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Fuel Flexibility Effects on Gas Turbine Operation

by

Wajid Ali Chishty

Gas Turbine Laboratory, Institute for Aerospace Research

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Present Utilization

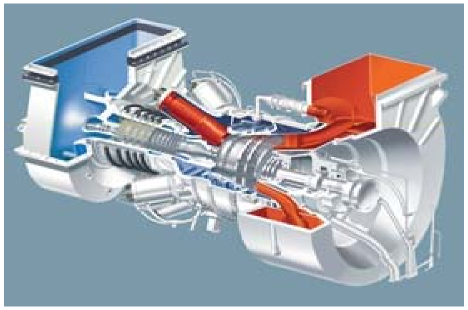
GP7200 (311 kN)

Industrial Trent (58 MW)

H-Series (400 MW)

(Ref: Lipton, 2005)

SGT-400 (13 MW)

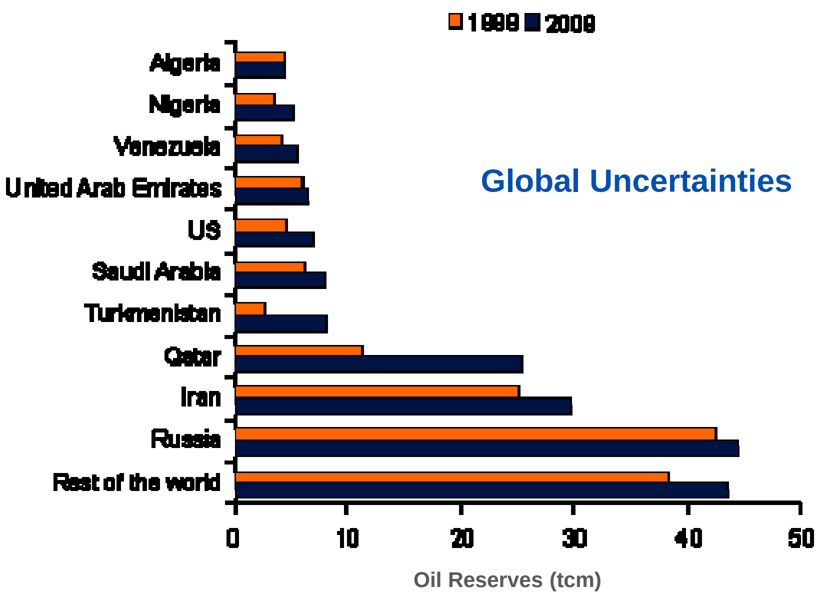


Trent 1000 (333 kN)

