IAGT 17 SYMPOSIUM
October 23rd - 25th, 2017
Fairmont Banff Springs Hotel

IAGT

# Gas Turbine Systems – Powering a Cleaner Future

## Environmental Considerations for GT Systems

- Clean Energy Considerations
- Air Pollution and GHG Emission Rates
- Canadian and International Standards
- Balancing Emission Prevention & System Efficiency

GT Cogen (GE)


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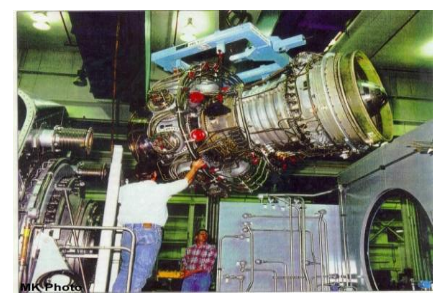


RB211 DLN


**Presented at the 2017 Symposium on Industrial Application of Gas Turbines (IAGT)**
**Banff, Alberta, Canada - October 2017**

# 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 27 000 MWe  installed in Canada***
***(~ 470 plants,  1150 units)***

# 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**

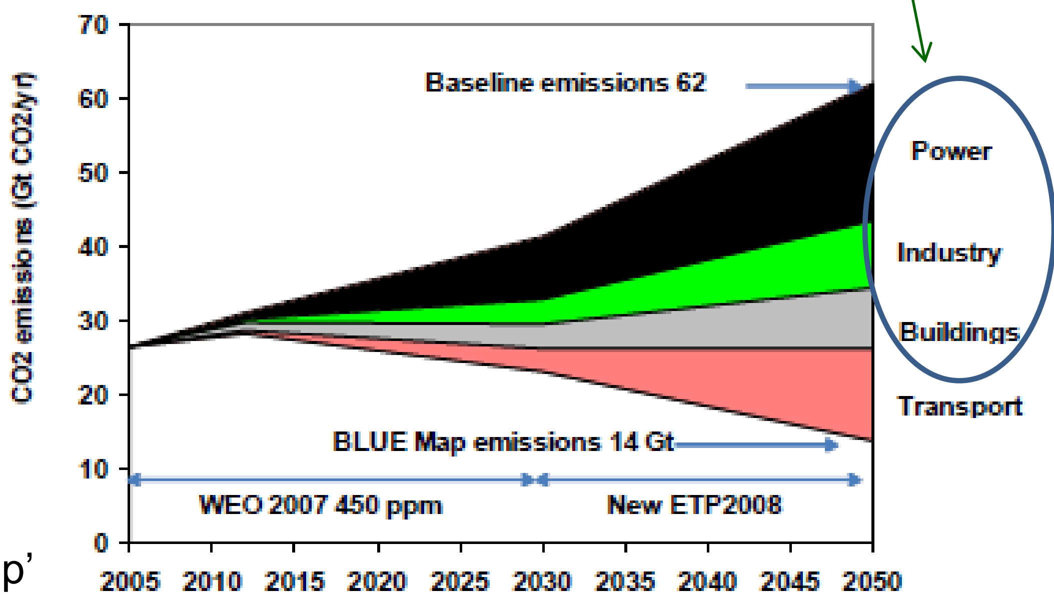
- CFCs

# 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

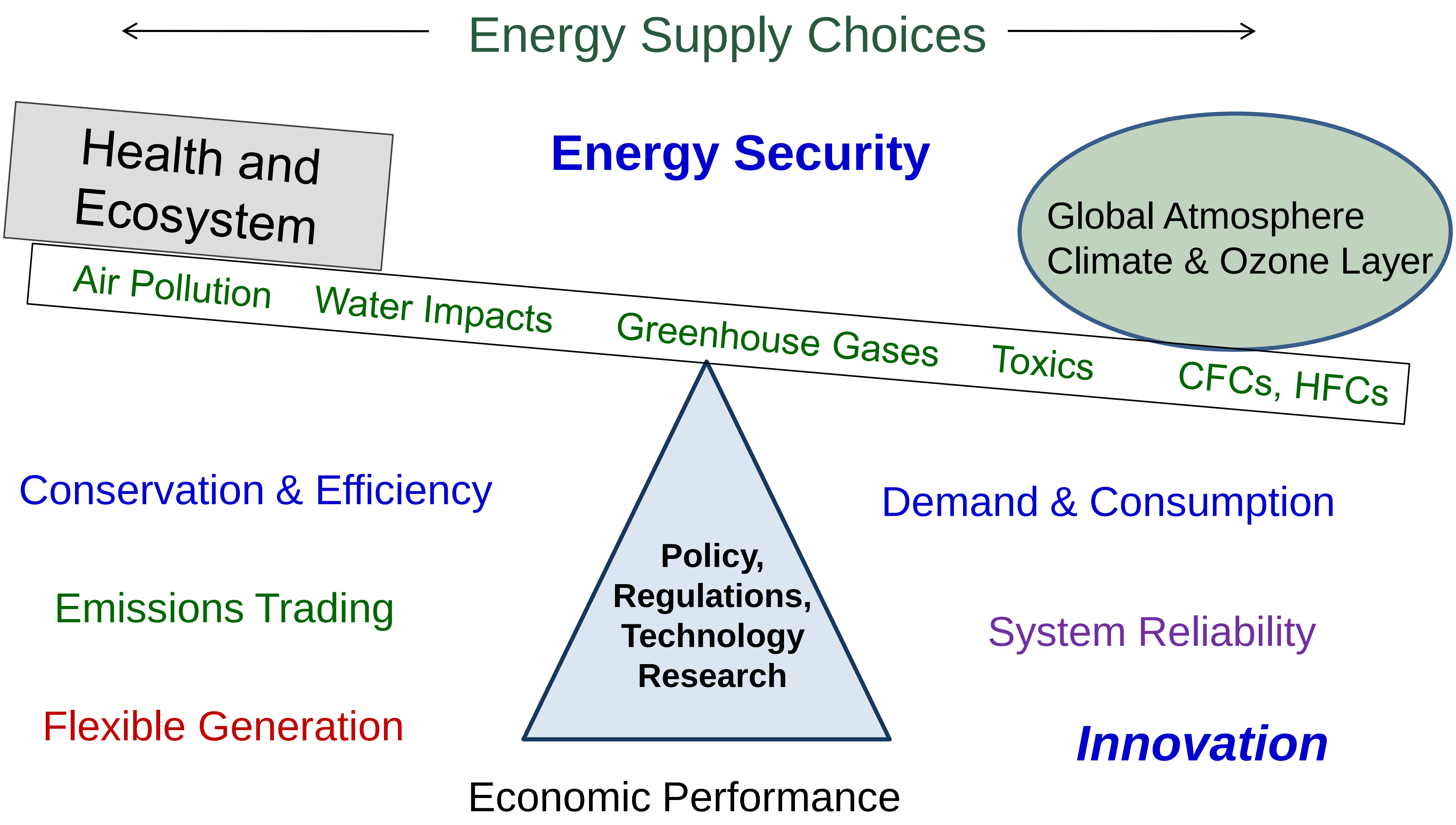
GT systems can do 25-30% of these reductions

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



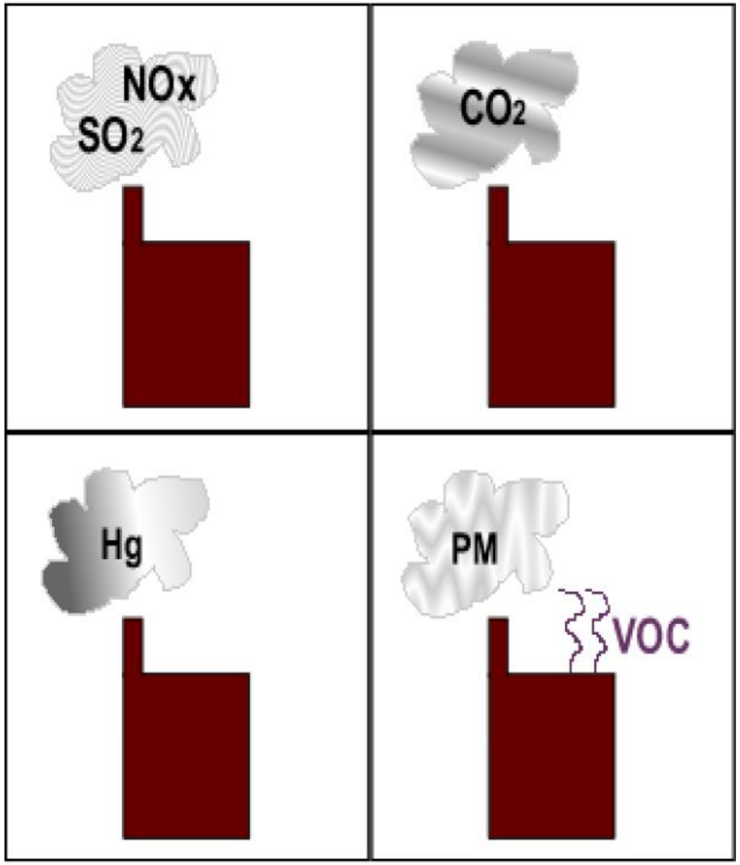

IEA WEO 'Blue Map'

