Gas Turbine Combustion: Emission and Operability

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Turbine Logic

Active Research Topics

- Experimental Combustion Dynamics
  - Mechanisms
  - Mitigation
- Effects of fuel composition variability
- Design of optically accessible research facilities
- Fluid dynamics of modern combustion systems

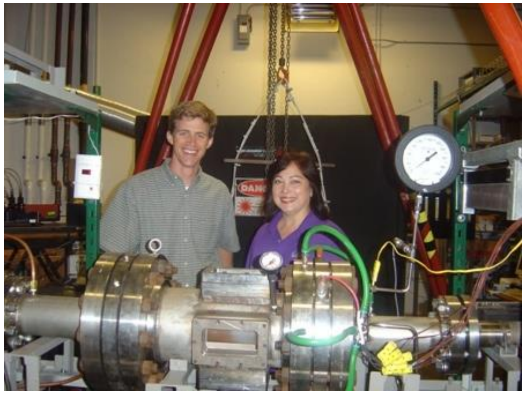
Co-Instructor Bio

Professor Tim Lieuwen

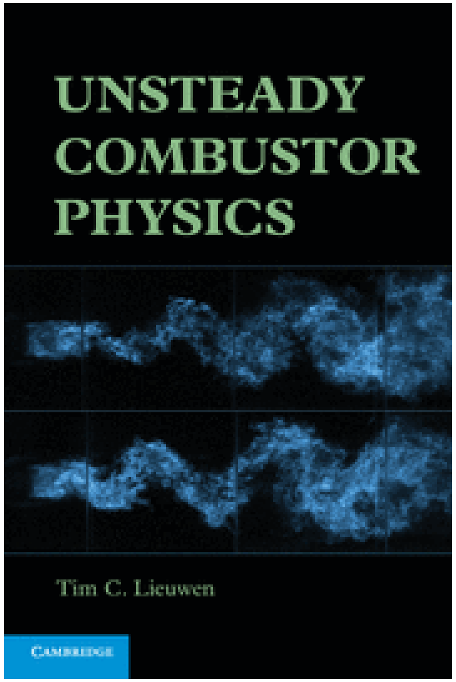
- Professor at Georgia Institute of Technology, focusing on combustion issues

- Published extensively on topic:
  - 4 books
  - Over 200 publications, numerous presentations at companies, international conferences

- Have worked with most gas turbine OEM's, suppliers, and power producers on topic
  - Predictive modeling
  - Risk assessment
  - Expert witness and litigation



Books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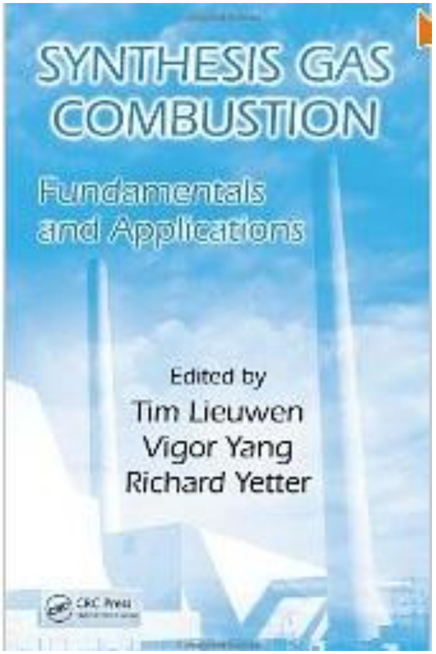
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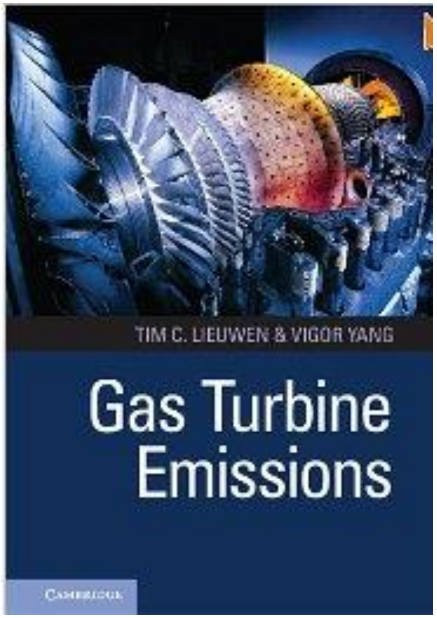
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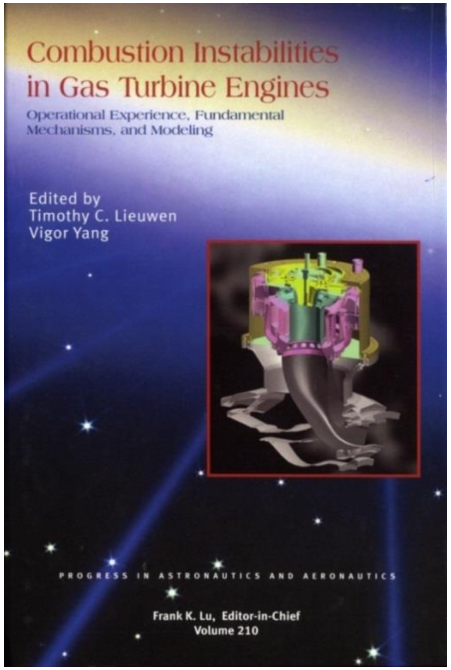
Combustion Instabilities
in Gas Turbine Engines
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PROGRESS IN ASTRONAUTICS AND AERONAUTICS
Frank K. Lu, Editor-in-Chief
Volume 210

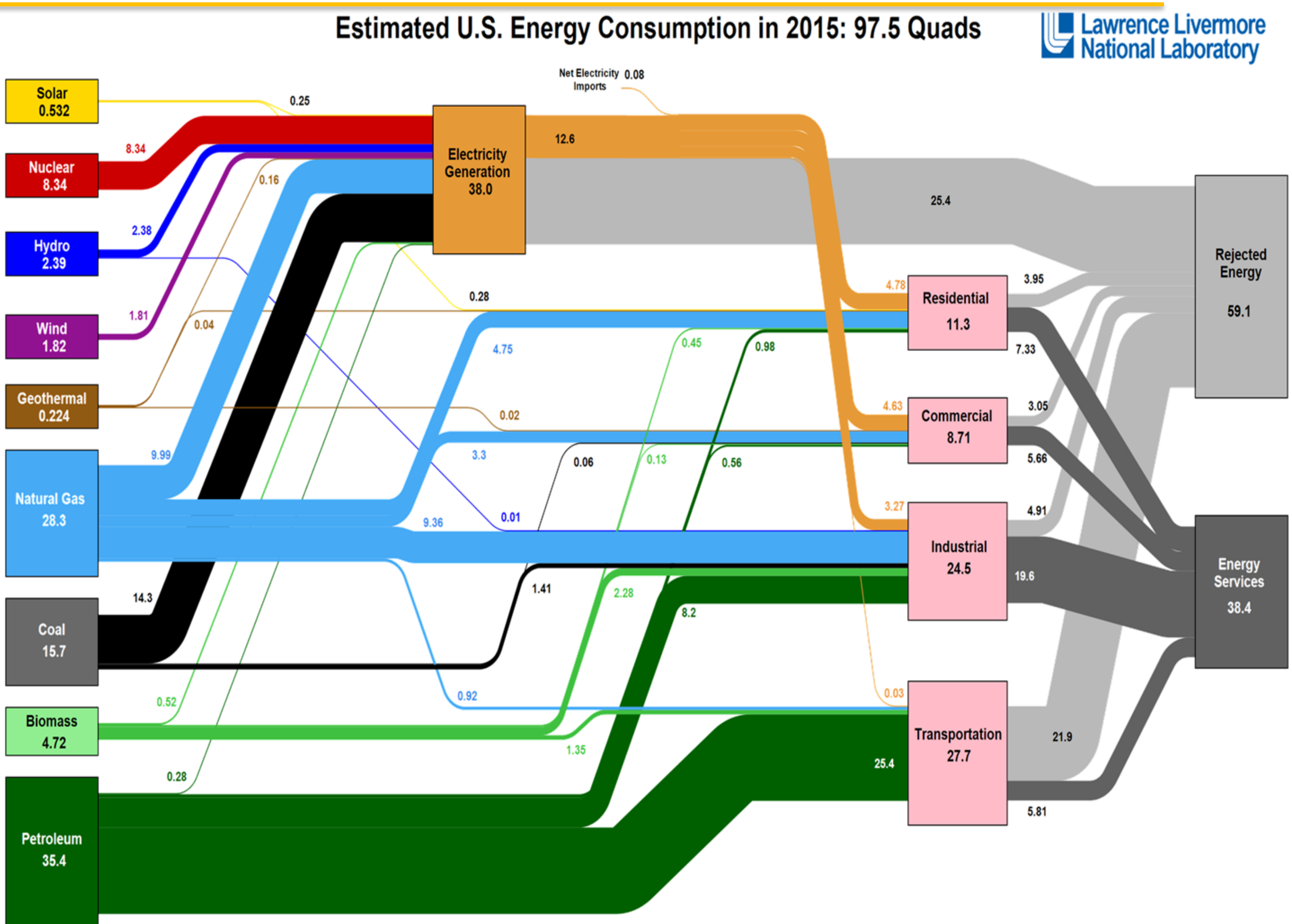
Global Renewable Energy Growth

- Global investment in renewables more than $270 billion in 2014*
  - >59 percent of net additions to global power capacity in 2014
- China leading world in investments

		START 2004[1]	2013	2014
INVESTMENT				
New investment (annual) in renewable power and fuels[2]	billion USD	45	232	**270**
POWER				
Renewable power capacity (total, not including hydro)	GW	85	560	**657**
Renewable power capacity (total, including hydro)	GW	800	1,578	**1,712**
Hydropower capacity (total)[3]	GW	715	1,018	**1,055**
Bio-power capacity	GW	<36	88	**93**
Bio-power generation	TWh	227	396	**433**
Geothermal power capacity	GW	8.9	12.1	**12.8**
Solar PV capacity (total)	GW	2.6	138	**177**
Concentrating solar thermal power (total)	GW	0.4	3.4	**4.4**
Wind power capacity (total)	GW	48	319	**370**
HEAT				
Solar hot water capacity (total)[4]	GW_{th}	86	373	**406**
TRANSPORT				
Ethanol production (annual)	billion litres	28.5	87.8	**94**
Biodiesel production (annual)	billion litres	2.4	26.3	**29.7**

* Source: Renewable Energy Policy Network, *2015 Global Status Report*

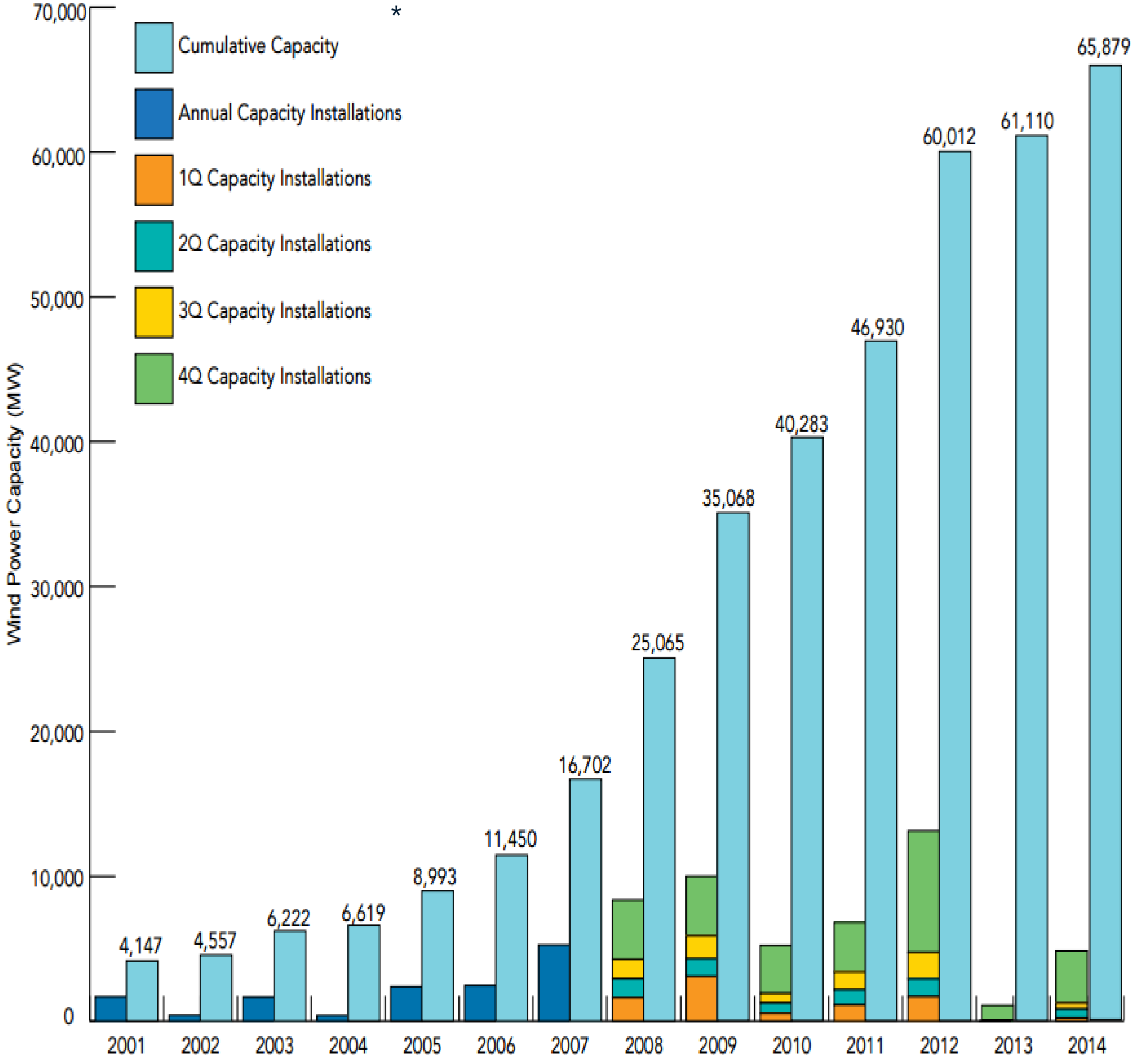
U.S. Energy System



Growing U.S. Wind Power Capacity

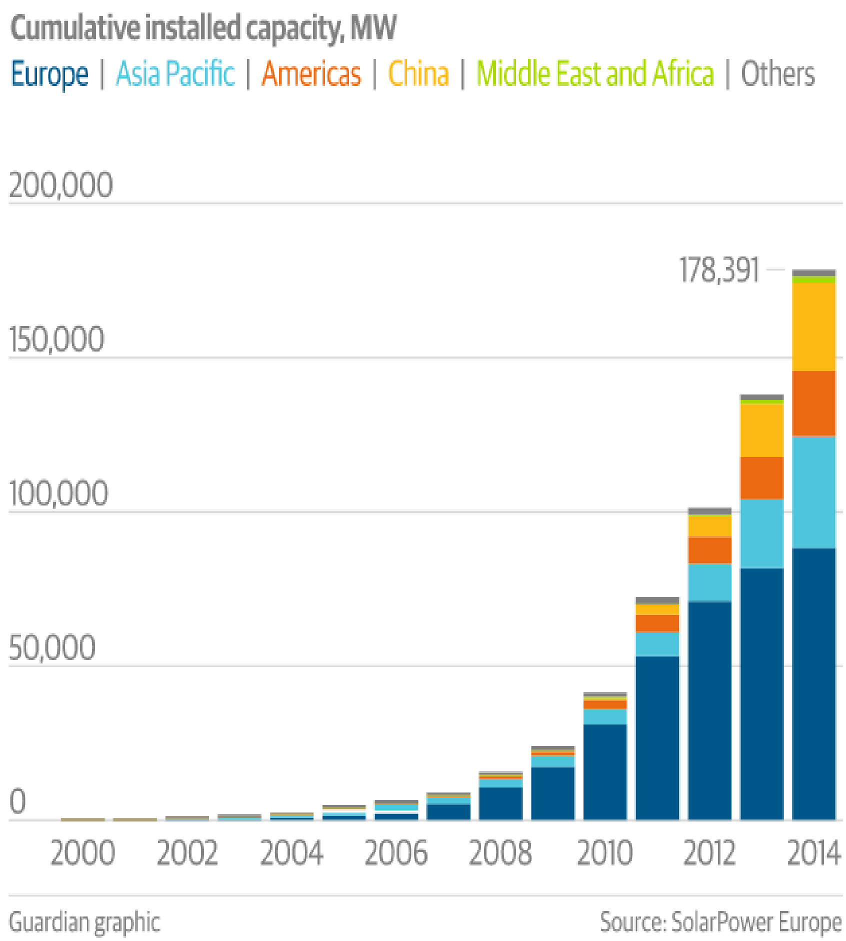
- Electricity generated by wind tripled in the last seven years, representing just under 5 percent of the nation's total end-use demand

- Wind now represents ~30% percent of electricity used on the ERCOT grid.



Source: American Wind Energy Association

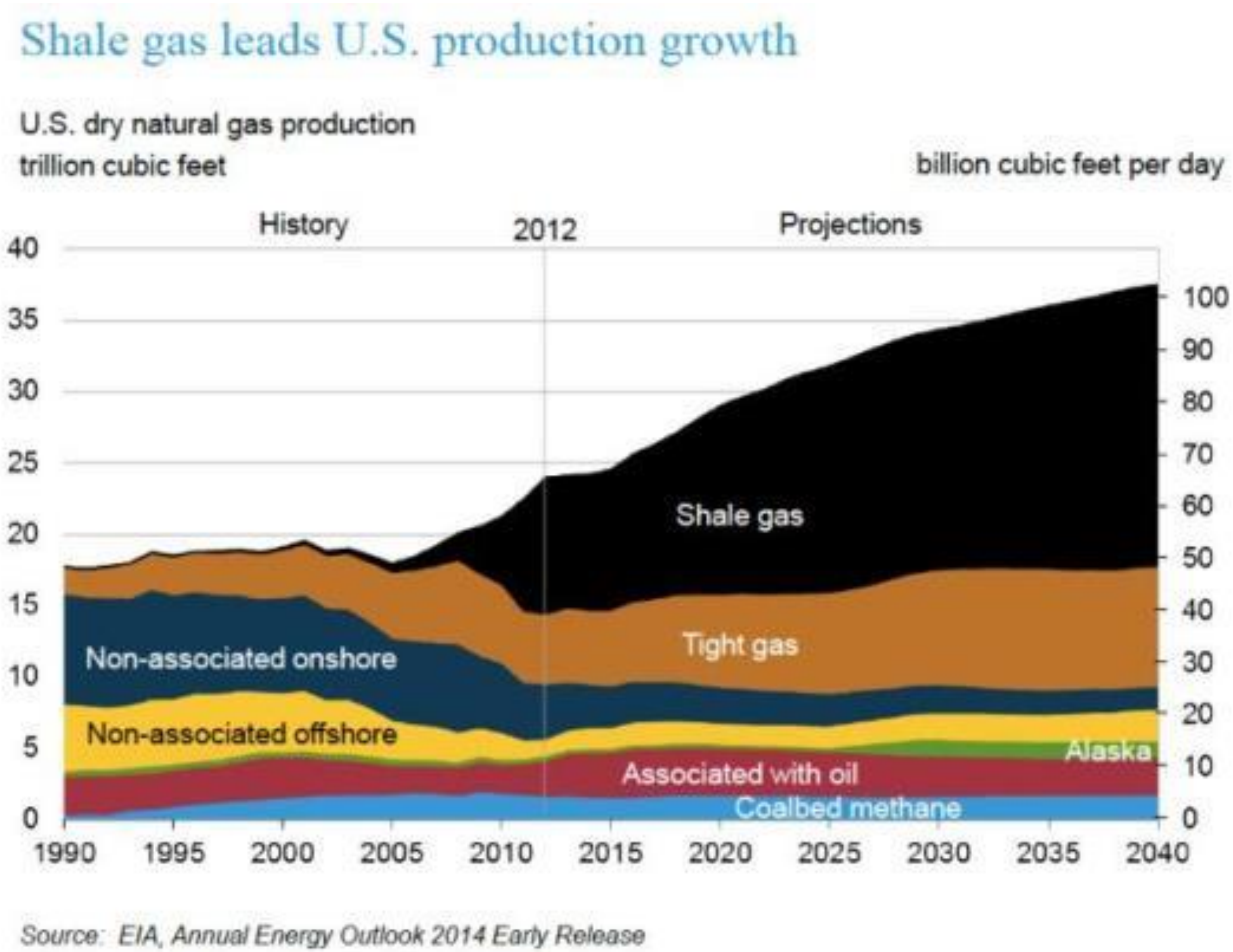
Demand for Solar Skyrocketing



- 40% of solar energy in Europe comes from utilities, rooftop contributes 60%
- China (10.6GW), Japan (9.7GW) and the US (6.5GW) were the three biggest global solar markets last year

* Source: GTM Research, Solar Market Insight Report 2015 Q1

Natural Gas Production



- U.S. gas production has increased every year from 2005:
  - 51 bcf/day(2005)
  - 74 bcf/day(2014)

U.S. Petroleum Production

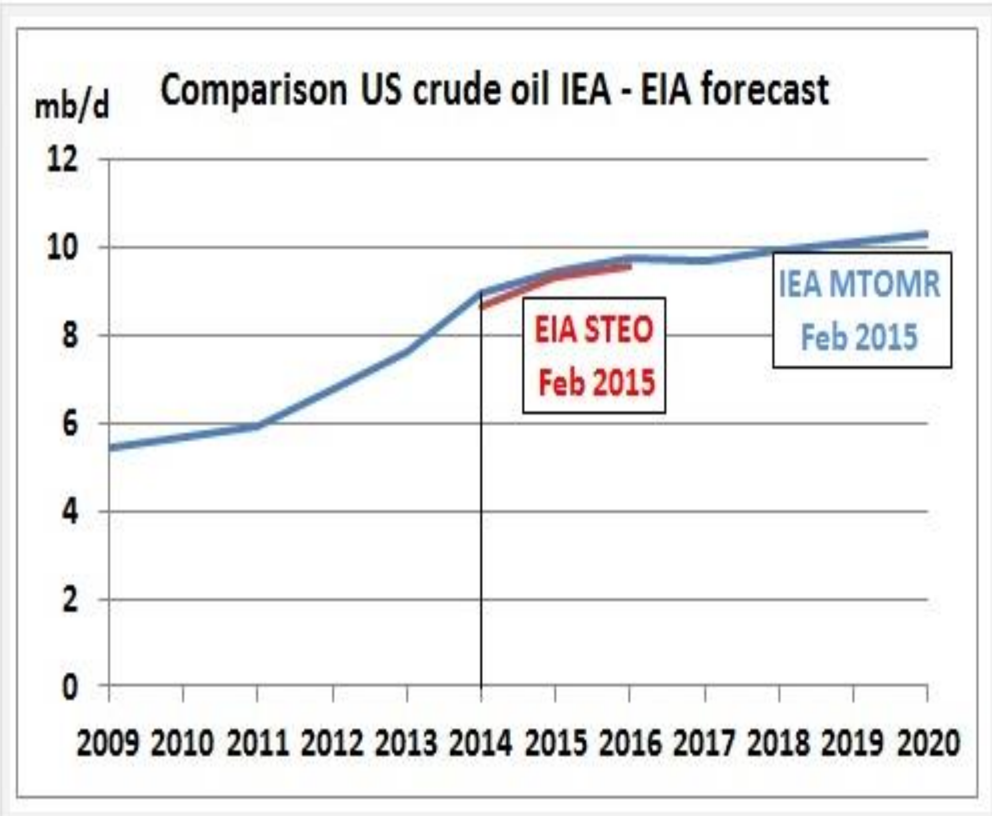


Fig 9: Comparison EIA – IEA crude oil forecast

- Both the U.S. Energy Information Administration's (EIA's) Short-Term Energy Outlook and the International Energy Agency's Medium Term Oil Market Report 2015 show U.S. production slowing down.

Coal and Global Energy Demand

- 40 percent of the world's electricity
- Coal still a major source for U.S. electricity generation, but dominance challenged due to:
  - Low natural gas prices, (NG Briefly surpassed coal in May 2014)
  - State renewable energy, standards, and
  - Environmental regulations.

Key Energy Challenges

- *Category pollutant and Carbon* Emissions
- *Oil* Imports and Energy Security
- *Water-Energy* Interactions

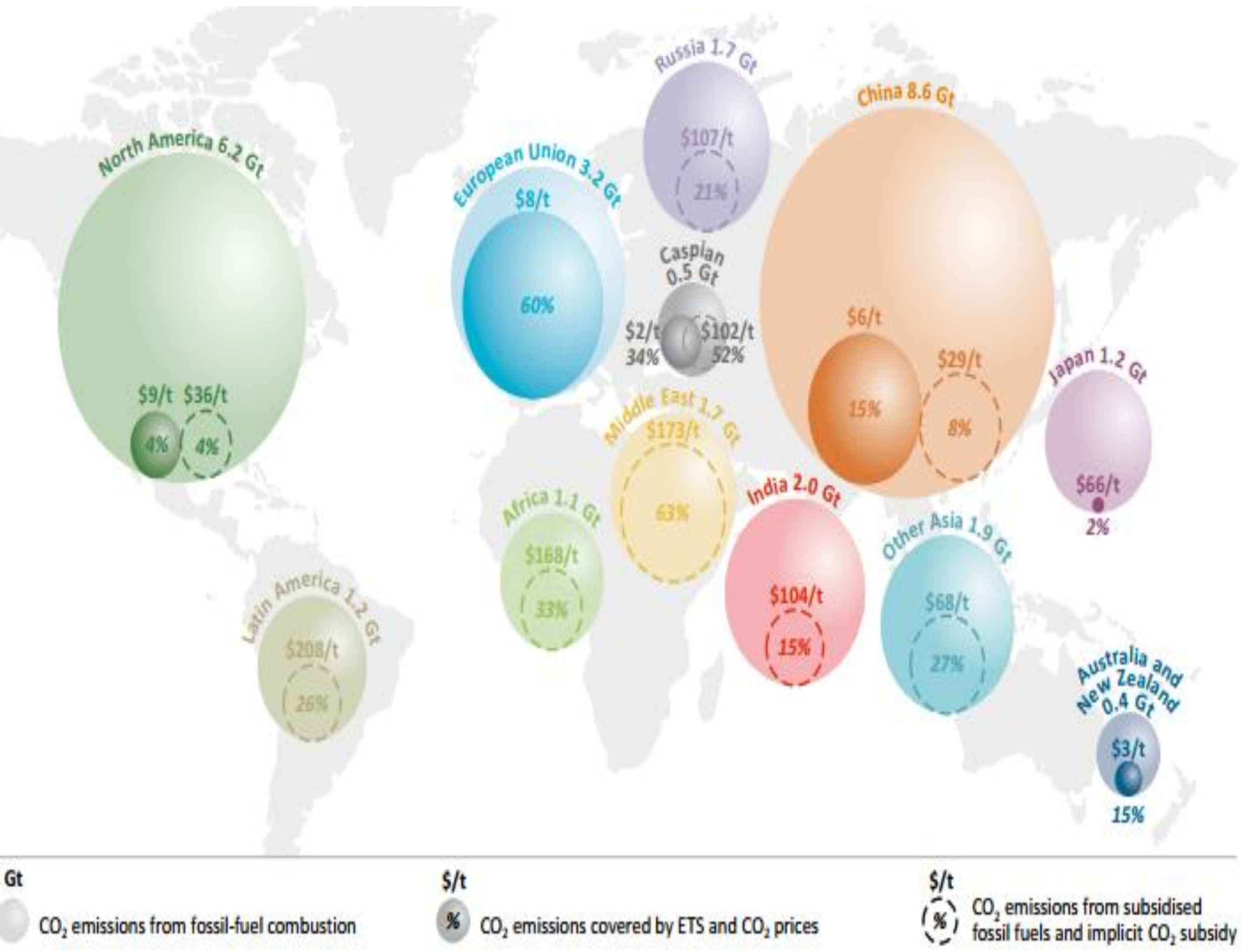
Carbon Connection to Climate Change/Global Warming

- Most of the carbon in the earth's atmosphere is in the form of carbon dioxide (CO_2) and methane (CH_4).
- Carbon is one several "greenhouse" or "radiatively active" gases in the atmosphere that absorb and emit heat radiated from the earth's surface
- Rising concentrations of atmospheric carbon dioxide can alter the Earth's atmosphere temperature profile
- Carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities, accounting for about 85% of all U.S. greenhouse gas emissions from human activities
- Main Sources:
  - Electricity
  - Transportation
  - Industry

Air Quality Impacts

Six Pollutants Regulated by Environmental Protection Agency (EPA) for environmental and human health impacts:	
Carbon monoxide (CO)	• colorless, odorless gas emitted from combustion processes. • Transportation sector largest source
Ground level ozone (O3)	• created by reactions of oxides of nitrogen (NOx) and volatile organic compounds (VOC) • Main component of smog • Affects human health (asthma, skin cancer, cataracts) and environment (crop growth)
Lead (Pb)	• Main sources today are ore and metals processing, piston-engine aircraft operating, leaded aviation fuel
Nitrogen oxides (NO and NO2, referred together as NOx)	• highly reactive gases formed when oxygen and nitrogen react at high temperatures during combustion • Reacts with CO and other compounds in the atmosphere to produce ground-level ozone and small particle pollution • Affects human health (respiratory)
Particulate Matter (PM) or Particle Pollution	• Complex mixture comprised of acids (such as nitrates and sulfates), organic chemicals, metals, and soil/dust particles • Contributes to serious health conditions – respiratory and cardiovascular
Sulfur oxides (SO2)	• Gas formed when sulfur is exposed to oxygen at high temperatures during fossil fuel combustion, oil refining, or metal smelting • Contributes to formation of acid rain

Annual CO_2 Emissions by Country

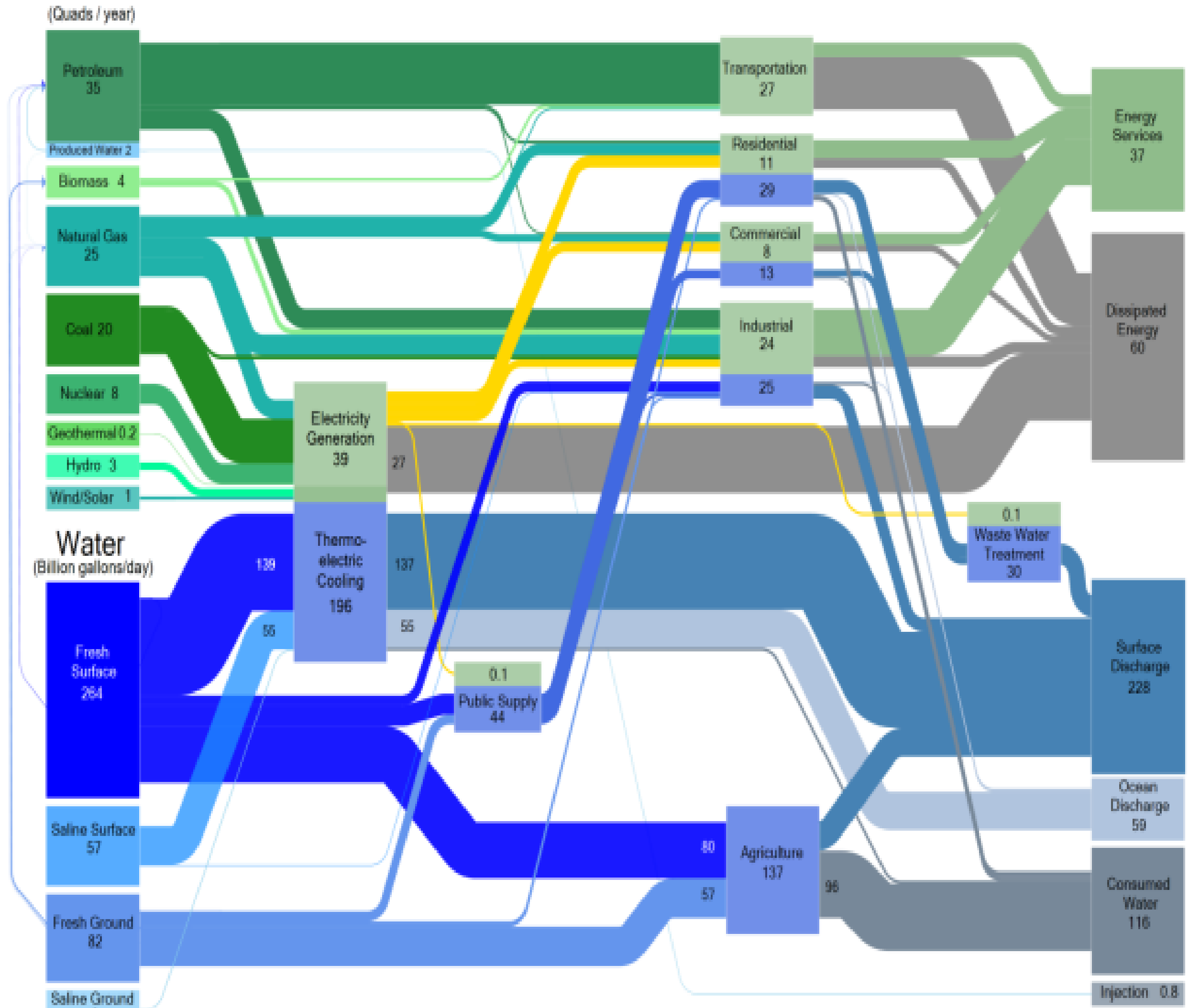


Snapshot

- EU emissions dropped by more than 200 Mt (over 6%),
  - Reduced demand for fossil fuels
  - Warmer winter
  - Increased use of renewables for power generation (12%)
- Japan's emissions estimated down 3% in 2014 relative to 2013
  - Lower oil demand
- United States, energy-related CO2 emissions in 2014 were 41 Mt higher (less than 1%) than the previous year but were around 10% below their peak in 2005 (5.7 Gt
  - Emissions from power sector down due to 11%
    - increase in renewables
    - limited increase in electricity demand,
    - Increase in natural gas use in industry and buildings)

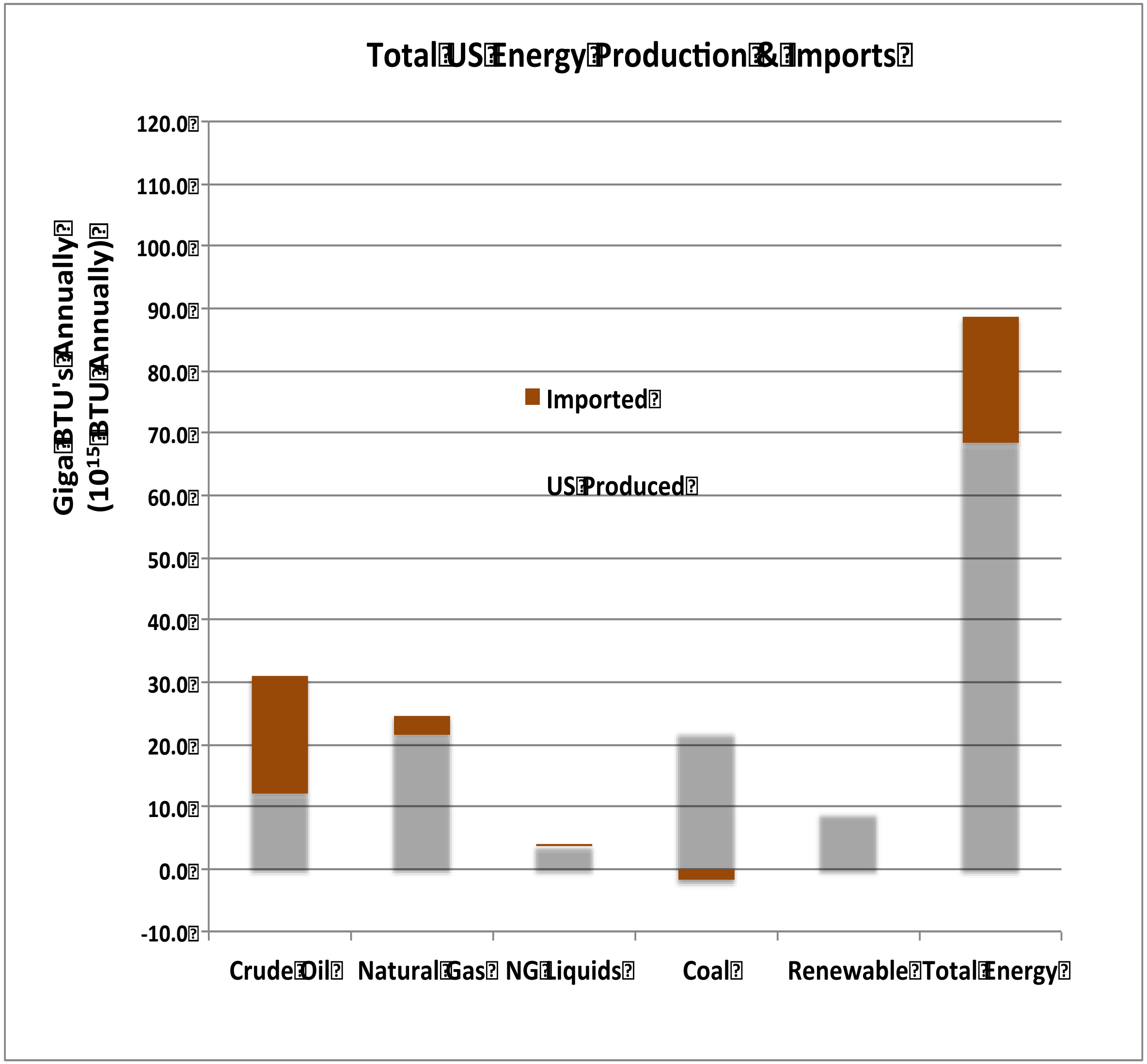
Energy –Water Nexus

- Energy sector competes directly with agriculture, the largest consumer of water, for water resources.
- Thermal energy devices are largest user of water
  - Withdraws large quantities of water for cooling
  - Dissipates tremendous quantities of primary energy in electricity conversion.



Energy reported in Quads/year. Water reported in Billion Gallons/Day.

National Security and International Relations



– U.S. is energy independent in power generation

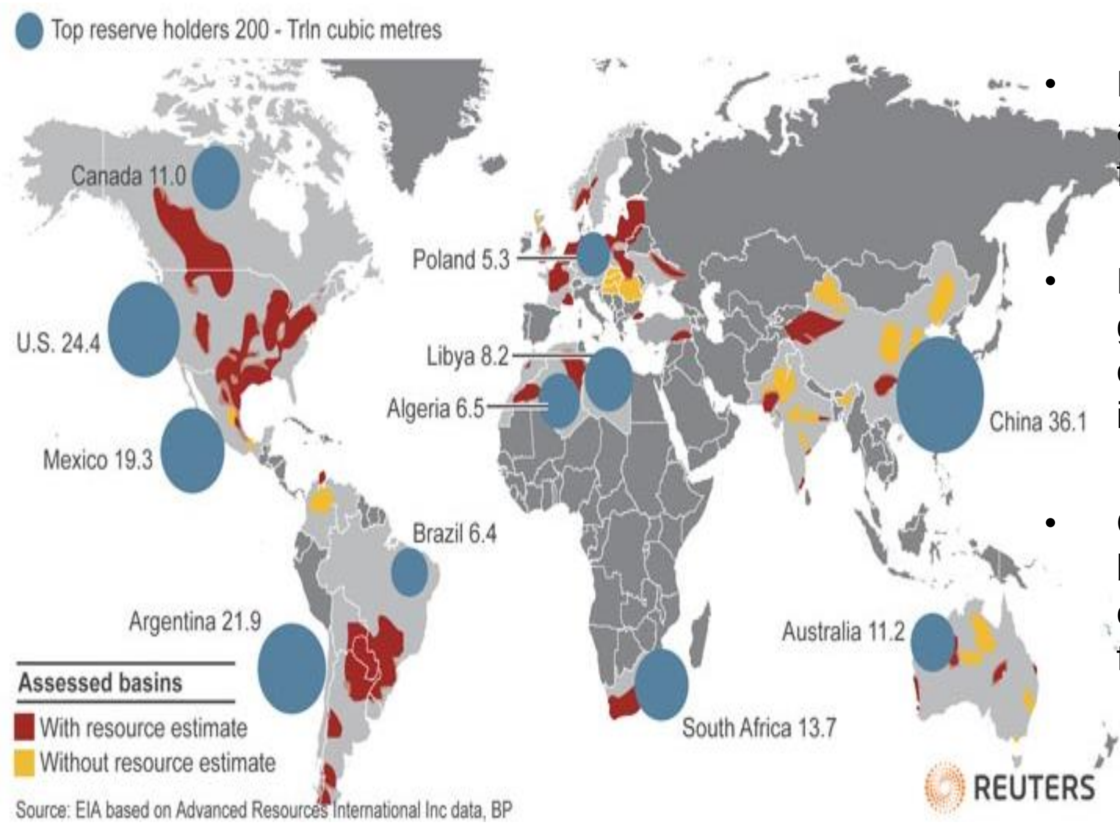
– U.S. imports 50% of its oil
  - energy security issue is coupled to transportation, oil imports

New Hydrocarbon Realities

- Rebirth of U.S. as major exporter of hydrocarbons
- World's largest exporter of refined products such as diesel, petrol (gasoline) and aviation fuel (kerosene).
- Net exporter of coal and in 2015 will be a net exporter of gas
- Despite volatile oil process, American liquefied petroleum gas (LPG) export volumes continue 5-year upward trend
  - climbed from 4.07 million barrels to 23.16 million in June 2014
  - Surpassing many big Arab producers; expected to replace Qatar as world's largest exporter by 2020
- Light-crude exports doubled since Jan. 2015
  - Exported between 120,000 and 140,000 barrels per day (bpd) in May 2015
- Import facilities redesigned for export
  - Freeport, Philips 66--America's sixth-biggest listed firm--spending a combined $3 billion on new facilities in Texas to export liquefied petroleum gas (LPG), and on an installation to process natural gas liquids (NGLs).
  - Cheniere, is spending $30 billion on two Texas facilities for liquefied natural gas (LNG) production.

