Unsteady Combustor Processes

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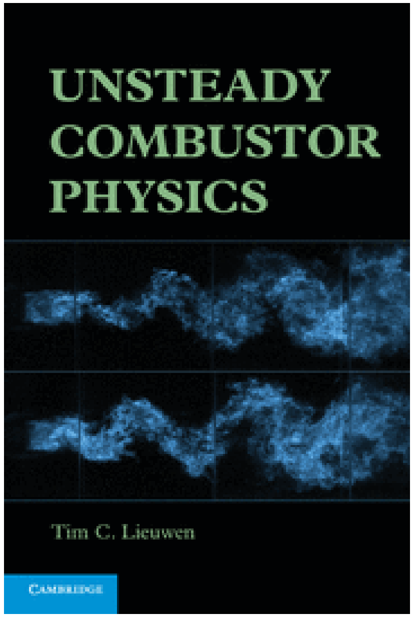
2018 Summer School on Combustion

References


UNSTEADY COMBUSTOR PHYSICS
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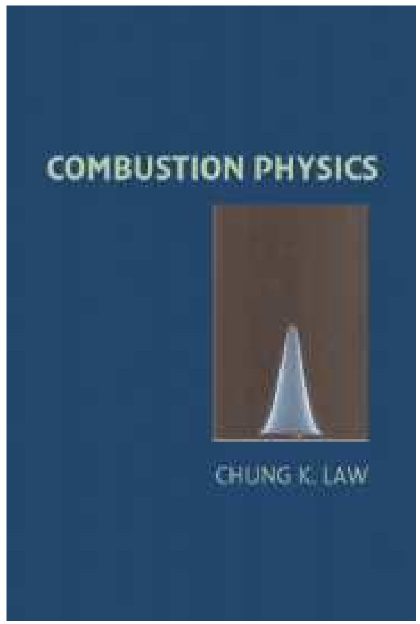
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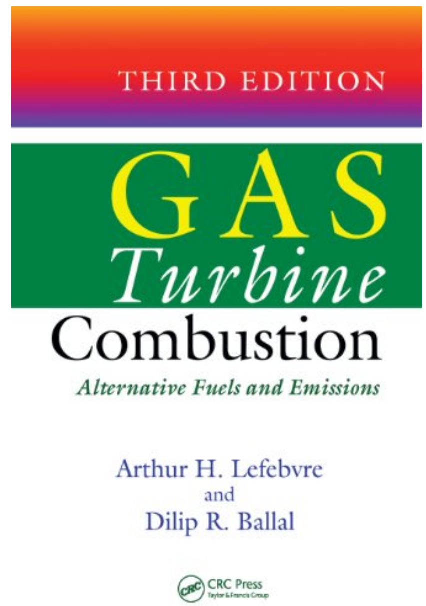
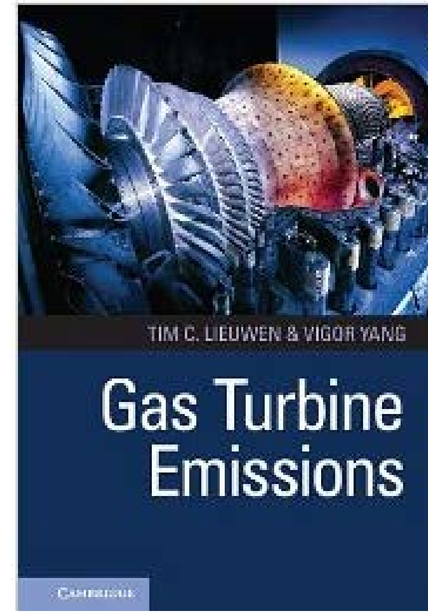

THIRD EDITION
GAS Turbine Combustion
Alternative Fuels and Emissions
Arthur H. Lefebvre
and
Dilip R. Ballal
CRC Press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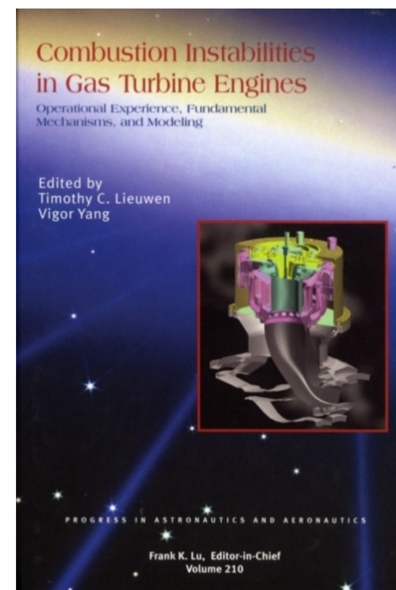
Gas Turbine Emissions


Combustion Instabilities in Gas Turbine Engines
Operational Experience, Fundamental Mechanisms, and Modeling
Edited by
Timothy C. Lieuwen
Vigor Yang
PROGRESS IN ASTRONAUTICS AND AERONAUTICS
Frank K. Lu, Editor-in-Chief
Volume 210

Course Outline

Key course themes –
Physical/Chemical processes → Unsteady combustion processes → Operational limits of combustion devices.

- A) Introduction and outlook — (1 hours)
- B) Flame Aerodynamics and Flashback — (1 hours)
- C) Flame Stretch, Edge Flames, and Flame Stabilization Concepts — (3 hours)
- D) Disturbance Propagation and Generation in Reacting Flows — (3 hours)
- E) Flame Response to Harmonic Excitation — (1 hours)

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- Constraints and metrics
- Emissions
- Autoignition
- Future outlook for needed research

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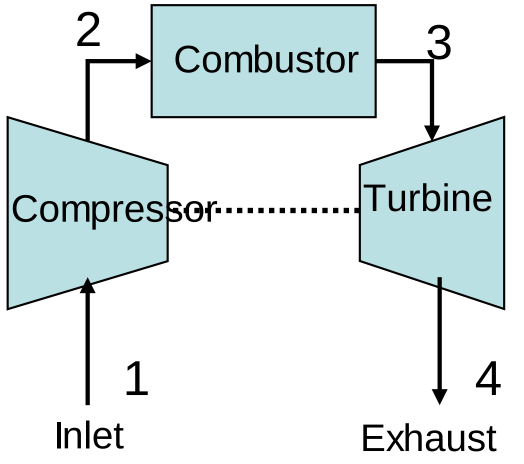
Gas Turbine Cycle

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



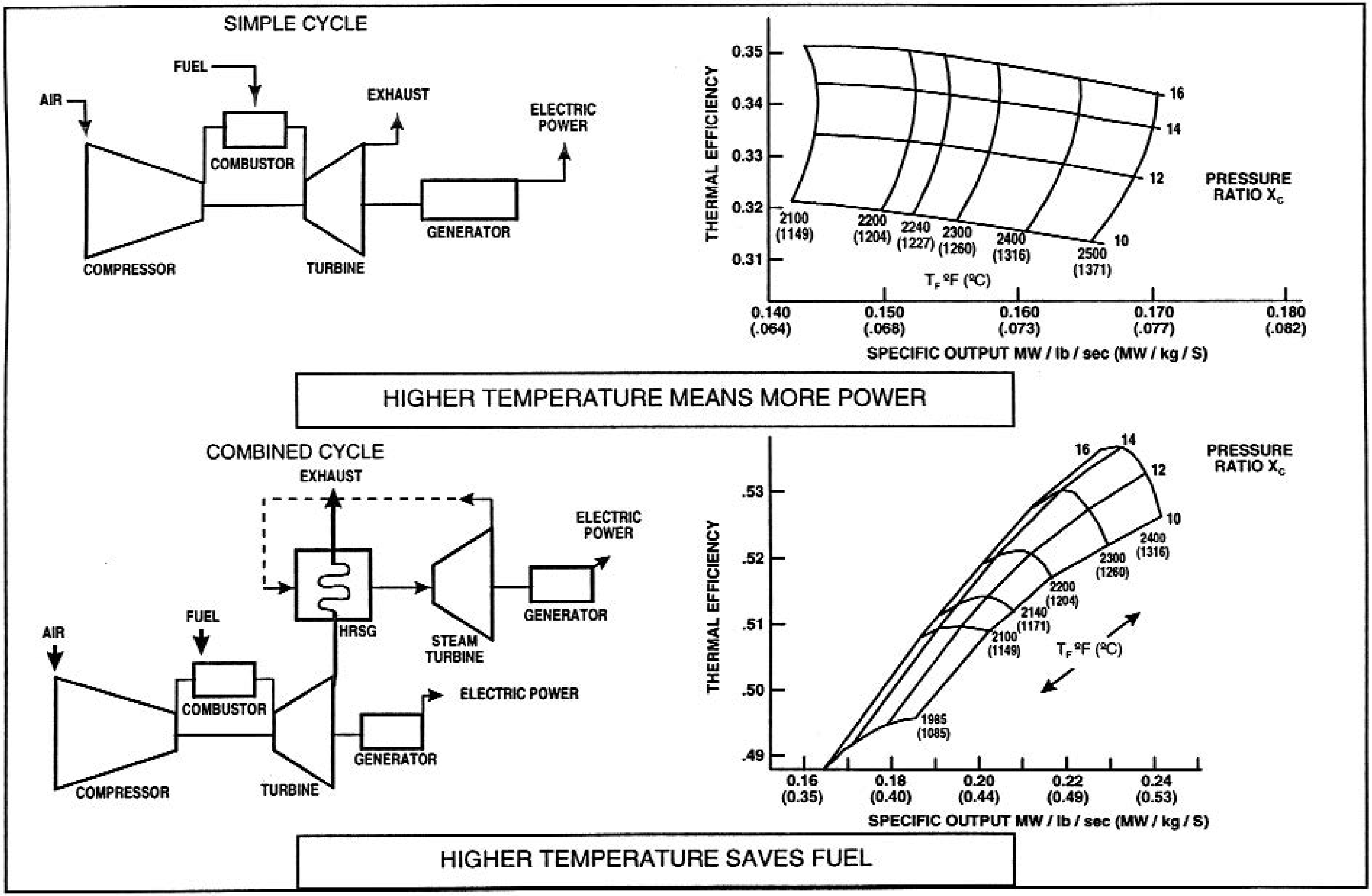
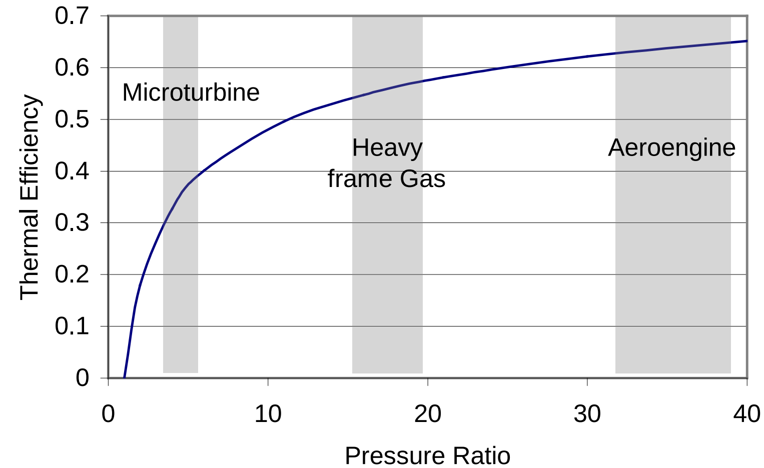


Figure 7. Gas turbine thermodynamics

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

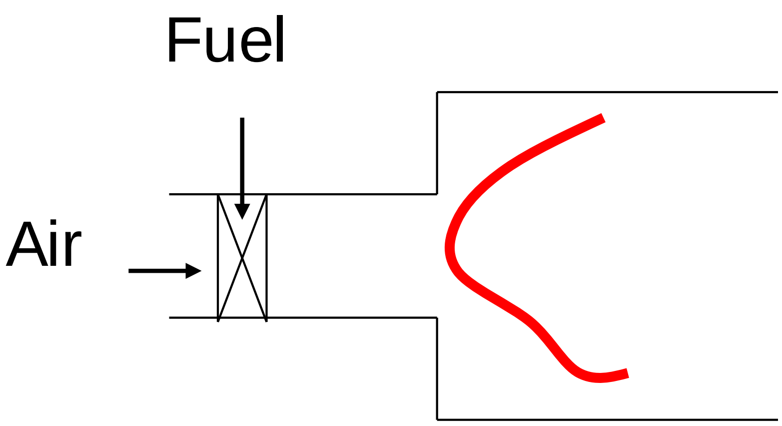
Role of Combustor within Larger Energy System



- 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

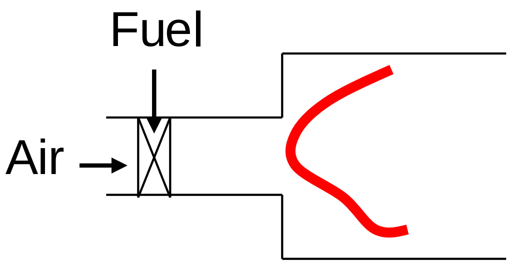
Combustor Performance Metrics

- 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

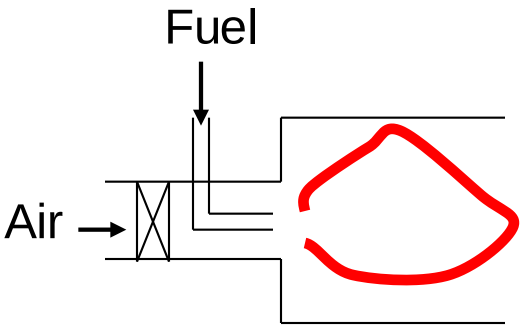


Premixed vs Non-Premixed Flames

- 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)