Present Challenges

Environmental Friendliness

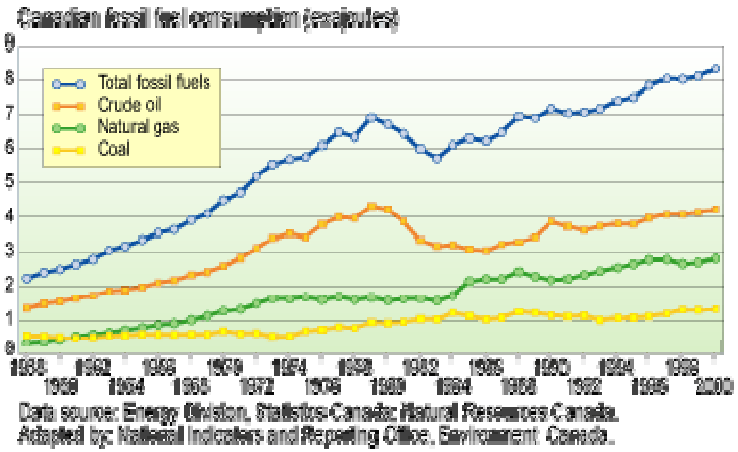
Fuel Flexibility

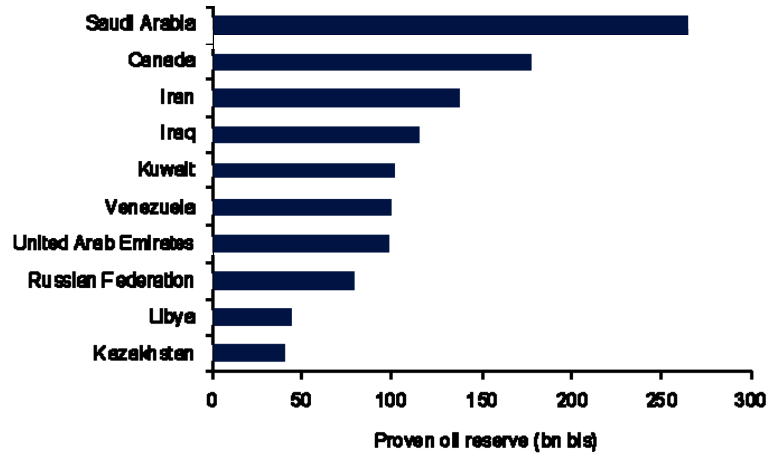


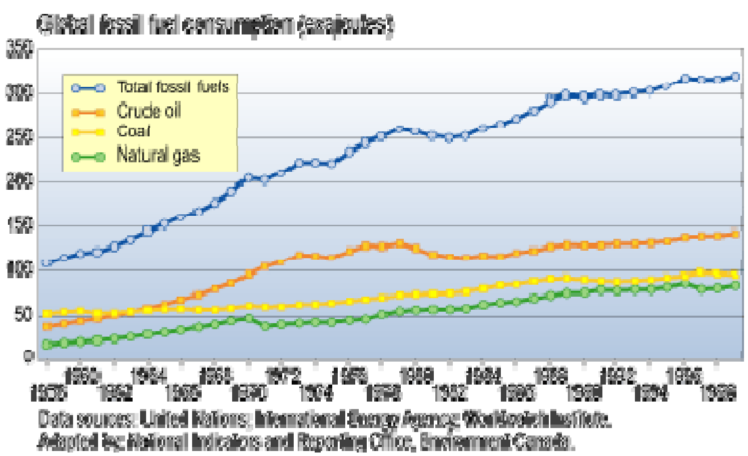
Global Uncertainties

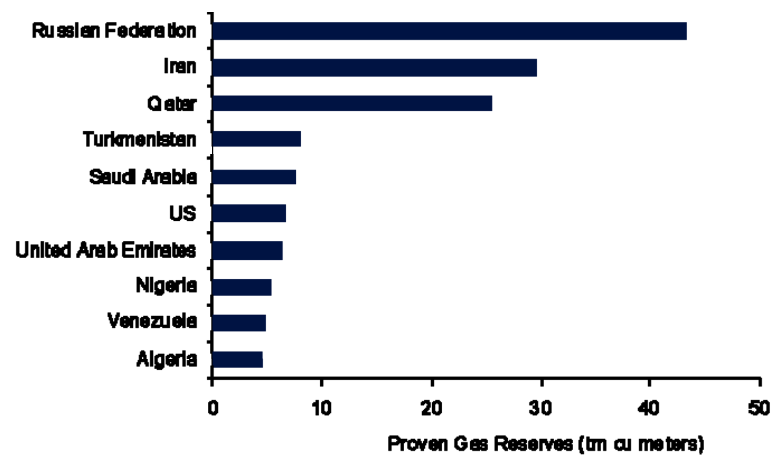
Customer Economics

Global Fuel Scenario





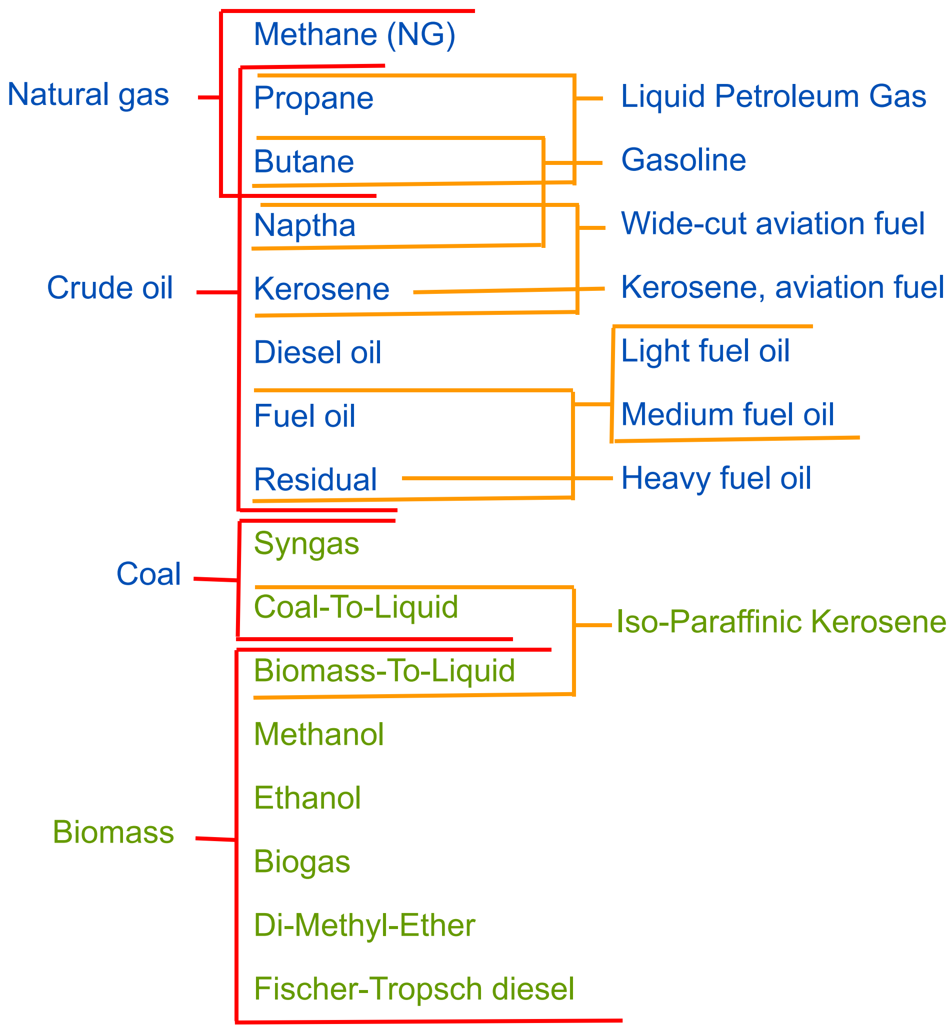


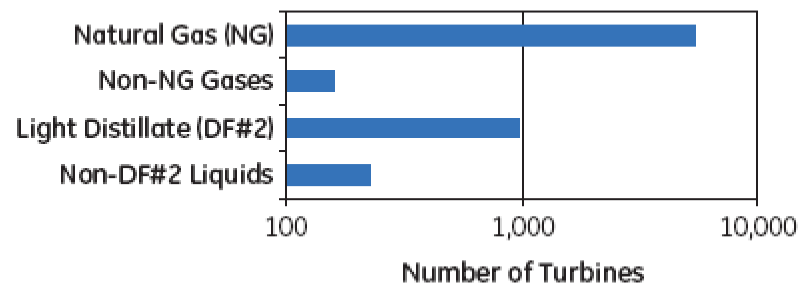


Fuel Flexibility Challenge

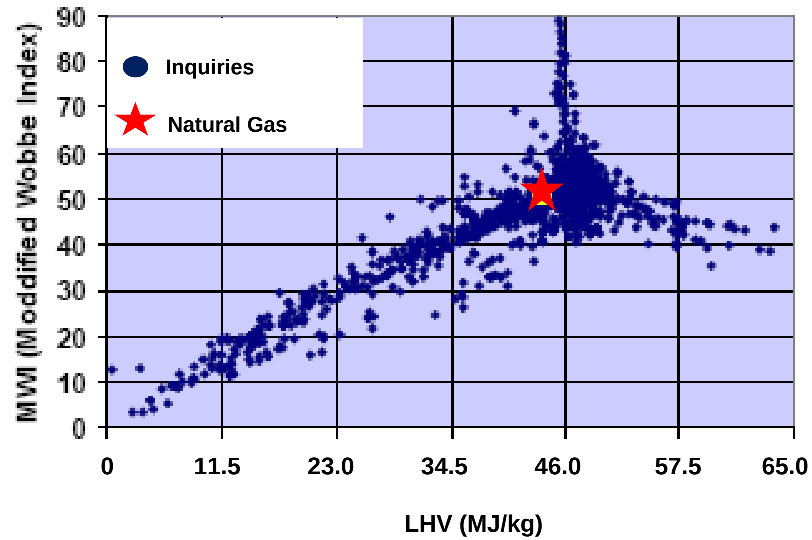
- Much tighter control (regulations) requirement on fuel specification in aviation gas turbines
- Requirement for industrial gas turbine – burn anything
- How does/can fuel affect gas turbine operation?
  - Combustion
  - Turbomachinery
  - Emissions
  - Hot gas path components
  - Maintenance
- Decision to utilize alternative fuels depends on these effects and the associated cost

Gas Turbine Fuels – Conventional & Alternative



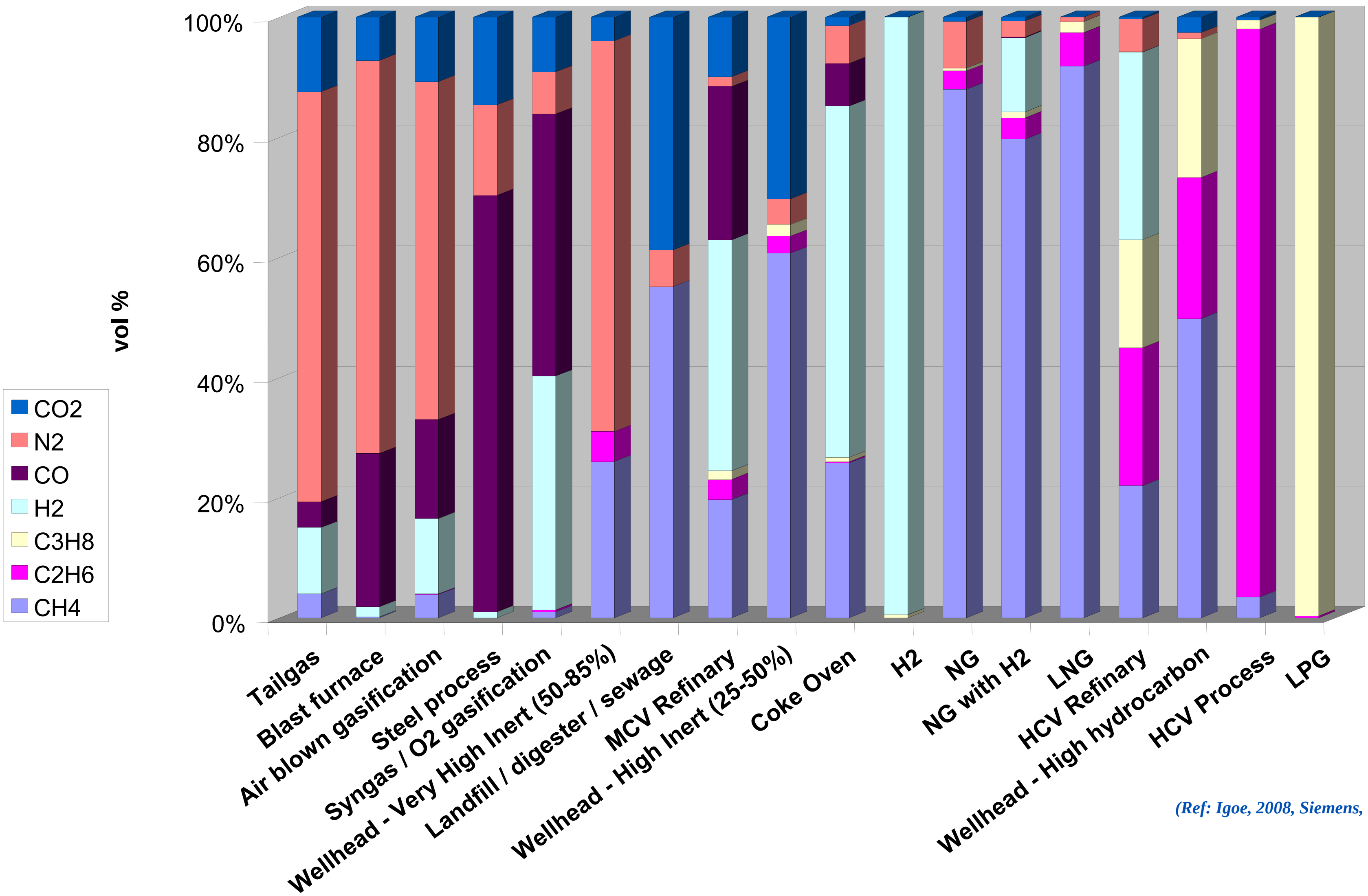


(Ref: Rahm et al, 2009, GE,ASME)