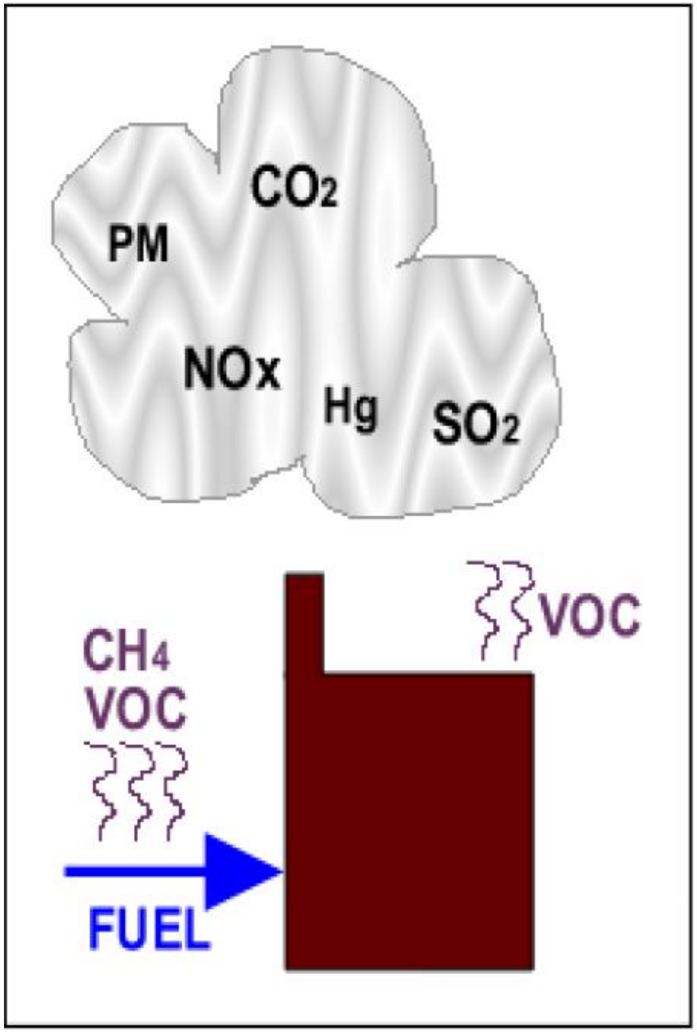
# Clean Energy Balancing Act



# Air Emissions

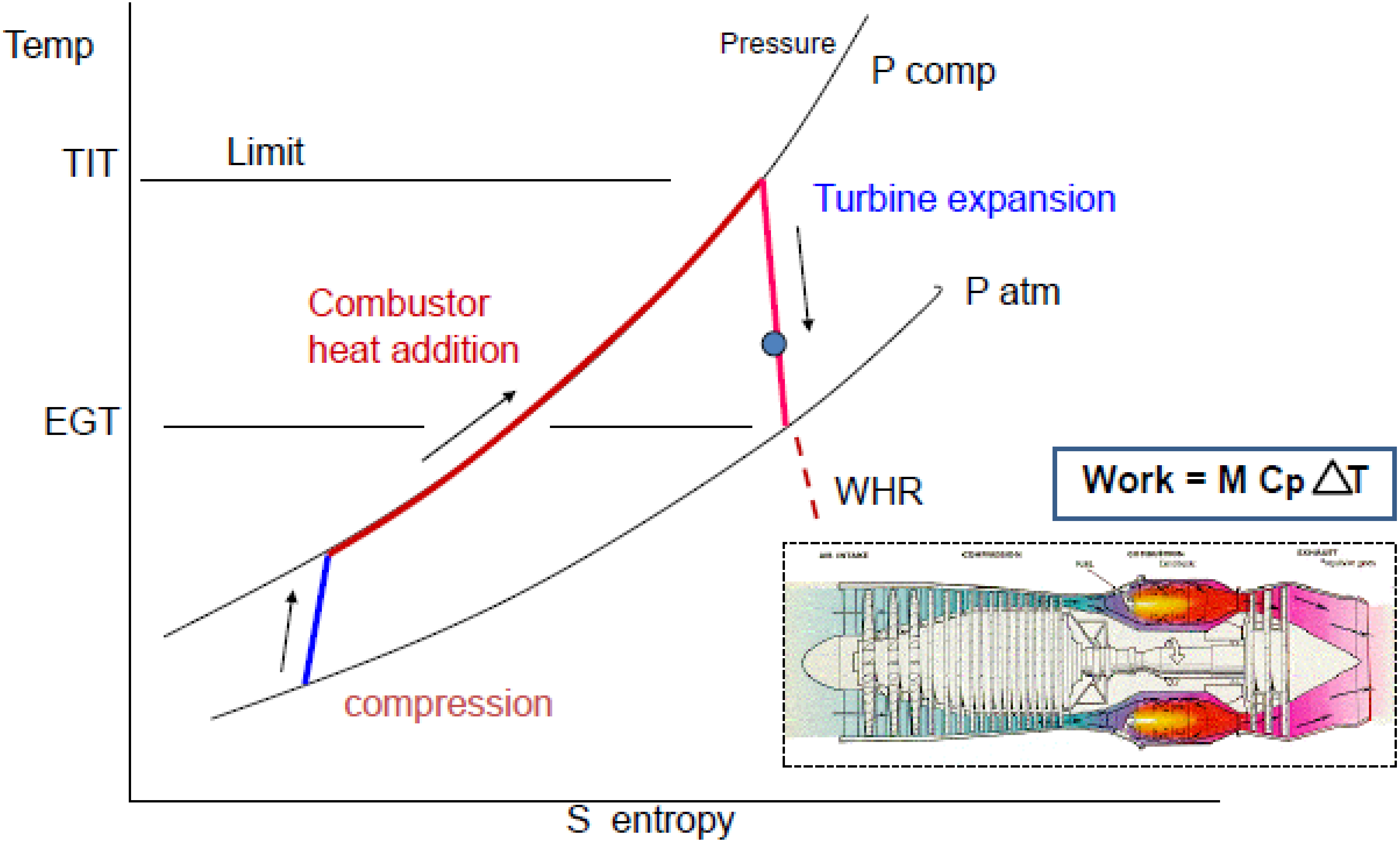
*(Smog, Acid Rain, Toxics, Climate Change,)*




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

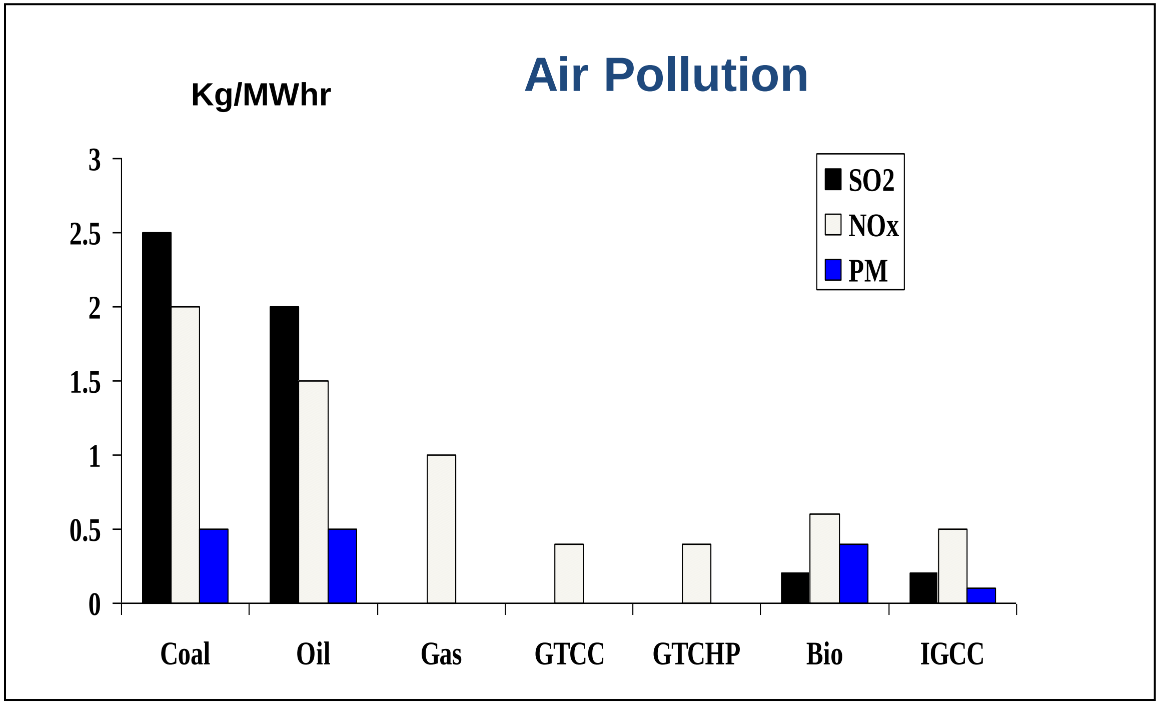
# Brayton Cycle;  Cycle diagram for Gas Turbine