Global Shale Reserves

Countries with Largest Deposits
(of 200 countries with known reserves)

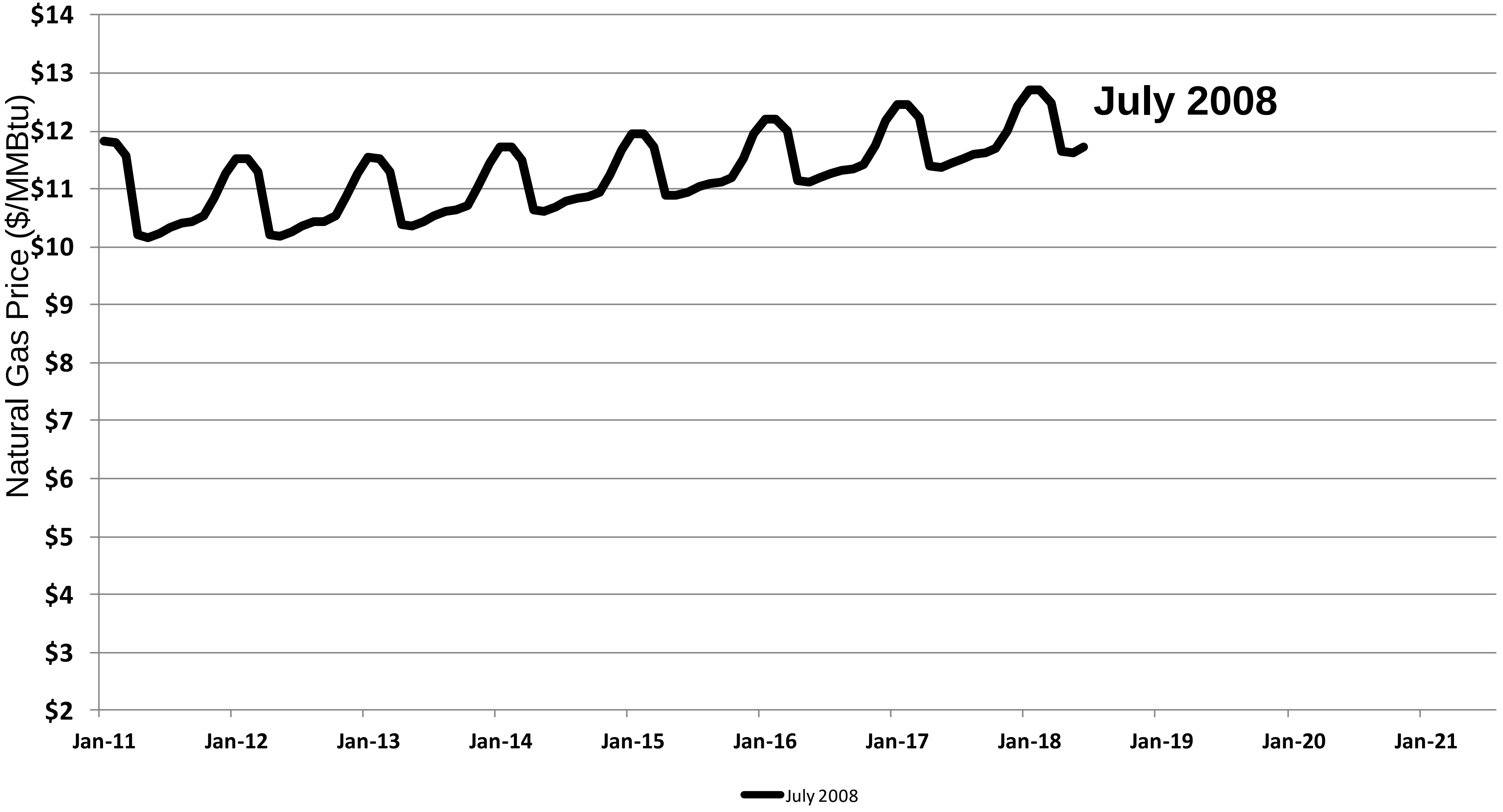


- Global energy demand projected to increase 35% by 2040, according to ExxonMobil 2014 Energy Outlook
- Natural gas is set to become a fuel of choice as residential and industrial demand shifts from less efficient coal and wood.
- Horizontal drilling and hydraulic fracturing grew U.S. shale production from 4.86 trillion cubic feet per year (Tcf/y) in 2010 to 8.6 Tcf/y in 2013
- China, Argentina and Mexico great potential, but political and infrastructure challenges considerably slowed development of new gas fields

Journal of Political Risk, Vol. 2, No. 1, January 2014.

Natural Gas – Key Trends and Impacts

It kind of snuck up on us…..



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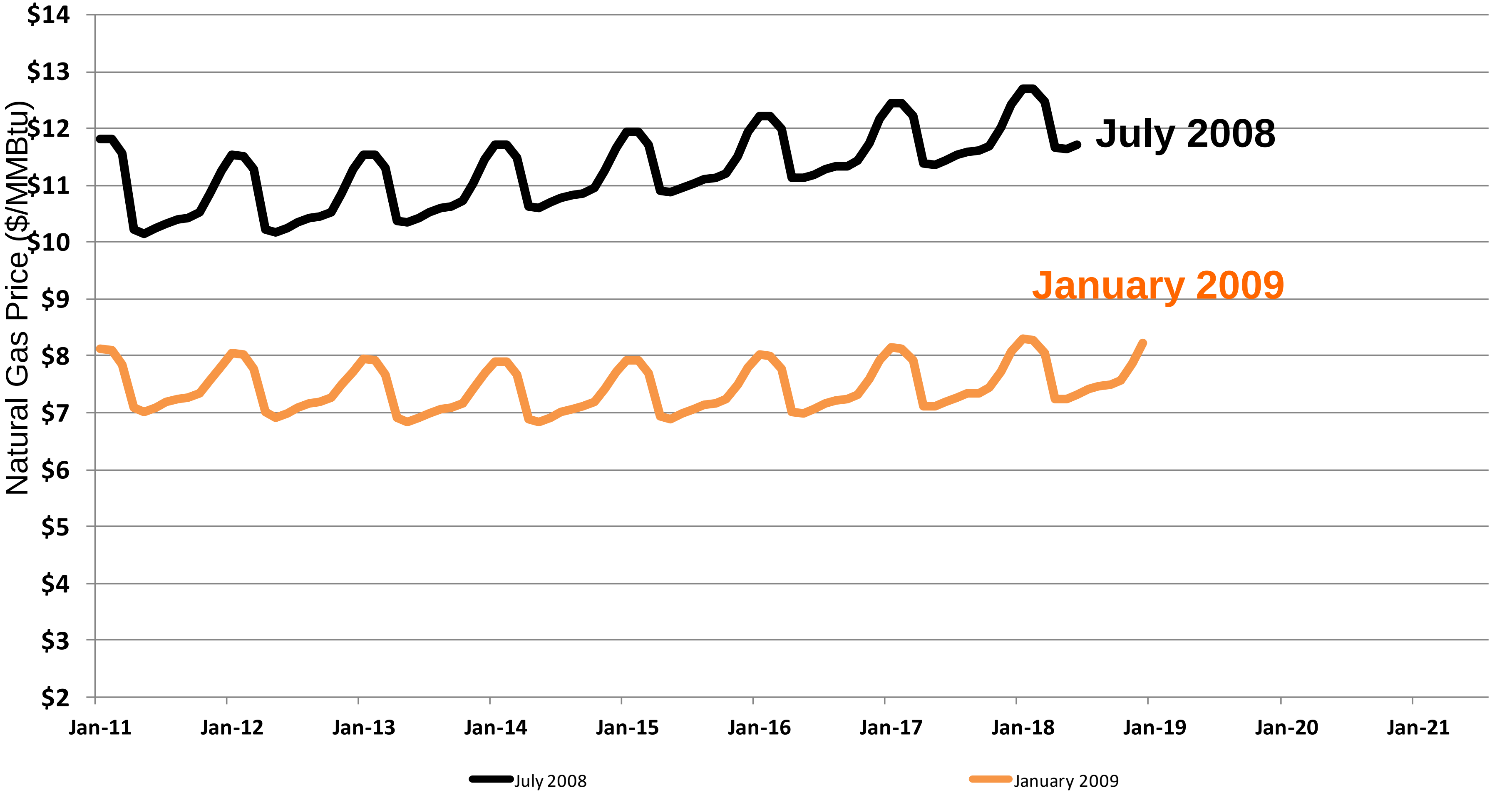

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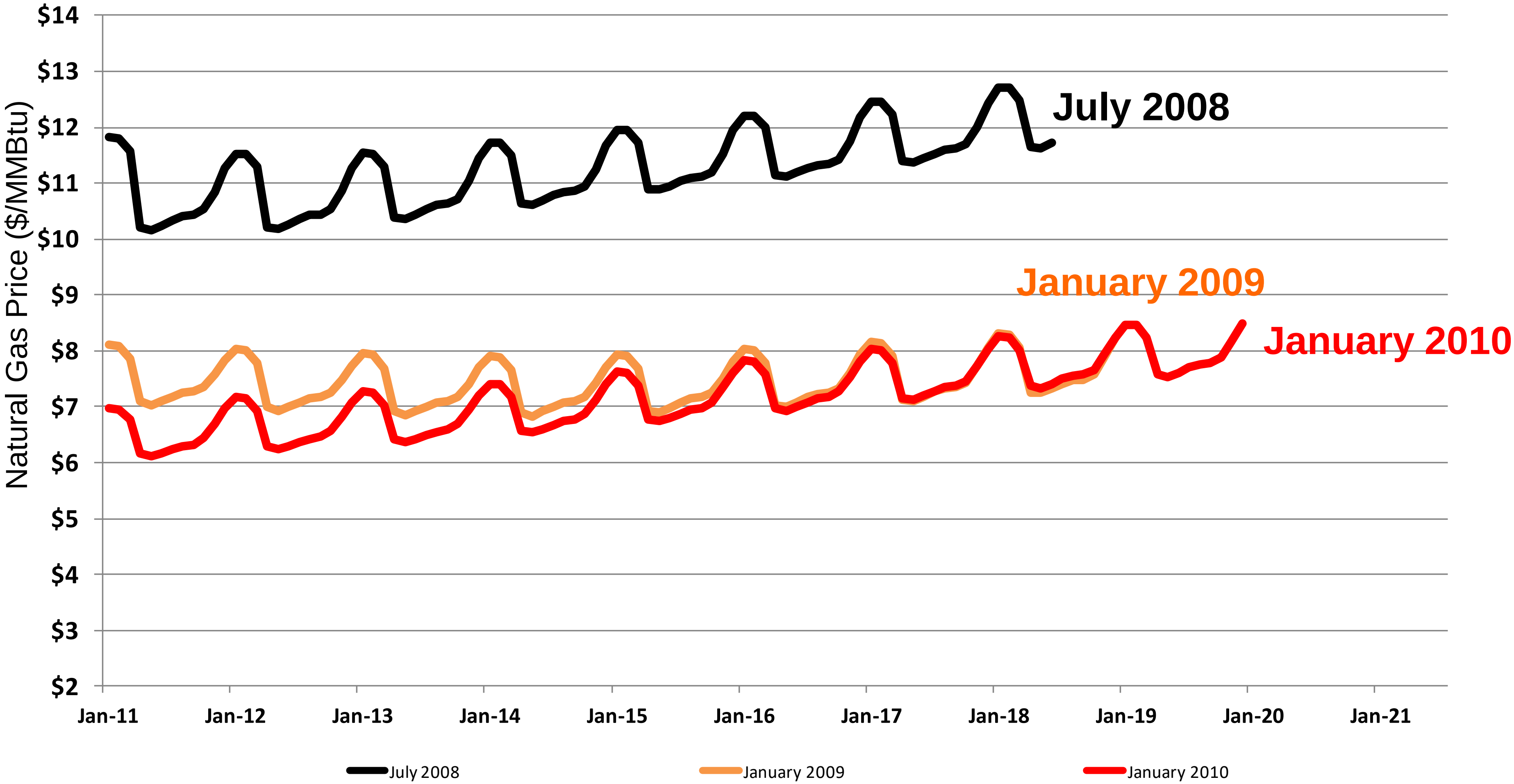

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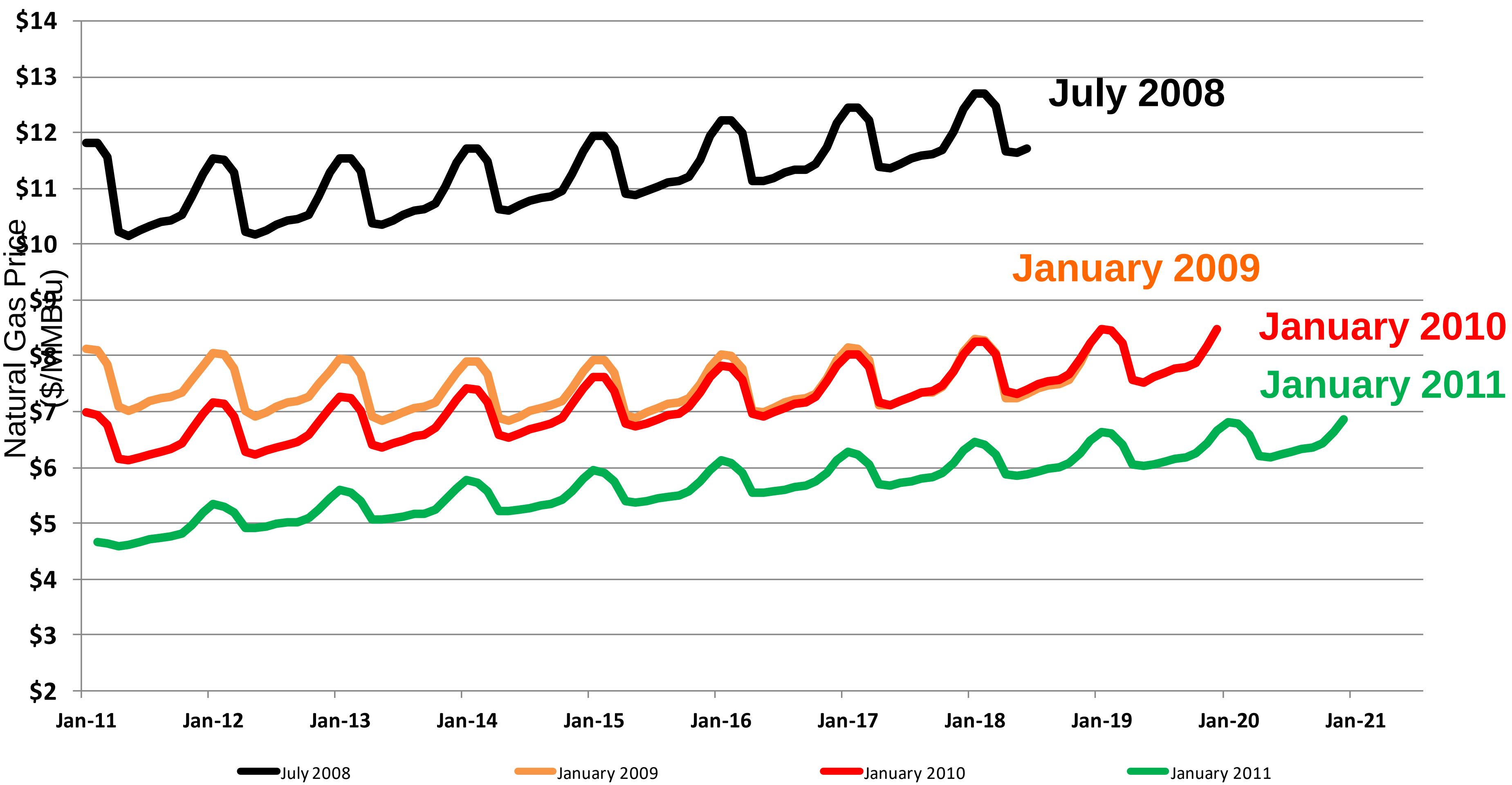

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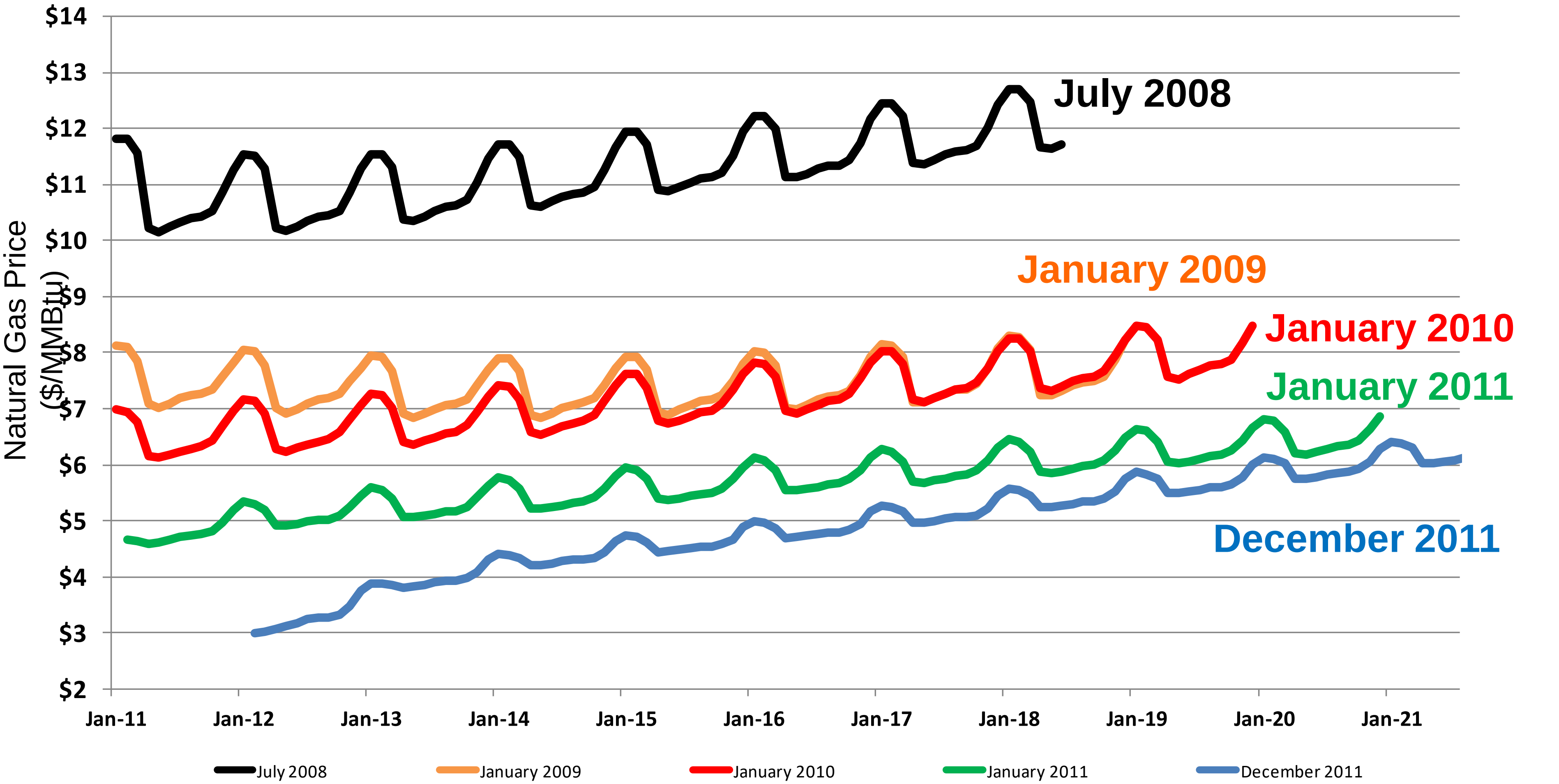
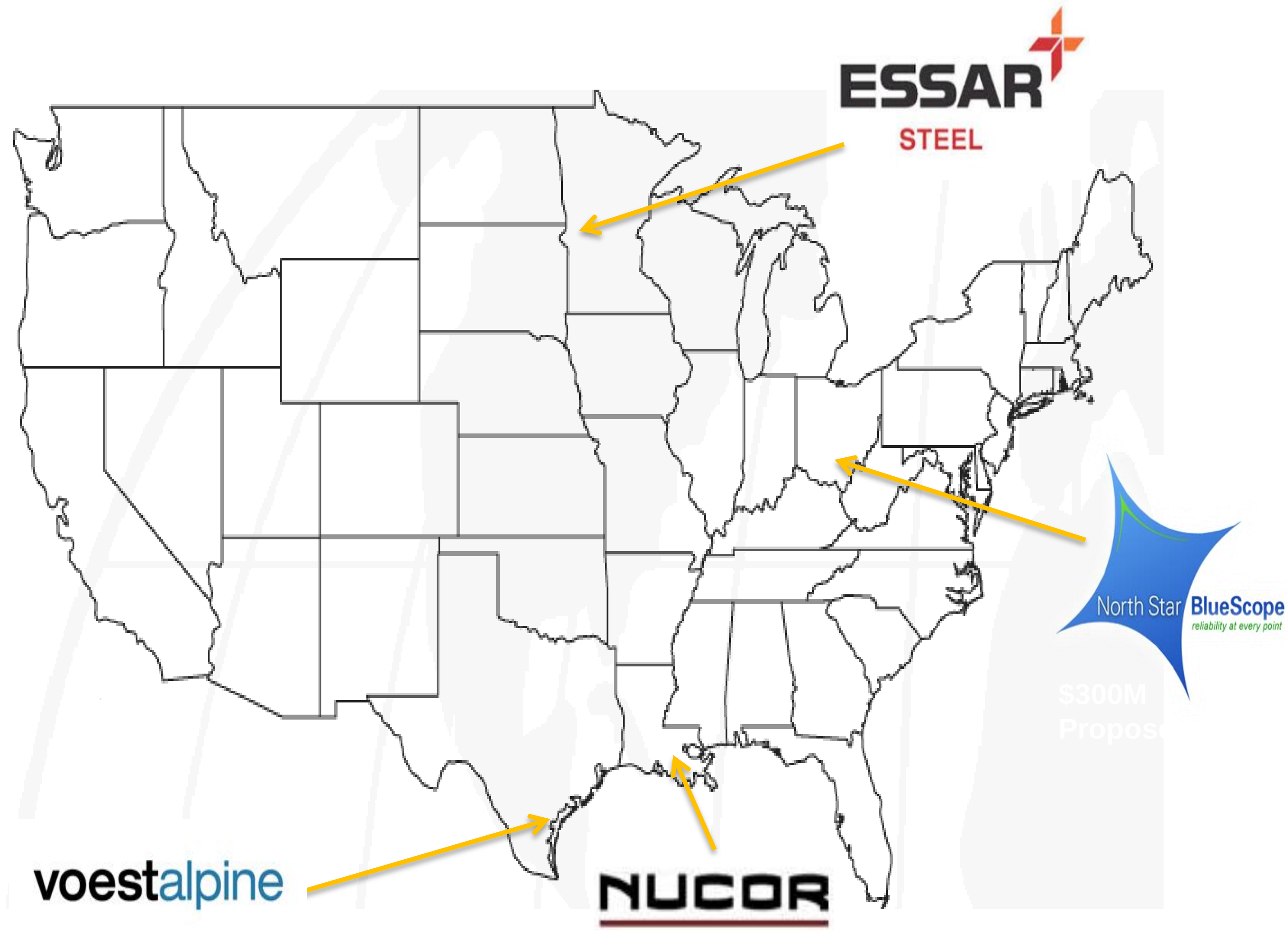


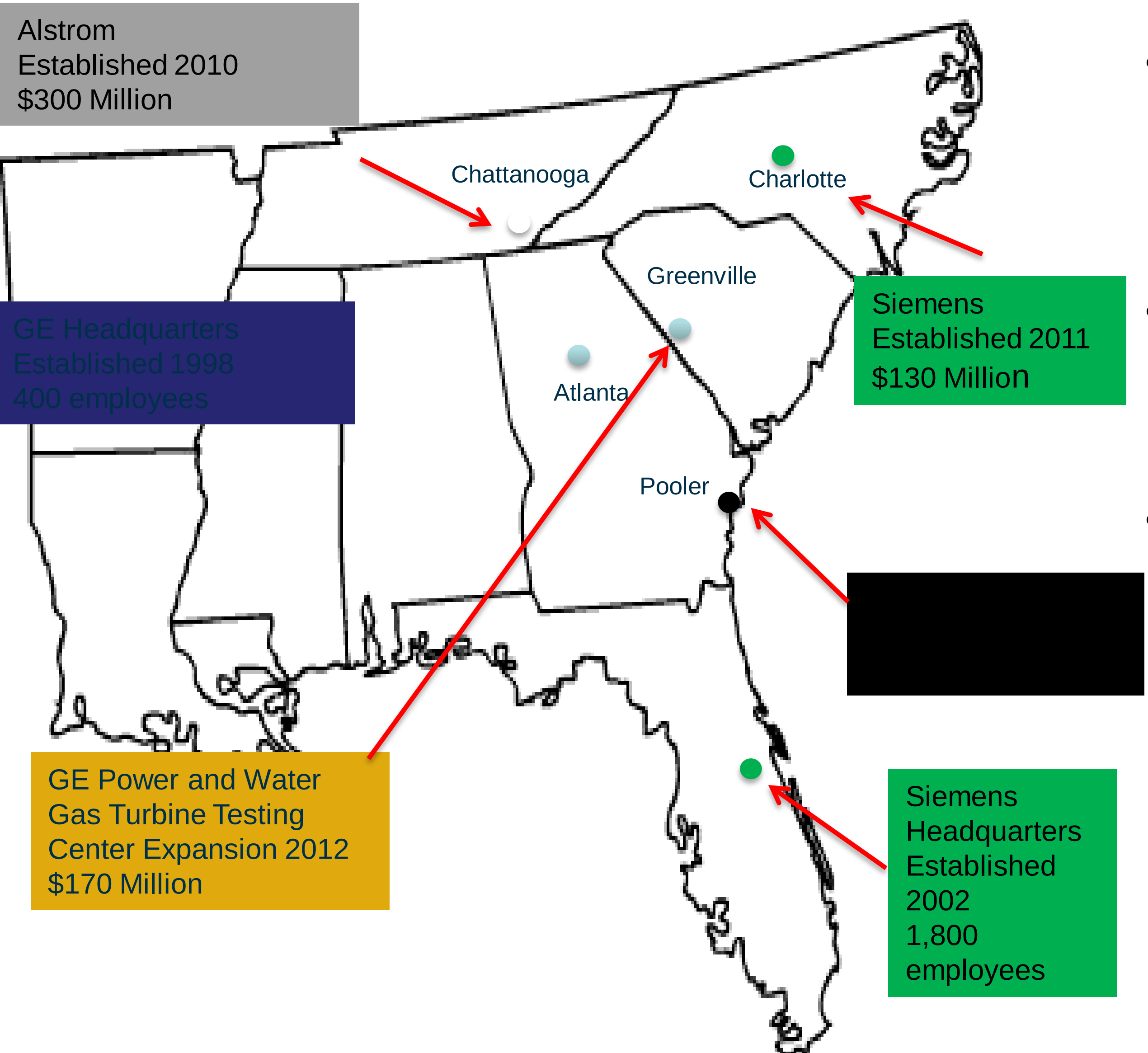
Natural Gas Industry Impact

- Manufacturing
- Power Generation
- LNG Exports
- Transportation
- Chemical Feedstock

Shale-Gas Revolution Spurs Wave of New U.S. Steel Plants



Gas Turbine Manufacturing



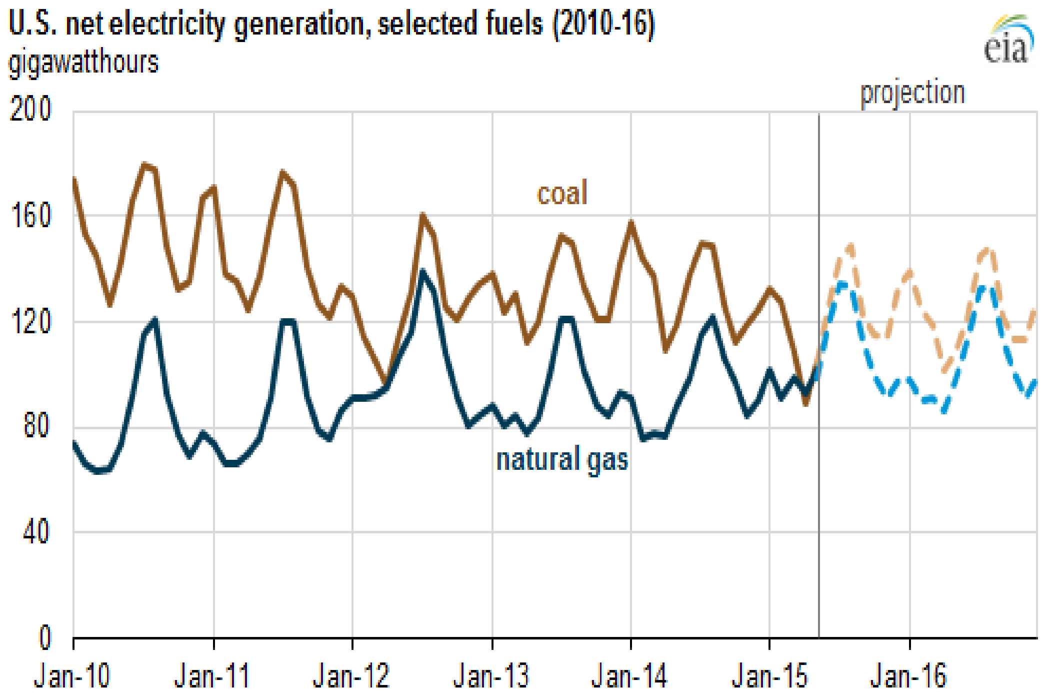
- New electric capacity additions dominated by gas turbines over last decade
- Top four OEMs increase presence in Southeast
- Percent of Heavy frame market :
  - GE – 40%,
  - Siemens – 20%,
  - MHI – 10%,
  - Alstom – 10%

Industry Impact

- Manufacturing
- Power Generation
- LNG Exports
- Transportation
- Chemical Feedstock

Power Generation – Natural Gas

- Natural gas increasingly the fuel of choice for power generation
- Current U.S. power generation capacity ~25%
- Dominant source of new capacity additions over last decade

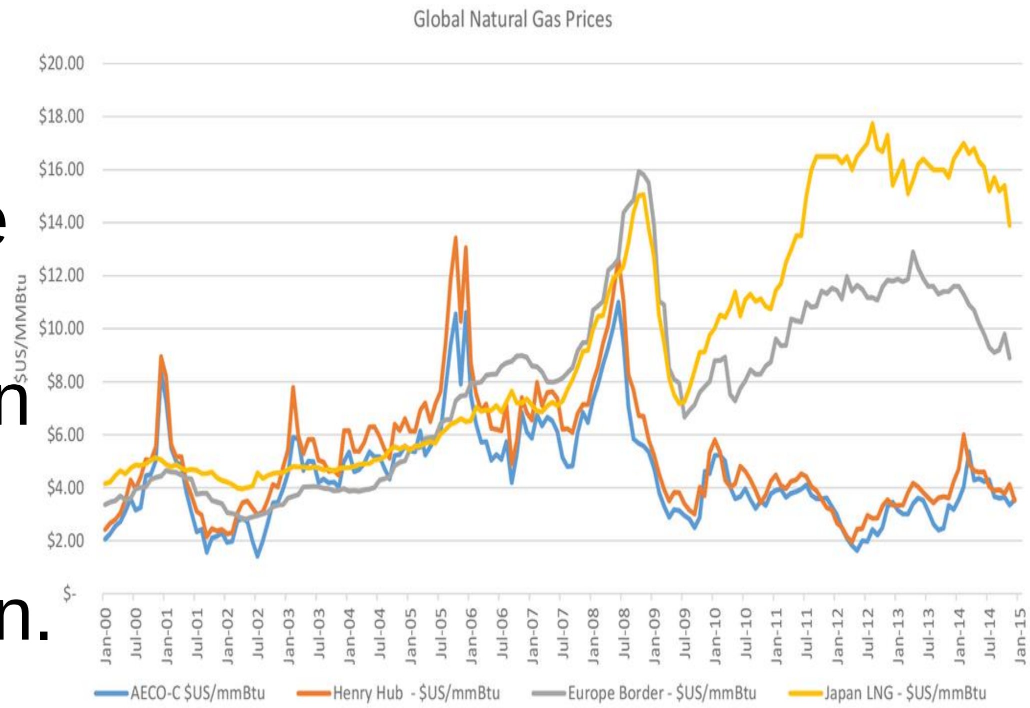


Industry Impact – LNG Exports

- **Manufacturing**
- **Power Generation**
- **LNG Exports**
- **Transportation**
- **Chemical Feedstock**

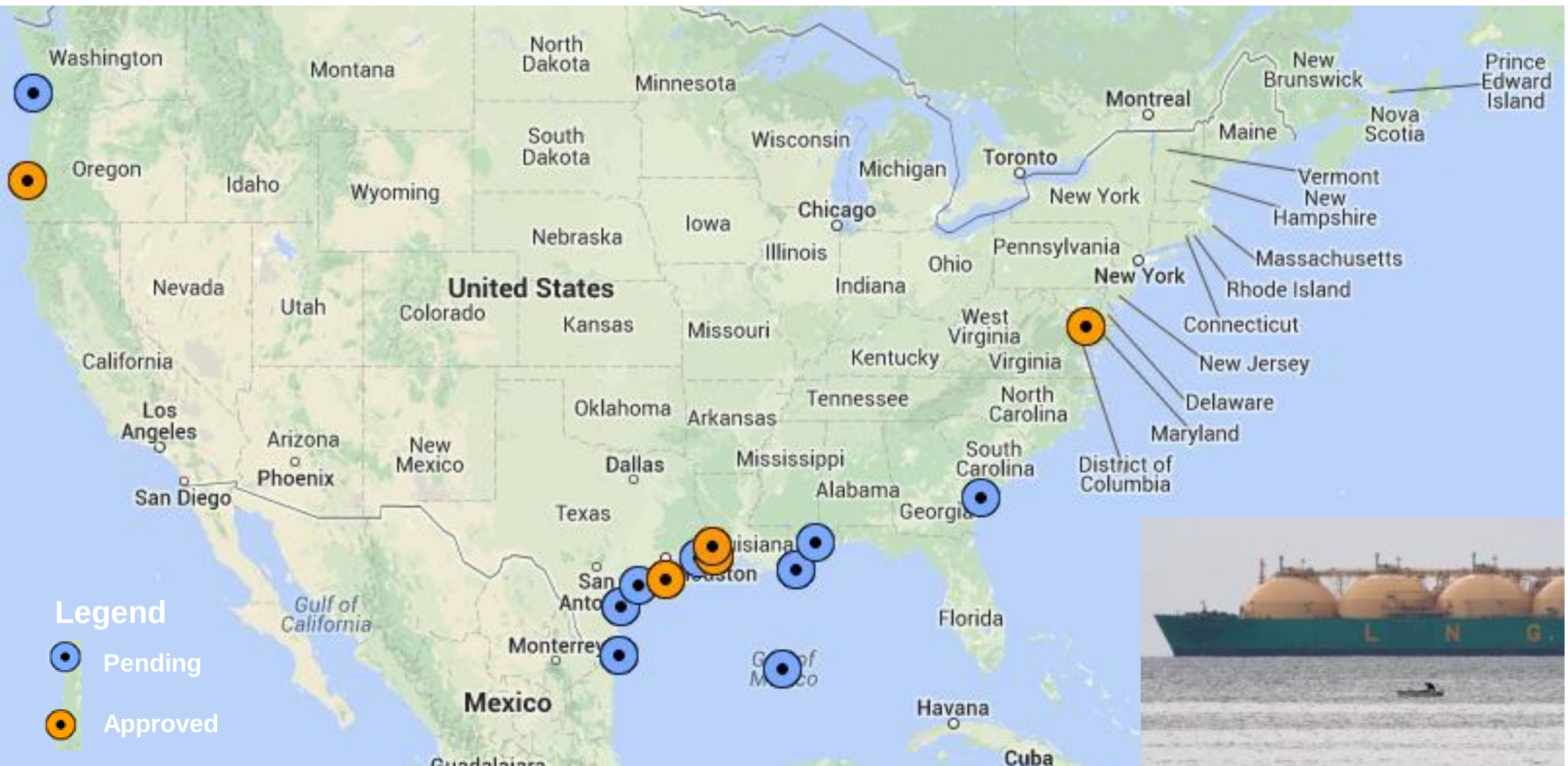
Natural Gas Prices Fueling Interest in Exports

- Arbitrage opportunities
- Higher prices expected to increase drilling activity and increasing production
- US NG a real bargain.



Pending and Approved LNG Export Projects

- DOE has approved seven applications for exporting liquefied natural gas (LNG) to non-free trade agreement nations
- 24 pending applications (including Elba Island, GA)



Industry Impact – Transportation

– **Manufacturing**

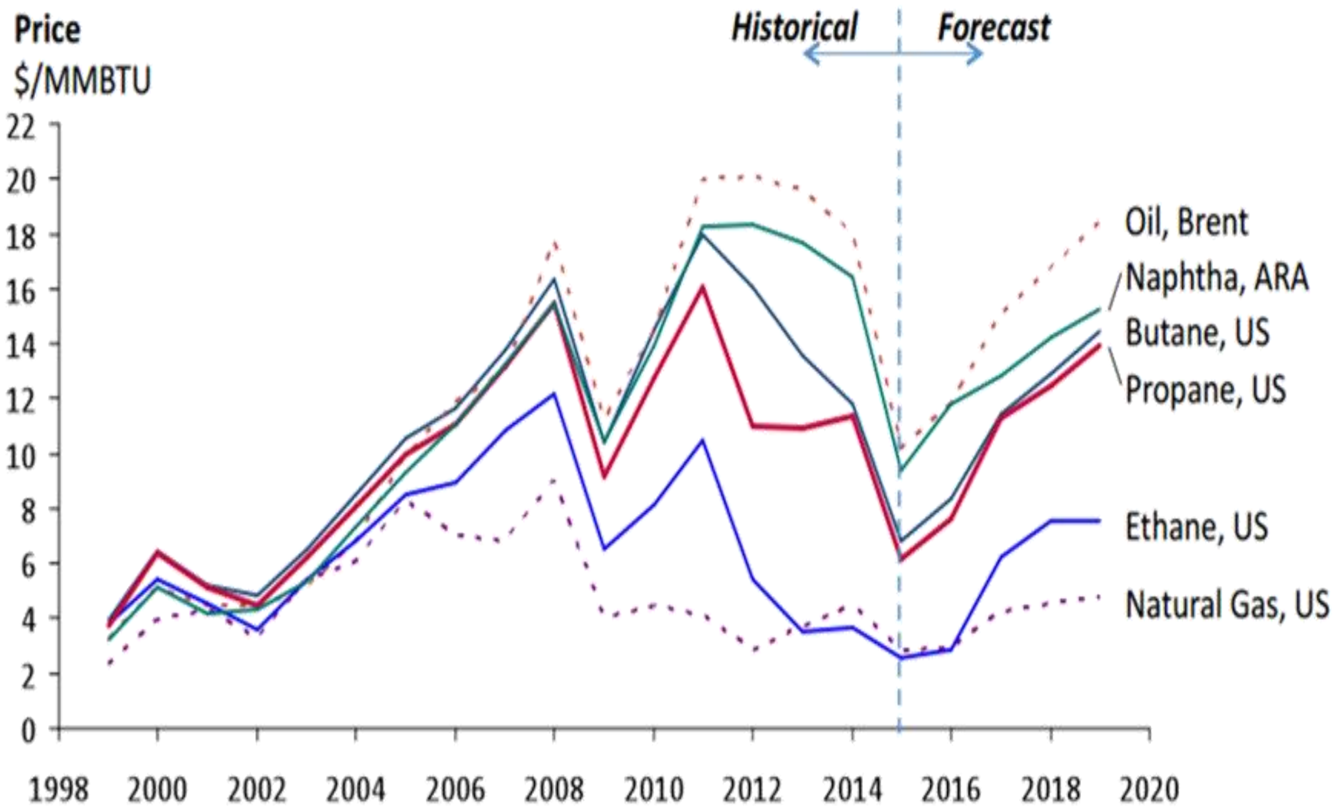
– **Power Generation**

– **LNG Exports**

– **Transportation**

– **Chemical Feedstock**

Oil-Gas Price Spread



Source: IHS energy price forecasts

Transportation movement to Natural Gas

- **Freight – Some Conversion Already Happening**
  - Rail industry pilot testing liquefied natural gas (LNG)-fueled locomotives.
  - Carriers buying long-haul trucks that run on natural gas
  - UPS converting 800 heavy 18-wheel vehicles to LNG
  - UPS has 1,000 delivery vehicles running on LPG
- Larger scale conversion contingent on price stability, logistical network development

Natural Gas and Transportation

- General Motors announces 2015 Chevy Impala will be available in a bi-fuel configuration, with a compressed natural gas (CNG) tank

- For reference:
  - Displacing 100% of gasoline and diesel in US today equivalent to roughly 85% of 2012 natural gas production

- Coupled electric power and transportation sectors?

