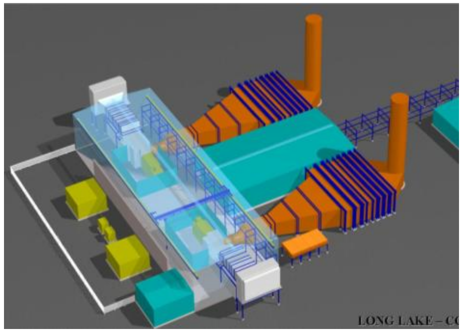
IAGT Fall Course 2012

October 18 & 19, 2012
Delta Toronto Airport West

Air Emissions Prevention

- Air Pollution and GHG Emissions
- Balancing Objectives for Clean Energy Systems
- Technologies for Low NOx & System Efficiency
- Tradeoffs and Synergies

Rolls Royce RB211 DLE



Nexen, Long Lake AB

Manfred Klein
Coordinator, Energy & Environment
NRCC Gas Turbine Labs

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DOW/TransAlta, Ft. Sask GTCHP

Typical Industrial Gas Turbine Energy Systems

- Simple Cycle, Standby power
- New Gas Combined Cycle
- Combined Cycle Repowering
- Large Industrial Cogen
- Oilsands Gasification
- Pipeline Compression
- Small Industrial Cogeneration
- Municipal District Energy



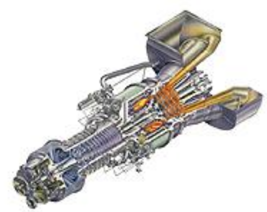
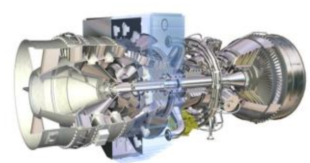
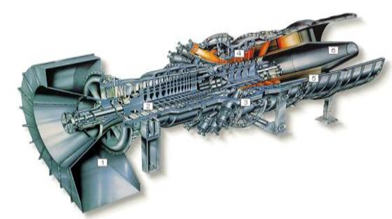
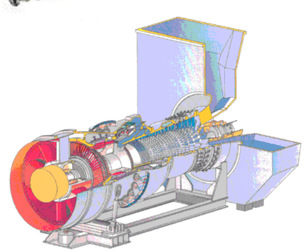
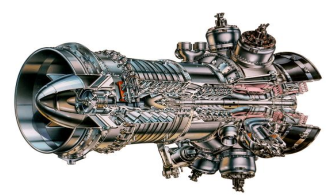
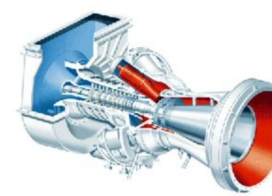
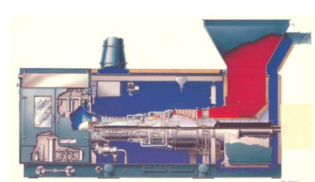
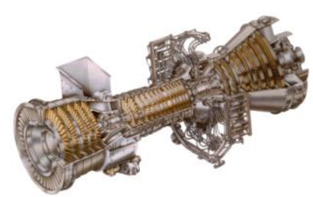



About 25 000 MW in Canada

Many different types of gas turbine units;

- Aeroderivatives
- Small industrials
- Large Frame Industrials

\+ Steam turbines & HRSGs


Air Pollution

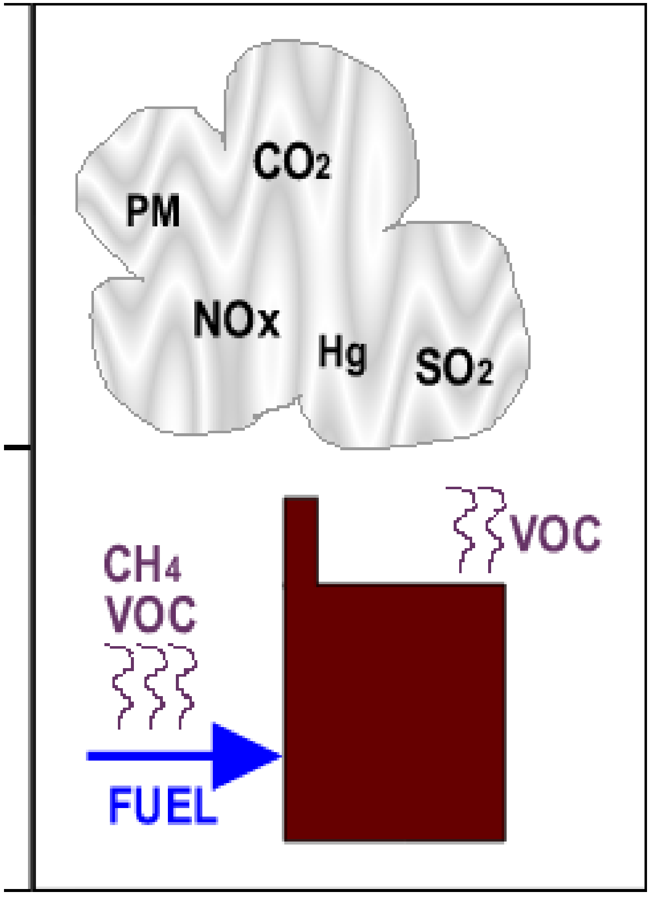
- Sulphur Dioxide SO_2
- Nitrogen Oxides NO_2
- Volatile Organics VOC
- Fine Particulates PM
- Ammonia NH_3
- Carbon Monoxide CO
- Ozone Depleting CFCs

Greenhouse Gases

- Carbon Dioxide CO_2
- Methane CH_4
- Nitrous Oxide N_20
- SF_6 et al

Air Emissions

System



"Cannot produce Air Pollution without making CO_2"

Air Pollution: *NOx Emissions*

$$O + N_2 \rightarrow NO + N$$
$$N + O_2 \rightarrow NO + O$$

3 Compounds of Concern:

NO, NO$_2$ smog, ***N$_2$O*** ghg

Thermal NOx:

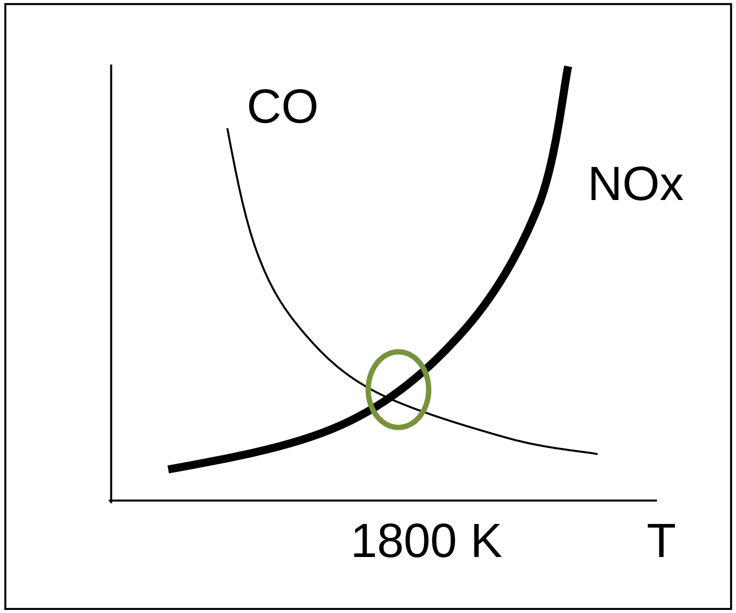
High Temperature Combustion

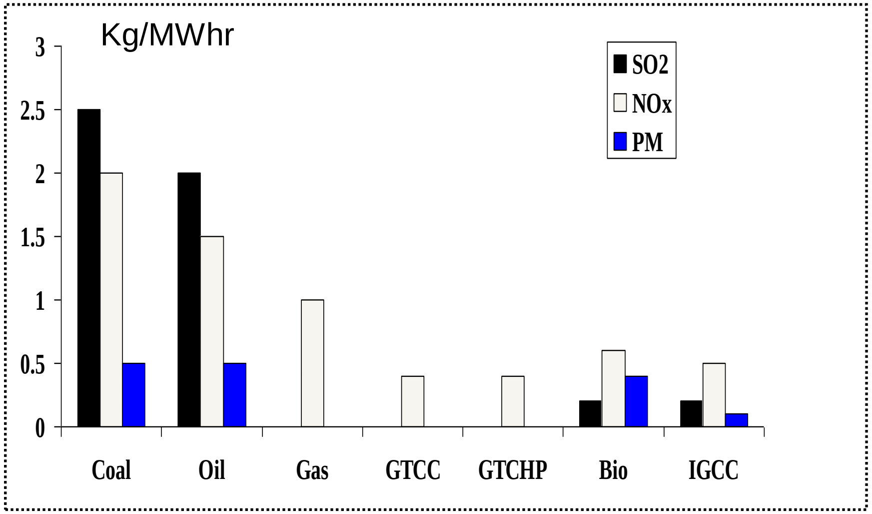
NOx increases with $T^{1.5}$ and $P^{0.5}$

Fuel NOx:

From N_2 Content of Oil, Coal

- *Nitrous Oxide is N_2O, a GHG*





Air Pollution from Thermal Energy

Greenhouse Gases; CO_2 Emission Rates

(Heat Rate$_{HHV}$ x Fuel CO_2 factor)

Coal	**85-95 kg/GJ**
Heavy Oil	**74 kg/GJ**
Natural Gas	**50 kg/GJ**

Examples

New Coal Boiler

10 GJ/MWhr x 90 kg$_{CO2}$/GJ

= 900 kg$_{CO2}$/MWhr

Gas Turbine Combined Cycle

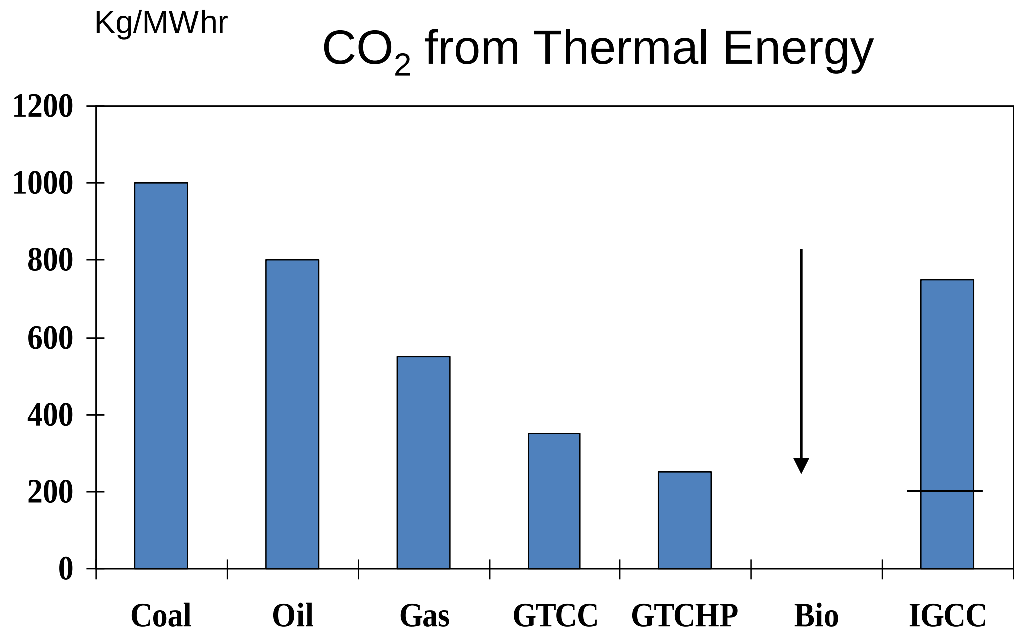
8 GJ/MWhr x 50 kg$_{CO2}$/GJ

= 400 kg$_{CO2}$/MWhr

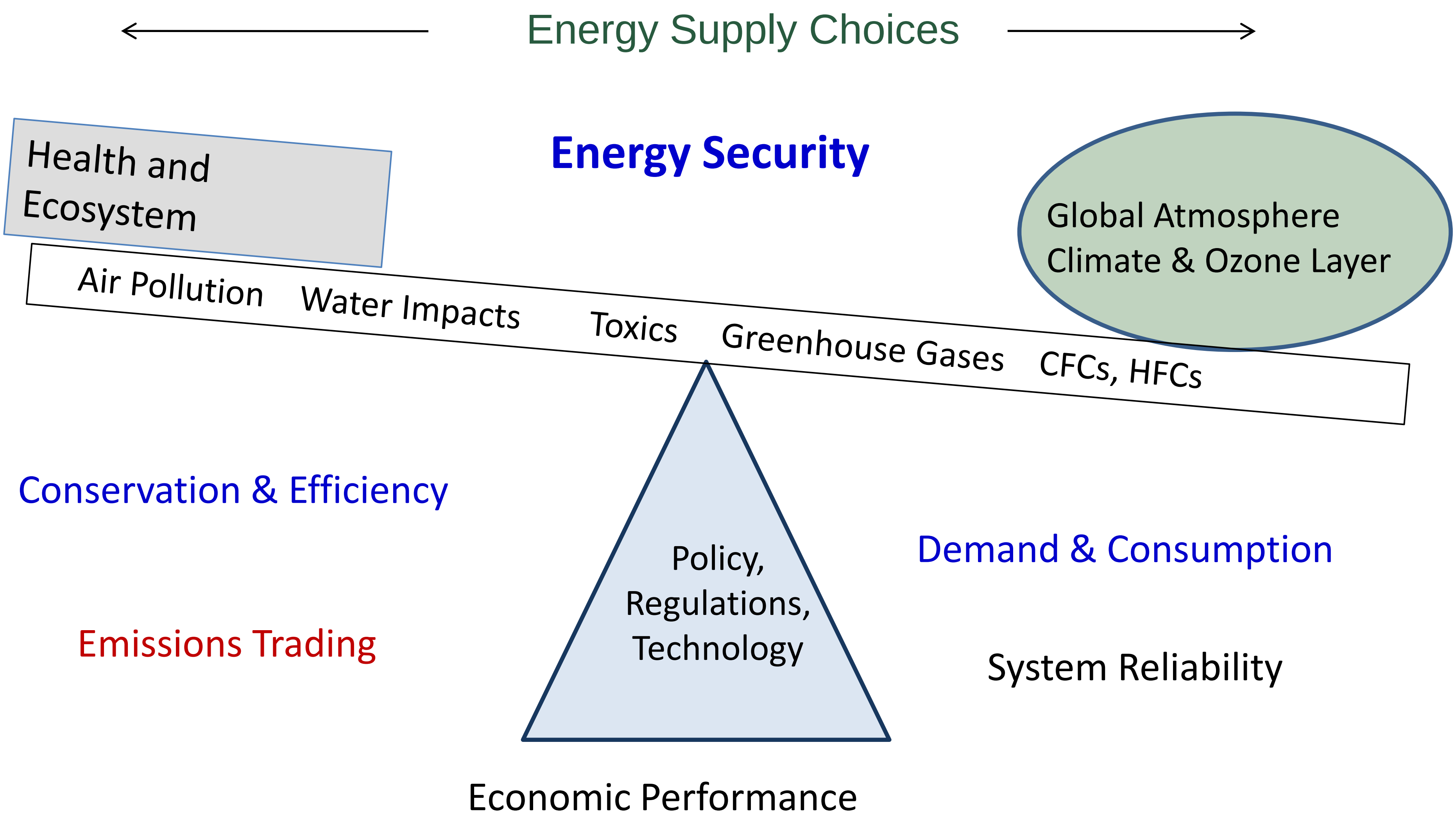
Gas Cogen (FCP)