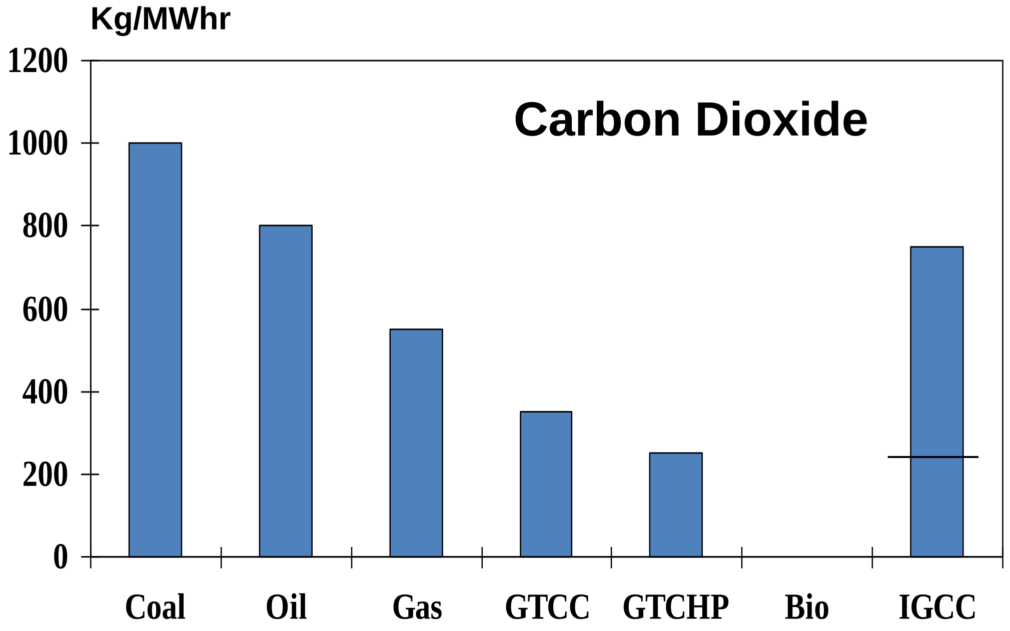

**Gas Turbine defined by high pressure hot air, as a gas, powering the blades**

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

# Comparison of Air Emissions from Various New Energy Generating Plants

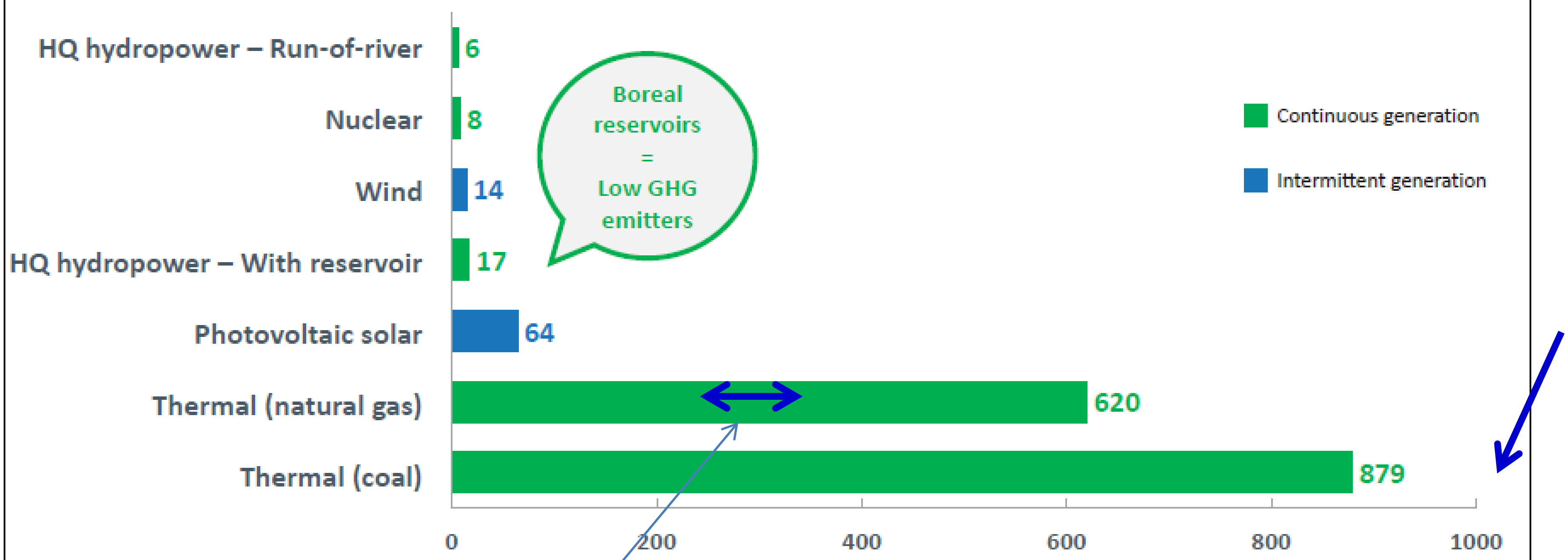



**Gas Turbine CHP plants have both Low $CO_2$ and Low Air Pollution**




*(Common Solutions)*

# Greenhouse Gas Emissions from Different Power Generation Options






From Hydro Quebec, 2016

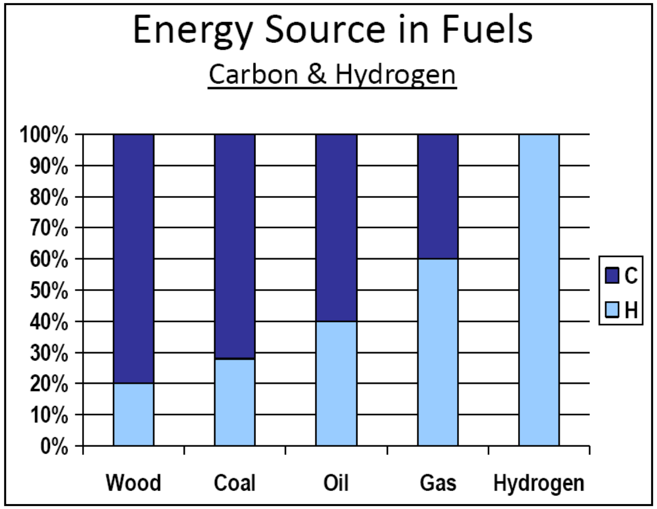
NG Cogen
(MK)

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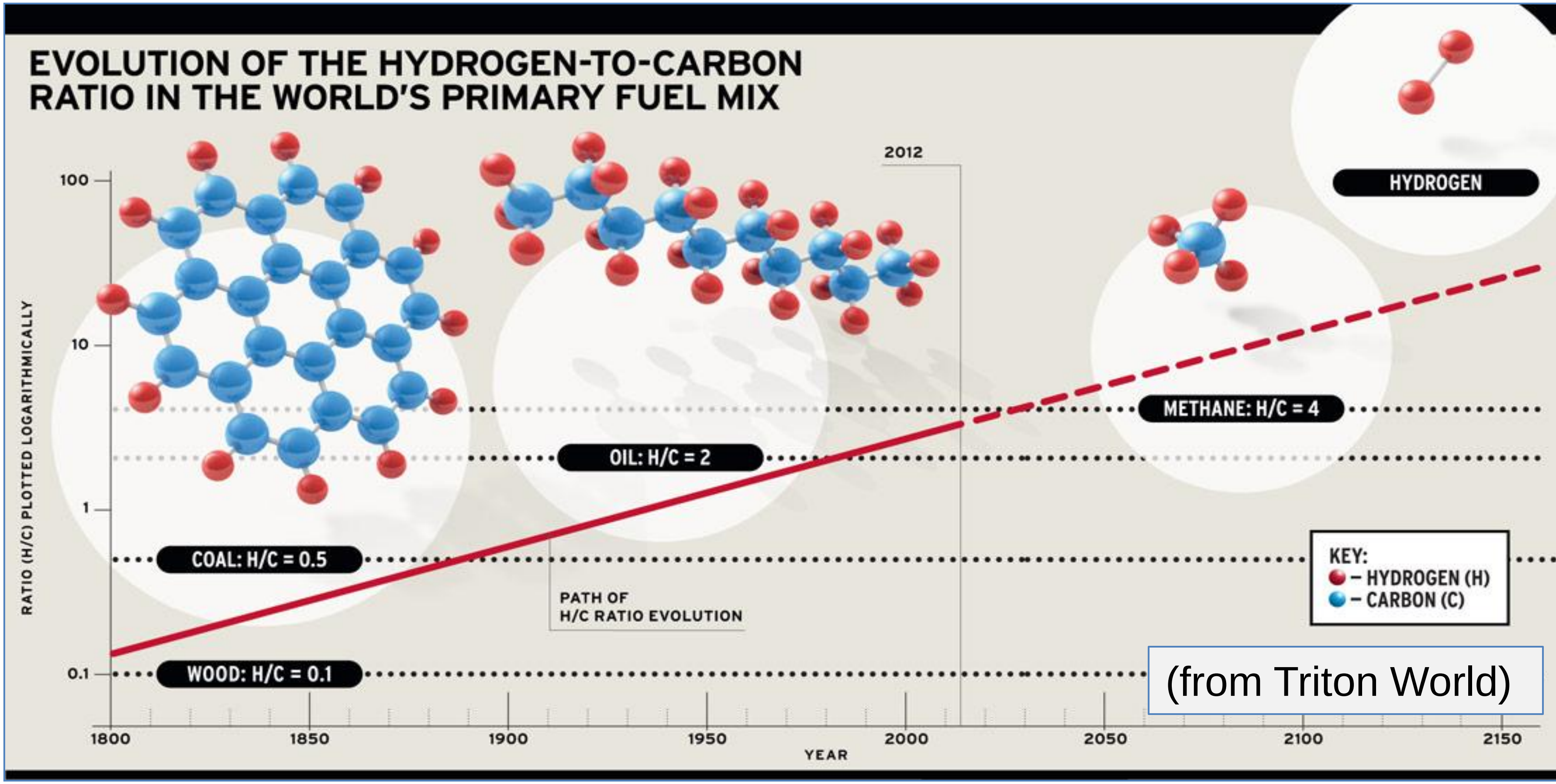
**$CO_2$ Rate Examples**  (Heat Rate$_{HHV}$ x $CO_2$ factor)

| | | | |
|---|---|---|---|
| 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 |

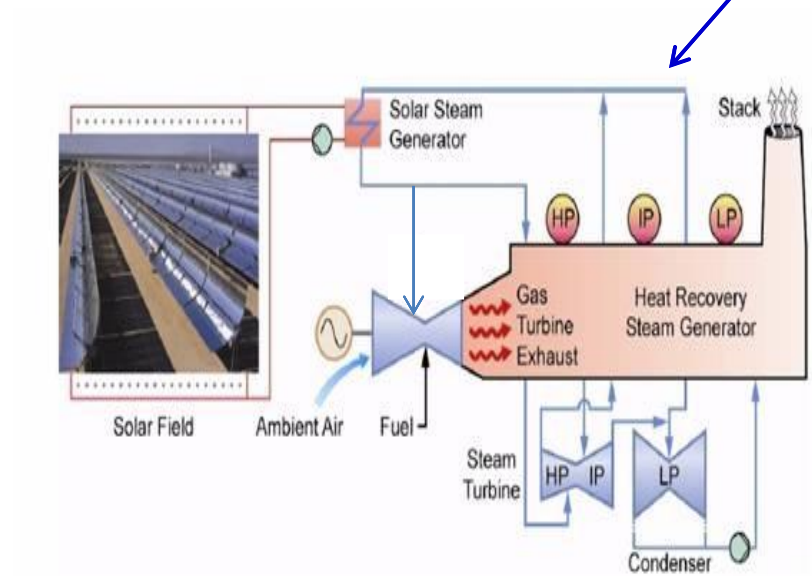



- **Fuel combustion produces heat, not power**
- **All materials burn as vapours (NG is there)**
- **Why is $H_2$-based NG given only 50% GHG reduction compared to coal boilers ?**
- **Is there a Roadmap for NG energy systems ?**