Industry Impact - Chemicals

- **Big impacts in the southeast, but significant state-to-state variations**
  - **Manufacturing**
  - **Power Generation**
  - **LNG Exports**
  - **Transportation**
  - **Chemical Feedstock**

Natural Gas to Chemicals

- Chemicals Industry in US: $770 Billion in 2013
  - Exports - $187B, 12% of US exports*
- Low cost natural gas and natural gas liquids enable US to be low cost producer of commodity chemicals, fertilizer, etc.
- New NG-chemicals plants
  - Royal Dutch Shell - $2B plant near Pittsburgh
  - ConocoPhillips and VX - $5B plant outside Houston
  - Formosa Plastics- $1.7B on Texas gulf coast
  - Exxon Mobil - $1.3B plant

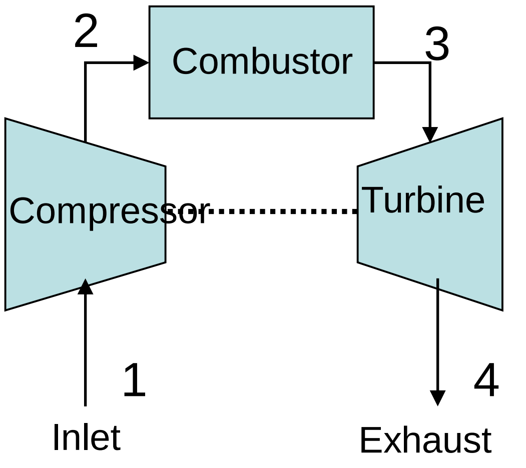
Announced and Proposed Chemical Plants

Outline

- Combustor context within larger system
- Emissions
- Operability
  - Blowoff
  - Autoignition
  - Flashback
  - Combustion Instabilities

Gas Turbine Cycle

- "Brayton Cycle"
  - Inlet » Compressor » Combustor » Turbine » Nozzle
  - Pr= Compressor Pressure Ratio



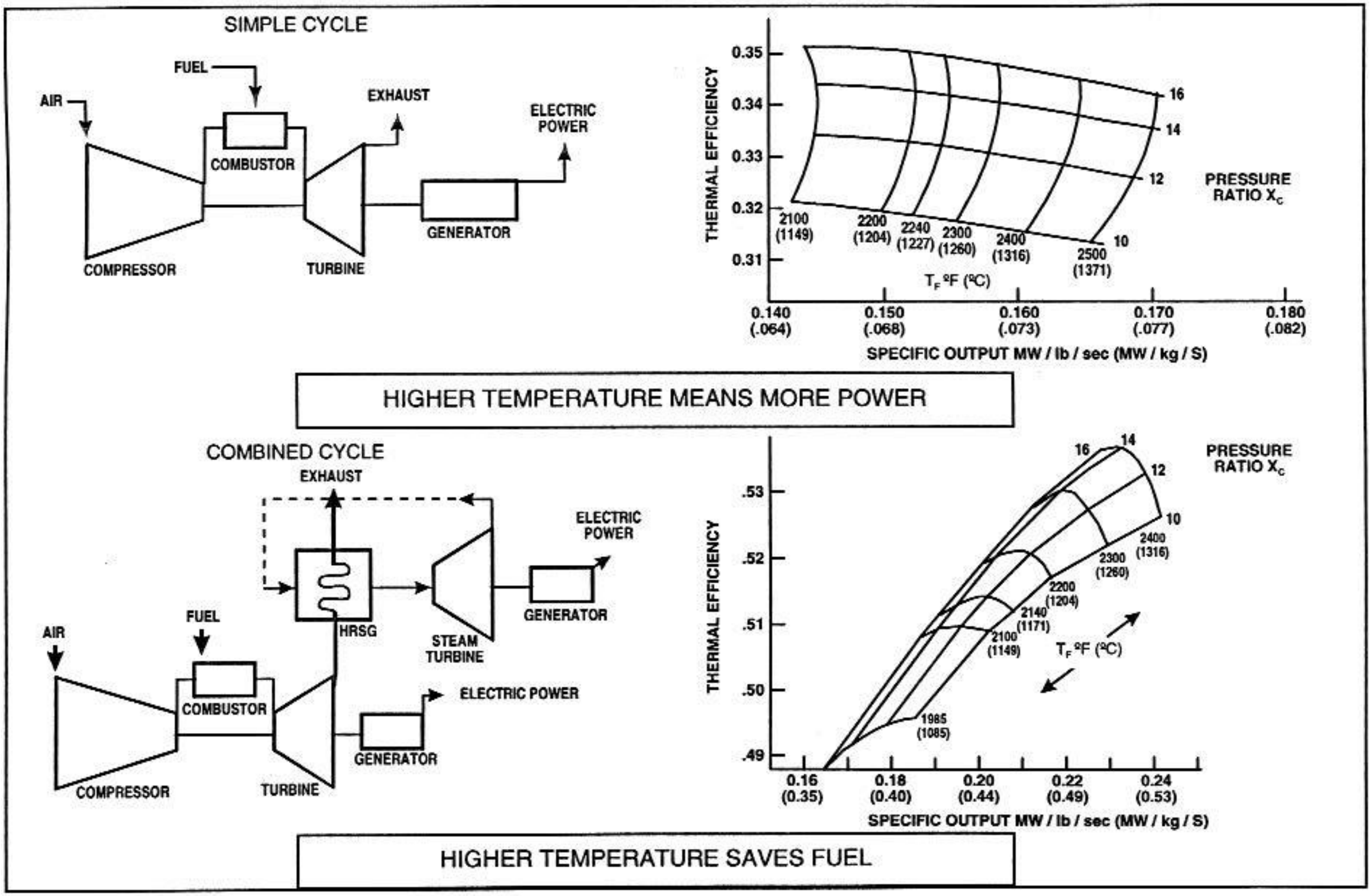
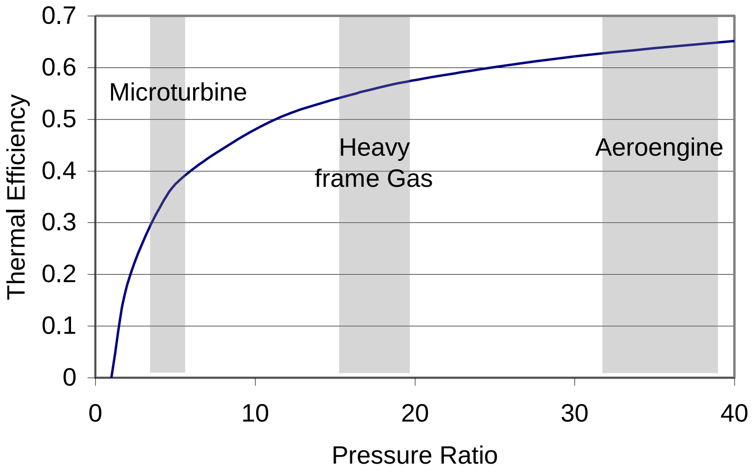


Figure 7. Gas turbine thermodynamics

Source: http://www.ge-energy.com/tools_and_training/tools/ge_reference_documents.jsp

Role of Combustor within Larger Energy System

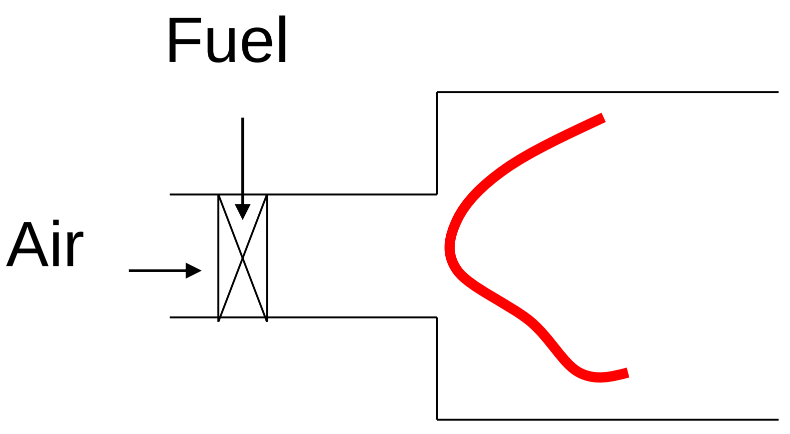
- Example: Ideal Brayton Cycle
  - $\eta_{th} = 1 - (Pr)^{-(\gamma-1)/\gamma}$
    - Pr = compressor pressure ratio
    - $\gamma = C_p/C_v$, ratio of specific heats



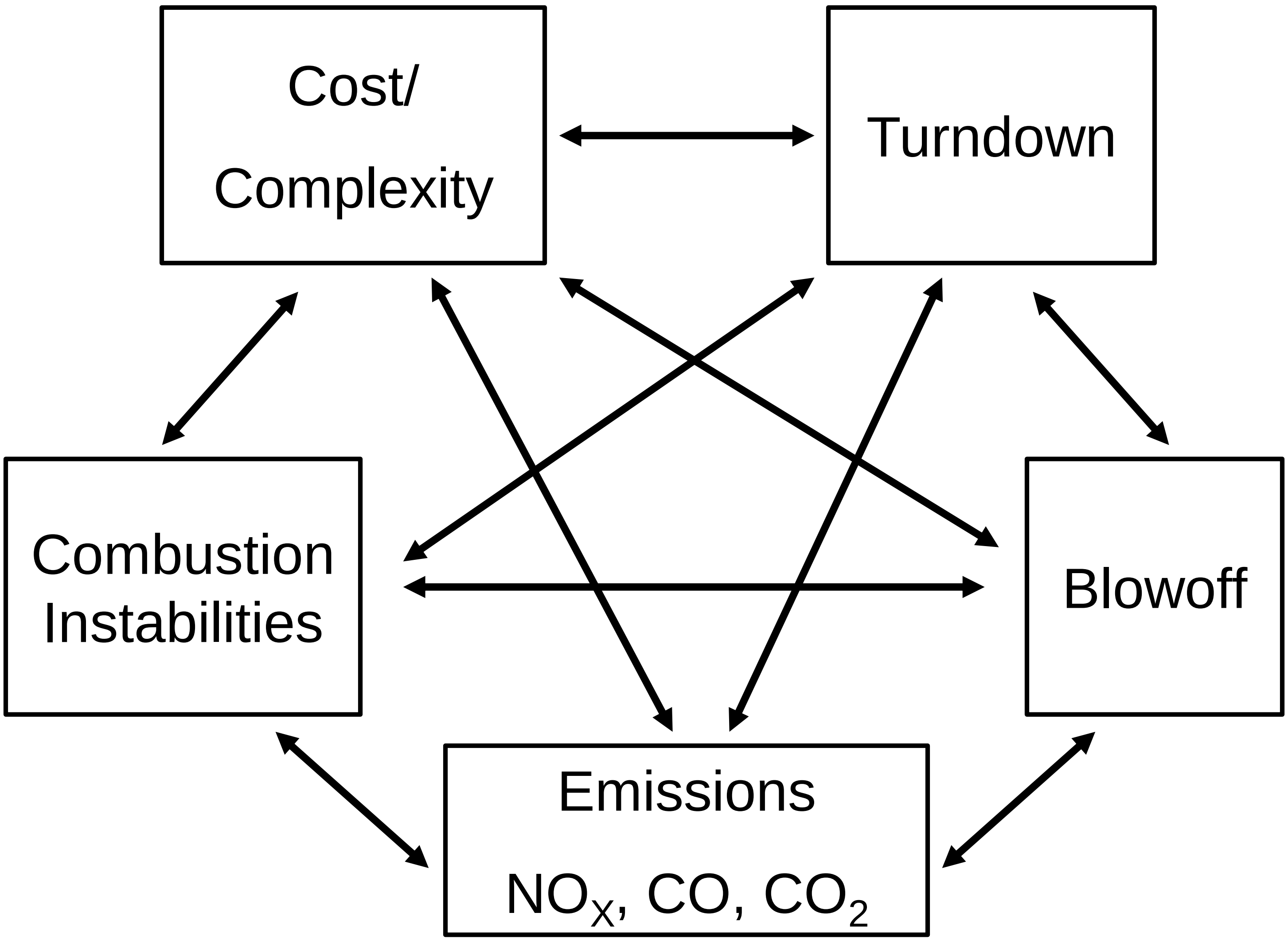
- Conclusions
  - Combustor has little effect upon cycle efficiency (e.g. fuel –> kilowatts) or specific power
  - Combustor does however have important impacts on
    - Realizability of certain cycles
      - E.g., steam addition, water addition, EGR, etc.
    - Engine operational limits and transient response
    - Emissions from plant

Combustor Performance Metrics

- What are important combustor performance parameters?
  - Burns all the fuel
  - Ignites
  - Pattern Factor
  - Operability
    - Blow out
    - Combustion instability
    - Flash back
    - Autoignition
  - Low pollutant emissions
  - Fuel flexibility
  - Good turndown
  - Transient response



Tradeoffs and Challenges



Alternative Fuel Compositions

Source of Fuel Gas	Typical Primary Constituents	Wobbe Index, BTU/scf (MJ/Nm3)	Comments
Associated Gas	20-100% CH_4, C_2H_6, C_3H_8, C_4+, CO_2	900–1600 (33.5–59.7)	Gas recovered during crude oil extraction. Significant variation in composition by reservoir.
Raw Natural Gas (Wellhead Gas)	CH_4, C_2H_6, C_3H_8, C_4+, CO_2	500–1350 (18.6–50.4)	Natural gas extracted from dry or wet reserves. Dry gas is primarily methane, ethane and propane. Wet reserves contain liquid hydrocarbon condensates including C5+. Significant variation in composition by reservoir.
Pipeline Quality Natural Gas	CH_4, C_2H_6, C_3H_8, CO_2, N_2	1085 – 1296 (40.5 – 48.3)	Natural gas with sufficient energy content, generally above 900 Btu/scf, for transport through commercial gas pipelines and sale to end-users.
LNG (Liquefied Natural Gas)	CH_4, C_2H_6, C_3H_8, CO_2, N_2	1100 – 1340 (41.0 – 49.9)	Natural gas processed to a liquid state. Produced by refrigerating treated natural gas to below -259°F and 1 atmosphere. LNG regasified and incorporated into pipeline.
NGL (Natural Gas Liquid)	C_2H_6, C_3H_8, C_4H_{10}, C_5+, and mixture	1600 – 1930 (59.6 –71.9)	Hydrocarbons heavier than methane recovered from raw natural gas in processing plants
LPG (Liquefied Petroleum Gas)	C_3H_8, C_4H_{10}, and mixture	1870 – 2125 (69.7 – 79.1)	Gaseous hydrocarbons generated from the refinery processes, crude oil stabilization plants.
Refinery Gas	40-60% H_2, CH_4, C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	1050-1250 (39.1 – 46.6)	Gas produced during crude oil refining.
Landfill	35-55% CH_4 CO_2, N_2	220 - 800 (8.2 – 29.8)	Gas produced when organic material decomposes in a landfill.
Digester	50-67% CH_4, CO_2, N_2	500 - 600 (18.6 – 22.3)	Anaerobic digester gas produced from farm waste, municipal waste, or from wastewater treatment plants.
Gasified Biomass	15-45% H_2, CH_4, CO, CO_2, N_2, H_2S	200 - 500 (7.4 – 18.6)	Gas derived from solid waste including metropolitan waste, wood, agriculture, food, tires, etc.
Coal Mine Methane	40-60% CH_4, N_2, O_2, CO_2	400 – 625 (14.9 – 23.3)	Methane trapped in coal seams mixed with air.
Coal Bed Methane	94-98% CH_4, CO_2	1070 – 1180 (39.9 – 44.0)	High methane concentration gas in coal seams. Sometimes called GOB gas.
Gasified Coal – Oxy Blown	30-45% H_2, CO, CO_2, CH_4	200 – 570 (7.4 – 21.2)	Coal derived gaseous products from oxygen-blown coal gasification.
Coke Oven Gas	45-60% H_2, CH_4, CO, N_2, CO_2, O_2, C_2+	650 - 850 (24.2 – 31.7)	Byproduct gas from the manufacture of coke used in the steel production process.

Source: L. Witherspoon and A. Pocengal, Power Engineering October 2008

Useful Fuel Grouping

- Higher Hydrocarbons
  - C_2H_6 - ethane
  - C_3H_8 – propane
  - C_4H_{10}, ….
  - $C_{10}H_{22}$ (decane, large constituent of jet fuel)
  - $C_{12}H_{26}$ (dodecane – large constituent of diesel fuel)

  } autoignition, combustion instabilities, NO_2 emissions

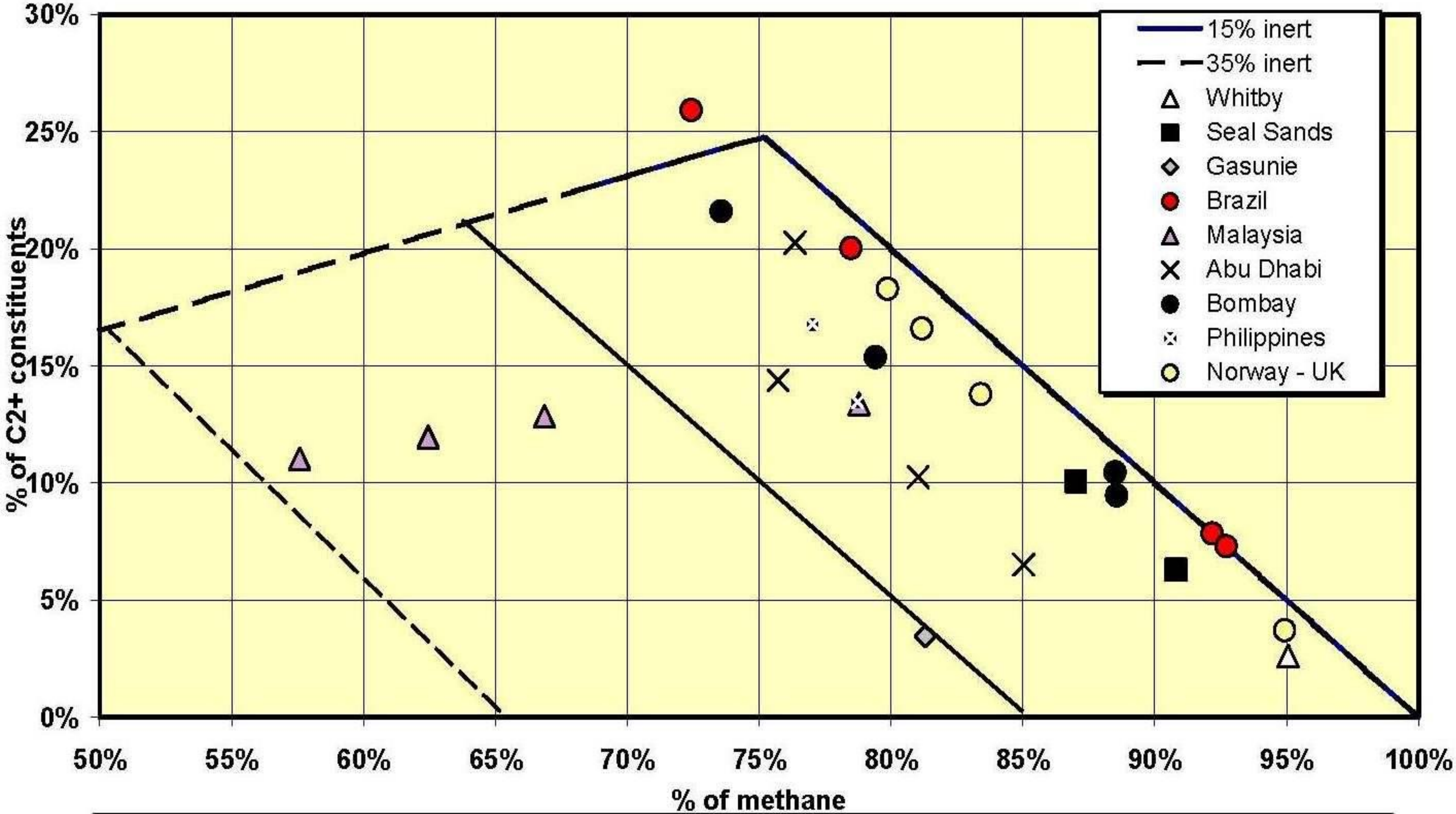
- H_2 content

  } flashback, combustion instabilities

- "Inerts"
  - N_2 - Nitrogen
  - CO_2 – Carbon Dioxide
  - H_20 – Water

  } blowoff, CO emissions, combustion instabilities

Natural Gas Composition Variability



Source: C. Carson, Rolls Royce Canada

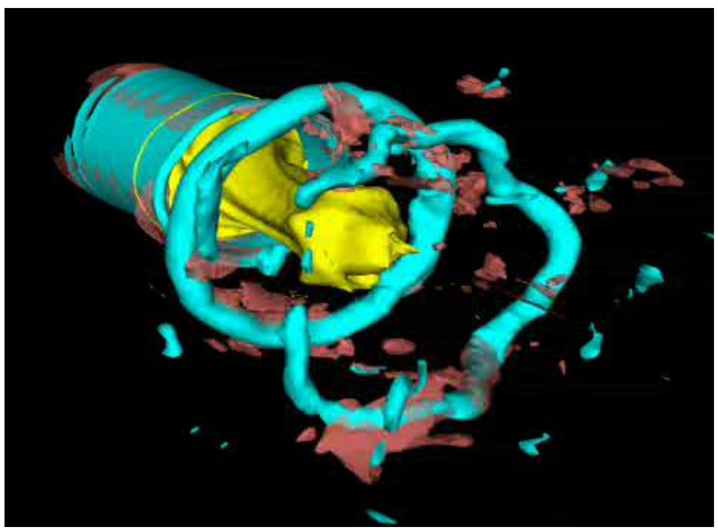
Operability issues have caused significant problems in deployment of low NO_X technologies

- Power
  - Example: Broken part replacement significant non-fuel related cost for gas turbines
- Industrial
- Residential
  - Example: issues in EU with deployment of low NO_X water heaters, burners

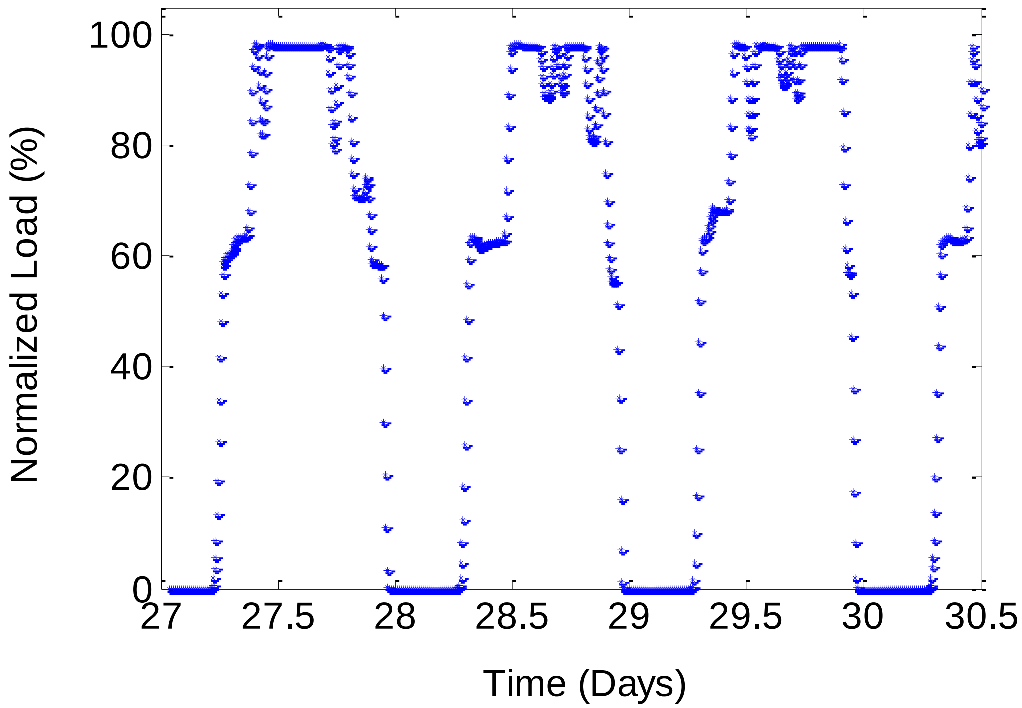
Goy *et al.*, in *Combustion instabilities in gas turbine engines: operational experience, fundamental mechanisms, and modeling*, T. Lieuwen and V. Yang, Editors. 2005. p. 163-175.

Combustion Instabilities

- Single largest issue associated with development of low NO_X GT's
- Designs make systems susceptible to large amplitude acoustic pulsations

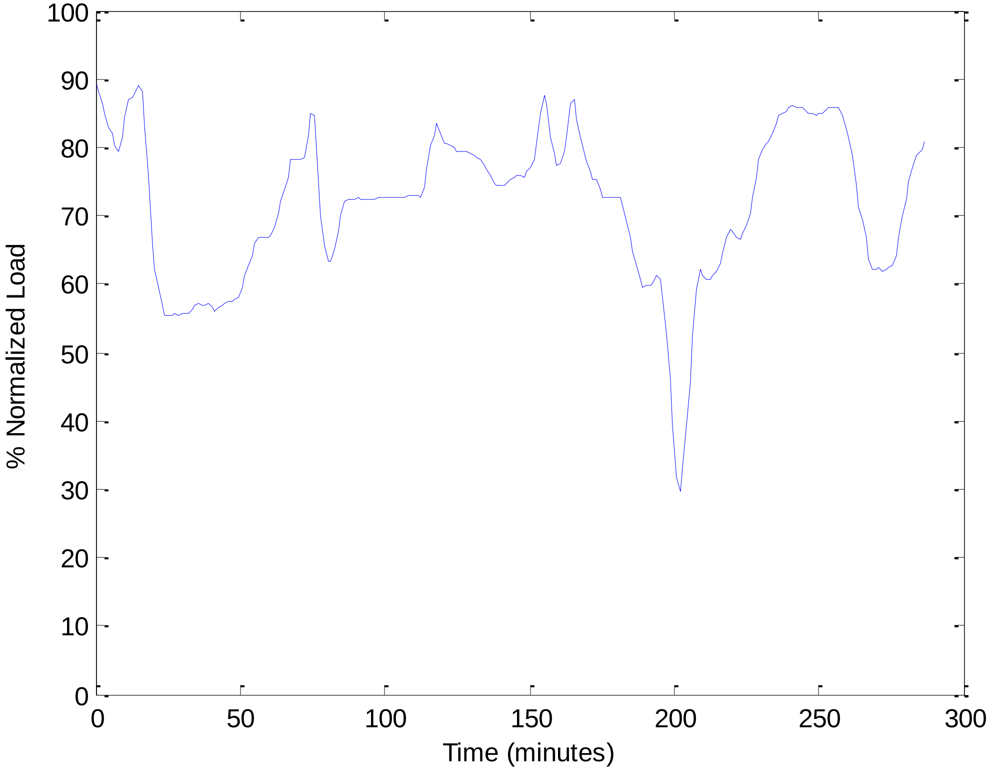


Turndown



- Operational flexibility has been substantially crimped in low NO_X technologies
- Significant number of combined cycle plants being cycled on and off daily

Transient Response Needs



- Locations with high penetration of wind and photovoltaic solar are seeing significant transient response needs
- Avoiding blowoff and flashback are key issues

Blowoff

- Low NO_X designs make flame stabilization more problematic

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Industry Advisory
June 26, 2008

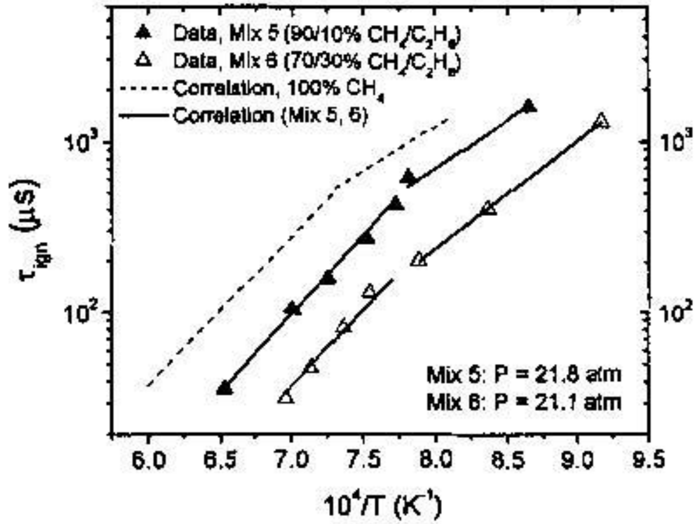
Background:

On Tuesday February 26th, 2008, the FRCC Bulk Power System experienced a system disturbance initiated by a138 kV transmission system fault that remained on the system for approximately 1.7 seconds. The fault and subsequent delayed clearing led to the loss of approximately 2,300 MW of load concentrated in South Florida along with the loss of approximately 4,300 MW of generation within the Region. Approximately 2,200 MW of under-frequency load shedding subsequently operated and was scattered across the peninsular part of Florida.

Indications are that six combustion turbine (CT) generators within the Region that were operating in a lean-burn mode (used for reducing emissions) tripped offline as result of a phenomenon known as “turbine combustor lean blowout.” As the CT generators accelerated in response to the frequency excursion, the direct-coupled turbine compressors forced more air into their associated combustion chambers at the same time as the governor speed control function reduced fuel input in response to the increase in speed. This resulted in what is known as a CT “blowout,” or loss of flame, causing the units to trip offline.

Autoignition

- Liquid fuels
- Higher hydrocarbons in natural gas
- Poor control of dewpoint



Images:

- B. Igoe, Siemens
- Petersen et. al. “Ignition of Methane Based Fuel Blends at Gas Turbine Pressures”, ASME 2005-68517

COMBUSTION BASICS

Stoichiometry

- Stoichiometric quantity of oxidizer is amount required to completely burn a quantity of fuel
- **Fuel-oxidizer ratio**, ***f***
  - sometimes **mass** fuel/mass oxidizer
  - or **moles** fuel/moles oxidizer
  - **Equivalence ratio** ϕ (or Φ) = $f_{actual}/f_{stoichiometric}$
    - $\phi = 1$; **stoichiometric**
      - just enough oxidizer to **completely consume** fuel
    - $\phi < 1$; **fuel lean** (excess ox.)
    - $\phi > 1$; **fuel rich** (excess fuel)

Adiabatic Flame Temperature

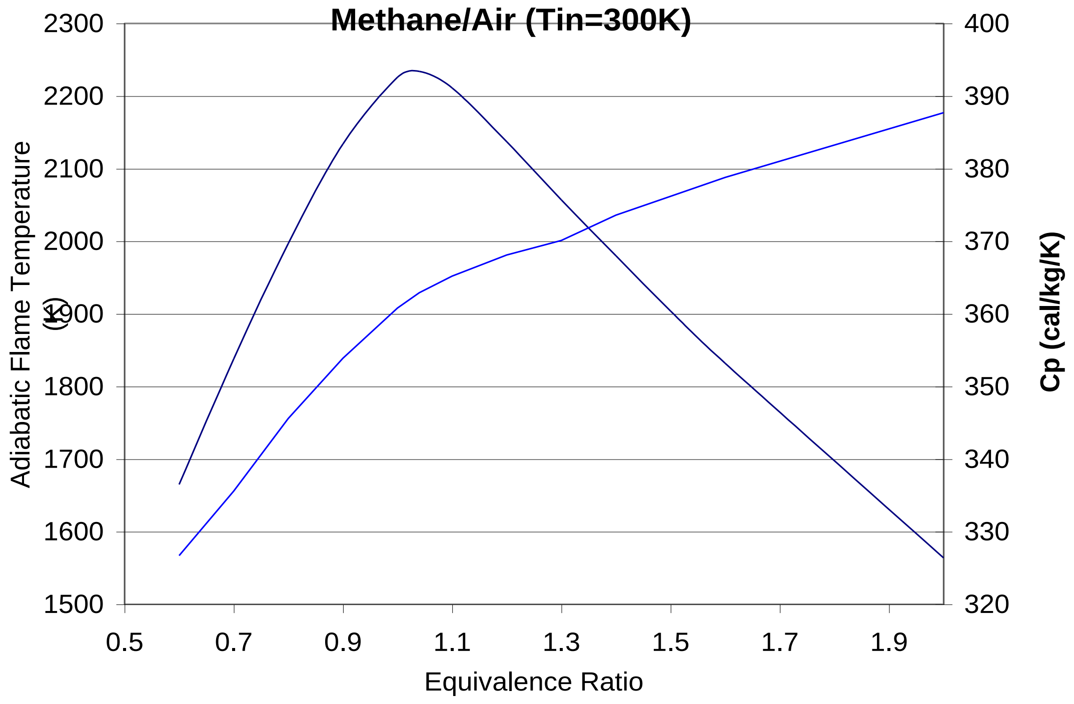
- Equilibrium temperature that would be achieved if reactants were
  converted to equilibrium products at constant pressure without heat addition or loss
  - **Adiabatic Flame Temperature (T_{ad})**

Typical Stoichiometric T_{ad}

• Methane	=	2226 K
• Acetylene	=	2539 K
• Propane	=	2267 K
• Hydrogen	=	2390 K
• Carbon Monoxide	=	2275 K

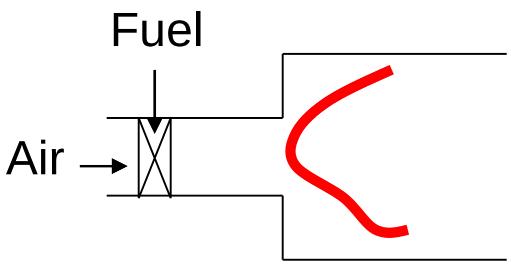
Summary on Flame Temperature

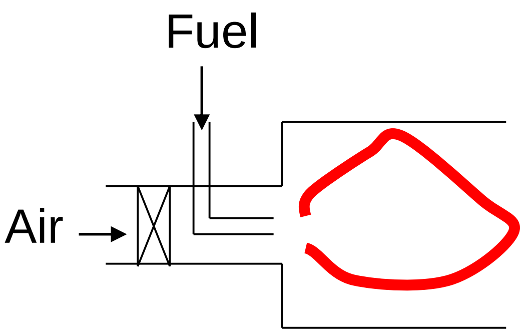
- Primarily depends upon fuel/air ratio and compressor discharge temperature
- Peaks near ϕ=1
  - No nonreacting fuel or air mass to heat up



Premixed vs Non-Premixed Flames

- Premixed flames
  - Fuel and air premixed ahead of flame
  - Mixture stoichiometry at flame can be controlled
  - Method used in low NOx gas turbines (DLN systems)
- Non-premixed flames
  - Fuel and air separately introduced into combustor
  - Mixture burns at ϕ=1
    - i.e., stoichiometry cannot be controlled
    - Hot flame, produces lots of NOx and more sooting
    - More robust, higher turndown, simpler





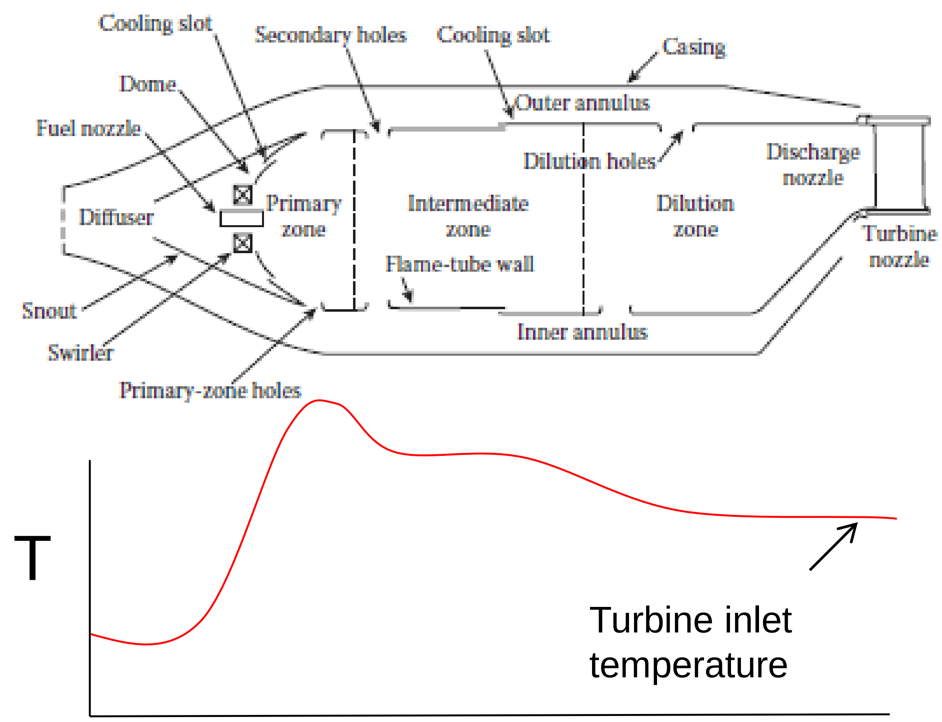
COMBUSTOR ARCHITECTURES

Main combustor components

- Diffuser to slow compressor discharge air velocity
- Liner and turbine component transition section
- Means for supplying the combustion zone with fuel
- Cross-fire tubes to light adjacent combustors in can combustion systems
- Ignitor

Conventional Diffusion/Non-Premixed Flame Combustor

- Global fuel/air ratio controlled by turbine inlet temperature requirements
- Staging used to achieve turndown and stable flame
  - Air is axially staged in this image
  - Nonpremixed flame in "primary zone"



Can Combustion Layout

- Needs cross-fire tubes
- Useful testing can be done with limited air supplies

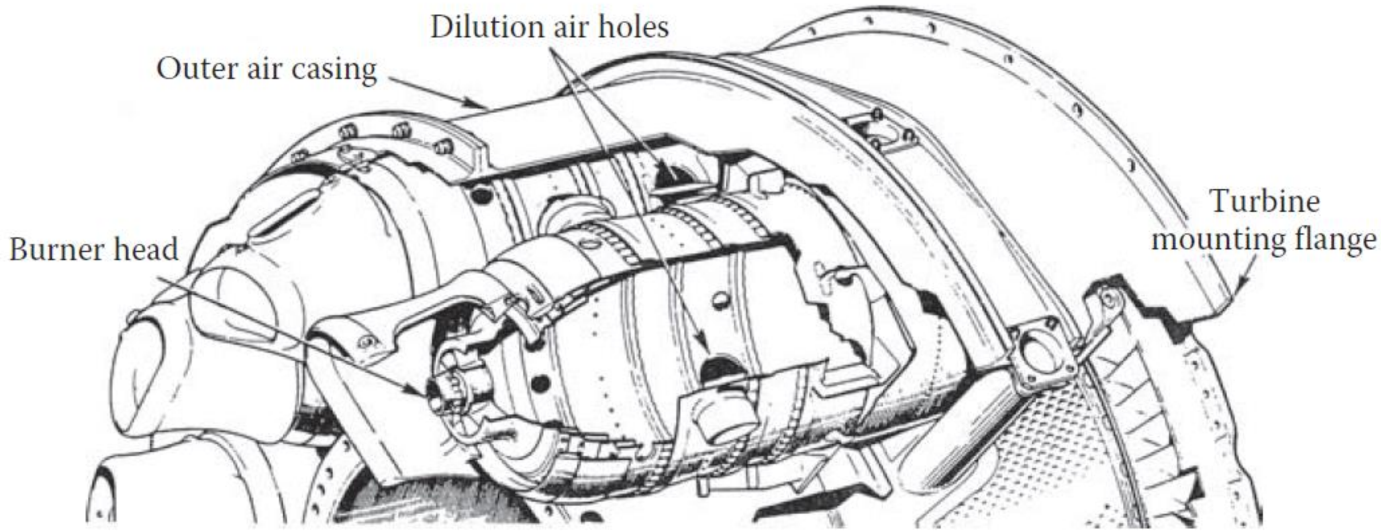


FIGURE 1.11
Tuboannular combustor arrangement. (Courtesy of Rolls Royce plc.)

Annular Combustor Layout

- Aircraft engines
- Aero-derivatives
- Siemens V-series
- Alstom GT24

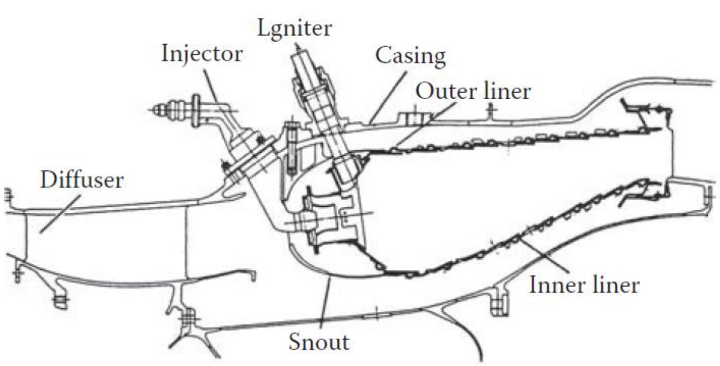
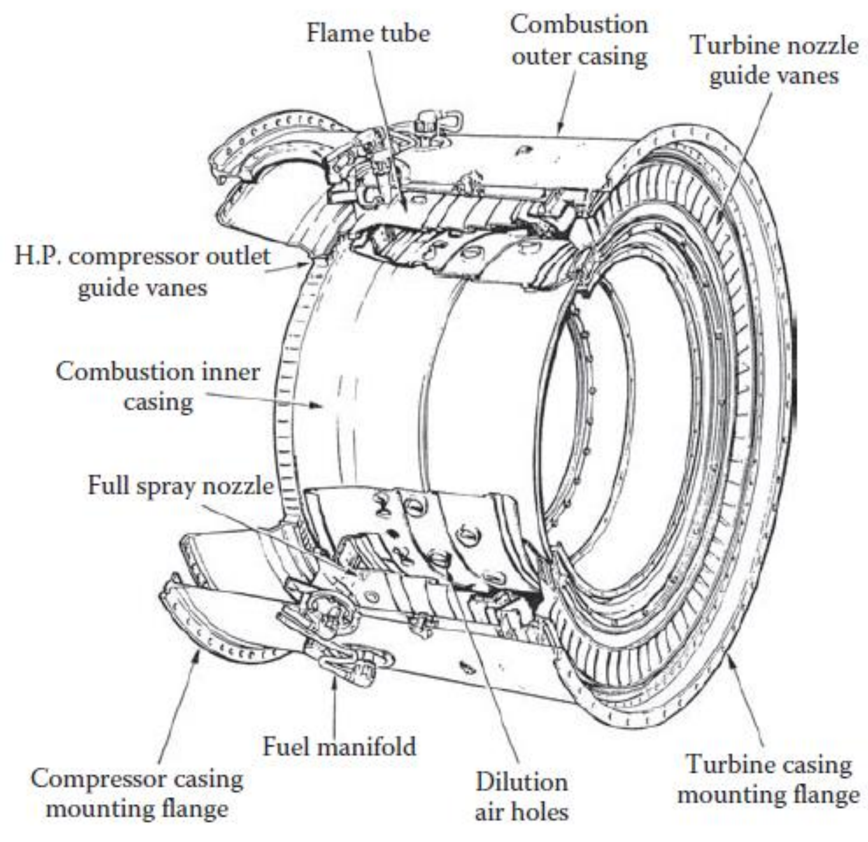


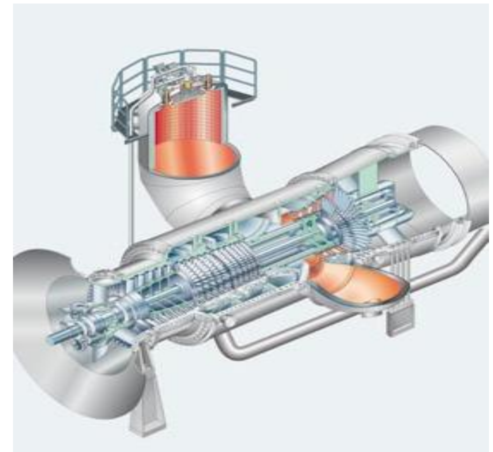
FIGURE 1.12
CF6-50 annular combustor.

