Reduced Turbine Emissions Using Hydrogen-Enriched Fuels

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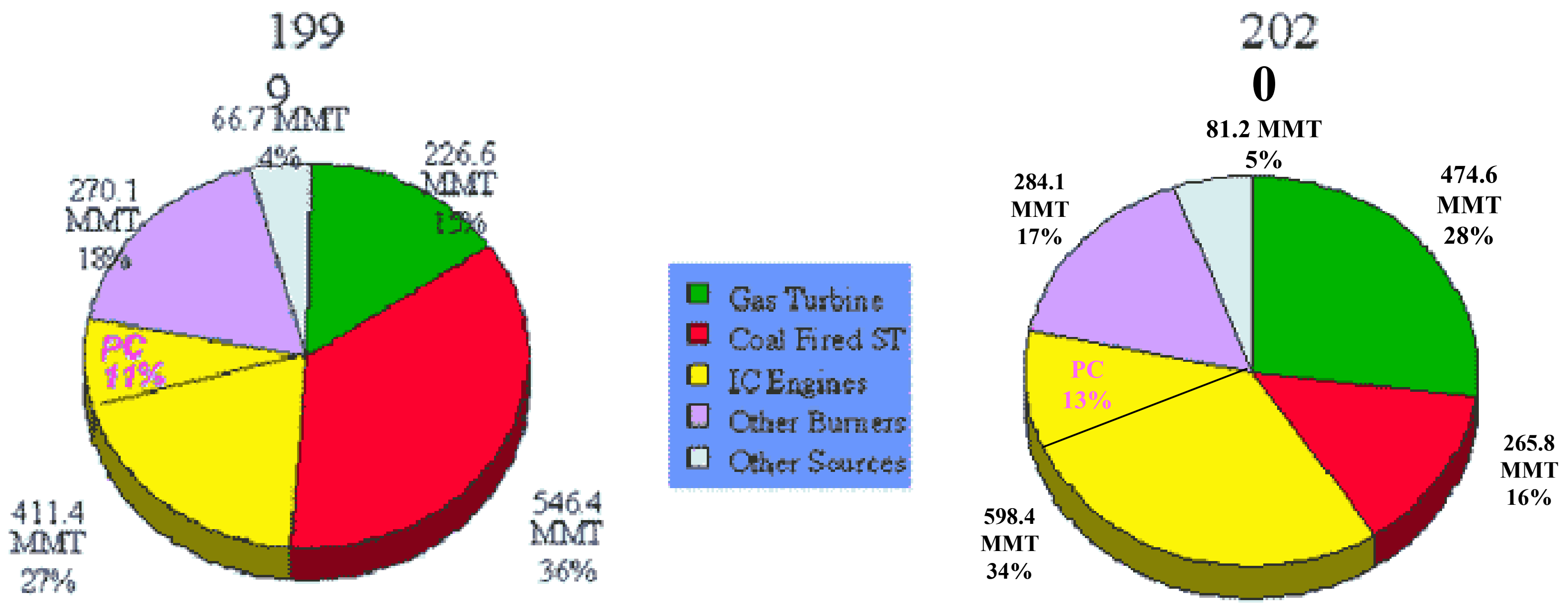
Relevance to DOE, FreedomCAR, and Hydrogen Technical Barriers and Targets

- Use of hydrogen in gas turbines provides a driver for increased hydrogen production and infrastructure development
  - Mechanism for near-term utilization of hydrogen
  - Relaxes more stringent and costly requirements of feed stock purity for fuel cell utilization
  - Field testing of emerging production technologies (approached by a major oil company to use H_2-enriched turbines as market pull for their developing H_2 production hardware)
- Added Environmental Benefits
  - Hydrogen-burning gas turbines enable optimal use of fuel lean combustion for NO_x control
  - Replaces hydrocarbon fuels for reduced CO_2 emissions
- Aids in the attainment of energy independence from foreign sources
  - Low-heating and medium-heating value fuels containing H_2 can provide significant source of cost-effective fuels for gas turbines
  - Enables use of domestically-produced H_2

U.S. CO_2 Emissions

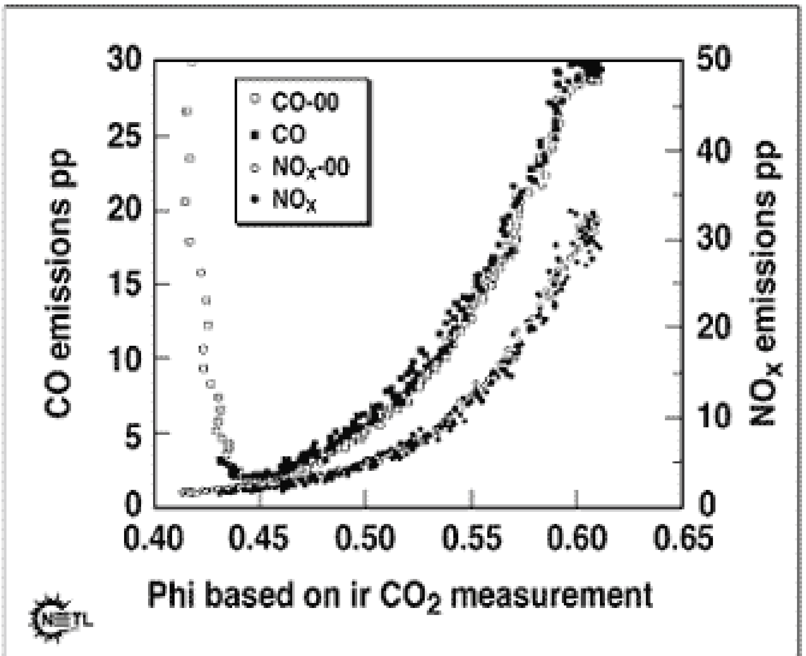


- Gas turbines are the fastest growing power production technology
- Passenger cars account for only a small fraction of total CO_2 emissions

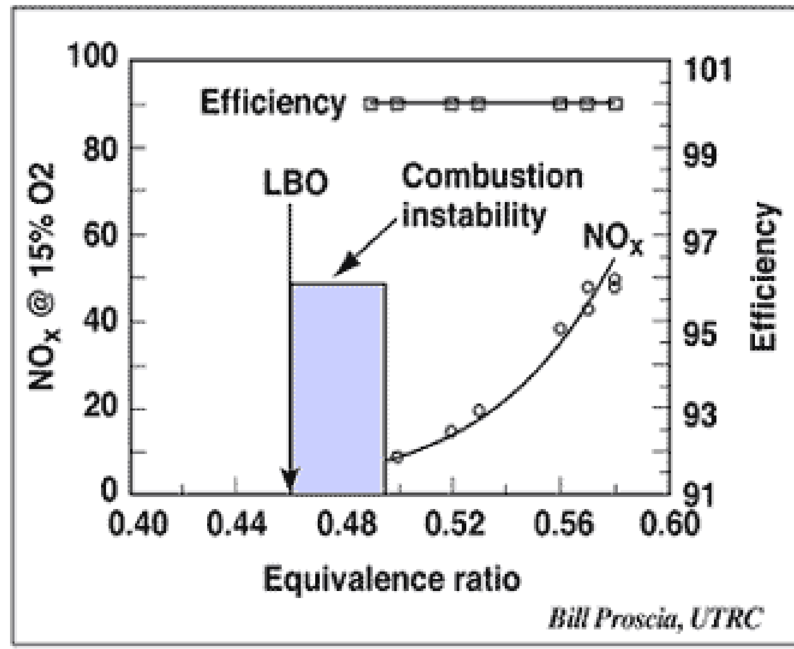
Source: Analysis of Strategies for Reducing Multiple Emissions from Power Plants: Sulfur Dioxide, Nitrogen Oxides, and Carbon Dioxide, EIA, Dec 2000