# Gas Turbines and Renewable Energy

WHR = RE

- Distributed Energy Systems
- Diversity in Unit Size, Applications
- Waste Heat Recovery, Efficiency
- Cogen and District Energy
- System Reliability, Islanding
- Fast Starts and Ramp Rates
- Cycle Innovations

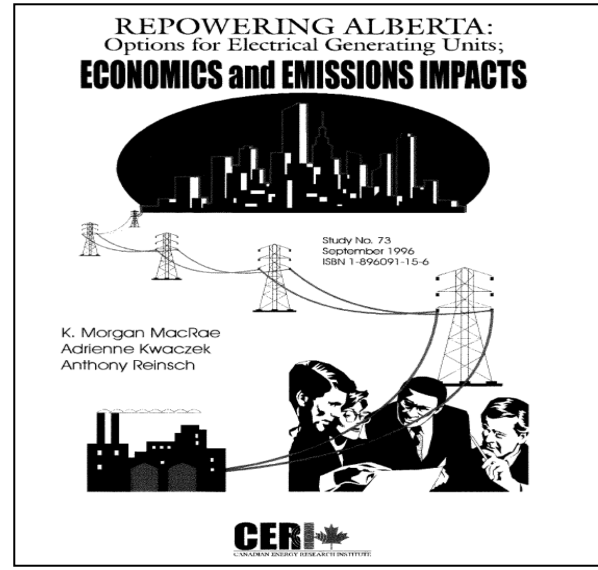



Hybrid Solar Energy GT System

# Some Things Done in Support of NG & CHP (1990-2005)

## CERI / EnvCan Economic Studies

- *Alberta Repowering,  Sept 1996*
- *Natural Gas Utilization for Nova Scotia Power Generation,  Oct 1997*



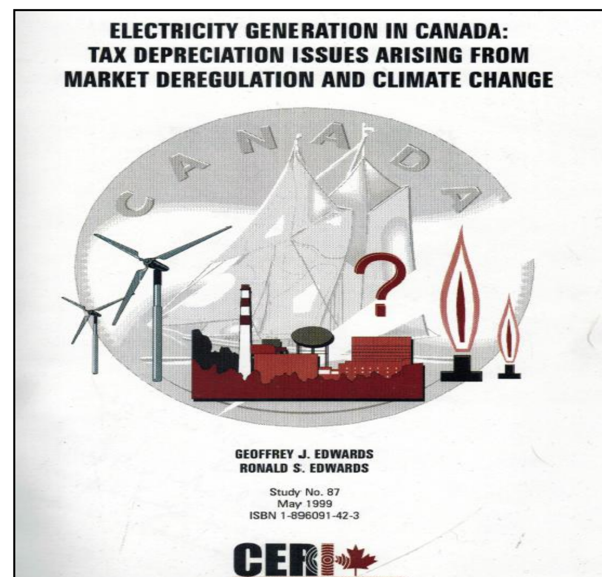

## Accelerated Capital Cost Allowance

**- Federal budget changes;**

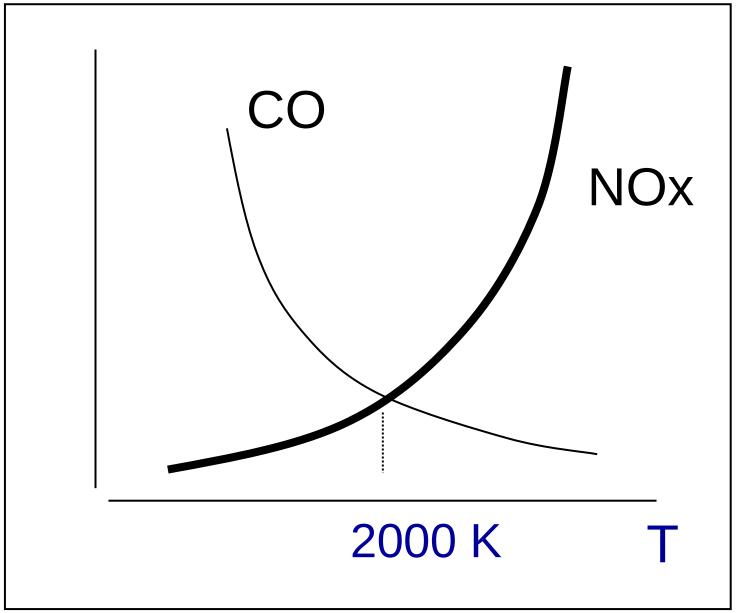
**2000 – Class 1;   from 4% to 8%,**
**15% for gas turbines**

**2005 -  Class 43.2**

- **new 50% ACCA rate ( > 72% eff'y)**
- **District Energy piping included**



# Air Pollution - *NOx Emissions*

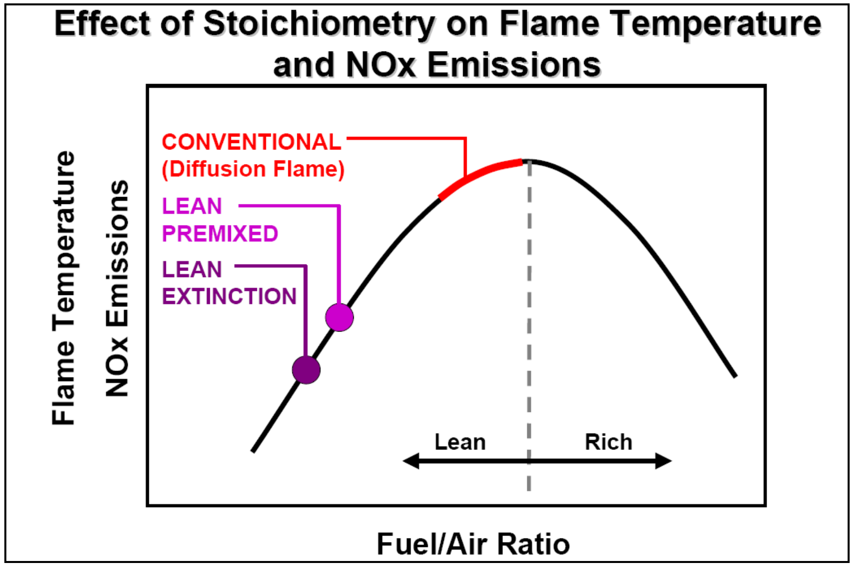



**$O + N_2 \longrightarrow NO + N$**

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

3 Compounds of Concern:

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




(Solar Turbines)

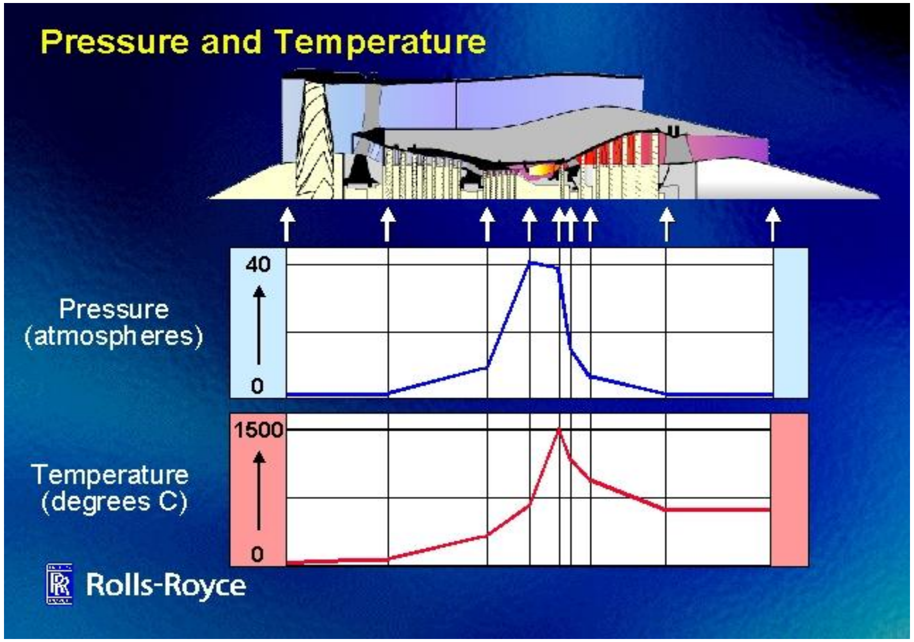
**Thermal NOx:**
**High Temperature Combustion**

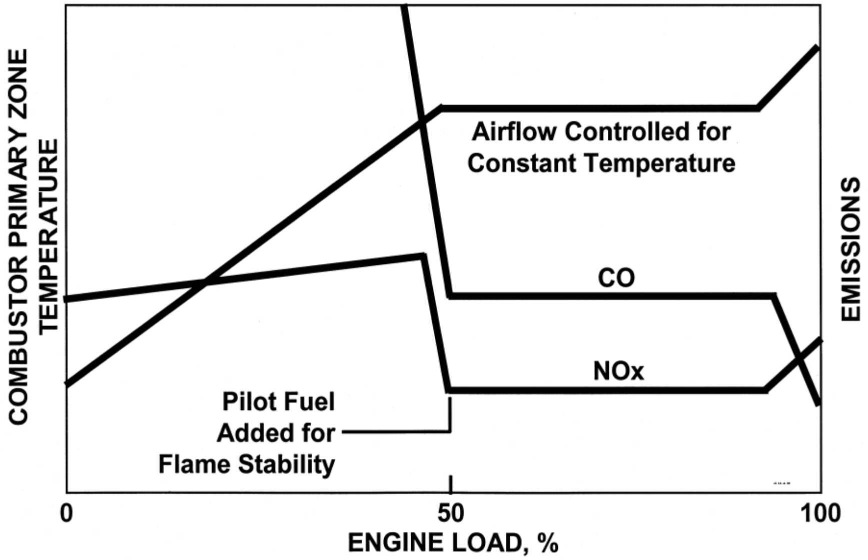
**Fuel NOx:**
**From $N_2$ Content of Oil, Coal**

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

# Factors Affecting NOx Emissions in Gas Turbines

- 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
- Tradeoffs w/ other emission types