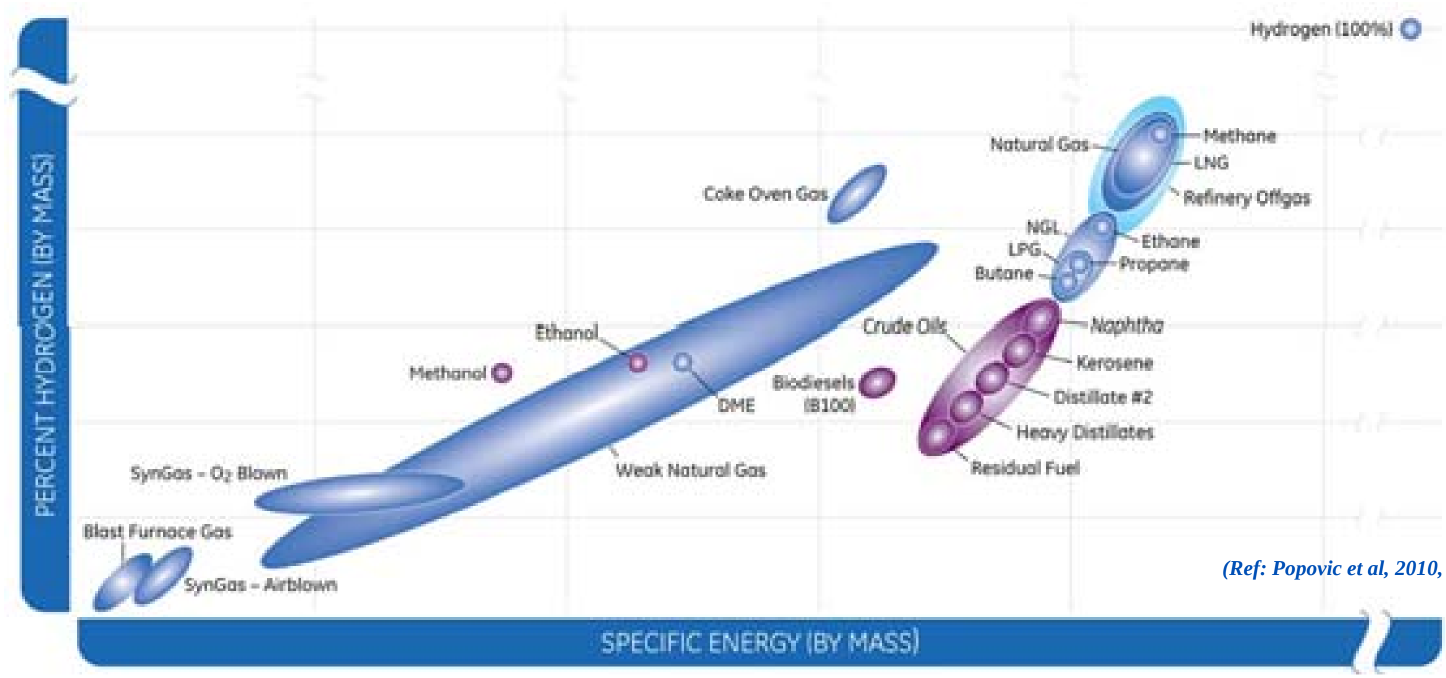
(Ref: Wisniewski & Handelsman 2010, GE, ASME)

Gas Turbine Fuels' Composition



(Ref: Igoe, 2008, Siemens, IAGT)

Gas Turbine Fuels' Properties



(Ref: Popovic et al, 2010, GE, ASME)

	Main Constituents	LHV (MJ/m^3)		U/L Flammability Ratio	
		Min.	**Max.**	**Min.**	**Max.**
Natural Gas	CH_4, C_2H_6	31.971	47.957	2.20	3.00
LPG	C_3H_8, C_4H_{10}	91.917	127.885	4.00	5.00
Air Blown Syngas	H_2, CO, N_2 , H_2O, CO_2	5.195	7.993	2.40	5.40
Oxygen Blown Syngas	H_2, CO, H_2O, CO_2	7.993	15.986	6.00	12.00
Refinery Offgas	H_2, C_2H_6, C_3H_8, C_4H_{10}, C_2H_4, C_3H_6	11.989	63.942	3.00	18.00
Blast Furnace Gas	H_2, CO, N_2 , H_2O, CO_2	2.997	4.996	1.50	3.00
Coke Oven Gas	H_2, CO, N_2 , H_2O, CO_2	11.989	19.982	6.00	8.00

Fuel Constituents – Characteristic Values

		LHV (MJ/kg)	Flammability Limits (Air-Fuel Ratio)		Autoignition (^oC)	Laminar Flame Speed (cm/s)
			Lean	U/L Ratio		
Methane	CH_4	50.048	34.26	3.35	537	44.8
Ethane	C_2H_6	47.511	31.11	4.58	472	47.6
Propane	C_3H_8	46.330	30.59	4.89	450	46.4
Butane	C_4H_{10}	45.725	27.16	5.00	462	44.9
Pentane	C_5H_{12}	45.343	28.24	5.96	284	43
Hexane	C_6H_{14}	44.925	27.64	6.58	225	
Methanol	CH_3OH	19.915	12.57	7.83	385	72.2
Carbon Monoxide	CO	10.113	7.23	19.92	609	52
Hydrogen	H_2	120.071	344.40	72.00	400	325

Syngas Related Issues – Composition Variations

- Gasifier type
- Process temperature
- Feed rate
- Amount of Oxygen
- H:C ratio in feedstock

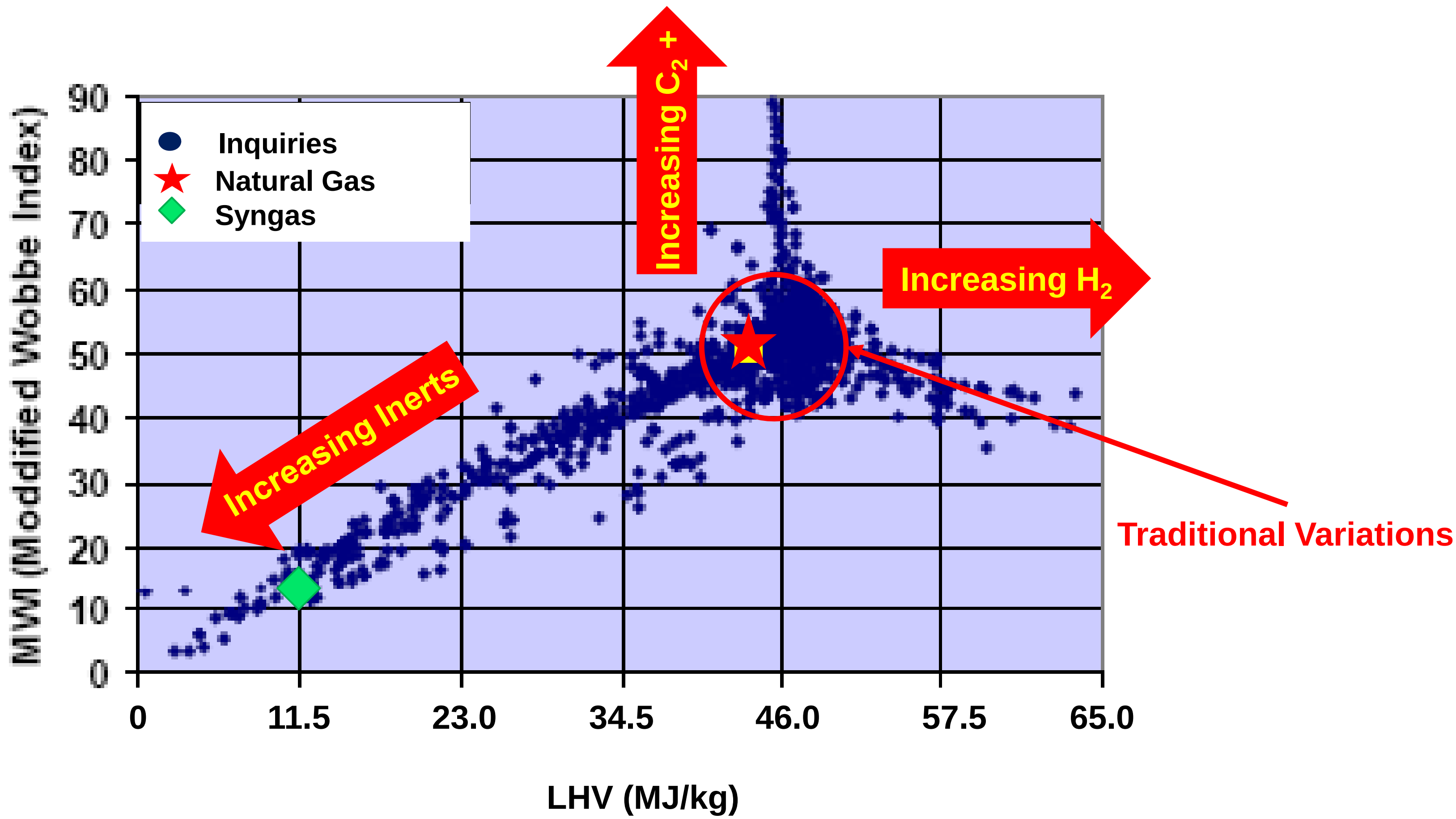
Feedstock Variation

Composition (Volume %)	Coal-Gas	Bio-Gas	Natural Gas
Hydrogen (H2)	14.0%	18.0%	--
Carbon Monoxide (CO)	27.0%	24.0%	--
Carbon Dioxide (CO2)	4.5%	6.0%	--
Oxygen (O2)	0.6%	0.4%	--
Methane (CH4)	3.0%	3.0%	90.0%
Nitrogen (N2)	50.9%	48.6%	5.0%
Ethane (C2H6)	--	--	5.0%
HHV (kJ/m^3)	6,417	5,315	39,450

