IAGT
Industrial Application of Gas Turbines

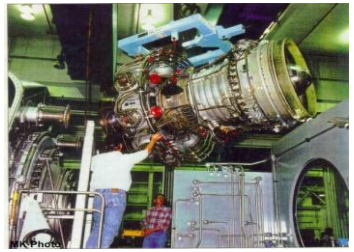
IAGT 2015 SYMPOSIUM

www.iagtcommittee.com — Oct 19-21, 2015, Banff, Alberta

# Air Pollution and GHG Emission Prevention

GT Cogen (GE)

- NOx and GHG Emission Rates
- Canadian and International Standards
- Balancing Emission Prevention & System Efficiency
- Technology & Economic Considerations



RB211 DLN

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**Presented at the 2015 Symposium on Industrial Application of Gas Turbines (IAGT)**
**Banff, Alberta, Canada - October 2015**
**The IAGT Committee shall not be responsible for statements or opinions advanced in technical papers or in symposium or meeting discussions.**

# Typical Industrial Gas Turbine Energy Systems

- Simple Cycle,  Standby power
- New Gas Combined Cycle
- Combined Cycle Repowering
- Utility Coal Gasification
- Large Industrial Cogen
- Oilsands Gasification
- Pipeline Compression

- Small Industrial Cogeneration
- Municipal District Energy
- Micro-T Distributed Power/Heat
- Waste Heat Recovery
- Process Off-Gases, Biofuels

***About 26 000 MWe  installed in Canada***
***(~ 470 plants,  1150 units)***

# Gas Turbine Systems in Canadian Industrial Sectors

**2014 estimate (M.Klein)**

| Installed MW | Simple Cycle | Combined Cycles | Comb. Cycle Cogen | Simple Cogen | Sector total |
|---|---|---|---|---|---|
| **Electric Power** | **4640** | **8310** | | | **12950** |
| **Gas Pipelines** | **4970** | **140** | | | **5110** |
| **Upstream Gas** | **180** | | **120** | **380** | **680** |
| **Oilsands & Refineries** | **115** | | **575** | **1860** | **2550** |
| **Chemicals, Forestry, Metals** | | | **3175** | **400** | **3575** |
| **Manufacturing** | **40** | | **1150** | **190** | **1380** |
| **Institutional** | | | **210** | **95** | **305** |
| **Est. Total** | **9945** | **8450** | **5230** | **2925** | **26550** |

- Not incl. retired units
- 22750 MW GTs, and 3800 MW of steam turbines

# Air Emissions

*(Smog, Acid Rain, Climate Change, Toxics)*

***Health & Ecosystems***

***Extreme, Unpredictable Weather***

## Air Pollution

- Sulphur Dioxide $SO_2$
- Nitrogen Oxides $NO_2$
- Volatile Organics VOC
- Carbon Monoxide CO

- Fine Particulate PM
- Mercury & Heavy Metals
- Ammonia

## Greenhouse Gases

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

**Ozone Depletion**

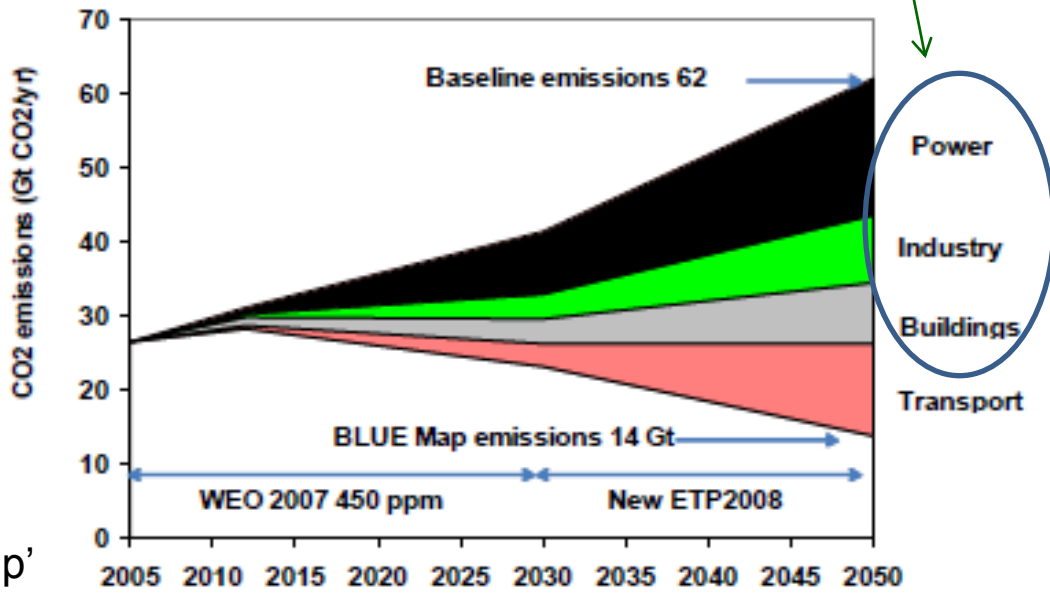
- CFCs

# What are Cleaner Energy Choices ?

- Aggressive Energy Conservation and **Efficiency**
- Small Renewable Energies, **Biomass Fuels**
- **High Efficiency Nat. Gas Systems (GTCC, GTCHP)**
- Large Hydro & Nuclear Facilities
- **Coal & Bitumen Gasification, Polygen w/CCS**
- **Waste Energy Recovery**

**GT systems can do 25-30% of these reductions**

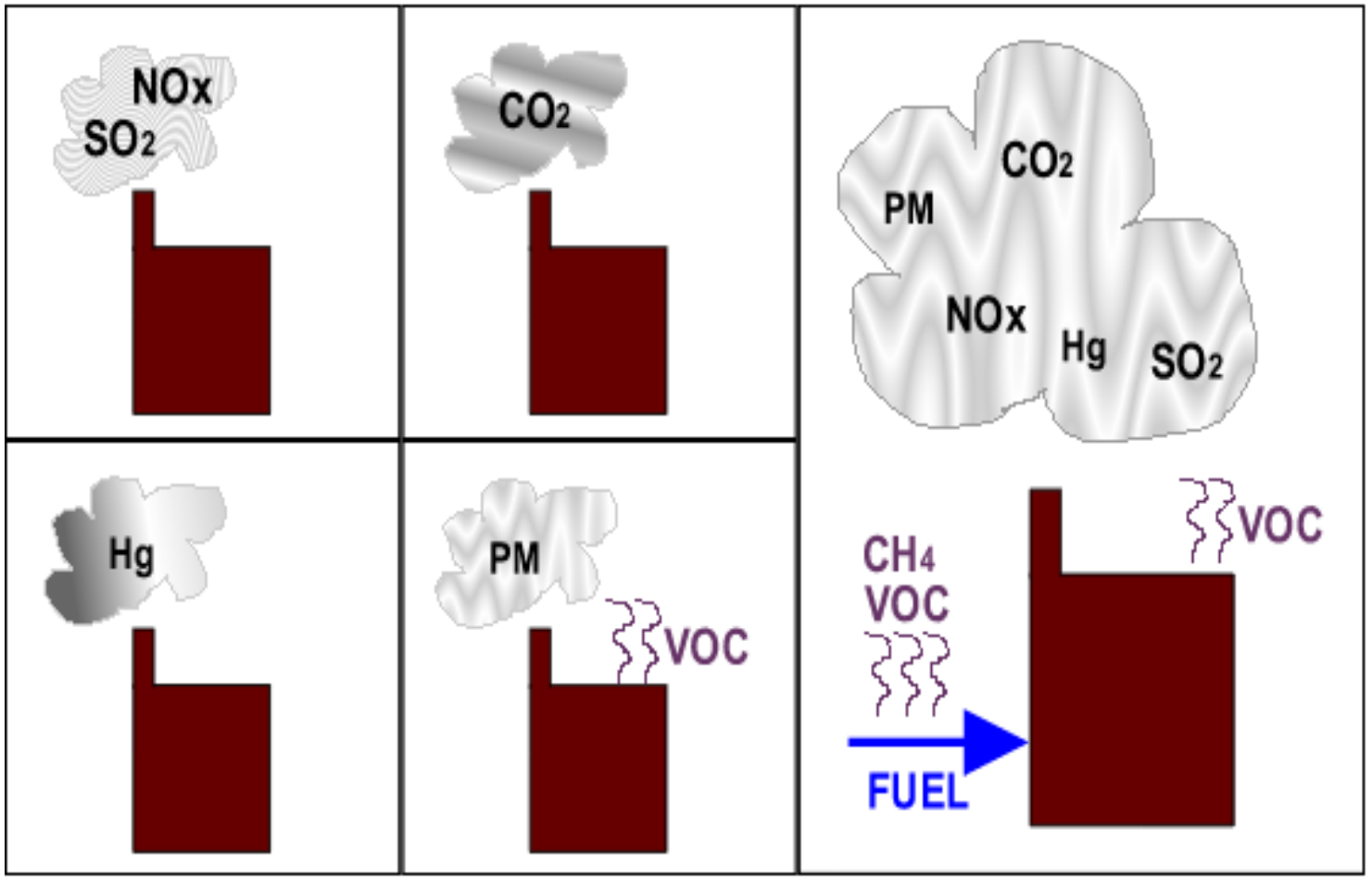
- ***Air Pollution***
- ***GHG Emissions***
- ***Air Toxics***
- ***Water Impacts***
- ***Energy Security***




IEA WEO 'Blue Map'

# Air Emissions

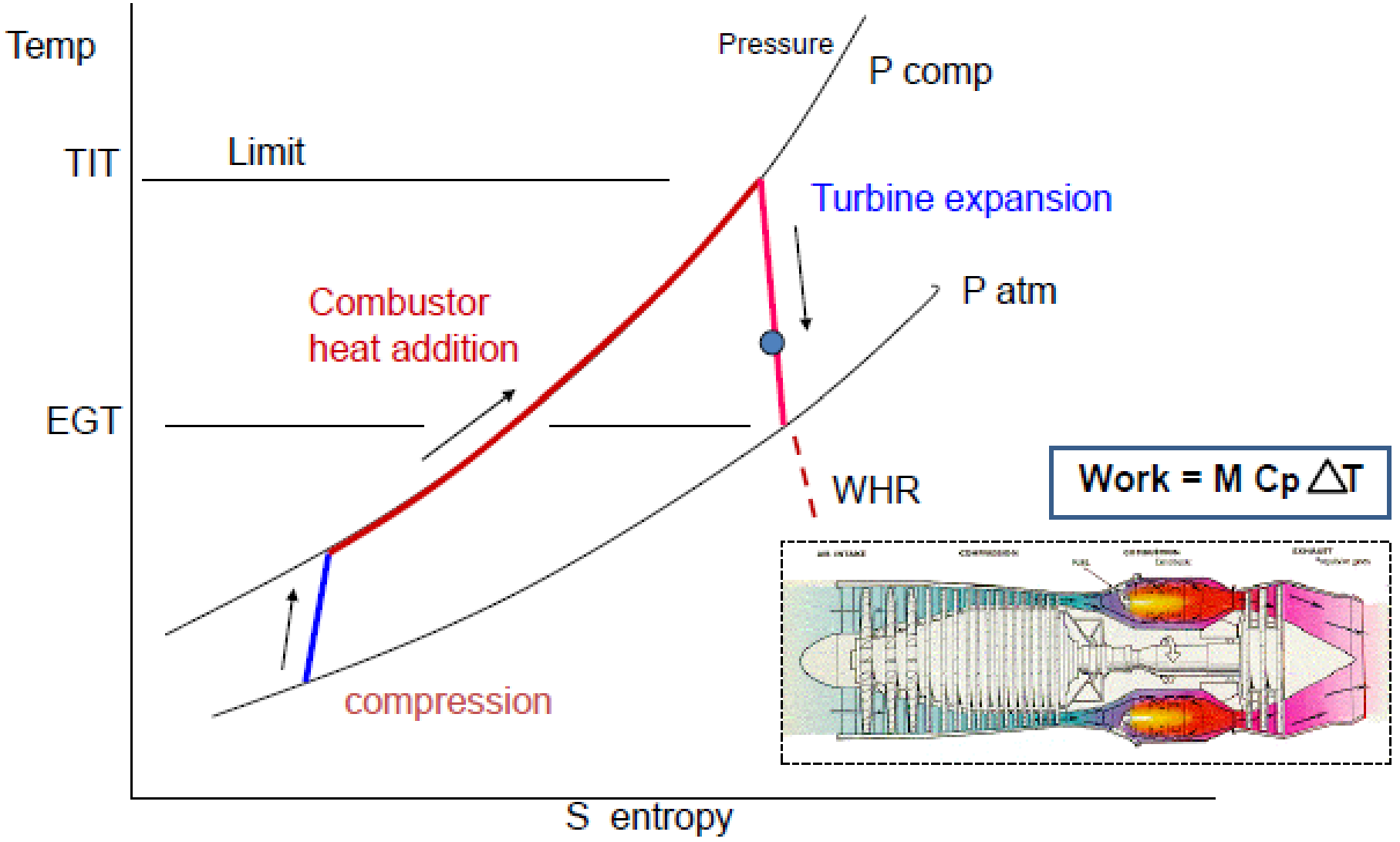
*(Smog, Acid Rain, Climate Change, Toxics)*




