifugal compressors

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Pipeline Compressor & Pump Stations

- **Multiple units at each station**
  - Added as system capacity was expanded
    - A mix of old and new, different sizes and types
    - Units dispatched according to demand
- **Pipeline flow conditions can vary greatly from initial design basis**
  - “Realtime” gas markets, new powerplant loads
  - Increased operational flexibility is a necessity

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Pipeline Compressor & Pump Stations

- **If the heart stops beating, the condition of the arteries doesn't matter much**
  - Gas won't flow without compression
  - Liquids won't move without pumps
- **Primary threat to compressor assets**
  - <u>Environmental Compliance</u>
    - NOx, Hazardous Air Pollutants
  - This threat to the "inside the fence" infrastructure is as significant as the integrity threat "outside the fence"

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Compressor R&D Overview

- **Mission Statement**
  - “Minimize the operating costs and capital requirements of compression service while meeting market demands and all applicable environmental regulations."

R&D Program Drivers

- **Horsepower Asset Management**
  - Least-Cost Environmental Compliance
  - Operational Life Extension
- **Operating Cost Reductions**
  - Fuel consumption
  - Maintenance expense
- **Operating Flexibility**
  - Minimize the extent to which new environmental regulations constrain unit operating ranges

Specific Challenges

- **Reciprocating Engines**
  - The mainstay compressor engines are no longer manufactured (2 and 4-stroke integrals)
    - Pipelines themselves are responsible for engine technology & environmental compliance innovation
    - If nothing done, would be forced to install electric compression to achieve air compliance
  - Replacement costs of ~$13.5 Billion
    - Pipeline capital required for integrity management, pipeline expansions and balance sheet repair
    - Electric units carry system security issues
    - Logistics of replacement are very difficult

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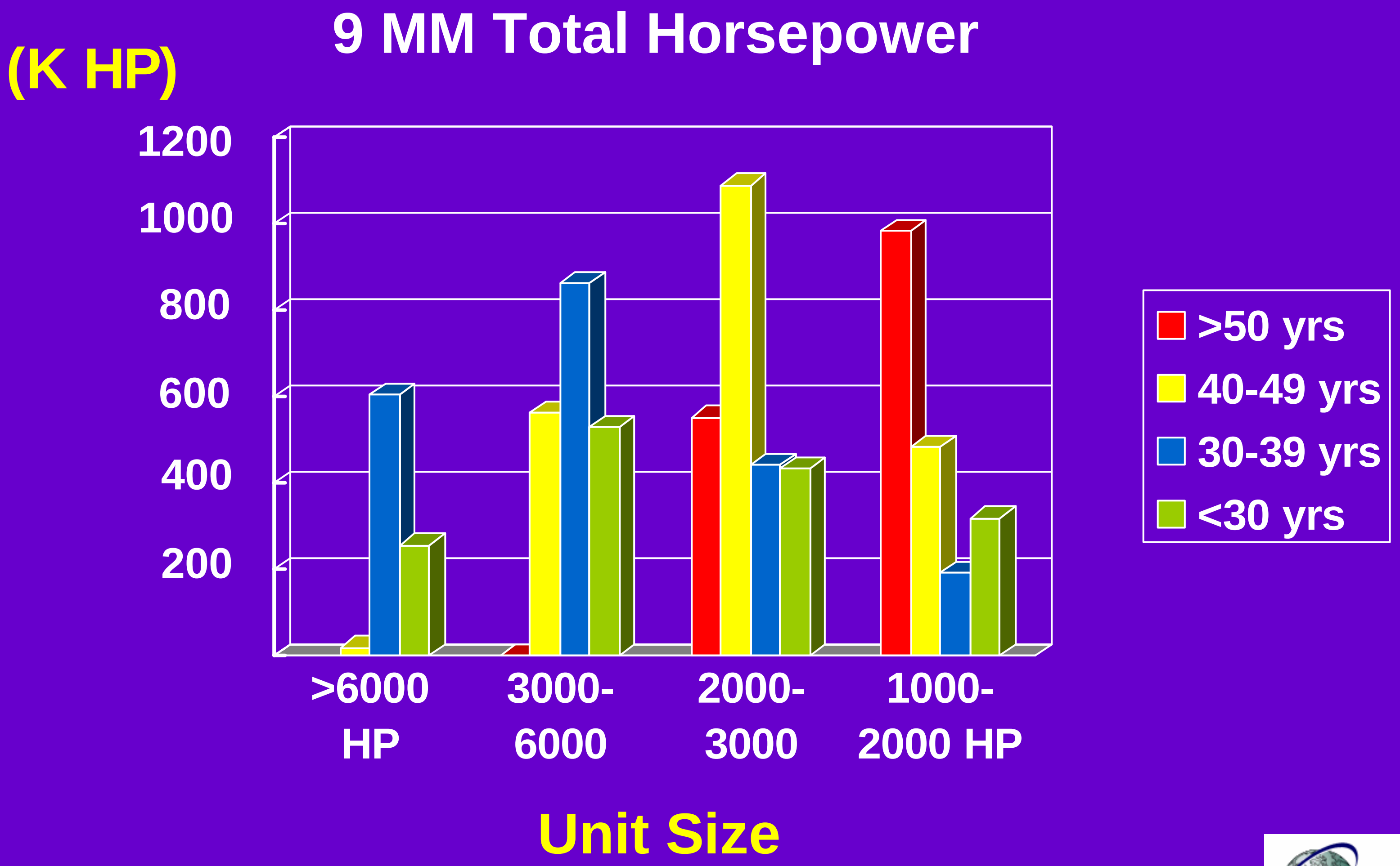
Age of Reciprocating Engine Fleet