Process Variation

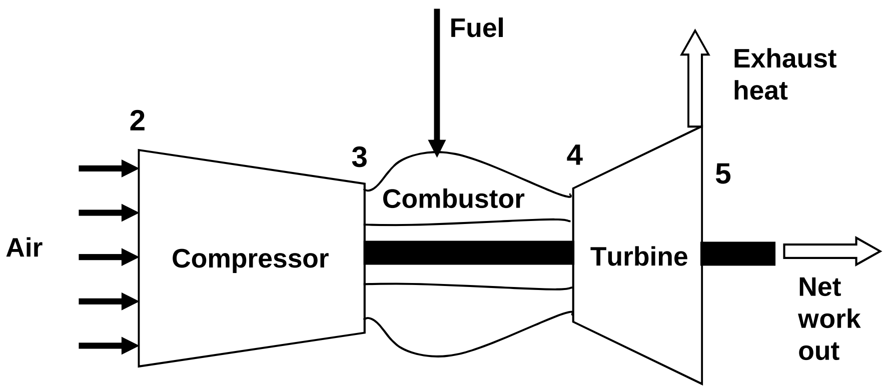
Composition (Volume %)	Min.	Max.	Avg.
Hydrogen (H2)	8.6	61.9	31.0
Carbon Monoxide (CO)	22.3	55.4	37.2
Carbon Dioxide (CO2)	1.6	30	12
Methane (CH4)	0	8.2	2.2
Nitrogen (N2)+ Argon (Ar)	0.2	49.3	12.2
Water (H2O)	0.1	39.8	7.8
Hydrogen/Carbon Monoxide Ratio	0.33	0.8	0.86

Fuel Flexibility Spread



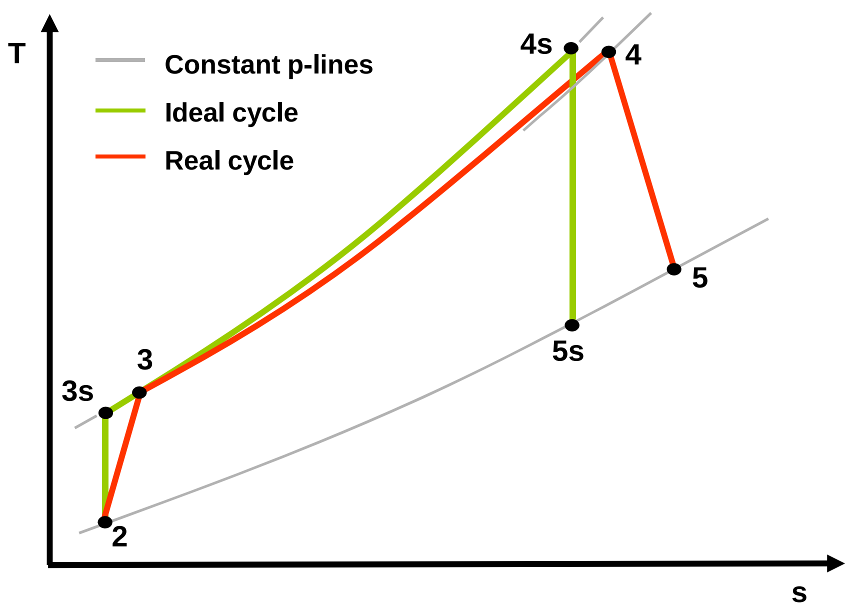
(Ref: Wisniewski & Handelsman 2010, GE, ASME)

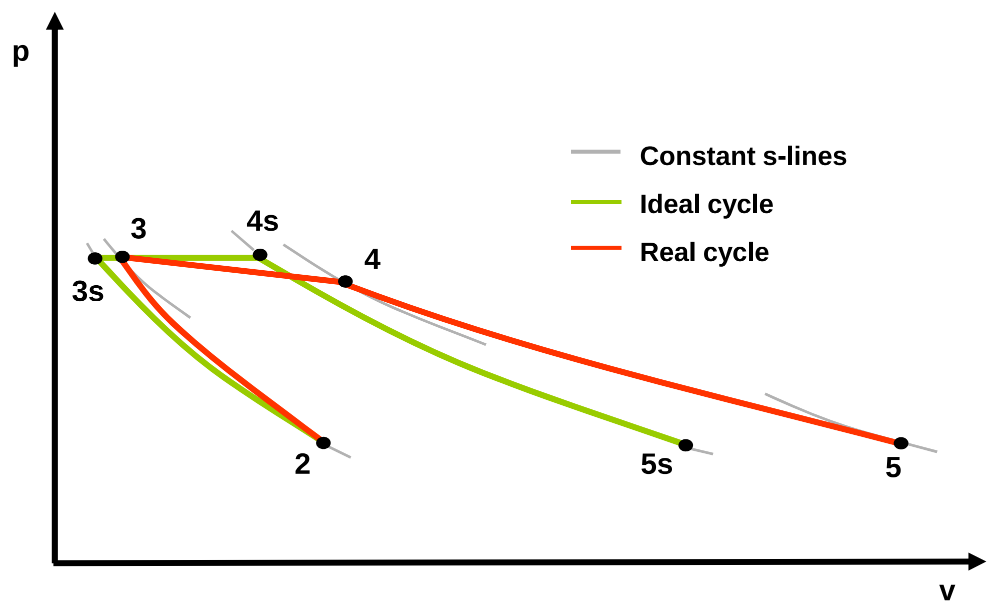
Thermodynamics of Gas Turbines



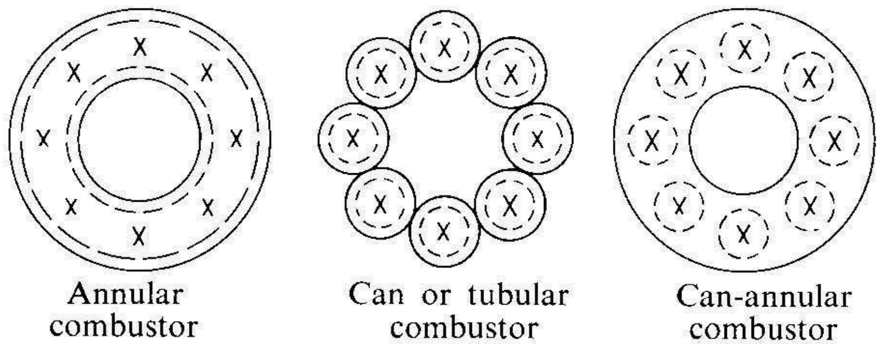
$$\eta_{th} = 1 - \left[\frac{1}{p_3/p_2}\right]^{(\gamma-1)/\gamma}$$

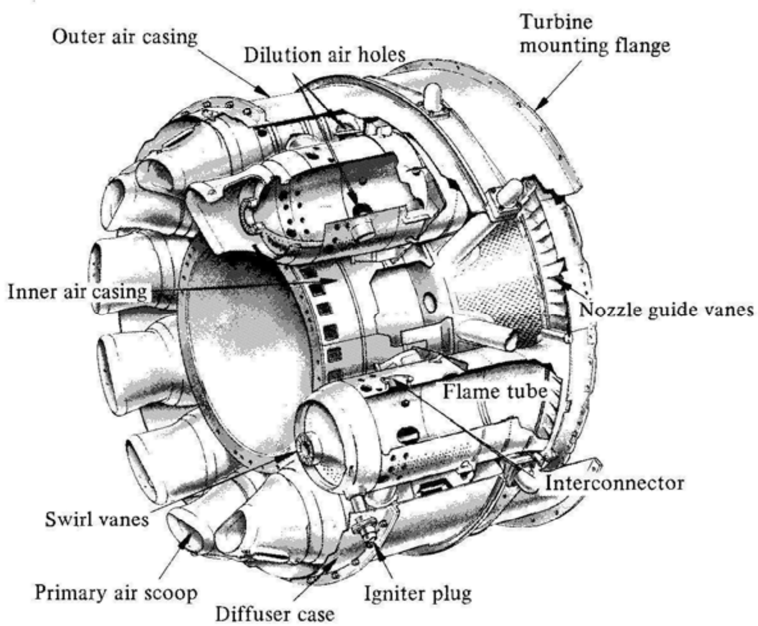
$$W_{sp} = \eta_{th}\left[\left(T_4/T_2\right) - \left(p_3/p_2\right)^{(\gamma-1)/\gamma}\right]$$