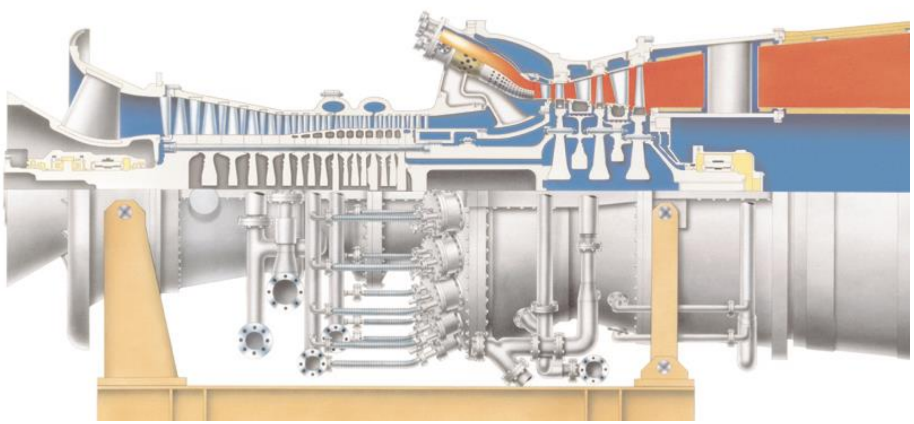


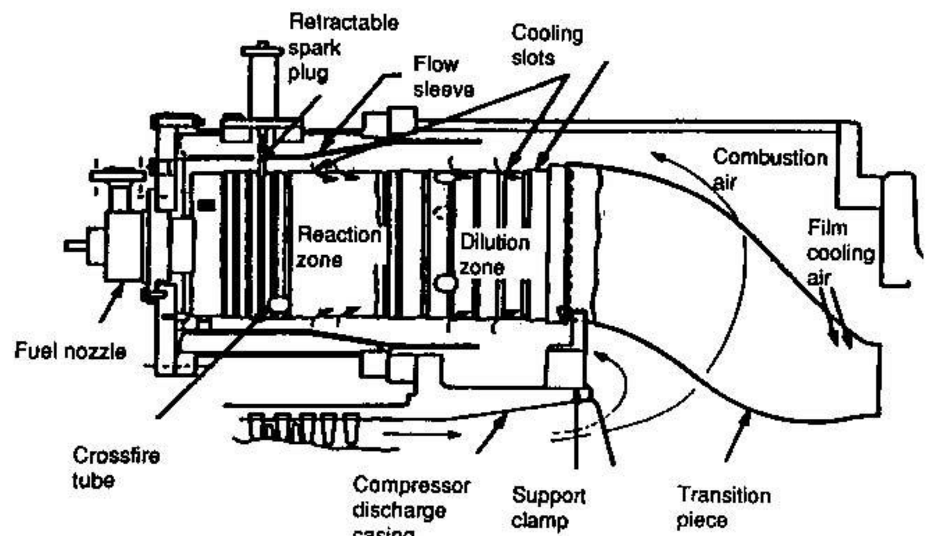
JRE 1.13
l1 annular combustor. (Courtesy of Rolls Royce plc.)

Frame Engine Layouts

- Can combustors set up for access without requiring engine dissembly
- Silo combustors







Aero-Derivative Combustors

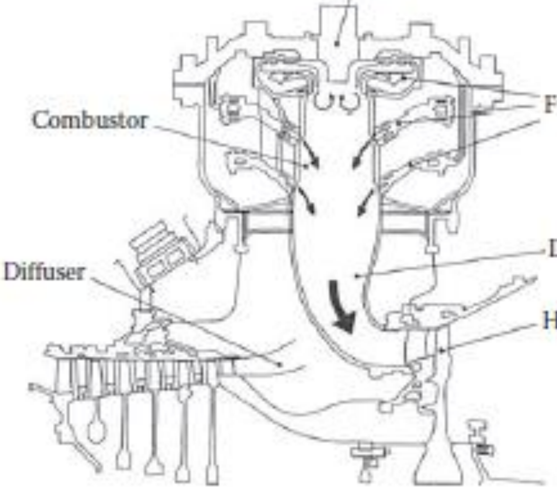


FIGURE 1.26
Industrial Trent DLE combustor. (Courtesy of Rolls Royce plc.)

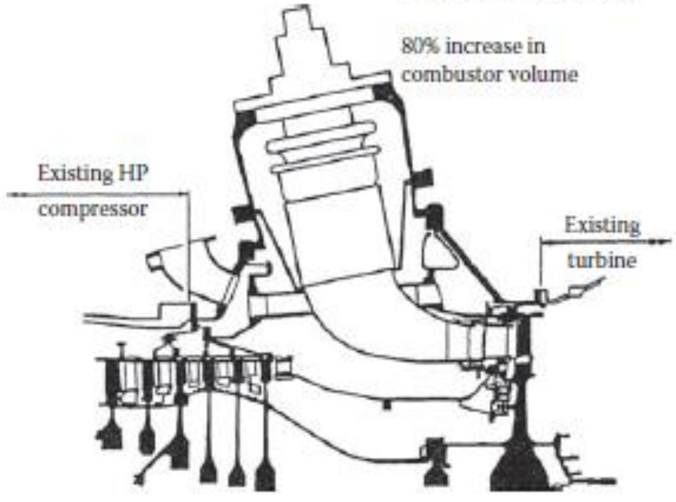
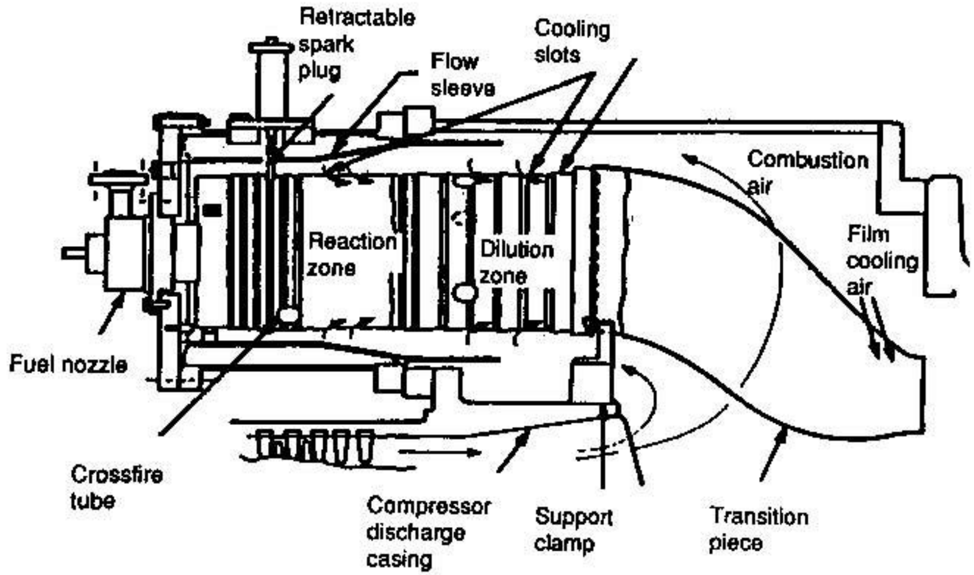


FIGURE 1.25
Industrial RB211 DLE combustor. (Courtesy of Rolls Royce plc.)

Combustor Configurations Nonpremixed

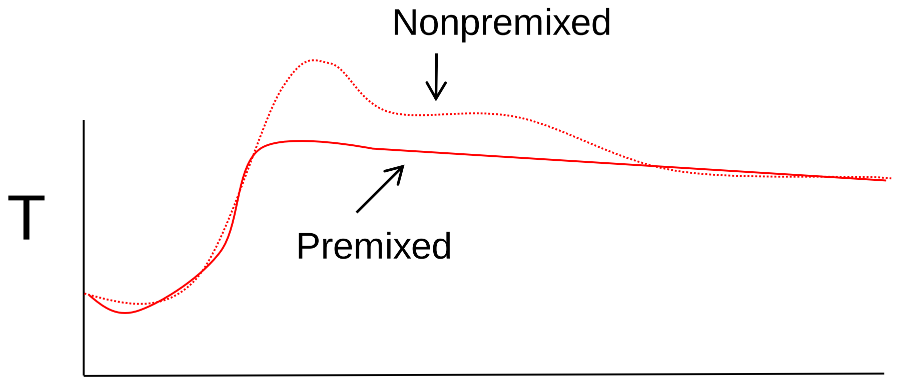
- Water/steam injection used for NOx control



Source: A. Lefebvre, "Gas Turbine Combustion"

Combustor Configurations
Dry, Low NOx (DLN) Systems

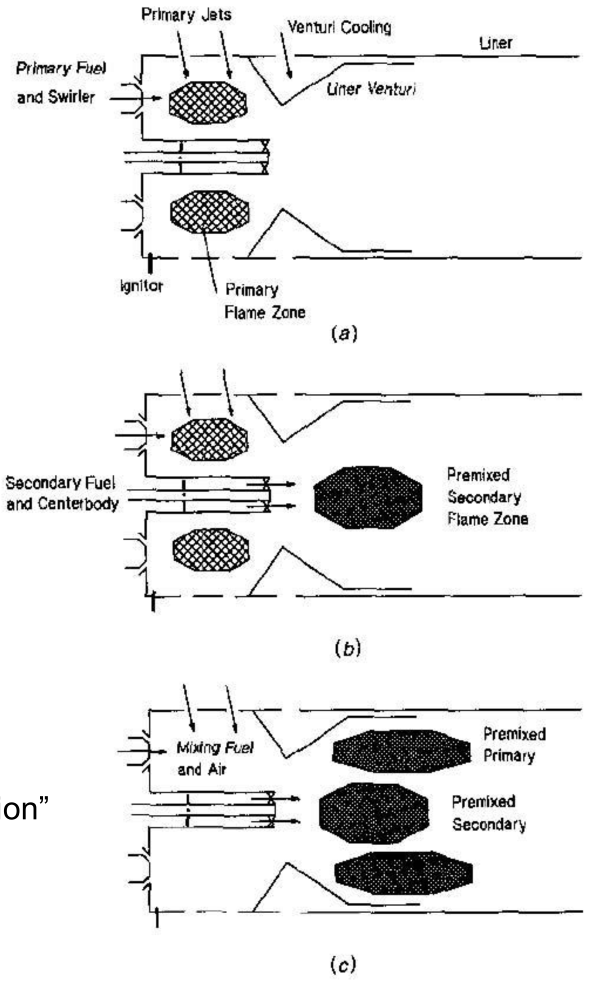
- Premixed operation
  - If liquid fueled, must prevaporize fuel (lean, premixed, prevaporized, LPP)
- Almost all air goes through front end of combustor for fuel lean operation – little available for cooling
- Multiple nozzles required for turndown



Source: A. Lefebvre, “Gas Turbine Combustion”

Combustor Configurations
Dry, Low NOx (DLN) Systems

- More complicated staging schemes required for turndown



Source: A. Lefebvre, "Gas Turbine Combustion"

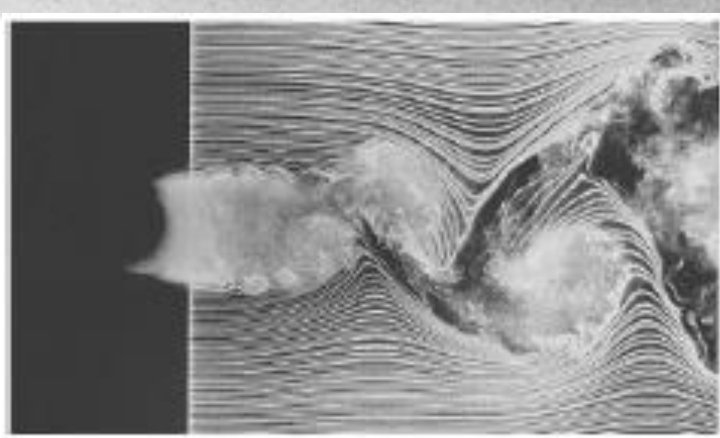
COMBUSTOR AERODYNAMICS

Canonical Aerodynamic Problems

- Swirl flow and vortex breakdown
- Bluff body flows
- Jets in Cross Flow
- Cavity Flows

Flow Unsteadiness

- Instantaneous and time averaged flow structure can differ significantly



References: Brown and Roshko, JFM, 1974; Prasad and Williamson, JFM, 1997; Crow and Champagne, JFM, 1971

Swirling jets

- The presence of swirl, i.e., azimuthal rotation, in the flow fundamentally changes both the time averaged and unsteady character of the flow
- The ratio of angular to axial velocity or momentum is a key control parameter dividing different types of flow behavior
- Define swirl number, *S*, as the ratio of axial to tangential momentum flux, S_m, or an azimuthal to axial velocity, S_v
- This momentum flux definition of swirl number is given by

where a is the radius

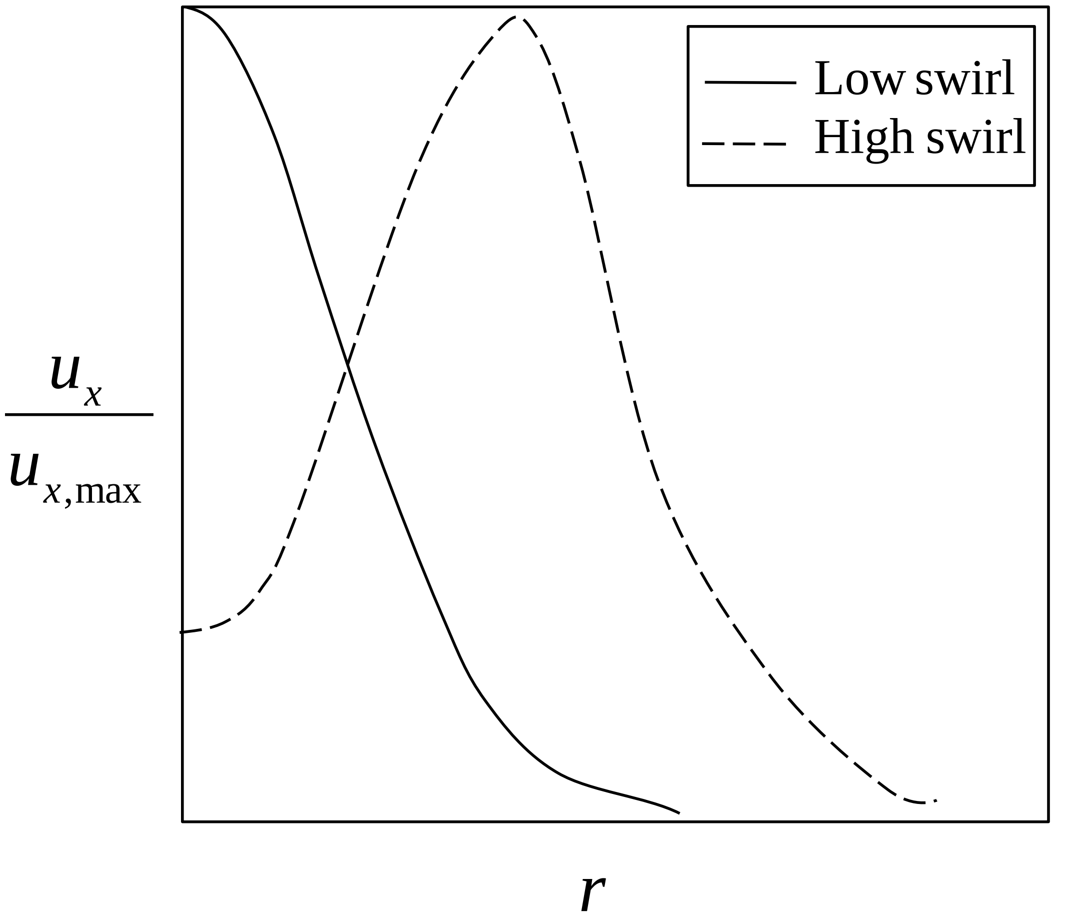
$$S_m = \frac{\int_0^\infty \rho u_z u_\theta r^2 dr}{a\int_0^\infty \rho u_z^2 r dr}$$

Swirling Jets

(a) Siemens

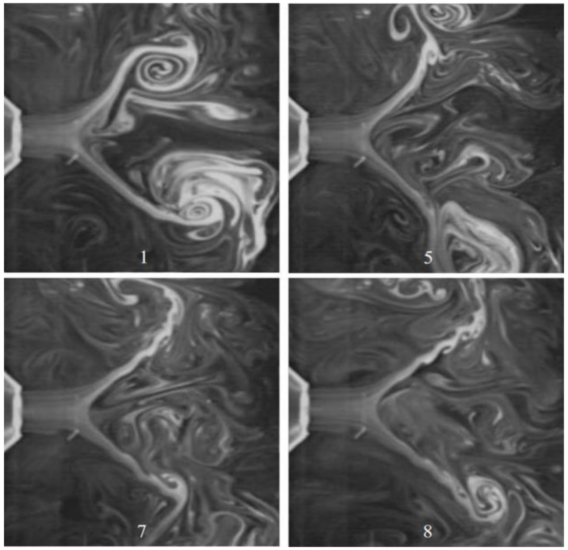
(b) GE DLN-1

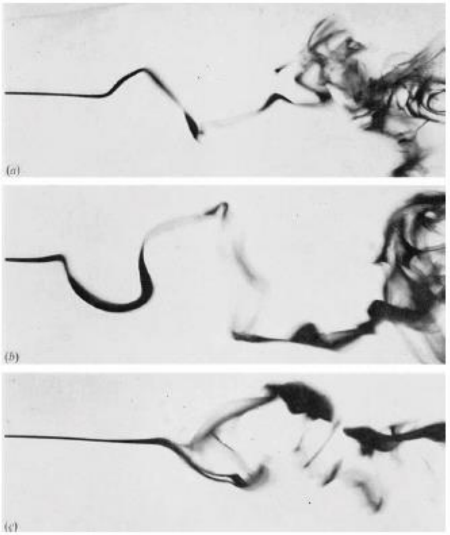
Flow Profiles

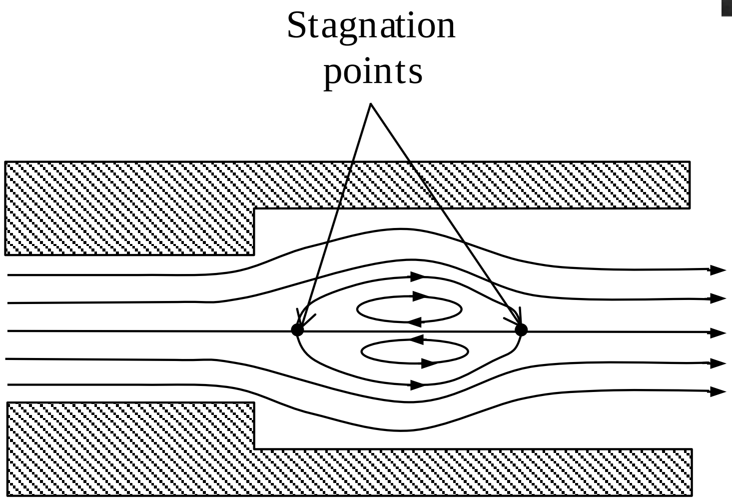


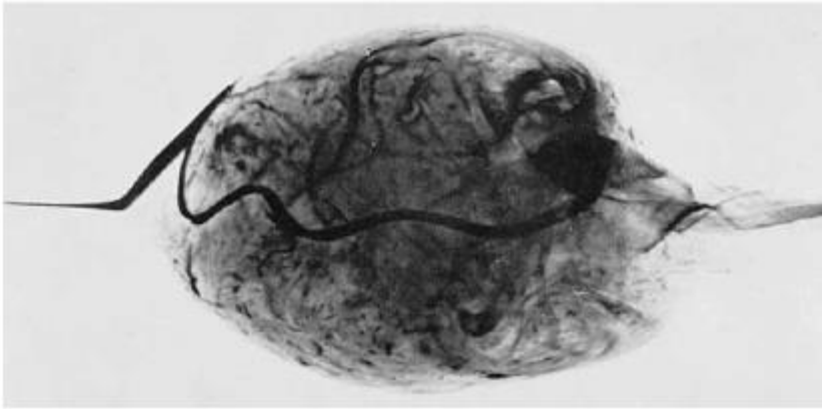
Flow Stability and Vortex Breakdown

- The degree of swirl in the flow, *S*, has profound influences on the flow structure
- Most prominent feature of high swirl number flows is the occurrence of "vortex breakdown", which is manifested as a stagnation point followed by reverse flow





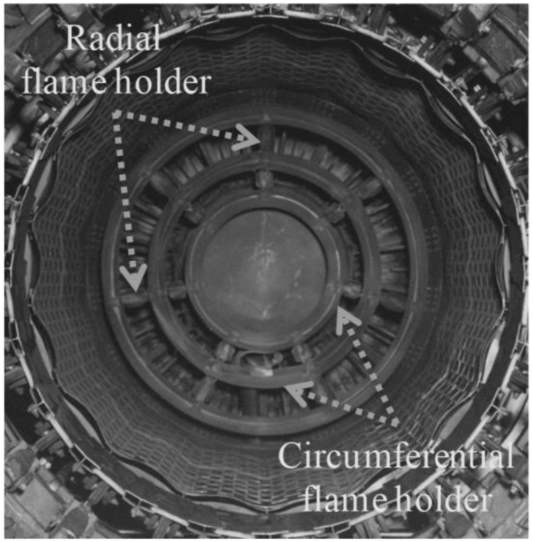


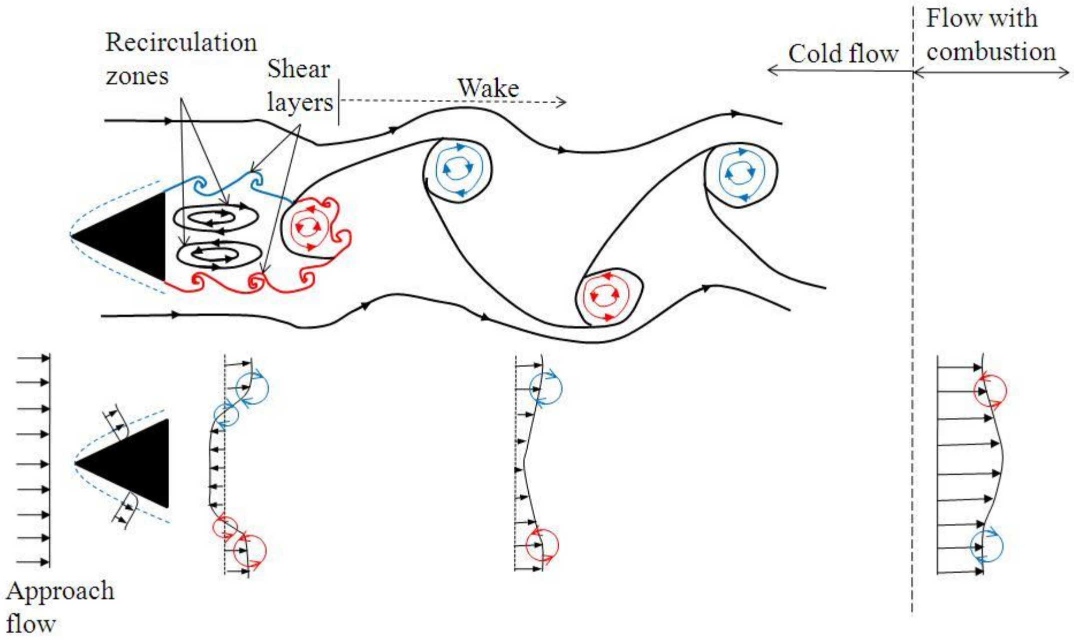


Billant et al., JFM, 1998
Sarpkaya, JFM, 1971

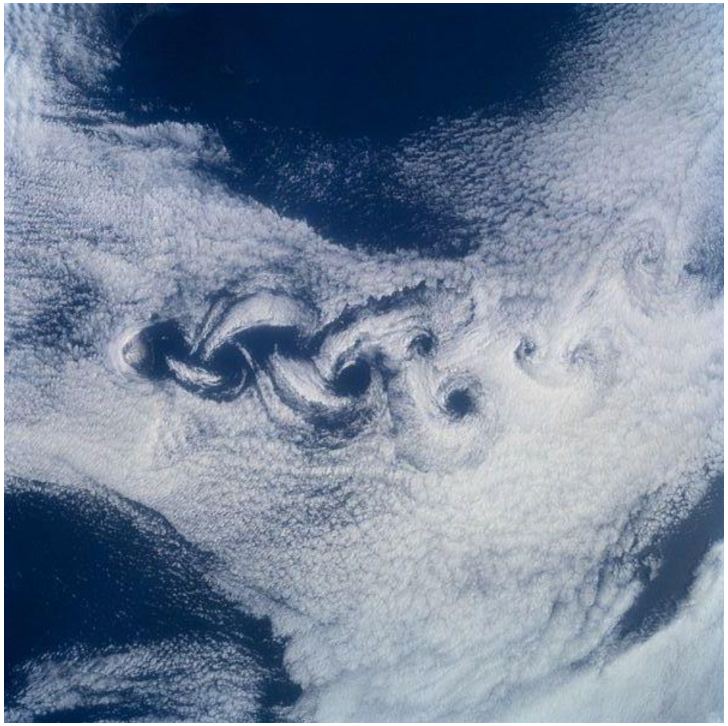
Wakes and Bluff body Flow fields

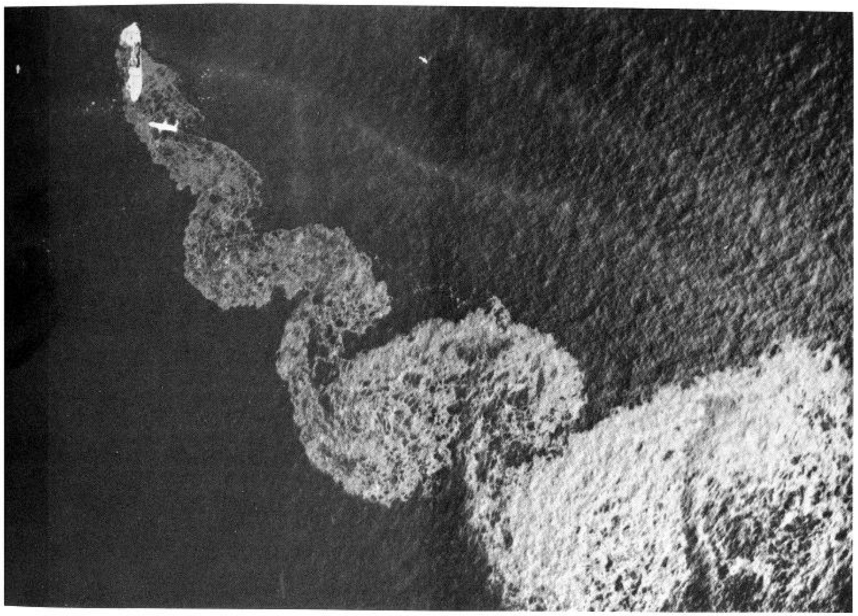
- Bluff bodies are routinely used in combustor applications as flame holders.





Wakes on a larger Scale





Van Dyke, *Album of Fluid Motion*

Wake Structure

- The shear layer forms the boundaries of the near wake separation bubble, consisting of recirculating flow that is at a low pressure relative to the free stream
  - The separation bubble ends where the shear-layers merge

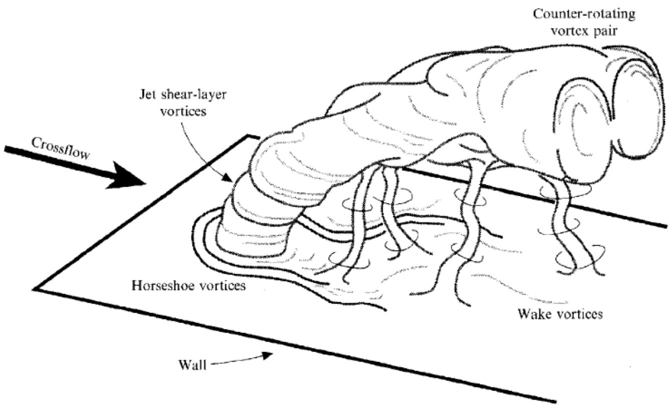
Prasad and Williamson, JFM, 1997

Jets in Cross Flow

- Correlation for the jet trajectory, based upon either jet velocity or concentration

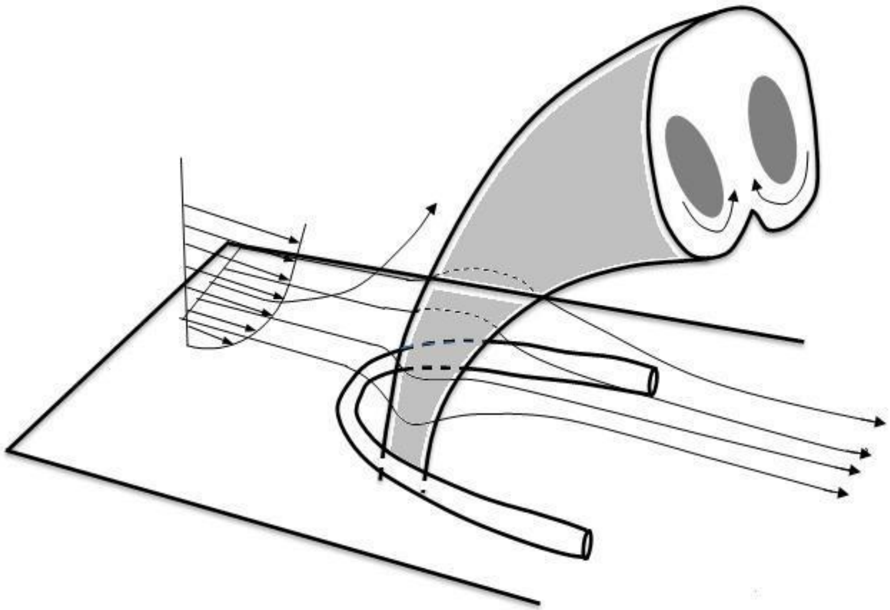
$$\frac{y}{D\sqrt{\frac{\rho_j u_j^2}{\rho_0 u_0^2}}} = A\left(\frac{x}{D\sqrt{\frac{\rho_j u_j^2}{\rho_0 u_0^2}}}\right)^B$$

- Coefficients vary between the ranges 1.2<A <2.6 and 0.28<B <0.34



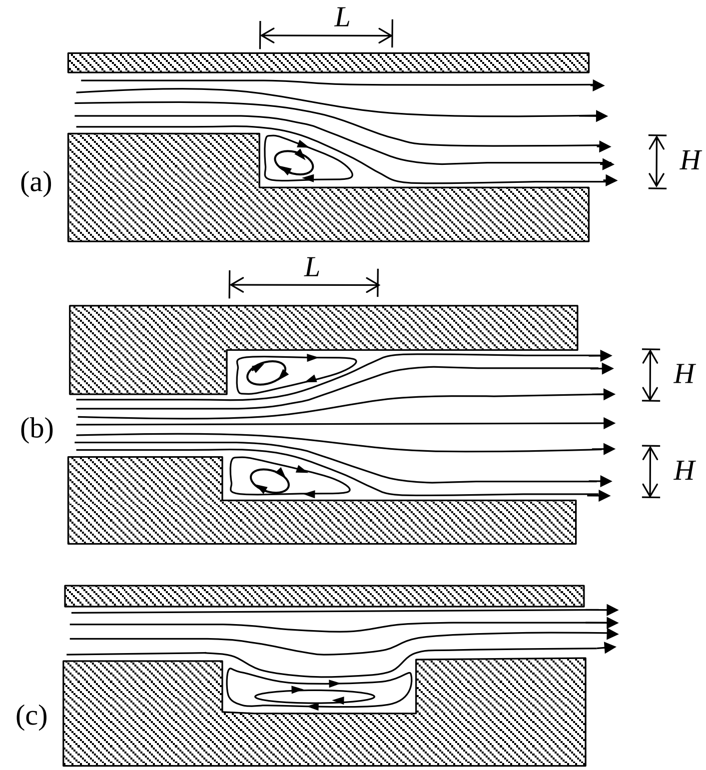
Jets in Cross Flow

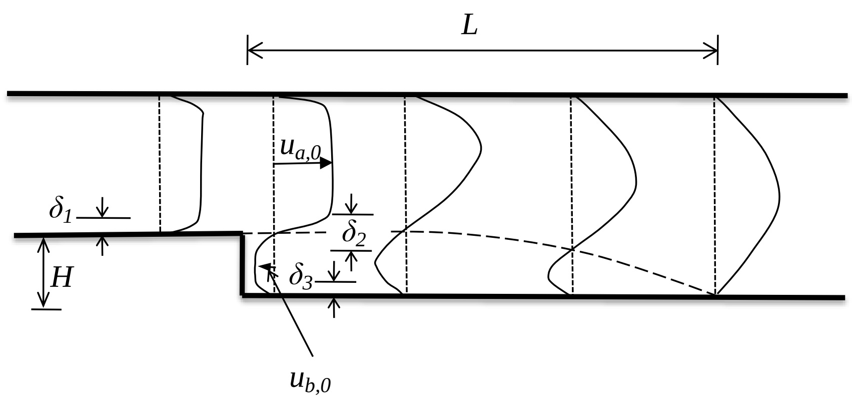
- Figure shows how the jet cross section is distorted from an initially circular to a “kidney” or “horseshoe” shape with a counter-rotating vortex pair
- This vortex flow stems from a complex re-orientation of the vorticity at the axisymmetric jet exit
- This counter rotating vortex pair plays an important role in jet-free stream mixing; indeed the jet velocity and concentration profiles decay faster than in free jets



Backward Facing Steps and Cavities

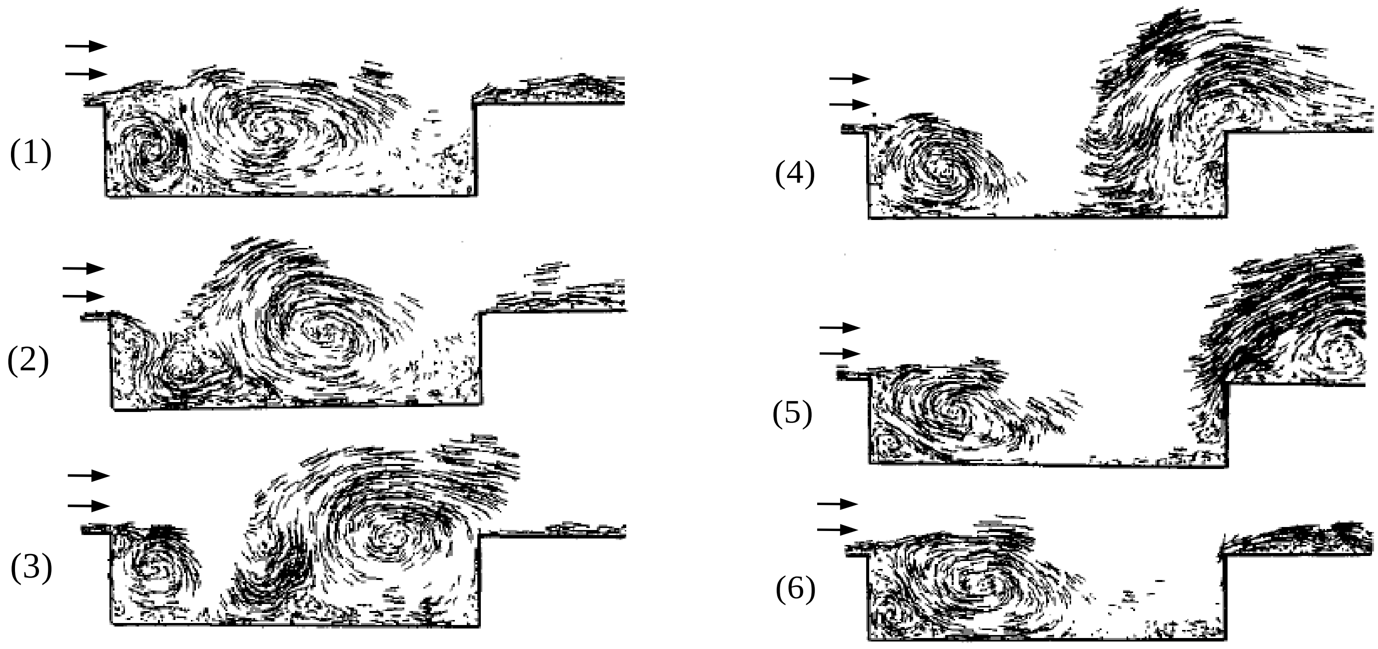
- Backward facing step and cavity configurations routinely used in combustion systems for flame stabilization because of the forced flow separation and flow recirculation





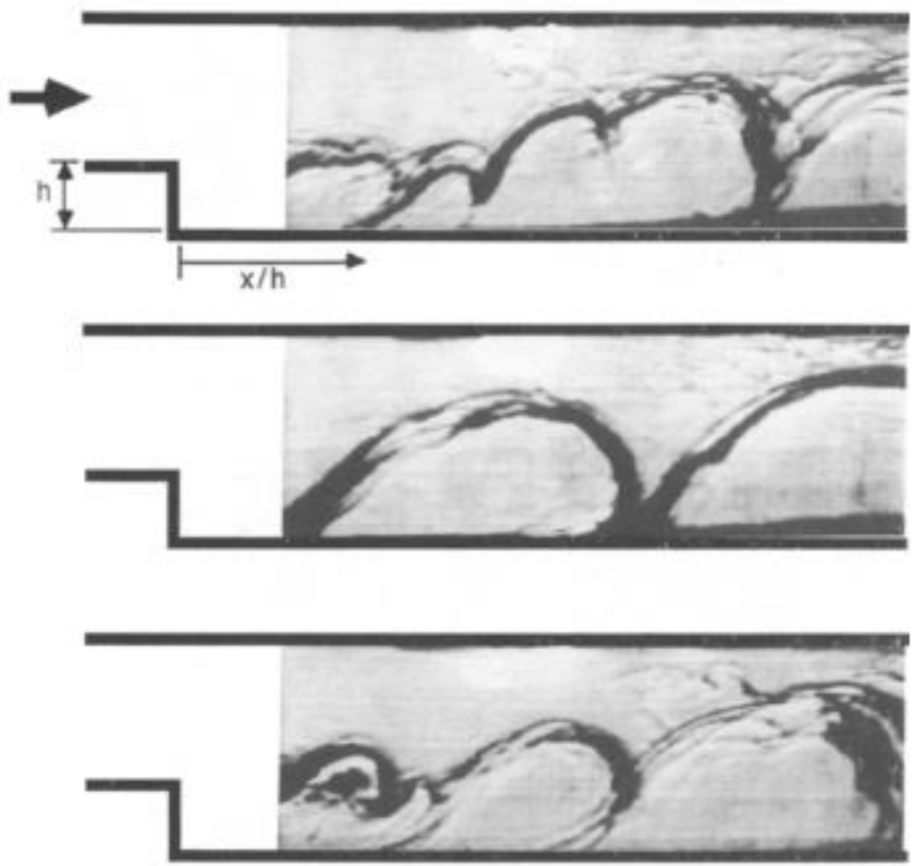
Flow Stability

- The recirculating flow behind the backward facing step or cavity also periodically detaches and convects downstream



Vortex element visualization of non-reacting *L/H*=4 cavity flow, showing downstream convection of recirculating flow

Image of Flame During Combustion Instability



McManus et al., C&F, 1990; Speth et al., AIAA2011-236

EMISSIONS

Combustion Chemistry

Overall or Global Reaction

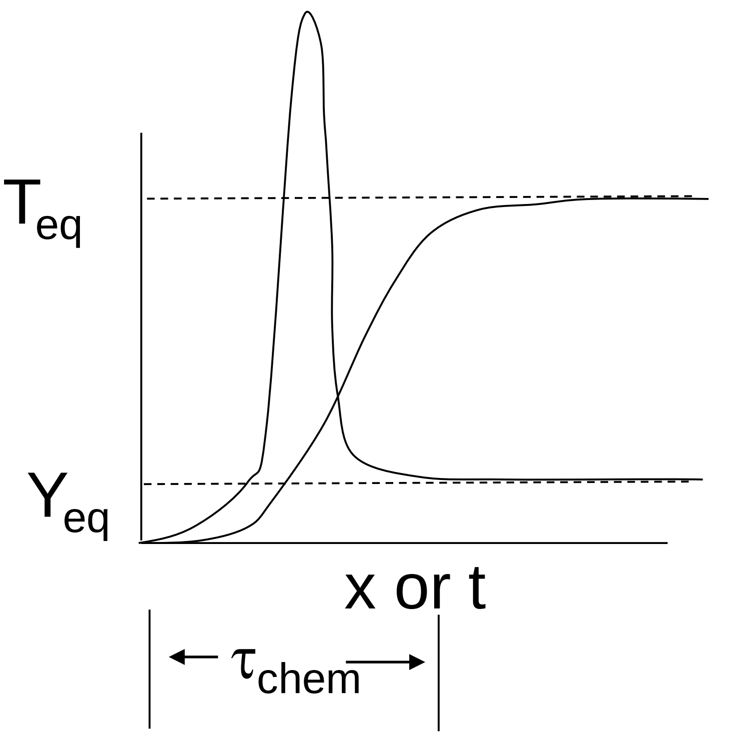
$$CH_4 + 2(O_2 + 3.77\ N_2) \rightarrow CO_2 + 2\ H_2O + 7.54\ N_2$$

Many ‘minor’ chemical species are formed in this process, including important pollutants

Much of our attention focuses on these ‘minor’ species

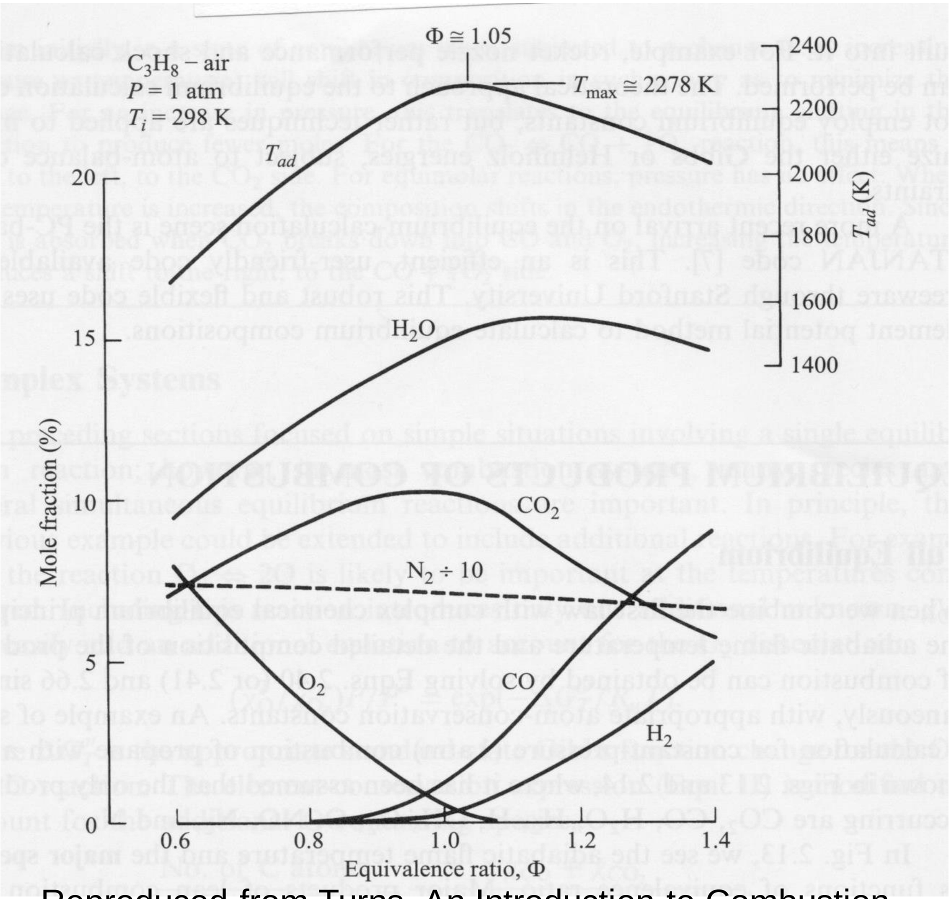
What happens through the flame

- Equilibrium describes where reaction is heading to if given enough time
  - i.e., what levels are species concentrations, temperatures being "pulled" toward
  - Major combustion species concentrations can be predicted from equilibrium calculations
- Kinetics describes chemical rates
  - i.e., how fast a rxn occurs as it tends toward equilibrium
  - Many minor specie concentrations controlled by kinetic influences