**Separate Emissions ??** ***System***

***"Cannot produce Air Pollution without making $CO_2$"***

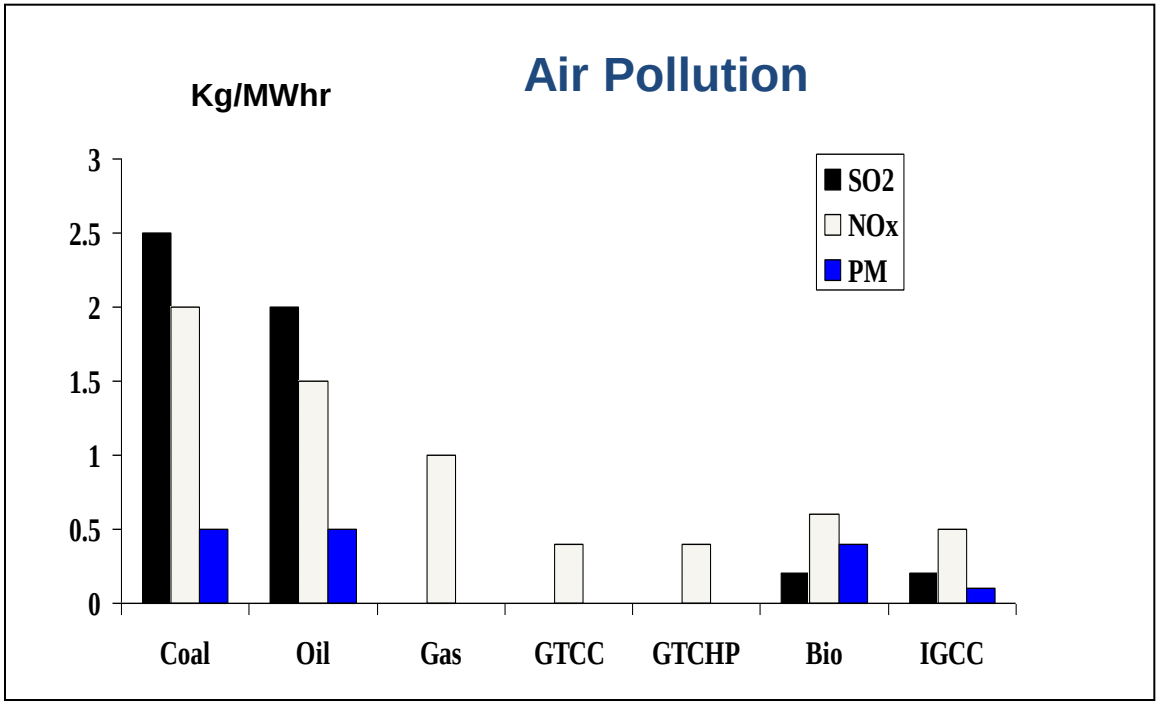
# Brayton Cycle; Cycle diagram for Gas Turbine




**Gas Turbine defined by high pressure hot air, as a gas, powering the blades**

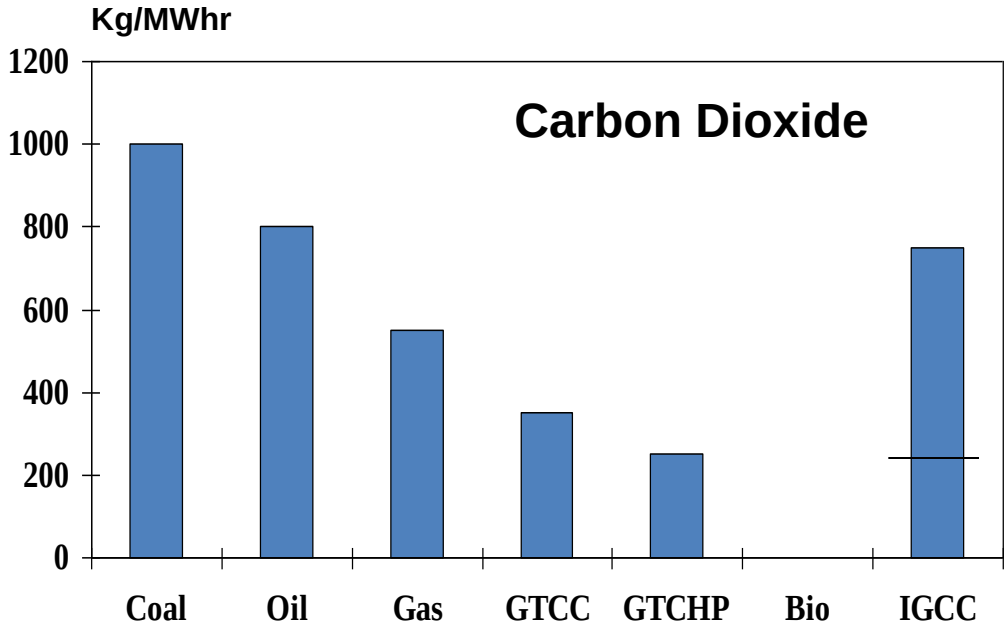
***(not because of gas fuel)***

# Comparison of Air Emissions from Various New Energy Generating Plants

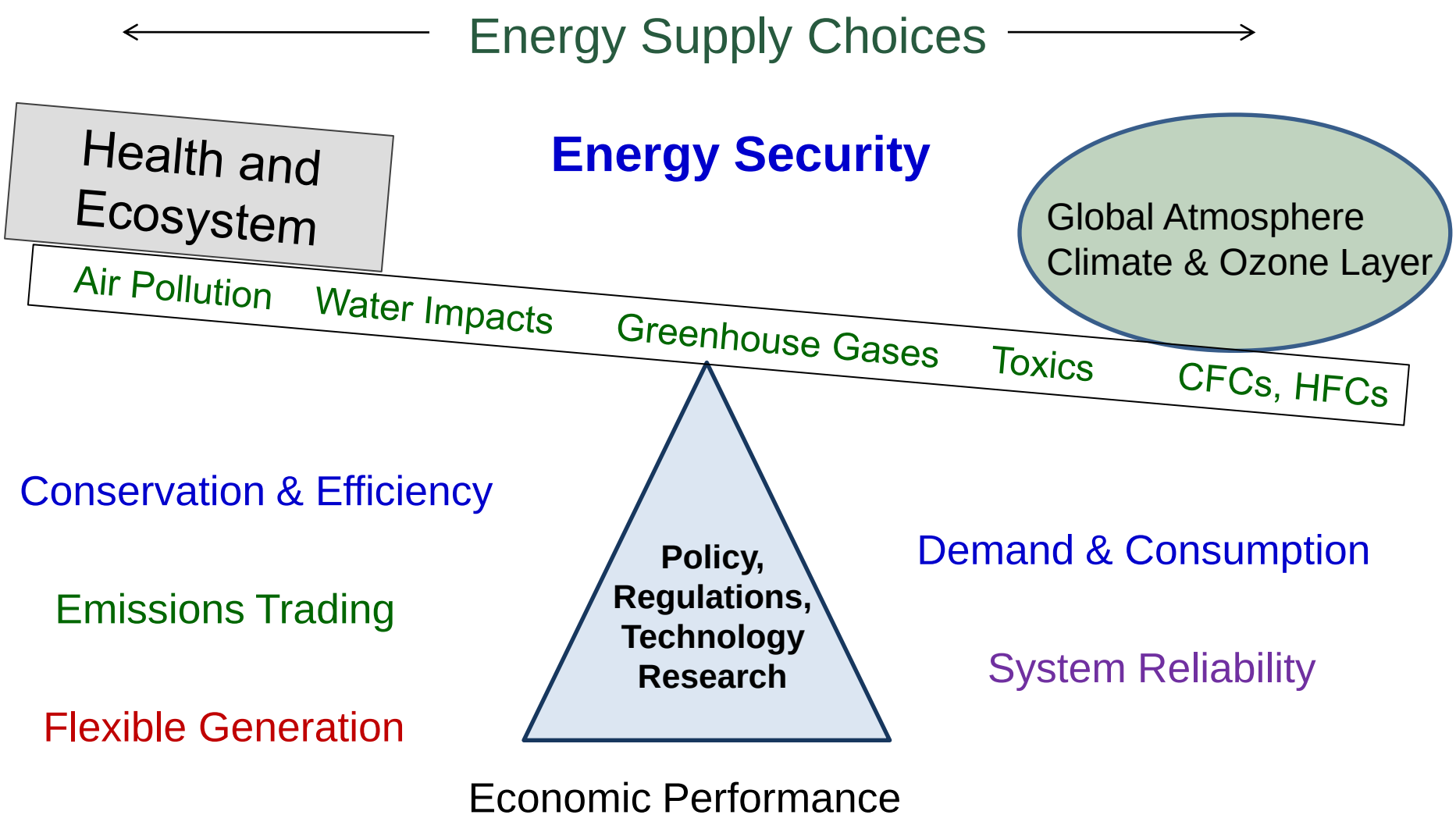



**Gas Turbine CHP plants have both Low $CO_2$ and Low Air Pollution**

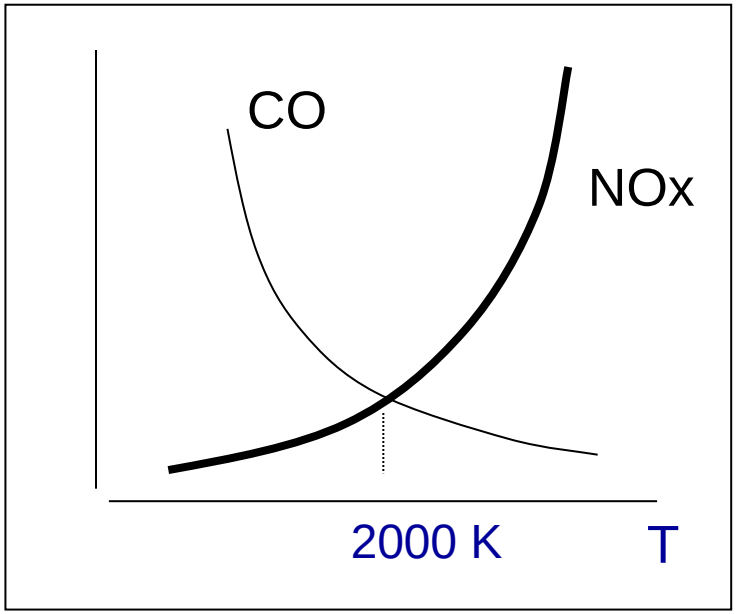
*(Common Solutions)*



# Clean Energy Balancing Act



# Air Pollution - *NOx Emissions*




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

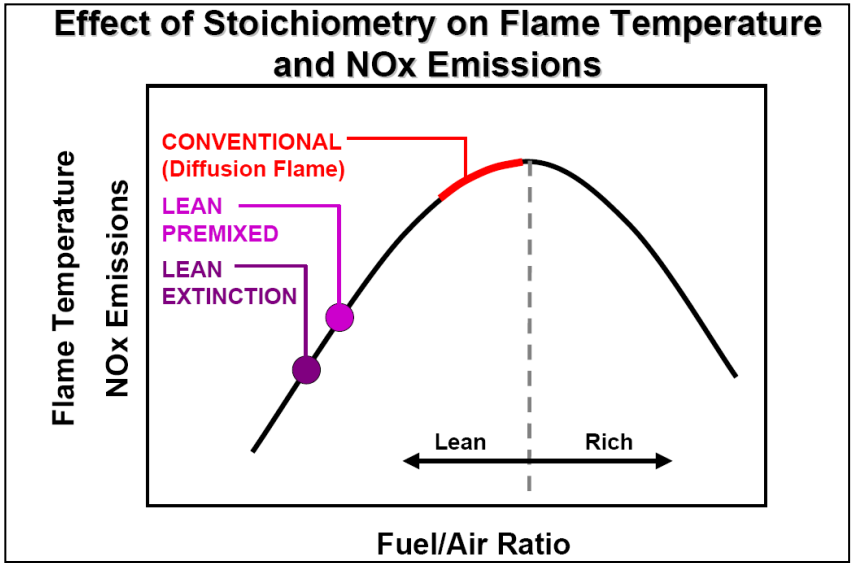
3 Compounds of Concern:

***NO, $NO_2$*** smog , ***$N_2O$*** ghg

**Thermal NOx:**
**High Temperature Combustion**

**Fuel NOx:**
**From $N_2$ Content of Oil, Coal**

- ***Nitrous Oxide is $N_2O$, a GHG***



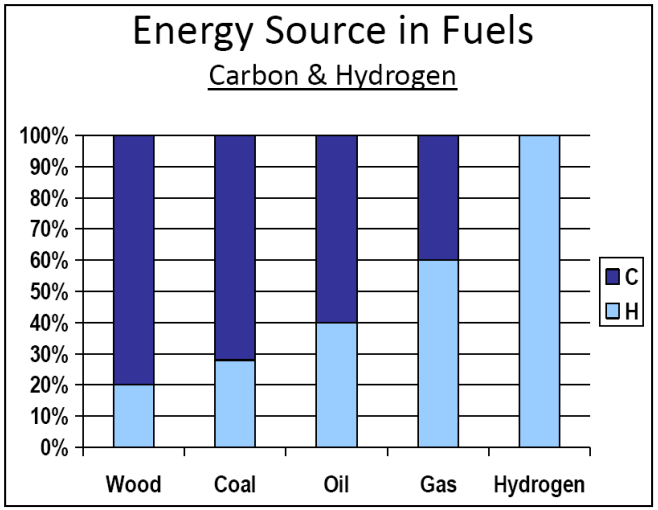

(Solar Turbines)

# Fuel Combustion

$$C_xH_y + (x + y/4)\,O_2 = x\,CO_2 + y/2\,H_2O + \text{heat}$$

| ***Energy Content*** | *BTU/lb* | *GJ/kg* |
|---|---|---|
| Carbon | 14 000 | 33 |
| Hydrogen | 61 000 | 142 |
| Sulphur | 4 000 | 9 |
| CO | 4 400 | 10 |

Coal ~ CH  Oil ~ $CH_2$  Nat. Gas $CH_4$

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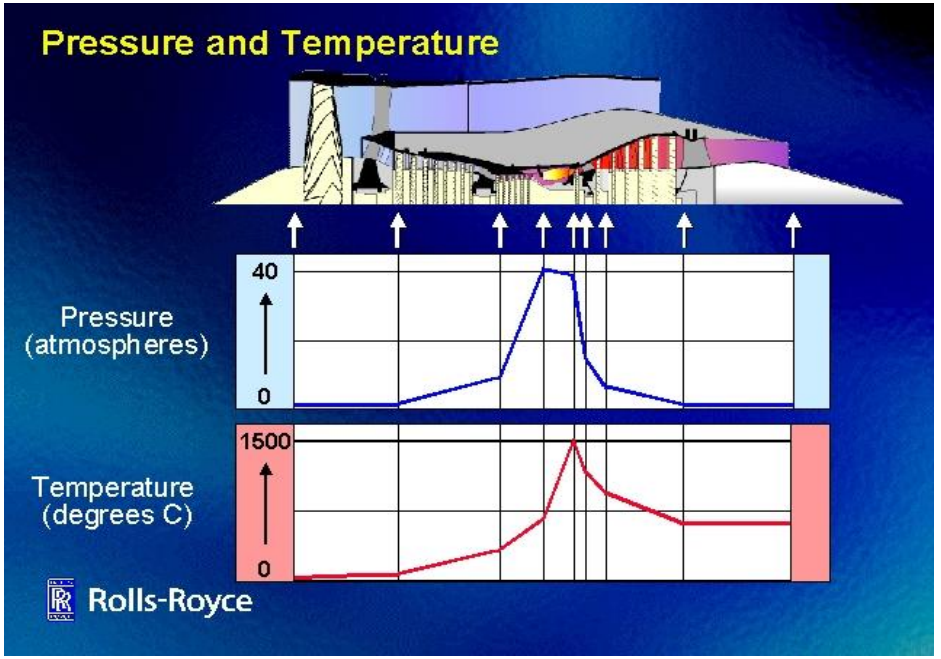
**$CO_2$ Rate Examples** (Heat Rate$_{HHV}$ x $CO_2$ factor)

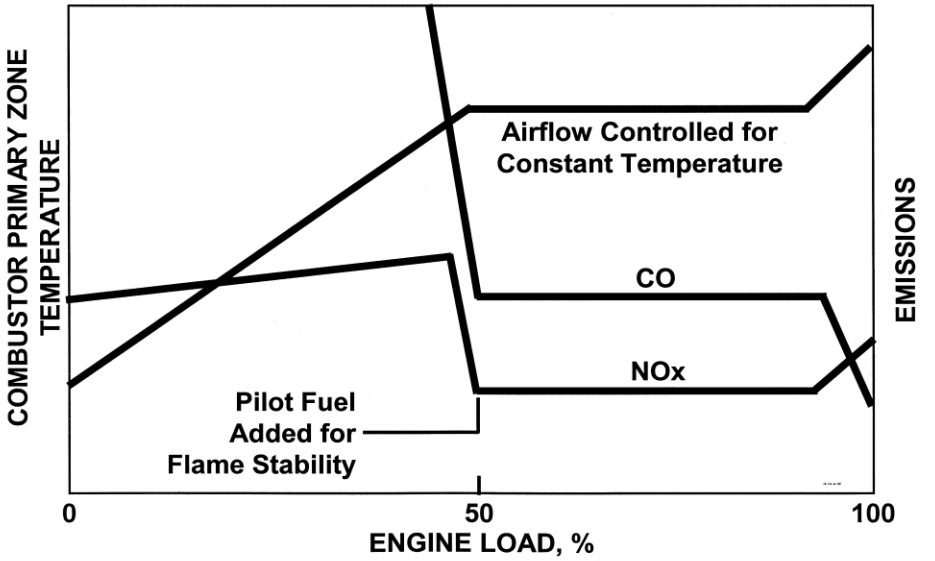
| | | | | |
|---|---|---|---|---|
| Coal Boiler | 10 GJ/MWhr | x 90 $kg_{CO2}$/GJ | = | 900 $kg_{CO2}$/MWhr |
| Gas Cogen | 6 GJ/MWhr | x 50 $kg_{CO2}$/GJ | = | 300 $kg_{CO2}$/MWhr |
| Car | 10 $\ell$/100km | x 20000 km x 2.4 kg/$\ell$ | = | 4.8 $t_{CO2}$/yr |

# Emissions in Gas Turbine Engines

## Factors Affecting NOx Emissions

- Unit efficiency ( *AIR* mass flow, Pressure Ratio, Turbine Inlet Temp)
- Engine type (Aero or Frame)
- Dry Low NOx combustor
- Part load, Operating Range, starts
- Cold and hot weather, humidity
- Type of air compressor (spools)
- $N_1/N_2$, Output Speeds
- Specific Power (kW, per lb/sec air)
- NOx Concentration vs Mass Flow



# ***Environmental & Regulatory Objectives***

- ***Prevention of Air Pollution and Toxics***
- ***Minimize GHGs***
- ***Energy Conservation***
- ***System Efficiency***
- ***Size and Location***
- ***Minimize Water Impacts***
- ***Noise***
- ***Reduce CFCs***
- ***Energy Security***
- ***Emissions Trading***

***Look for solutions with;***

***Clear Objectives***
***Multiple Economic Benefits***
***Systems Analysis***
***Balanced Approach***

# Importance of Environmental Units

A.

- **ppm at Exhaust**
- **ppb at fence line**
- **$mg/m^3$**

- **kg per Fuel Input**

B.

- **mass per time (t/yr)**
- **kg per MWe output**
- **kg per MWth**

***Concentration based units, in ppm and mg/m3, require $O_2$ content (15%)***

***- some of these inherently include system efficiency***

***($CO_2$ emissions at 35 000 ppm ? )***

# Emissions Criteria

**Traditional concentration (ppm, mg/m$^3$) and fuel input (g/Gj$_{in}$ , lb/MMBTU) criteria;**

- **difficult to interpret**
- **do not give appropriate design signal**
- **do not encourage system efficiency**
- **do not encourage Pollution Prevention**

- **Aviation uses 'LTO' Operations Cycle**
- **Recip engines have kg/MWhr rules**

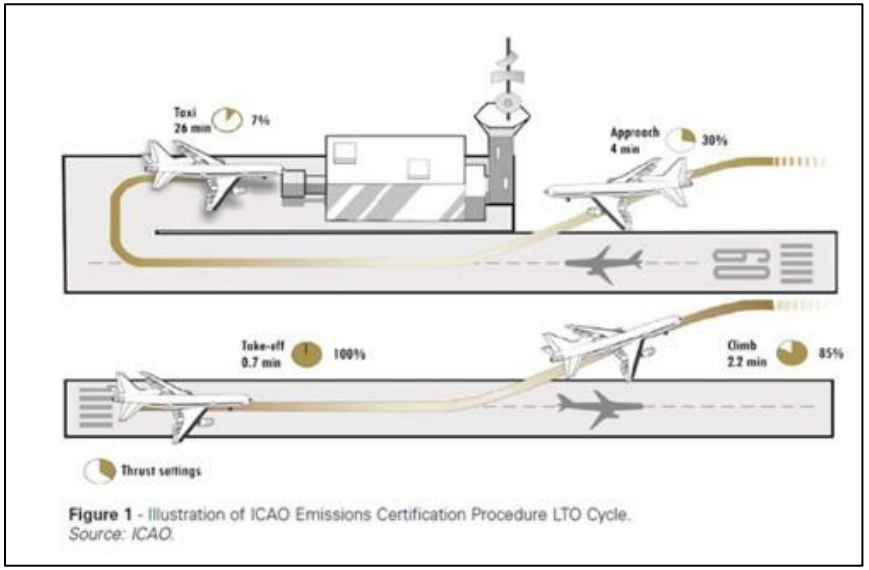


Figure 1 - Illustration of ICAO Emissions Certification Procedure LTO Cycle.
*Source: ICAO.*