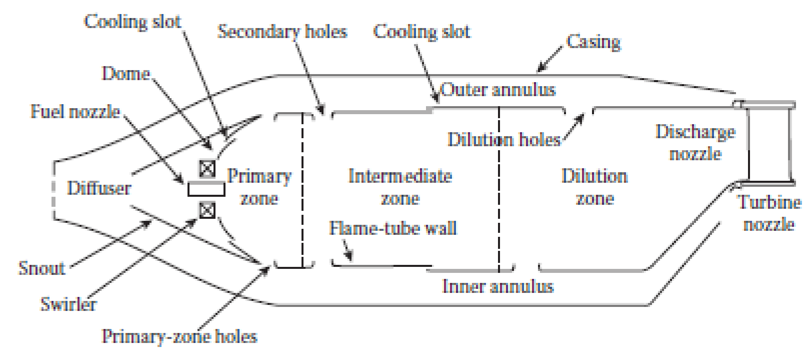


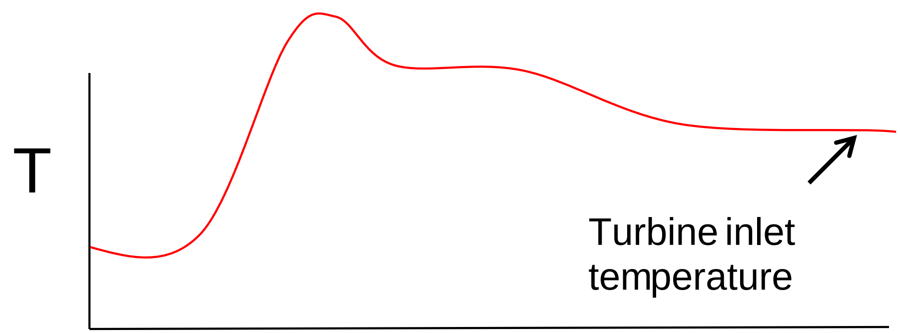
- Non-premixed flames
  - Fuel and air separately introduced into combustor
  - Mixture burns at f=1
    - i.e., stoichiometry cannot be controlled
    - Hot flame, produces lots of NOx and more sooting
    - More robust, higher turndown, simpler



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"



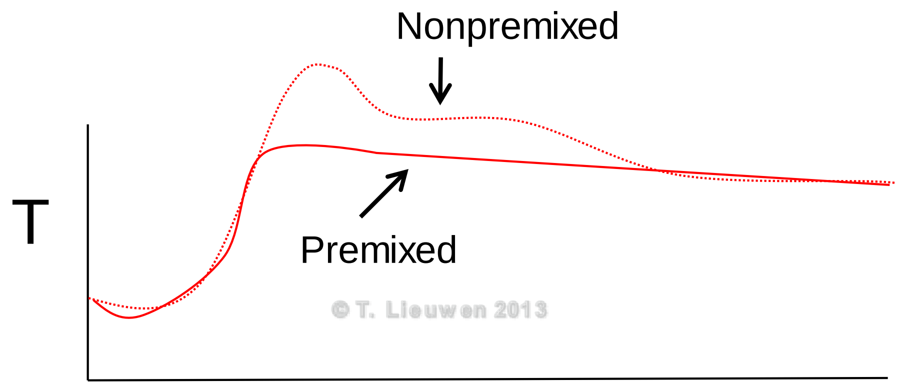


Combustor Configurations Dry, Low NOx (DLN) Systems

- 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



Can Combustion Layout

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

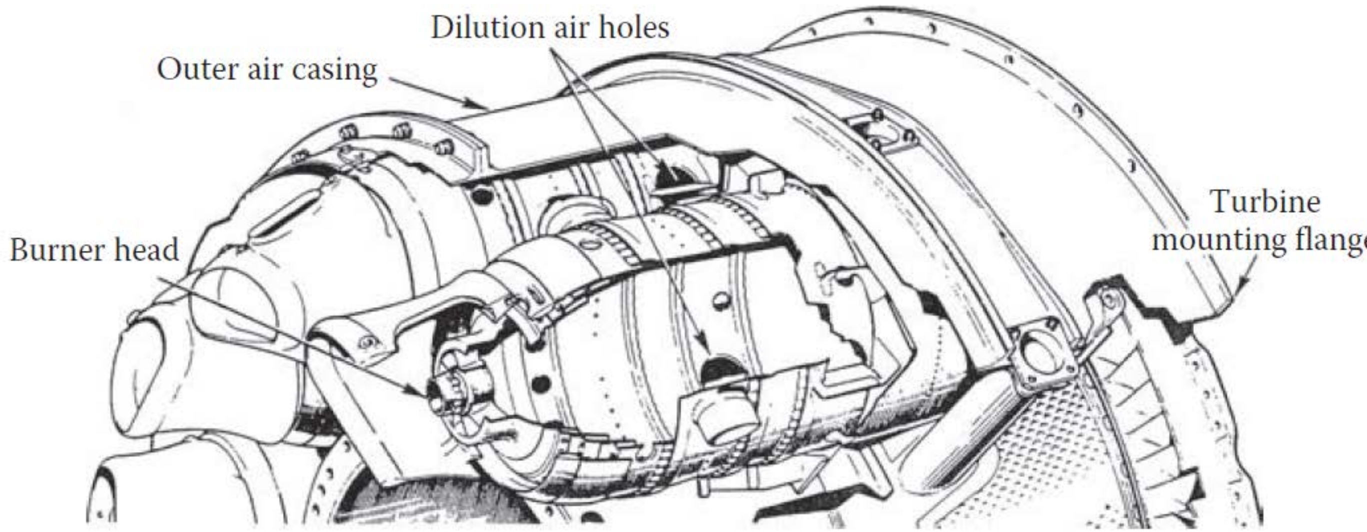


FIGURE 1.11
Tuboannular combustor arrangement. (Courtesy of Rolls Royce plc.)

Annular Combustor Layout

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

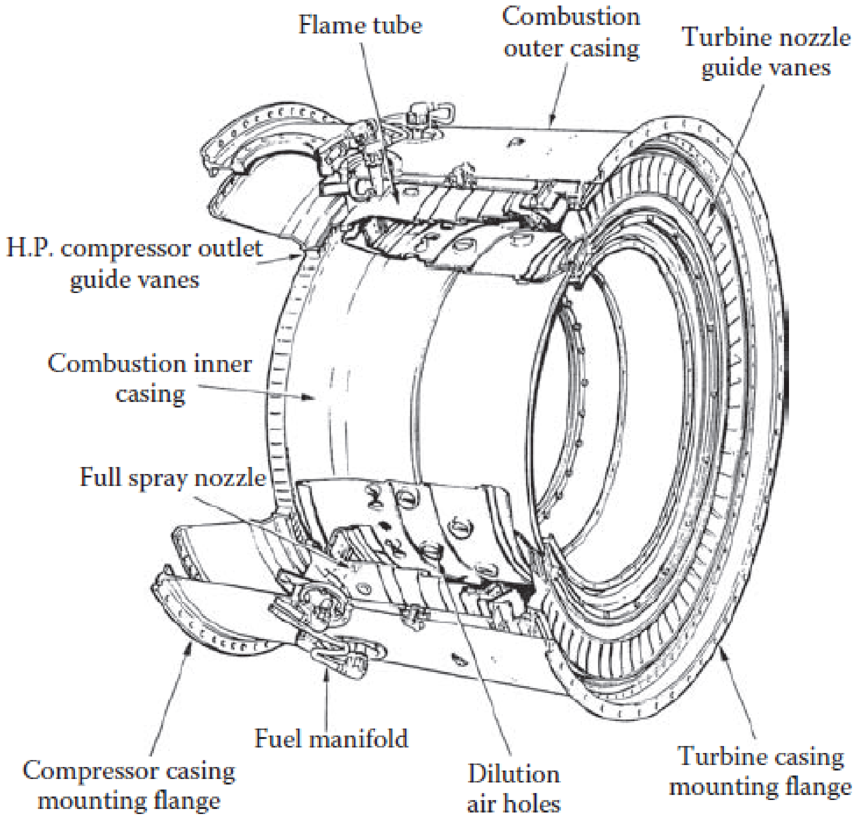
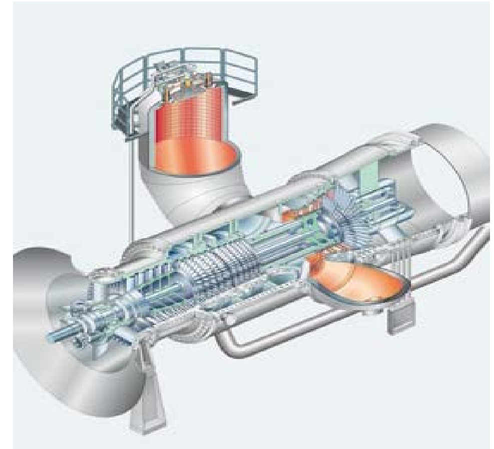
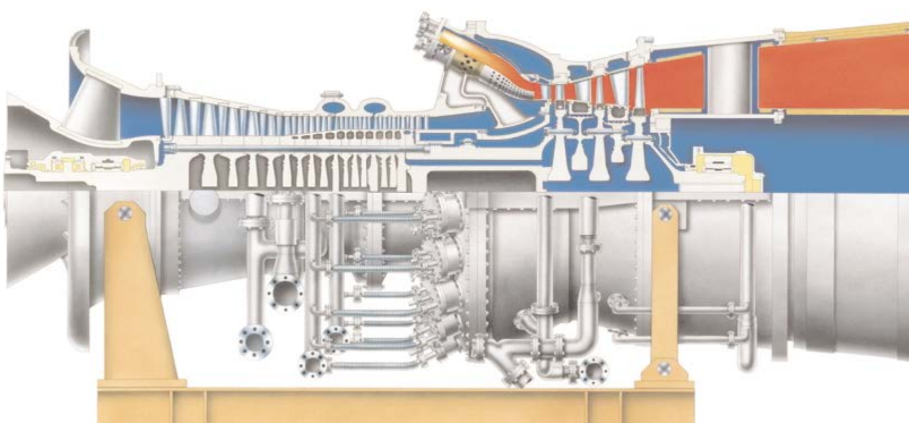


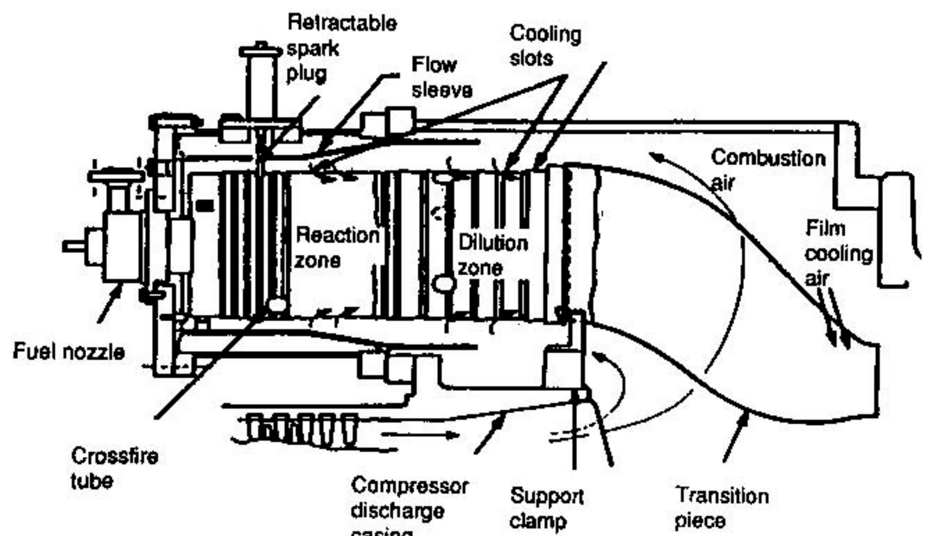
FIGURE 1.13
RB211 annular combustor. (Courtesy of Rolls Royce plc.)

Frame Engine Layouts

- Can access combustors without requiring engine dissembly
- Silo combustors







Aero-Derivative Combustors

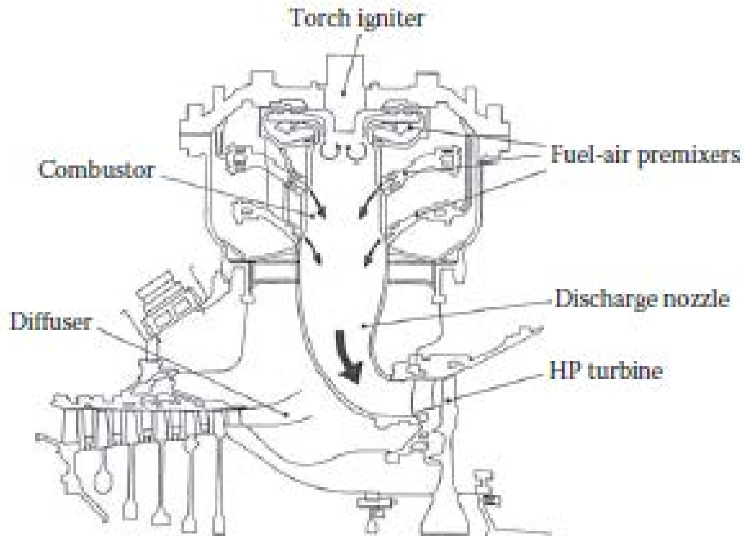


FIGURE 1.26
Industrial Trent DLE combustor. (Courtesy of Rolls Royce plc.)