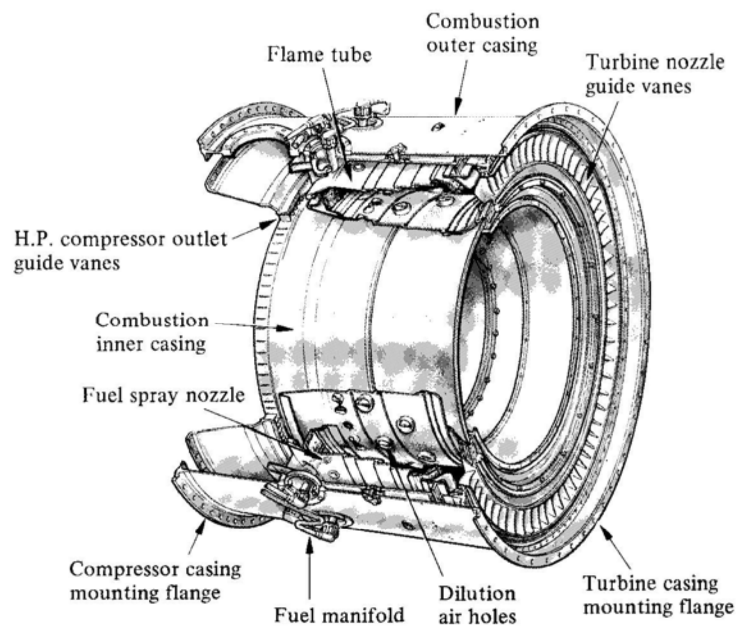




Types of Combustors

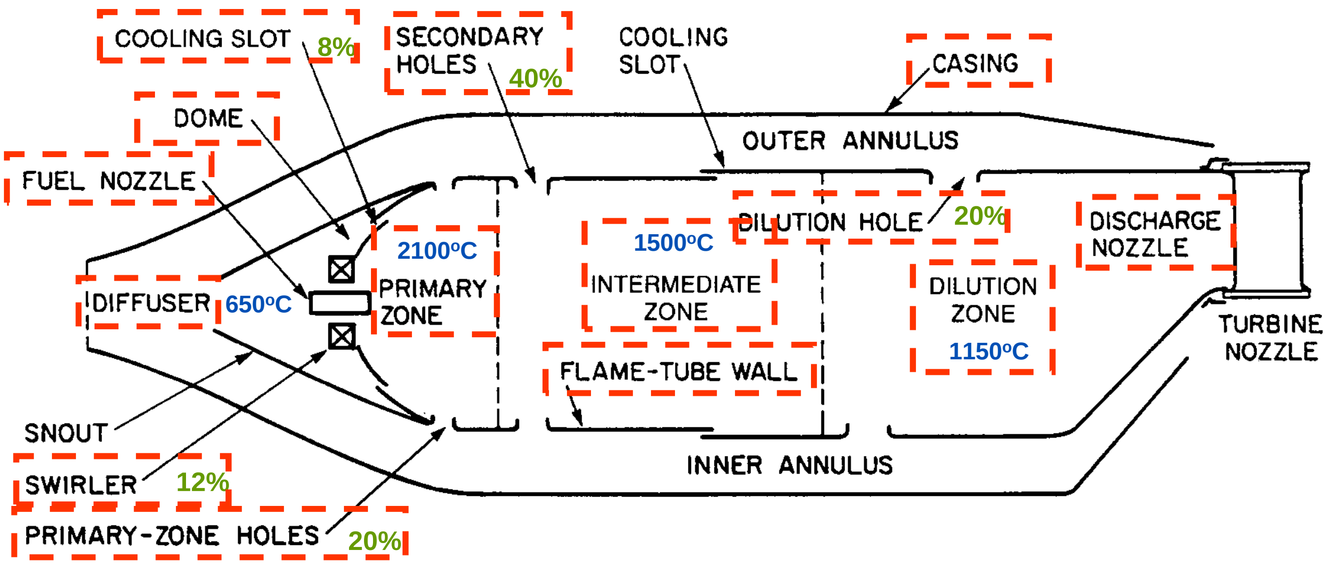






(Ref: Hill & Peterson, 1992)

Combustor Anatomy



(Ref: Lefebvre, 1998)

Fundamentals of Combustion

- What is combustion?
  - Rapid oxidation generating heat, or both light and heat
  - Chemical reaction between a fuel and an oxidant

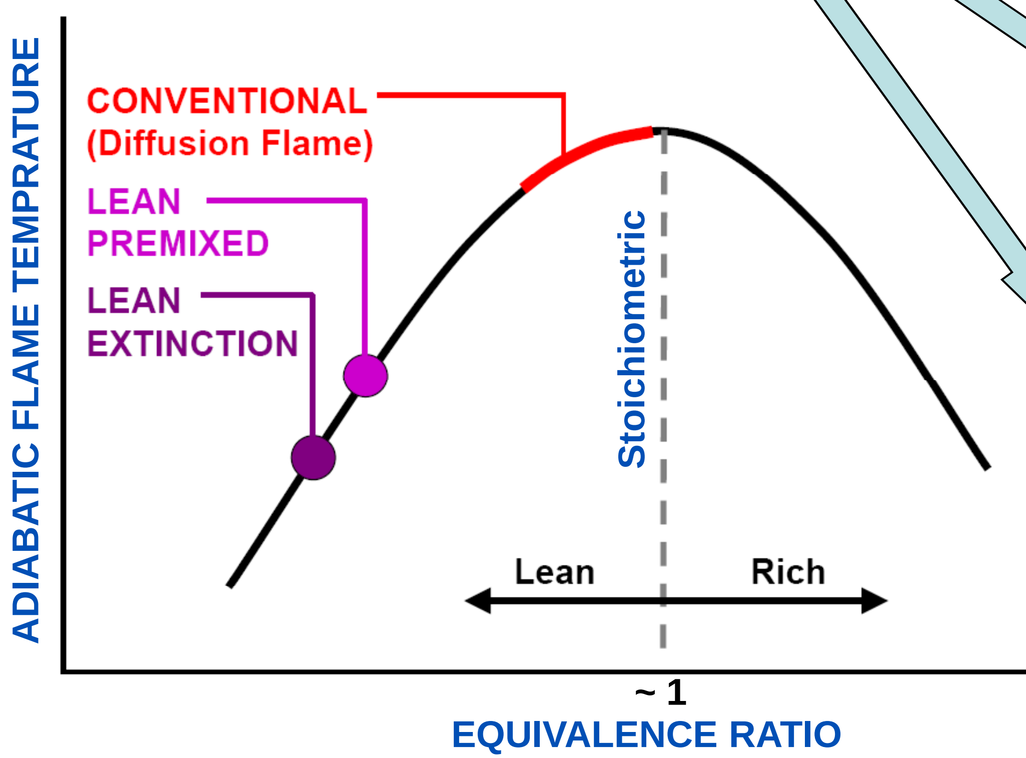
    $CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O + \text{Heat}$

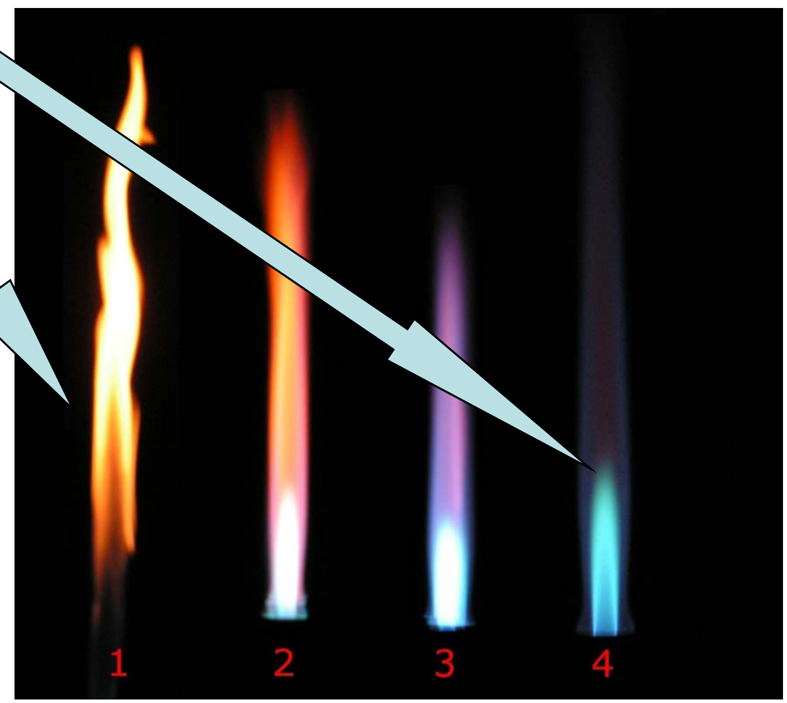
- What is flame?
  - A self-sustaining propagation of localized reaction zone at subsonic velocities

Rich vs. Lean Combustion

$$C_xH_y + \left(\frac{x + y/4}{\phi}\right)(O_2 + 3.76N_2) \rightarrow aCO_2 + bCO + cH_2O + dH_2 + eO_2 + 3.76\left(\frac{x + y/4}{\phi}\right)N_2$$