5 GJ/MWhr x 50 kg$_{CO2}$/GJ

= 250 kg$_{CO2}$/MWhr



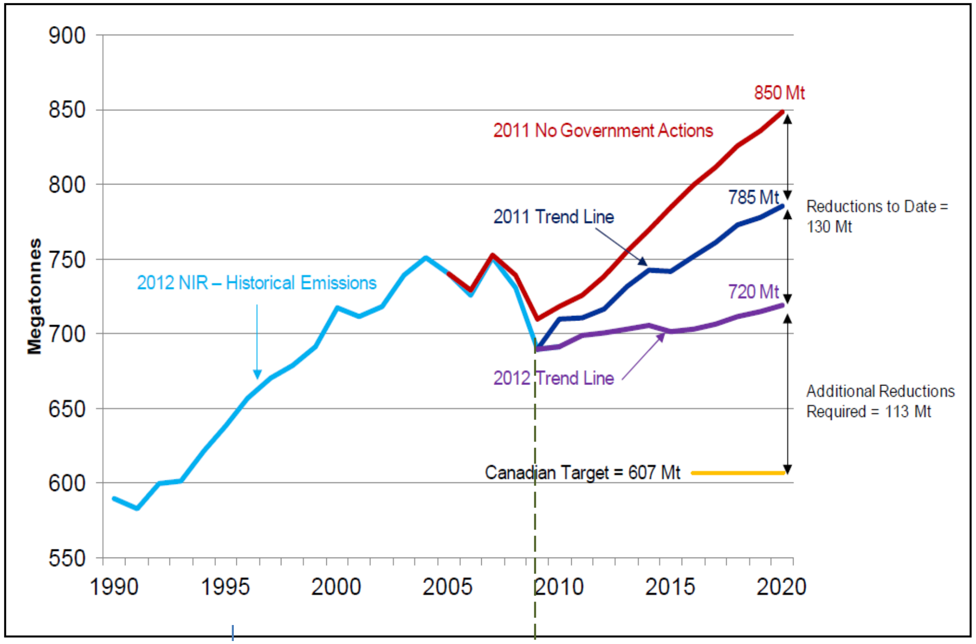
Clean Energy Balancing Act



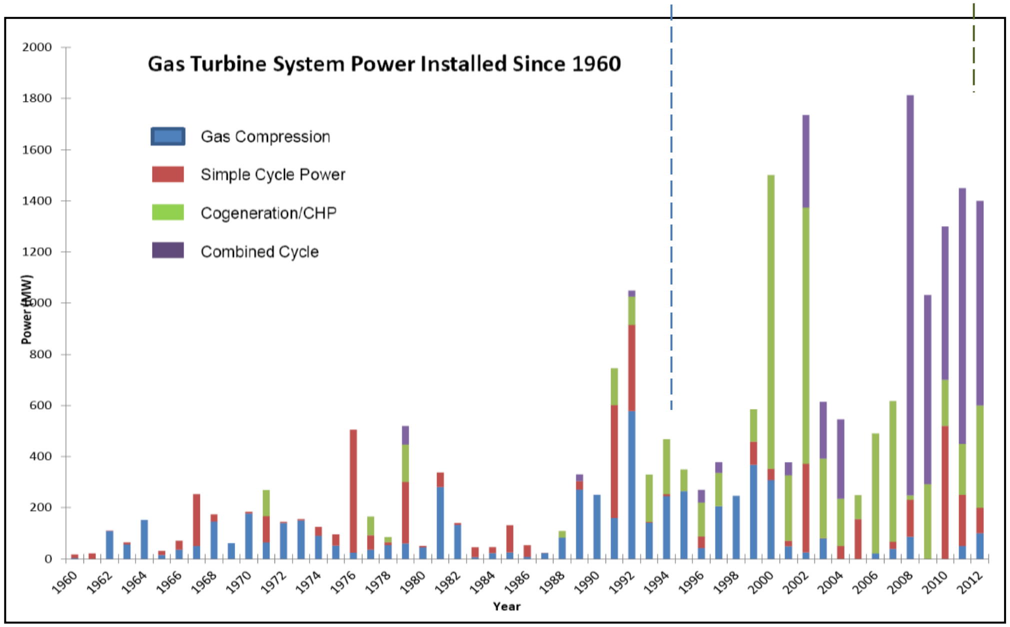
CLEANER ENERGY

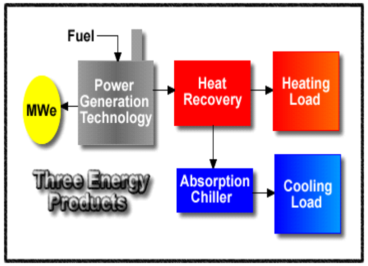
New GTCHP and Combined Cycle systems with natural gas fuel have likely accounted for about 30% of Canada's GHG avoidance since 1995, plus 250 KT of air pollution reductions. About 70 TWhrs now generated from;

- 6000 MWe of GTCHP (+150 PJ heat)
- 7000 MWe of GTCC
- 2000 MWe of peak power



Canada's Emissions Trends 2012



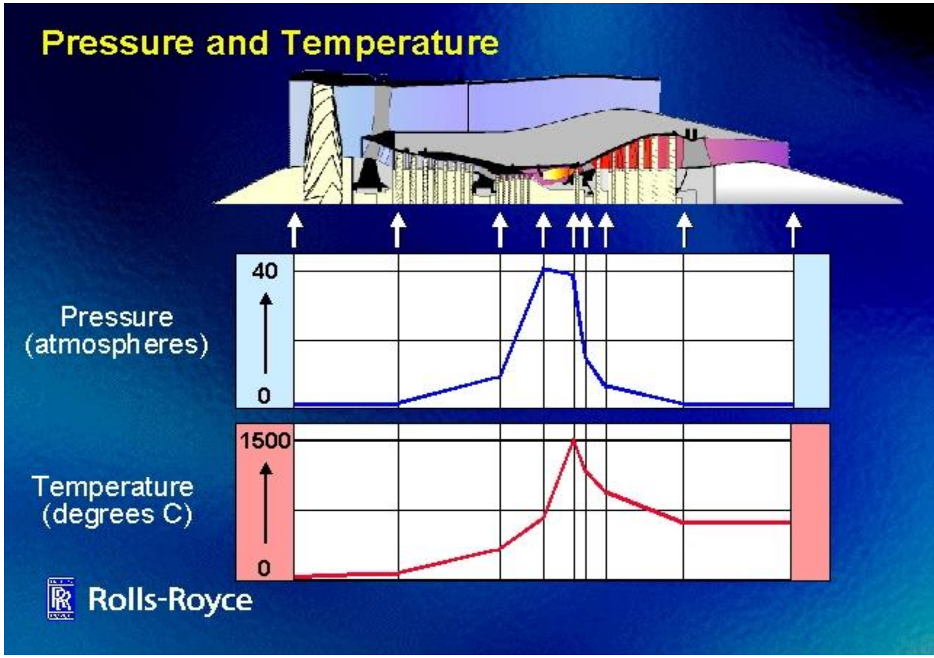


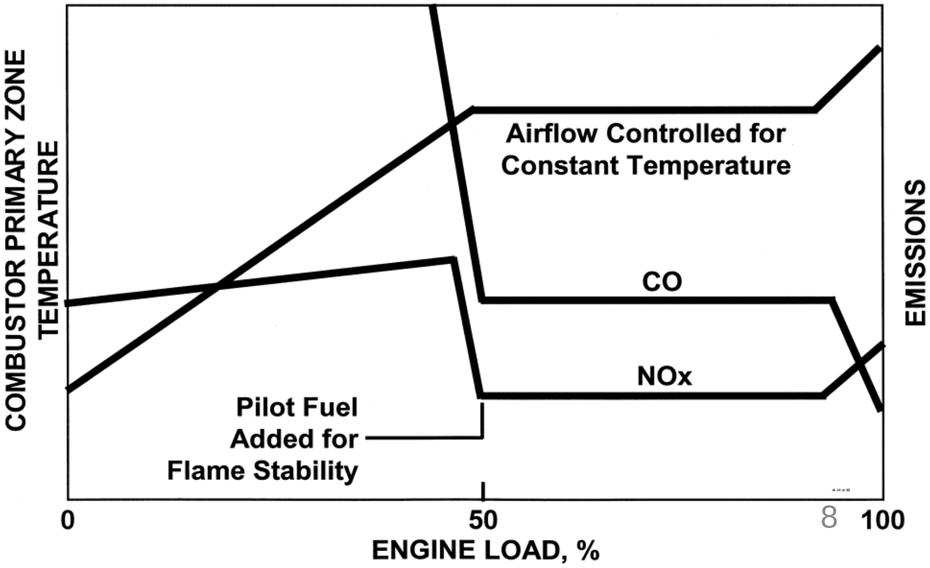
'Cleaner Energy'

Emissions in Gas Turbine Engines

Factors Affecting NOx Emissions

- Unit efficiency (PR, mass flow, Turbine Inlet Temp)
- Engine type (Aero or Frame)
- Dry Low NOx combustor
- Full & Part load operation, starts
- Cold and hot weather
- Type of air compressor (spools)
- N_1/N_2, Output Speeds
- Specific Power (kW, per lb/sec air)
- NOx Concentration vs Mass Flow





Sample Emissions Unit Conversions for NOx

Percent O_2 conversions for ppmv

from 25 ppmv at 15% O_2 to value for 16% O_2 = 21 ppmv

3% O_2 = 76 ppmv

NOx ppmv to mg/Nm^3 with the same % O_2 basis

from 50 mg/m^3 = 24 ppmv

Natural Gas at 15% O_2 (LHV Basis, fuel input)

25 ppmv NOx = 0.1 lb/MMBTU (= 43 g/GJ)

1 lb_{NOx}/MMBTU = 252 ppmv

Diesel fuel at 15% O_2 (LHV Basis, fuel input)

25 ppmv NOx = 0.10 lb/MMBTU (= 43.5 g/GJ)

From **Solar Turbines** (mysolar.cat.com)
See "Customer Support" Toolbox

Gas Turbines - *NOx Emissions* (ppm at 15% O_2)

- Uncontrolled ; Older Units: 100-200 ppm
  Newer Units (High Firing Temp.) 200-300 ppm

Mass Rate/Energy Output NOx Estimate

- need mass airflow in kg/hr

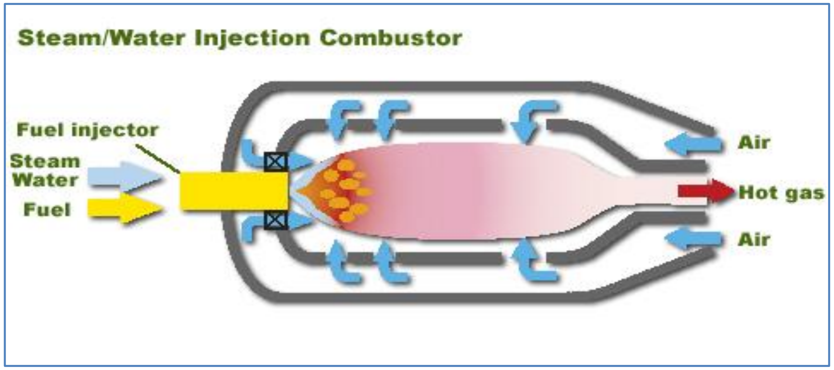
$$\frac{\text{ppm} \times \text{MassFlow (kg/hr)} \times \text{m.wt.}}{\text{Power (MW)}} = \_\_ \ \text{Kg}_{NOx} / \text{MWhr}$$