Trade-offs Associated with Lean Premixed Combustion Systems

- Lean Premixed Combustion (LPC) is method of choice for NO_x control in Gas Turbines



At ultra lean conditions a tradeoff exists between NOx and CO emissions



Ultimately, lean operation is limited by the onset of flame instability and blowout

- ***Hydrogen-enrichment extends the lean flammability limit and reduces CO emissions***

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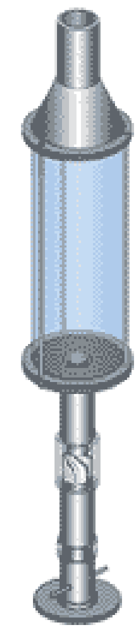
Approach

Lean Premixed Swirl Burner Experiments

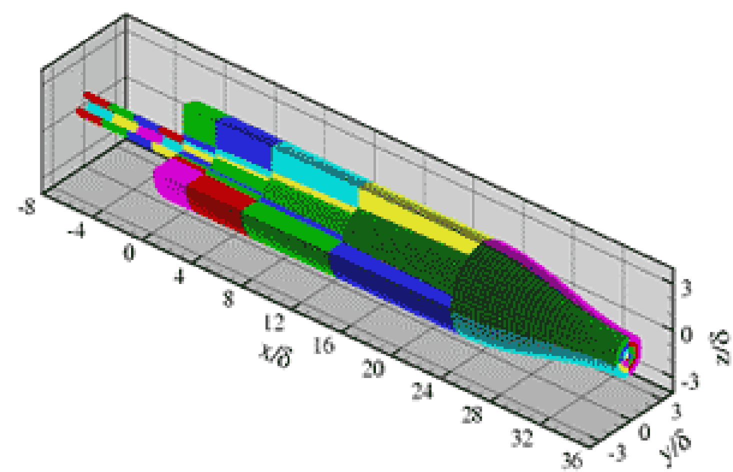
- Establish scientific data base for lean premixed swirl burners typical of Dry Low NO_x gas turbine burners
- Emphasize H_2-enriched fuels over wide range of pressures
- Design and fabricate a lean premixed swirl burner with well-characterized boundary and flow conditions
- Quantify effects of H_2 addition on flame stability and emissions
- Leverage existing Sandia expertise in experimental diagnostics development



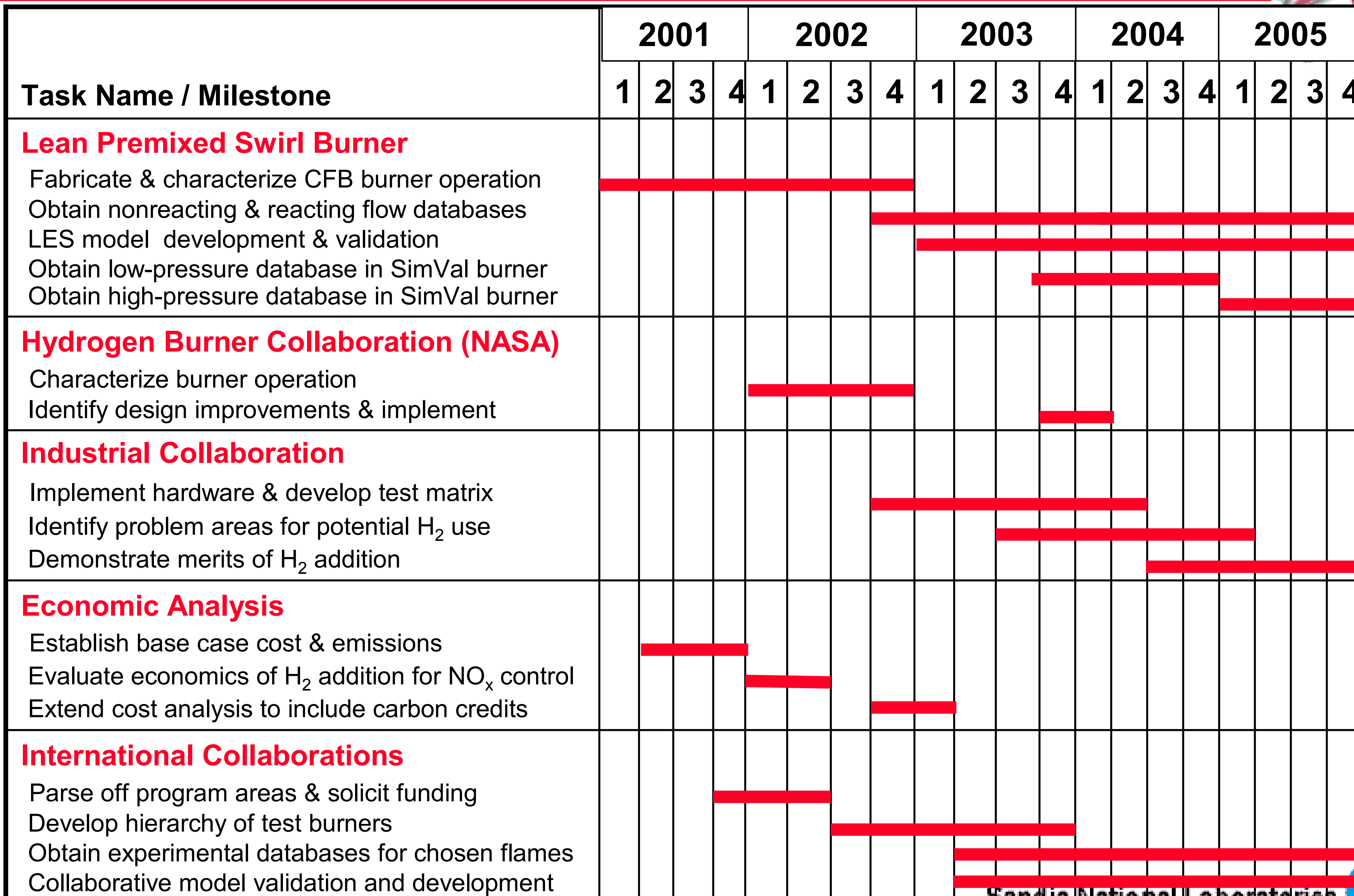
Sandia CRF Confined Flow Burner

Large Eddy Simulation Model Development

- Parallel development of next generation simulation capability based on Large Eddy Simulation (LES)
- Detailed model development and validation at atmospheric pressure
- Extended validation at realistic operating pressures and temperatures
- Bridge gap between laboratory and gas turbine environment through collaborations with industry