# 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/m³) 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**

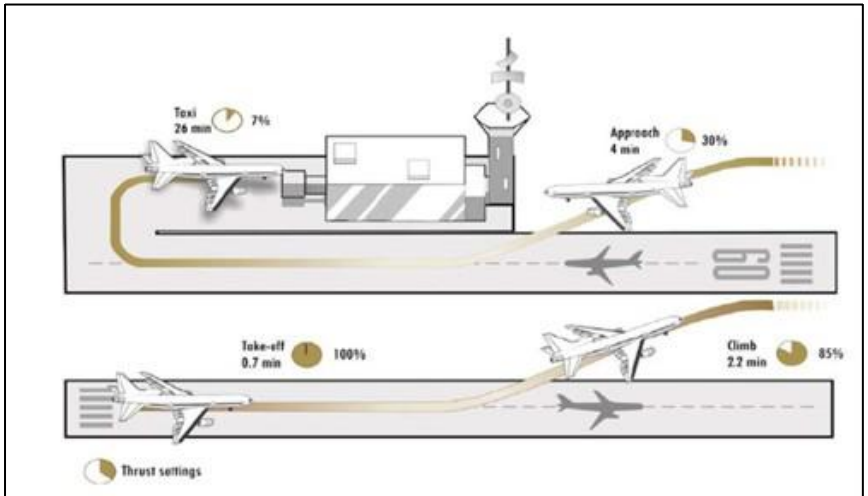



Figure 1 - Illustration of ICAO Emissions Certification Procedure LTO Cycle.
*Source: ICAO.*

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

## Output-based Rules;

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

**tonnes/yr**

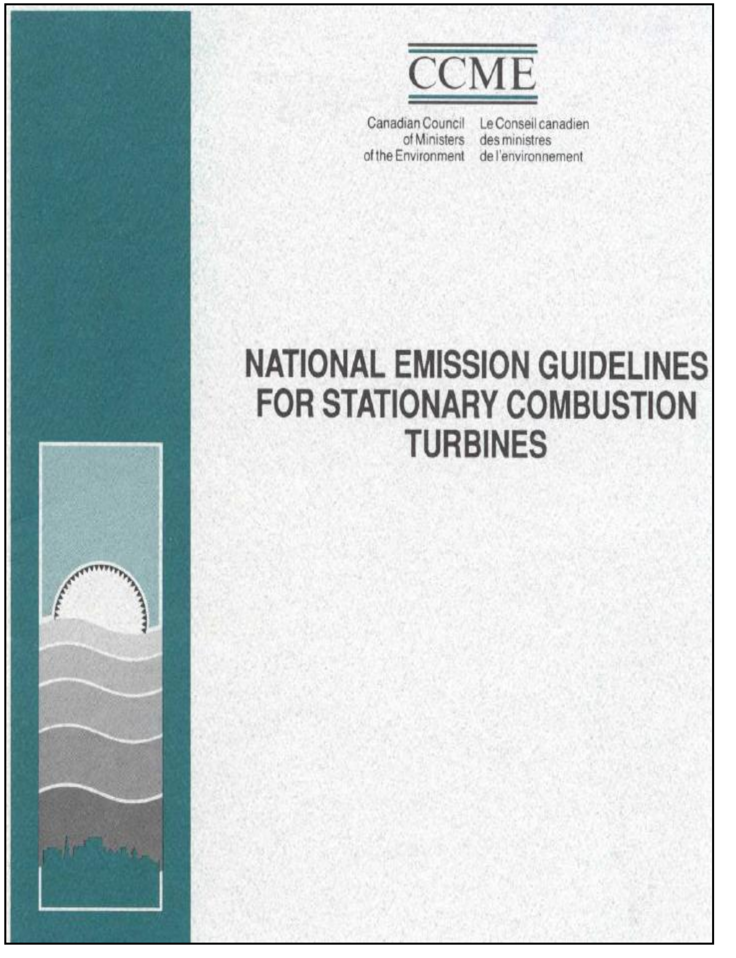
**$/tonne**

**$/MWhr**

Lbs/HpHr

# Canadian GT Emission Guidelines (1992)

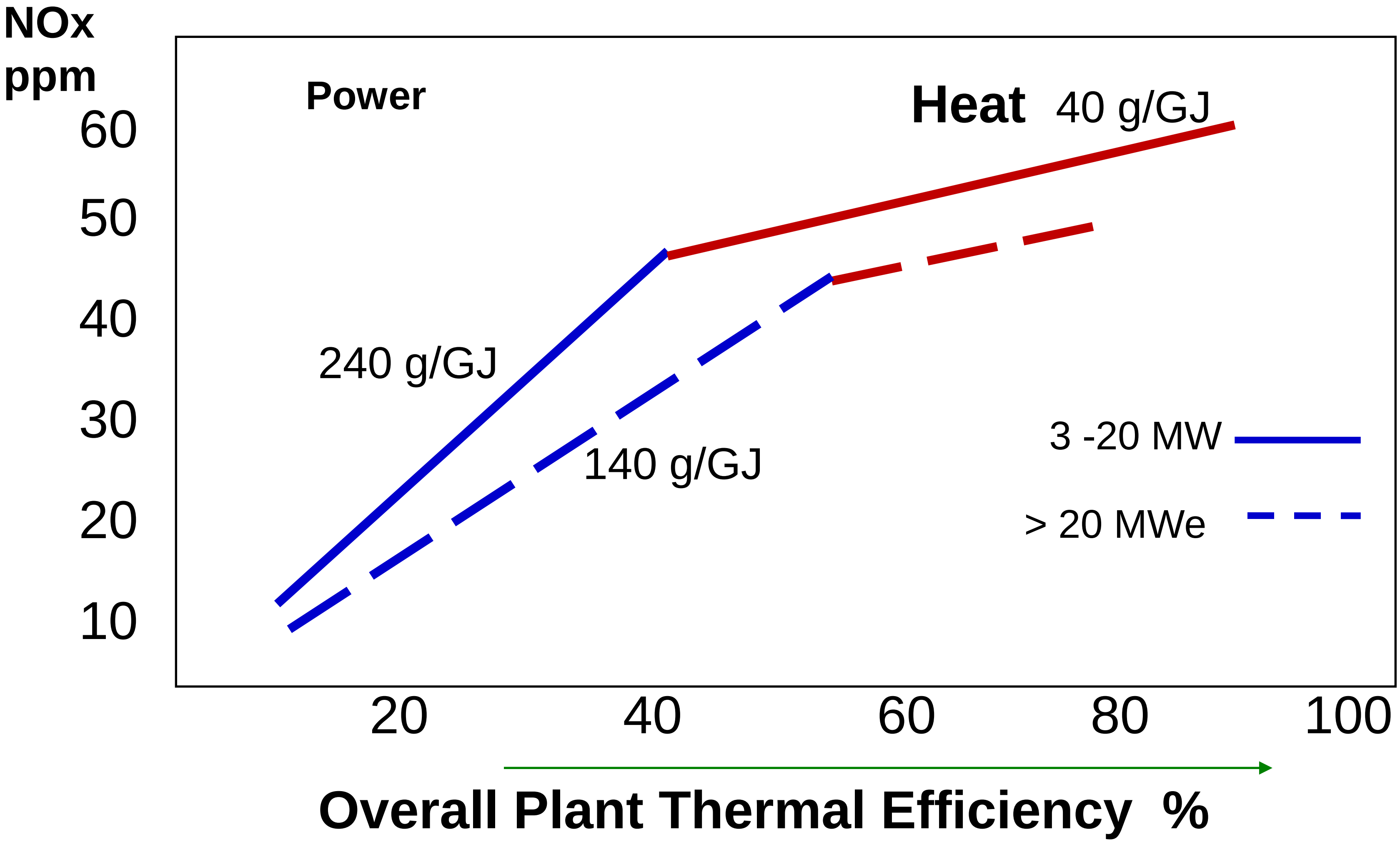
- NOx Prevention Technology
- Output-Based Standard for Efficiency ($140$ g/GJ$_{out}$ Power + 40 g/GJ Heat)
- Engine Sizing Considerations
- Promotes Cogeneration and low $CO_2$
- Peaking units (<1500 hrs/yr)
- Flexible Emissions Monitoring
- Quality of Energy
- Cold Weather considerations
- Clean Energy linkages




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

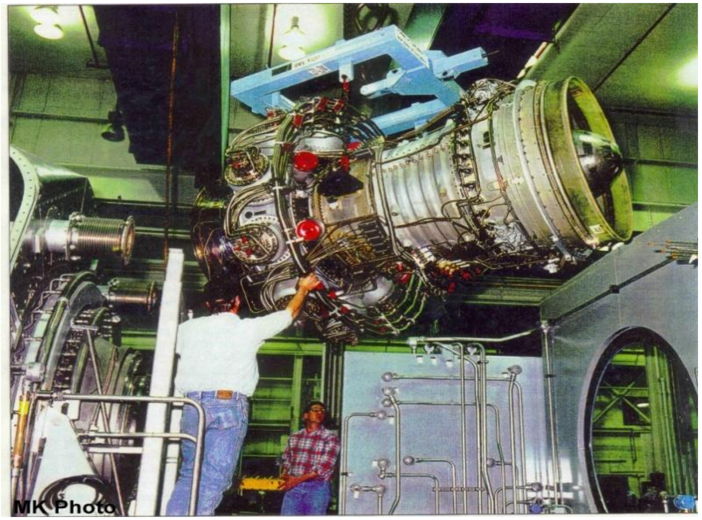
# Canadian CCME Gas Turbine Guideline (1992)

*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 | $\geq$ 1 and < 4 | 500 | 75 |
| Non-peaking combustion turbines - Electricity Generation | $\geq$ 1 and < 4 | 290 | 42 |
| Peaking combustion turbines – all | $\geq$ 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 |