Equilibrium Hydrocarbon/Air Combustion Products

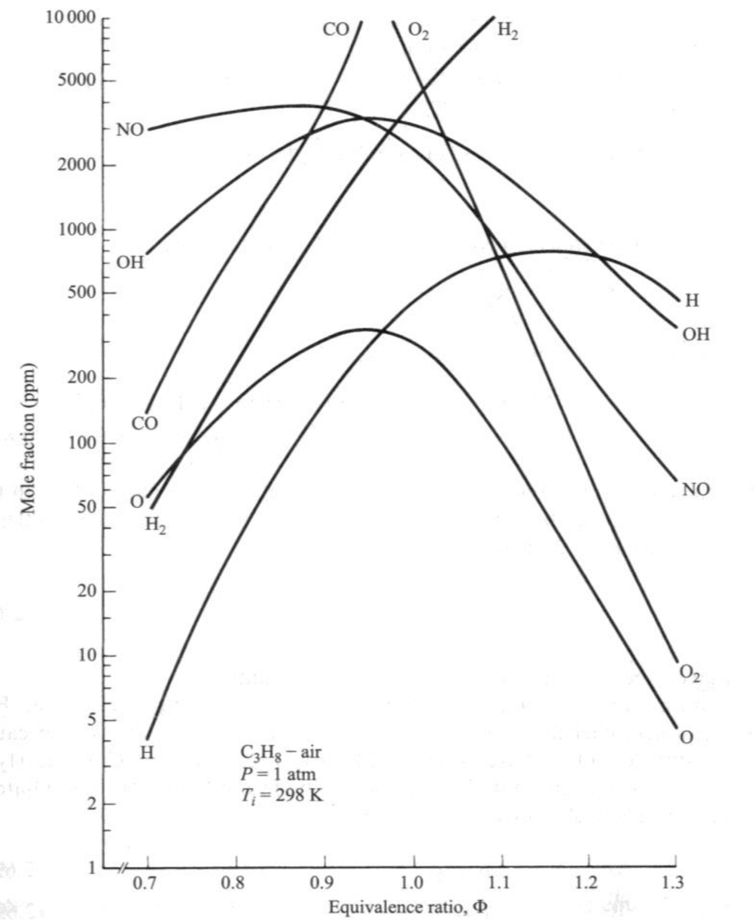
- Major products:
  - Lean: CO_2, H_2O, O_2
  - Rich: CO_2, CO, H_2O, H_2, O_2



Reproduced from Turns, An Introduction to Combustion, 2000

Equilibrium Hydrocarbon/Air Combustion Products (2)

- Minor Products:
  - – NO, OH, O, H, H_2 (ϕ<1), CO (ϕ<1)



Emissions

- NOx – Reactions with nitrogen in air and/or fuel
- CO – Incomplete or rich combustion
- UHC – Incomplete combustion
- SOx – sulfur in fuel
- Particulates (soot, smoke)
- CO_2? – Major project of hydrocarbon combustion

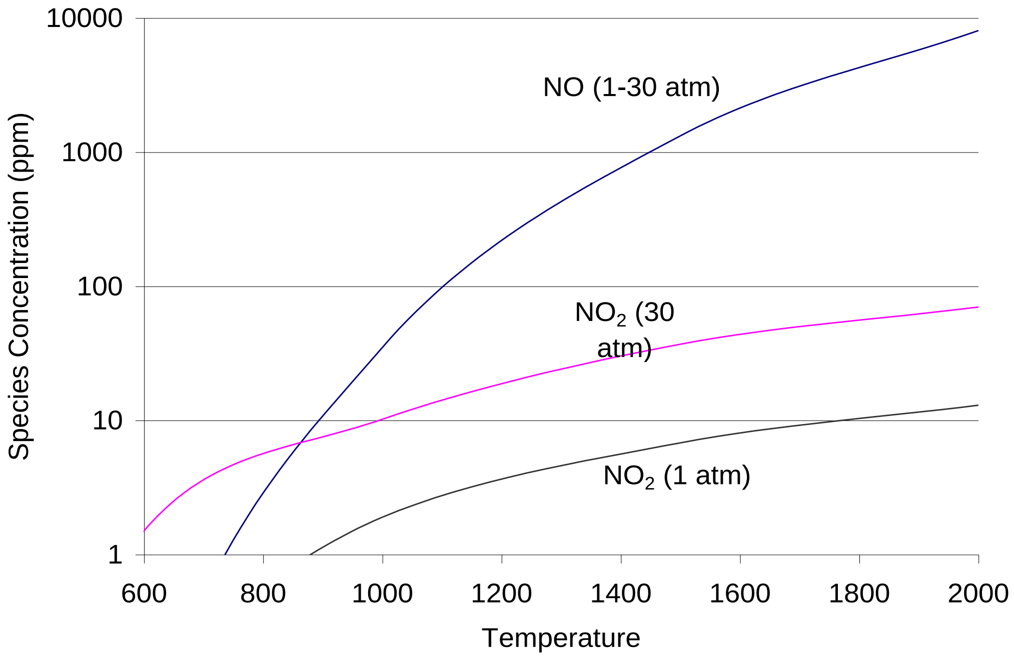
Influenced by both fuel choice and combustion conditions

NOx Emissions

- NOx -Nitrogen Oxides
  - NO, N_2O, NO_2, etc.
- NOx formed when fuel is burned in air
  - $Nox = NOx|_{flame} + NOx|_{post\text{-}flame} = a + b\tau_{residence}$
- Flame generated NOx
  - N_2O
  - Prompt NOx
  - NNH
  - Fuel NOx
- Post-flame NOx
  - Zeldovich reaction (Thermal NOx)

Equilibrium Pollutant Concentrations, NO and NO_2

- NO levels pressure independent
- Most NO_x formed at combustion conditions is NO, not NO_2
  - NO converted to NO_2 in atmosphere (note crossover at low temps)
- NO emissions from lean, premixed combustors strongly influenced by non-equilibrium phenomenon
  - NO usually increases with pressure, p^n (n~0.5-0.8)
  - Non-equilibrium NO values less than equilibrium values

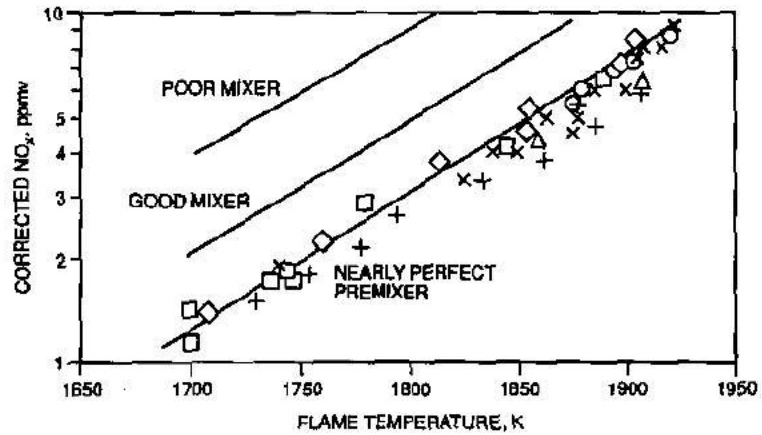


Zeldovich Reaction

- Reaction 1: $O + N_2 => NO + N$
- Reaction 2: $N + O_2 => NO + O$
- Net reaction: $N_2 + O_2 => 2NO$
- Reaction rate increases exponentially with flame temperature
- Often called “thermal” NOx

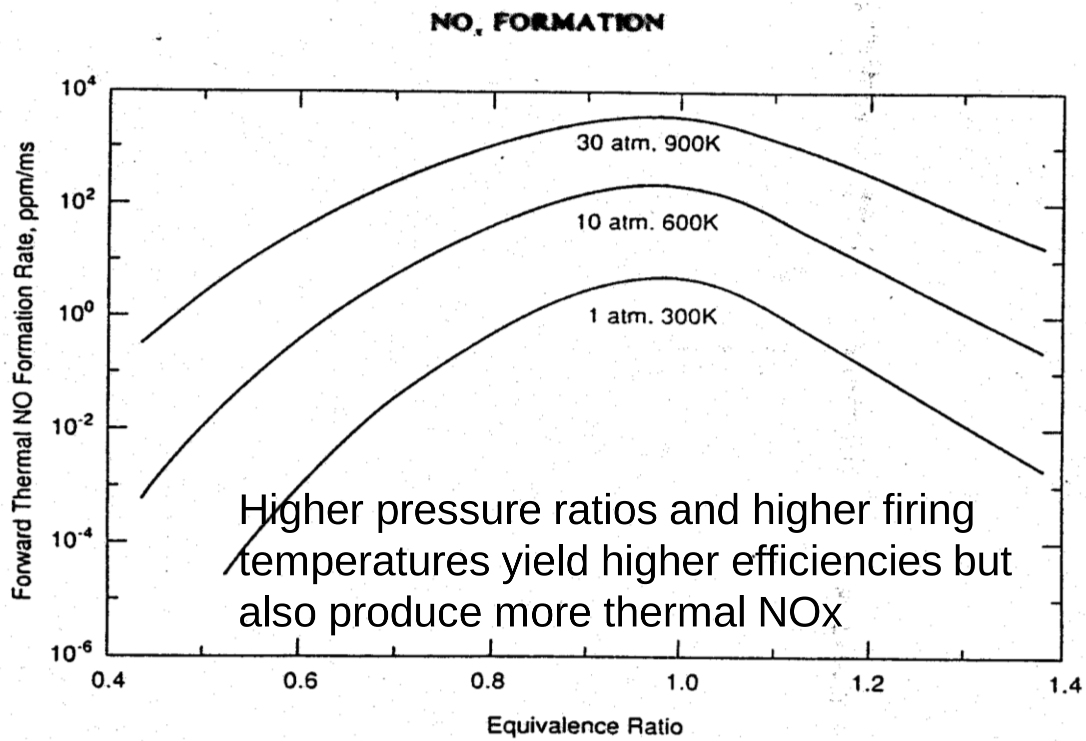
Pollutant Trends, Thermal NOx

- Primarily formed at high temperatures (>1800 K), due to reaction of atmospheric oxygen and nitrogen
  - Water/steam injection used to cool flame in nonpremixed combustors
  - Fuel lean operation to minimize flame temperature is a standard strategy in DLN combustors



Source: A. Lefebvre, “Gas Turbine Combustion”

Thermal NOx formation Rates

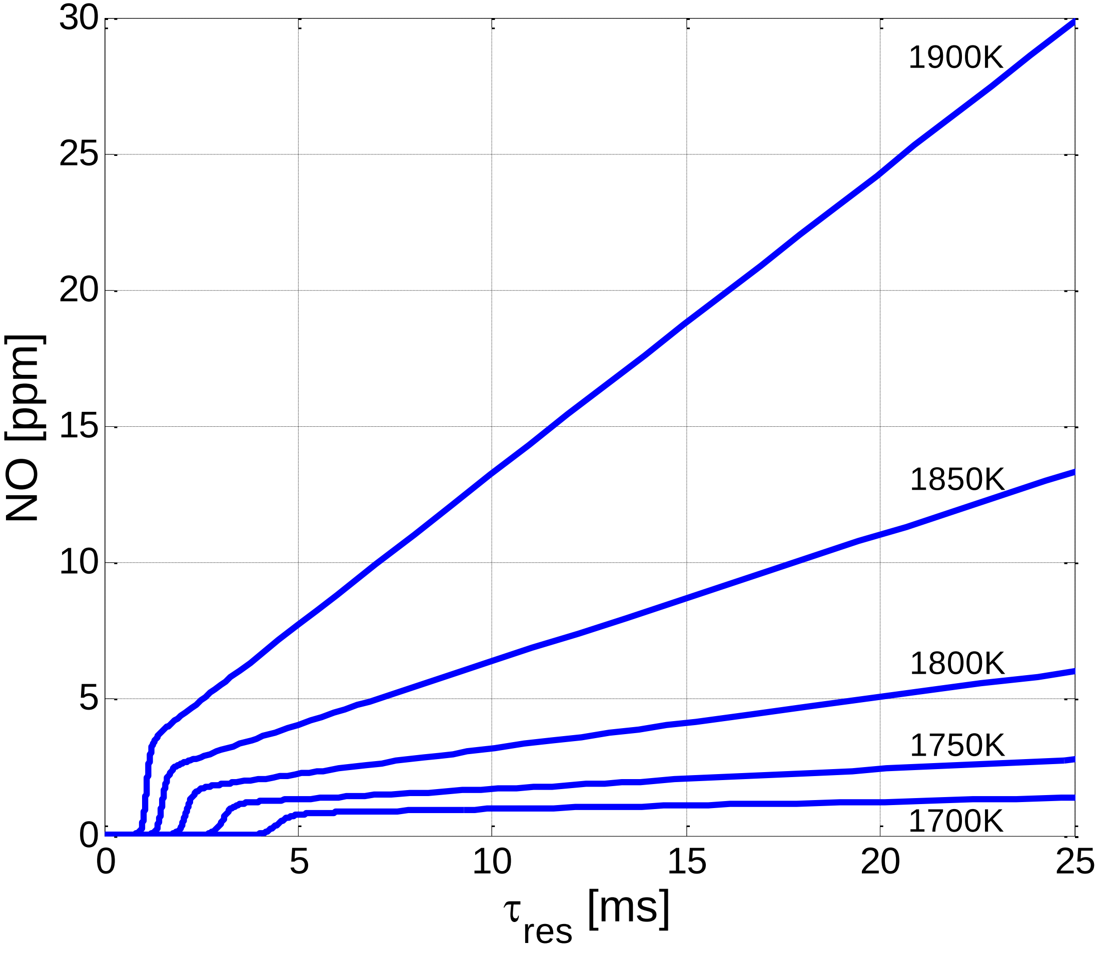


Higher pressure ratios and higher firing temperatures yield higher efficiencies but also produce more thermal NOx

FIGURE 1 Forward thermal NO formation rate with inlet conditions typical of laboratory (1 atm, 300 K), utility gas-turbine (10 atm, 600 K) and aeropropulsion gas-turbine (30 atm, 900 K) combustion.

NO levels start low and tend towards equilibrium – i.e., longer residence time leads to more thermal NOx

CH_4/Air, varying T_{ad}, p=15atm, T_{in}=635K (τ = 0, taken at T = 640K)



NO_2 Formation
(Brown or Yellow Plume)

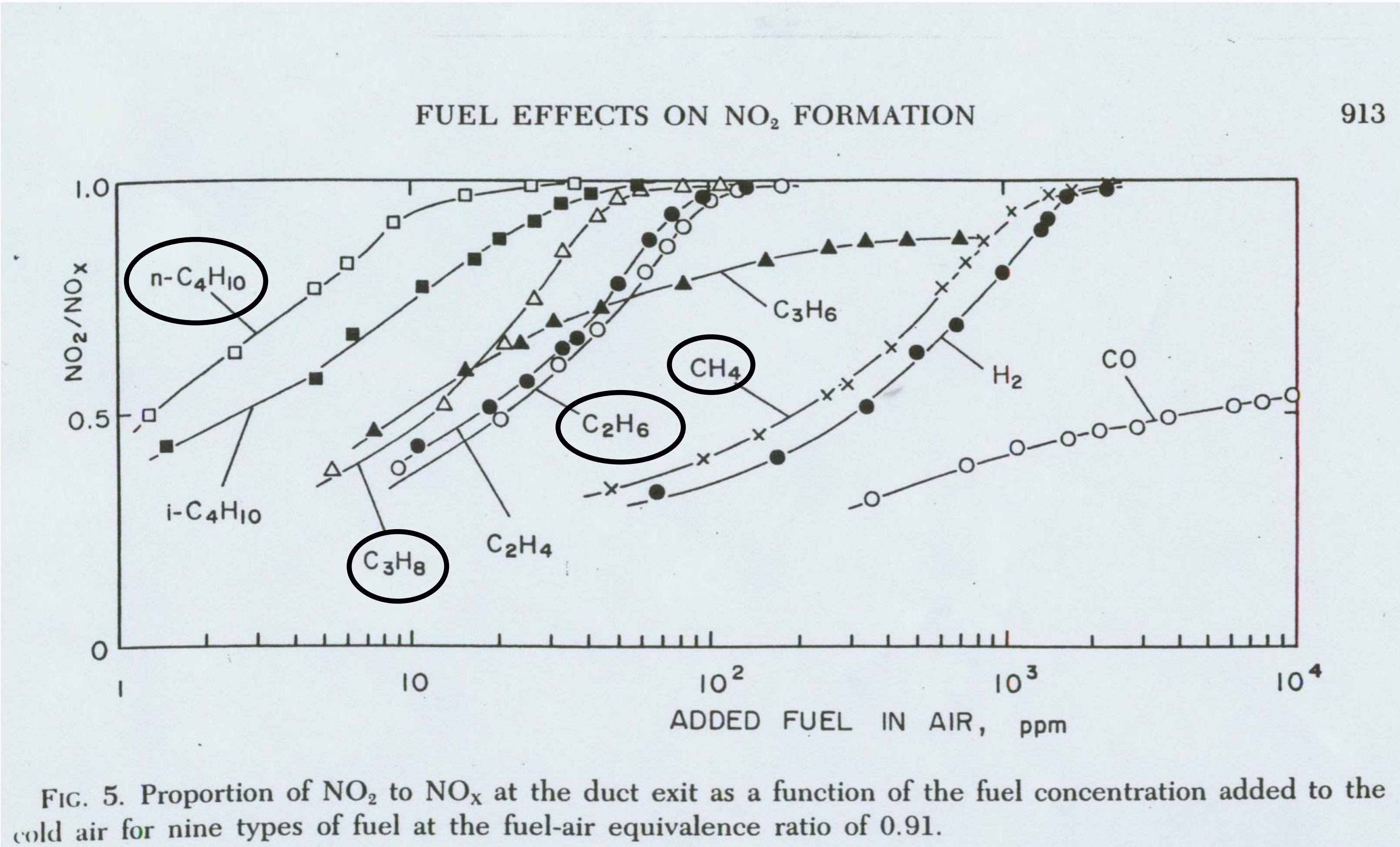
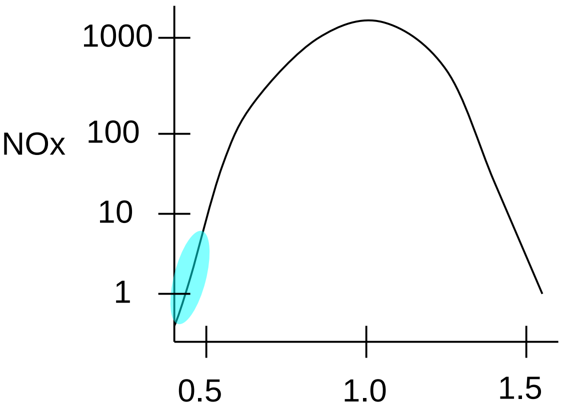


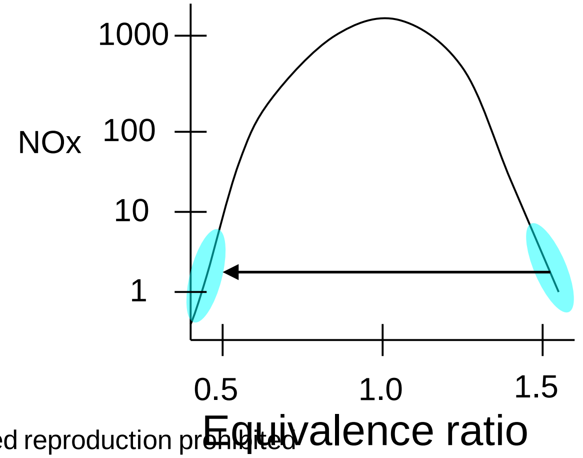
FIG. 5. Proportion of NO_2 to NO_X at the duct exit as a function of the fuel concentration added to the cold air for nine types of fuel at the fuel-air equivalence ratio of 0.91.

Low NOx combustion concepts

- Lean burning
  - DLN (Dry, low NOx)
    - Key issues: turndown, combustion instability, blowoff, flashback (in higher H_2 applications)
  - LPP (Lean, premixed, prevaporized)
    - Key issues: same as above, autoignition



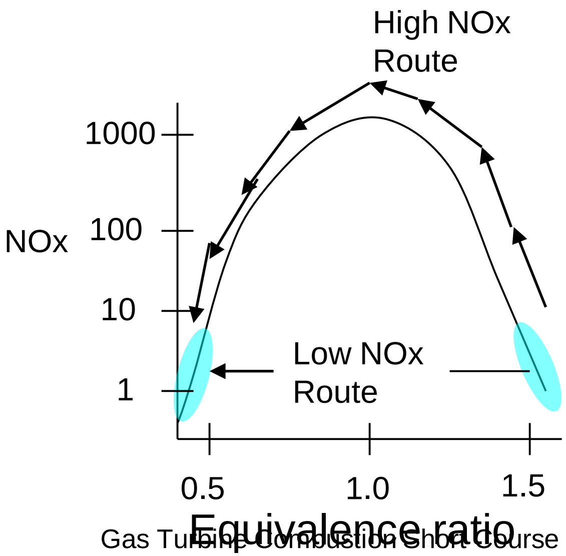
- Rich burning
  - RQL (rich burn, quick quench, lean burn)
    - Key issues: soot, quench mixers

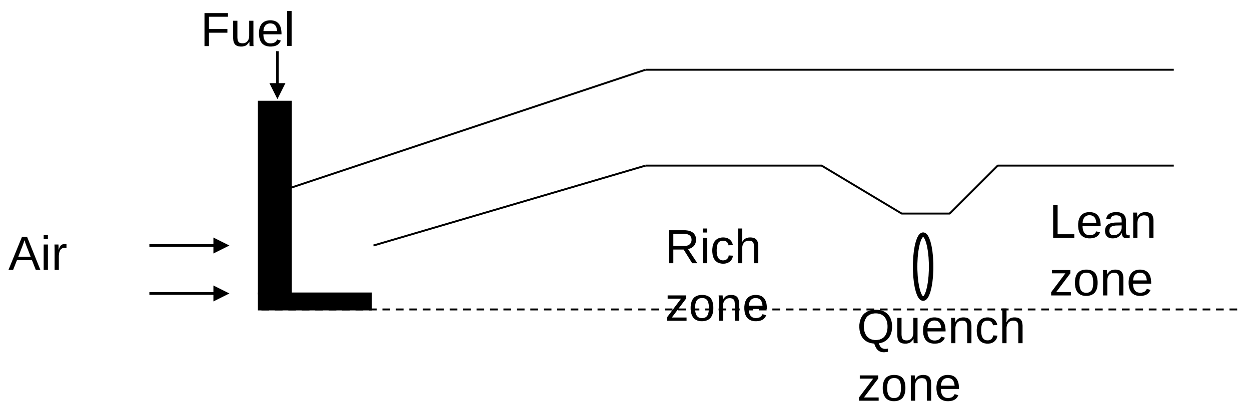


- Catalytic
  - Low temperature catalytic combustion
  - Key issues: cost, catalyst durability

Combustor Configurations
Rich burn, quick quench, lean burn (RQL)

- Rich head end
- Mixture quickly mixed with excess air
- Lean burn downstream
- Realized to some extent in many conventional combustors
- Intensive development by P&W

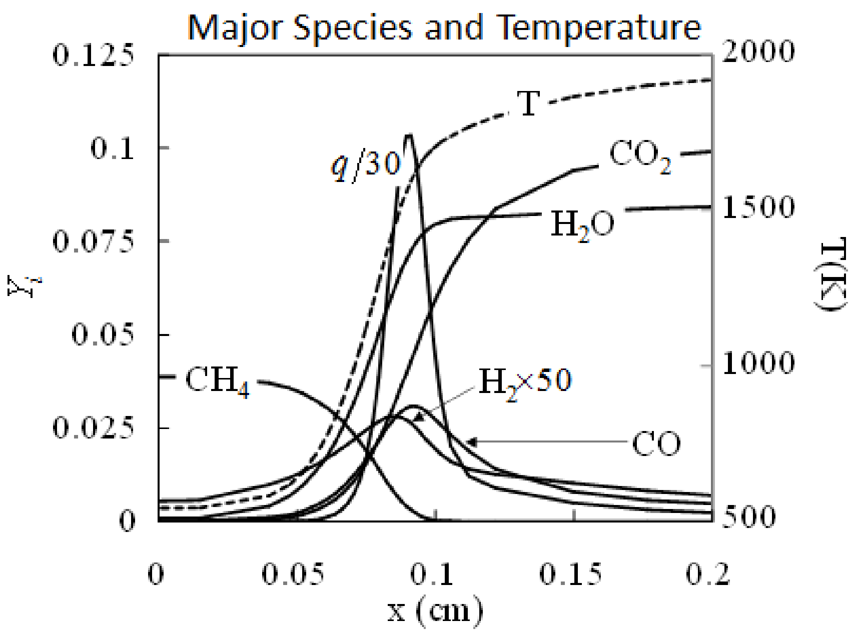


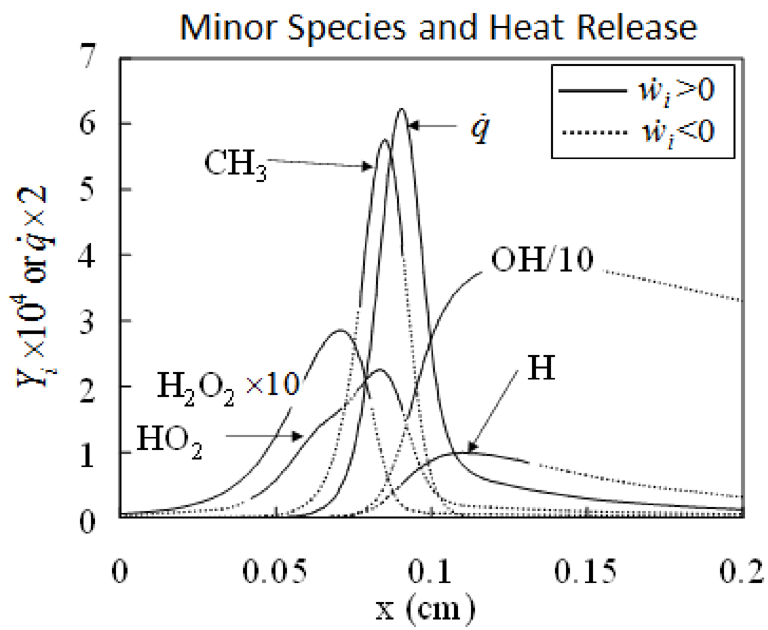


Source: A. Lefebvre, "Gas Turbine Combustion"

CO Emissions

- Combustion of hydrocarbons actually occurs through multiple steps; a simple 2 step conceptualization of actual process is
  - Step 1: Fuel reacts to form “intermediate species”, including CO
  - Step 2: CO reacts to form CO_2
- Without “step 2”, you get CO emissions!

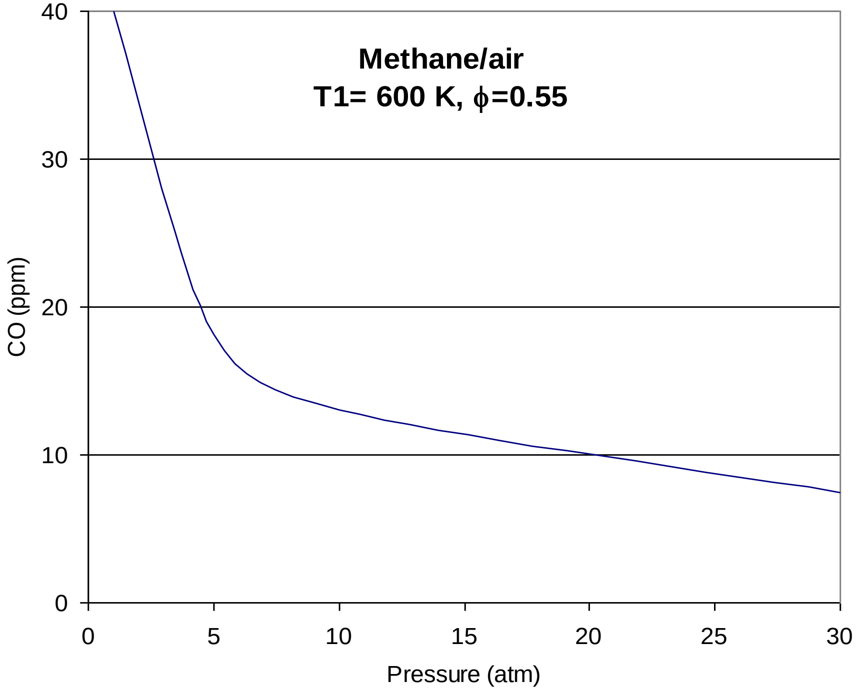


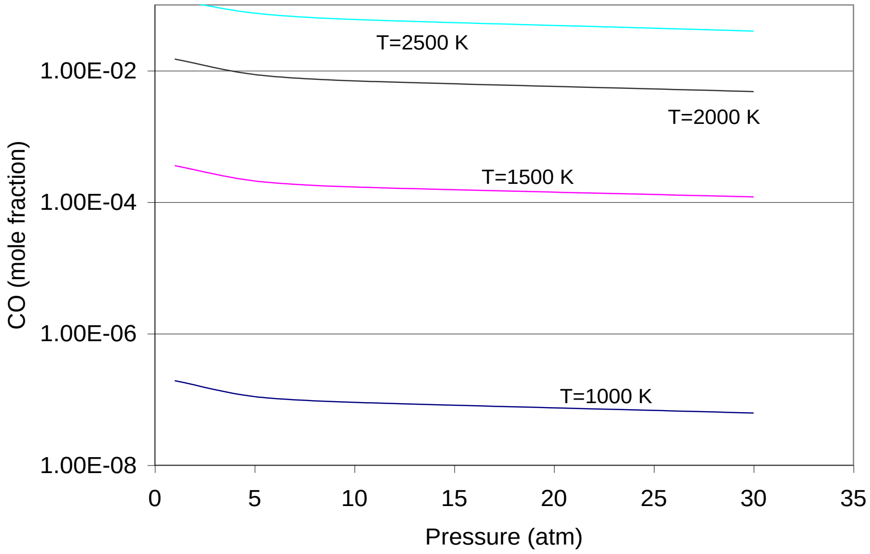


Equilibrium Pollutant Concentrations, CO

- equilibrium CO levels for reaction

$$CO + 1/2O_2 ... \rightleftarrows CO_2.$$

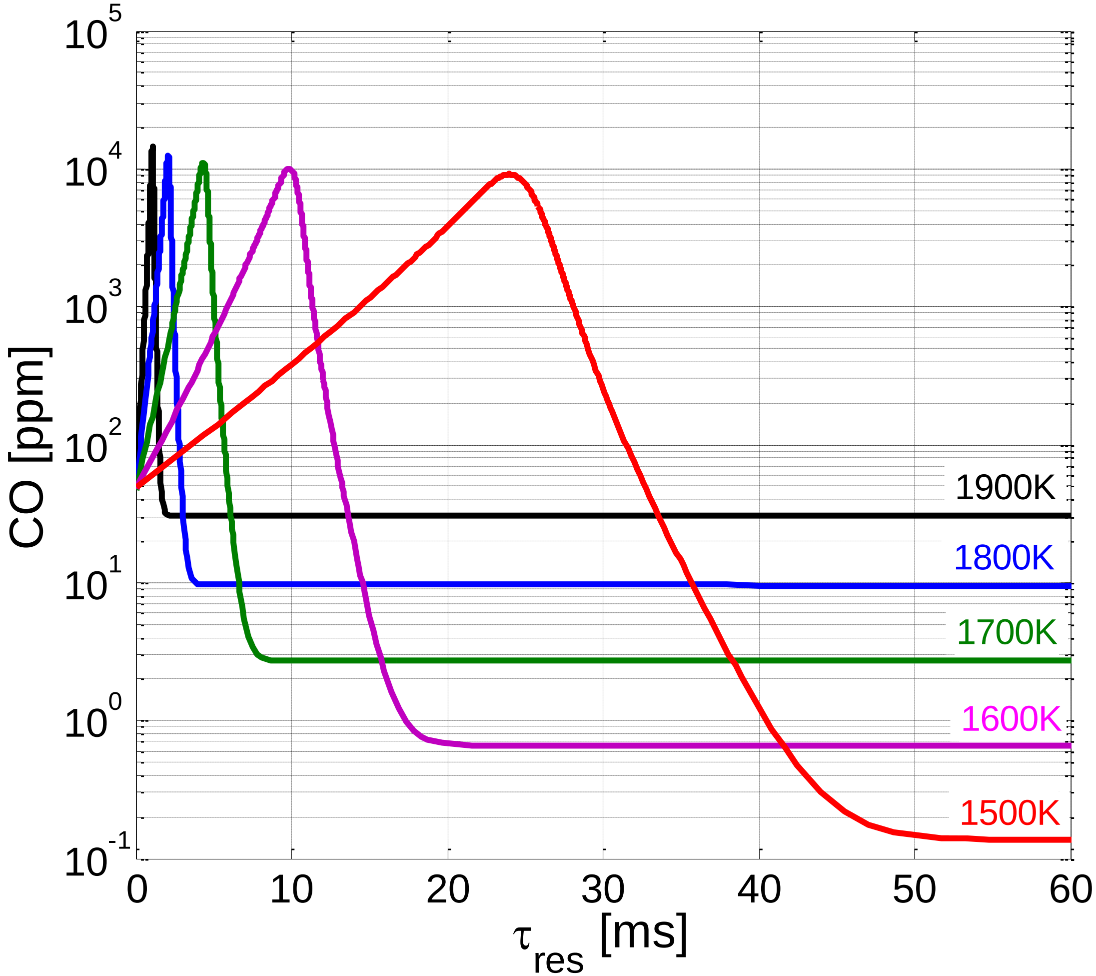




Quenching Leads to CO

- Step 2 will not happen if the combustion products are "quenched" or cooled prematurely
  - Occurs at low temperatures where insufficient residence time to oxidize CO
  - Occurs where cooling air is mixed into the flow
- CO levels relax down toward equilibrium – i.e., longer residence time is better
- Step 2 will also not happen if there is a shortage of O atoms – fuel-rich combustion
  - Typically not encountered in gas turbines

CH_4/Air, varying T_{ad}, p=15atm, T_{in}=635K (τ = 0, taken at T = 640K)

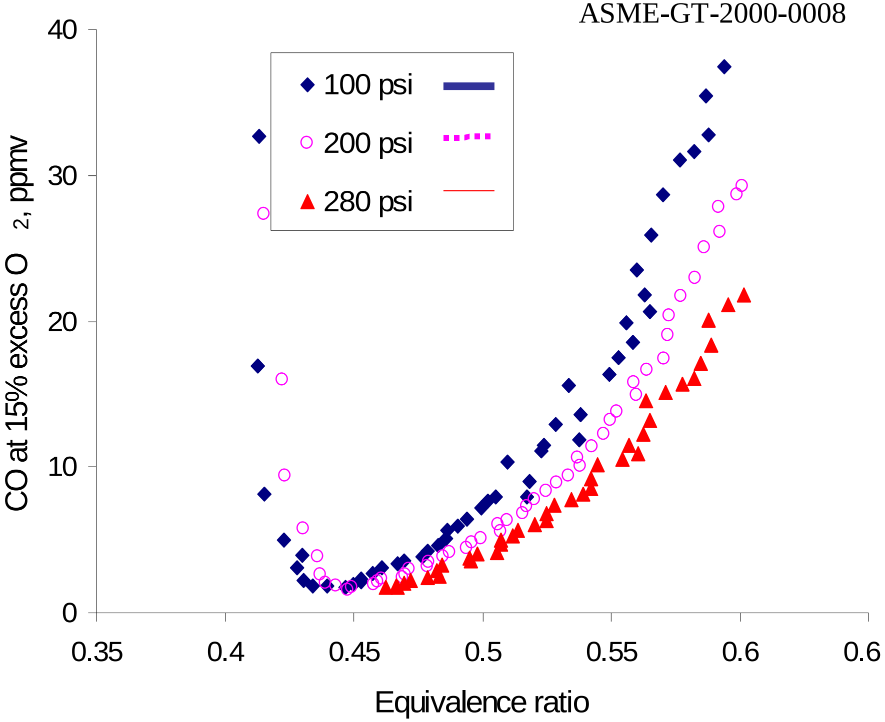


Pollutant Trends, CO and UHC

– Rich flames – large amounts formed due to insufficient oxygen to react fuel to CO_2

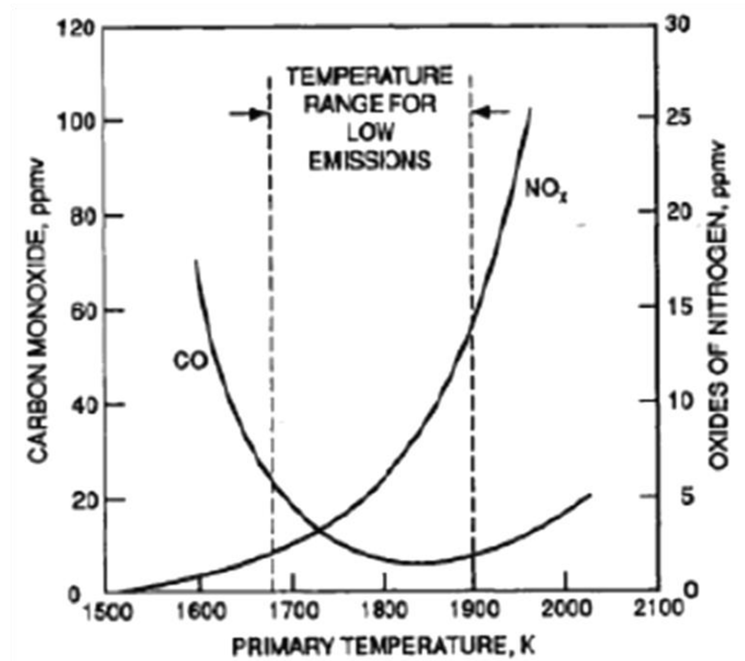
– Lean flames – incomplete combustion
  - Slow CO conversion
    - High CO levels formed in flame that relax slowly to equilibrium
  - Low power, low temperature operation
  - Limits turndown range
- Unburned hydrocarbons (UHC) also associated with incomplete combustion

From A. Kendrick, *et al*, ASME-GT-2000-0008



NOx-CO Tradeoff

- Almost always
  - Low power operation limited by CO
  - High power limited by NOx
  - Competing trends in terms of temperature and residence time



Lefebvre, Gas Turbine Combustion, 1999

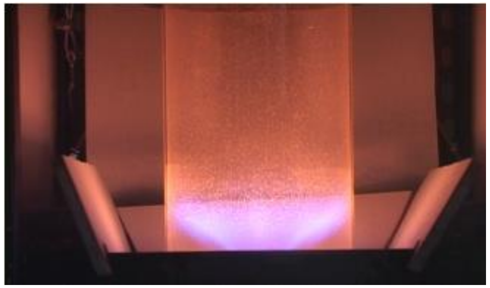
SOx Emissions

- SOx (SO_2 and SO_3)
- SO_3 reacts with water to form sulfuric acid
- $SO_3 + H_2O \rightarrow H_2SO_4$
  - Occurs with fuels containing sulfur, such as coal or residual oils
  - Very high conversion efficiency of fuel bound sulfur to SOx
    - i.e., can't minimize SOx emissions through combustion process (as can be done for NOx), it must be removed in pre- or post-treatment stage

Particulate Matter

- Fine carbon particles formed in flame
  - Particles may or may not make it through flame
  - Competition between soot formation and soot 'burn-out'
- Nearly zero in lean, premixed flames
- Occurs in fuel-rich flames and diffusion flames
- Cause of yellow luminosity in flames
  - Increases radiative heat transfer loading to combustor liners
- Particulate matter in exhaust related to respiratory ailments in humans
  - Small particles ingested into lungs
  - May contain adsorbed carcinogens

Conventional Liquid Fuel Flame



Natural Gas Premixed Flame

Combustor Operability Issues

- Blowout (“static stability”)

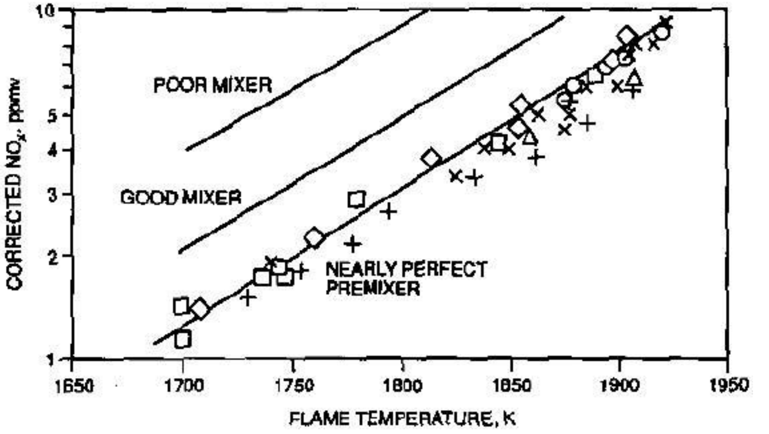
- Combustion Instability (“dynamic stability”)

- Flashback

- Autoignition

Auto-Ignition

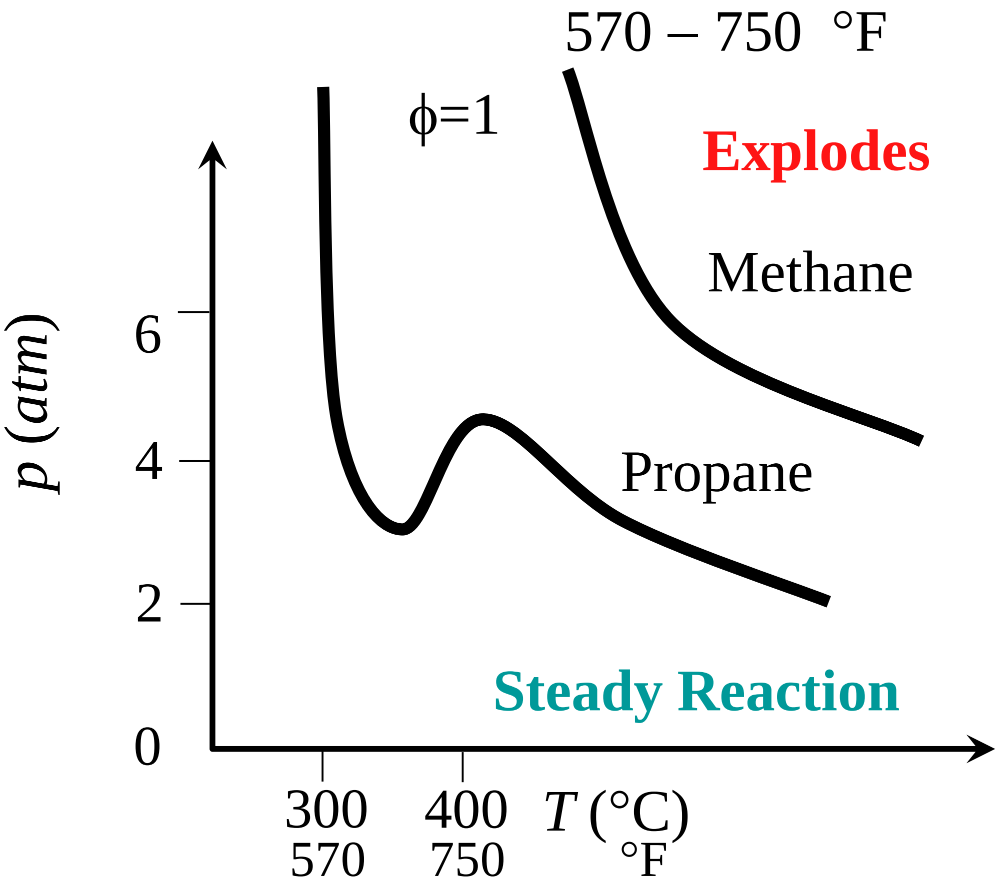
- In premixed systems, premature ignition is a significant concern
  - temperature above which a fuel-air mixture can spontaneously ignite is called the “auto-ignition temperature”
  - amount of time it takes to spontaneously ignite is known as “ignition delay time”



- Competes with need for good premixing for NOx reduction

Operability: Autoignition

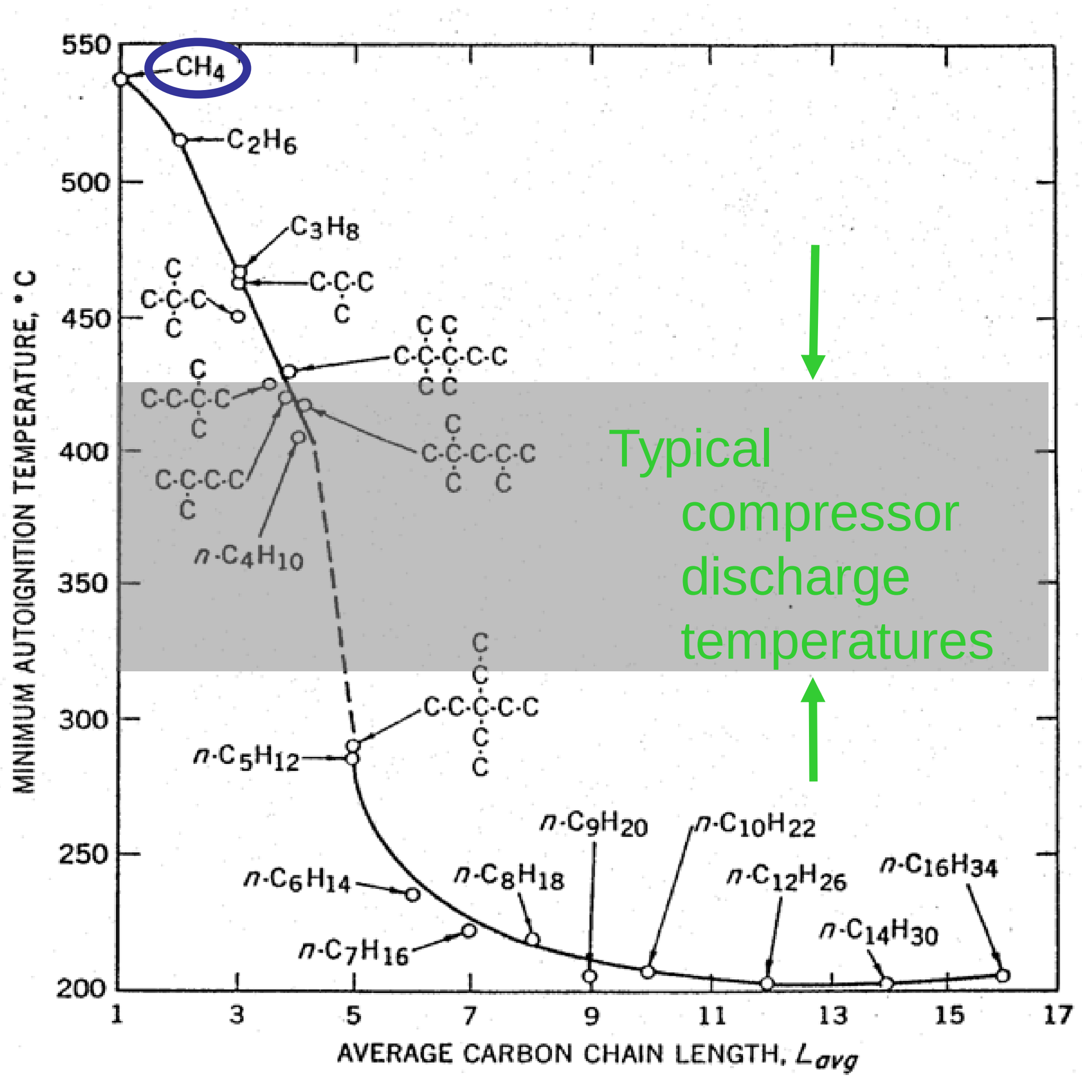
- Methane has significantly higher autoignition temperatures than higher hydocarbons
  - Important consideration for LNG, particularly with high pressure ratio aeroderivatives



Correlations for Higher HC influence on Natural Gas Ignition Times

- Methane has relatively long ignition times
  - Ignition of small amounts of higher hydrocarbons can substantially decrease time delays
  - Raises autoignition concerns for high pressure ratio, DLN systems (e.g. aeroderivatives)
- Spadacinni and Colket correlation:
  - $t_{ign} = 1.77 \times 10^{-14} \exp(18693/T) [O2]^{-1.05} [CH4]^{0.66} [HC]^{-0.39}$
    - [HC] – concentration of all other higher hydrocarbons
    - $T_{initial}$>1200 K (extrapolating to lower temps is not accurate)
    - Spadaccini, L. J., Colket, M. B, Ignition Delay Characteristics of Methane Fuels, Prog. Energy Combust. Sci., Vol 20, pp431-460, 1994.