Project Timeline



Current Status

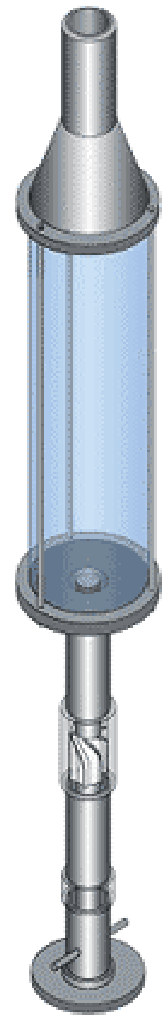
- Comprehensive experimental-computational program focused on *hydrogen-enriched* lean premixed gas turbines established
  - Detailed diagnostics being applied in swirling-flow dump-combustor configurations
  - Benchmark experimental databases under development
- Comprehensive simulation capability based on the Large Eddy Simulation (LES) technique in place
  - Massively-parallel high-fidelity simulations of key target flames being performed
  - Device relevant issues related to transient combustion being systematically treated
- Hierarchy of laboratory-scale burners and target flames identified and at various stages of development
  - Emphasis placed on complex phenomena associated with *hydrogen-enriched* lean premixed combustion
  - Detailed subgrid-scale model development and collaborative model comparisons underway

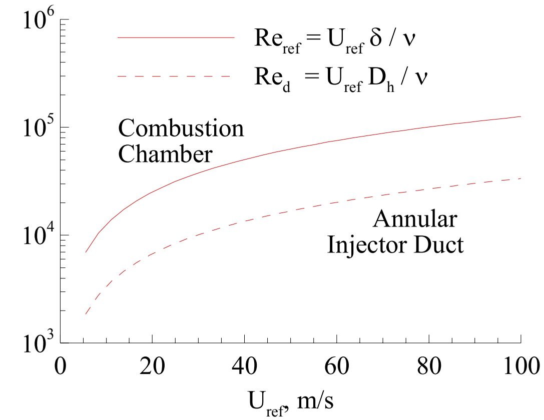
CRF Confined Flow Burner

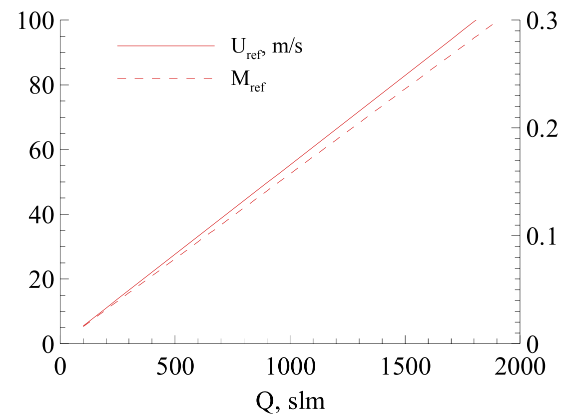
- *Established as test bed for <u>all</u> working groups*

- **Design provides well-defined non-ambiguous boundary conditions for LES**
- **Makes optimal use of advanced laboratory and diagnostic capabilities at CRF**

- **Injector Section (Note $D_h = D_o - D_i$)**
  - **D_i = 20 mm (centerbody diameter)**
  - **D_o/D_i = 1.4**
  - **L = 320 mm (16 D_i)**
  - **Choked at inlet, houses premixing-, swirler-, and wake-mixing sections**
- **Burner Section**
  - **D_b = 115 mm (5.75 D_i)**
  - **L_b = 485 mm (24.25 D_i)**
  - **Ceramic face plate, quartz outer wall**
- **Nozzle Section**
  - **D_e = 50 mm (2.5 D_i)**
  - **L_n = 230 mm (11.5 D_i)**
  - **High Mach number flow at exit**



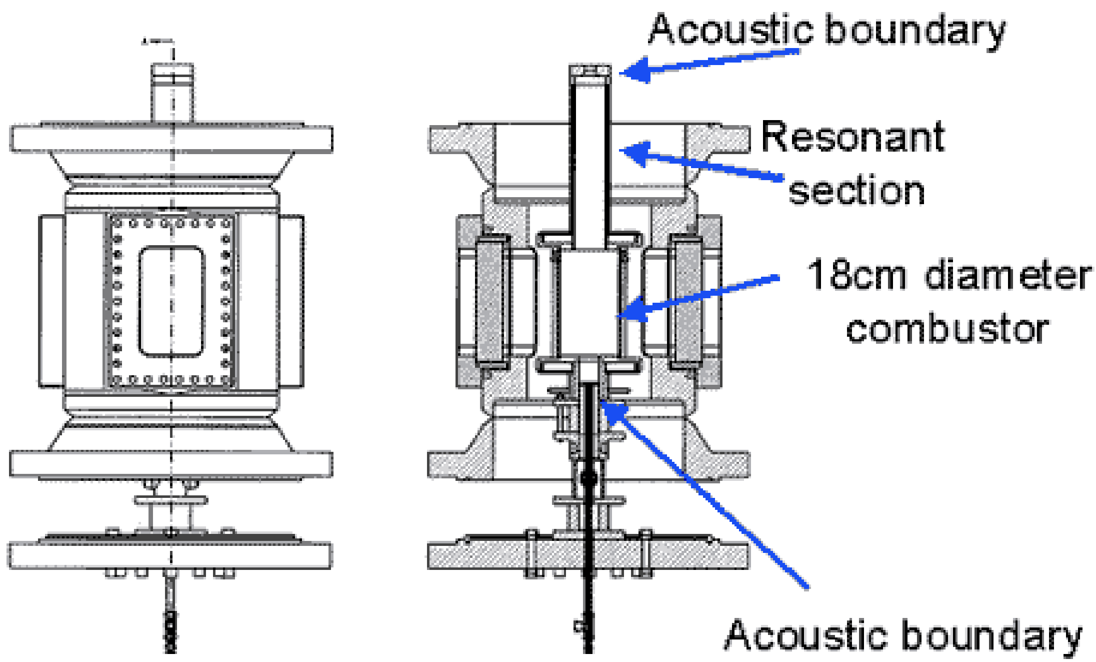




Complimentary to NETL SimVal Burner

SimVal Combustor

Pressure:
30 atm max.
Inlet temperature:
800 K max.
Air flow:
1.4 kg/s max
Fuel:
Natural Gas



- **CRF burner will be used to provide complete high-fidelity validation datasets at 1 atmosphere**
- **NETL burner will facilitate investigations at device relevant pressures.**
- **NETL has delivered SimVal hardware to CRF**

Experimental Capabilities

Diagnostic	Quantity	Comments
Particle Image Velocimetry	Instantaneous velocity field	Velocity, vorticity and strain fields.
OH and CH PLIF	Instantaneous OH/CH distributions	Flame zone structure and characteristics (thickness, local extinction).
Simultaneous OH & CH PLIF/PIV	Simultaneous velocity/OH/CH fields	Turbulence/flame interactions. Flame stability/extinction
Simultaneous OH and CO PLIF	Forward reaction rate of CO+OH=CO2+H	Characterize CO production and burnout
Simultaneous Raman/Rayleigh/LIF	N2, O2, CH4, H2, H2O, CO2, CO, OH, NO and Temperature	Turbulent mixing, flame structure and chemistry. Validation of flame chemistry models.