ICAO - *aircraft (kg$_{NOx}$/thrust)*

## Output-based Rules;

**Mass per Product Output; *kg/tonne, kg/MWhr, g/GJ$_{out}$***

**tonnes/yr**

**$/tonne**

**$/MWhr**

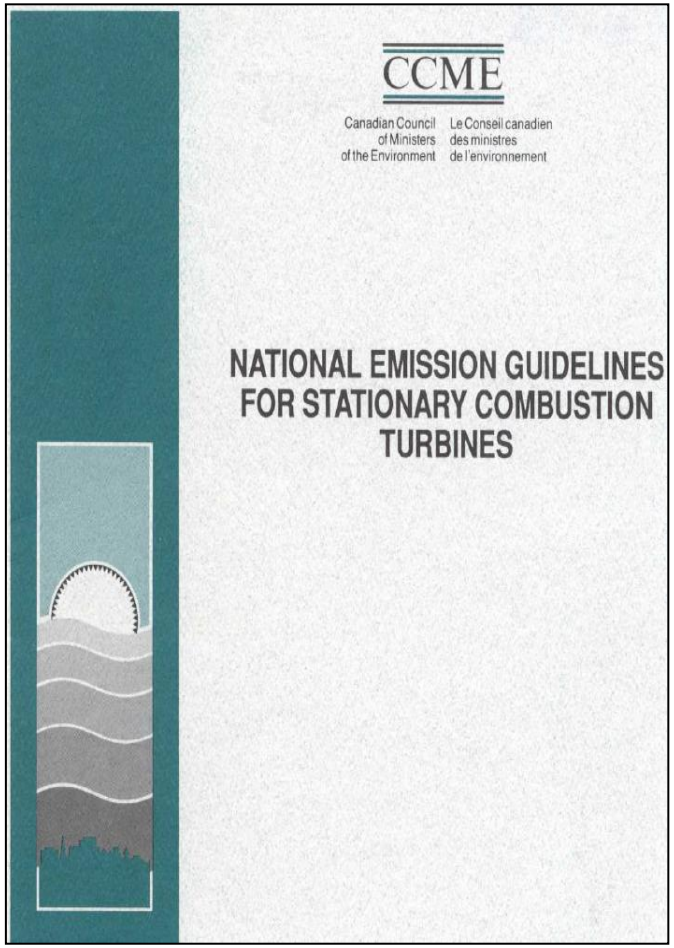
Lbs/HpHr

# Canadian GT Emission Guidelines (1992)

- **Guideline Reflects National Consensus**
- **NOx Prevention Technology**

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

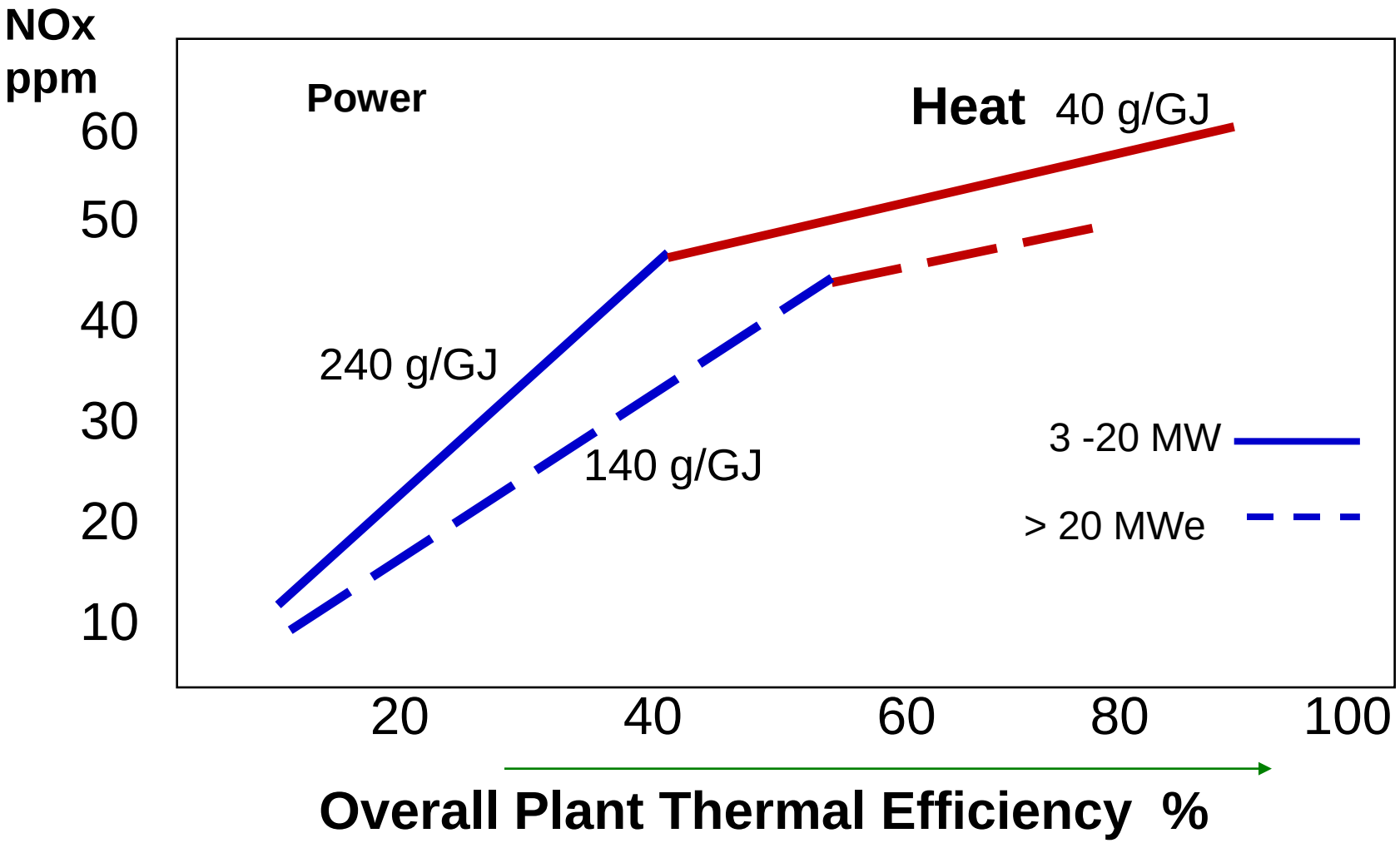
- **Engine Sizing Considerations**
- **Promotes Cogeneration and low $CO_2$**
- **Peaking units (<1500 hrs/yr)**
- **Over Entire load range**
- **Flexible Emissions Monitoring**
- **Energy Output reporting (?)**
- **Cold Weather considerations**




**CCME** - Canadian Council of Ministers of Environment

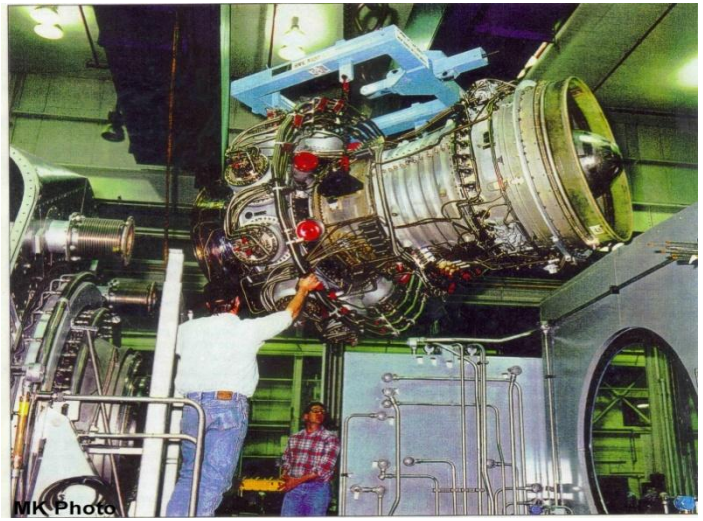
# Canadian CCME Gas Turbine Guideline (1992)

***Energy Output-based Guideline allows higher NOx for smaller units, which tend to have higher system CHP efficiency***



## Emission Guideline based on industry consultation, and …..

TCPL Nipigon Waste Heat Recovery, 1991




Rolls Royce RB211 DLE

TransAlta Ottawa Hospital Cogen, 1991

GE LM6000 steam injection

# British Columbia MOE Emission Rules (developed in 1992)

| Turbine Size (MW) | Emission Limit ($mg/m^3$) [1] | | | Emission Monitoring Requirement |
|---|---|---|---|---|
| | $NO_X$ | CO | $NH_3$ [3] | |
| 3.3 - 25 | 80 | 80 | - - | As specified by Regional Manager |
| >25 | 17 or 48 [2] | 58 | 7 | Continuous |

**Note:**

* This is based on the 1992 document, which still applies.

[1] Referenced to 20°C, 101.325 kPa, and dry gas conditions, corrected to 15% $O_2$. Averaging Period 1-hour.

[2] 48 $mg/m^3$ applies to gas pipeline application and other installations where SCR is demonstrated to be inappropriate

[3] The Ammonia limit is based on the assumption that selective catalytic reduction (SCR) technology has been employed to control $NO_X$ emissions.

## Alberta Environment NOx Emission Guidelines

(Gas Turbines for Electricity Generation, 2005)

| **Size** | **Alberta 2005 (kg/MWhr)** | *CCME* (kg/MWhr) |
|---|---|---|
| 3-20 MWe | **0.6** | *0.86* |
| 20-60 Mwe | **0.4** | *0.5* |
| over 60 MWe | **0.3** | *0.5* |

# Draft Guidelines for the Reduction of Nitrogen Oxide Emissions from Natural Gas-Fuelled Stationary Combustion Turbines

| Application | Turbine Power Rating (MW) | $NO_x$ Emission Limits ($g/GJ_{(power\ output)}$) | $NO_x$ Emission limits (ppmv)@ 15% $O_2$ |
|---|---|---|---|
| Non-peaking combustion turbines - Mechanical Drive | ≥ 1 and < 4 | 500 | 75 |
| Non-peaking combustion turbines - Electricity Generation | ≥ 1 and < 4 | 290 | 42 |
| Peaking combustion turbines – all | ≥ 1 and < 4 | exempt | exempt |
| Non-peaking combustion turbines and Peaking combustion turbines – all | 4 - 70 | 140 | 25 |
| Non-peaking combustion turbines – all | > 70 | 85 | 15 |
| Peaking combustion turbines – all | > 70 | 140 | 25 |

# *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/m3 = 24 ppmv

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

- 25 ppmv NOx = 0.099 lb/MMBTU (= 42.9 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

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**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)

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

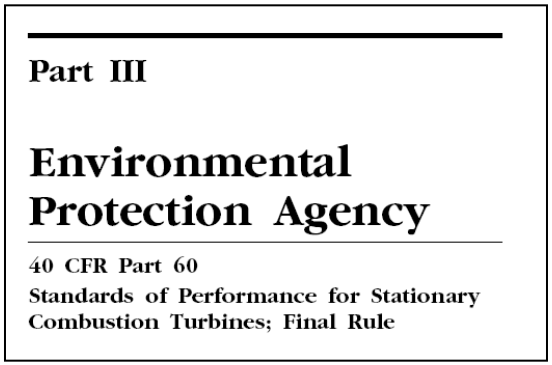
***( for CHP, can include the 'MWth' for a lower emission factor)***

# New US EPA Rules for Gas Turbines (2006)

**Can choose Output-based, or Concentration-Based Rules** *(EPA OAR-2004-0490)*

| Size, Heat Input (MMBTU/hr) | | ppm | lb/MWhr |
|---|---|---|---|
| *(New Units, Natural Gas Fuel)* | | | |
| < 50 | (electricity, 3.5 MWe) | 42 | 2.3 |
| | (mechanical, 3.5 MW) | 100 | 5.5 |
| 50 to 850 | (3 – 110 MW) | 25 | 1.2 |
| Over 850 | (> 110 MW) | 15 | 0.43 |
| **Units in Arctic, Offshore** | | | |
| | < 30 MW | 150 | 8.7 |
| | > 30 MW | 96 | 4.7 |

- MW could include MWth for waste heat in CHP
- Efficiency based, SCR likely not required
- Flexible Emissions Monitoring



Part III

Environmental Protection Agency

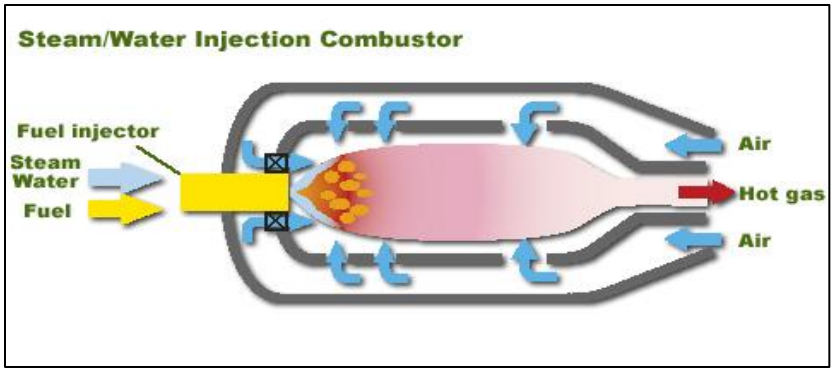
40 CFR Part 60

Standards of Performance for Stationary Combustion Turbines; Final Rule

# NOx Reduction Methods

## Steam/Water Injection

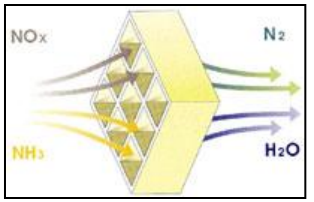
- Prevention, 2/3 red'n to 1 kg/MWhr
- Some Combustion Component Wear
- Plant Efficiency Penalty
- Depends upon value of plant steam

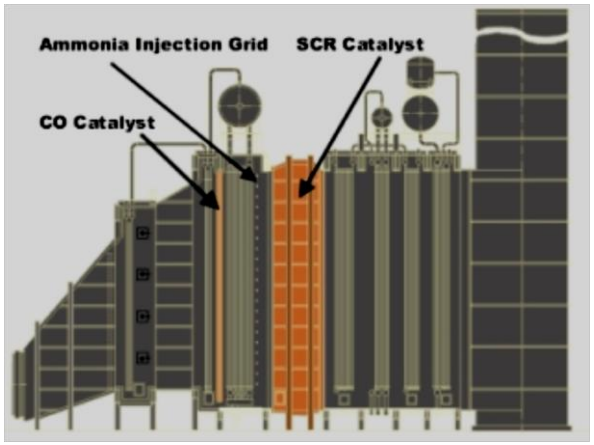



(Kawasaki)