Example (30 MWe unit, air = 100 kg/sec)

$$\frac{25 \text{ ppm}}{10^6} \times \frac{360\,000}{30 \text{ MW}} \frac{\text{kg}}{\text{hr}} \times \frac{46}{29} = \mathbf{0.48 \ kg/MWhr}$$

(for CHP, can include the 'MWth' for a lower emission factor)

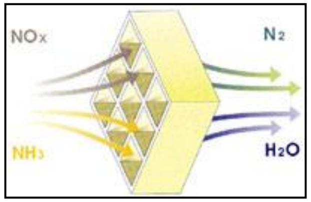
NOx Reduction Methods



(Kawasaki)

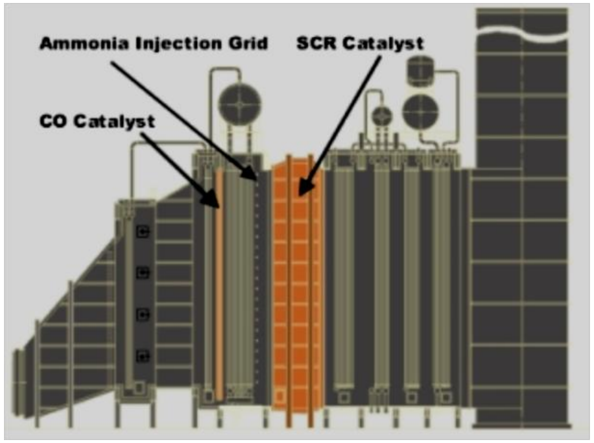
Steam/Water Injection

- Prevention, 2/3 red'n to 1 kg/MWhr
- Some Combustion Component Wear
- Plant Efficiency Penalty
- Depends upon value of plant steam



Selective Catalytic Reduction (SCR)

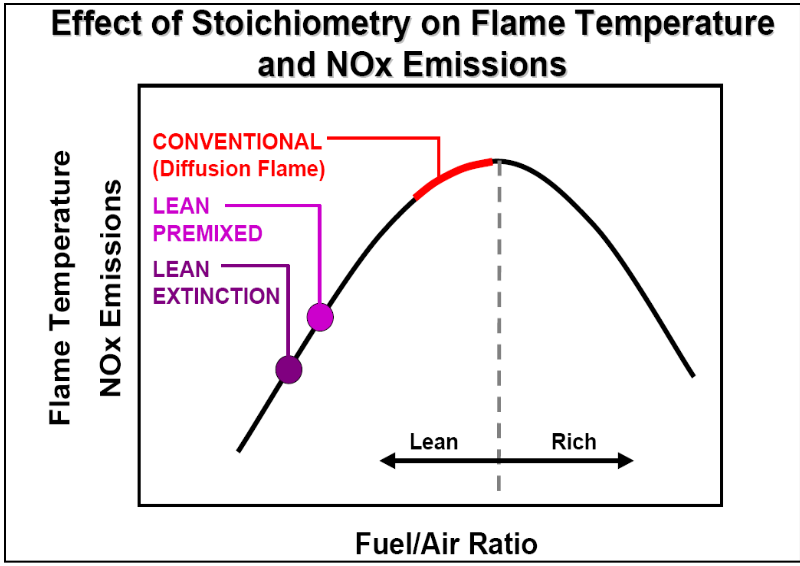
- NH_3 injection into HRSG catalyst (~ 80% NOx red'n)
- Backend Control
  - Ammonia emissions & handling (toxic)
  - fine PM, N_2O ?
  - Cold Weather, Cycling duty - ammonia slip
  - Efficiency losses in HRSG
  - Full Fuel Cycle impact – Prod'n, Delivery etc



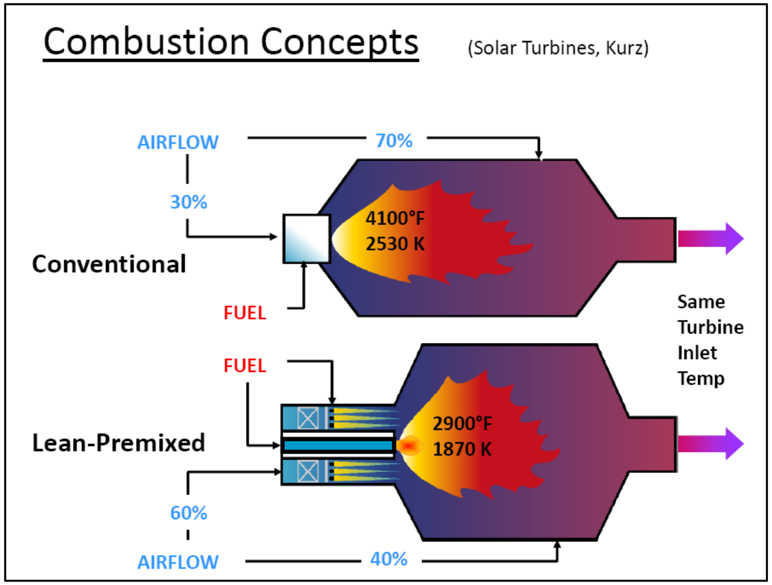
IST Aecon

Dry Low Emissions Combustion

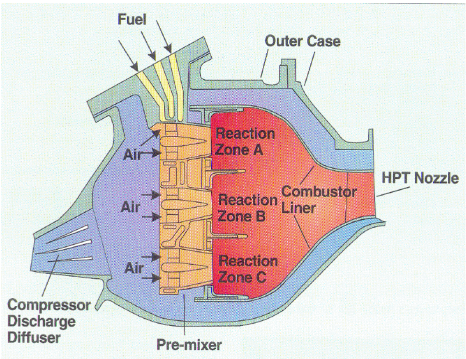
- Preventative reduction by 60-90%
- Maintains High Efficiency
- Larger Combustor Volume, more airflow
- Good experience with large industrial units
- Some Reliability Issues for Aeroderivatives
- Too Low Values may lead to inoperability and combustor problems
- How important are CO emissions?
- Effects of Plant Cycling
- Applied to Syngas combustion ?

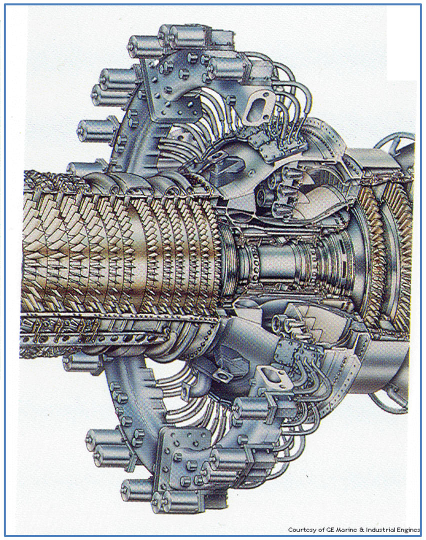


(Solar Turbines)

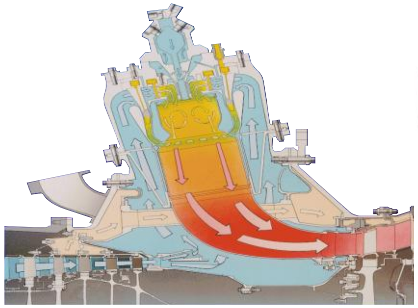


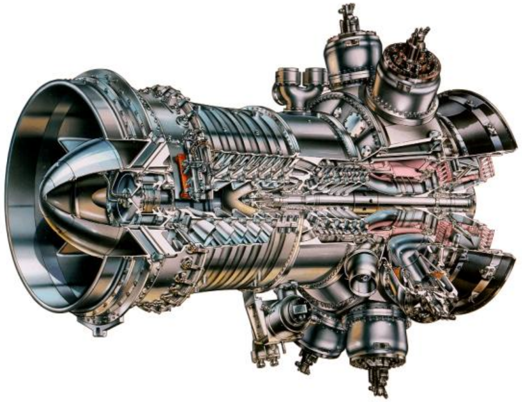
Aero-Derived DLN Systems





General Electric LM6000 DLE
Triple Annular Dome

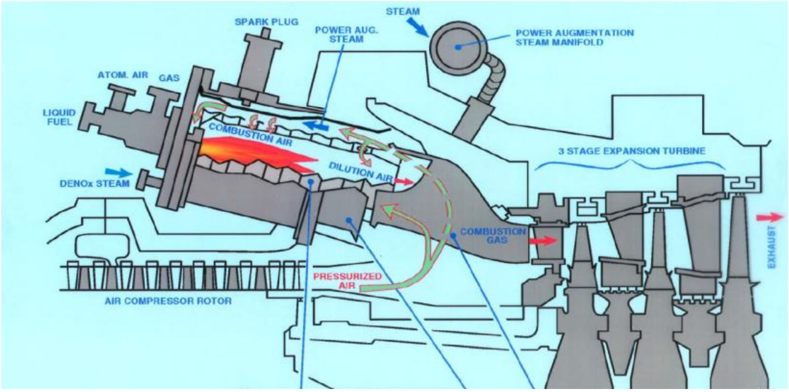




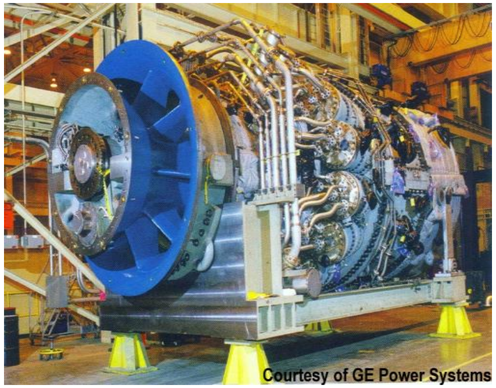
Rolls Royce RB211 DLE

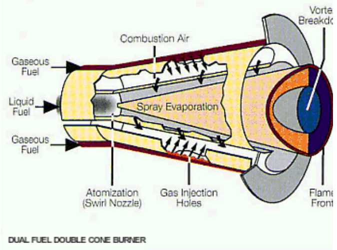
(Series staged)