LES Capabilities

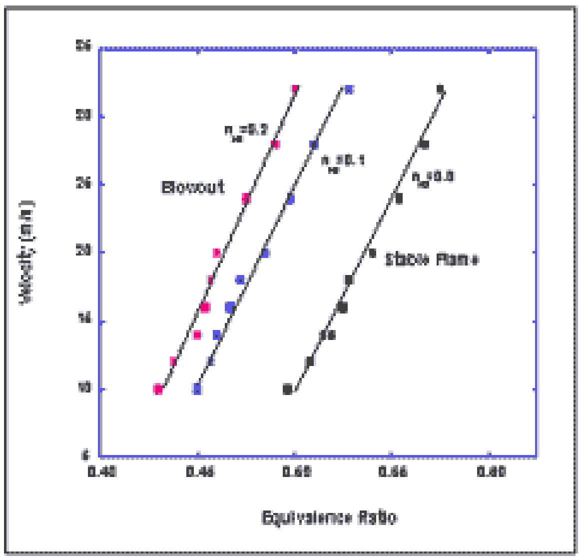
- Theoretical Framework
  - Fully-coupled compressible conservation equations of mass, momentum, total energy, species (multicomponent, mixture-average)
  - Generalized treatment of equation of state, thermodynamics and transport (high-pressure, real-gas, liquid, cryogenic fluids …)
  - Dynamic modeling for treatment of subgrid-scale turbulence and scalar mixing
  - Full treatment of multiple-scalar mixing, finite-rate chemical kinetics
  - Full treatment of multiphase phenomena, particulates, sprays
- Numerical Framework
  - Implicit multistage scheme using dual-time stepping with generalized all-Mach-number preconditioning (Eulerian-Lagrangian formulation)
  - Fully-conservative, staggered, finite-volume differencing in generalized curvilinear coordinates, time-varying mesh capability
  - Highly scalable, massively parallel with general distributed multi-block domain decomposition

Validation Sequence for Target Flames

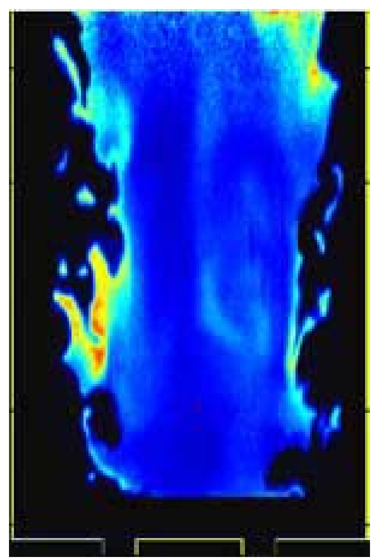
- **Cold-flow PIV, LDV measurements**
  - Time-averaged characterization of burner inlet conditions
  - Instantaneous, time-averaged structure of planar velocity field
  - Time-averaged profiles of mean, rms, cross-stress terms
- **Reacting PIV, LDV, PLIF measurements**
  - Companion datasets analogous to cold-flow measurements above
  - Instantaneous, time-averaged characterization of minor species fields
  - Time-averaged profiles of simultaneous velocity-scalar correlations
  - Instantaneous, time-averaged flame zone structure
- **Raman-Rayleigh-LIF point/line measurements**
  - Instantaneous, time-averaged characterization major species, temperature
  - Instantaneous reaction-rate imaging

CRF Burner : *Experimental Progress*

- **Burner operation characterized over a range of conditions ✓**
- **Quantified effect of H_2 addition on lean flame stability ✓**