**Environment Canada May 2016**

# 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/Nm³ 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

# 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

# *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***

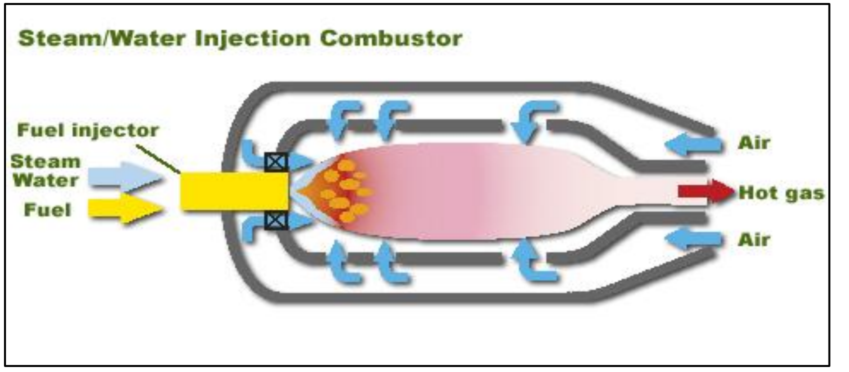
***Look for solutions with;***

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

# NOx Reduction Methods

**Steam/Water Injection**

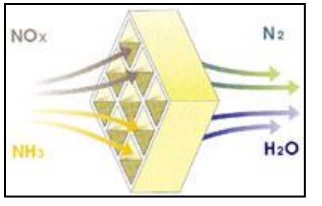
- Prevention, 2/3 red'n to 1 kg/MWhr
- Some Combustion Component Wear
- Plant Efficiency Penalty
- Depends upon value of plant steam

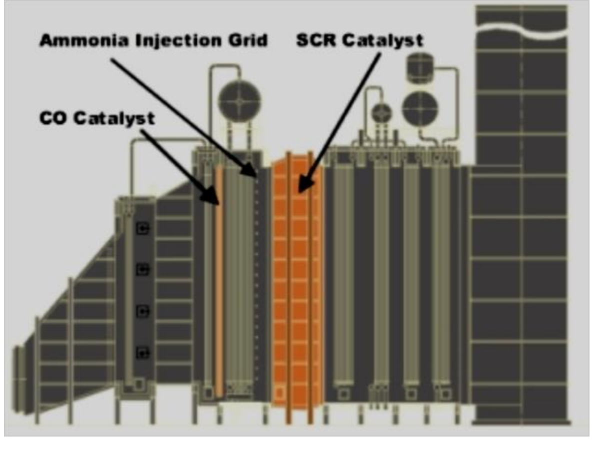



(Kawasaki)

**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**

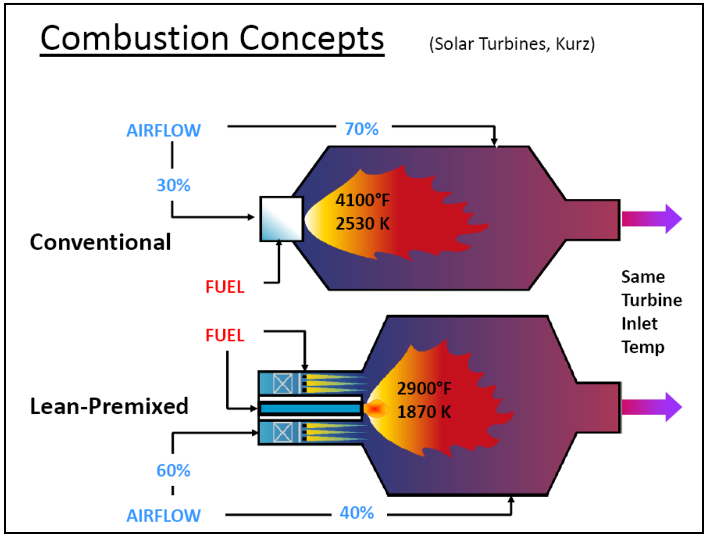


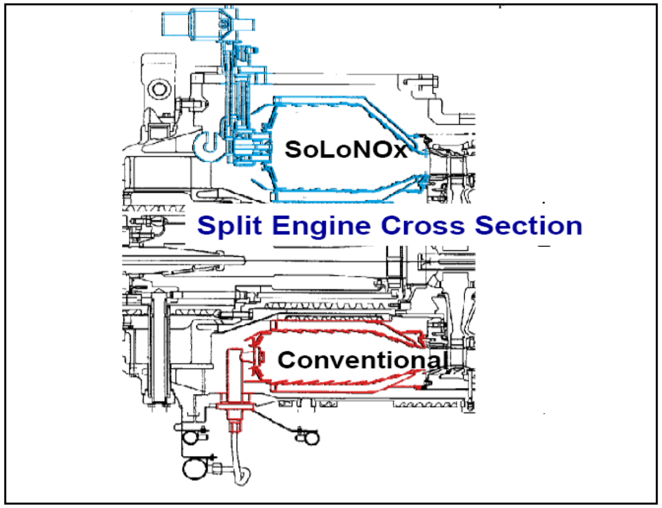




IST Aecon

# Dry Low Emissions Combustion

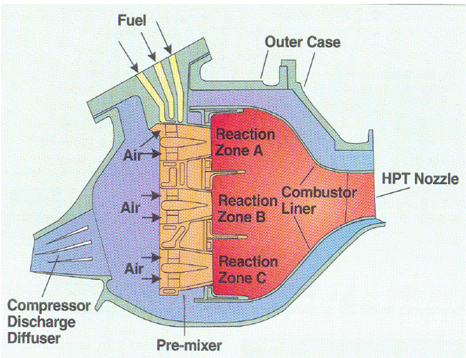
- Preventative reduction by 60-90%
- Maintains High Efficiency
- Good experience with large industrial units
- Some Reliability Issues for Aeroderivatives
- Too Low Values may lead to inoperability and combustor problems
- How important are CO emissions?
- Mech. drives need wide operating range
- Effects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

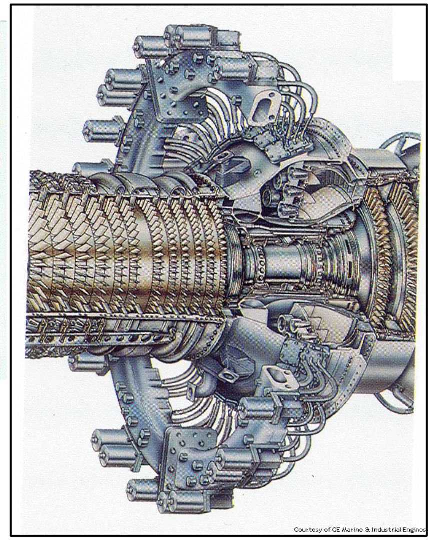



Solar SoLoNox

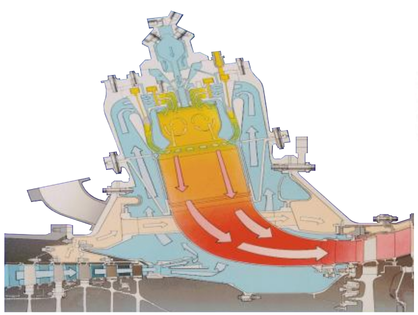
# Aero-Derived DLN Systems

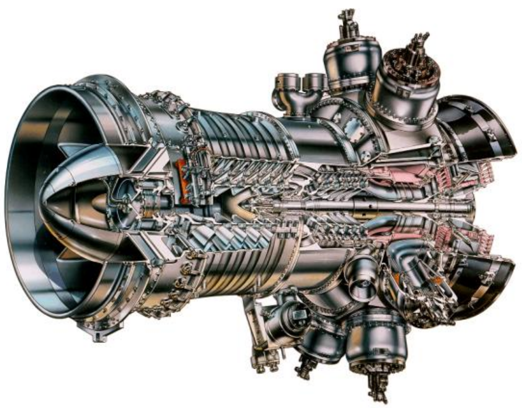



**General Electric LM6000 DLE**

Triple Annular Dome

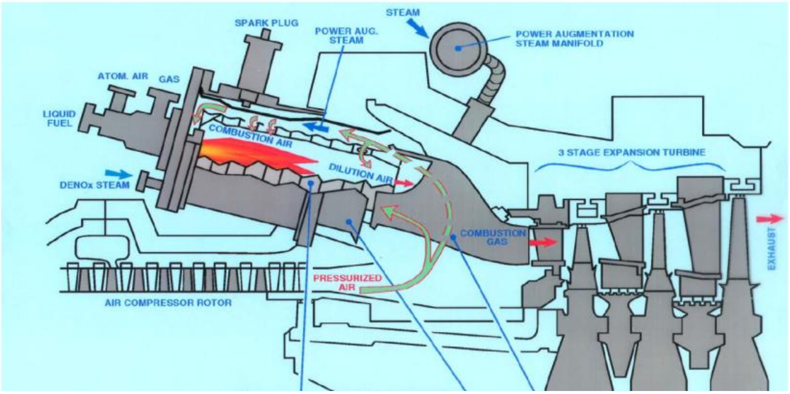




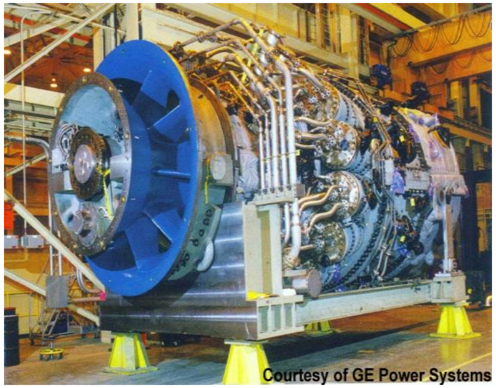
**Rolls Royce RB211 DLE**

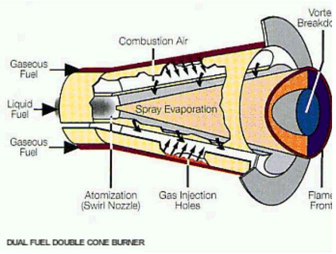
(Series staged)