## Selective Catalytic Reduction (SCR)

- $NH_3$ injection into catalyst in HRSG
- ~ 80% NOx Reduction
- **Backend Control**
  - **Ammonia emissions & handling (toxic)**
  - **fine PM emissions, $N_2O$ ?**
  - **Cycling duty - ammonia slip**
  - **Efficiency loss in HRSG**
- **Marginal, low $/tonne benefit after DLN**

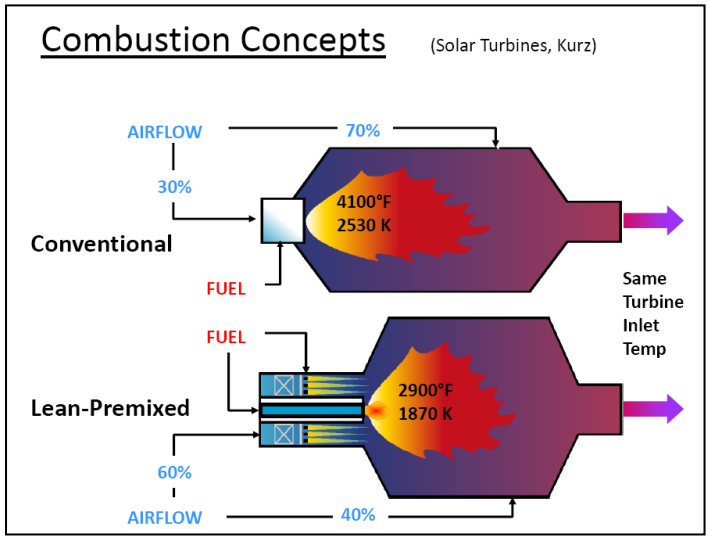


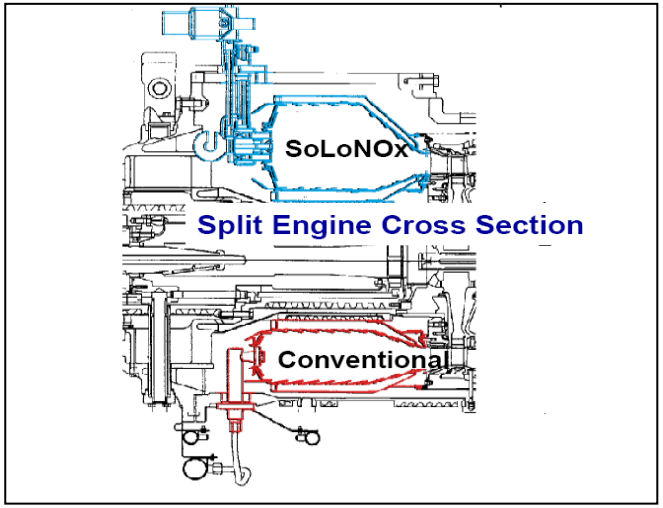




IST Aecon

# Dry Low Emissions Combustion

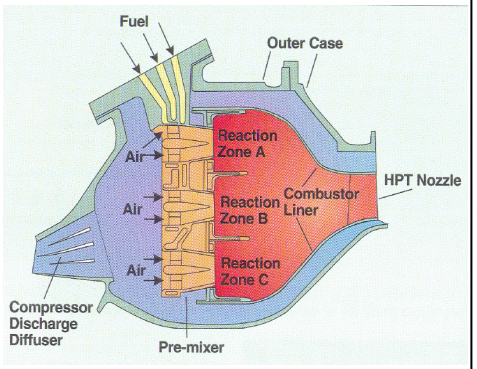
- **Preventative reduction by 60-90%**
- **Maintains High Efficiency**
- **Good experience with large industrial units**
- **Some Reliability Issues for Aeroderivatives**
- **Too Low Values may lead to inoperability and combustor problems**
- **How important are CO emissions?**
- **Mech. drives need wide operating range**
- **Effects of Plant Cycling, Transients**
- **Operating range,  fuel Wobbe range ?**

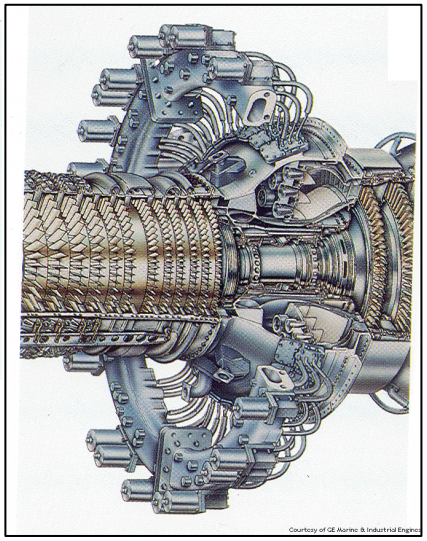



**Solar SoLoNox**

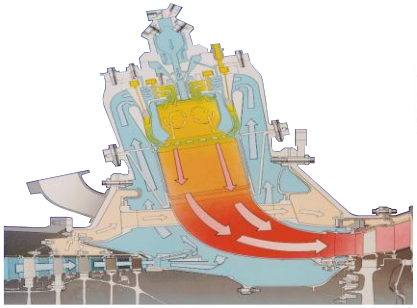
# Aero-Derived DLN Systems

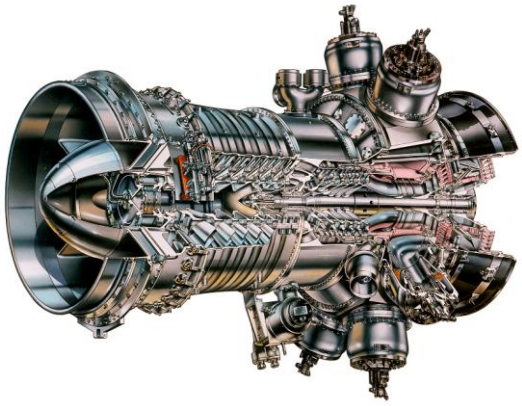


**General Electric**
**LM6000 DLE**

Triple Annular Dome

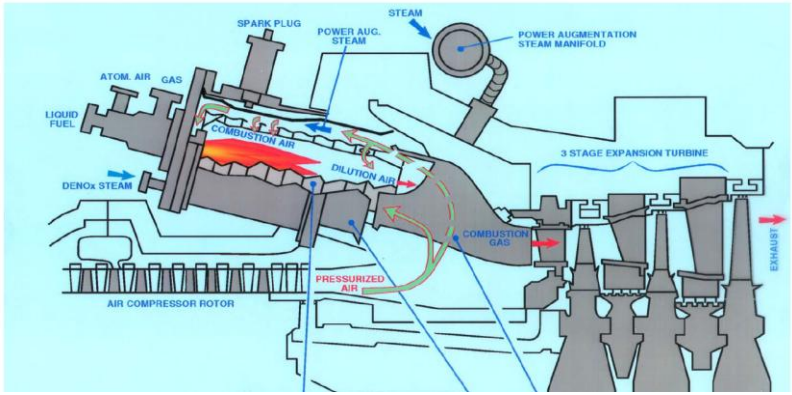


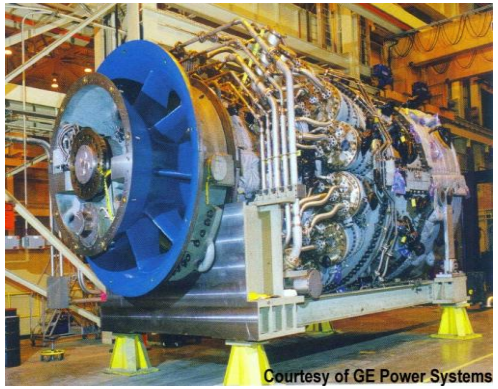


**Rolls Royce RB211 DLE**

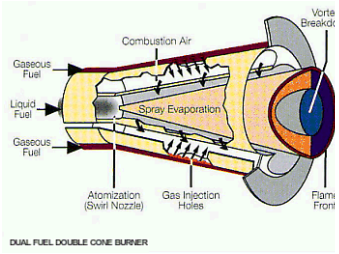
(Series staged)

# Large Frame Unit DLN



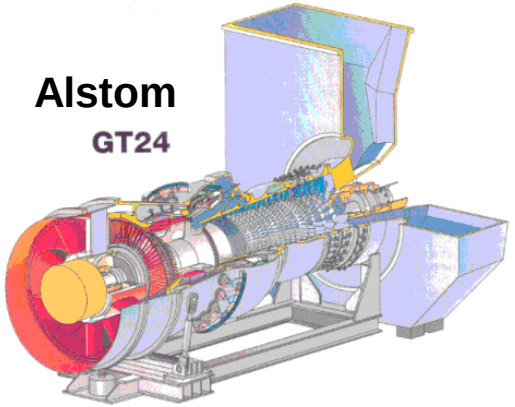




**GE Frame 7**
**DLN2**




Annular EV burner

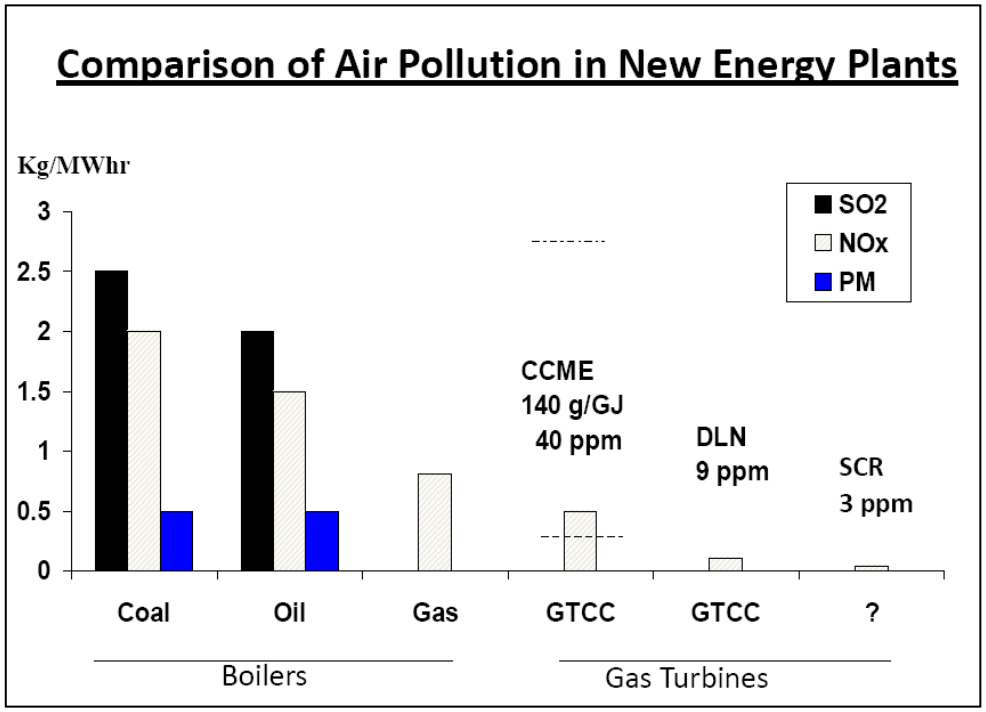
**Alstom**
**GT24**



# ***EA Assessments of Gas Turbine Plants***

(2002 Study, for *TransCanada P/L and Environment Canada)*

- **Companies may be required to install added ammonia-based SCR controls after DLN**
- **Ammonia transportation & handling is a serious local health and safety issue**
- **Given the capital & operating costs and collateral impacts associated with SCR systems, the environmental benefits do not justify the economic expense.**




**Marginal, low $/tonne benefit after DLN**

(T. McCann, B. Howard, M. Klein, 2003)

# Emissions Valuation; 300 MWe GTCC Plant

| 2 TWhrs | With SCR System | | DLN Without SCR | |
|---|---|---|---|---|
| | tpy | $000/yr | tpy | $000/yr |
| **NOx** | 100 | 200 | 400 | 800 |
| **Ammonia** (5 ppm) | 50 | 250 | 0 | 0 |
| **PM 2.5** | 50 | 250 | 0 | 0 |
| **$N_2O$** x 310 | 10 000 | 200 | 0 | 0 |
| **$CO_2$** | 727000 | 14540 | 720000 | 14400 |
| **GHG** (from $NH_3$) | 600 | 12 | 0 | 0 |
| | | **$15450 K** | | **$15200 K** |

**Air Pollution @ $2000 & $5000/tonne**

**GHGs @ 20/tonne**

# Gas Turbine Operability in Cold Climates

- How well does DLN operation adjust to very cold ambients ?