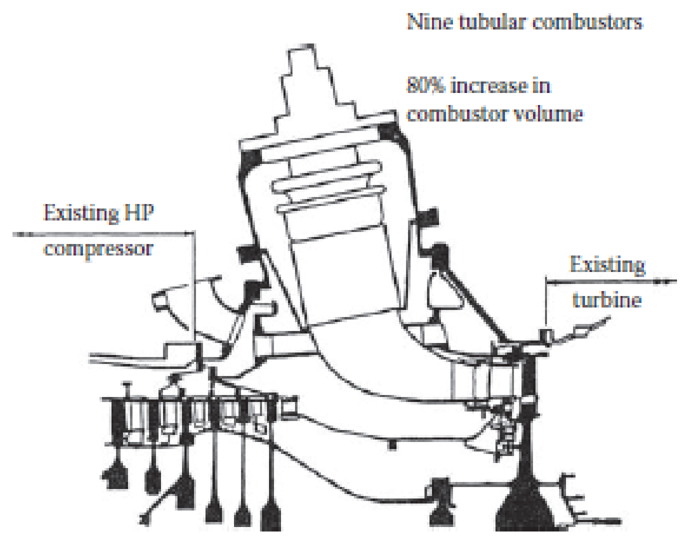
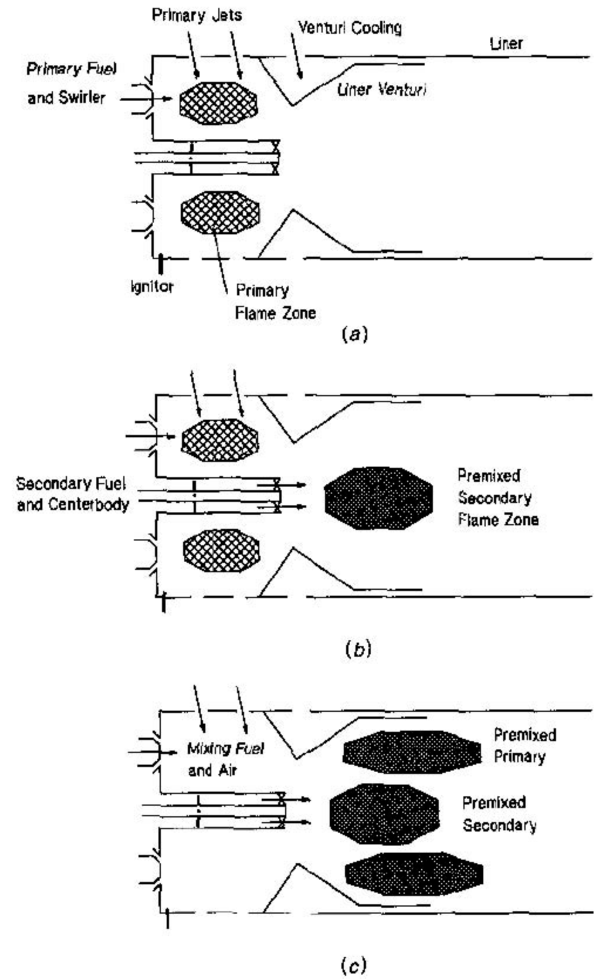


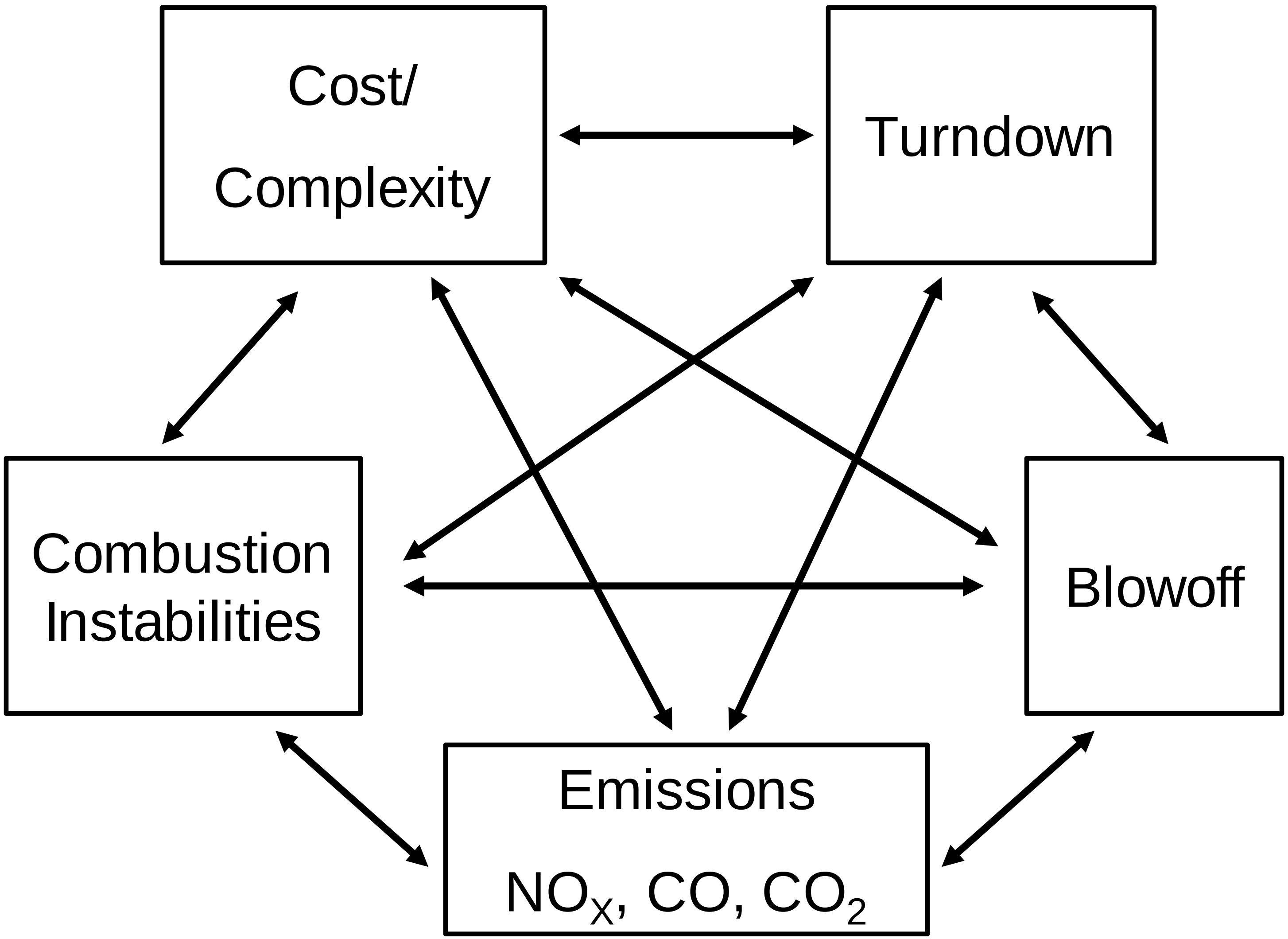
FIGURE 1.25
Industrial RB211 DLE combustor. (Courtesy of Rolls Royce plc.)

Combustor Configurations
Dry, Low NOx (DLN) Systems

- More complicated staging schemes required for turndown



Tradeoffs and Challenges



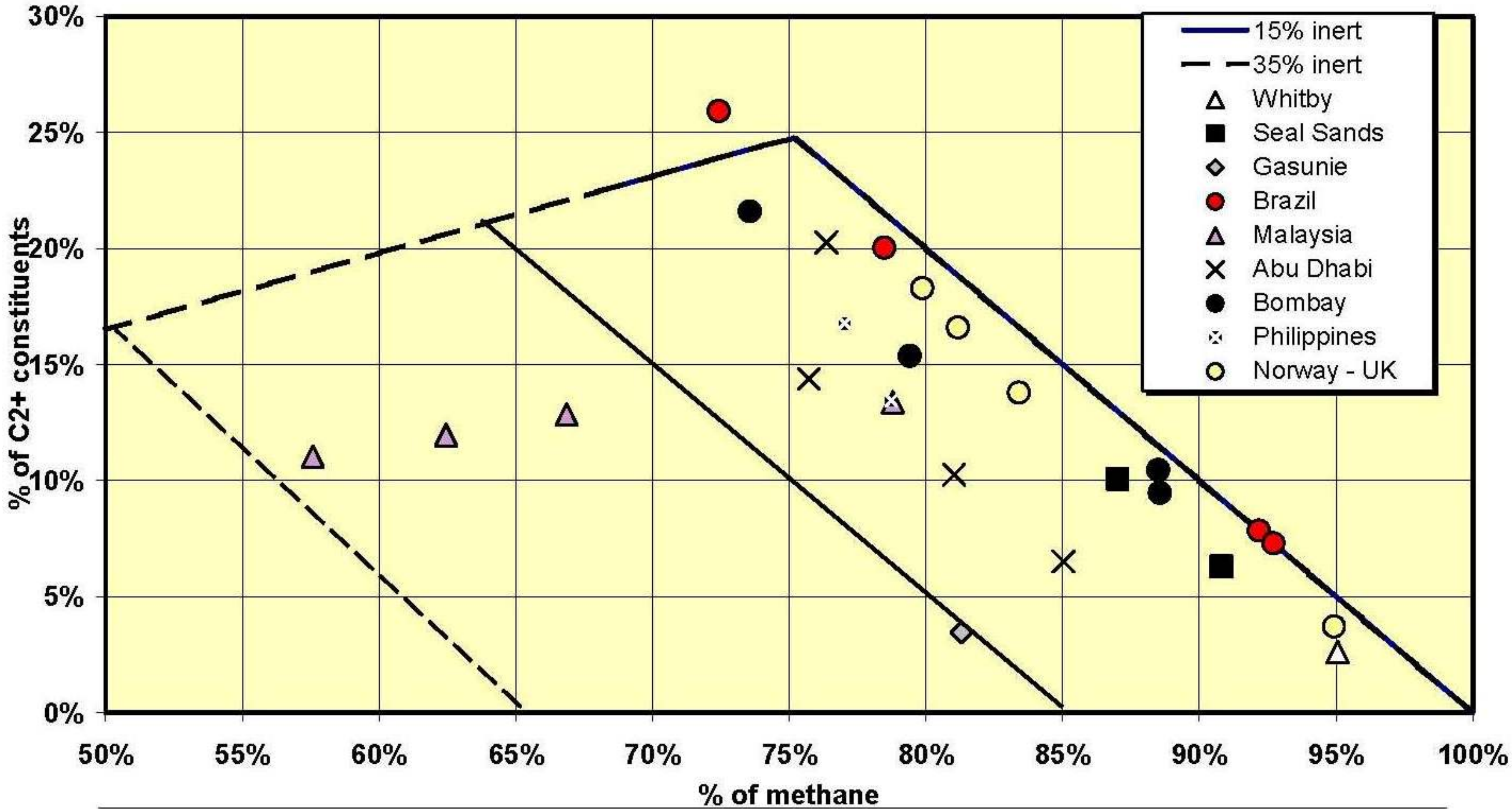
Alternative Fuel Compositions

TABLE 3 DESCRIPTION OF GASEOUS FUELS

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.

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

Natural Gas Composition Variability



Source: C. Carson, Rolls Royce Canada

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

Operability issues of low NOX technologies

- Power
  - Example: Broken part replacement largest non-fuel related cost for F class 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.

Calpine: Equipment Failures From Siemens Turbines

February 24, 2005: 15:43 p.m. EST

SAN FRANCISCO -(Dow Jones)- Calpine Corp.'s (CPN) unexpected costs due to equipment failure in the fourth quarter were related almost entirely to turbines purchased from Siemens AG (SI), a Calpine executive said Thursday in a conference call with Wall Street analysts.

Calpine reported a fourth-quarter net loss of $172.8 million, compared with net income of $119.6 million in the final quarter of 2003. The company, which has built its huge fleet of natural gas-fired power plants in the U.S. over the past several years, said equipment-failure costs of $45.3 million were a significant part of the downturn in results. The fourth-quarter loss of 39 cents a share surprised Wall Street analysts, who had been expecting a loss of 14 cents on average, according to First Call.