Specific Challenges

- **Gas Turbines**
  - Extremely aggressive emissions requirements are shortening product development cycles
    - Industry emphasis is to expedite field testing to characterize equipment performance
  - Gas turbine blades are high O&M cost item
    - Developing condition-based replacement criteria instead of existing calendar-based replacement criteria

The Big Picture

- **Existing compressor infrastructure must be maintained**
  - Over half of the recip HP is >40 years old
    - Over 80% is >30 years old
  - Recips face continual emissions pressure
    - Pipeline capital must be conserved for other needs
- **Maintain vs. replace existing capacity?**
  - \$1.5MM/yr R&D program = 10 cents/HP/yr
  - Replacement at \$1500/hp = \$75/HP/yr for 20 years

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The Big Picture

- **Compressor station O&M costs**
  - 56% of all pipeline maintenance costs
    - (Compressor fuel not included in this)
  - Compressor fuel use = 700 Bcf/yr
    - Cost of $3.1 Billion/yr (at $4.50/mmBtu)
    - An opportunity to make gas more competitive
- **Operating Flexibility**
  - Limited operating range cause high marginal costs of compression service
    - Additional units must be dispatched
    - Poor load factors, high amortized maintenance costs
    - High fuel consumption at part-load operation

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Current Technical Program

- **2004 Budget: $1.375 MM**
- **2003 Budget: $1.6 MM**
- **Program Elements**
  - Improve reliability of low-NOx equipment
  - Increase margin of NOx compliance
  - Increase Operating Flexibility
  - O&M Cost Reduction

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R&D Program:
Reliability of Low NOx Technology

- Develop low emissions technology that is more robust and less maintenance-intensive than existing retrofit options

- **Need/Driver**
  - **Meet stringent emissions standards when reciprocating engines eventually lose grandfathered status**
  - **Maintain long-term asset serviceability at modest cost. Replacement cost of single 2000hp unit = $3 MM. Reduce O&M expenses and improve availability of low-NOx retrofits**

- **Technical Approach/Deliverables**
  - **Develop very low-NOx compression ignition system (MicroPilot) for 2SLB engines by 2006**
  - **Expanded two-cycle engine testbed at CSU Engines Lab (Clark TLA to accompany Cooper GMV)**

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R&D Program: Increase Margin of Emissions Compliance

- Drive emissions further below permitted levels to avoid permit excursions and allow greater unit operating range.
- **Need/Driver**
  - Many NOx retrofits were purchased for their maximum reduction capabilities, often narrowing the operating range of the equipment and/or risking permit violations at off-design point operation or due to minor upsets.
- **Technical Approach/Deliverables**
  - **Field qualify new Solar-Mars ABC combustor liner by 2004.**
  - **Develop turbocharger maps to define range of turbo operating window for low-NOx performance.**
  - **Obtain accurate measurement of air flow through engines via sensor embedded in turbocharger compressor diffuser.**

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R&D Program: Increase Operating Flexibility