  (-30 to - 50$^{o}$C)

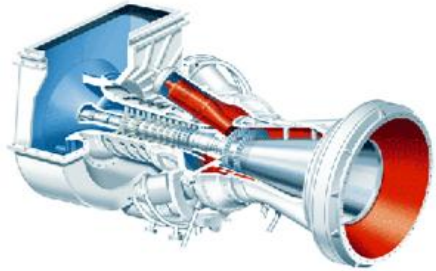
- How can unit power & efficiency be optimized during cold weather ?

- Acoustic Oscillations, noise

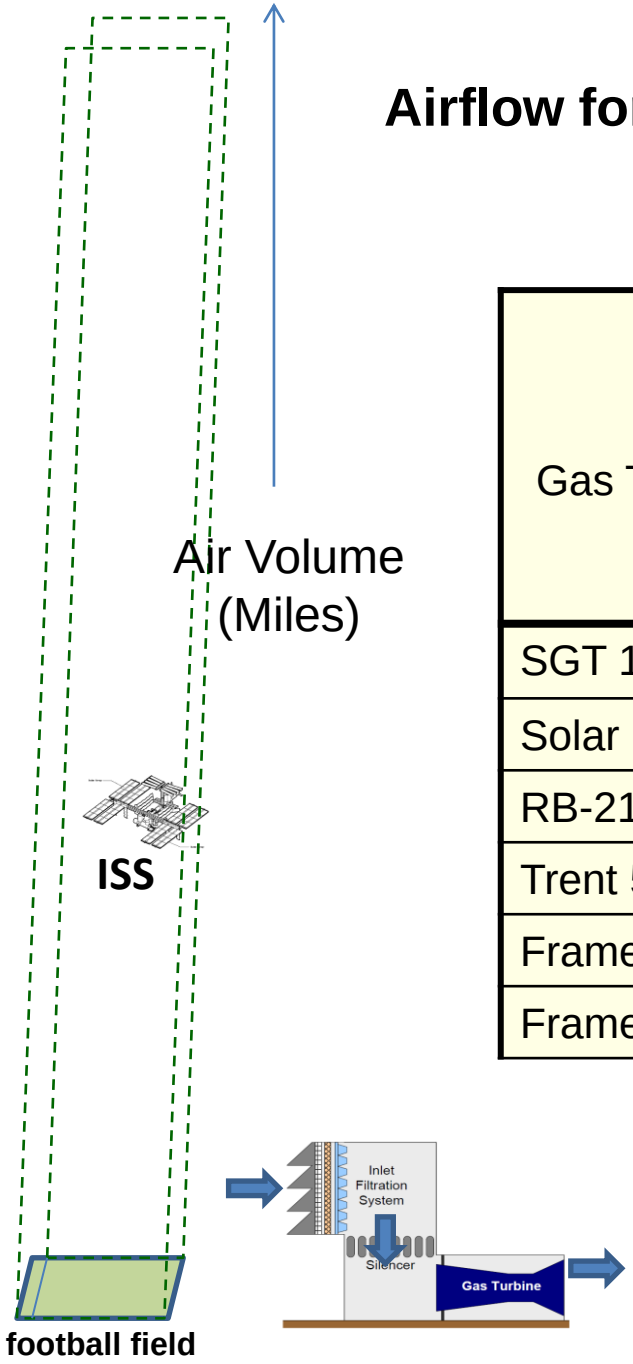
- How important are CO emissions?

- Can an Output-based design contribute to solutions?

- Effects of Specific Power
  - kW per kg/sec airflow



# Airflow for Power Output; Parameters for Gas Turbines




| Gas Turbine | ISO (MW) | airflow (lb/sec) | Air ingested per year (Miles above football field) | Foulant ingested per year at 1 ppm ambient (lb) |
|---|---|---|---|---|
| SGT 100 | 5 | 39 | 53 | 1230 |
| Solar Mars | 10 | 92 | 126 | 2900 |
| RB-211 | 27 | 199 | 272 | 6276 |
| Trent 50 | 51 | 340 | 464 | 10722 |
| Frame 7EA | 85 | 655 | 894 | 20656 |
| Frame 7FA | 173 | 971 | 1,325 | 30620 |

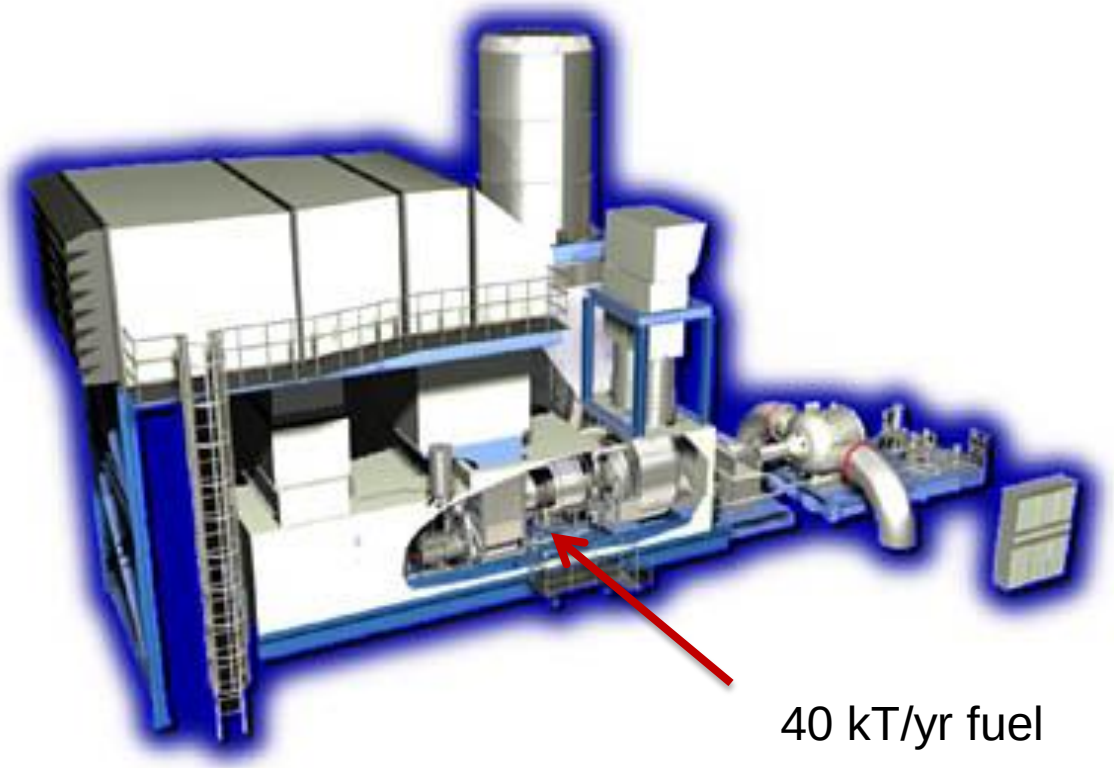
(C. Meyer-Homji, Bechtel)

**Are there $PM_{2.5}$ particulate emissions from gas-fired turbines?**

***(AP42 - 0.07 lb/MWhr ?)***

?

2 million t/yr Air



40 kT/yr fuel

Air Filter
99.8%

**Does dry NG combustion produce fine PM emissions?**

**What is the Inlet-Exhaust mass balance ?**

**Are there any Air Toxics ?**

**All of the gas turbine's power and efficiency depend upon its high pressure airflow.**

**Air must be clean to avoid compressor blade fouling, and blocking turbine blade cooling holes.**

**Air Filters are the largest part of the system, and part 'clean' emissions profile**

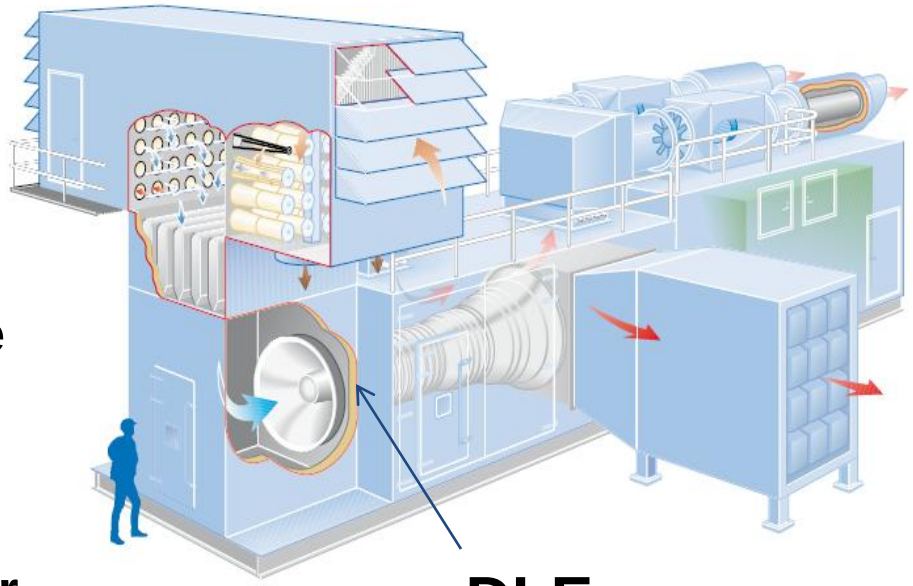
Pulse Jet Filter cartridges

# New Gas Turbine Systems

**New pre-mix DLE combustors have most incoming air going through direct combustion**

**Modern turbine air filter systems are cleaning the incoming air by 99 %**

**Small amounts of PM can escape, but must go through DLE combustor**



# Some Questions …

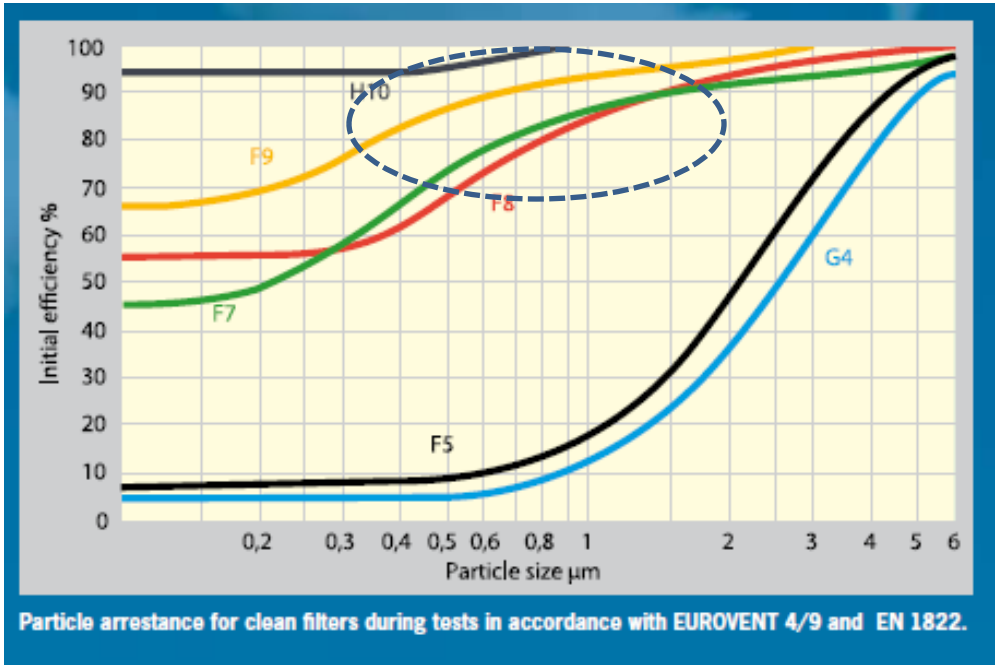
• Modern gas turbine air filter systems are cleaning the incoming air by over 99 %

• Higher capture efficiency for fine PM < 2 um

Has this been taken into account in PM emission factors ?