Financial Times

Power in Latin America

23 July 99, Issue 49

Daggers Drawn over Nehuenco

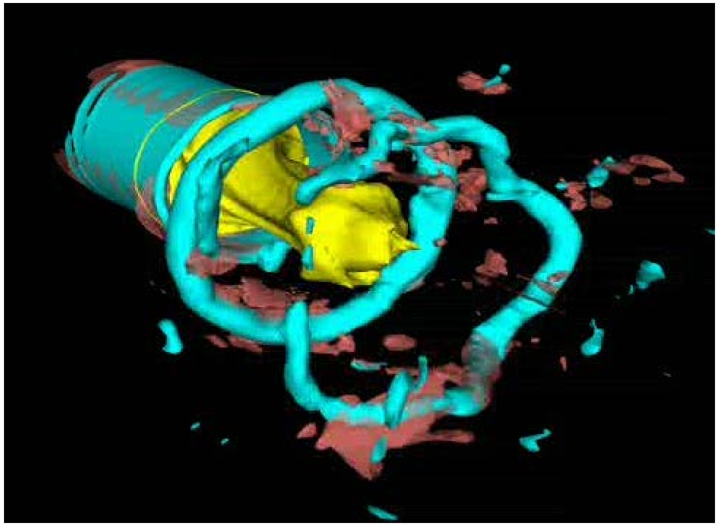
“The Patience of Chile’s Colbun power company has finally run out over the continued non-performance of the Siemens-built Nehuenco generating plant. Exasperated by repeated break-downs at the new plant and under pressure from increasingly reluctant insurers – (and with lawsuits looking likely) – the generator announced that it will not accept the $140m combined-cycle plant - built and delivered by the Germany equipment manufacturer.

Siemens, together with Italy’s Ansaldo, took the turnkey contract for the 350 MW plant in 1996 and should have had it in service by May of last year. The startup was delayed till January. Since then matters have worsened. There have been two major breakdowns and, says Colbun, there have been no satisfactory explanations.

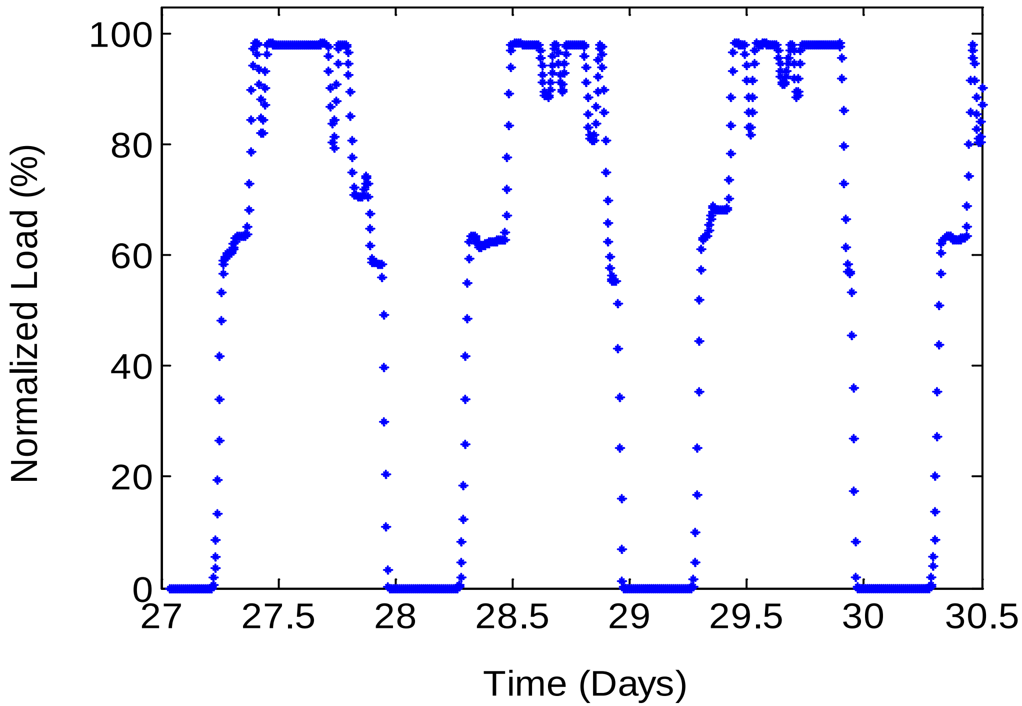
The trouble could not have come worse for Colbun. The manly hydroelectric generator, which is controlled by a consortium made up of Belgium’s Tractebel, Spain’s Iberdrola and the local Matte and Yaconi-Santa Cruz groups, has been crippled by severe drought in Chile, which has slashed its output and thrown it back – without Nehuenco – onto a prohibitively expensive spot market.”

Combustion Instabilities

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

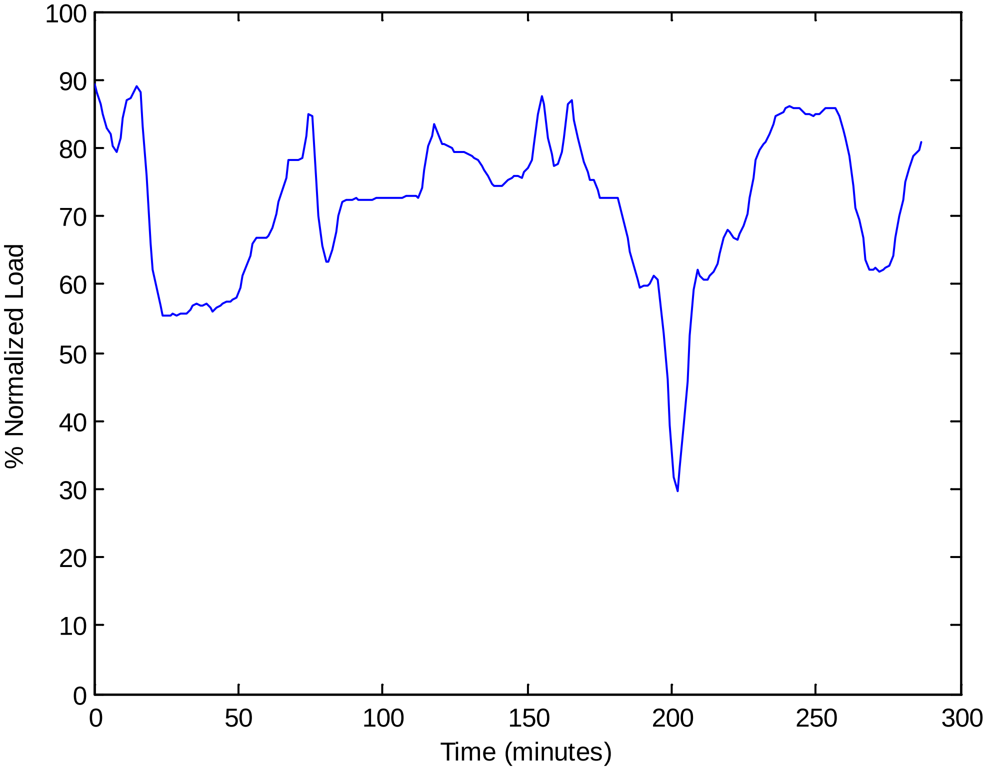


Turndown



- 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

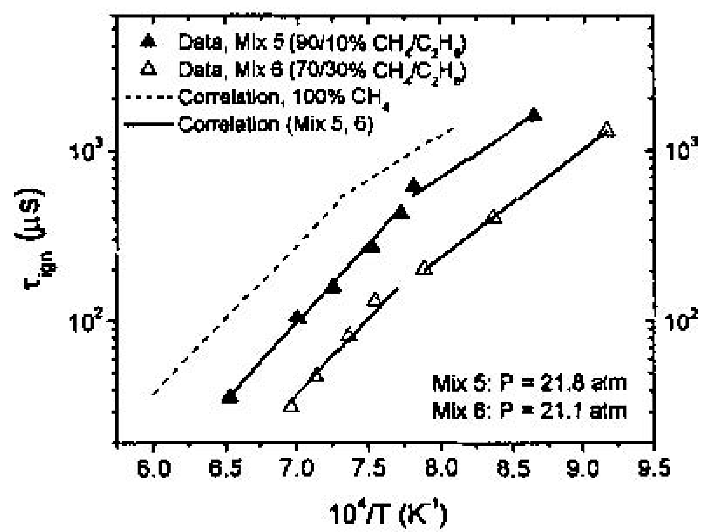
Background:

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

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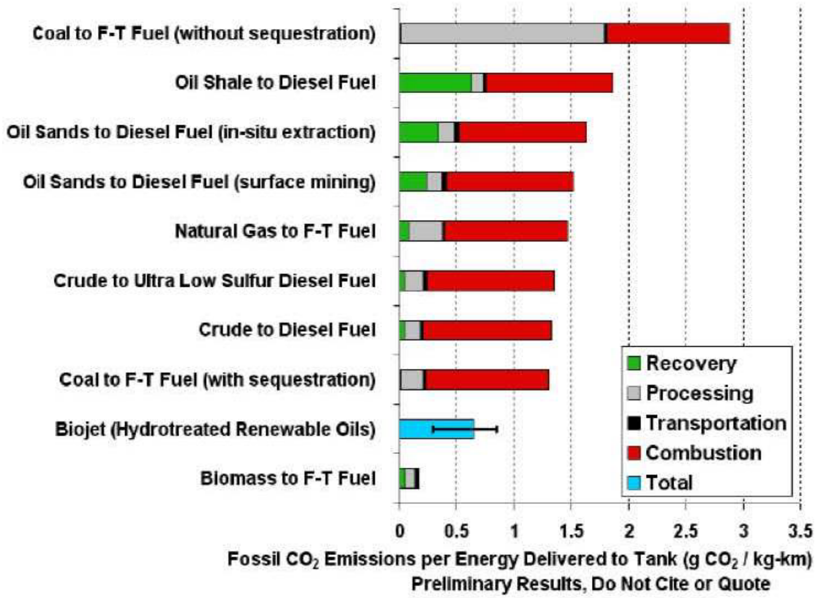
Emissions

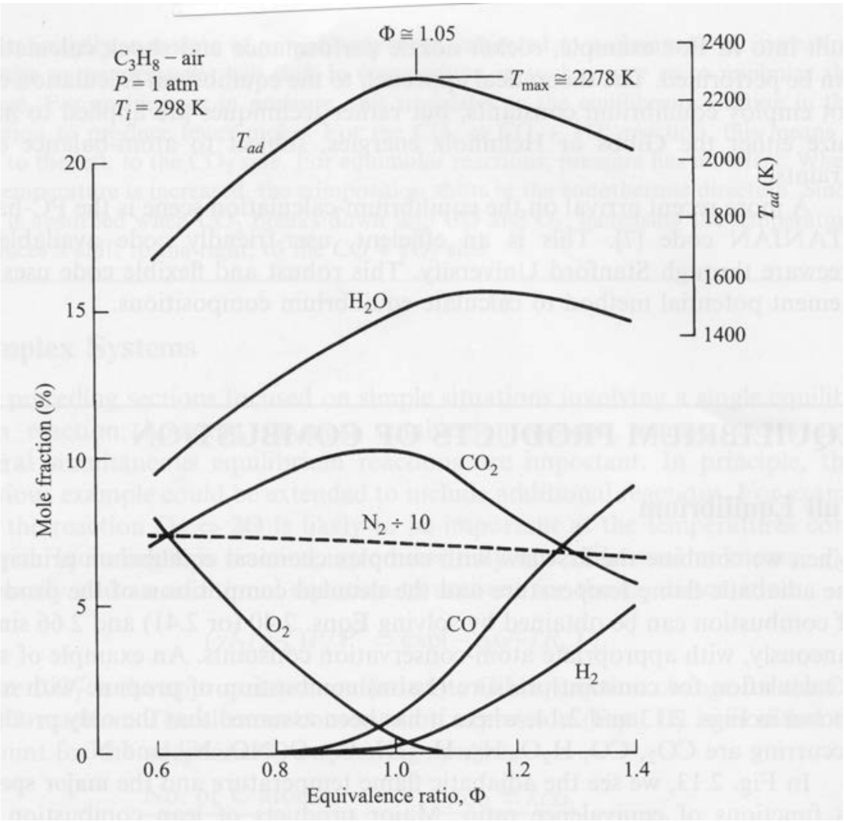
- NOX – Reactions with nitrogen in air and/or fuel
- CO – Incomplete or rich combustion
- UHC – Incomplete combustion
- SOX – sulfur in fuel
- Particulates (soot, smoke)
- CO2 and H20? – Major project of hydrocarbon combustion



(Hileman et al., 2008)