Large Frame Unit DLN



GE Frame 7 DLN2

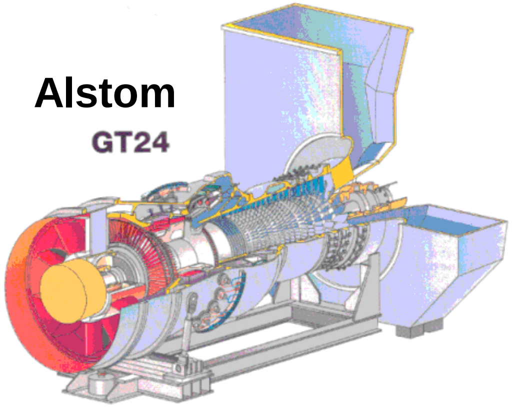




Annular EV burner

Alstom

GT24

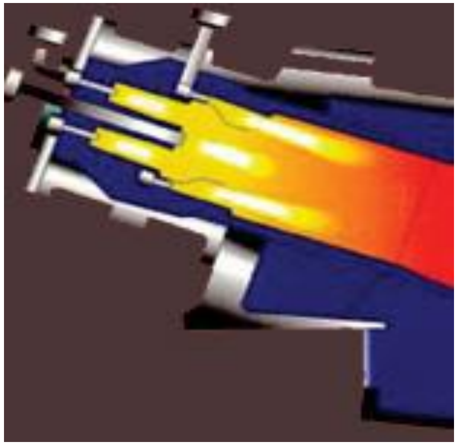


DLN Combustor Dynamics

Acoustic Oscillations Under Transient Conditions, caused by;

- Ultra-Low NOx ppm Design
- CO and turndown req'ts
- Cold weather conditions
- Ambient Temp, Pressure Ratio, Fuel properties (Nat Gas, LNG, Syngas ...)

- Natural Frequencies, Resonance, Vibration, Trips & Shutdown



(turbinetech.com)

Cyclic Loading

GTCC Unit with reheat steam turbines

- Potential brown plumes during long startups

Fine Particulate Emissions

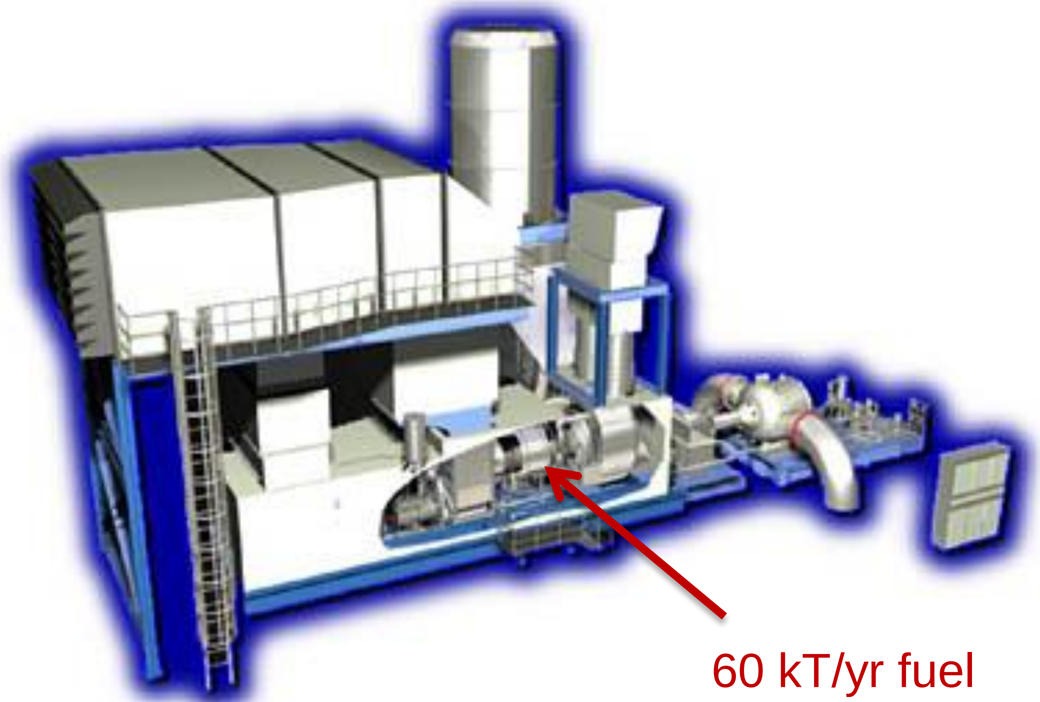
(AP42 - 0.07 lb/MWhr ?)

Does dry NG combustion produce $PM_{2.5}$ emissions?

2 million t/yr Air

Air Filter 95 - 99.5%

?



60 kT/yr fuel

Ambient air properties & Filter efficiency ?

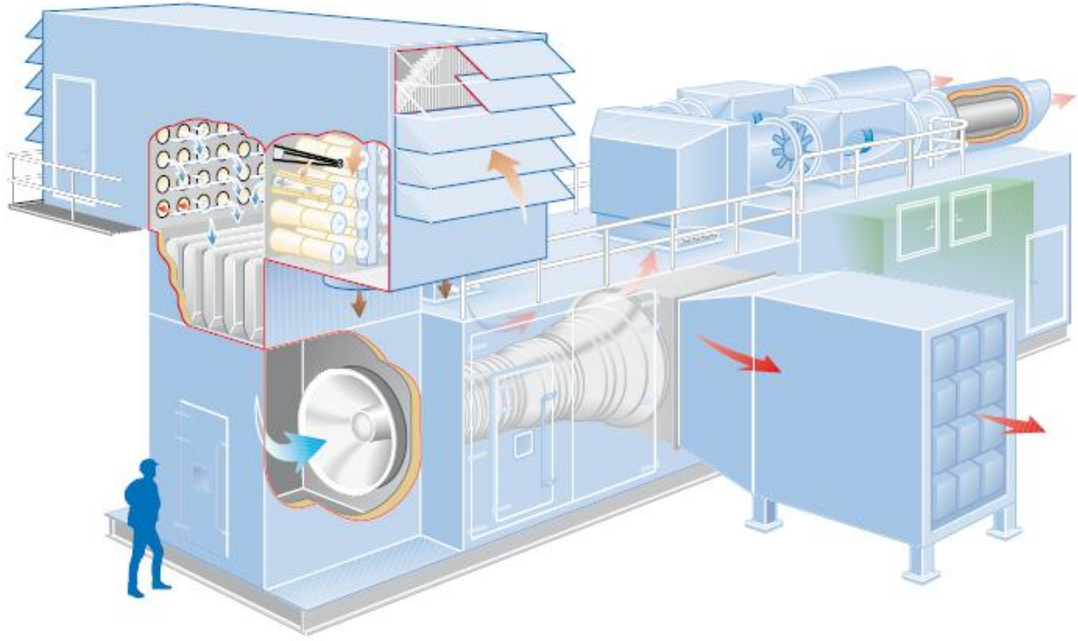
What is the Inlet-Exhaust mass balance ?

Are there any Air Toxics ?