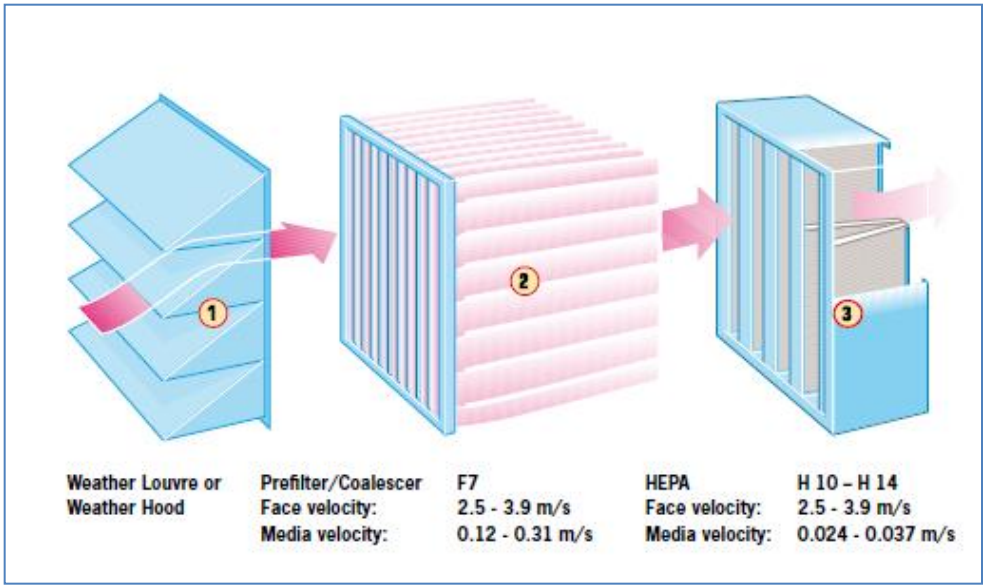
- System mass balance
- Combustor effects

- How is the measured PM created?
- Speciation of PM matter ?
- upstream raw gas C2/C3 ?
- eroding material from GT parts, or some lube oil ?



Particle arrestance for clean filters during tests in accordance with EUROVENT 4/9 and EN 1822.

Camfil Farr F7, F9, H10 filters



**45 MW LM6000 gas turbine, 7000 hrs**

***AP-42; PM @ 10 000 kg/yr ?***

**0.13 tonnes of air ingested per sec;**

**3.3 million tpy air, or 2.5 billion $m^3$ (volume of Vancouver)**

**Ambient $PM_{10}$ @ 40 ug/$m^3$ = 100 kg of $PM_{10}$ ingested (incl. 10 kg of $PM_{2.5}$)**

**Air filter can capture 95+ % of $PM_{2.5}$ < 1 kg released ?**

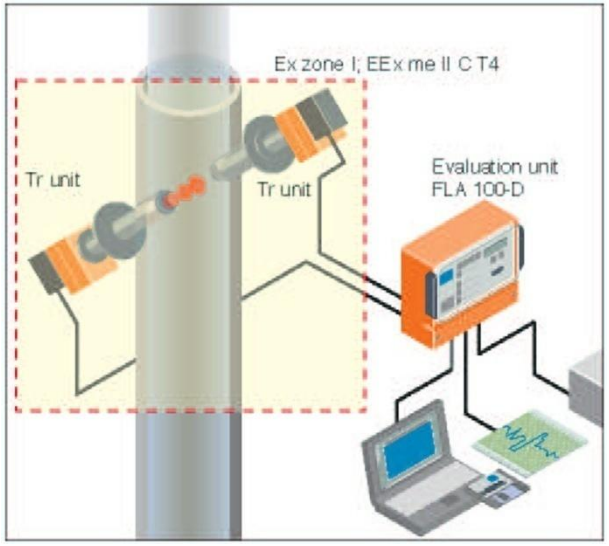
# Emissions Measurement

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

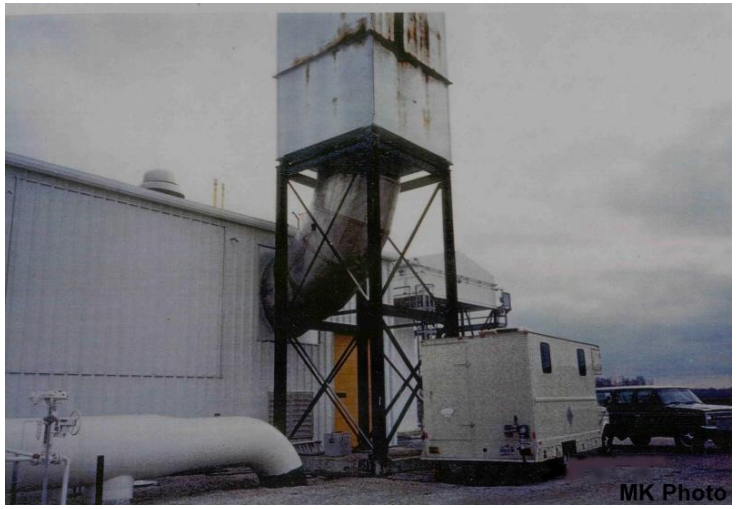
- **Continuous Emissions Measurement**
- **Process Estimation Methods**
- **Surrogate & parametric methods**
- **Predictive Emissions Monitoring**

**PEMs;**

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



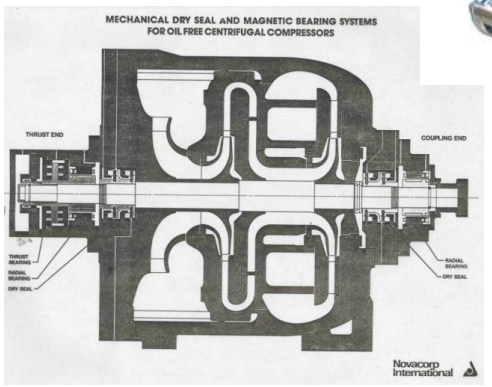

CEM Specialties




Env Can CEM van, Ontario

# 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**



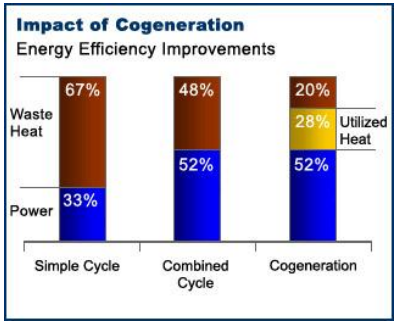

Gas Compressor Dry Gas Seals

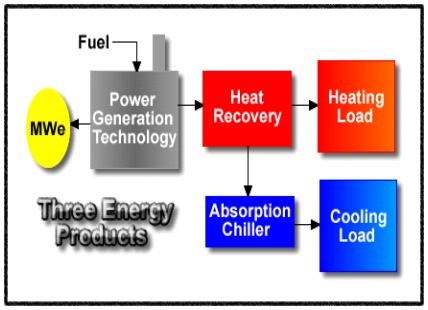
# Critical Elements for Cogen (CHP) Systems

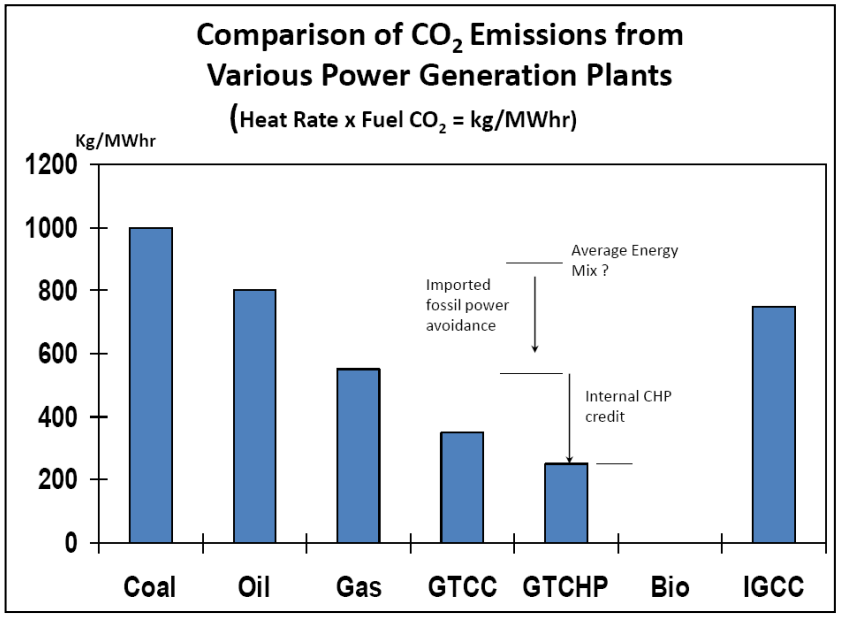
***CHP - Producing 2-3 forms of energy from the same fuel, in same process***

- **Awareness of Opportunities**
- **Site, Sizing to Match Thermal Load**
- **Seasonal Heat/Cooling Design**
- **Electrical Utility Interconnection**
- **Energy Quality,  Heat:Power ratio**
- **Low Air Pollution, Local Impacts**
- **Greenhouse Gases & Allocation**
- **Output-based Emission Rules**
- **Integrated Business Case**

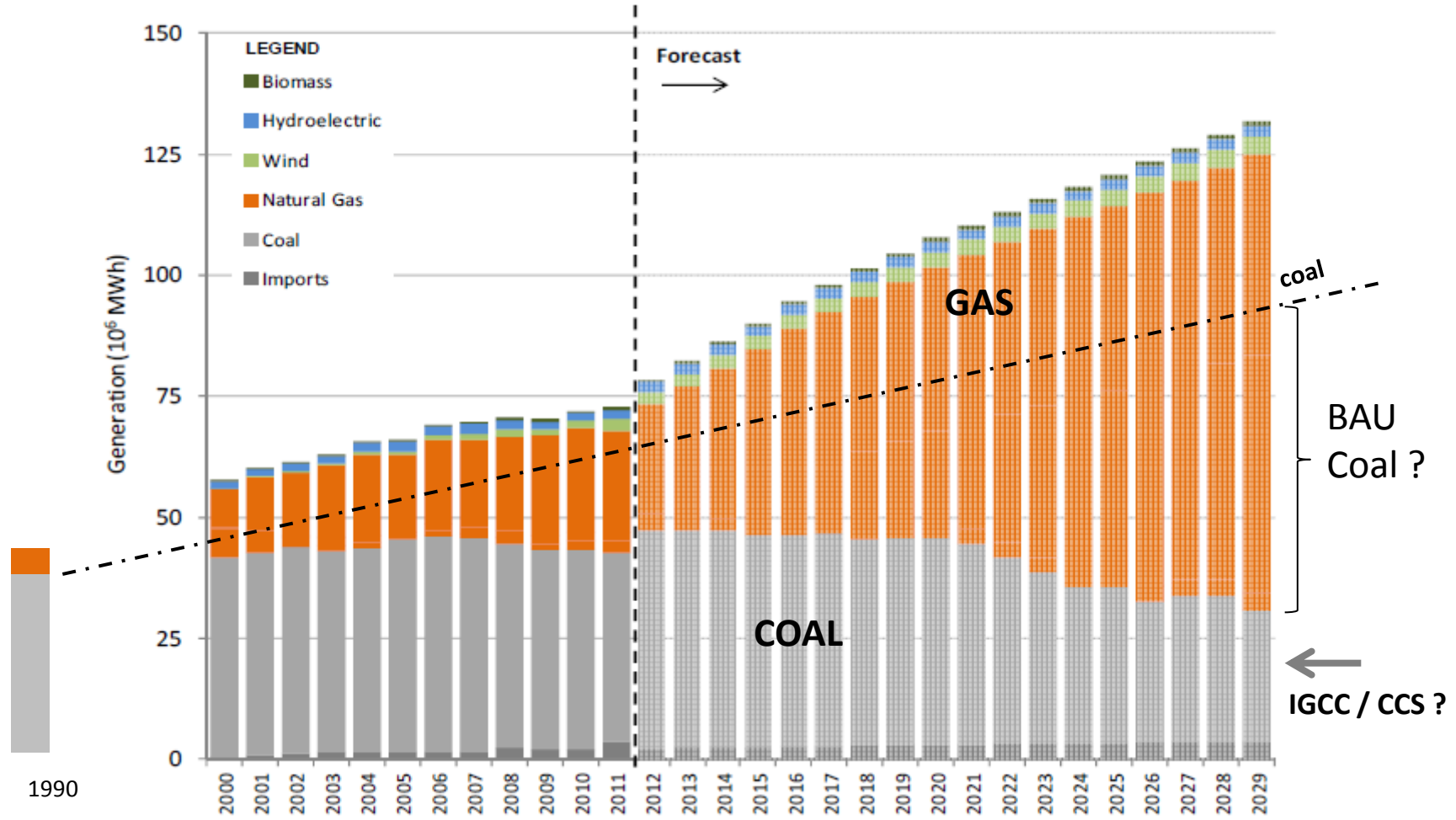
***(CHP more effective than CCS for GTCC)***