Equilibrium Hydrocarbon/Air Combustion Products

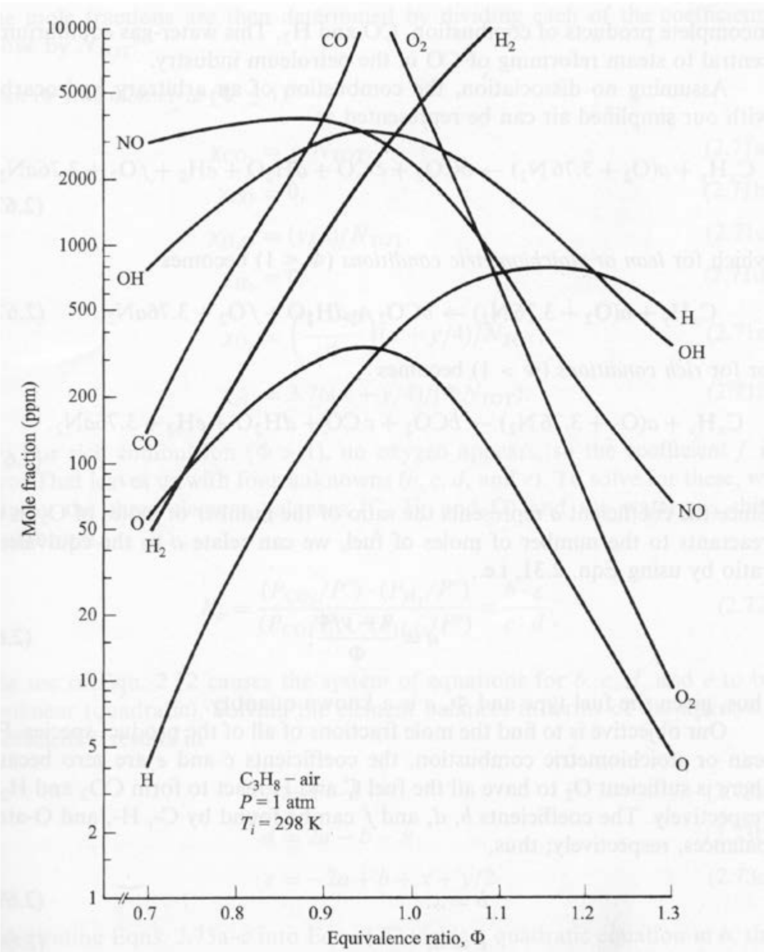
- Major products:
  - Lean: CO2, H2O, O2
  - Rich: CO2, CO, H2O, H2, O2



Reproduced from Turns, An Introduction to Combustion, 2000

Equilibrium Hydrocarbon/Air Combustion Products (2)

- Minor Products:
  - NO, OH, O, H, H2 (f<1), CO (f<1)



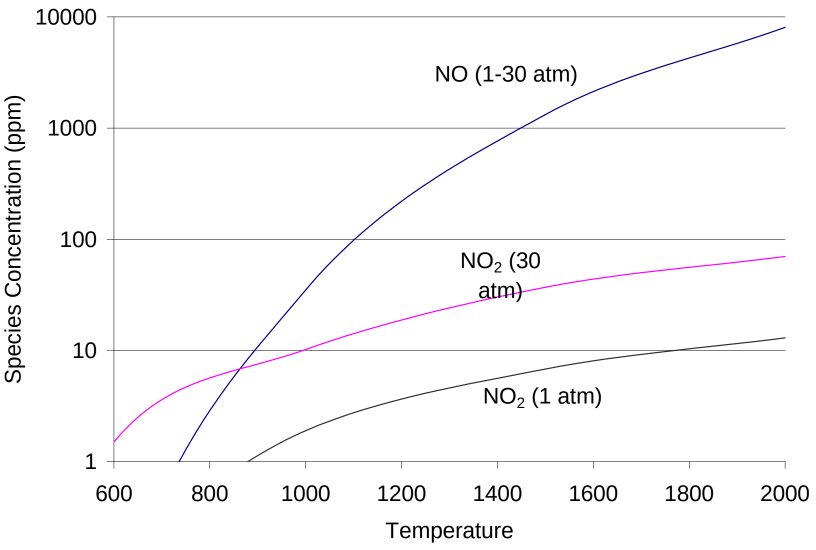
Reproduced from Turns, An Introduction to Combustion, 2000

NOx Emissions

- NOx stands for Nitrogen Oxides
  - NO, N2O, NO2
- Different mechanisms for NOx formation
  - Nox=NOx|flame+NOx|post-flamea =a+btresidence
- Flame generated NOx
  - N2O
  - Prompt NOx
  - NNH
  - Fuel NOx
- Post-flame NOx
  - Zeldovich reaction (Thermal NOx)

Equilibrium Pollutant Concentrations, NO and NO2

- NO levels pressure independent
- Most NOx formed at combustion conditions is NO, not NO2
  - NO converted to NO2 in atmosphere (note crossover at low temps)
- NO emissions from lean, premixed combustors strongly influenced by non-equilibrium phenomenon
  - NO usually increases with pressure, pn (n~0.5-0.8)
  - Non-equilibrium NO values less than equilibrium values

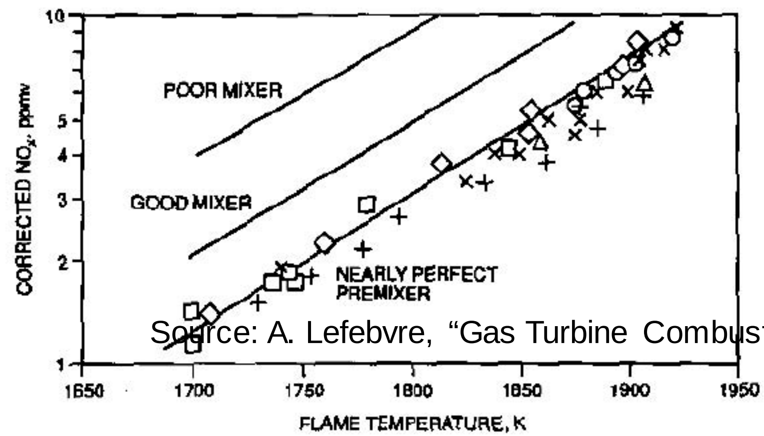


Zeldovich Reaction

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

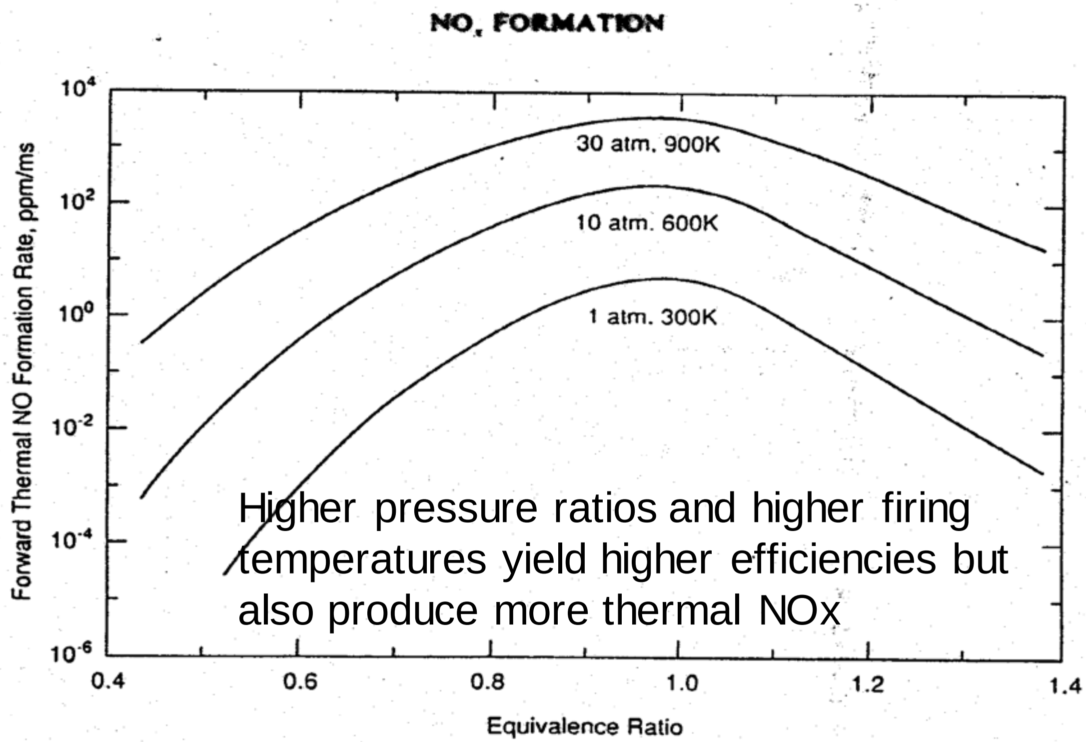
Pollutant Trends, Thermal NOx

- 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

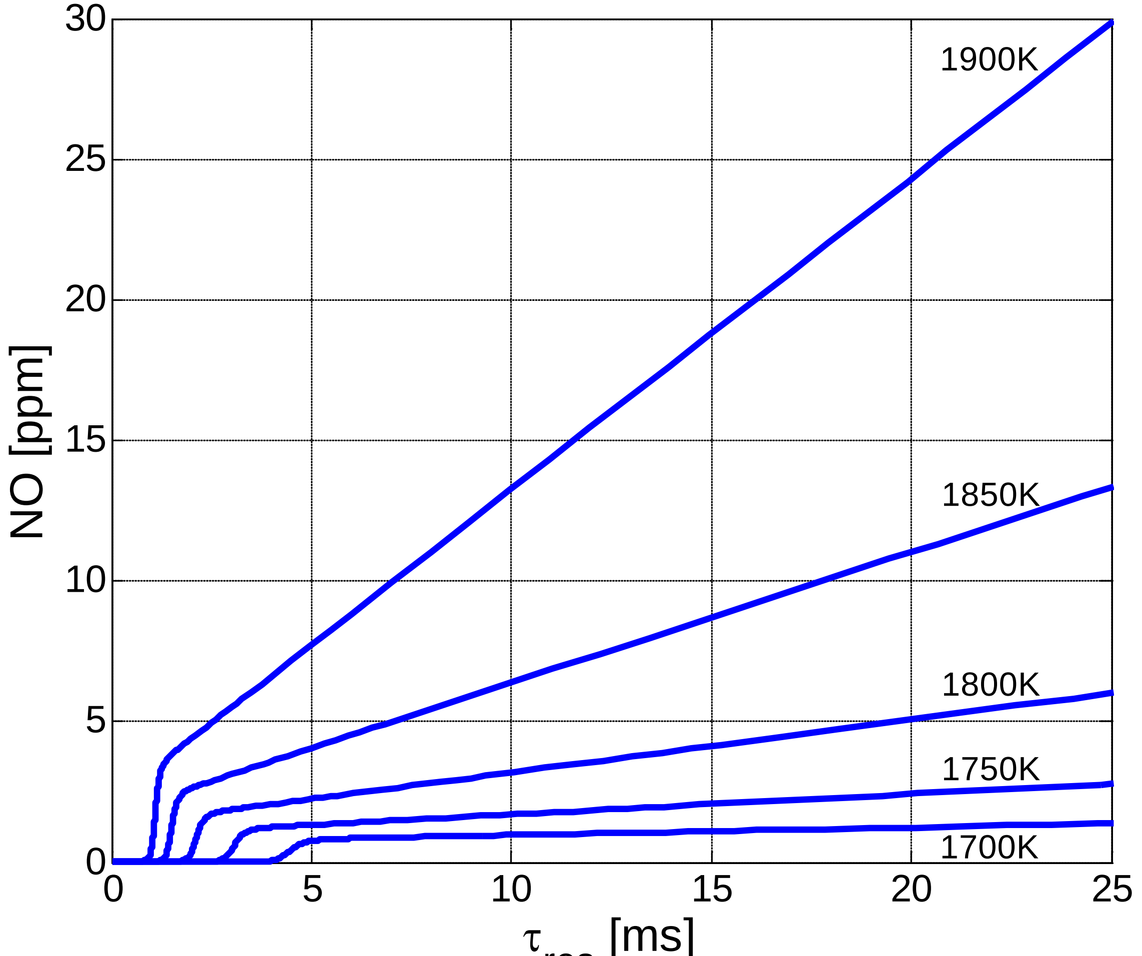


Higher pressure ratios and higher firing temperatures yield higher efficiencies but also produce more thermal NOx

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.