$\phi > 1$ $\phi < 1$



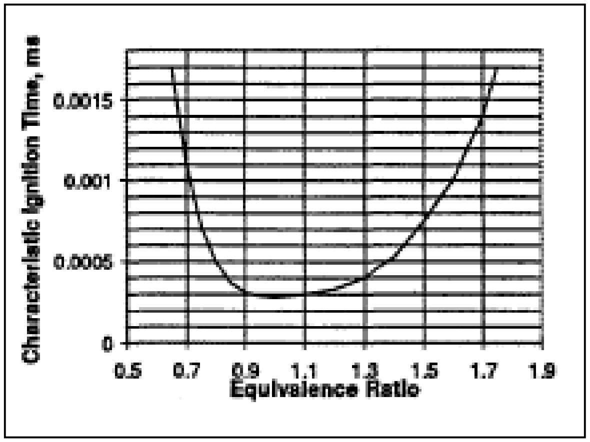


Basic Combustion Concepts

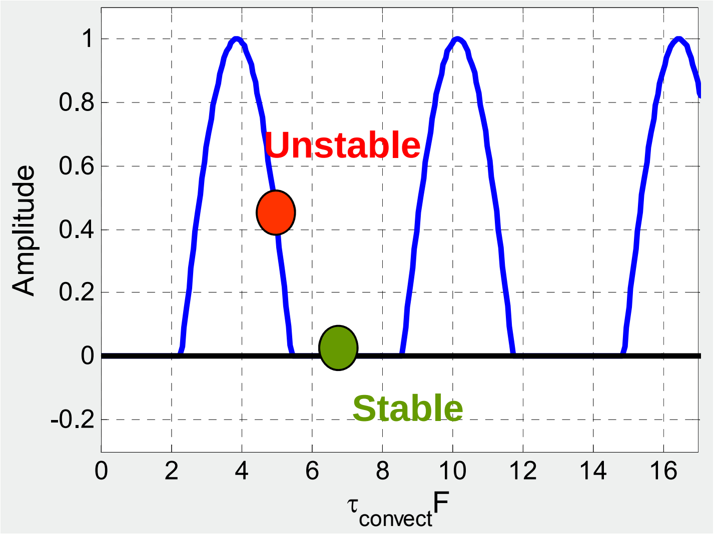
- Fuel-air ratio
- Stoichiometry
- Equivalence ratio
- Pattern factor
- Ignition delay
- Autoignition
- Flame speed
- Lean blowout
- Flashback
- Adiabatic flame temperature
- Combustion efficiency

Combustion Dynamics

- Unsteady rate of heat input in phase with the pressure oscillations
- The instability grows to high-amplitude and hardware damaging pressure oscillations
- Susceptibility of DLN combustors to oscillations
- Mechanisms responsible for oscillations in premixed combustors
  - Fuel-air ratio oscillations
  - Vortex shedding
- Dynamics depends on
  - Cos ($\tau_{convect}$F)>0 → unstable
  - Cos ($\tau_{convect}$F)< or = 0 → stable



(Ref: Zukoski, 1978)

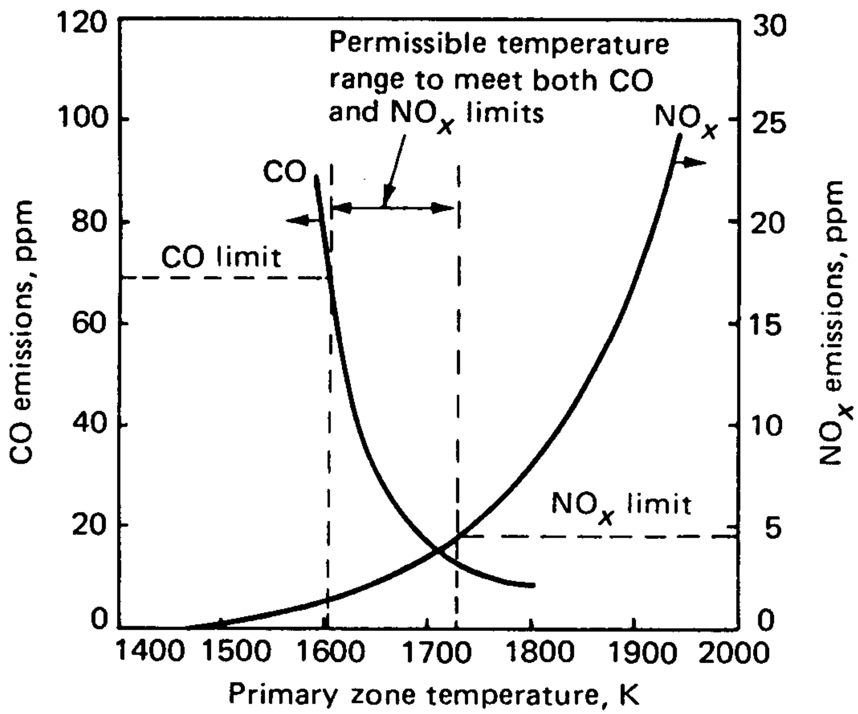


(Ref: Lieuwen, 2008)

Gas Turbine Related Pollutants

Pollutant	Effect	Mechanism
CO	Toxic	Incomplete combustion, dissociation of CO2 (weak or rich FAR in primary zone, low reaction temperature, poor mixing, quenching by liner cooling air)
UHC	Toxic	Incomplete combustion, (poor atomization, insufficient flame speed, quenching by liner cooling air)
C (particulates, smoke(95%))	Toxic, visibility	High temperature fuel oxidation under very rich equivalence ratio (very rich FAR in PZ, short intermediate zone, poor atomization)
NO_x (NO and NO_2)	Toxic, smog precursor, ozone depletion	Thermal NO (N2+O->NO, N+OH->NO) (T_{PZ} >1850K) Prompt NO (N2+CH-> HCN-> CN-> CNO->NO) Fuel NO (oxidation of fuel bound N2 mainly heavy distillate fuel)
SO_x (SO_2 and SO_3)	Toxic, corrosive	Oxidation of fuel bound sulfur
GHG (CO_2, H_2O and N_2O)	Global warming	Combustion of fossil fuels

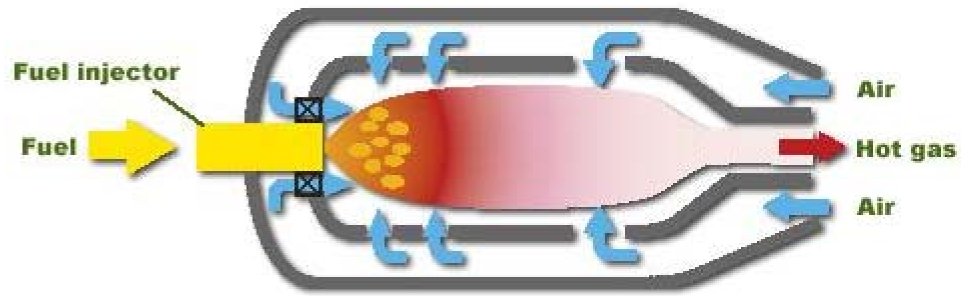
Influence of Primary Zone Temperature on CO and NOx Formation



(Ref: Lefebvre, 1998)

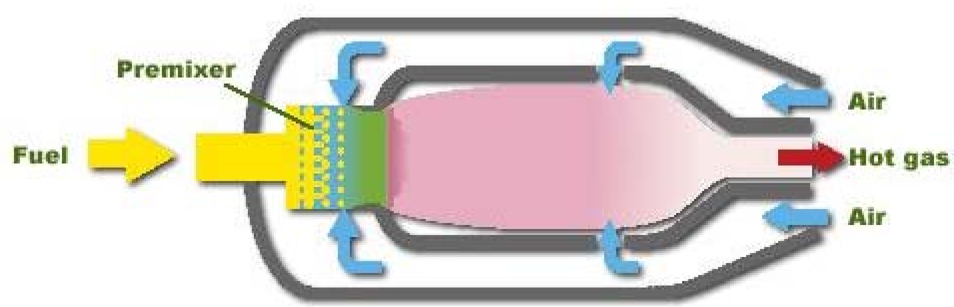
Premixed vs. Non-premixed Combustion

Diffusion



	Mixing	Autoignition	Flashback	Emissions	Fuel Flexibility
Diffusion	Critical	No	No	Higher	Good
Premixed	Good	Possible	Possible	Low	Challenging

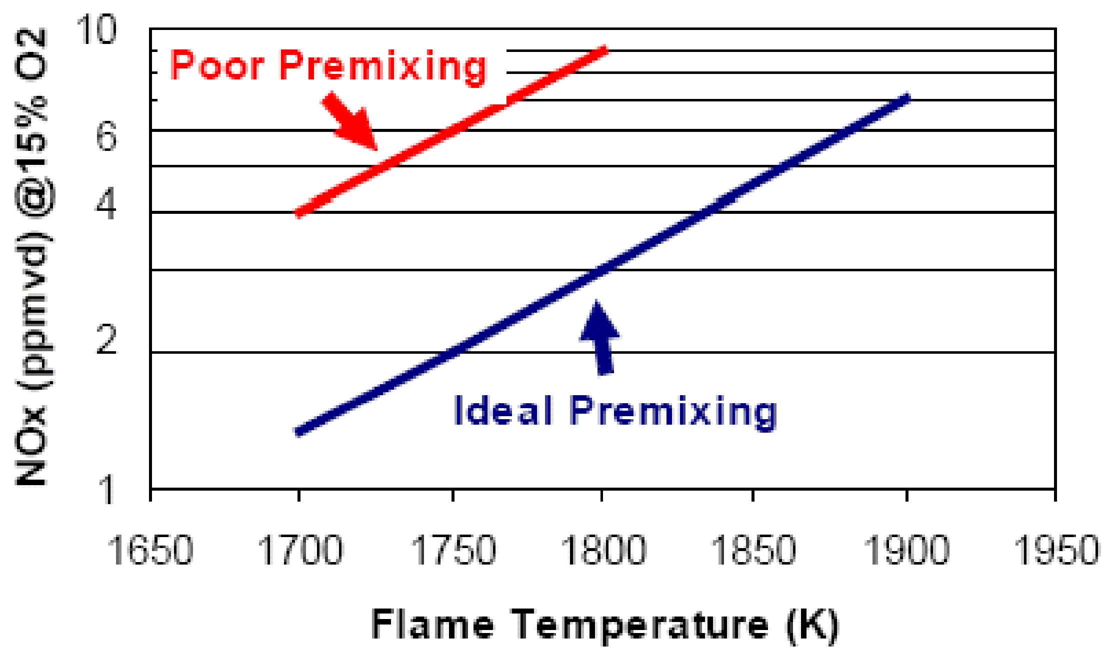
Premixed



Low NOx Technologies

- Wet Low-NOx
- Catalytic Combustion
  - Cool combustion module
  - Selective catalytic reduction (SCR)
- Dry Low-NOx
  - Rich-burn Quick-quench Lean-burn (RQL)
  - Lean Premixed (LP)
  - Lean Premixed Prevaporized (LPP)
  - Lead Direct Injection (LDI)