# PowerGen Estimated Potential for Alberta, 2030




**Gas-fueled CHP & GTCC systems with new 70 TWhrs could avoid 30 Mt/yr of GHGs & 400 kT/yr of air pollution**

**Adapted from (from AESO, 2012)**

**Water Conservation, Efficiency, and Productivity Plan – Electric Power Generation**

**August 2012**

# Industrial Cogeneration/CHP Potential

**New GT Simple Cogens**

- Replace existing old industrial boilers with GT/HRSG Combinations

Existing 2400 MWe

New Potential 5000 MWe

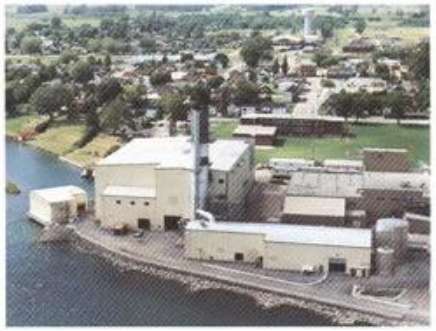
GTAA Pearson

Whitby Cogen

**Combined Cycle Cogen facilities**

Existing 5300 MWe

New Potential 6000 Mwe



Cardinal Power, ON

Kingston Cogen

**Municipal District Energy**
(hot water or steam)

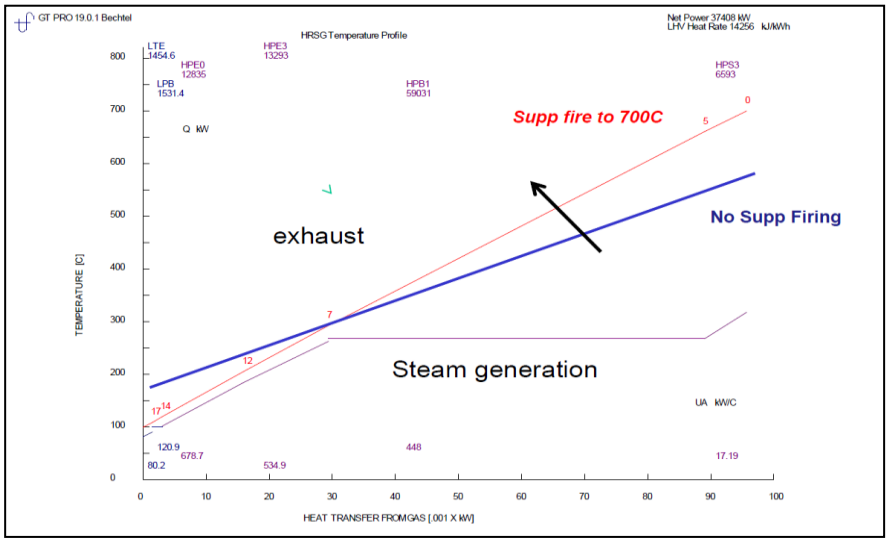
New Potential 3000 MWth

Markham ON, Recip trigen

York University

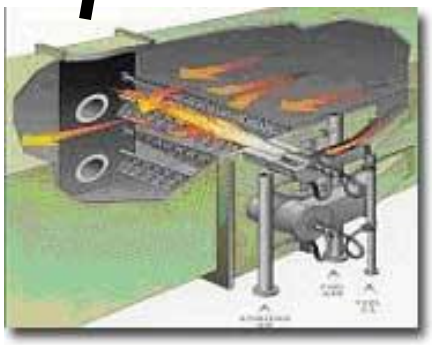
# Waste Heat and Duct Burners in CHP

- **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**



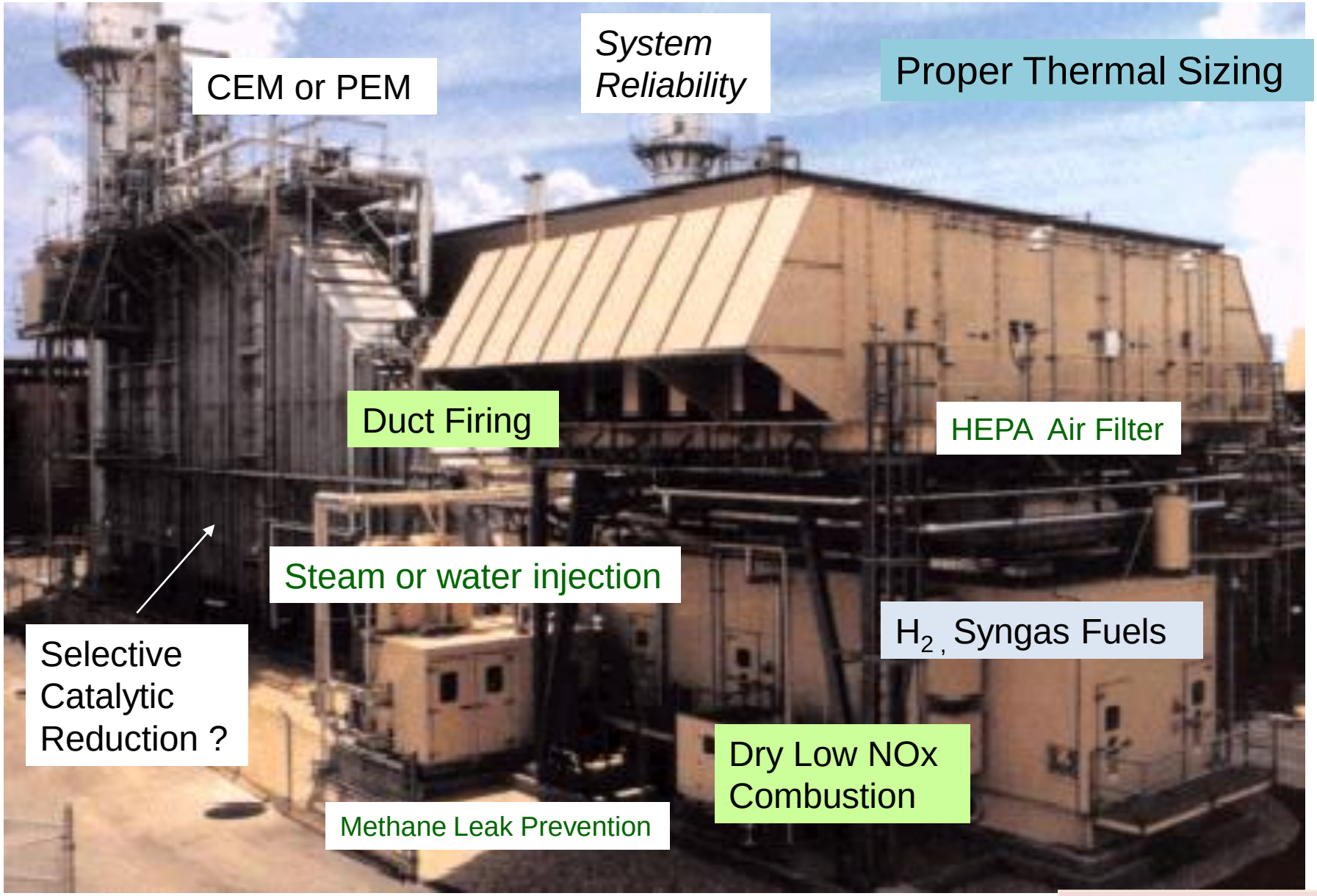

C. Meyer-Homji, Bechtel Corp.

JOHN ZINK COMPANY



(Coen)

# Gas Turbine Emission Prevention & Control (NOx, GHGs)




**Maximizing System Output CHP Efficiency**

*GE Power Systems*

# LNG System Environmental Performance

## Process Efficiency

- Liquefaction design choices
- Feed conditions
- Precooling methods
- Compressor speeds, Axial Inlet
- Variable Speed Electric Drives
- TurboExpanders, Abs.Chillers
- Flaring red'n, use BOG fuel

## Fuel Efficiency

- Compressor drivers, Inlet Conditioning, GTCC efficiency
- WHR and Cogeneration, Minimize losses
- Industrial vs Aeroderivative GTs
- Onsite vs GTCC/Hydro Imports, transmission
- Transient and Ambient Conditions
- High System Reliability

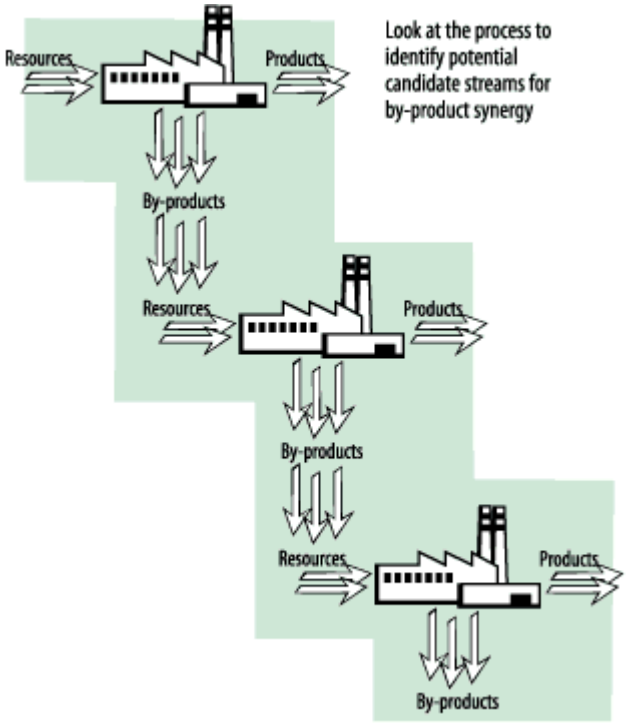
**"Cleanest LNG" ?**

**< 0.3 $t_{CO2}$ per $t_{LNG}$**

**- other impacts**

# Air Emissions; System Synergies

- CAC, toxic & $CO_2$ emissions must occur simultaneously in combustion
- They can be prevented all at once
- All power from fuel combustion generated originally from a 'Heat' system
- Small & medium sized gas turbines
  - high CHP efficiency
- Duct burners in HRSGs – good for cogen
- Renewable energies & integration of GTs
- GT power from high Inlet Airflow
  – reduce ambient PM ?




*By-product Synergies, IISD*

# Air Emissions;  System  Tradeoffs

•Small High pressure Dry Low NOx combustor
- reliability ?

• CO emissions;  potential brown plumes during long startups

• SCR systems and collateral impacts
- net $ cost per tonne increase

• Pipeline system upsets from unreliable DLN;
- more fugitive GHGs

• Large GTCC systems, require steam condensers
- Water impacts

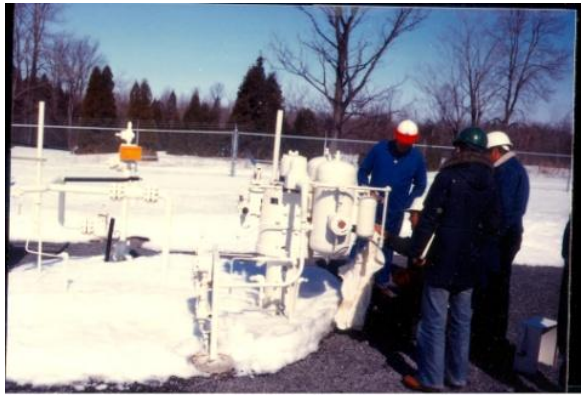
• Plant cycling affects efficiency & visible emissions

# Training and Outreach Opportunities

- **Canada-wide skills shortage**
- **Huge CAPEX & OPEX implications**

## Technical Training & Plant Tours

- **Concepts, Examples, Rules of Thumb**
- **Energy systems, Emissions, O&M**
- **For scientists, engineers, analysts, economists, students - young and old**
- **Cost-effective investments**



- Consensus
- Policy Clarity
- Balanced solutions
- Cost-effectiveness

# Concluding Remarks

- ***A gas turbine* is an *engine* in a system, *uses Air for power***
- **Gas Turbines have Very Low Air Emissions**
- **Maximize Energy Conservation, System Efficiency**
- **All Plant Emissions Need to be Addressed - System Design**
- **Combustor Reliability is a Challenge**
- **Output-based Standards can be Superior**
- **Integration & Balance; Air Pollution ⟷ Carbon Dioxide**

Presented at the 2015 Symposium on Industrial Application of Gas Turbines (IAGT)
Banff, Alberta, Canada - October 2015
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