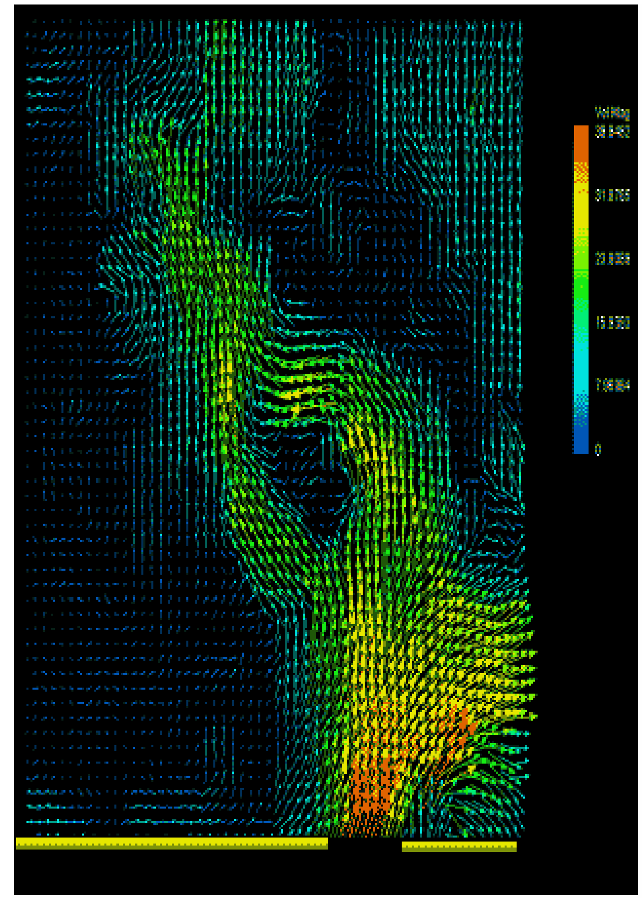


OH PLIF Image



- **Flame structure characterized using OH imaging ✓**

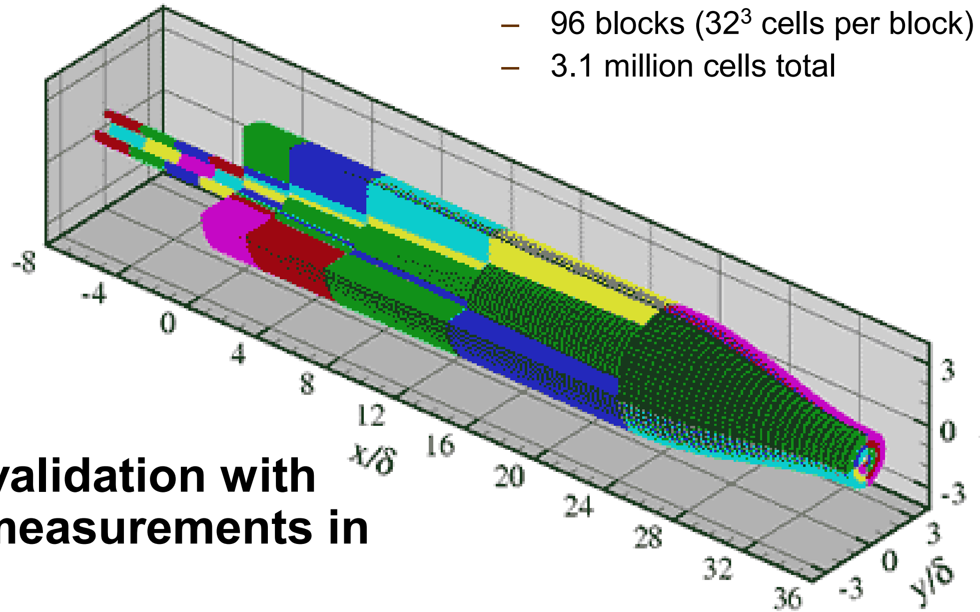
Particle Image Velocimetry



- **Velocity field characterized in nonreacting flow ✓**

CRF Burner: *Model Progress*

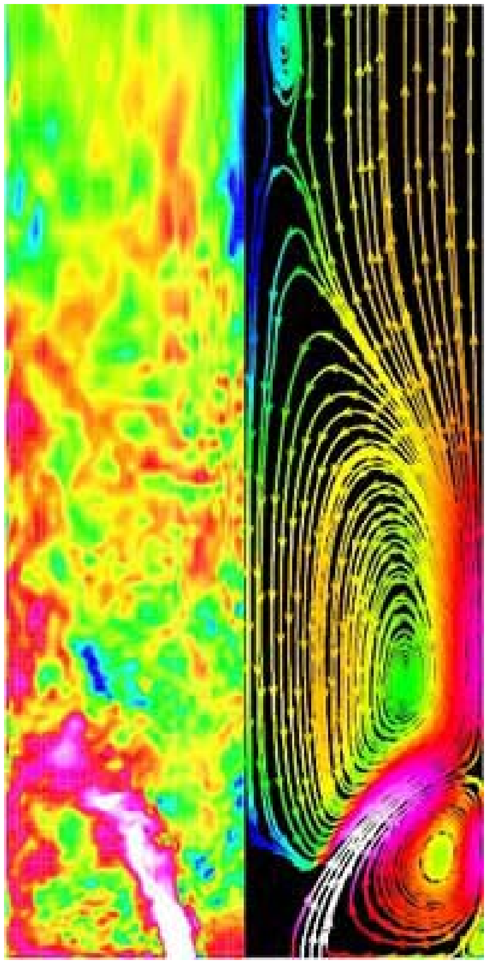
- **Baseline operating conditions, target cases, and corresponding grid configuration established ✓**
- **Grid resolution requirements for high-fidelity (wall-resolved) simulations of target cases established ✓**



- **Generalized multi-block decomposition**
  - 96 blocks (32^3 cells per block)
  - 3.1 million cells total

- **First high-fidelity simulations for validation with Particle-Image-Velocimetry (PIV) measurements in progress**
- **Development of multiple-scalar combustion closure based on approximate deconvolution methodology in progress**

Instantaneous and Mean Flow Characteristics Established

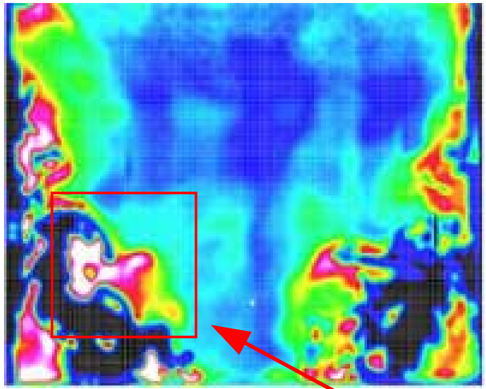


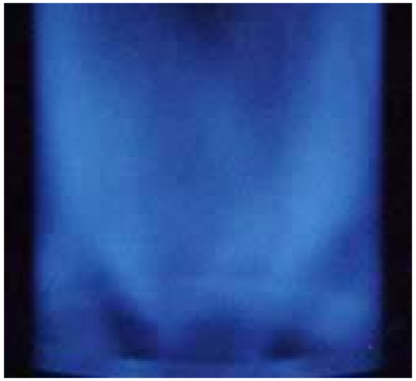
Flame structure:

- Premixed flame fronts
- Local quenching.
- Extinction, re-ignition
- Strained and freely propagating

Flow structure:

- Primary toroidal recirculation zone
- Unsteady stagnation point
- Flow separation and reattachment
- Secondary, tertiary recirculation zones





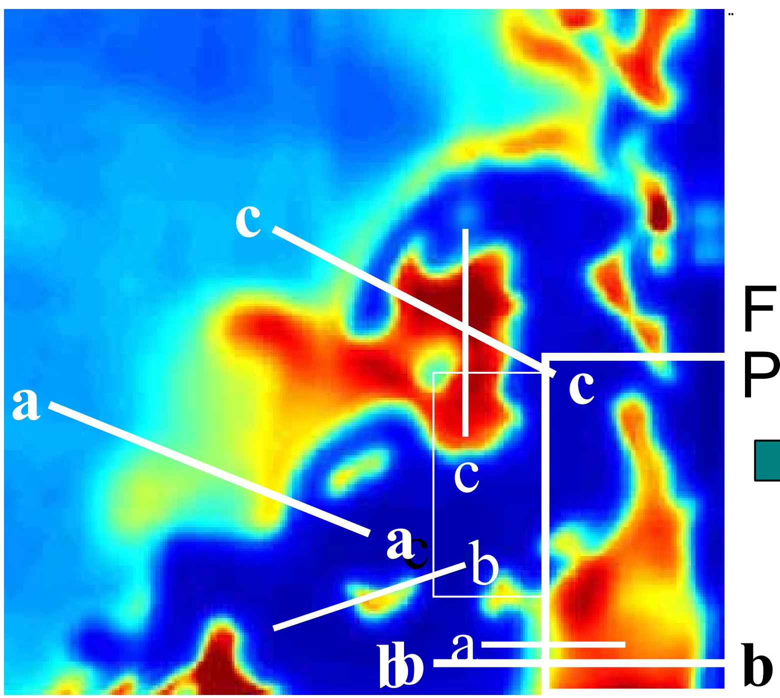
OH measurements highlight local flame characteristics

LES calculations highlight complex fluid dynamic interactions

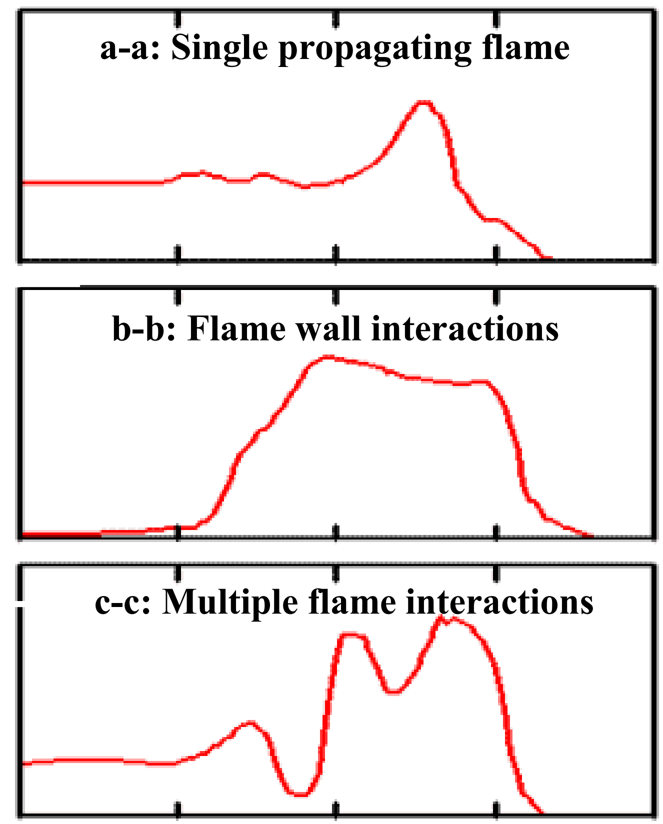
- Turbulent combustion involves strong interaction between flow and chemistry
- Plots left show turbulent velocity field obtained using LES
- Plots above show corresponding OH PLIF image and flame luminosity