Auto-ignition Behavior as a function of Fuel Type



Petersen's Data – Hydrogen Effects

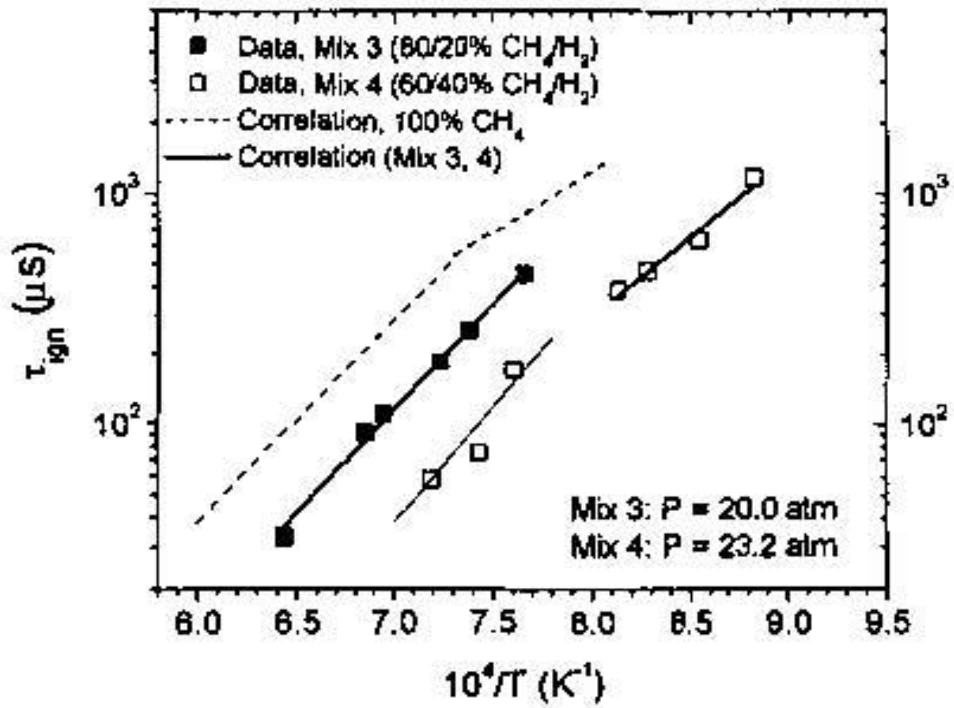


Fig. 4 Ignition delay times for the methane/hydrogen blends in comparison to the methane-only data at similar pressures.

- Petersen et. al. "Ignition of Methane Based Fuel Blends at Gas Turbine Pressures", ASME 2005-68517

Petersen's Data – Ethane Effects

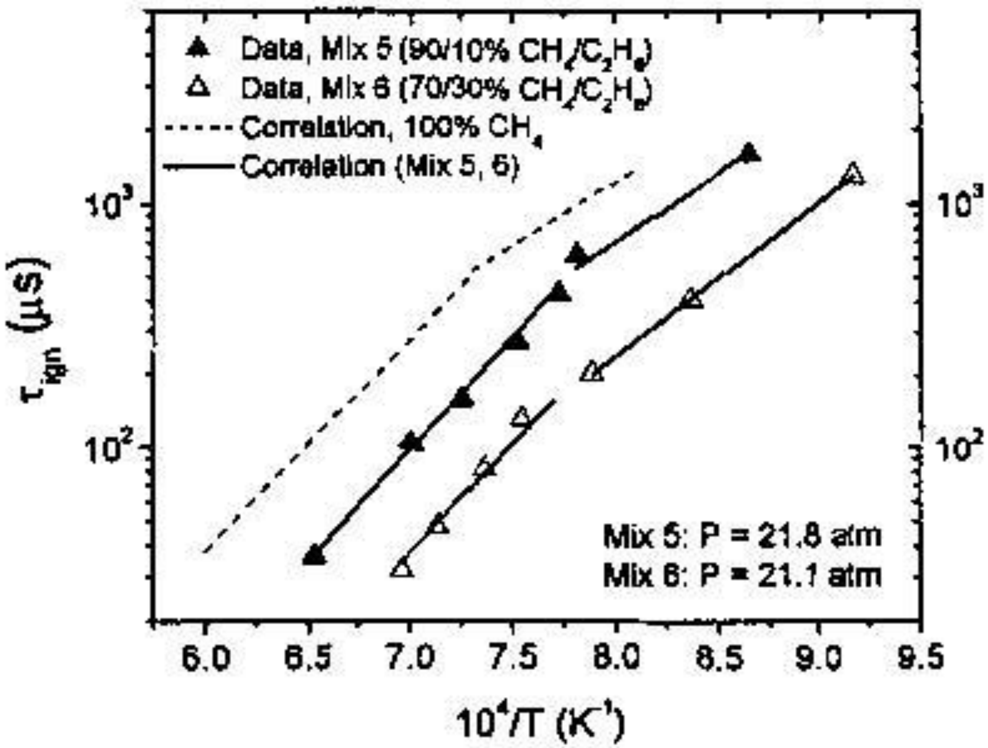


Fig. 5 Ignition delay times for the methane/ethane blends in comparison to the methane-only data at similar pressures.

- Petersen et. al. "Ignition of Methane Based Fuel Blends at Gas Turbine Pressures", ASME 2005-68517

Petersen's Data – Propane Effects

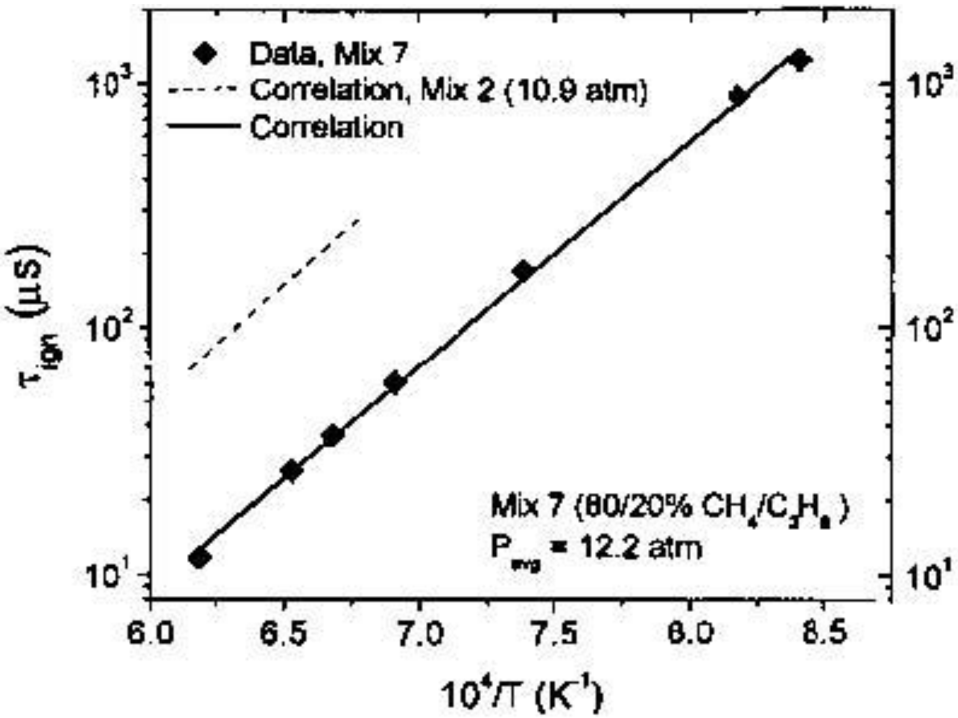


Fig. 6 Measured ignition delay times for the methane/propane blend in comparison to the methane-only data at similar pressures.

- Petersen et. al. "Ignition of Methane Based Fuel Blends at Gas Turbine Pressures", ASME 2005-68517

Effects of Hydrocarbon Condensation

HP turbine blade showing gross erosion of shroud and front seal fin

HP Seal Segments showing severe thermal erosion

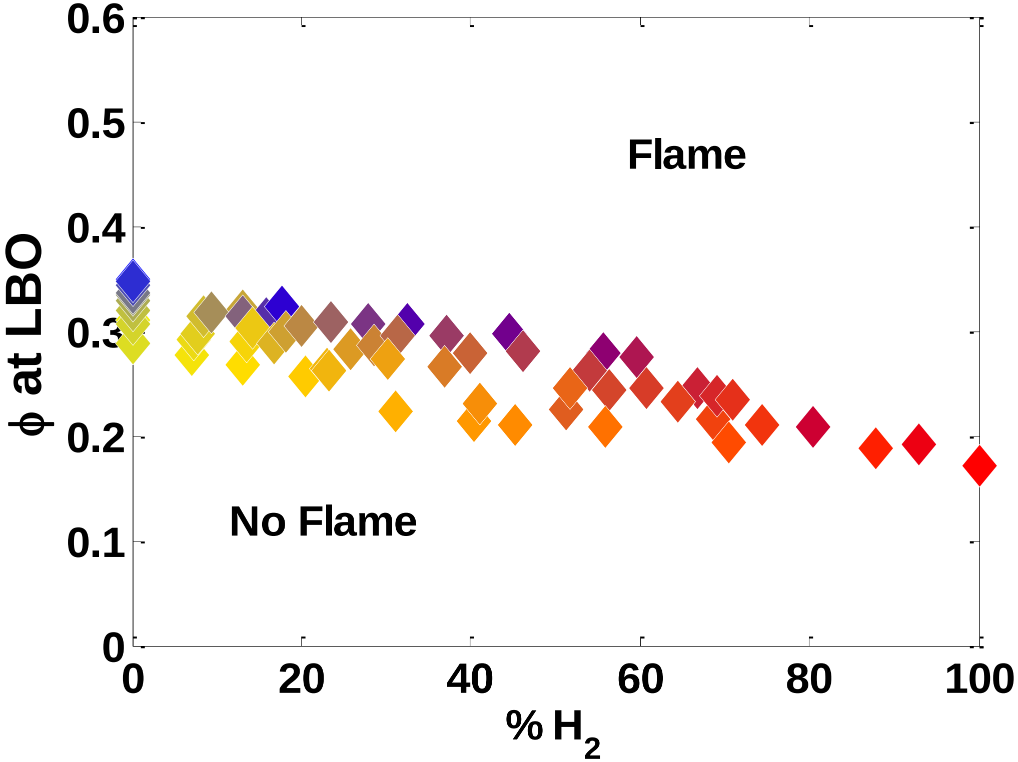
Combustor Outer Wall showing extreme overheating

Source. C. Carson,
Rolls Royce Canada

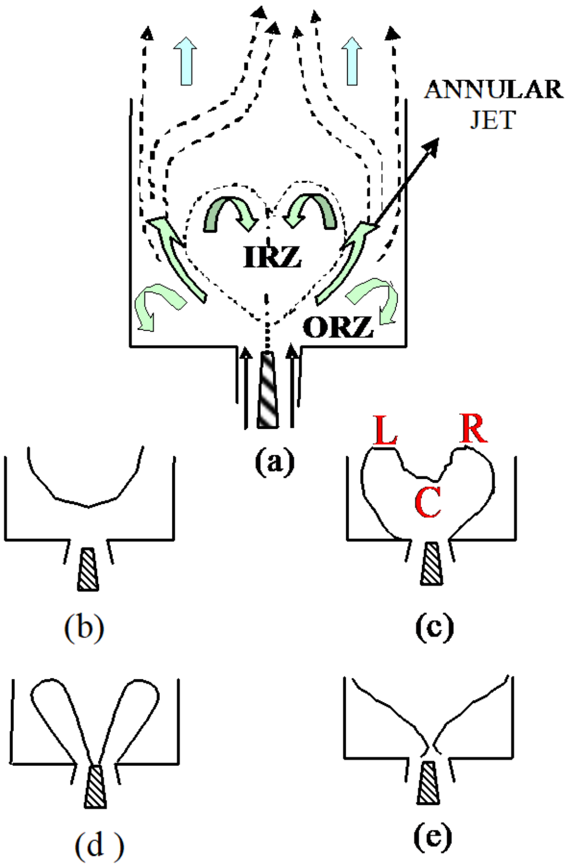
Operability Issues- Blowoff

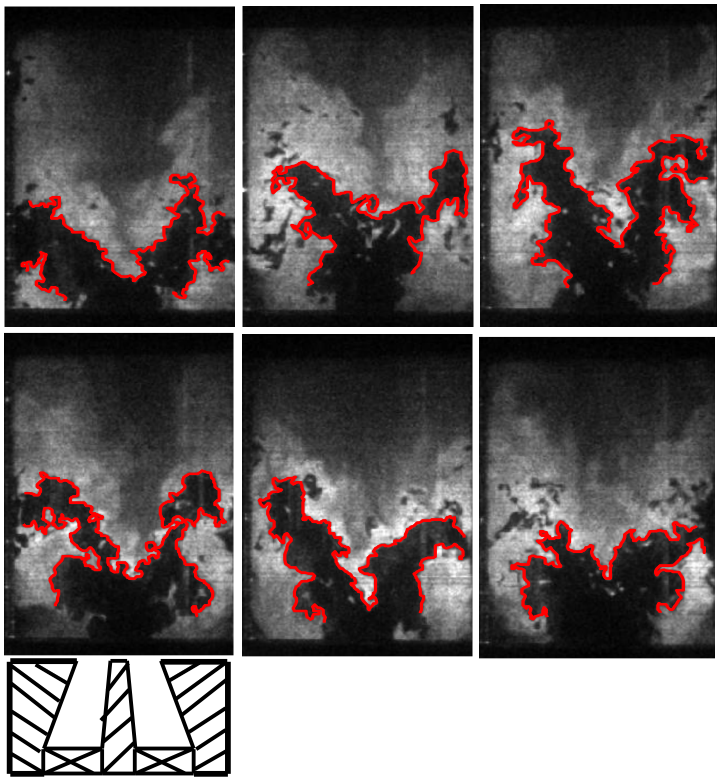
- Blowoff significantly influenced by:
  - Diluents generally contract blowoff limits (particularly CO_2)
  - H_2 addition significantly extends blowoff limits

Conditions: U_0=60 m/s, T=460K, P=4.4atm,



"Local Blowoff" Changes in Possible Flame Configurations





•From Kumar and Lieuwen

Flashback and Flameholding

- Flashback:
  - upstream propagation of a premixed flame into a region not designed for the flame to exist
  - Occurs when the laminar and/or turbulent flame speed exceeds the local flow velocity
    - Reference flow speed and burning velocity?
- Flameholding:
  - flame stabilizes in an undesired region of the combustor after a flashback/autoignition event
  - Problem has hysteretic elements
    - Wall temperature effects
    - Boundary layer and swirl flow stability effects

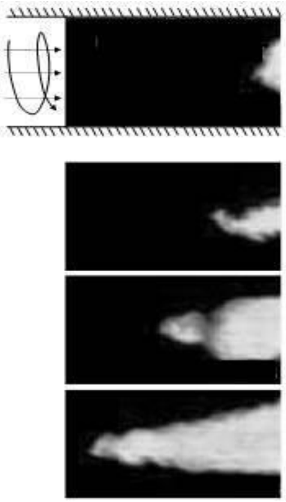
Flashback

- Flashback mechanisms
  - In boundary layer
  - In core flow
    - seems unlikely given very high flow velocities
  - Strong acoustic pulsations lead to nearly reverse flow
  - Combustion induced vortex breakdown
- More problematic with fast propagating flames
  - Think hydrogen!

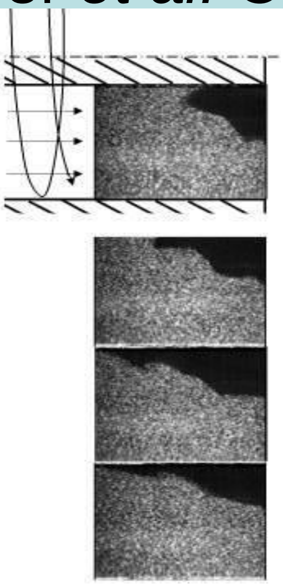
Flashback and Flameholding Mechanisms

- Flashback in the boundary layer
- Flame propagation into core flow
  - We'll focus on swirl flows
- Combustion instabilities
  - Strong acoustic pulsations lead to nearly reverse flow
    - Note: $p'/p \sim u'/c = Mu'/u$
    - i.e. $u'/u = (1/M)p'/p$

- Significance of above mechanisms is a strong function of:
  - Fuel composition
  - Operating conditions
  - Fluid mechanics



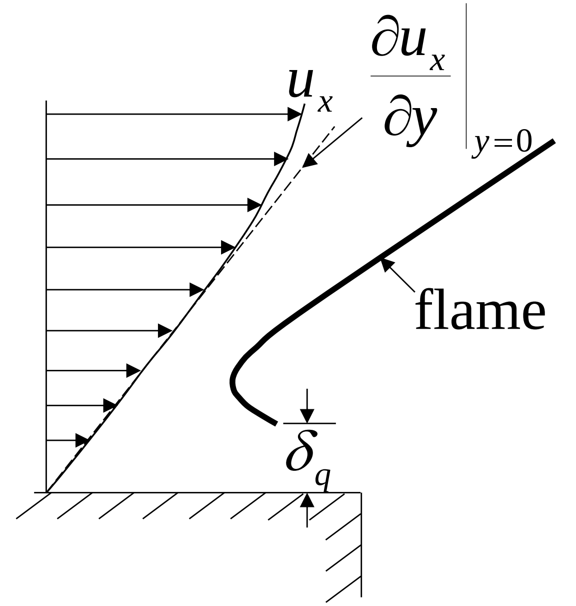
Kröner *et al.* CST 20



Heeger *et al.* Exp. In Fluids 2010

Boundary Layer Flashback

- Flashback occurs if flame speed exceeds flow velocity at distance, δ_q from the wall $u_x(y=\delta_q) = s_d^u(y=\delta_q)$
  –



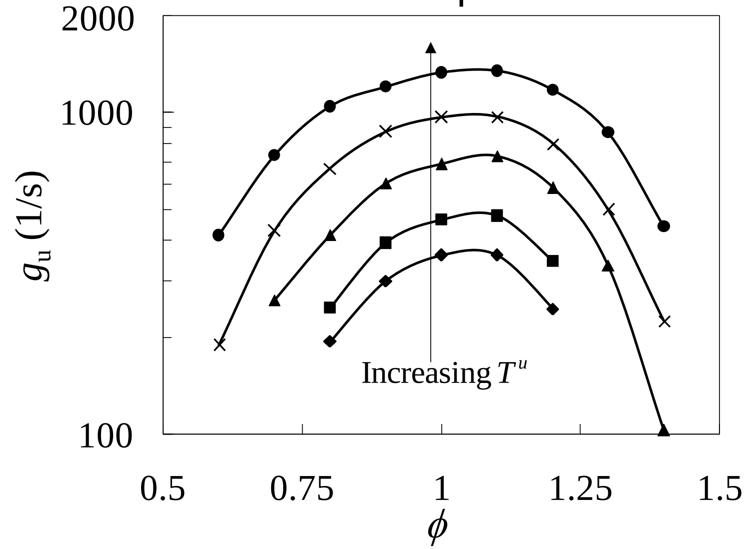
$$u_x(y=\delta_q) \approx \frac{\partial u_x}{\partial y}\delta_q \Rightarrow \frac{g_u \delta_q}{s_d^u} = 1$$

g_u

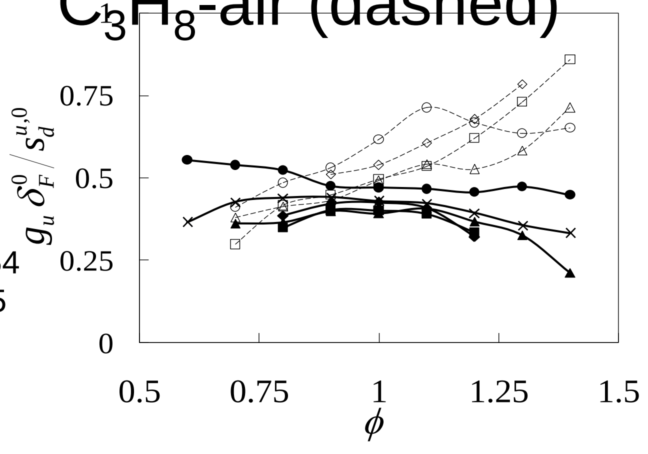
Boundary Layer Flashback

- Typical results

CH_4-air

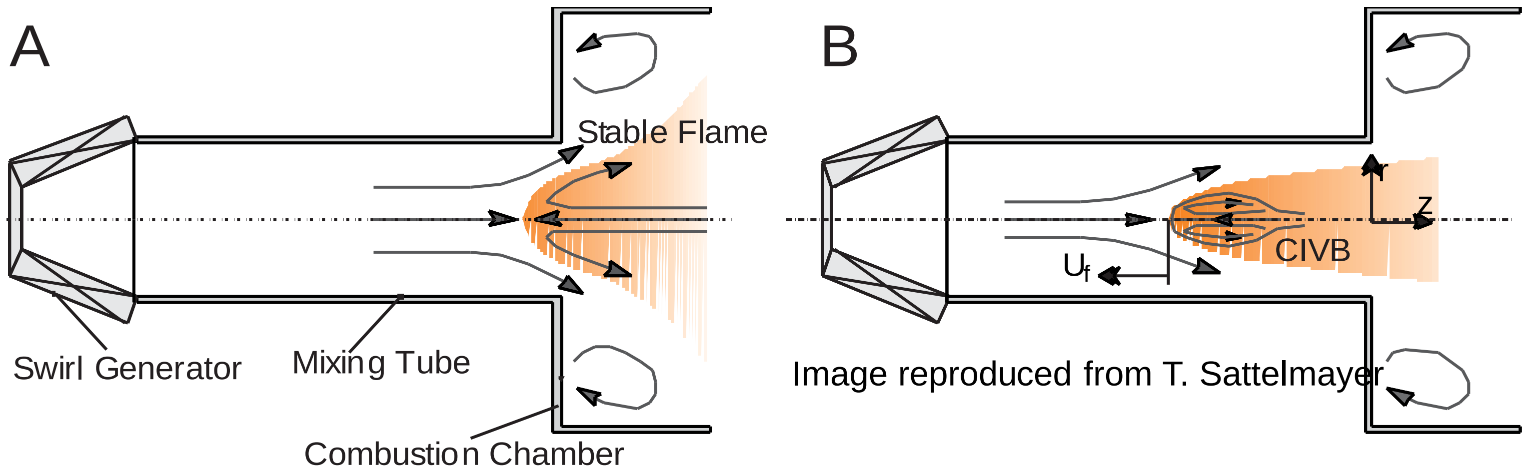


CH_4-air (solid) and C_3H_8-air (dashed)



Data for figures obtained from:
Grumer Ind. & Eng. Chem. 1954
Dugger Ind. & Eng. Chem 1955

Core Flow Flame Propagation

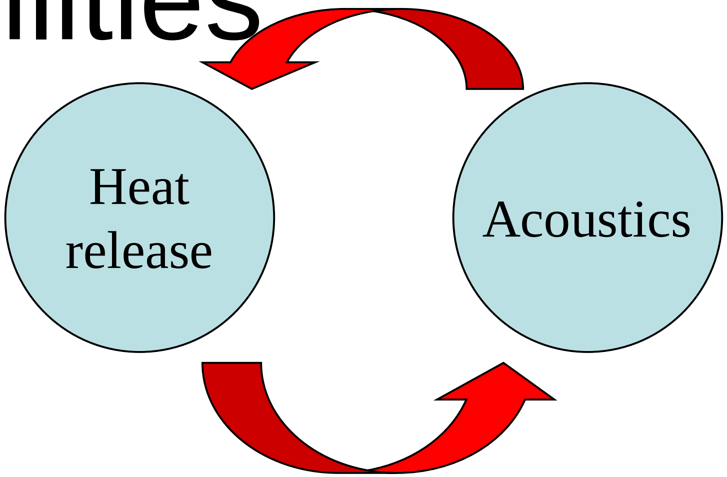


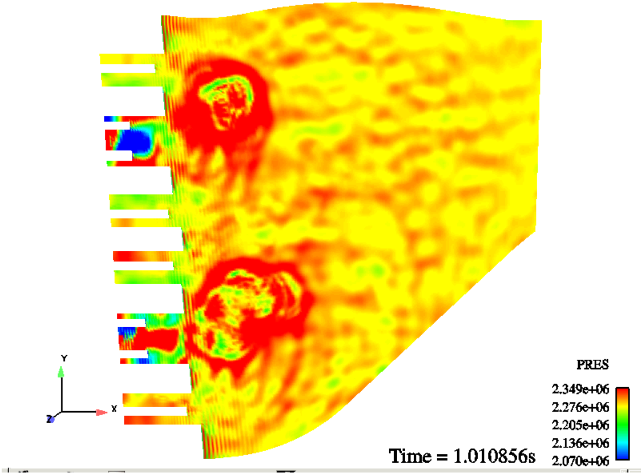
- Vortex breakdown – flame interaction
  - Can occur even if flame speed everywhere less than flow speed
  - Gas expansion across a curved flame:
    1. Adverse pressure gradient & radial divergence imposed on reactants
    2. Low/negative velocity region generated upstream of flame
    3. Flame advances further into reactants
    4. Location of vortex breakdown region advances upstream

Operability: Combustion Instabilities

Motivation – Combustion Instabilities

- Large amplitude acoustic oscillations driven by heat release oscillations
- Oscillations occur at specific frequencies, associated with resonant modes of combustor





Video courtesy of S. Menon

Key Problem: Flame Sensitive to Acoustic Waves

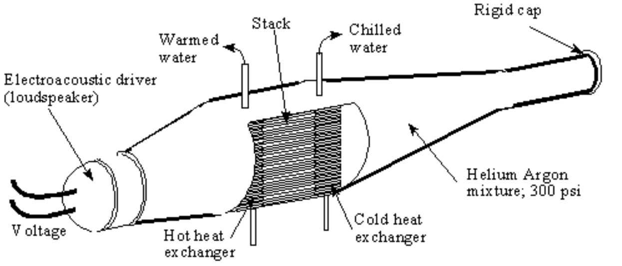
Video from Ecole Centrale – 75 Hz, Courtesy of S. Candel

Key Problem: Combustor System Sensitive to Acoustic Waves

Rubens Tube

Thermo-acoustics

- Rijke Tube (heated gauze in tube)
- Self-excited oscillations in cryogenic tubes
- Thermo-acoustic refrigerators/heat pumps



Purdue's Thermoacoustic Refrigerator

Combustion Dynamics Nomenclature

- Many common terms for combustion dynamics
  - Dynamics, Humming, Rumble, Oscillations, Pulsations, Instability, Screech
- Low Frequency Dynamics (LFD)
  - Rumble, Cold Tone, Helmholtz Mode
- Mid Frequency Dynamics (MFD or IFD)
  - Hum, Hot Tone, Longitudinal Mode
- High Frequency Dynamics (HFD)
  - Screech, Transverse instability
  - Very destructive

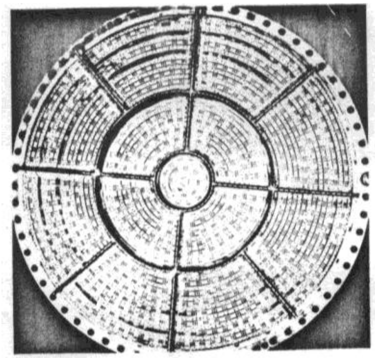
Historical Experience with Combustion Instabilities

From Liquid Propellant Rocket Combustion Instability, Ed. Harrje and Reardon, NASA Publication SP-194

Liquid Rockets

- F-1 Engine
  - used on Saturn V
  - largest thrust engine developed by U.S
  - Problem overcome with over 2000 (out of 3200) full scale tests

Injector face destroyed by combustion instability, Source: D. Talley



From Liquid Propellant Rocket Combustion Instability, Ed. Harrje and Reardon, NASA Publication SP-194

Ramjets and Afterburners

- Systems prone to damage because of light construction
  - Damage to flame holders, spray bars

- Ramjets: un-starting of inlet shock

Mig-29 with RD-33 Engines

"Moskit" Ramjet Powered Missile

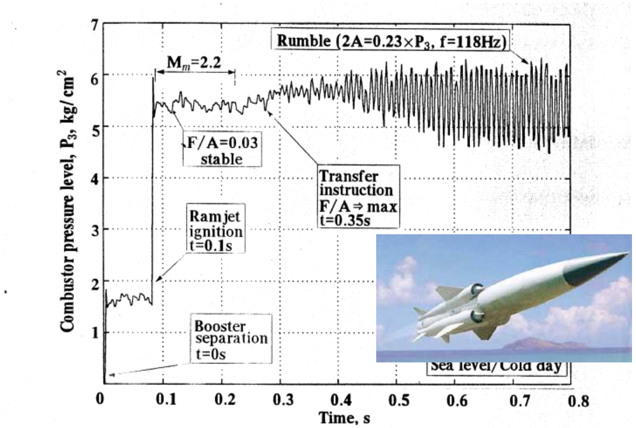
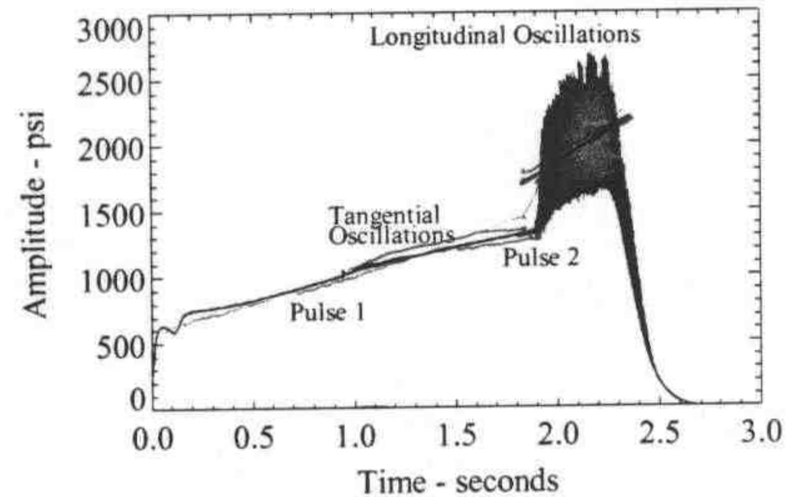


Fig.1.1. Ramjet engine transient process from stable combustion to combustion instabilit

Images courtesy of E. Lubarsky

Solid Rockets

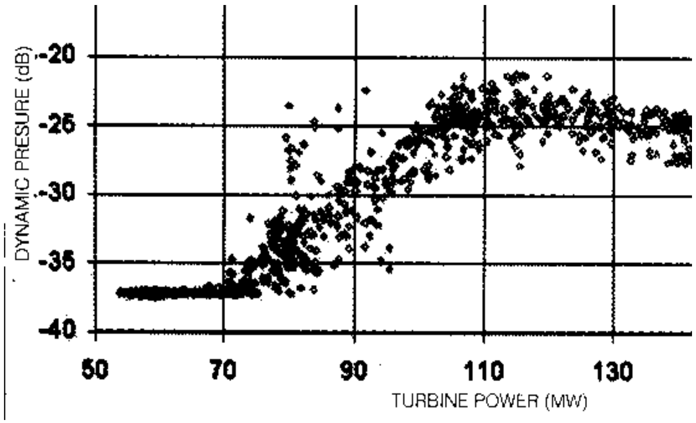
- Examples:
  - SERGEANT Theater ballistic missile – tangential instabilities generated roll torques so strong that outside of motor case was scored due to rotation in restraints
  - Minuteman missile –USAF experienced 5 flight failures in 1968 during test due to loss of flight control because of severe vibrations
  - Space shuttle booster- 1-3 psi oscillations (1 psi = 33,000 pounds of thrust)
- Adverse effects –thrust oscillations, mean pressure changes, changes in burning rates



From Blomshield, AIAA Paper #2001-3875

Gas Turbines

- Dry low NOx systems have huge dynamics problems!
  - Introduced by low emissions designs
- Some reasons:
  - Operate near lean blowout:
    - system already right on stability line, small perturbations give very large effects
  - Minimal combustor cooling air (to minimize CO) as in aero combustors:
    - acoustic damping substantially reduced
  - High velocity premixer for flashback:
    - Pressure maximum at flame
  - Compact reaction zone for CO
    - Heat release concentrated at pressure maximum

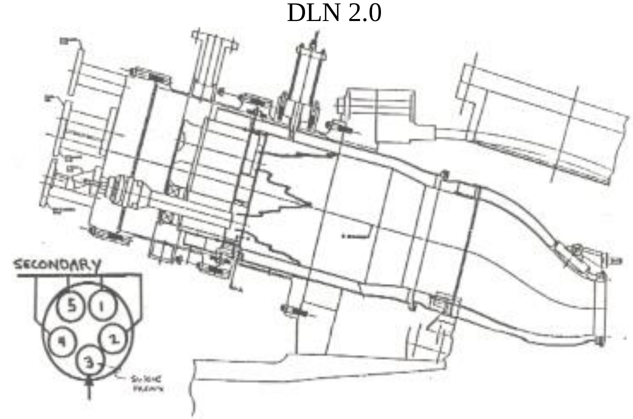


From "Flamebeat: Predicting Combustion Problems from Pressure Signals", by Adriaan Verhage, in Turbomachinery, Vol. 43(2), 2002

Case Study: GE Energy

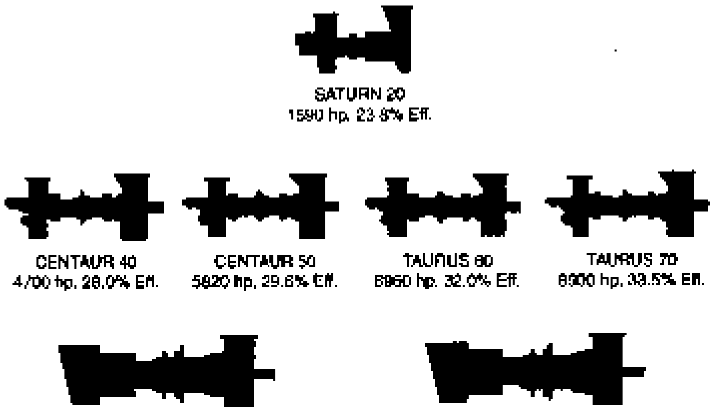
- DLN-1.0
  - Started with single fuel nozzle
  - Went to multiple nozzles to minimize dynamics
- DLN-2.0
  - Less stable but lower NOx, CO than DLN1
  - Has controllable fuel split betwee burners
  - Splits used to minimize dynamics
- DLN 2.0+ - 2.6
  - Similar ideas using variable fuel splits
  - Cross fire tubes cause different combustors to acoustically interact

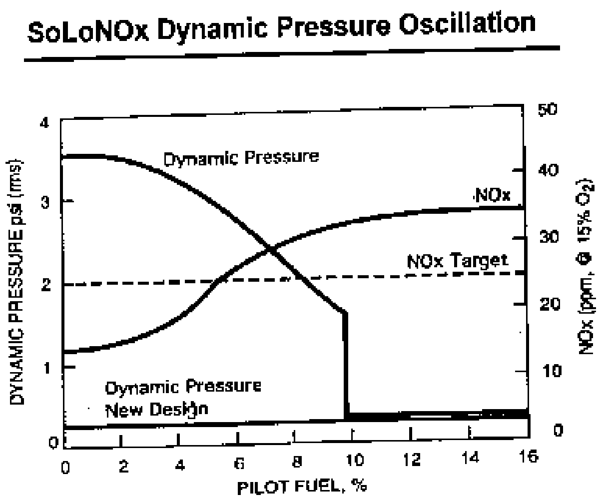
DLN 2.0



From “Combustion Instability in Stationary Gas Turbine Combustors”, Jeff Lovett, presentation at AGTSR Combustion Workshop III, 1996

Case Study: Solar Turbines





From "Experience at Solar Turbines with Combustion Oscillations in Lean Premixed Combustion", presentation at 1995 AGTSR meeting

- Centaur 50
  - Oscillation below 0.5 psi from 50-90% load
  - Full load oscillations > 0.5 psi, 430 Hz
  - 6-16% pilot used to minimize oscillations
  - Injector fretting, sheet metal fatigue
- Mars 100
  - Acceptable oscillations at full load
  - Fretting, metal fatigue
  - 360 Hz oscillation
  - Increasing pilot reduces amplitude