DLN combustor have most incoming air going through direct combustion

Modern gas turbine air filter system is cleaning the air by over 99 %

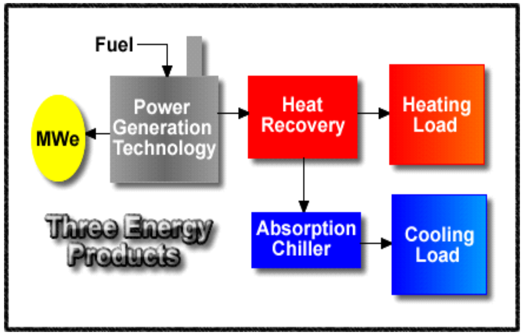
Small amount of PM escapes, but must go through DLE combustor

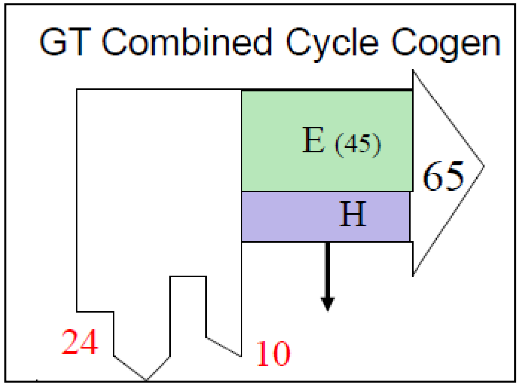


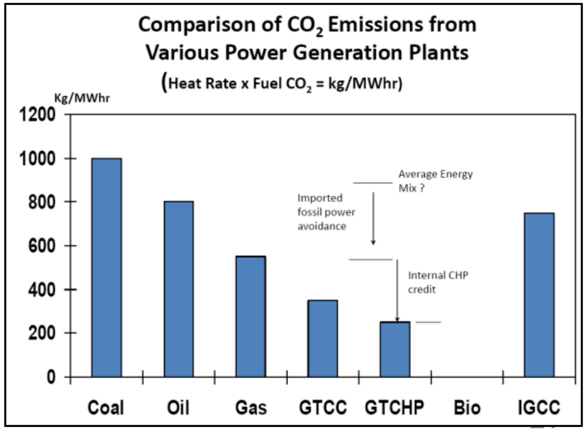
Critical Elements for CHP Systems

Producing 2-3 forms of energy from the same fuel, in same process

- **Awareness of Opportunities**
- **Nearby Site, Business Case**
- **Plant Sizing to Match Thermal Load**
- **Heat to Power ratio**
- **Seasonal Heat/Cooling Design**
- **Utility Interconnection, T&D savings**
- **Availability of Gas, Bio, H_2 fuels**
- **Low Air Pollution, Local Impacts**
- **GHG Allocation (*Fuel Chargeable to Power*)**
- **Output-based Emission Rules**
- **Energy Quality (*Exergy)***







Quality of Energy

- Electricity & Shaft Power — High
- Industrial Process Heat
- Cooling
- High Pressure Steam
- Hot Water
- Space Heating — Low

- **All of these can be made with same fuel**
- **Need to Use Energy at Best Level**
- **Environmental Standards could Encourage this**
- **80% efficiency ?   GHG emissions allocation ?**

Quality of Energy - *Examples of Exergy Factors*

Energy Form	Exergy Factor
Mechanical energy	1.0
Electrical energy	1.0
HP steam (600 psi and T=740 °C)	0.72
HP steam (600 psi and T_{sat}=250 °C)	0.47
LP steam (15 psi and T_{sat}=100 °C)	0.24
Hot water (T_{sat}=90 °C)	0.22

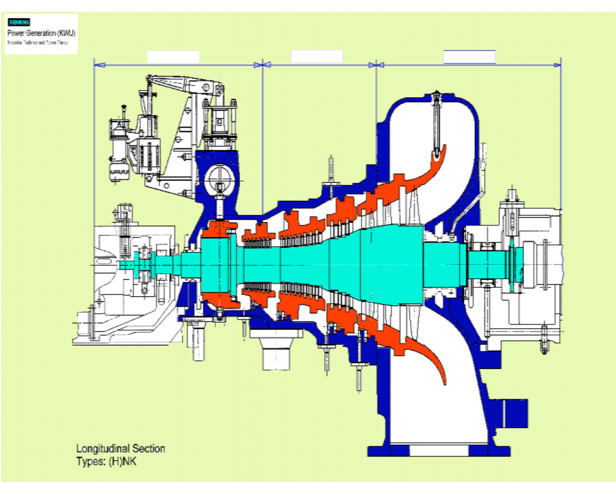
The ‘exergy’ of an energy form or a substance is;

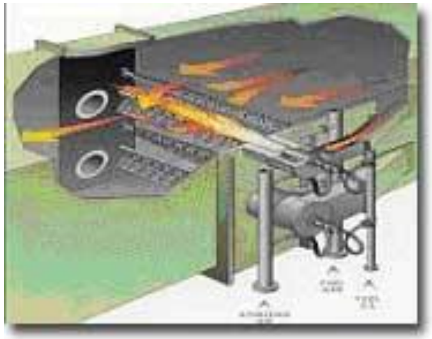
- a measure of its usefulness or quality,
- the maximum work which can be produced by a system or flow of energy

Waste Heat and Duct Burners in CHP

- Waste Heat & Steam Turbines = Emissions Prevention
- Duct Burners for auxiliary firing can double/triple steam output from HRSG ~100 % efficiency for heat)
- Duct burners can add a bit of combustion NOx … but they allow a smaller size of GT engine for given heat load (reduces annual fuel & emissions)
- Also increases heat transfer, lowers stack temp
- Allows for greater fuel flexibility, using waste fuels

IST





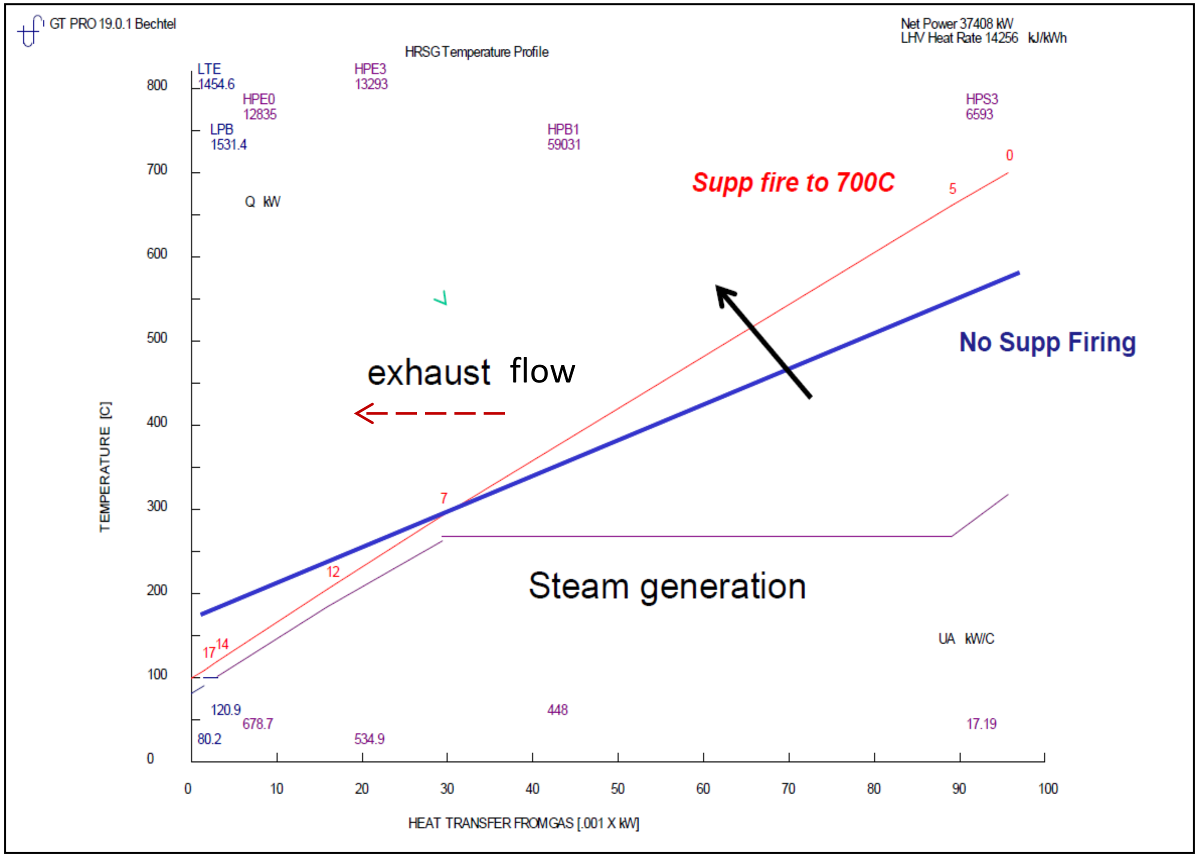
(Coen)

Duct Firing

Creates higher Heat:Power ratio which can enhance system efficiency and plant operating flexibility.

To meet periodic high steam demands;

- Lowers stack exhaust temperature, improving heat recovery and efficiency



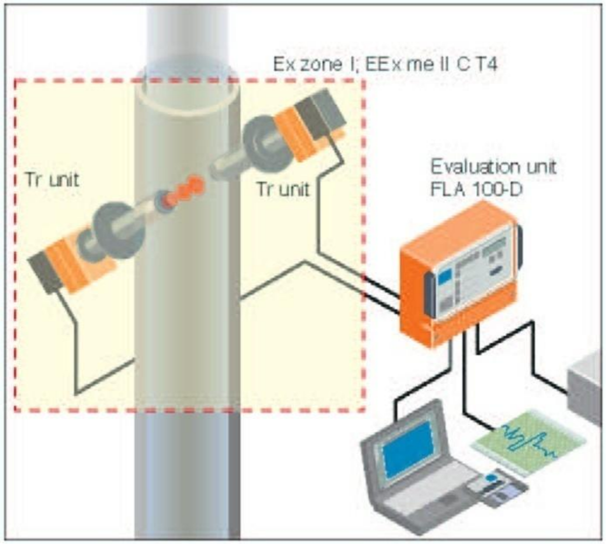
C. Meyer-Homji, Bechtel Corp.