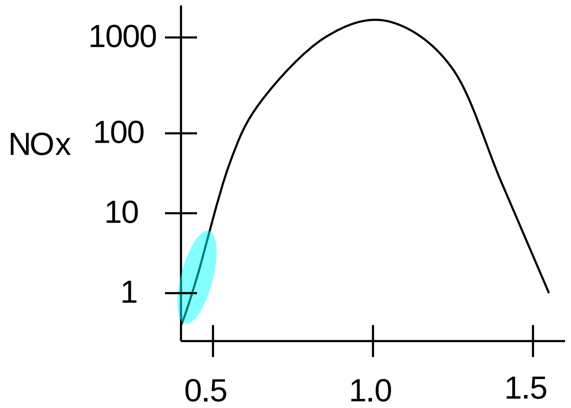
NO levels start low and tend towards equilibrium – i.e., longer residence time leads to more thermal NOx

CH4/Air, varying Tad, p=15atm, Tin=635K (t = 0, taken at T = 640K)



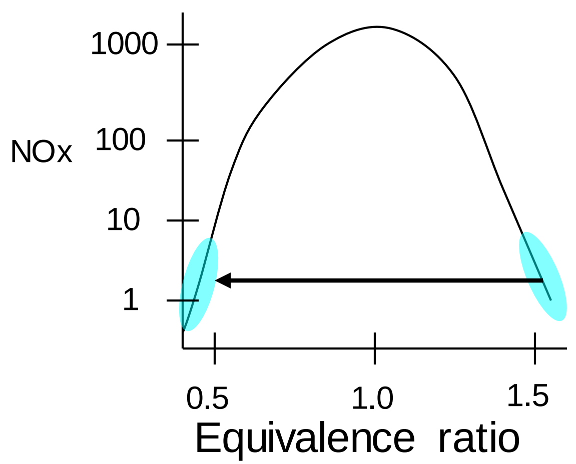
Low NOx combustion concepts

- Lean burning
  - DLN (Dry, low NOx)
    - Key issues: turndown, combustion instability, blowoff, flashback (in higher H2 applications)
  - LPP (Lean, premixed, prevaporized)
    - Key issues: same as above, autoignition



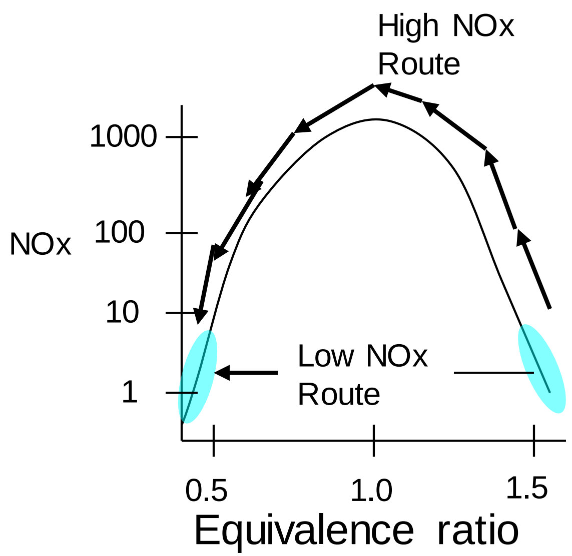
- Rich burning
  - RQL (rich burn, quick quench, lean burn)
    - Key issues: soot, quench mixers

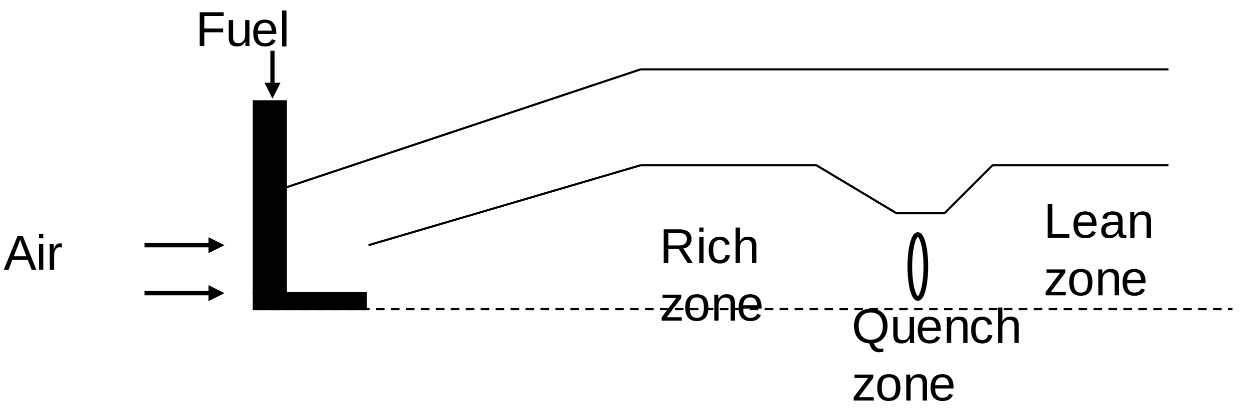
- Catalytic
  - Low temperature catalytic combustion
  - Key issues: cost, catalyst durability



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

- Rich head end
- Mixture quickly mixed with excess air
- Lean burn of H_2/CO downstream
- Realized to some extent in many conventional combustors

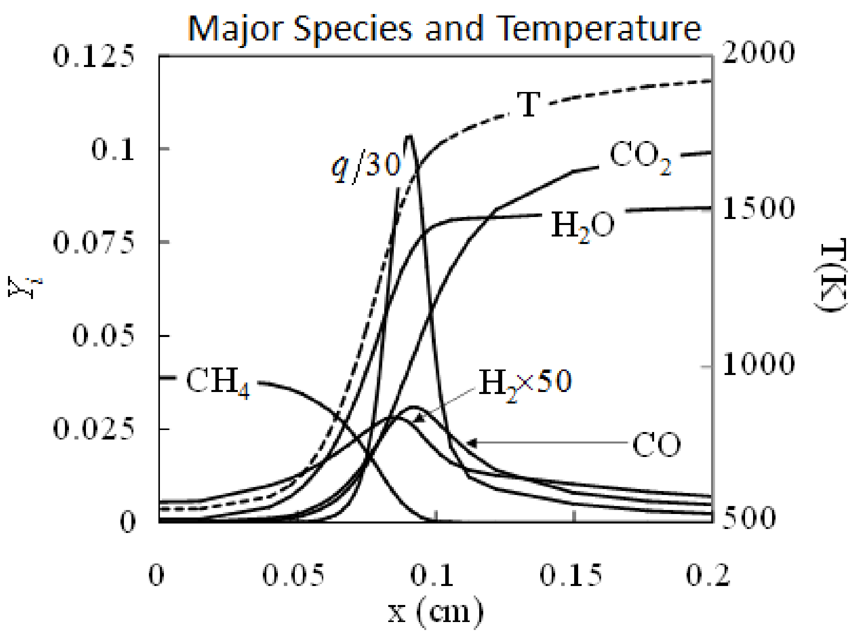


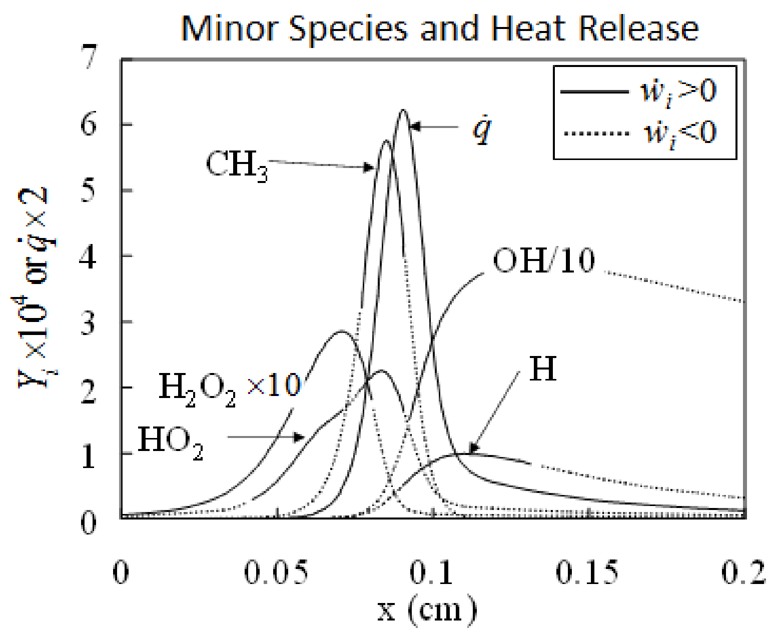


Source: A. Lefebvre, "Gas Turbine Combustion"

CO Emissions

- A simple 2 step conceptualization of CO formation and oxidation is
  - Step 1: Fuel reacts to form “intermediate species”, including CO

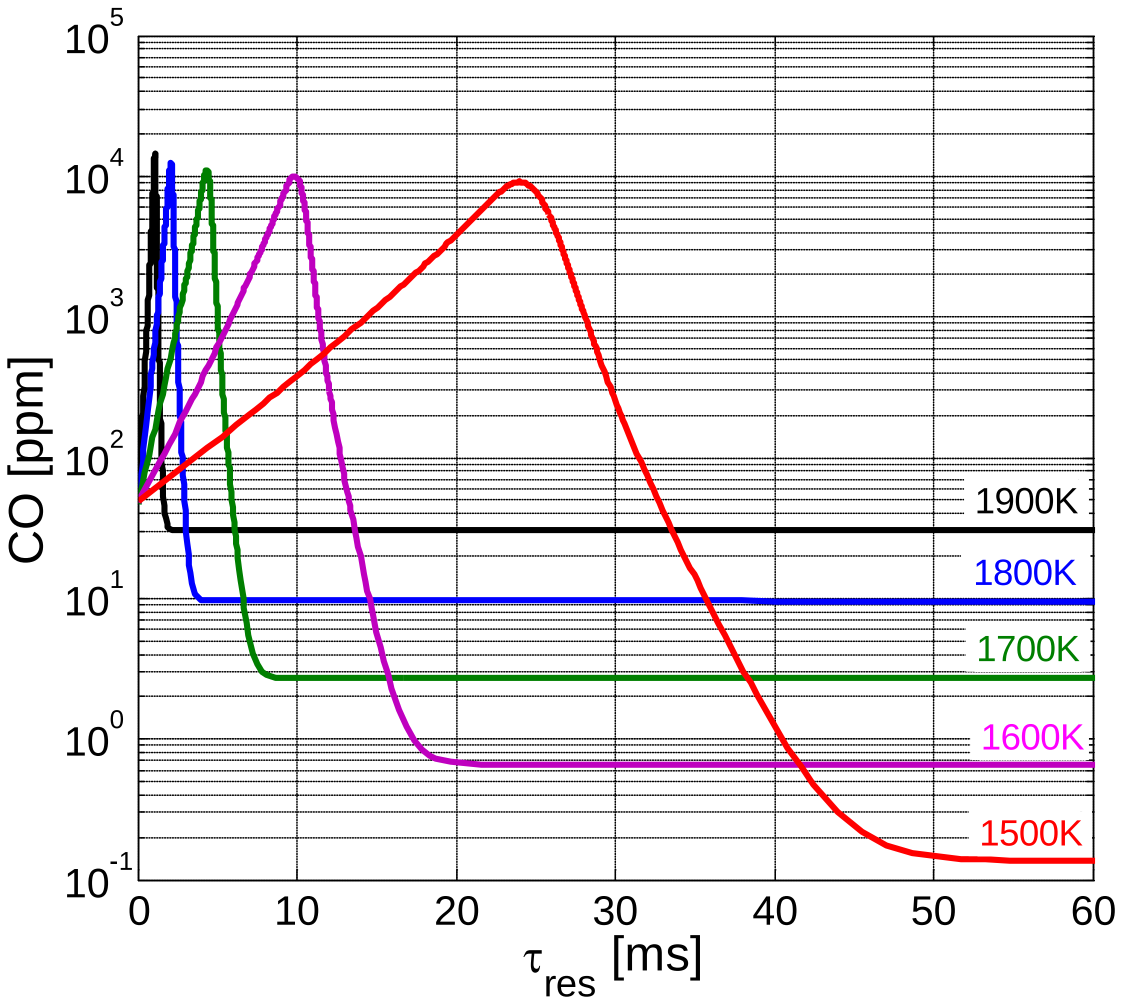




Quenching Leads to CO

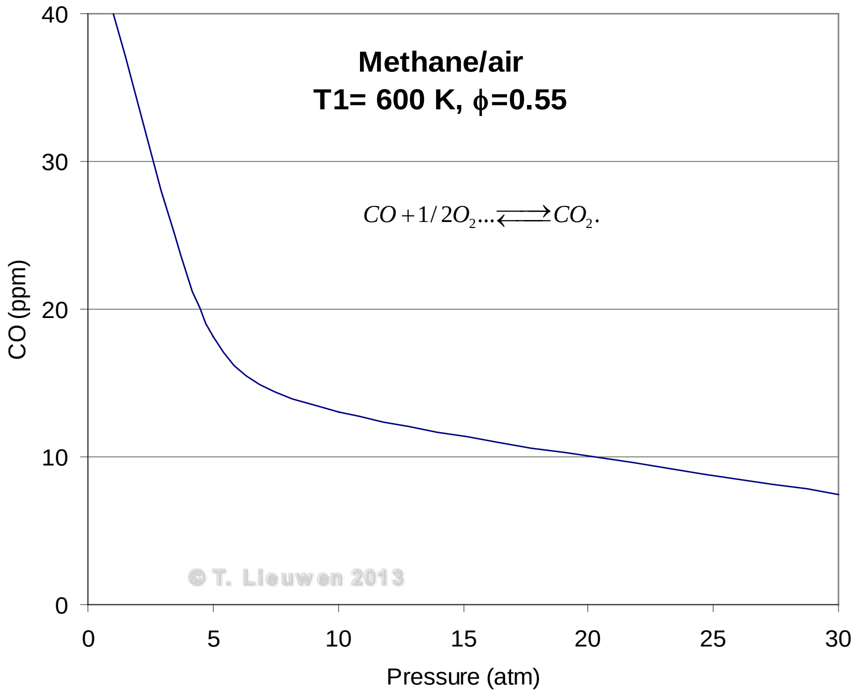
- Step 2 will not happen if the combustion products are "quenched" or cooled prematurely
  - Occurs at low temperatures where insufficient residence time to oxidize CO
  - Occurs where cooling air is mixed into the flow
- CO levels relax down toward equilibrium – i.e., longer residence time is better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