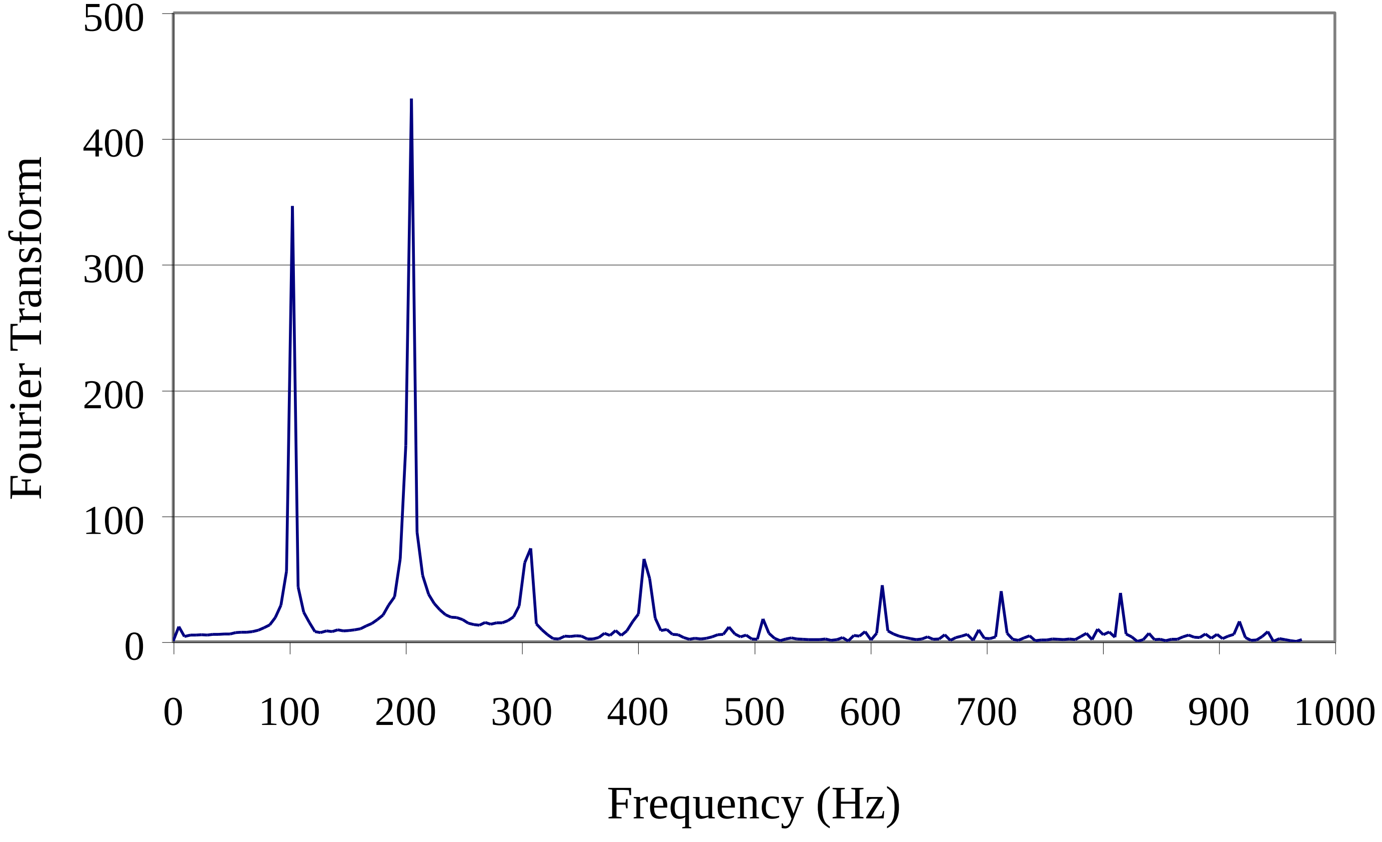
Combustion Instabilities – Basic Characteristics

Frequency of Oscillation

Natural Frequencies

- Combustion chamber is like an organ pipe
  - Has natural frequencies at which it oscillates

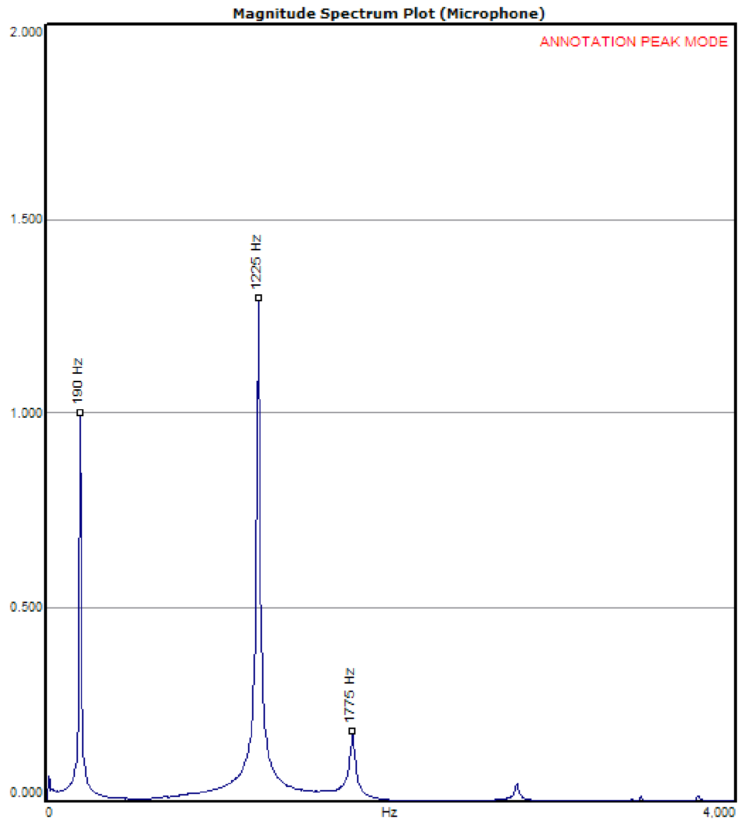
Fourier Transform of Combustor Pressure



During an instability, combustion process generally excites one or more of the natural acoustic modes of the combustor

Resonant Modes – You can try this at home

- Helmholtz Mode
  - 190 Hz
- Longitudinal Modes
  - 1,225 Hz
  - 1,775 Hz
- Transverse Modes
  - 3,719 Hz
  - 10,661 Hz



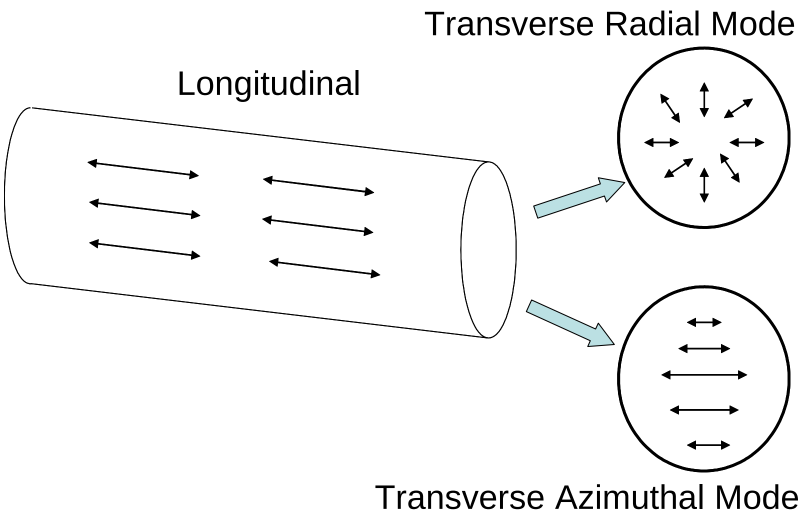
Slide courtesy of R. Mihata, Alta Solutions

Types of Combustor Modes

- Bulk (Helmholtz) modes, entropy modes
  - Low frequency (LFD), often <50 Hz
  - “Rumble”

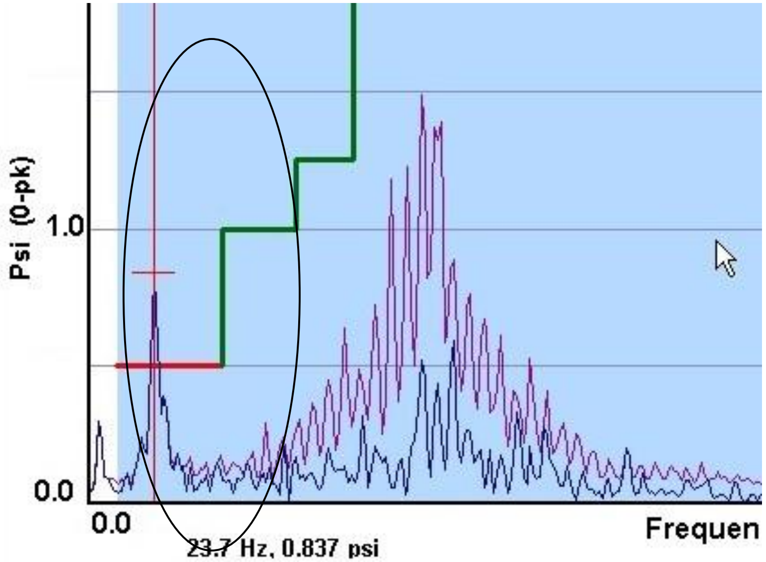
- Longitudinal modes
  - Mid frequency range, 100’s Hz

- Transverse Modes
  - High frequency, often >1000 Hz
  - “Screech”



Low Frequency Modes
Entropy Modes

- Usually occur very near blowout conditions
  - “Cold tone”
- Frequencies often in the 10-40 Hz range
- Apparently caused by partial flame extinction
  - convection of “hot spots” through nozzle
- Frequency
  - Period of oscillations: T_a=L/u +L/c
  - L = combustor length
  - U = Mean flow velocity
  - c= sound speed =$(\gamma RT)^{1/2}$
    - γ – specific heats ratio
    - R ~ Gas constant
    - T – Temperature
  - Frequency = 1/T_a

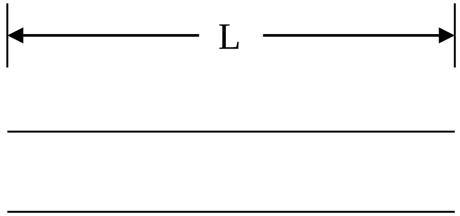


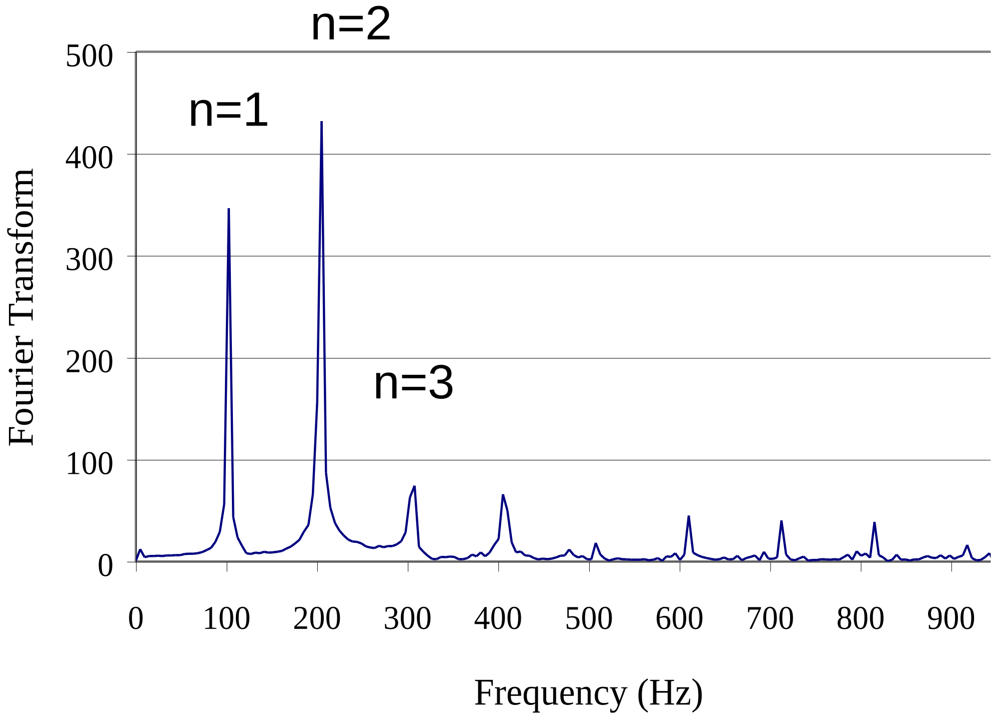
24 Hz Rumble from S/W501F
Courtesy of Calpine Corp.

Longitudinal Modes

- Example: duct

with two open end





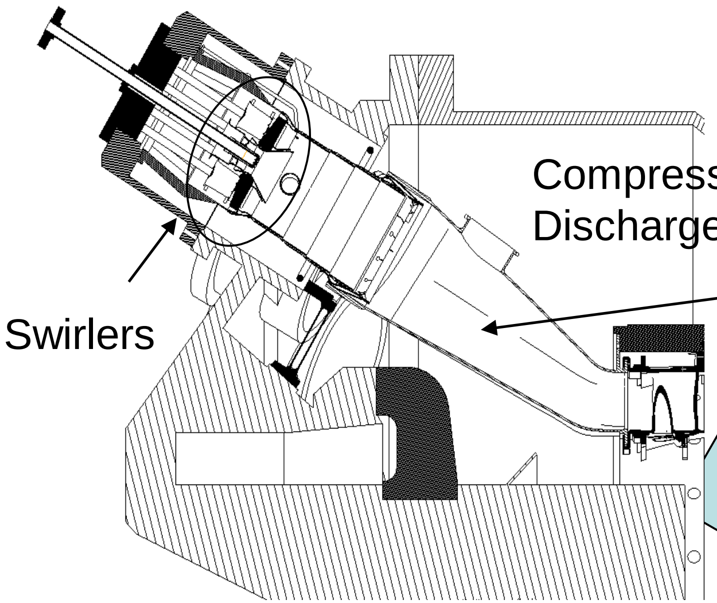
- Natural Frequencies:

$$f_n = nc/2L$$

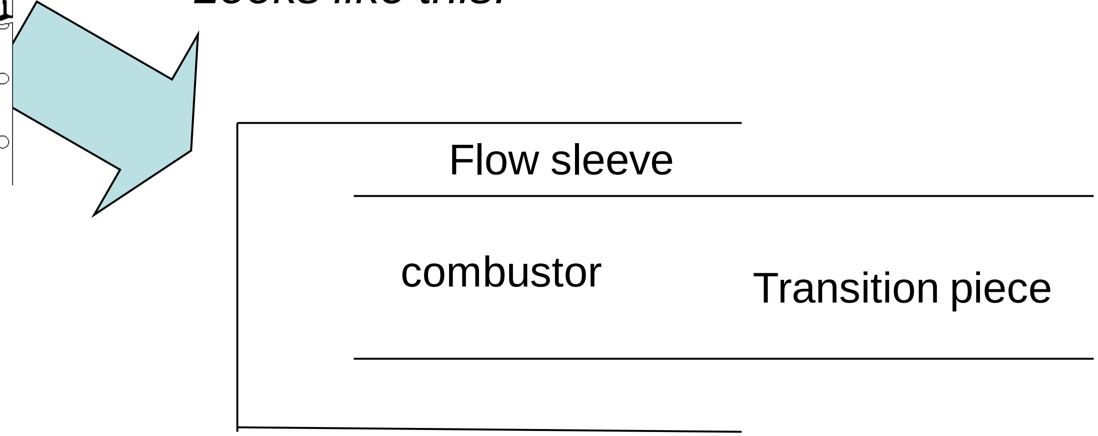
n=1, 2, ….

Longitudinal Modes in Realistic Combustors

To a sound wave, this:

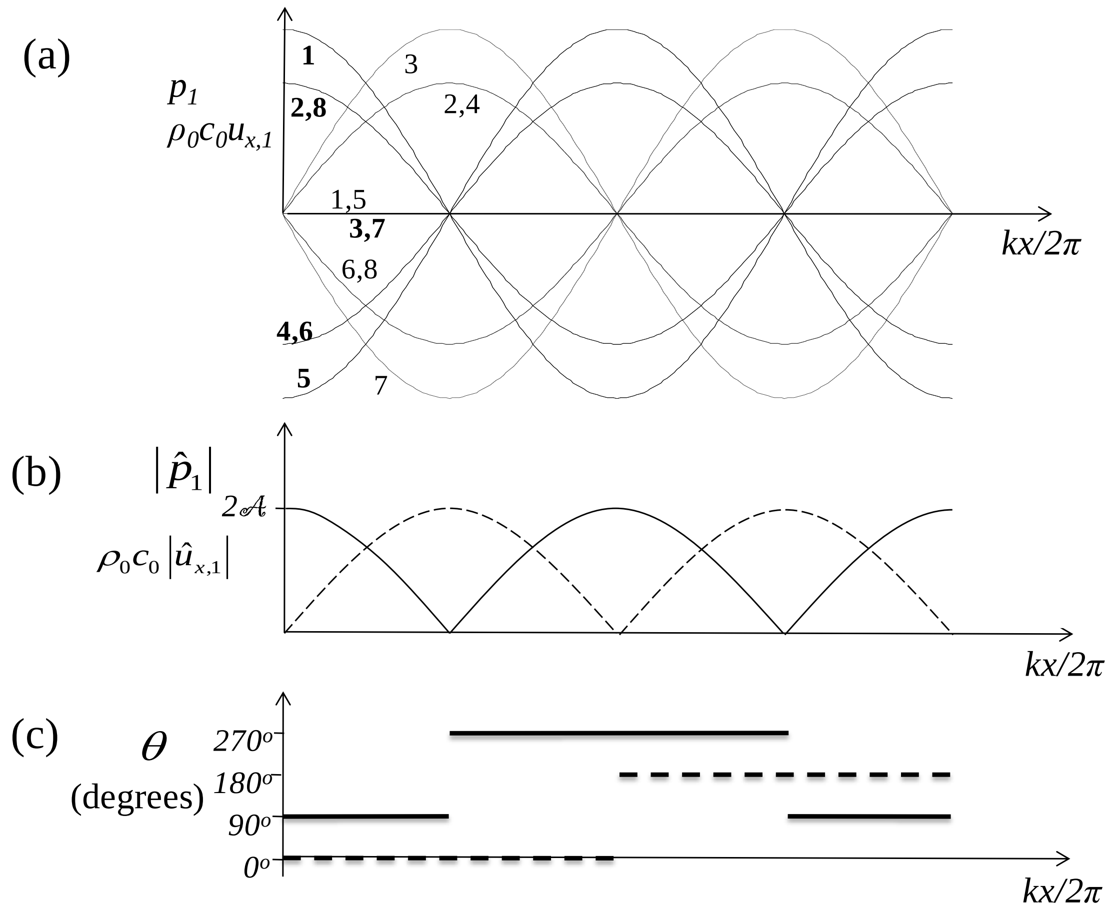


Looks like this:



Mode Shapes/Standing Waves

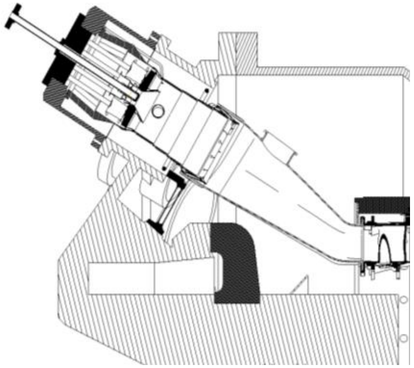
- At each spatial location, pressure amplitude oscillates sinusoidally
- P(x,t)=A(x)sin(wt)
  - Solid line
  - i.e., amplitude of variation depends upon spatial location
- U(x,t)=B(x)sin(wt+ϕ)
  - Dashed line



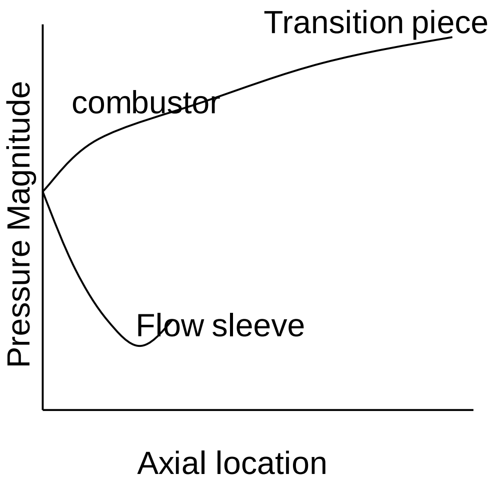
Spatial dependence of pressure (solid) and velocity (dashed) in a standing wave.

Mode Shapes

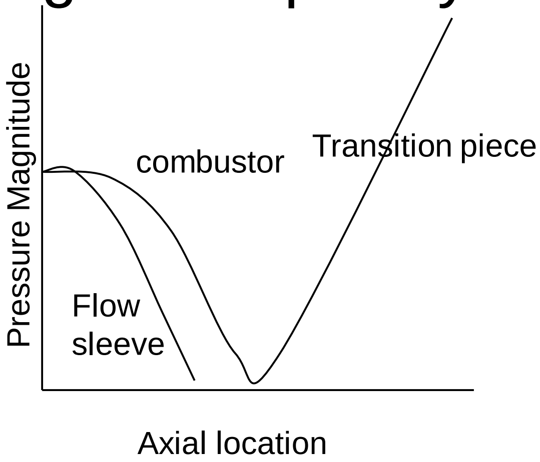
- At each spatial location, pressure amplitude oscillates sinusoidally
  - However, amplitude of variation depends upon spatial location
  - Makes comparison of amplitude across modes difficult
- Dynamics amplitude is a function of transducer location!



Lower frequency mode



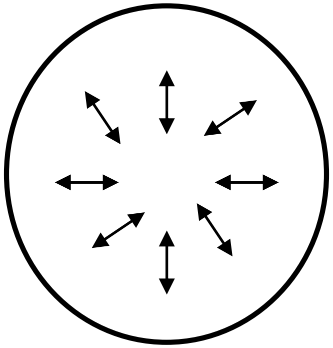
higher frequency mode



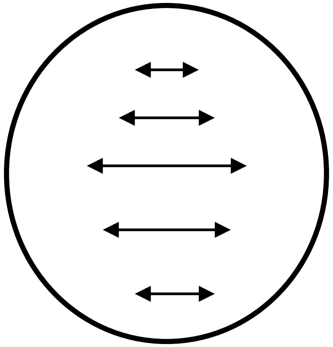
Transverse (Screech) Modes

- $f = \beta c / D$
  - β = 0.59, 0.97, 1.22, …
  - D – diameter
- Example: 13.25” diameter can at 2700 F
  - f=1423, 2340, 2940, … Hz
- Particularly destructive

Radial (1-R)



Azimuthal (1-T)

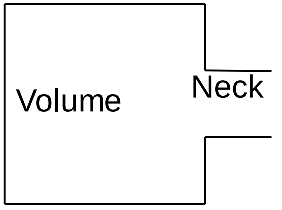


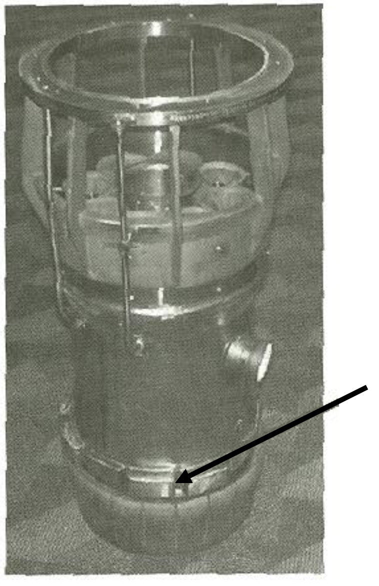
Helmholtz modes

- Tone you hear blowing across a milk jug
- Natural Frequency:
  - S_1 = Neck X-sect area
  - V_2 = Volume
  - L_1= Neck length

$$f = \frac{c}{2\pi}\sqrt{\frac{S_1}{L_1 V_2}}$$

- Used as a damping strategy
  - e.g., used by Siemens, Mitsubishi for screech damping



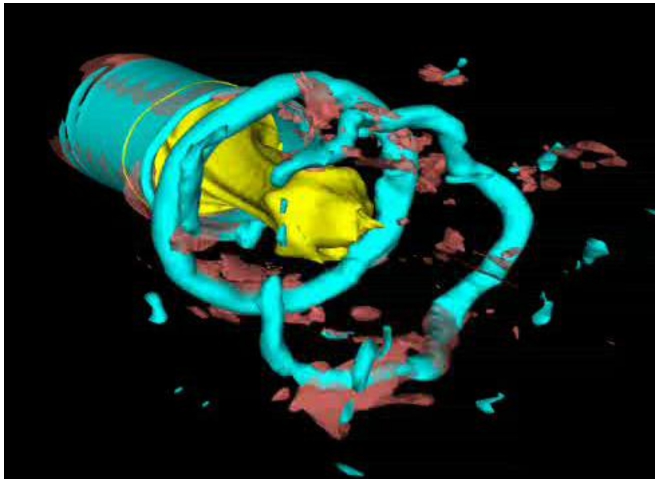


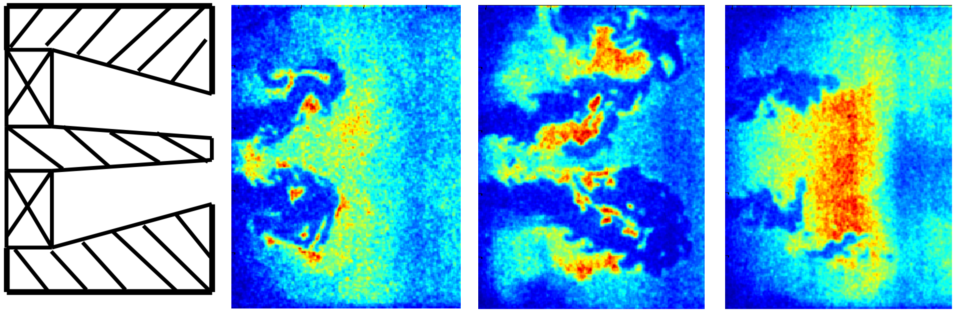
Combustion Instabilities – Basic Characteristics

Mechanisms/Conditions of Occurrence

Why do Instabilities Occur?

- Important to establish details of feedback loop responsible for oscillations
  - Referred to as instability "mechanism"
  - Variety of mechanisms possible
- 2 important mechanisms in DLN combustors
  - Equivalence ratio of reactive mixture oscillates and disturbs flame
  - Vortices in combustor distort flame

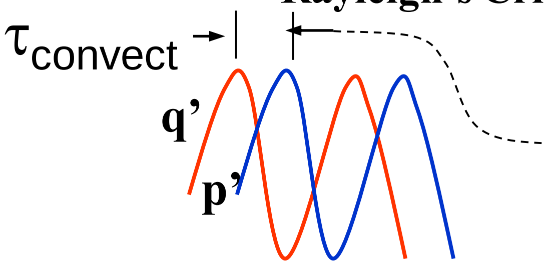




Rayleigh's Criterion and Conditions for Self-Excited Oscillations

Driving **Flame adds energy to acoustic field when**

Rayleigh's Criterion is satisfied:



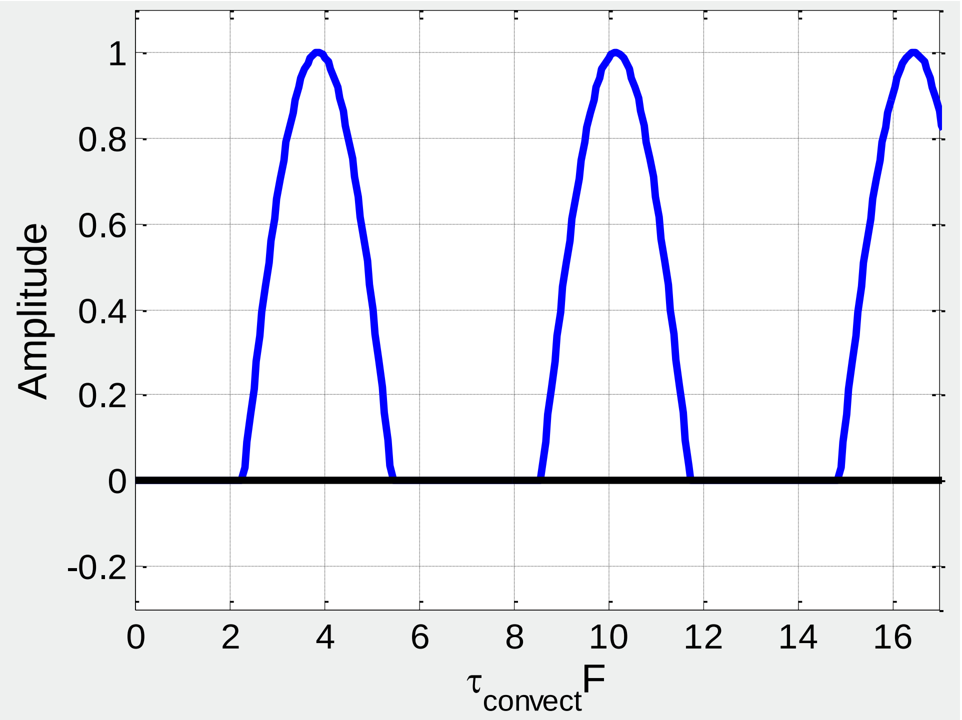
Pressure and heat release in phase (more precisely, when their phase θ_{pq}< 90º)

Damping **Oscillations damped by viscosity, heat transfer, sound radiation…**

Condition for Instability : **Driving of Oscillations** **>** **Damping of Oscillations**

Conditions of Occurrence

- Instabilities can occur when:
  - $\cos(\tau_{convect}F)>0$
    - $\tau_{convect}$ = time required for mixture to convect from fuel injection point to flame
    - F= natural combustor frequency



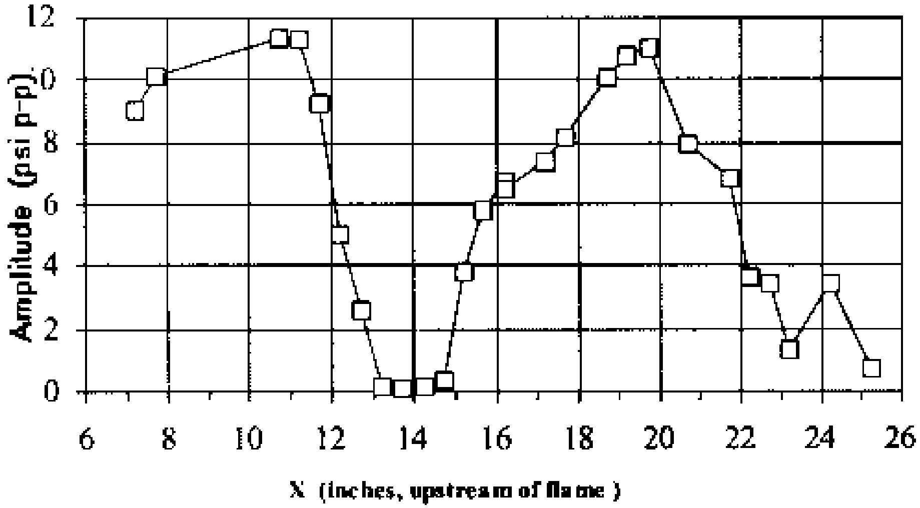
Data Illustrating Role of Convective Delay

Premixer Length Variation

•Data shows "instability bands" of a single mode

•Implication:

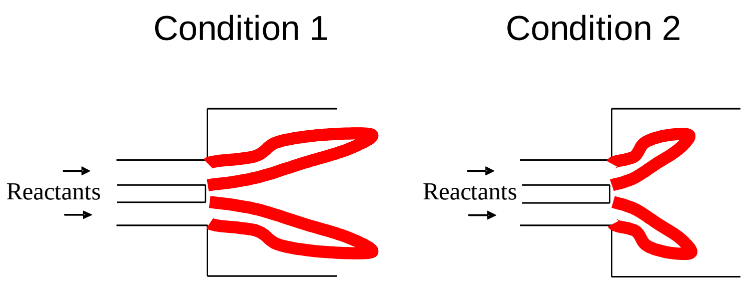
- "hot tone" a misnomer (instabilities depend upon convective time, combustors not necessarily more unstable at high power levels)

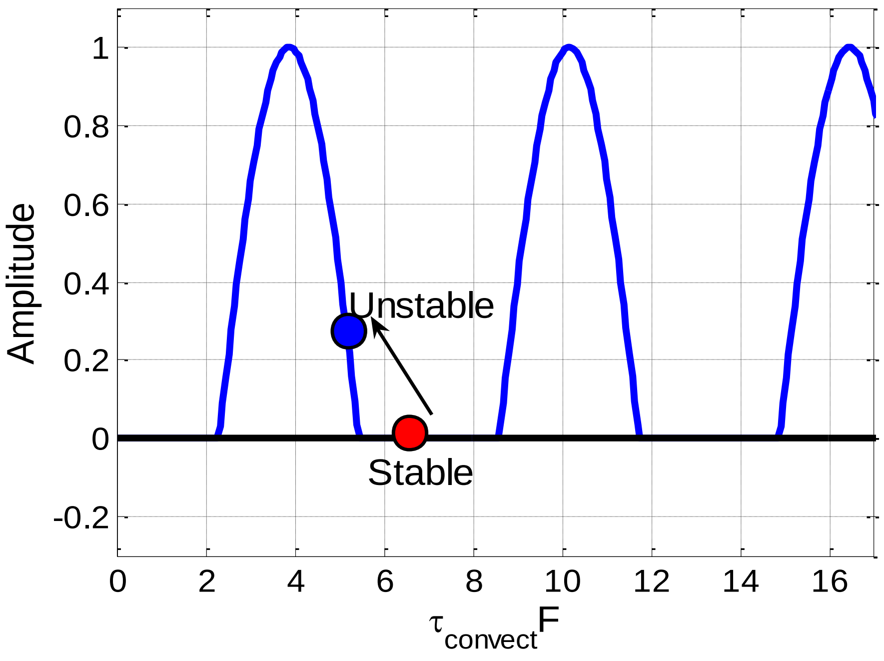


From Lovett, J., and Uznanski, K., Prediction of Combustion Dynamics in a Staged Premixed Combustor, ASME Paper # 2002-GT-30646

Effects of Fuel/Operating Conditions on Conditions of Occurrence

- Key effect of fuel/operating conditions on dynamics is through alteration of flame shape/location

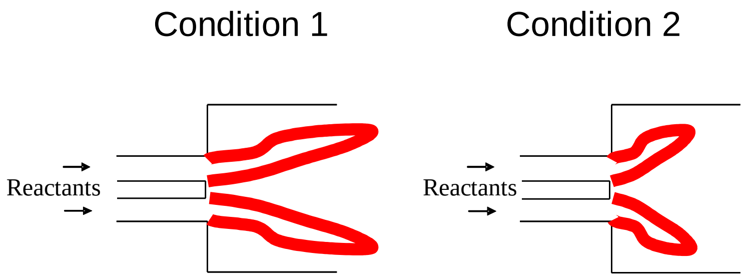


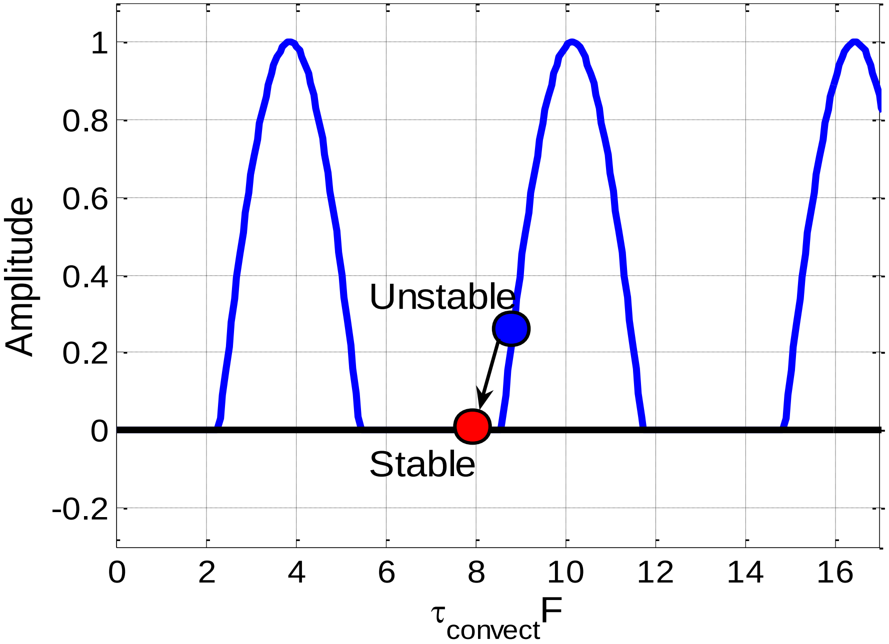


Example where dynamics made worse

Effects of Fuel/Operating Conditions on Conditions of Occurrence

- Key effect of fuel/operating conditions on dynamics is through alteration of flame shape/location



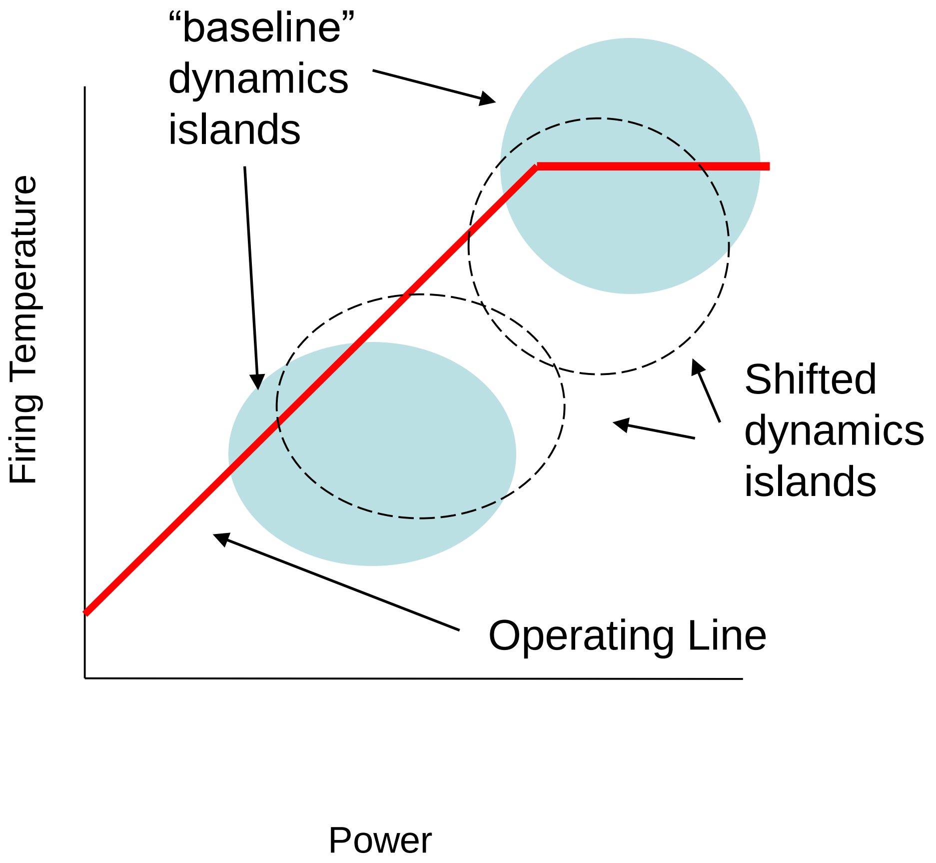


Example where dynamics made better

- Poinsot Video

Fuel Effects

- Change in fuel does not change susceptibility to dynamics (either for better or for worse), rather it moves instability islands
  - Very system and operating condition dependent
- Cannot make definitive comments on whether dynamics will be “better” or “worse:

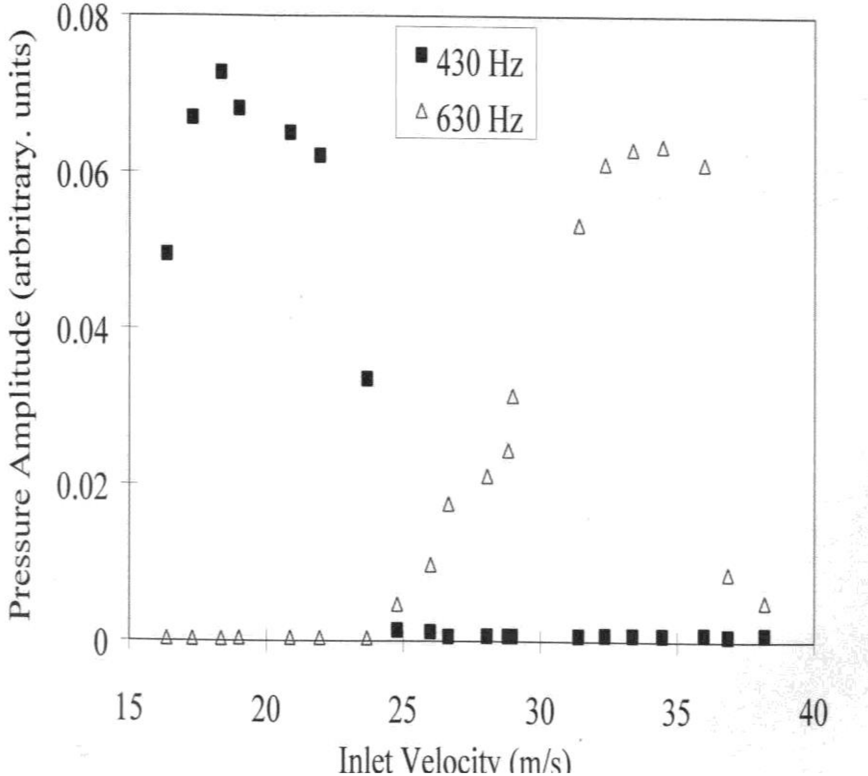


Data Illustrating Role of Convective Delay

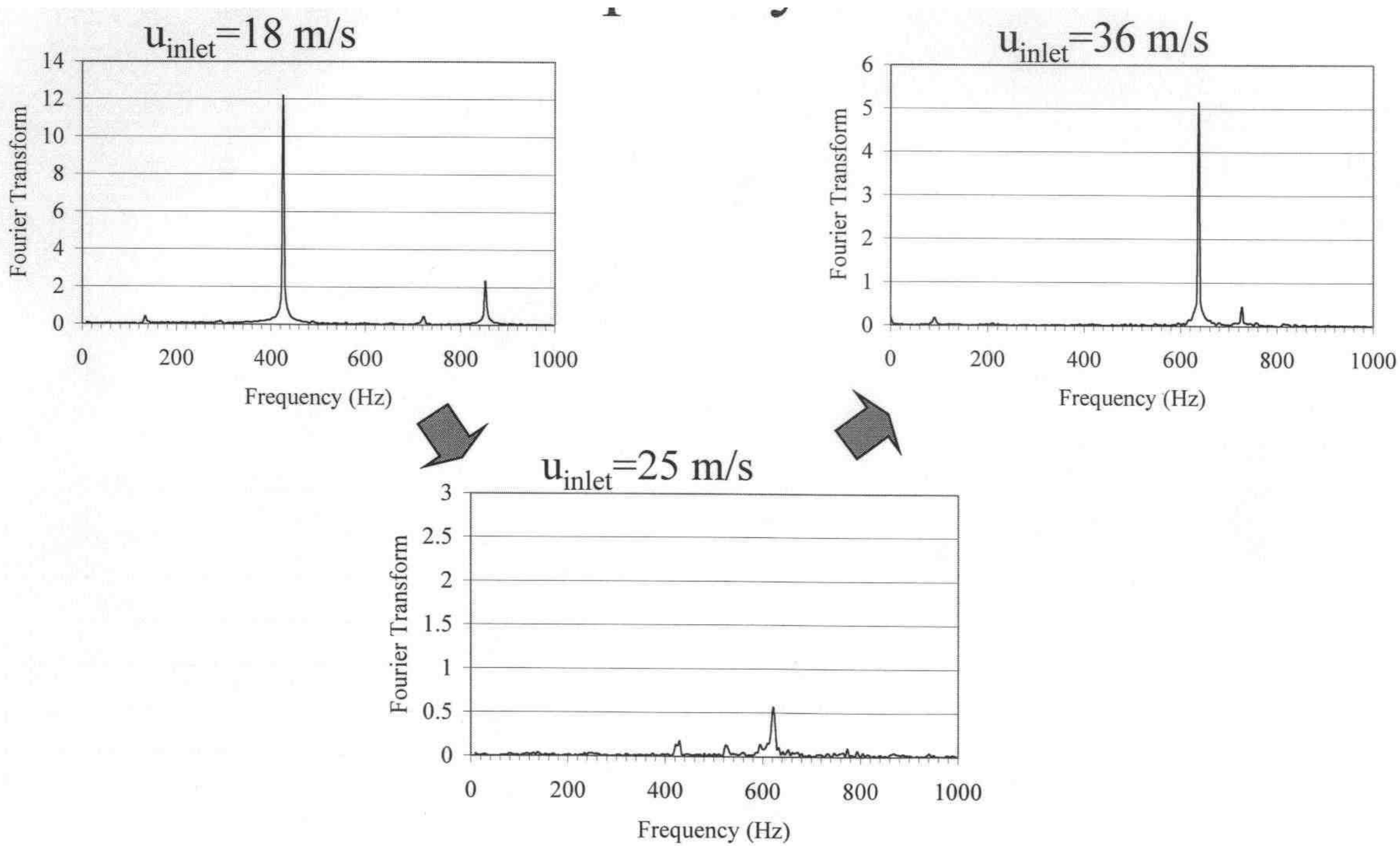
Premixer velocity variation

- Data shows variation of instability amplitude with premixer velocity
  - 430 Hz mode excited at lower premixer velocities
  - -630 Hz mode excited at higher premixer velocities