- **Allows for a smaller Gas Turbine engine choice, or avoids an additional Boiler**
- **Important for *Heat Recovery Allowance***

Emissions Measurement

- Compliance and Emission Inventories
- Emissions Trading - NOx, SO_2, CO_2

- Continuous Emissions Measurement
- Process Estimation Methods
- Surrogate & parametric methods
- Predictive Emissions Monitoring

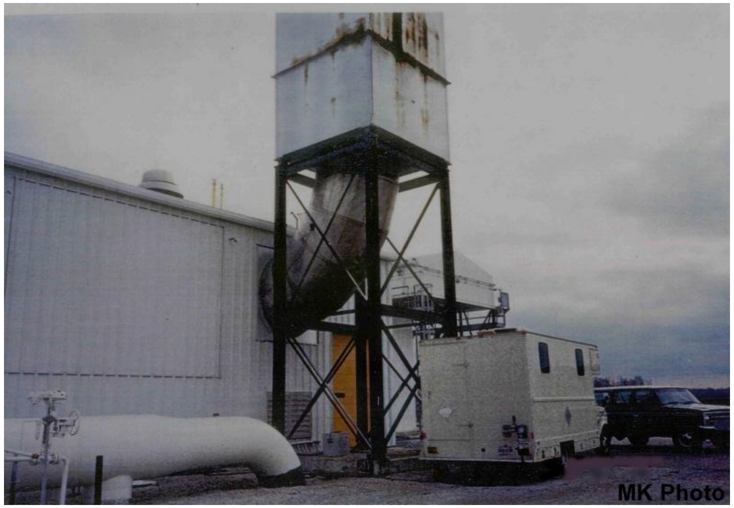


CEM Specialties

PEMs

- *good predictability of GT operation*
- *cost-effective emissions reporting*
- *process efficiency optimization*

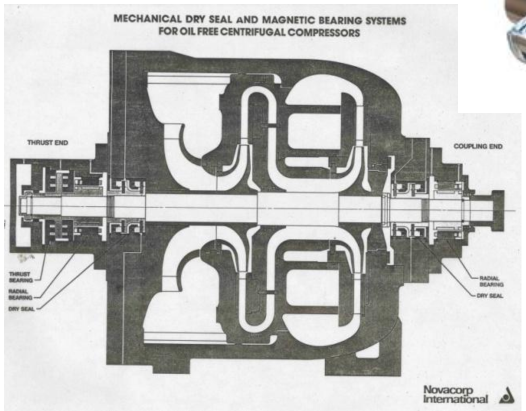
Emissions Averaging Time is Important



Env Can CEM van at TCPL in Ont. 1995

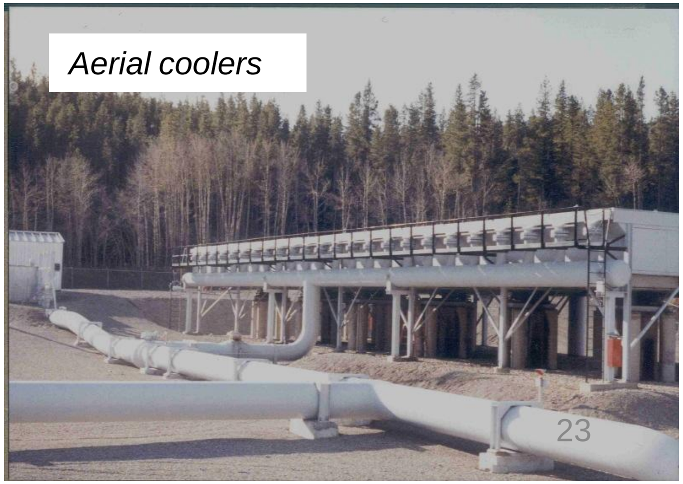
Env'tl Solutions for Gas Pipeline Compression

- **Efficient and Reliable Gas Turbine, with DLN Combustion**
- **Minimizing Stops and Starts**
- **Waste Heat Recovery**
- **Gas-to-Gas Exchange, Aerial Coolers**
- **Dry Gas Seals to reduce methane leakage, and reduced Venting**
- **Air or Hydraulic Engine Starters**
- **System Optimization**



Gas Compressor Dry Gas Seals

TCPL/EPCOR, Nipigon, ON



Aerial coolers

Fuel Flexibility - Combustion Characteristics of SynGas Fuels

Hydrogen

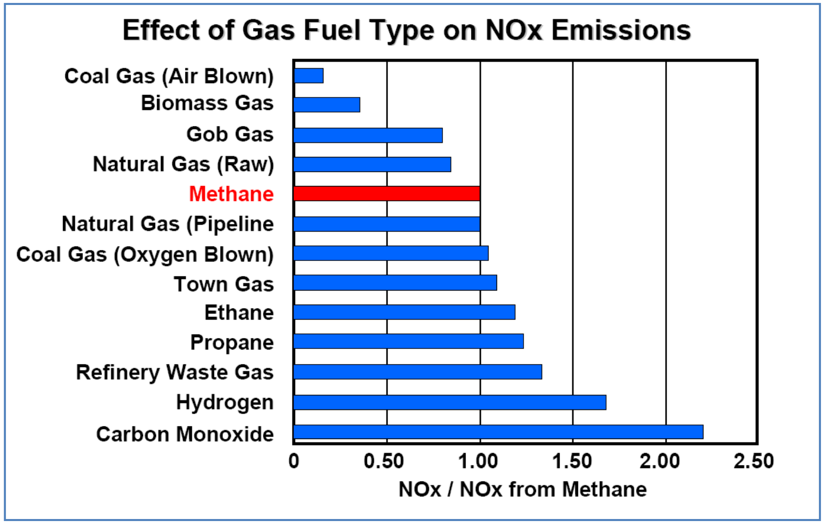
- High Volume and Heat Value
- High Flame Temp. and Speed
- Flashback, auto-ignition
- Higher NOx ?

Carbon Monoxide

- High Flame Temp.
- High Density
- Low flame speed
- Toxicity

Fuel Properties	CH_4	H_2	CO
LHV [MJ/kg]	50.3	119.9	10.1
[MJ/m^3]	33.9	10.2	12.6
Flame speed in air [cm/s]	43	350	20
Stoich. comb. temp. [K]	2227	2370	2374
Density [kg/m$^3_{STP}$]	0.72	0.09	1.25
Specific heat [kJ/kg K]	2.18	14.24	1.05
Flammability limits [vol %]	5 - 15	4 - 75	12.5 - 74

(Hannemann et al, Siemens)