Local Flame Characteristics Established

Instantaneous OH Field

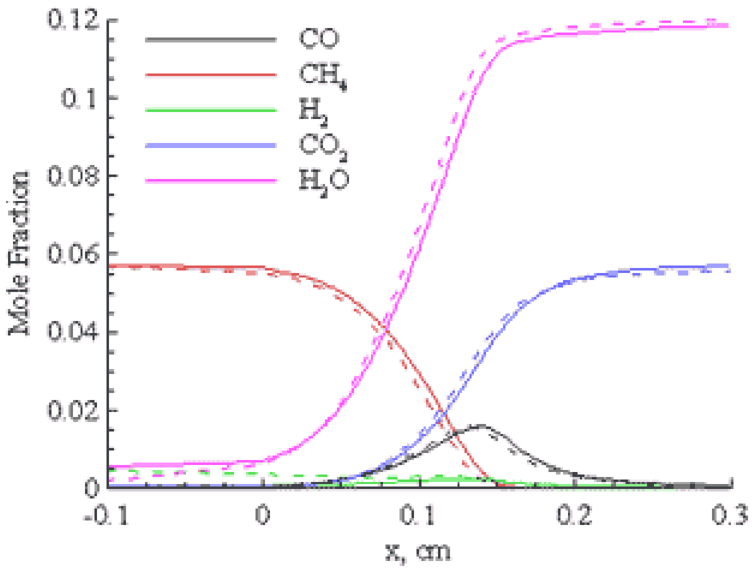


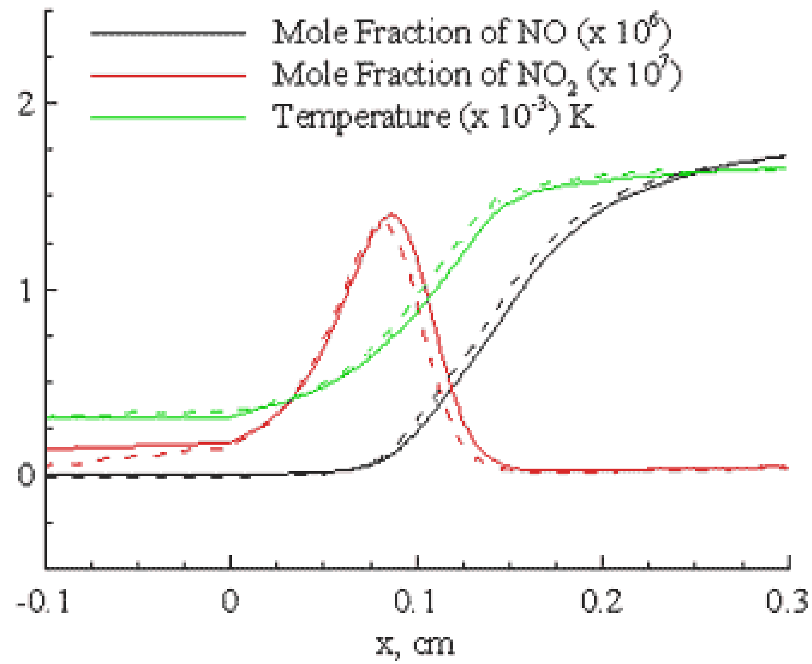
Flame Profiles



Flame structure changes locally with mixture properties and fluid dynamics

Ideal Flame Structure With Detailed Chemical Kinetics Analyzed





- Solid lines represent pure CH_4-Air flame ($\Phi_{Global} = 0.6$)
- Dashed lines represent CH_4-Air flame enriched with 10 % H_2

Current Collaborations

University

Vanderbuilt (Diagnostics)
Heidelberg (Kinetics)
Darmstadt (LES Development)
Lund Technical (Diagnostics)
Cranfield (Diagostics)
U. Oklahoma (LES Validation)
Cornell (Diagnostics)
U. London (LES Validation)
Toronto (Diagnostics)

Government

Sandia (LES Development & Validation, Diagnostics)
NETL(LES Validation, Diagnostics)
WPAFB (LES Validation, Diagnostics)
AFOSR (LES Validation, Diagnostics)
NASA (Diagnostics, LES Validation)

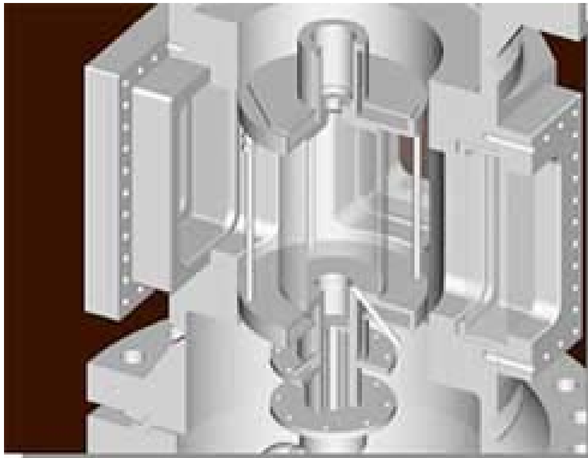
Industrial

General Electric (LES Development)
Pratt & Whitney (LES Development)
Rolls Royce (LES Development)
Praxair (H_2 Utilization)
Pinnacle West (H_2 Utilization)

NETL Collaboration: *Approach & Progress*

Approach
- Extend data base for lean premixed swirl burners to realistic pressures and temperature. Emphasis on H_2-enriched fuels
- Atmospheric-pressure tests in SimVal burner at Sandia; high-pressure tests at NETL
- Utilize Sandia's diagnostic expertise for the development of high pressure diagnostics in realistic gas turbine environments

SimVal Burner



Progress

Sandia Burner Completed ✓
- Atmospheric pressure operation
- Design optimized for Sandia CRF laboratory facilities
- Full optical access for optimal use
- Of advanced diagnostics

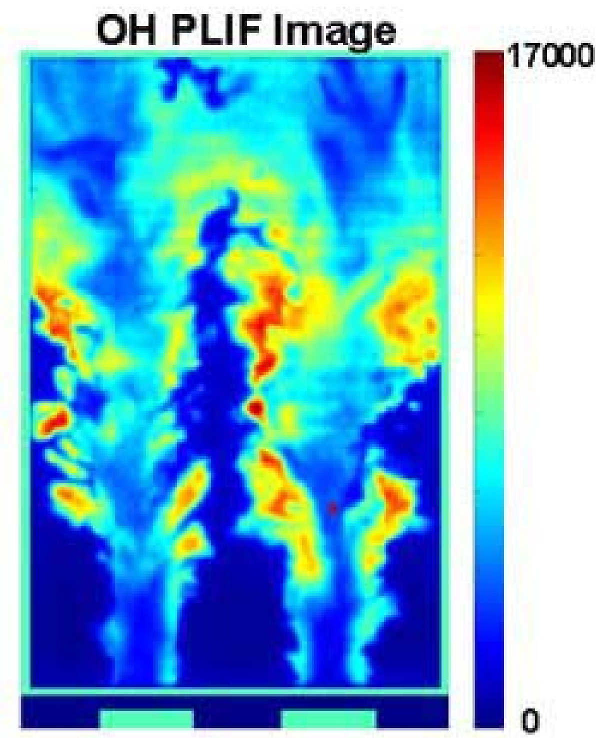
NETL Burner Completed ✓
- Operation to 30 atmospheres
- Inlet temperature to 800 K
- Optical access
- Limited datasets at elevated pressure