# Large Frame Unit DLN




**GE Frame 7 DLN2**

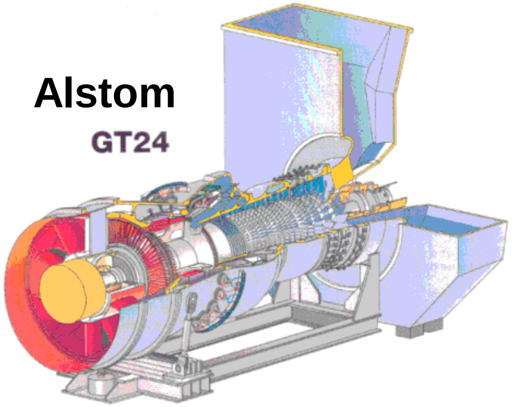



Annular EV burner

**Alstom**

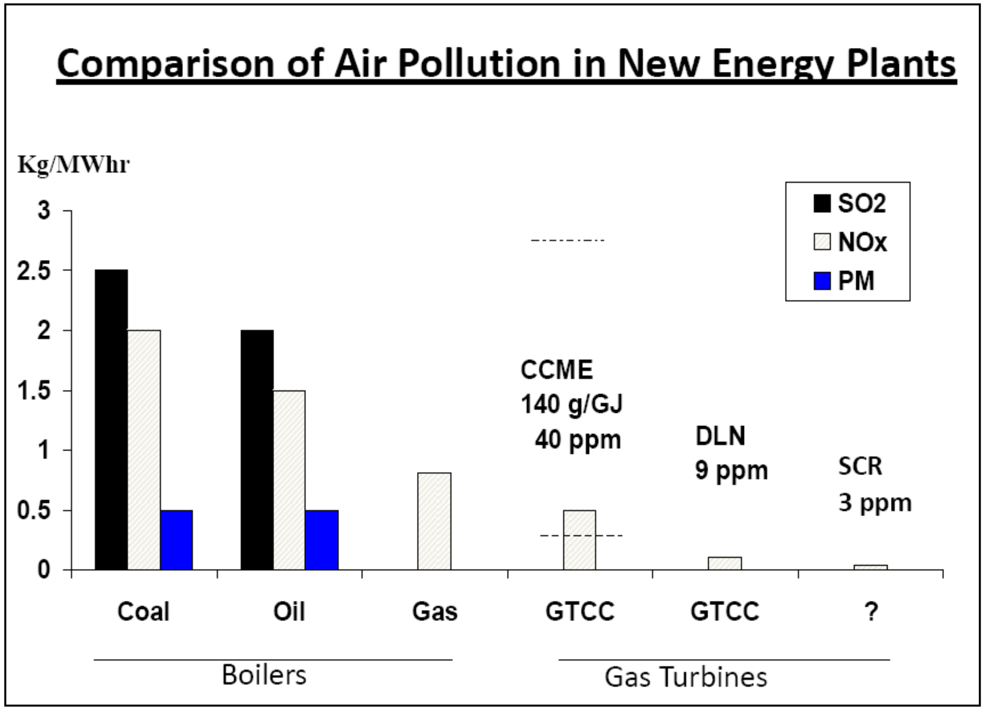
**GT24**



# ***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, <u>the environmental benefits do not justify the economic expense</u>.**




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

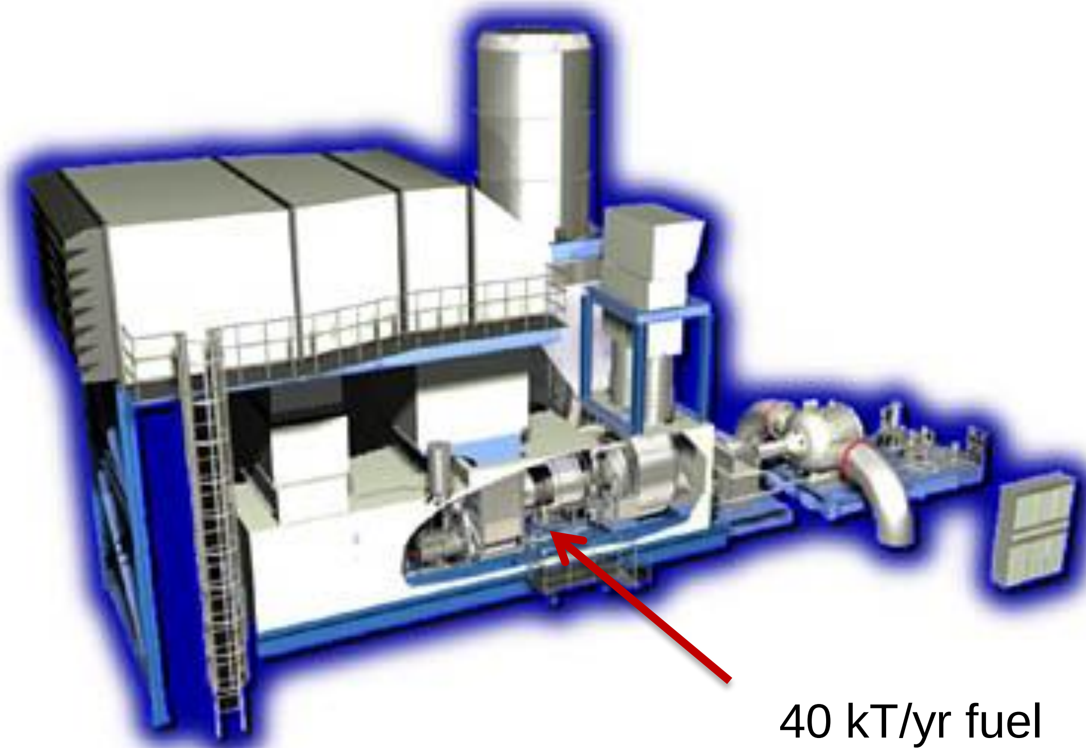
(T. McCann, B. Howard, M. Klein, 2003)

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

*(AP42 - 0.07 lb/MWhr ?)*

?