Influence of Premixing

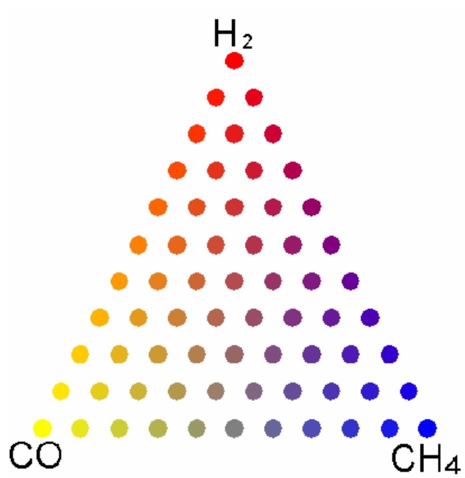


Important Combustor Performance Parameters

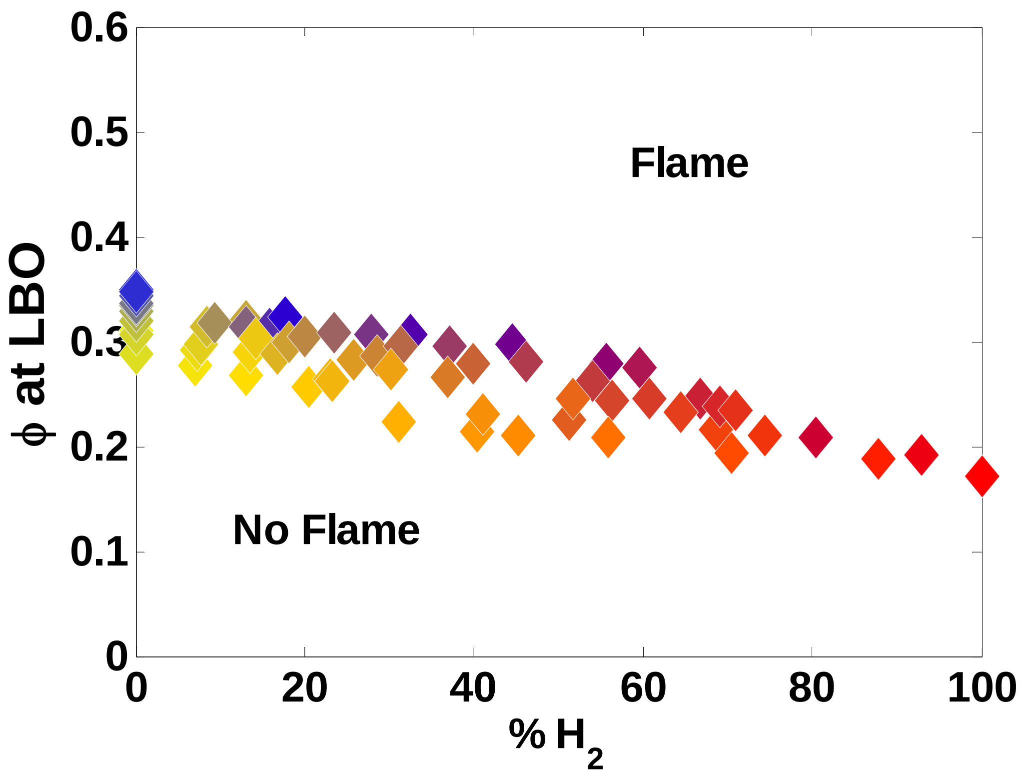
- Wide operability
  - Blow-off limits
  - Flashback and auto-ignition limits
  - Static and dynamic stability (spatial and temporal flame anchoring)
- Low emission
- Good turndown
- Durability

Fuel Composition Issues – Flame Blowoff

- H_2 addition significantly extends blowoff limits
- Diluent addition contracts blowoff limits



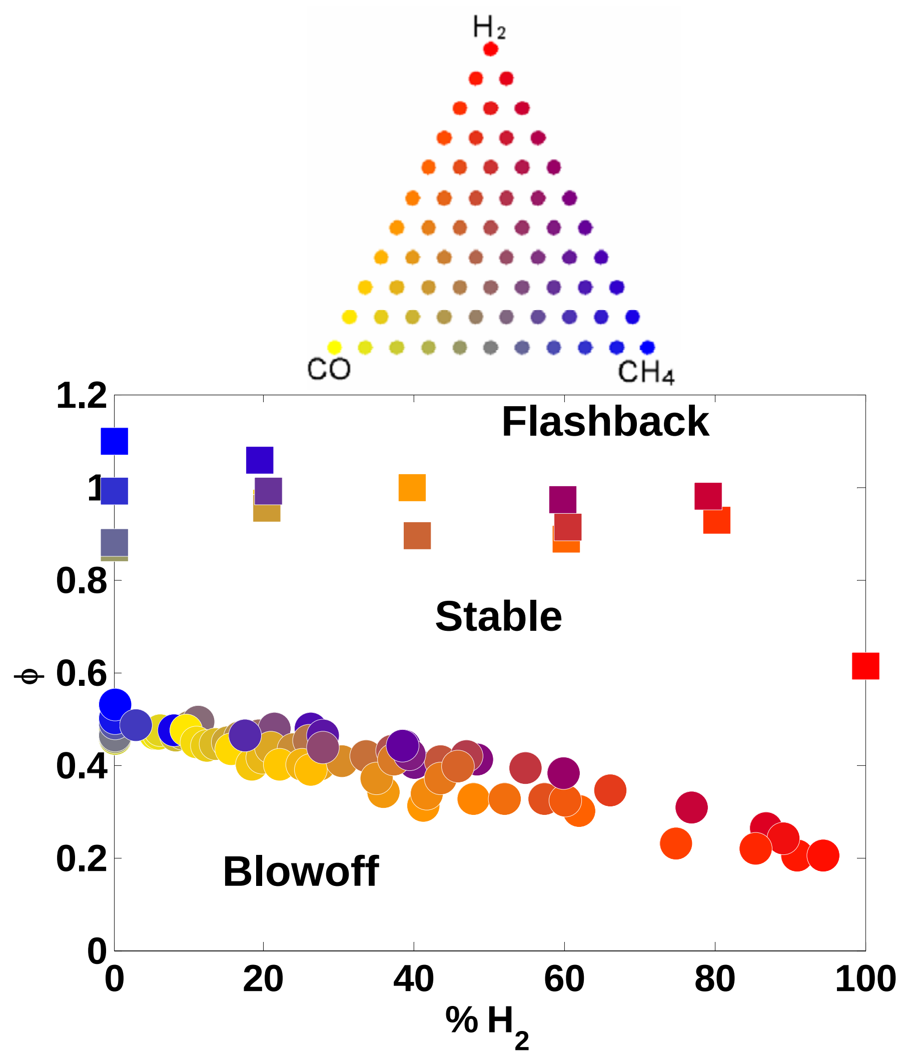
Conditions: U_0=60 m/s, T=460K, P=4.4atm,



(Ref: Lieuwen et al, 2008)

Fuel Composition Issues – Flame Flashback

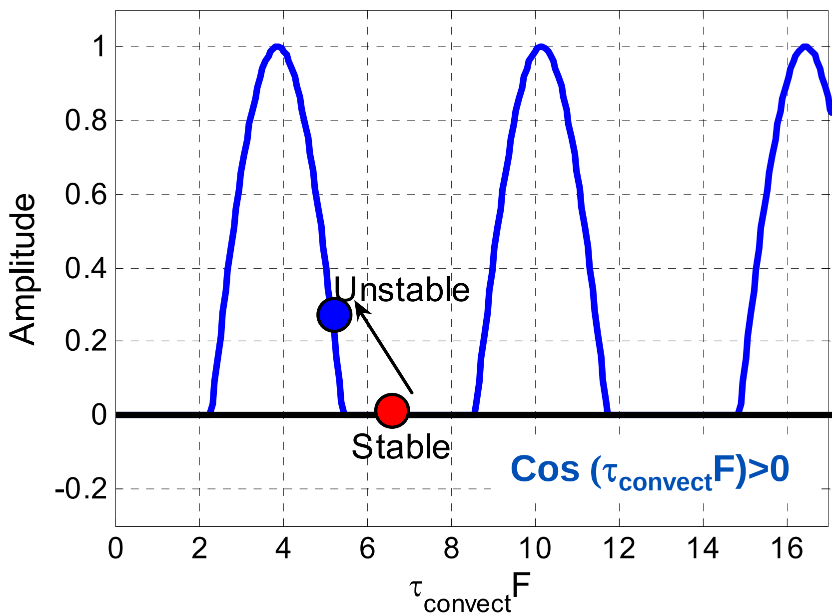
- Multiple flashback mechanisms
  - In boundary layer
  - In core flow
  - Strong acoustic pulsations lead to nearly reverse flow
  - Combustion induced vortex breakdown
- Different fuel properties influence these mechanisms differently
- Strong dependence of turbulent flame speed on fuel composition
- Hydrogen influence on flashback