- Enable horsepower to operate at rated capacity throughout the year.
- **Need/Driver**
  - **Volatile market demands requires operation over a wider range of pipeline flows and ambient conditions.**
- **Technical Approach/Deliverables**
  - **Evaluate inexpensive options for closed-loop engine control components: Pressure, oxygen, NOx and knock sensors.**
  - **Optimize turbocharger selection and performance**
  - **Develop designs for optimized retrofit top-end of engine (cylinders, heads) for ultra-low NOx and HAPS and high efficiency.**

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R&D Program:
O&M Cost Reduction

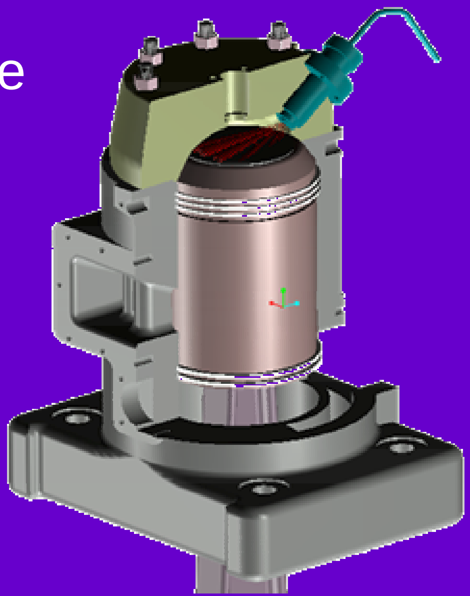
- Reduce the variable costs of compressor station operation
- **Need/Driver**
  - **Compressor station maintenance = 56% of total system maintenance costs ($188MM of $336MM)**
- **Technical Approach/Deliverables**
  - **Remaining creep life of solid gas turbine blades**
  - **Identify rate of turbine blade metal degradation**
    - **Condition-based turbine blade replacement criteria is extremely valuable for PRCI members. $200K/engine savings over 6 years for a typical blade replacement deferral.**

Key Ongoing Project

- Turbocharger Optimization
  - Conducted at industry-developed Turbocharger Testing and Research Facility of Kansas State U.
  - Most pipeline engines are turbocharged
- Turbocharger performance is central to engine emissions, operating range, O&M costs
  - Rigorous effort to define/develop
    - Models of air flow through pipeline engines
    - Standardized turbo performance measurements and metrics
    - Sources of turbo performance losses and subsequent component design improvement options
    - Engine/turbo integration issues and turbo selection models
    - Turbo maintenance practices

Key Ongoing Project

- Micropilot ignition system for 2-stroke engines
  - Cofunded with DOE and Woodward Governor
    - $1.7MM total, industry share = $700K
    - Woodward Governor Co. will commercialize
  - Targeting very low NOx, fuel savings, reduced O&M.
    - Oil injection (1%) provides very high-energy ignition jet to light off very lean charge
    - Reduced first cost vs. conventional low-emissions technologies
    - Concept derived from very large dual-fuel engines (Fairbanks-Morse, Wartsila)
  - Field test sites being identified now



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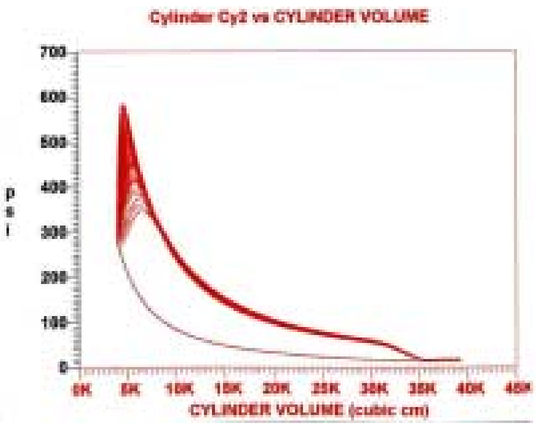
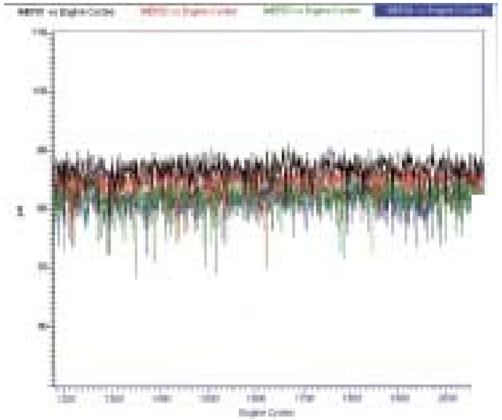
Combustion Analysis