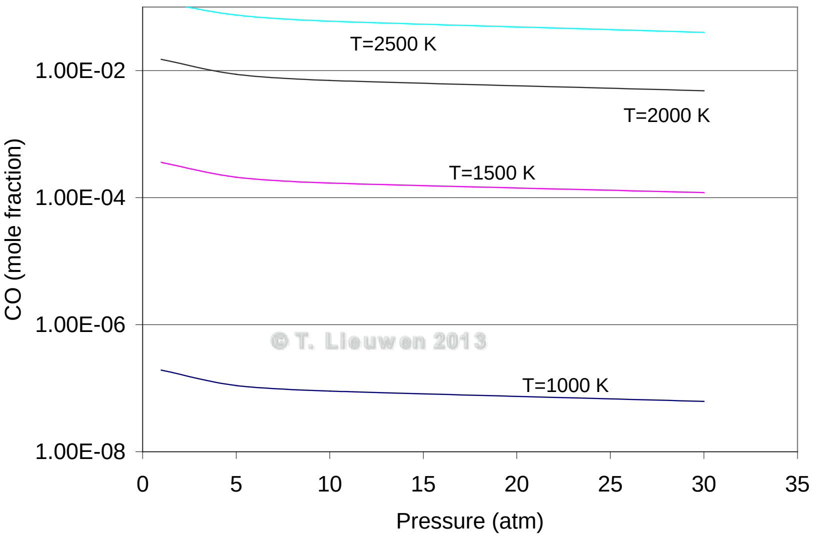
CH4/Air, varying Tad, p=15atm, Tin=635K (t = 0, taken at T = 640K)



Equilibrium Pollutant Concentrations, CO

Equilibrium CO levels for reaction

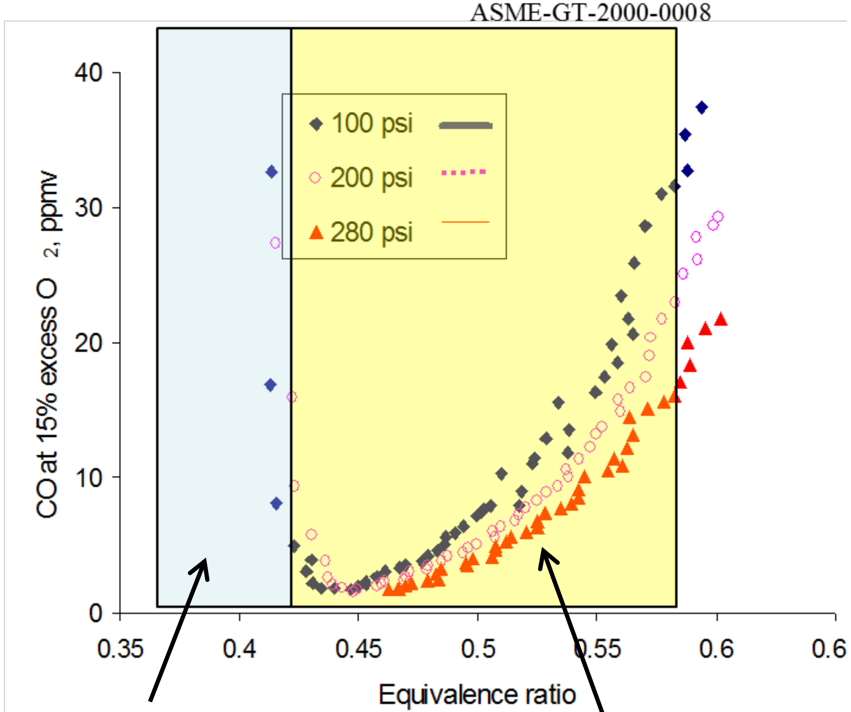




Equilibrium Pollutant Concentrations, CO

- CO emissions from lean, premixed combustors strongly influenced by non-equilibrium effects
  - Near equilibrium for range of f values
  - Rapid departure from equilibrium for low f
  - Occurs due to quenching of reactions
  - Thus, non-equilibrium effects cause CO levels to exceed their equilibrium values

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

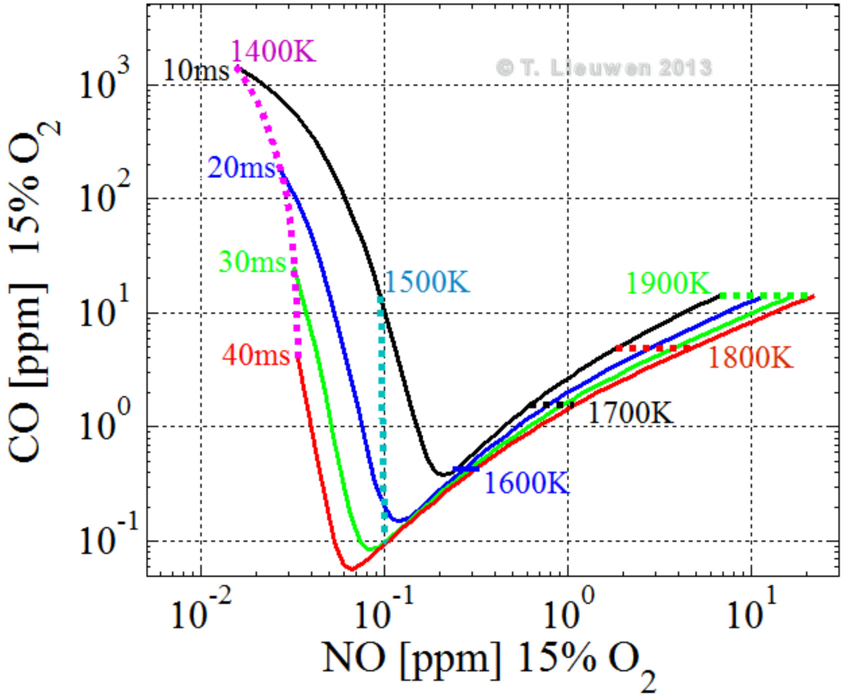


Kinetically controlled

Equilibrium controlled

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



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

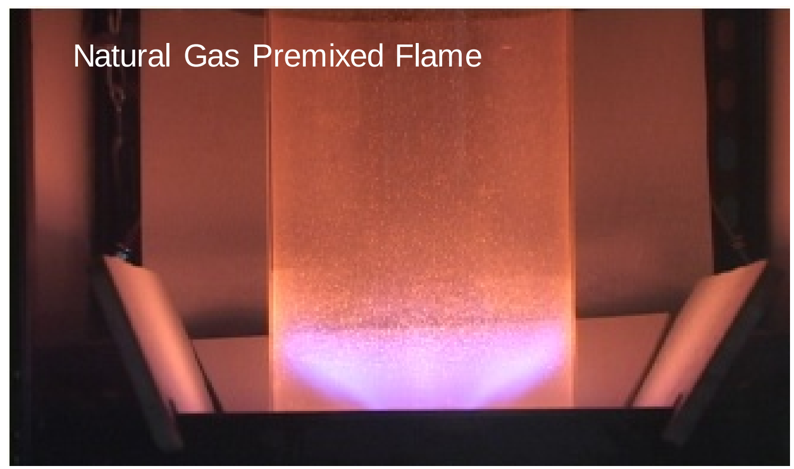
Particulate Matter

- Fine carbon particles formed in flame
- Particles may or may not make it through flame
- Competition between soot formation and soot ‘burn-out’

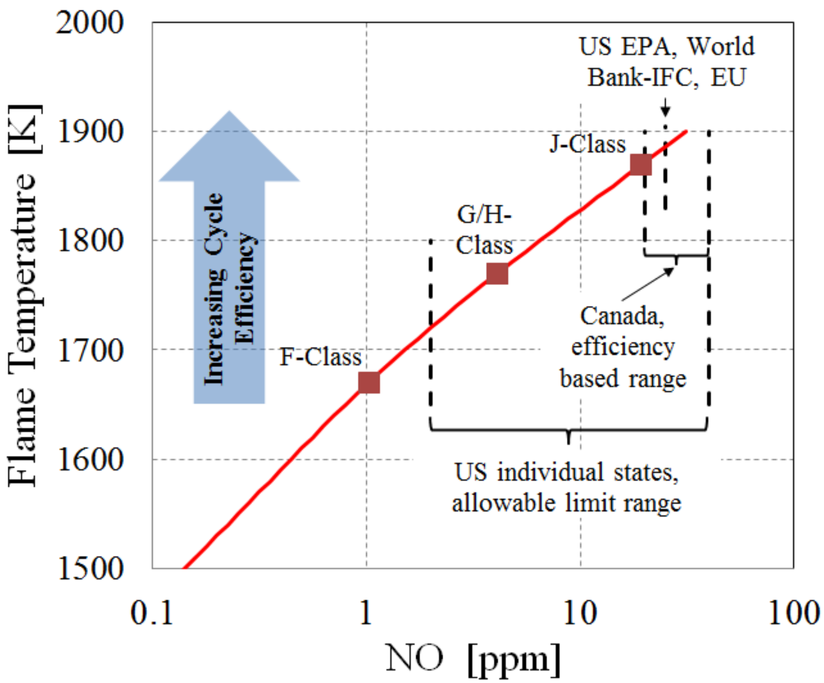
- Nearly zero in lean, premixed flames
- Occurs in fuel-rich flames and diffusion flames

- 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



NOx-Efficiency (CO2) Tradeoffs



- Future turbine efficiency improvements may be NOx rather than turbine inlet temperature limited!

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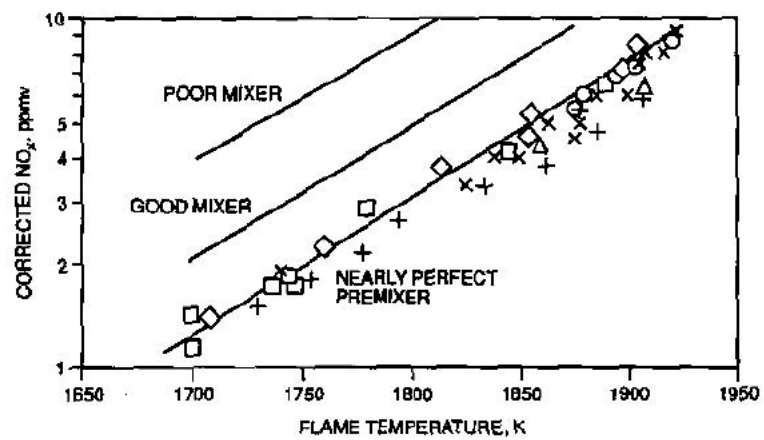
- A) Introduction and Outlook
- B) Flame Aerodynamics and Flashback
- C) Flame Stretch, Edge Flames, and Flame Stabilization Concepts
- D) Disturbance Propagation and Generation in Reacting Flows
- E) Flame Response to Harmonic Excitation
- Constraints and metrics
- Emissions
- Autoignition
- Future outlook for needed research

Autoignition

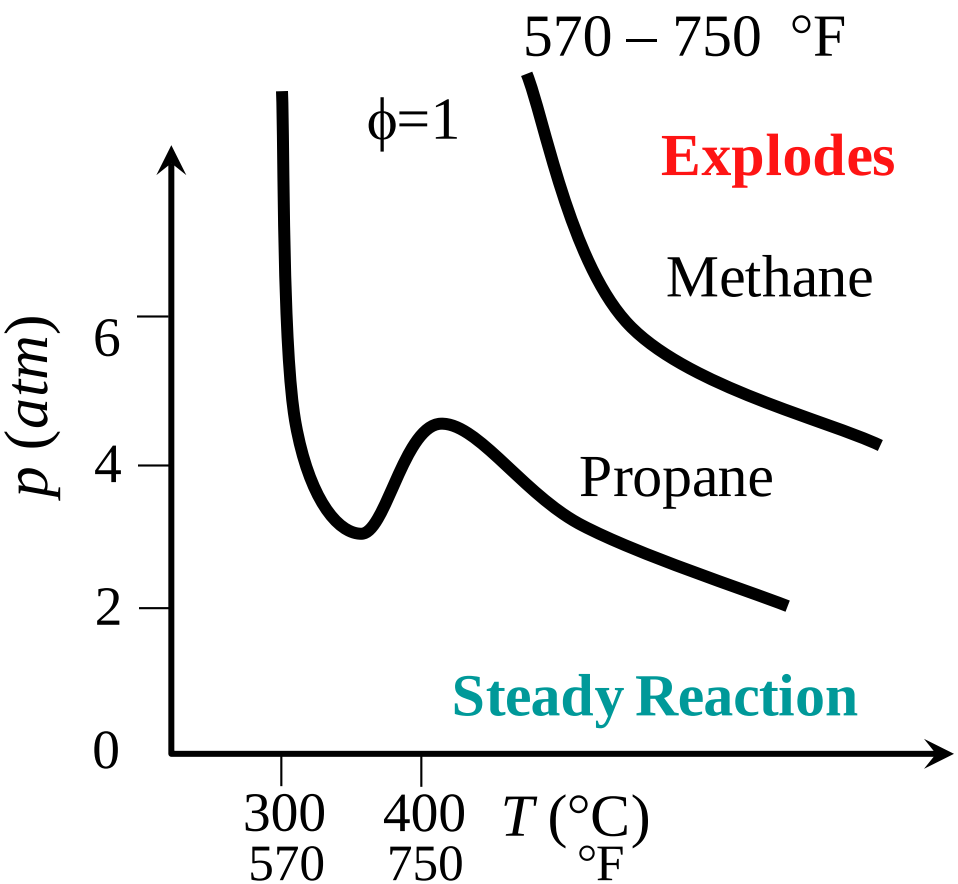
- In premixed systems, premature ignition is a significant concern
  - temperature above which a fuel-air mixture can spontaneously ignite is called the “autoignition temperature”
  - amount of time it takes to spontaneously ignite is known as “ignition delay time”