NASA Collaboration: *Approach & Progress*

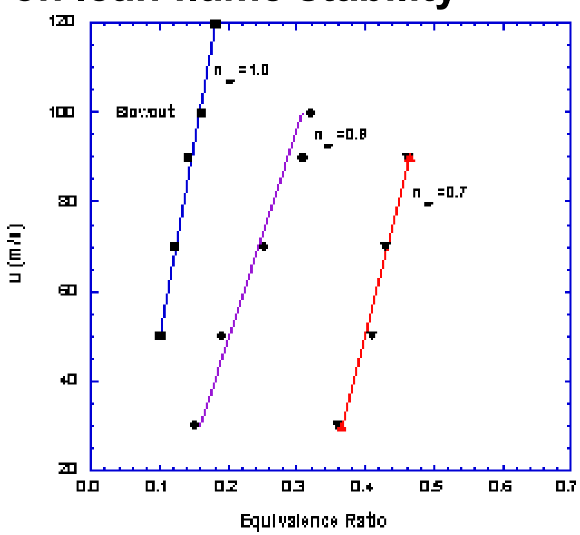
Approach

- Program focuses on the development of H_2-fueled burner for aircraft application
- Atmospheric- pressure testing at Sandia high-pressure tests at NASA GRC

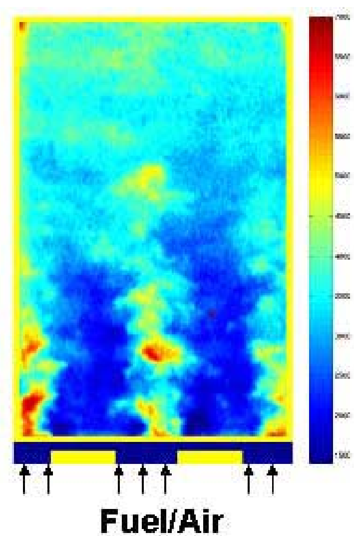
- Burner operation characterized ✓



- Quantified effect of H_2 addition on lean flame stability ✓



- Acetone PLIF used to quantify fuel/air mixing ✓



- Flame structure characterized using OH imaging ✓

GEAE Collaboration: *Approach & Progress*

Approach

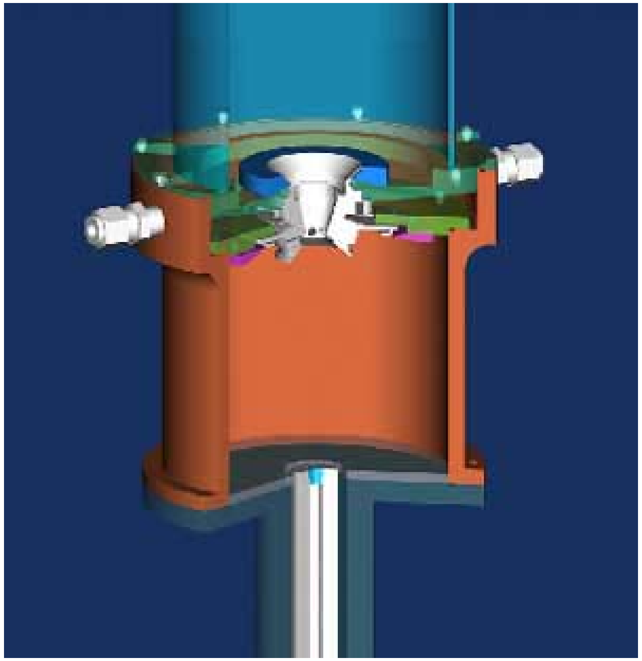
- Select fuel injector for lean premixed operation
- Apply advanced diagnostics and LES to understand problematic areas related to industrial gas turbines
- Identify problem areas where hydrogen addition could be beneficial and demonstrate merits of H_2 enrichment

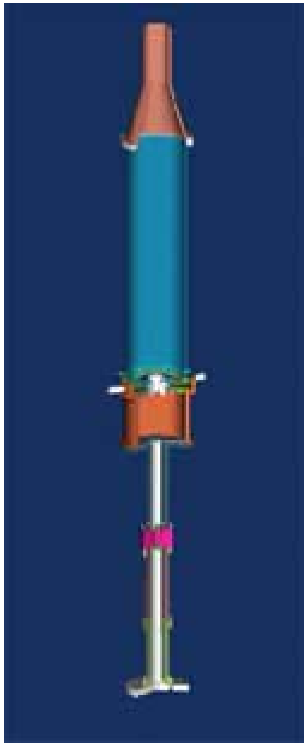
- Diagnostics implemented ✓
  - PIV, OH and CO PLIF
  - Raman Scattering

- Design issues identified ✓
  - Lean blowout limits
  - Lean emissions (NO_x, CO)
  - Fuel-air mixing
  - Combustion instabilities

- Completed hardware for swirlcup installation in Confined Flow Burner ✓

GEAE Swirlcup Injector





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International Efforts

IEA Technical Working Group on Modeling

- Develop an international effort to address fundamental and applied aspects of H_2-enriched fuels for lean premixed gas turbine combustion
- Define program research areas
- Establish a validated simulation capability based on the LES technique
- Establish a complementary experimental capability for database acquisition

Progress

- Primary program focus is the *use of gas turbines in "zero-emission" H_2 applications* ✓
- Administrative framework established. Technical and Strategy Committee members selected with Sandia co-chairs on each ✓
- Technical and Strategy groups met in Fall, 2002 to discuss procedures related to multi-nation tasks and to review technical progress ✓
- Working group meeting was held in Spring, 2003 ✓

Group Members

- Sandia
- University of Heidelberg
- Darmstadt University
- Lund University
- Cranfield University
- National Energy Technology Laboratory
- University of Toronto
- NASA Glenn

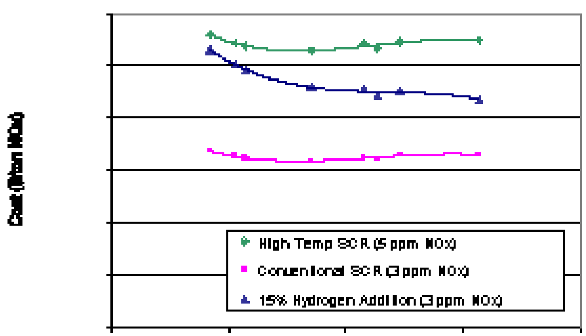
Related Efforts

International Workshop on Modeling and Validation of Combustion in Gas Turbines

Workshop home page:
www.ca.sandia.gov/CGT

- Objective is to establish a collaborative validation capability based on the LES technique
- Focused on turbulent, swirl-stabilized flames and the complex flow dynamics in gas turbine combustors
- Construct database repository on Web for selected flames to be used for model validation ✓