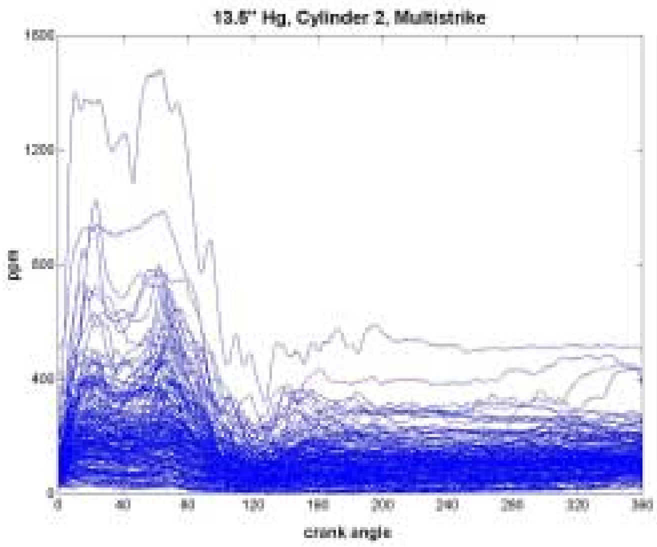
Colorado State University - Engines & Energy Conversion Laboratory

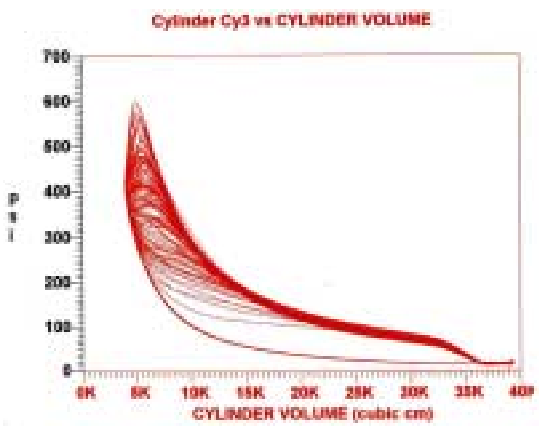


PV Diagrams
Stable Combustion

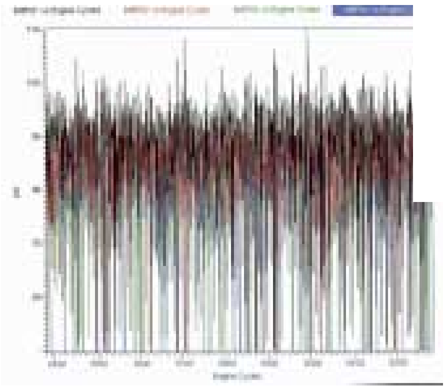


IMEP
Stable Combustion





PV Diagrams
Near Lean Limit



IMEP
Near Lean Limit

Key Ongoing Project

- SoLoNOx Cold Ambient Emissions Testing
  - Cofunded with Solar Turbines, $175K total project cost
  - Low-NOx gas turbine emissions at low-temperature ambients are very erratic, and can exceed permitted levels
    - ~500,000 HP of Solar units subject to low ambients
  - Continuous emissions and engine operating data being collected over two winters on Mars 100, Taurus 60, Centaur 40 & 50
    - Results will allow control system modifications that will maintain NOx compliance

Key Ongoing Project

- Turbine Blade Non-Destructive Evaluation
  - Conducted at SwRI to develop NDE technique for air-cooled blades (Rolls-Royce RB-211)
    - Extend life of blades by avoiding calendar-based blade replacement
    - Current inspection practice is very imprecise, causes needless blade replacement, yet misses some cracked blades entirely
  - Presently evaluating multiple NDE options
    - Critical crack size defined, this affects selection of method
  - Similar work on different blade types has proven extremely valuable to members

Key Ongoing Project

- Ion Sensor
  - In-cylinder combustion sensor
    - A combustion monitoring method that measures the ionic properties of cylinder gases
    - Can monitor and diagnose incipient misfire, poor air-fuel ratio control, early detonation
    - Main sensor for closed-loop engine control system and continuous combustion monitoring
  - Enabling technology for inexpensive emissions monitoring of NOx and CO
    - Entering into Beta-testing phase

Where do we go from here?