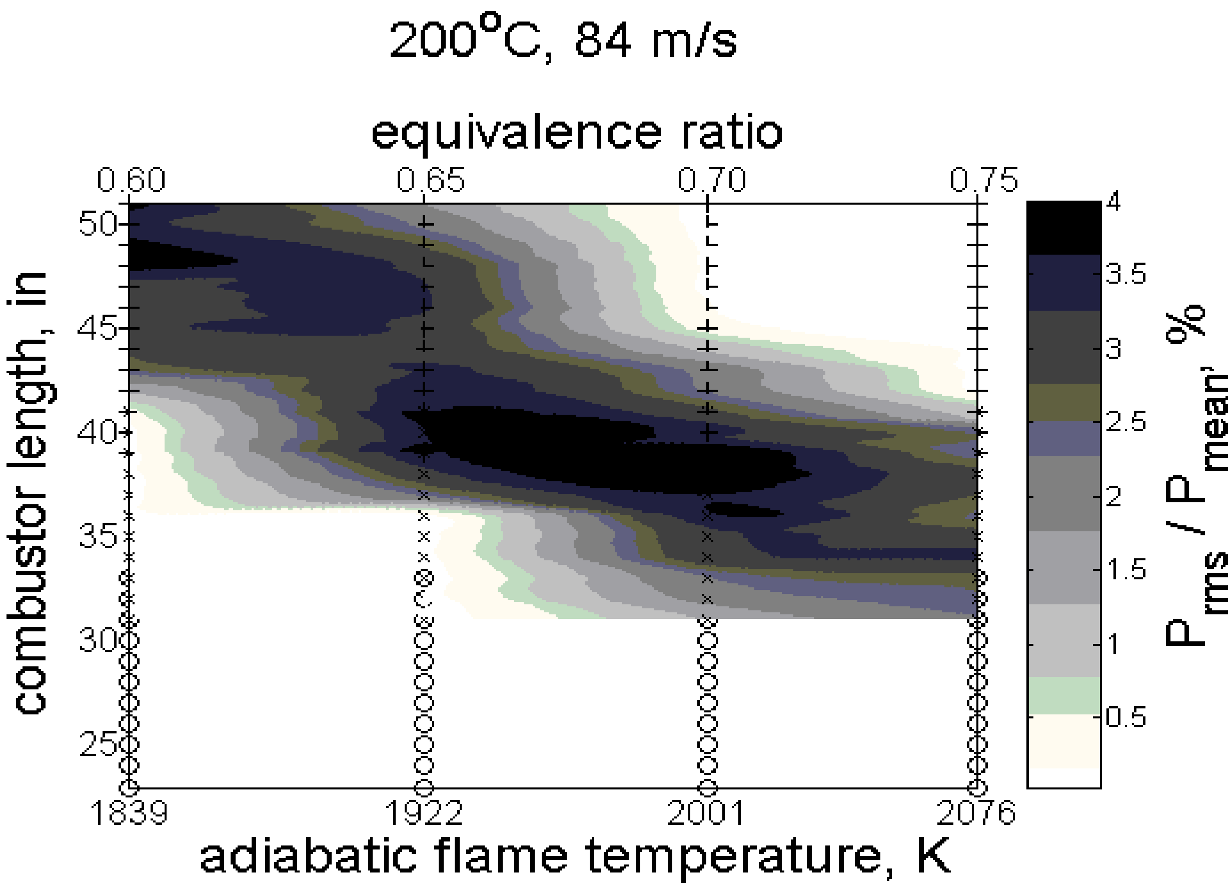
- Instabilities occur at nearly same value of $f\tau \sim f/u$



Data Illustrating Mode Switching



Key Conclusion:
Some condition exists where any combustor is unstable



Data courtesy of D. Santavicca

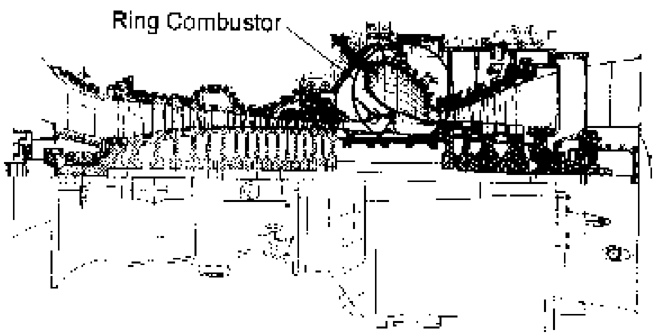
Mitigation Strategies

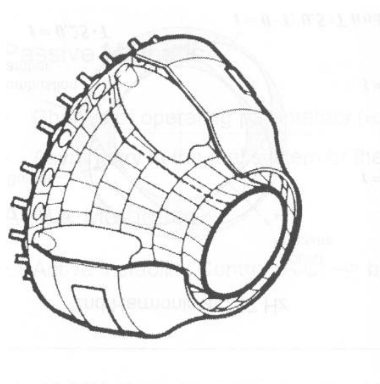
Passive Control approaches

Industry approaches

- Increased piloting
  - Solar Mars 100
  - GE LM6000
- Resonators
  - GE LM6000
  - Pratt and Whitney
  - S/W
- Decoupling fuel line acoustics by choking/de-tuning
  - Almost all
- Symmetry breaking, Fuel/Air profile
  - GE
  - Siemens VX4.3A
- Convective time variation
  - Siemens VX4.3A – Cylindrical burner outlet (CBO) welded onto several premixers
  - Solar

Case Study - Siemens VX4.3A



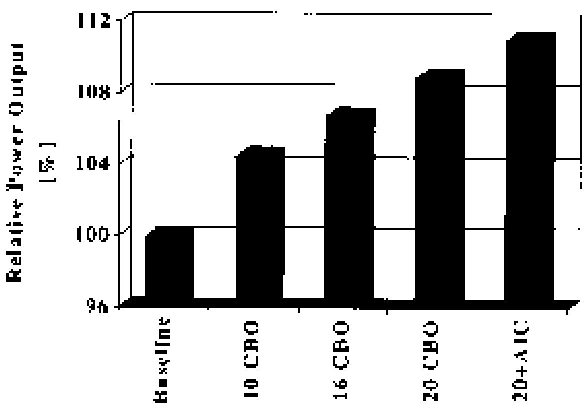


From “Application of Active Combustion Instability Control to a Heavy Duty Gas Turbine”, J. Hermann et al., presentation at 1997 Workshop on Dynamics and Control of Combustion Instabilities in Propulsion and Power Systems

- Dynamics problems near full load in VX4.3A
  - 217 and 433 Hz (2nd and 4th harmonics)
  - Problem dealt with by
    - “Symmetry breaking” – varying premixer config. around circumference
    - ABO’s and CBO’s

Case Study - Siemens VX4.3A

Symmetry breaking, CBO's, ABO's



From "Suppression of Dynamic Combustion Instabilities by Passive and Active Means", by P. Berenbrink and S. Hoffman, ASME Paper 2000-GT-0079

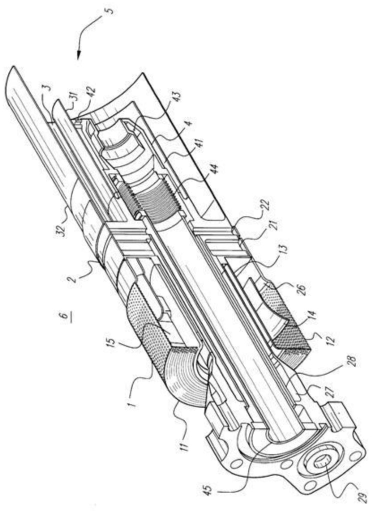
- Asymmetric burner outlets (ABO's)
  - Attempts to break coherence of vortex structures
- Cylindrical burner outlets (CBO's)
  - Vary convective time lag for equivalence ratio oscillation mechanism

Case Study - GE Energy

Flame structure, fuel staging

Flame distribution

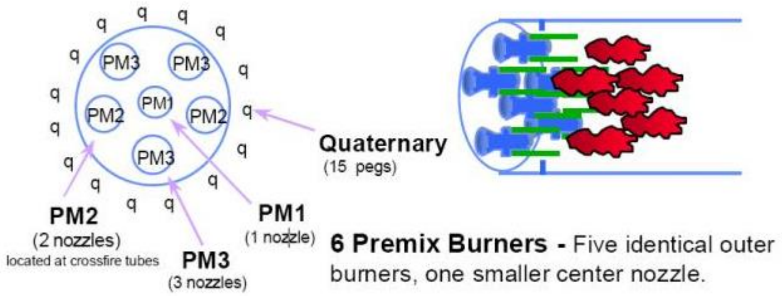
- Affects convective delay time
  - FA profile
    - – Manipulate fuel profile exiting burner
    - – Controls spatial arrival of fuel at the flame zone
      - – Radial; Tuthill et al
        - • US 6,438,961 B2
      - – Axial; Mick & Cohen
        - • US 5,551,228



US 6,438,961 B2
Tuthill et al

> Fuel staging

- – Multiple nozzles per combustor provides degrees of freedom in fuel staging
  - e.g., Assymetric fuel distribution among nozzles
  - – Davis et al - US 5,491,970



2000-GT-0086; Vandervoort et al

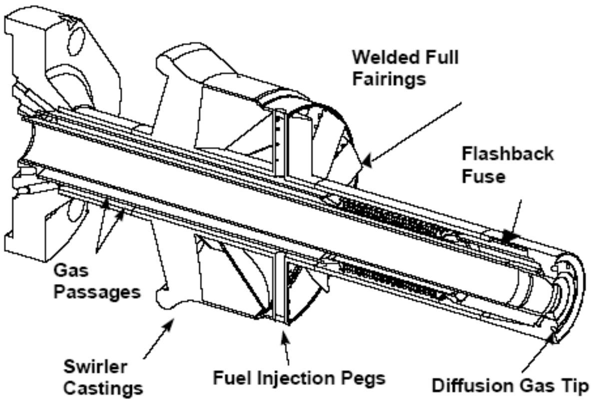
Case Study - GE Energy

Dynamic premixer response

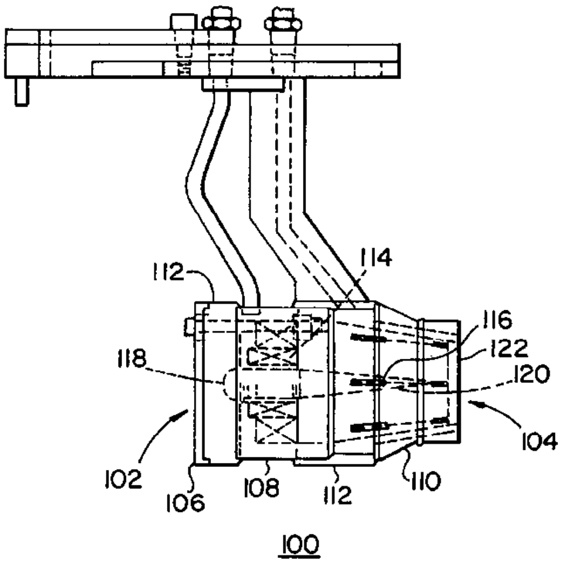
- **> Acoustically responsive fuel flow rate**
  - – Generate stabilizing F/A fluctuations

    when nozzle subjected to dynamics
  - – Black
    - US 5,211,004
  - – McManus, Sanderson & Goldmeer
    - EP 1 416 226 A2

- **> Vary convective delay time**
  - – Dean
    - US 6,272,842 B1



2000-GT-0086, Vandervoort et al



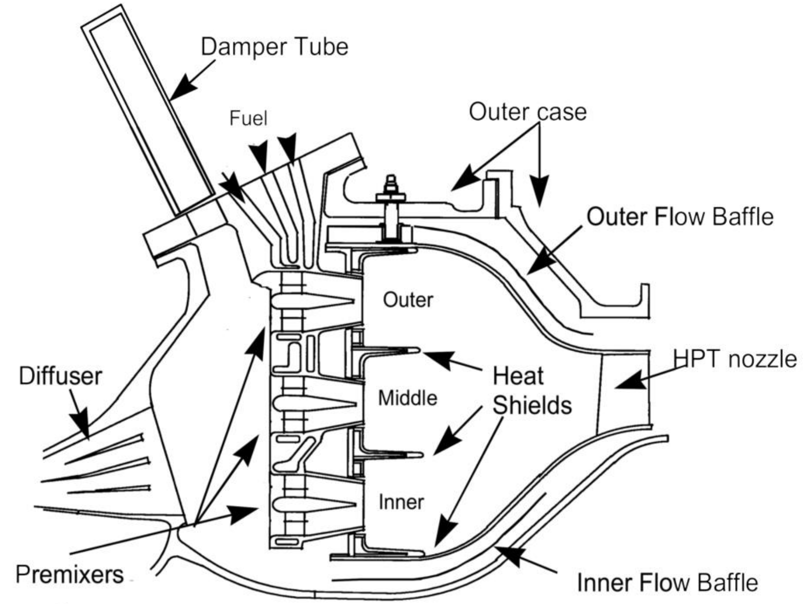
Case Study- GE Transportation

LM6000

¼ Wave tubes of three different lengths

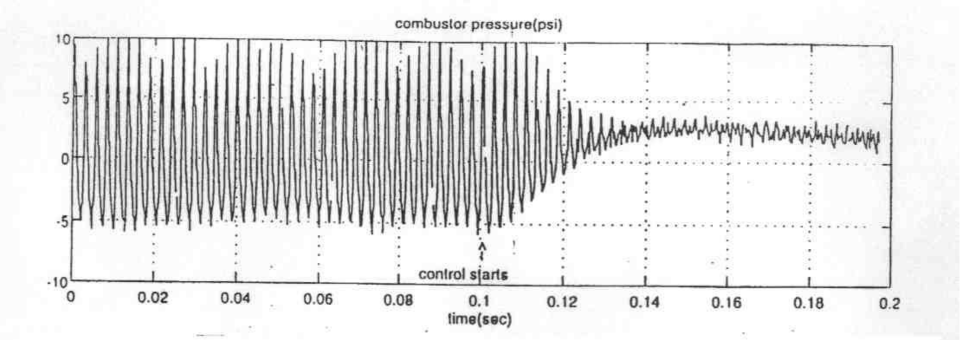
to compensate for temperature variations - > frequency variations

Fuel splits/scheduling



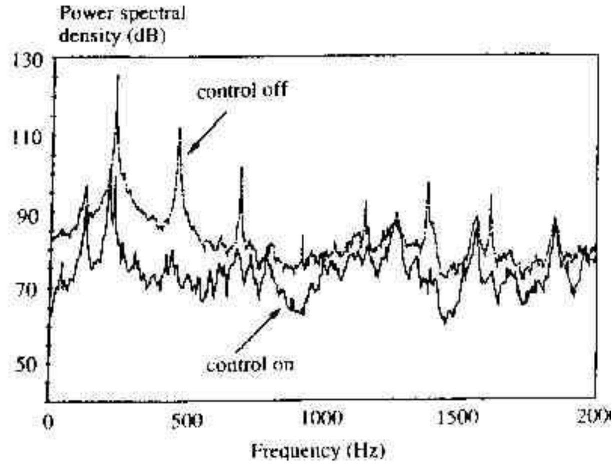
Active Methods

- Key idea:
  - Pulse fuel in combustor with secondary injector out of phase to oscillations



From Zinn and Neumeier, Archiv. Combust., Vol. 15(3-4), 1995

- Implemented by Siemens on VX4.3A series engines



From Poinsot et. al., Proc. Comb. Symp., 1988, pp.1363-1370

Measurement/Monitoring issues

Basic Monitoring System Configuration

Charge Amp Box

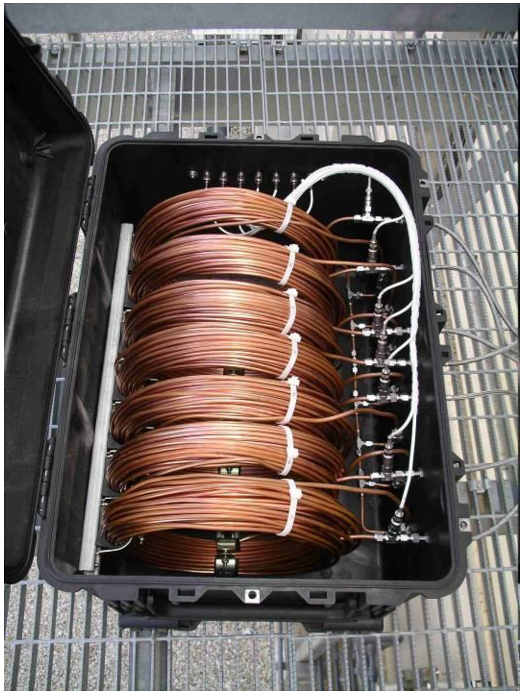
Pressure Sensor

Purging System

Monitoring System

Slide courtesy of R. Mihata,
Alta Solutions

GT Tuning (Portable CDM)

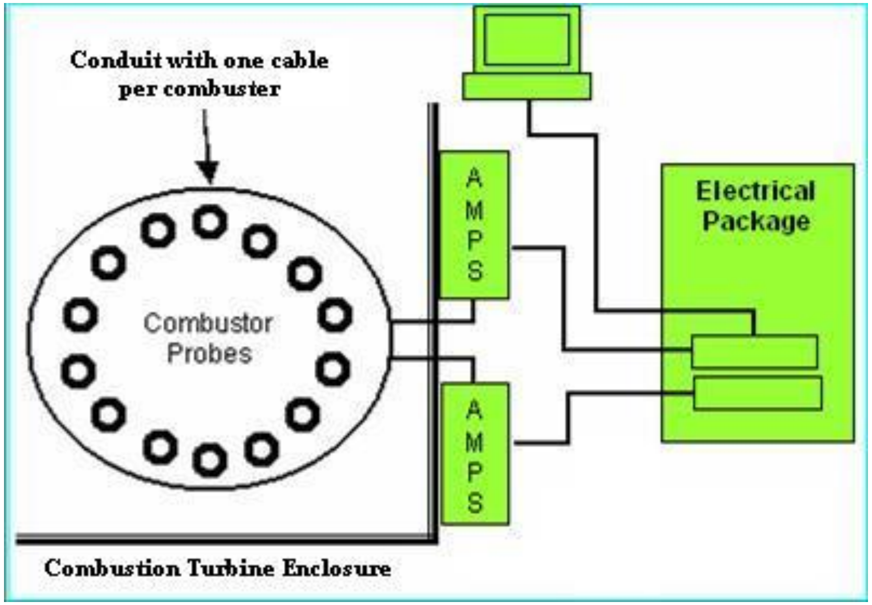


- Typically performed seasonally
- Optimizes emissions versus dynamics for conditions during tuning
- Moveable from turbine to turbine or site to site as required

Slide courtesy of J. Brooks and M. Turner, Gas Turbine Efficiency

Monitoring (Permanent CDM)

- Major Components
  - Pressure sensors
  - Sensor manifolds
  - Charge amplifiers
  - Semi-infinite tubes
  - PC/analyzer



Slide courtesy of J. Brooks and M. Turner, Gas Turbine Efficiency

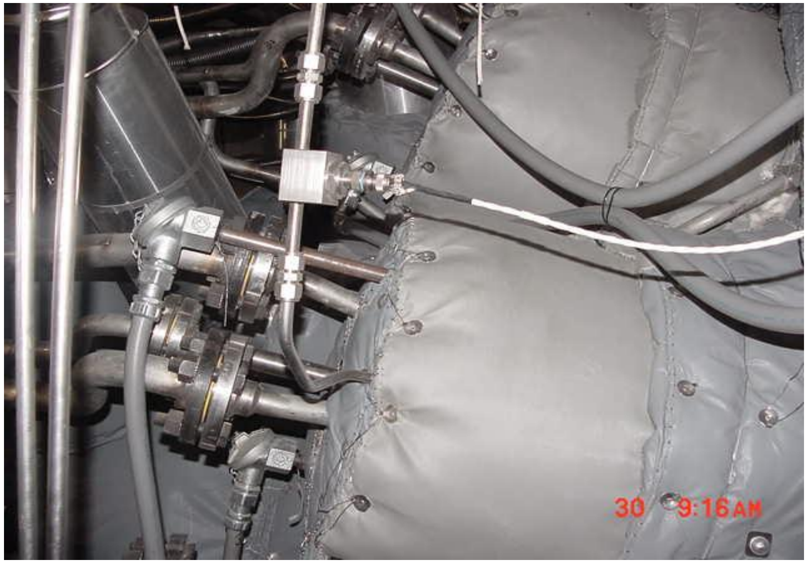
Permanent CDM

- Continuous monitoring in some or all of the combustors.
- Alerts operators (visually and/or audibly) when limits are passed
- Continuous logging of alarms
- Allows tuning on an as needed basis
  - Fuel quality changes
  - Ambient air changes
  - Change in combustion hardware (e.g., damaged nozzle, cracked transition, nozzle obstructions)
- Remote or local access for expert analysis or tuning

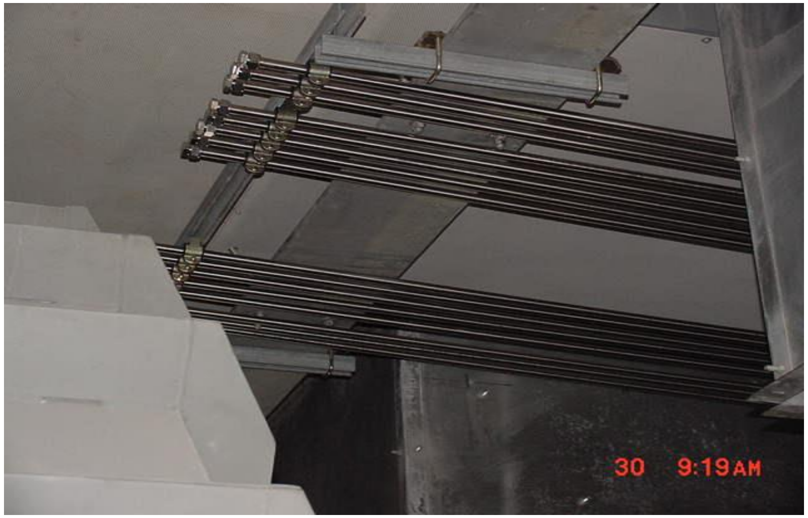
Slide courtesy of J. Brooks and M. Turner, Gas Turbine Efficiency

Siemens 501F Installation

- Major Components
  - Pressure sensors
  - Sensor manifolds
  - Charge amplifiers
  - Semi-infinite tubes
  - PC/analyzer

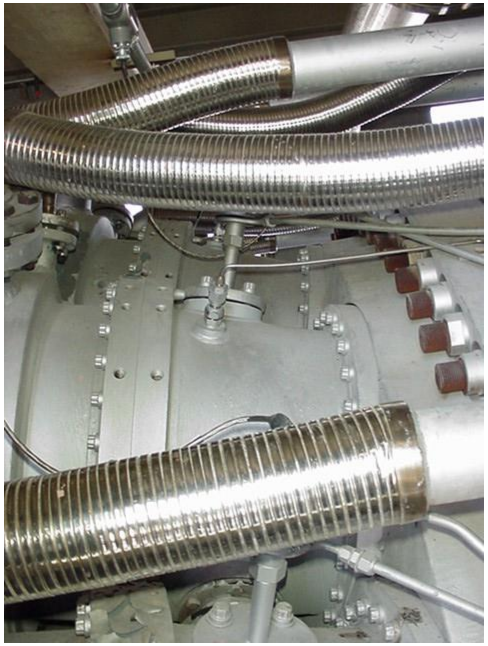


Slide courtesy of J. Brooks and M. Turner, Gas Turbine Efficiency

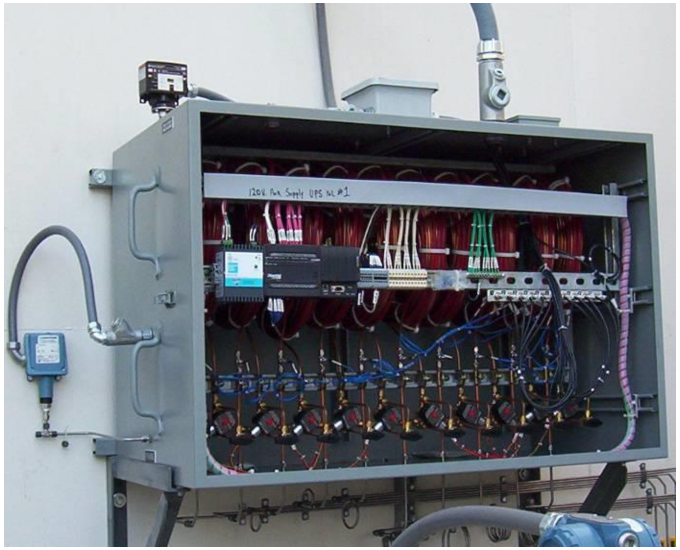


GE Installation

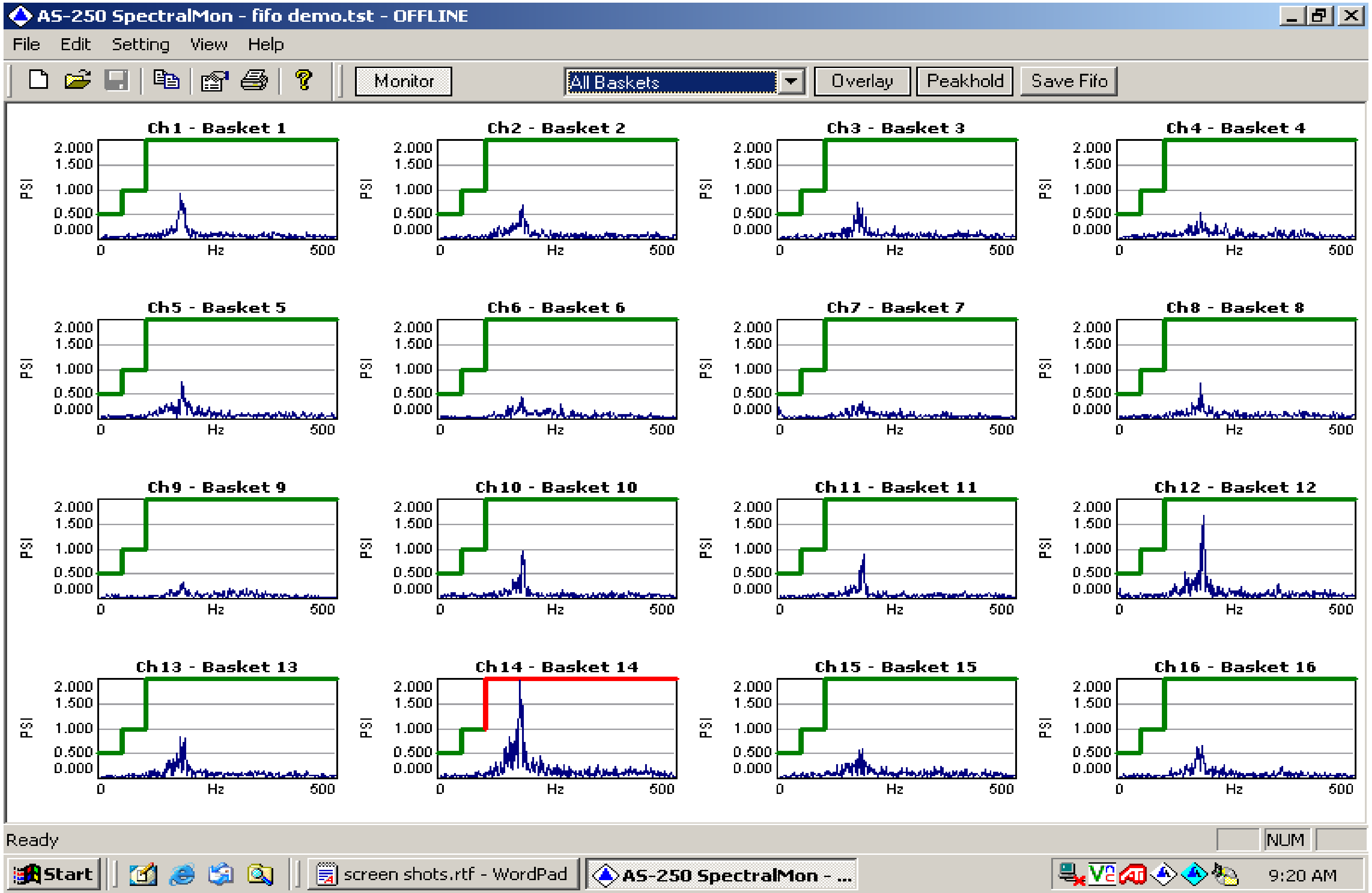
- Major Components
  - Pressure sensors
  - Sensor manifolds
  - Semi-infinite tubes
  - PC/analyzer
  - Purge system



Slide courtesy of J. Brooks and M. Turner, Gas Turbine Efficiency

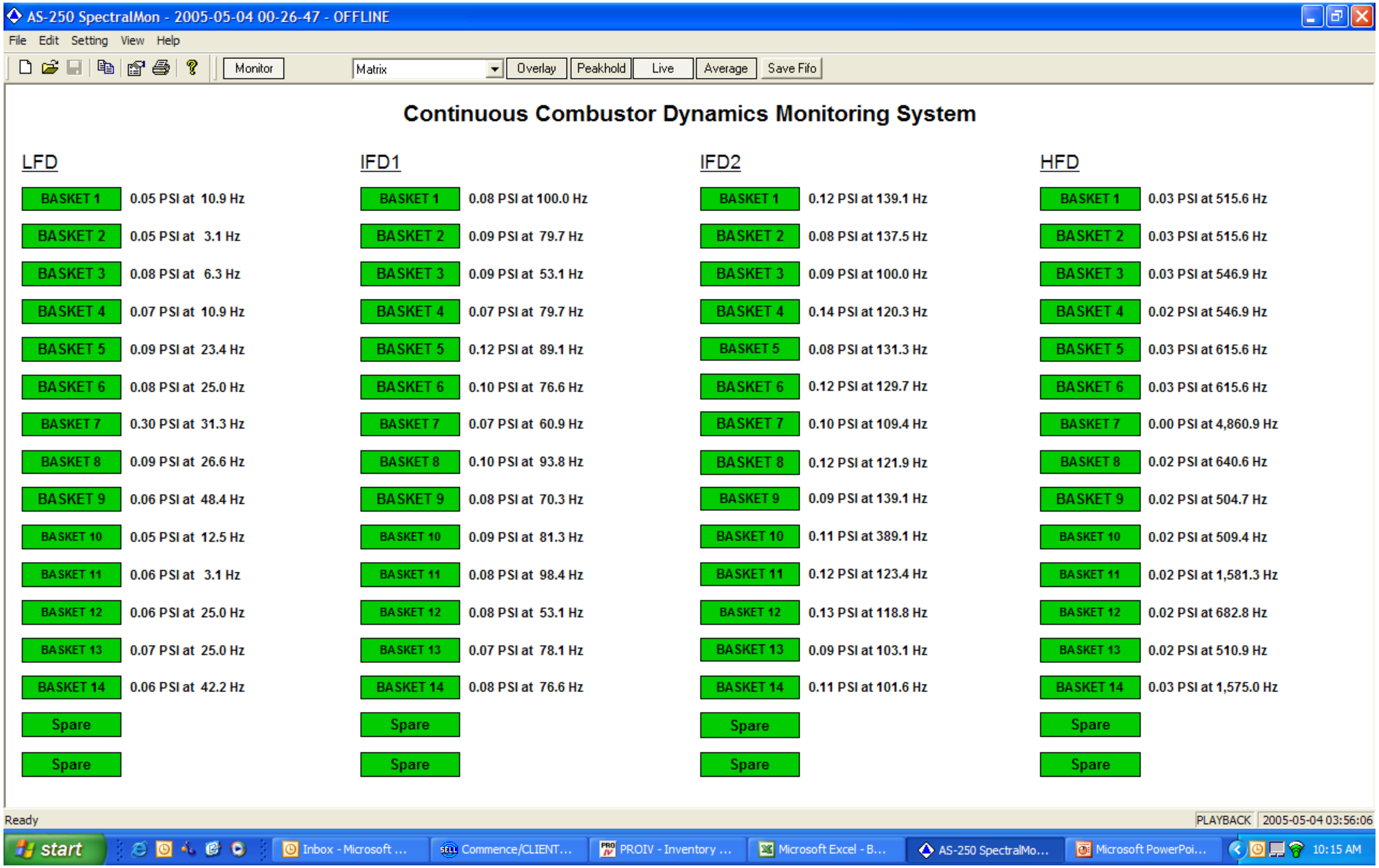


Screen Display of Combustor Baskets



Slide courtesy of J. Brooks and M. Turner, Gas Turbine Efficiency

Screen Display of Combustor Baskets



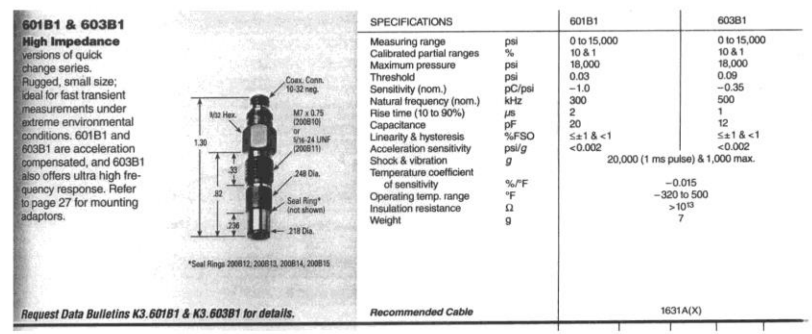
Slide courtesy of J. Brooks and M. Turner, Gas Turbine Efficiency

Acoustic Transducers

- Several Types of Transducers
  - Capacitive (varying distance changes capacitance)
  - Piezoresistive – Deformation of material changes resistance
  - Piezo-electric - Varying strain generates charge

Piezo-electric Pressure Measurements

- Operating Principle: Varying strain generates charge
  - Lose piezo-electric effect at high temps, above Curie temp
    - Typically good to ~500 F
    - Vibro-meter product literature claims their transducer good to ~1150 F
  - If your dynamics amplitude is gradually decreasing with time, you should check your transducer!



601B1 & 603B1

High Impedance versions of quick change series. Rugged, small size; ideal for fast transient measurements under extreme environmental conditions. 601B1 and 603B1 are acceleration compensated, and 603B1 also offers ultra high frequency response. Refer to page 27 for mounting adaptors.

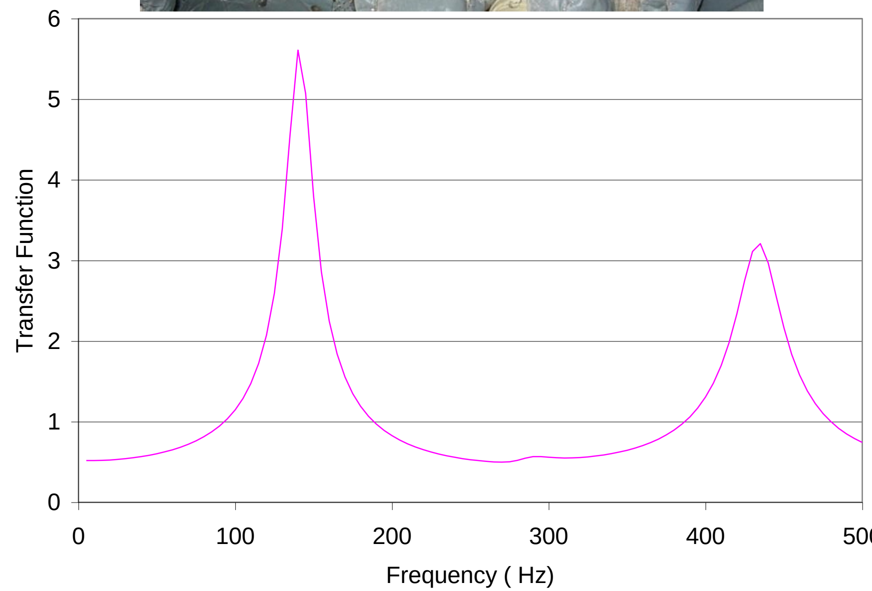
SPECIFICATIONS		601B1	603B1
Measuring range	psi	0 to 15,000	0 to 15,000
Calibrated partial ranges	%	10 & 1	10 & 1
Maximum pressure	psi	18,000	18,000
Threshold	psi	0.03	0.09
Sensitivity (nom.)	pC/psi	−1.0	−0.35
Natural frequency (nom.)	kHz	300	500
Rise time (10 to 90%)	μs	2	1
Capacitance	pF	20	12
Linearity & hysteresis	%FSO	≤±1 & <1	≤±1 & <1
Acceleration sensitivity	psi/*g*	<0.002	<0.002
Shock & vibration	*g*	20,000 (1 ms pulse) & 1,000 max.	
Temperature coefficient of sensitivity	%/°F	−0.015	
Operating temp. range	°F	−320 to 500	
Insulation resistance	Ω	$>10^{13}$	
Weight	g	7	
Recommended Cable		1631A(X)	

Request Data Bulletins K3.601B1 & K3.603B1 for details.

From Kistler product literature

Standoff Tubes

- Frequency response issues
  - Pressure at measurement and transducer location not the same due to wave reflections, dissipation in tube
  - Transfer function = TF = ratio of pressure magnitudes at the 2 locations
  - Ideal standoff tube: TF=1
- Look what happens if you just put in a piece of pipe without infinite coil



What Causes Acoustic Wave Reflections?

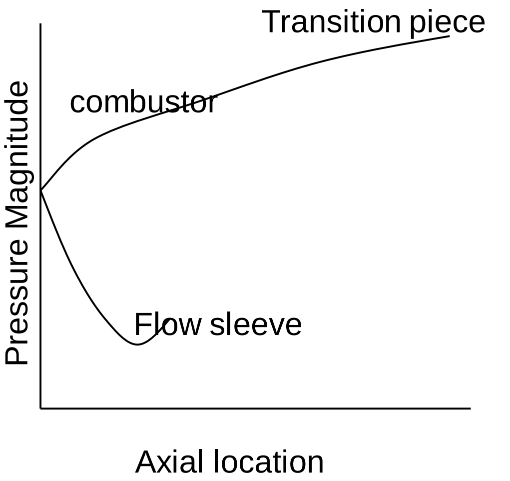
- Area Discontinuities
  - Try to minimize differences in piping/valving diameters
- Valves
  - Volume in valves causes some unavoidable effects
- Sharp bends/kinks in pipe
  - Try to keep all bend radiuses greater than 10X pipe radius

"Accuracy" of measurement system

- "Accuracy" (ratio between actual pressure and that measured by transducer) of system depends upon:
  - Standoff tube characteristics
  - Sensor calibration

- HOWEVER, DO WE REALLY CARE ABOUT ACCURACY?
  - Pressure amplitude varies spatially, thus you'd get a different number if you measured the pressure at a different location anyway
  - No one knows, based upon first principles, what an "acceptable" level of dynamics is – *its all based upon field experience*
    - using a given measurement/standoff tube system, at a given measurement point
    - "acceptable" levels will need to be adjusted if measurement point or measurement system is changed

- What we really care about is CONSISTENCY from one machine and can to the other
  - Standoff tube characteristics should be same from can to can and engine to engine
  - System in place for recalibration of sensors over appropriate time interval
  - Not clear that "more accurate" flush mounted transducers are more useful than those remotely located



Errors in Spectral Estimates
Aliasing

- Can only resolve frequencies up to one half the sampling frequency
- If frequencies are present that are greater than one half the sampling frequency, can get spurious results
  - Referred to as "aliasing"
  - Solution: make sure you have anti-aliasing filters in your DAQ (low pass filter with $f_{cutoff}<f_s/2$)

- ARE YOU MONITORING FOR SCREECH?

Further Questions?

- Feel free to contact me

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Quiz

- 1. Which of the following pollutants would you expect to grow as the engine power of a DLN system decreases?
  - CO
  - NOx
  - Particulates
  - SOx

Quiz

- 2. Which of the following operability parameters would you expect to see vary non-monotonically with engine pressure ratio for a natural gas fueled, DLN system?
  - CO emissions
  - Combustion instabilities
  - Autoignition
  - Blowoff

Quiz

- 3. Which of the following factors can cause combustion instability amplitudes to change after tuning?
  - – Ambient temperature
  - – Fuel composition
  - – Engine wear
  - – All the above

Quiz

- 4. Which of the following is generally the most significant factor limiting H_2 levels in DLN systems?
  - Combustion instabilities
  - Flashback
  - Blowoff
  - High NOx emissions

Quiz

- 5. Which of the following operability parameters would you expect to see vary non-monotonically with engine pressure ratio for a natural gas fueled, DLN system?
  - – CO emissions
  - – Combustion instabilities
  - – Autoignition
  - – Blowoff