Economic Analysis



Cost to retrofit Gas Turbines with NO_x Control

- Energetics Inc. performed technical cost analysis ✓
- Cost comparisons with Dry Low NO_x combustors and Selective Catalytic Reduction showed 20% H_2 addition is cost competitive ✓
- H_2 addition up to 20% offers NO_x levels below 1 ppm and reduced CO_2 emissions ✓
- Extended analysis showed up to 60% H_2 addition is cost competitive when carbon credits are included ✓

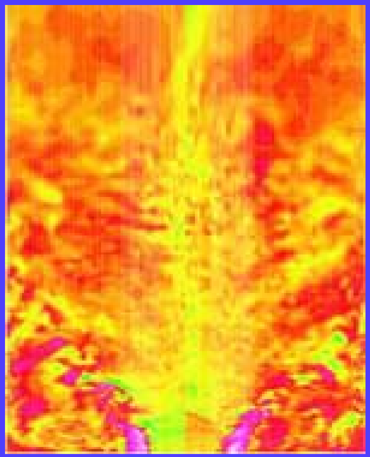
Working Groups

IEA Technical Working Group on Modeling

- Primary program focus is the *use of gas turbines in "zero-emission" H_2 applications* ✓
- An administrative framework has been established. Technical and Strategy Committee members were selected with Sandia co-chairs on each ✓
- The Technical and Strategy groups met in Fall, 2002 to discuss procedures related to multi-nation tasks and to review technical progress ✓
- A working group meeting was held in Spring, 2003 ✓

Project	Organization
H_2 Enrichment / Diagnostics	Sandia
LES Development	Sandia
Kinetics	Heidelberg
Hydrogen Burner	NASA Glenn
LES Development	Darmstadt
Diagnostics	Lund Technical
Diagnostics	Cranfield
High Pressure Experiments	NETL
Diagnostics	Toronto

LES of swirl burner

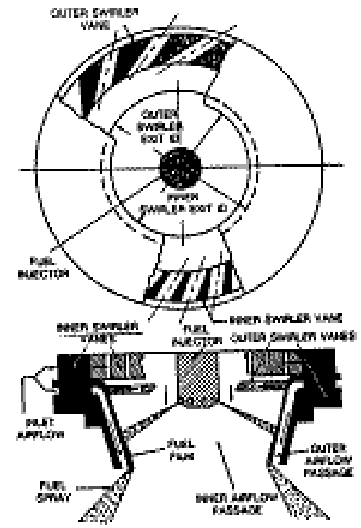


AIAA Fluid Dynamics Technical LES Working Group

- Goal is development of predictive design tools for next generation aerospace and industrial applications
- Group focus is joint LES/laboratory investigations on prototypical configurations with industrial impact
- Participants are NRL, GEAE, Pratt & Whitney, WPAFB, U. Cinncinati, FOI-Stockholm, NCSU, Rolls-Royce, Alstom, SNL, U. Poitiers & CNRS, CTR and GATECH

New Collaborations

Swirl Injector



Pratt and Whitney

- P & W will supply fuel injector to emphasize different aspects of practical gas turbine combustors (flow and flame dynamics)
- Fundamental data needed for LES model development
- Sandia will apply advanced diagnostics and LES to characterize combustion process and obtain detailed datasets
- Identify problem areas where hydrogen addition could be beneficial

Wright Patterson Air Force Base (emerging)

- WPAFB has extensive high-pressure diagnostic capabilities that complement Sandia capabilities
- Available high-pressure test facilities for realistic combustion pressures and temperatures

Proposed Future Work and Milestones

- Obtain detailed measurements of the velocity, temperature and species concentration fields in atmospheric pressure burner at Sandia (swirl burner)
- Establish LES model validity through comparisons with experimental database (swirl burner)
- Develop laser diagnostics for high pressure application (NETL)
- Complete evaluation of fuel/air mixing and implement improvements in hydrogen burner (NASA)
- Obtain NO_X and CO emissions data in hydrogen burner (NASA)
- Explore issues surrounding the use of H_2 as an alternative gas turbine fuel (NASA)
- Complete experimental measurements in production injector (GEAE)
- Identify areas where H_2 addition could prove beneficial and demonstrate potential merits of H_2-enrichment in these areas (GEAE)
- Explore potential use of H_2 addition as a “control knob” to eliminate instabilities related to fuel lean operation in practical gas turbines (GEAE)

Responses From 2002 Review Panel

- **Panel strongly endorsed continuation of this project**
  - No criticisms or questions, continued funding recommended
  - Score 95 (rank 2 in session, highest score was 96)
- **Goals and objectives being addressed properly**
  - Cost competitive even at 15% H_2 due to avoided cost of NO_x removal
  - Goal to use hydrogen to reduce NO_x emissions deemed solid
- **Approach viable and project well planned and on track**
  - Strong project management and research tools
  - Good use of laboratory resources and capability
- **Significant progress being made with reasonable milestones**
  - All milestones met or exceeded, significant results produced
  - Strong commercial collaboration in place and growing
- **Excellent communication, collaborations and publication record**

Publications

- Schefer, R. W., “Hydrogen Enrichment for Improved Lean Flame Stability, ” International Journal of Hydrogen Energy, 2003 (to appear).
- Wicksall, D. M., Schefer, R. W., Agrawal, A. K. and Keller, J. O., “Simultaneous PIV-OH PLIF Measurements in a Lean Premixed Swirl-Stabilized Burner Operated on H2/CH4/Air, “Proceedings of the Third Joint Meeting of the U.S. Sections of the Combustion Institute, March 17-19, Chicago, IL (2003).
- Wicksall, D. M., Schefer, R. W., Agrawal, A. K. and Keller, J. O., “Fuel Composition Effects on the Velocity Field in a Lean Premixed Swirl-Stabilized Burner, “ Proceedings of ASME Turbo Expo 2003: 48th ASME International Gas Turbine and Aero Engine Technical Congress and Exposition, June 16-19, Atlanta, GA (2003),
- Schefer, R. W., Smith, T. D. and Marek, C. J., “Evaluation of NASA Lean Premixed Hydrogen Burner, “ Sandia Report SAND2002-8609, January, 2003 (submitted to Combustion Science and Technology).
- Schefer, R. W., Wicksall, D. M. and Agrawal, A. J., “Combustion of Hydrogen-Enriched Methane in a Lean Premixed Swirl-Stabilized Burner,“ Twenty-Ninth Symposium (International) on Combustion, Sapporo, Japan, July 21-26, 2002 (to appear).
- Vagelopoulos, C. M., Oefelein, J. C. and Schefer, R. W., “Response of Lean Premixed methane Flames to Hydrogen Enrichment, “ Proceedings of the Third Joint Meeting of the U.S. Sections of the Combustion Institute, March 17-19, Chicago, IL (2003).
- Vagelopoulos, C. M., Oefelein, J. C. and Schefer, R. W., “Effects of Hydrogen Enrichment on Lean Premixed Methane Flames, “ 14th Annual U.S. Hydrogen Conference and Hydrogen Expo USA, March 4-6, Washington, D.C. (2003).
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