- **Pursue Electric Motor Emissions Parity**
  - Develop Retrofit Technology that approximates electric motor emissions levels, using optimized components in legacy recip engine blocks
    - Requires <u>complete</u> understanding of engine airflow and in-cylinder mixing and ignition phenomena
    - CFD modeling of combustion. New ignition & sensors.
- **Substantial improvements in engine performance via optimized components**
  - Repower & Uprate existing engine frames to meet incremental capacity demands without triggering Federal New Source Review

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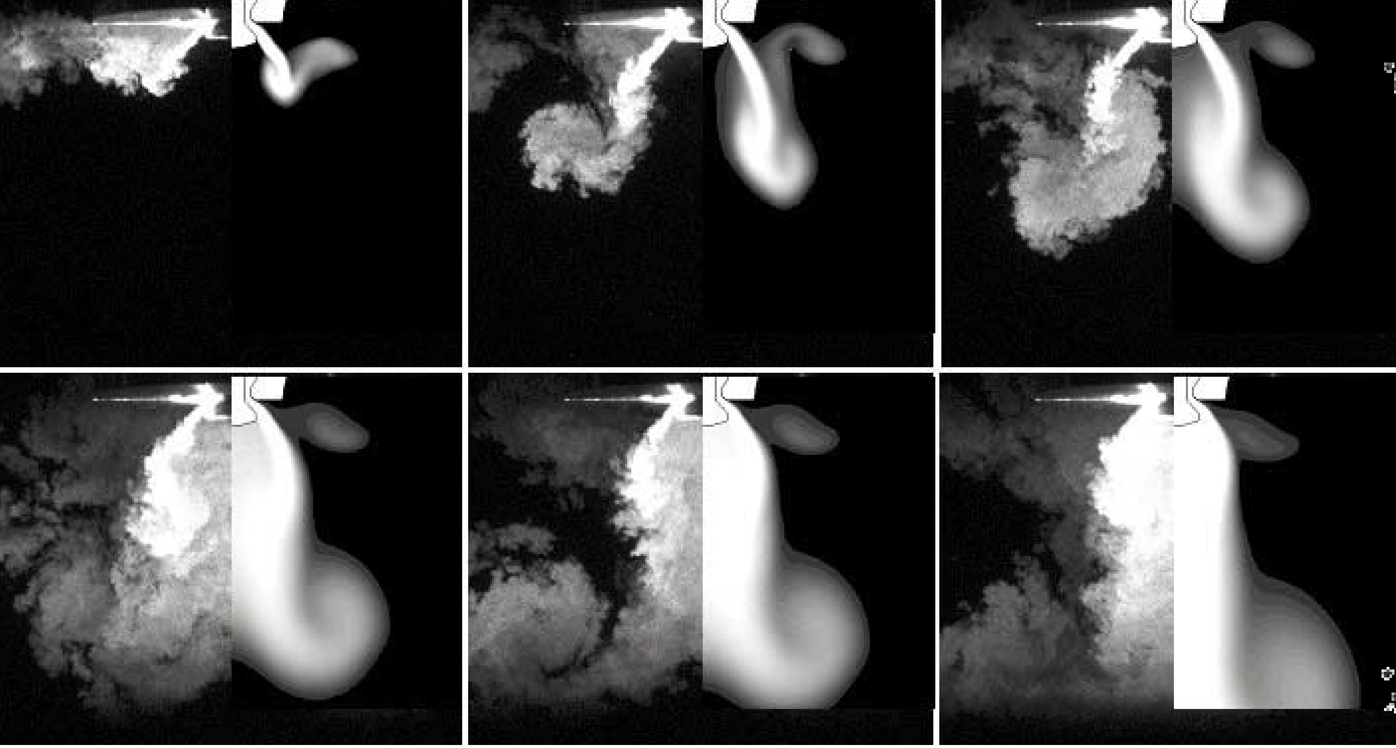
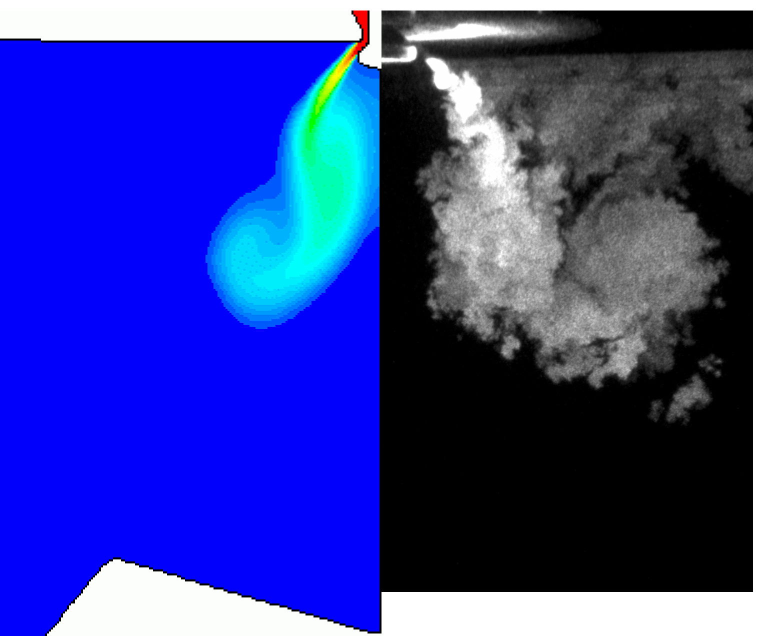
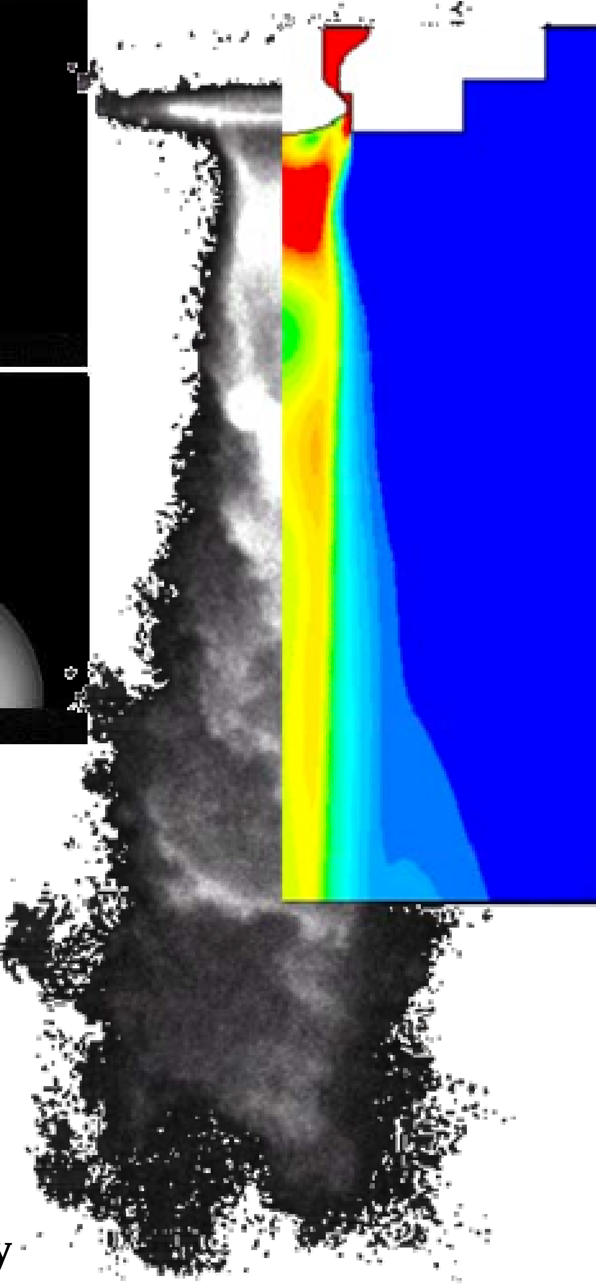




CFD Results with PLIF Validation

Colorado State University
EECL



Where do we go from here?

- **Aggressive engine performance targets**
  - NOx: .25 to .5 g/bhp-hr
  - Fuel: approaching 5000 BTU/hp-hr
  - Maintenance interval: 10,000 hours
  - Management and Control
    - Self-diagnosing for maintenance needs & performance decay
      - **Identifies the guilty component**
    - Fully-automated for control and optimization across all ambient and operational conditions. Avoids misfire and detonation.
- **Result: 35% reduction in cost of compression**
  - Implement for < 1/3 the cost of new units
  - Conserves large amounts of capital

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How do we get there?

- **Need continuation of**
  - Detailed combustion modeling
  - Air flow modeling through engine
  - Component adaptation & optimization
    - Ignition systems
    - Fuel delivery and injection systems
    - Turbochargers
    - Exhaust scavenging & inlet air system
    - Closed loop control systems
  - “Systematic Engine Uprates”

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