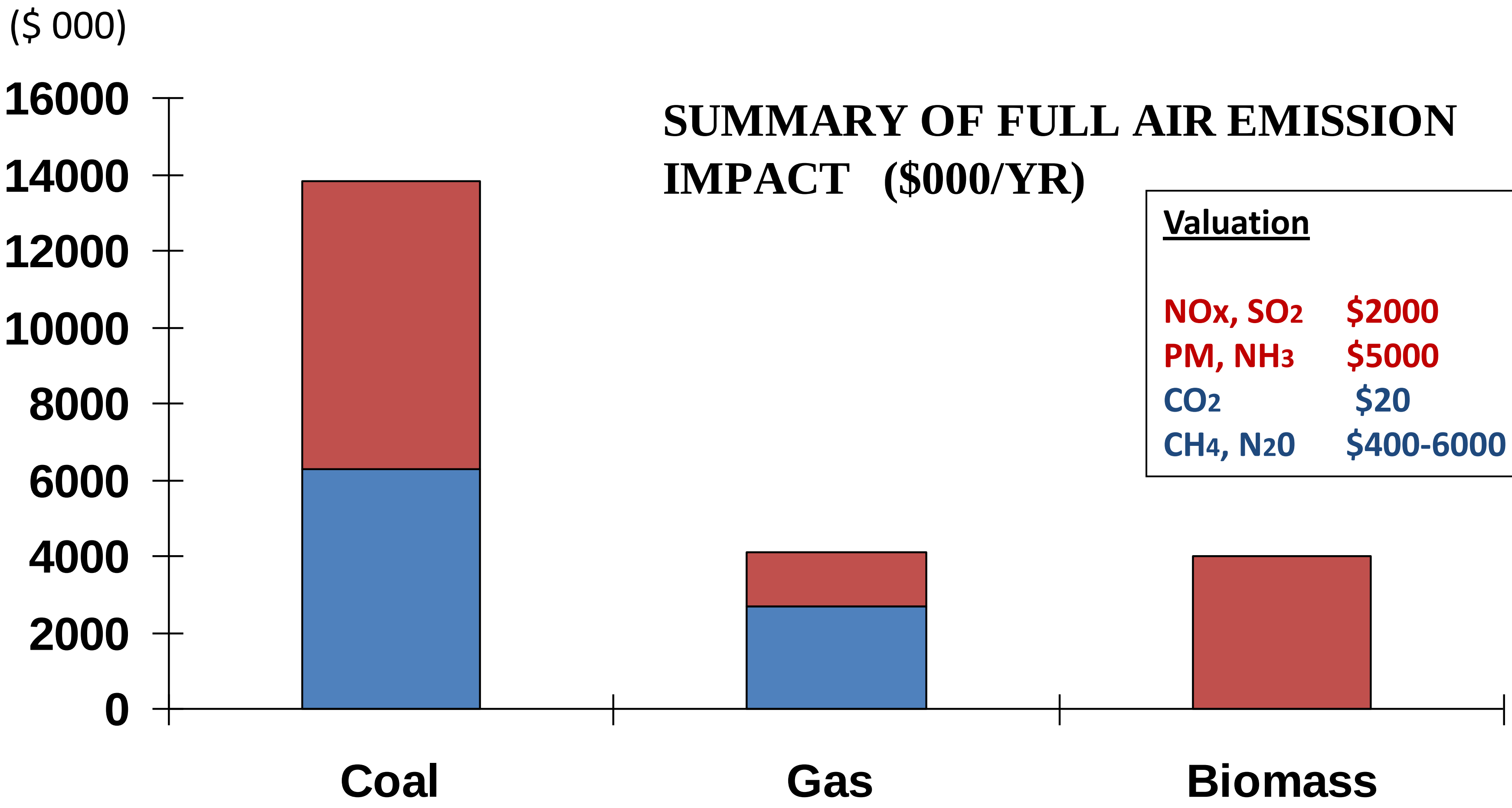


L. Cowell, Solar Turbines

Nexen Long Lake, 7EAs with syngas

Full Fuel Cycle Emission Example (3 TWhrs)

(Production, Processing, Delivery, End-use)



Valuation

NO_x, SO_2	$2000
PM, NH_3	$5000
CO_2	$20
CH_4, N_20	$400-6000

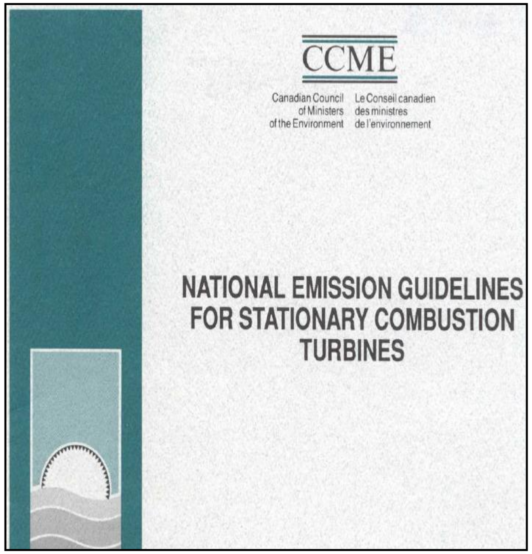
(based on “Full Fuel Cycle Emissions”, Klein, IAGT 1999)

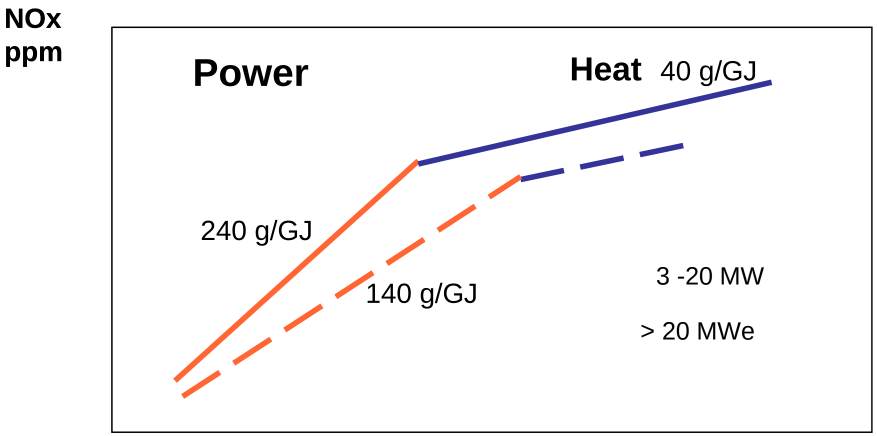
Canadian GT Emission Guidelines (1992)

- Guideline Reflects National Consensus
- Balanced NOx Prevention Technology

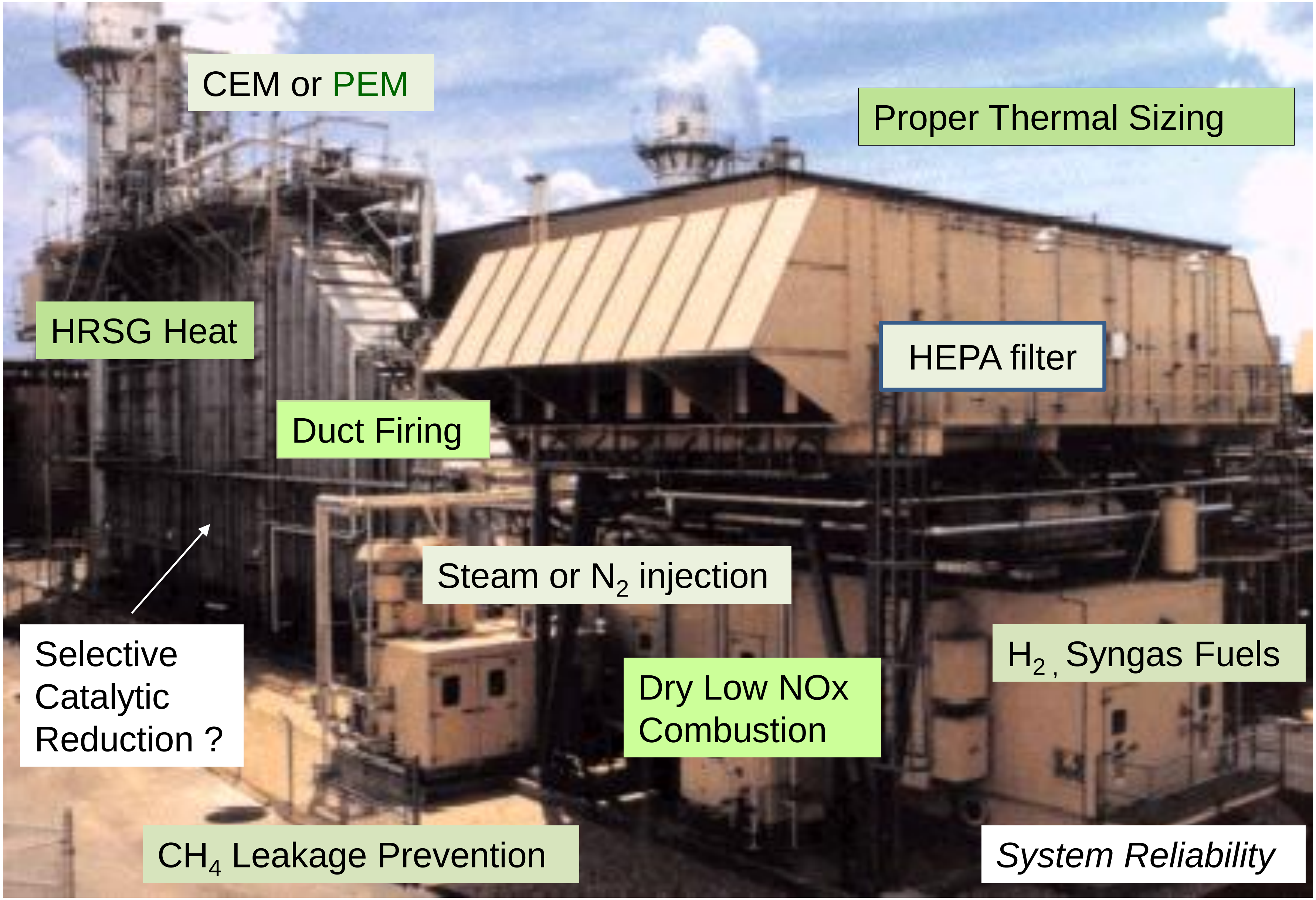
- **Output-Based Standard for Efficiency (140 g/GJ$_{out}$ Power + 40 g/GJ Heat)**

- Engine Sizing Considerations
- Promotes Cogeneration and low CO_2
- Peaking units (<1500 hrs/yr)
- Over Entire load range
- Flexible Emissions Monitoring
- Cold Weather considerations





Gas Turbine Emission Prevention & Control (NOx, GHGs)



GE Power Systems

Maximizing System Output CHP Efficiency

Concluding Remarks

- Gas Turbine Systems have very low Air Emissions (GHGs, NOx/CO, toxics)
- All types of Emissions can be prevented with System Integration
- Many Synergies and Tradeoffs - Balancing of priorities?
- ***BAT*** = Waste Heat, DLN Combustion, Syngas fuels, CHP & Polygeneration
- System Efficiency and Combustion Reliability are important
- Tech Issues ; Specific Power, Duct Burners, Plant Cycling, SCR controls?
- Advantages of ‘Output-based’ emission rules
- Need Training and Site Visits


TCPL Cornwall, 1982


GTAA Plant Tour, 2006


TCPL Carseland, 2012