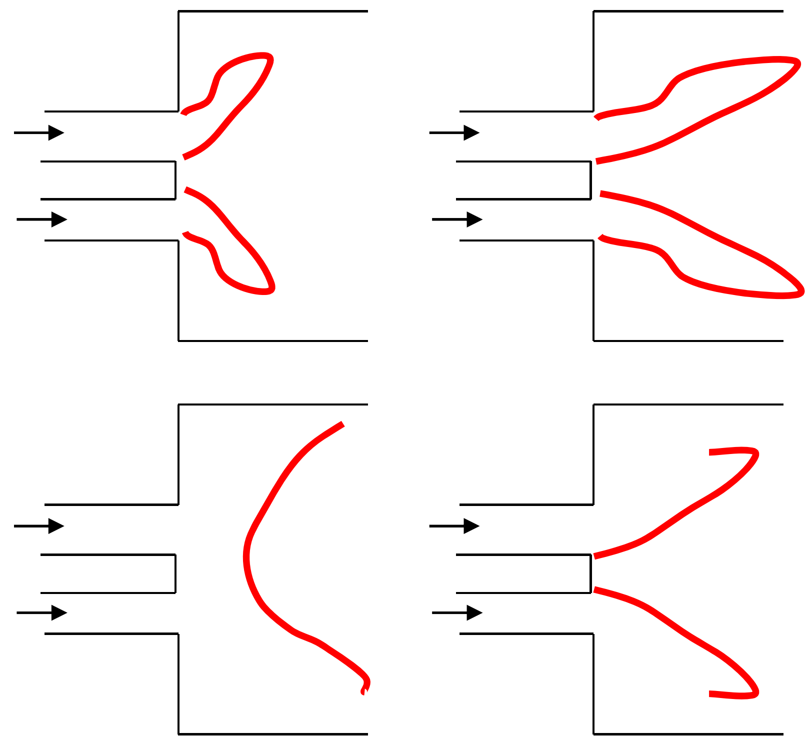


(Ref: Lieuwen et al, 2008)

Fuel Composition Issues – Flame and Combustion Stability

- Fuel composition variations influence
  - Flame shape
  - Flame standoff location
- Alteration in flame shape and location can worsen or improve combustor dynamics via $\tau_{convect}$





(Ref: Lieuwen, 2008)

Fuel Composition Issues – Emissions

- Strongly dependant on composition

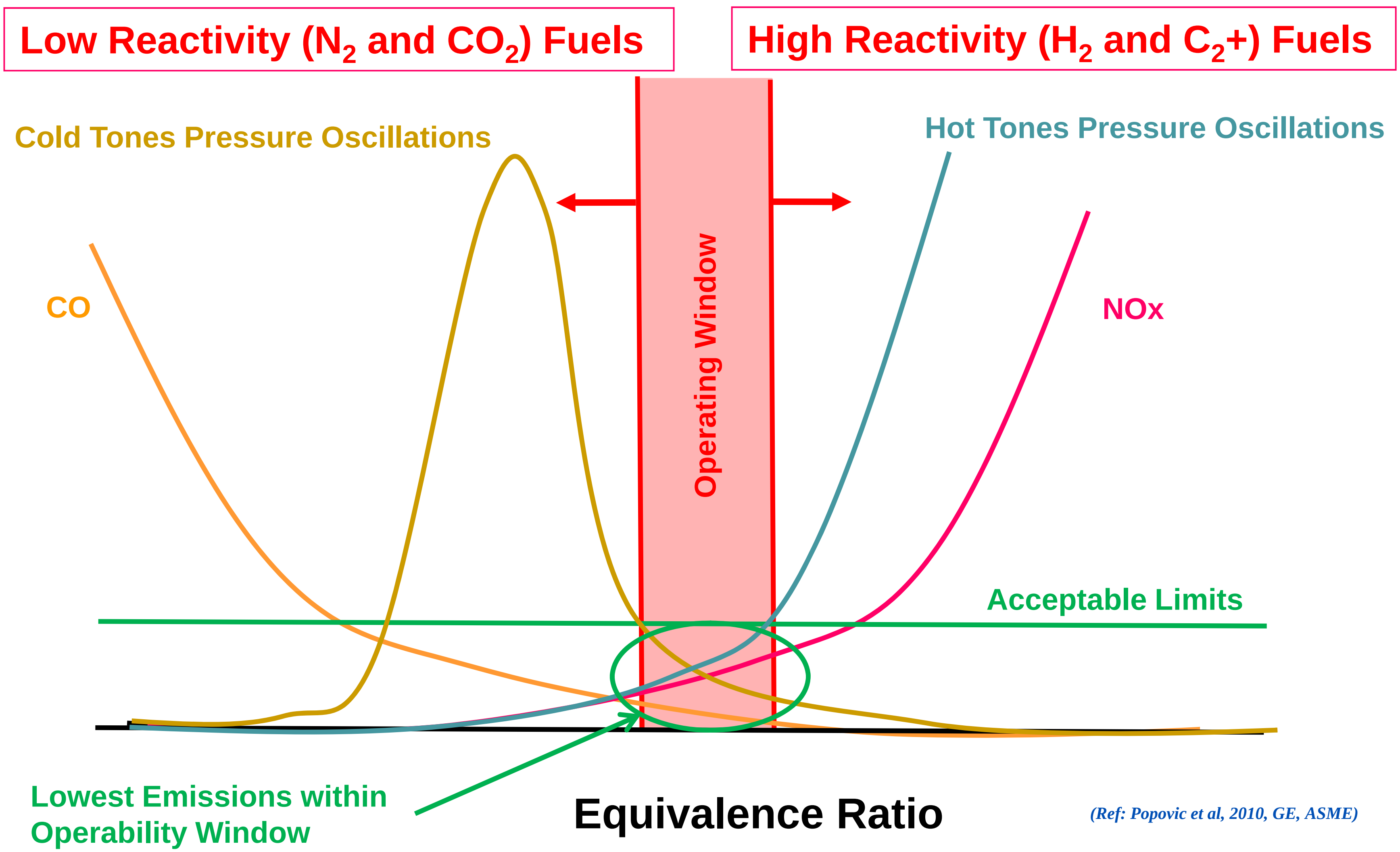
- Reactive fuel blends having high H_2 or C_2+ compositions
  - Increase NOx formation
  - Decrease CO formation at part load

- Fuels having high inert constituents
  - Reduce NOx formation
  - Increase concentration of CO and UHC in exhaust

Syngas Emissions

- Strongly dependant on composition
- In general syngas produce lower emissions for combined cycles
- VOC emissions low
- SOx emissions low
- CO emissions
  - Unburned syngas CO from insufficient mixing and equivalence ratio lower than ignition range
  - Incomplete combustion of HC contents
- NOx emissions
  - Thermally generated: Increase with increase in H2 contents due to higher firing temperatures. Decrease with increase in H2 contents due to leaner combustion potentials
  - Flame-generated: Increase with increase in H2 contents due to higher flame temperatures
  - Fuel-bound: Increase if ammonia not removed prior to combustion. Decrease if burned rich.
  - Increase with increase in CO:H2 ratio

Dry Low NOx Operation within Emissions & Dynamics Limits



Effects on Hardware Changeability & Durability

- Increased fuel reactivity causes thermal distress to premixer and hot gas-path components due to:
  - Higher flame temperature and flashback propensity
  - Susceptibility to high temperature thermoacoustic pressure oscillations
- High reactivity fuels require
  - Alternate fuel as well as purging system for starting and shutdown
- Reduced fuel reactivity due to addition of Inerts require
  - Larger sized injectors to compensate for higher fuel flow rate requirement
- Reduced fuel reactivity cause hardware distress due to
  - Low temperature combustion dynamics
- Syngas use may cause increased component corrosion

Re-Cap

- Challenges facing gas turbine technology
- Fuels scenario
- Fuel types and characteristics
- Fuel flexibility challenge
- Combustion basics
- Low NOx combustion technologies
- Effects of variations in fuel composition on:
  - Gas turbine operability and durability
  - Gas turbine emissions

Reference Material

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Thank You

For more information on the presented material, please contact:

Dr. Wajid Ali Chishty

Gas Turbine Laboratory, Institute for Aerospace Research
National Research Council Canada
1200 Montreal Road, M-7, Ottawa, ON K1A 0R6
Tel: (613) 993-2731, Fax: (613) 957-3281
Wajid.Chishty@nrc-cnrc.gc.ca