- Competes with need for good premixing for NOx reduction



Operability: Autoignition

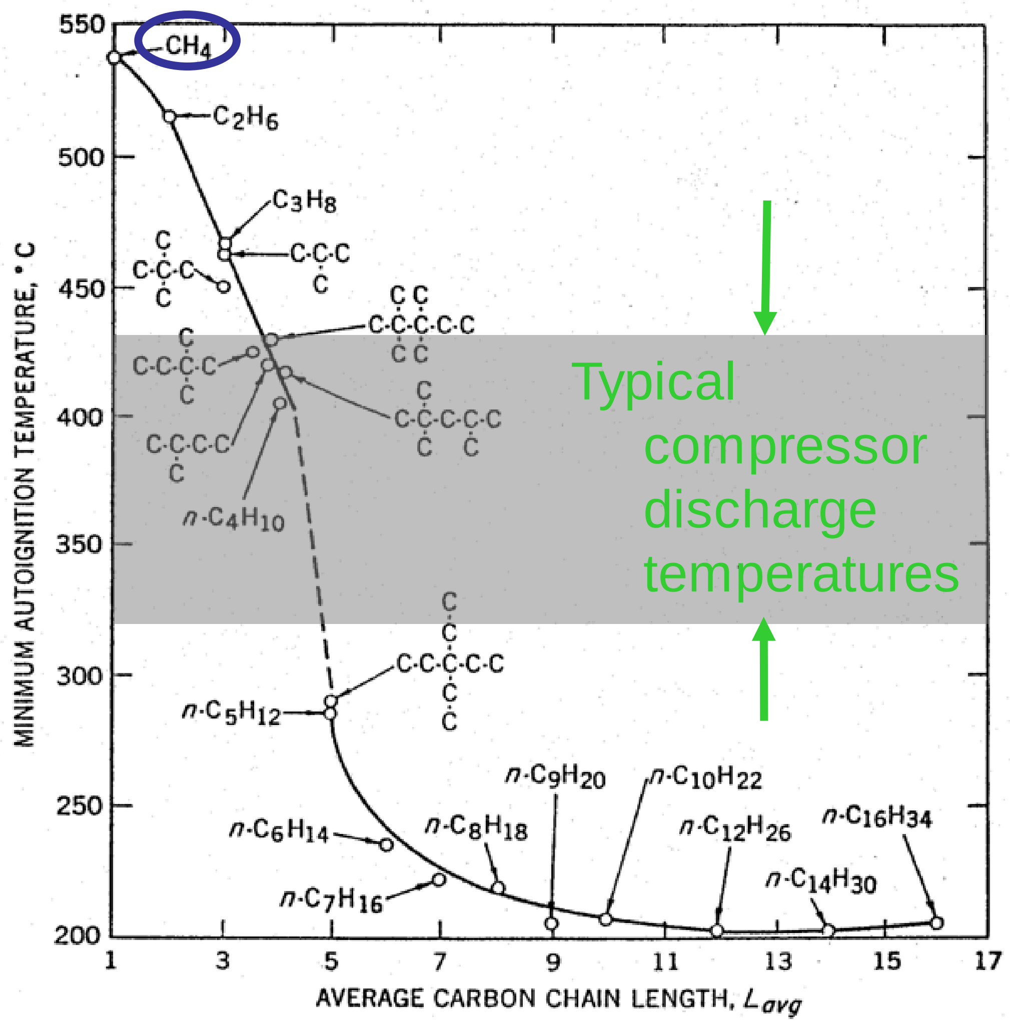
- Methane has significantly higher autoignition temperatures than higher hydocarbons
  - Important consideration for LNG, particularly with high pressure ratio aeroderivatives



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:
  - $t_{ign}=1.77 \times 10^{-14} \exp(18693/T)\ [O_2]^{-1.05} [CH_4]^{0.66} [HC]^{-0.39}$
    - [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 – Ethane Effects

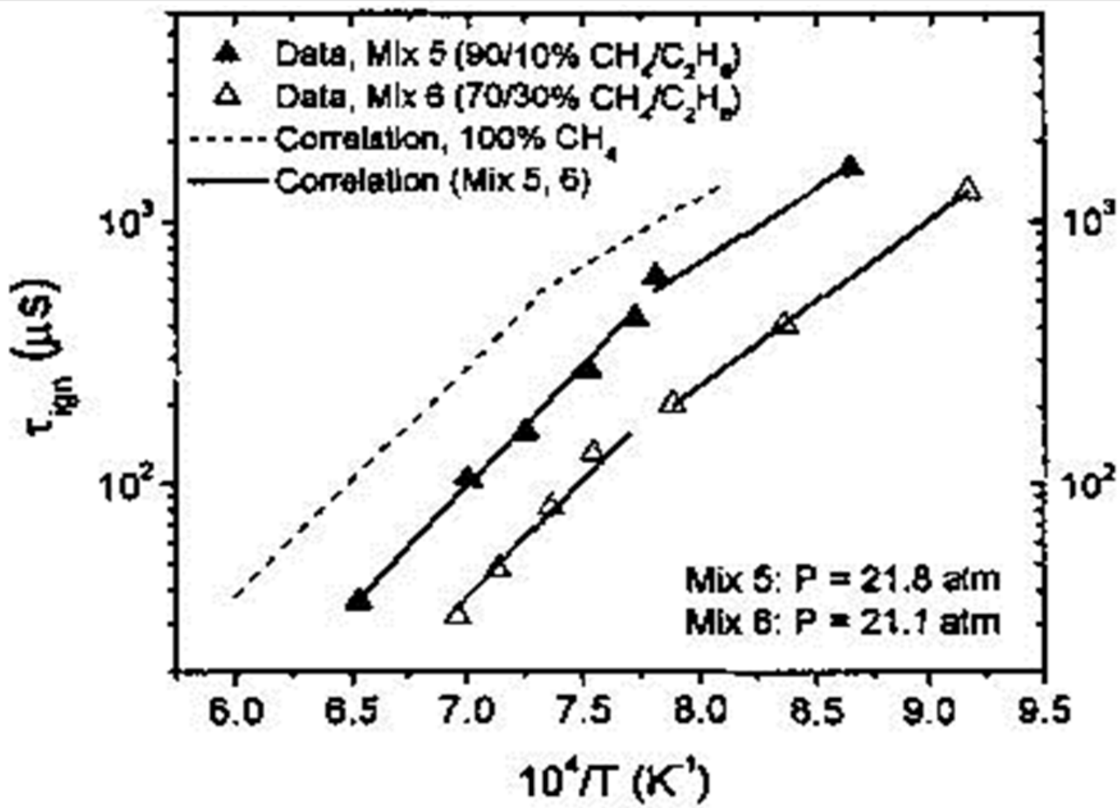


Fig. 5 Ignition delay times for the methane/ethane blends in comparison to the methane-only data at similar pressures.

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

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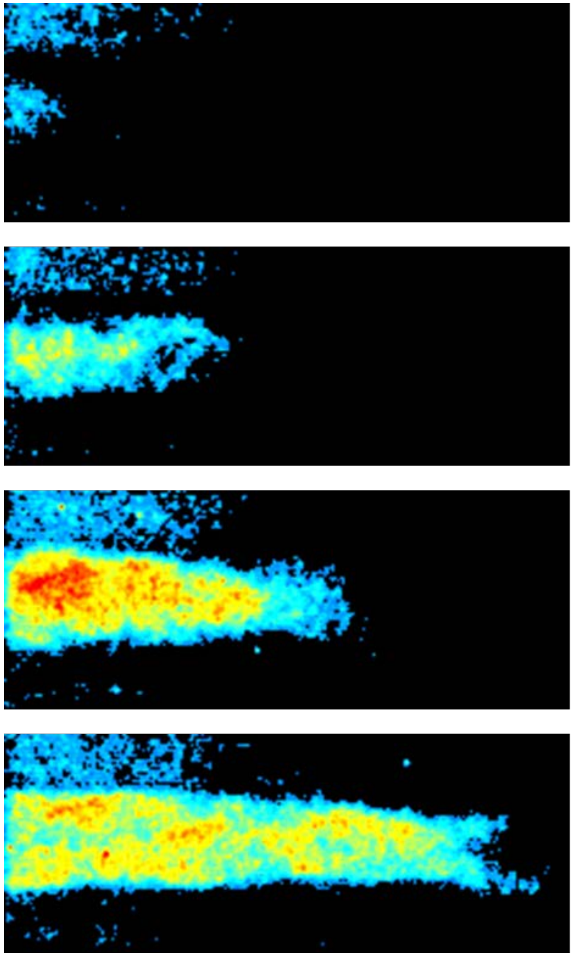
Combustion challenges in a CO_2 constrained world

- CO_2 emissions set by fuel and cycle choice
  - Sets combustion configuration and challenges
  - High pressure combustion
  - Exhaust gas recirculation
  - Pre-combustion carbon capture
  - Post-combustion carbon capture
  - Bio-fuels (near zero net CO_2 emitting fuels)

Pre-combustion Carbon Capture

- Carbon removed prior to combustion, producing high H2 fuel stream
  - IGCC
- High H2 introduces significant combustion issues
  - VERY high flame speed – causes flashback
    - Warranties generally limit H2 <5% by volume
  - Plants burning high H2 fuels use older, high NOx technology



80% H_2 20% CH_4 flashback at 281 K, 1 atm, nozzle velocity of 58.7 m/s, and Φ = 0.426

Post Combustion Carbon Capture

- Sequesterable stream preferably composed primarily of CO2 and H2O
  - Oxy-combustion
    - Control flame temperature by diluting oxygen with recycled steam or CO2
  - Exhaust gas recirculation

Kimberlina Power Plant

Significant Issues associated with generating a sequesterable exhaust

- Air:
  - O_2/N_2 ratio fixed
  - Stoichiometry varied to control flame temperature
  - Emissions:
    - NO_X a major pollutant
    - CO to a lesser extent

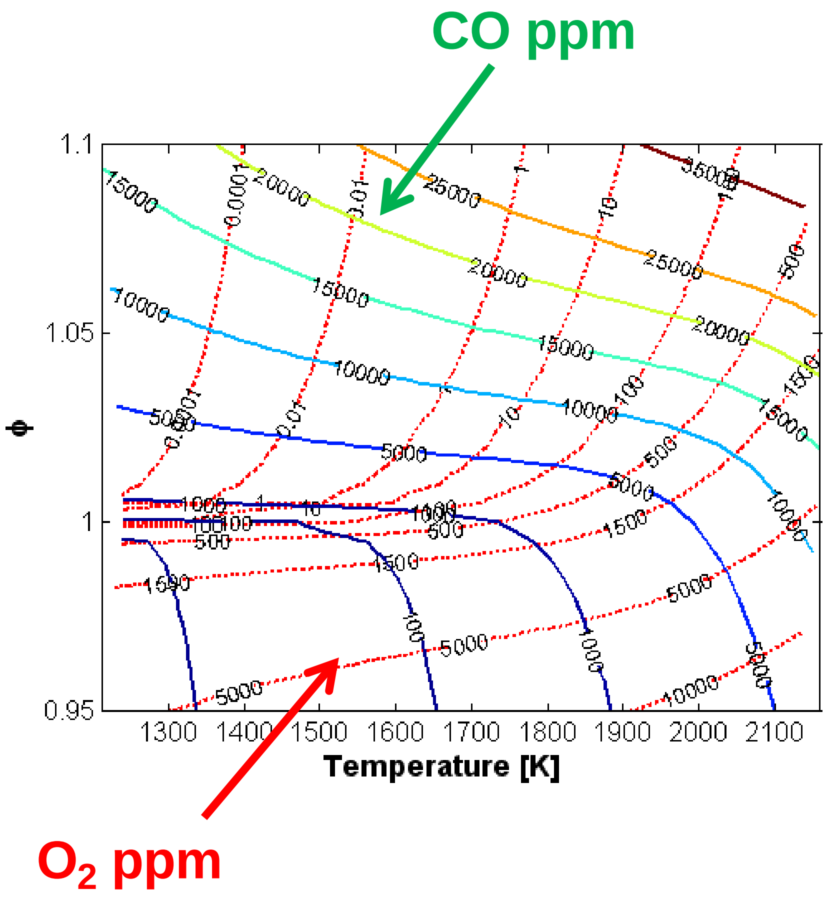
- **Oxy-System:**
  - CO_2/O_2 ratio varied to control flame temperature
  - Stoichiometry close to 1
  - Emissions:
    - Near zero NOx emissions
    - CO and O_2 emissions

Component	Canyon Reef	Weyburn pipeline
CO_2	>95%	96%
CO	-	0.1%
H_2O	No free water < 0.489 m^{-3} in the vapour phase	<20ppm
H_2S	<1500 ppm	0.9%
N_2	4%	<300ppm
O_2	<10ppm (weight)	<50ppm
CH_4	-	0.7%
Hydrocarbon	<5%	-
Temperature	<49°C	-
Pressure	-	15.2 MPa

Table 1. Specifications for two CO_2 transport pipelines for EOR

Challenges: Emissions

- Emissions:
  - CO: high CO2 levels lead to orders of magnitude increase in exhaust CO
  - O2: normally, a major exhaust effluent; requires operating slightly rich to minimize



Concluding Remarks

- Many exciting challenges associated with
  - Fuel flexibility
  - Air quality emissions and CO_2
  - Operational flexibility
  - Reliability
  - Low cost