2 million t/yr Air



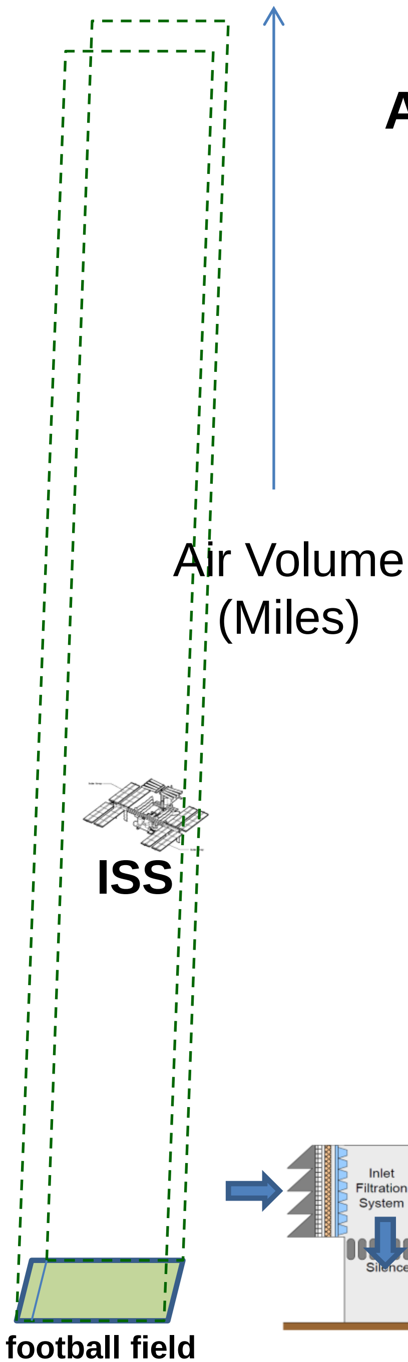
40 kT/yr fuel

Air Filter
99.8%

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

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

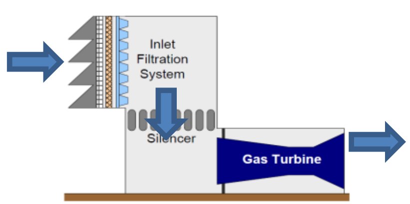
**Are there any Air Toxics ?**




# 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)



**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,  part 'clean' emissions profile**

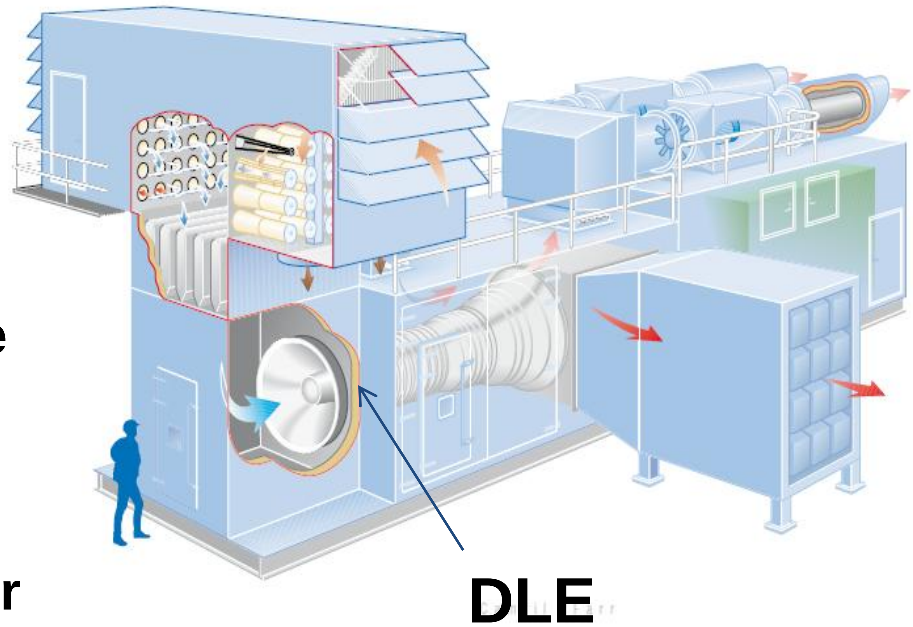
Pulse Jet Filter cartridges

# New Gas Turbine Systems

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

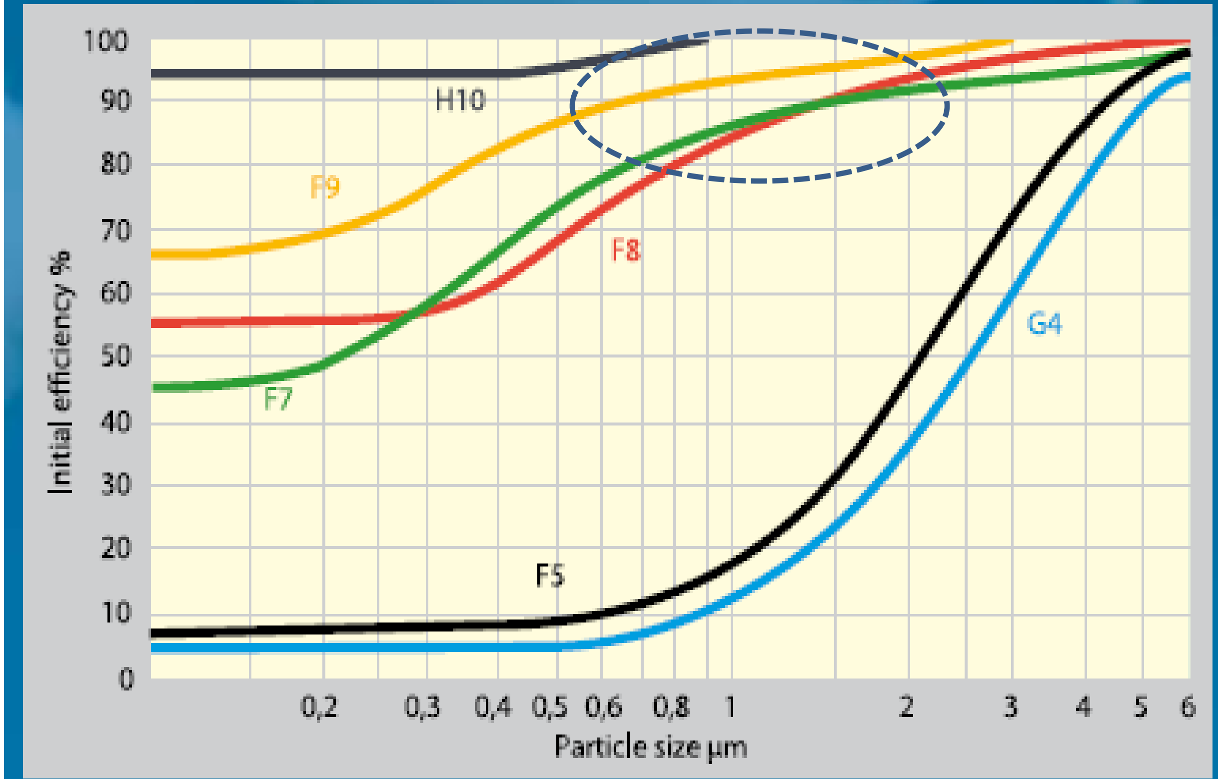
**Modern turbine air filter systems are cleaning the incoming air by 99 %**

**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 %
- High capture efficiency for fine PM < 2 um

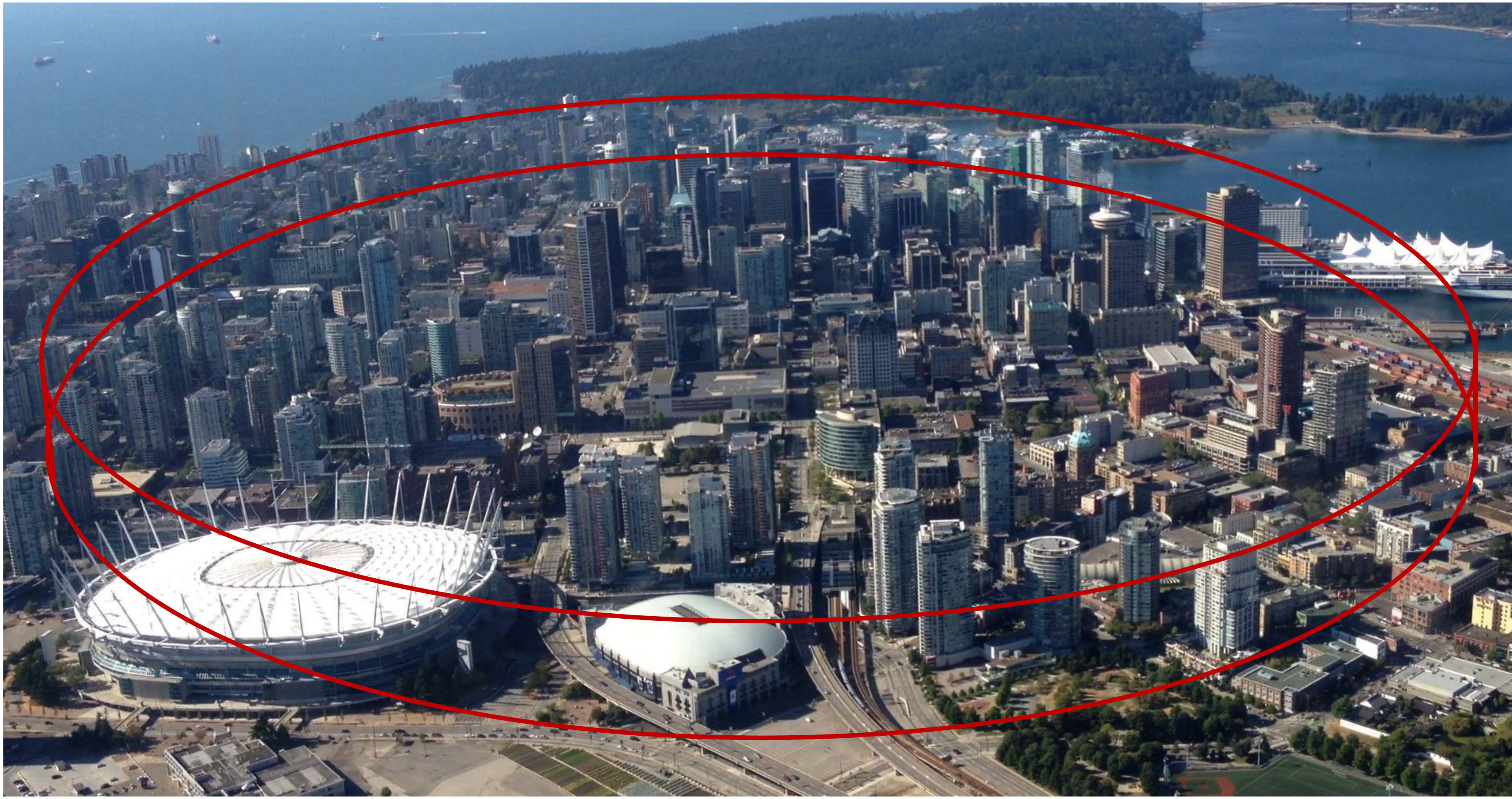


Particle arrestance for clean filters during tests in accordance with EUROVENT 4/9 and EN 1822.

Camfil Farr
F7, F9, H10 filters

**Has this been taken into account in PM emission factors ?**

- **System air flow mass balance**
- **DLE Combustor effects**
- **Speciation of PM matter ?**
- **upstream raw gas C2/C3 ?** **SCR effects**
- **eroding material from GT parts, or some lube oil ?**



<u>45 MW LM6000 gas turbine,   7000 hrs</u>

*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)**

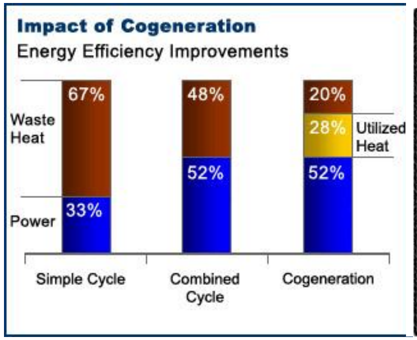
**Ambient $PM_{10}$ @ 40 ug/$m^3$  = 100 kg of $PM_{10}$ ingested (incl. 10 kg of $PM_{2.5}$ )**

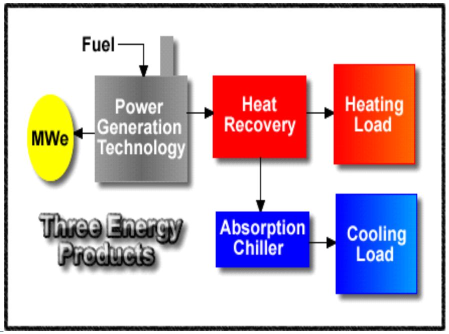
**Air filter can capture 95+ % of $PM_{2.5}$   < 1 kg released,  + a few kg from fuel ?**

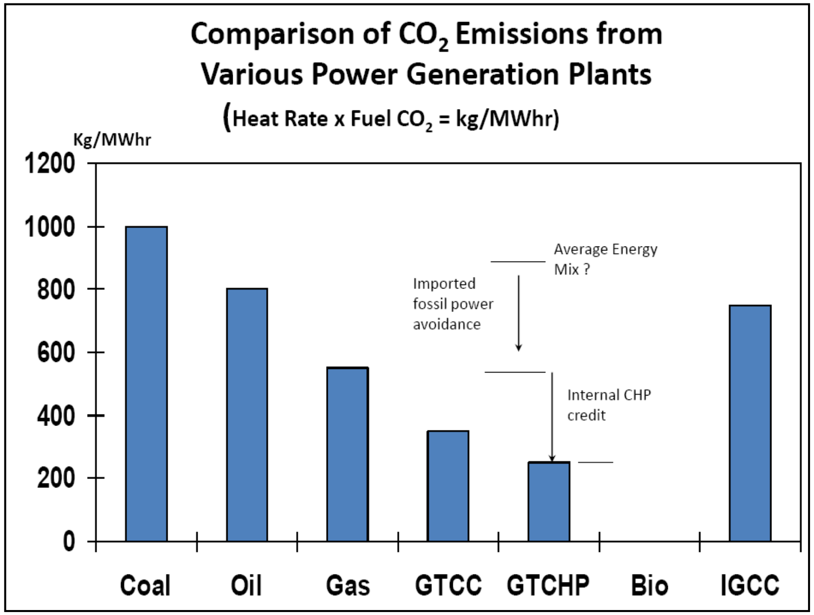
# Critical Elements for Cogen (CHP) Systems

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

- 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 is also an 'Adaptation' measure



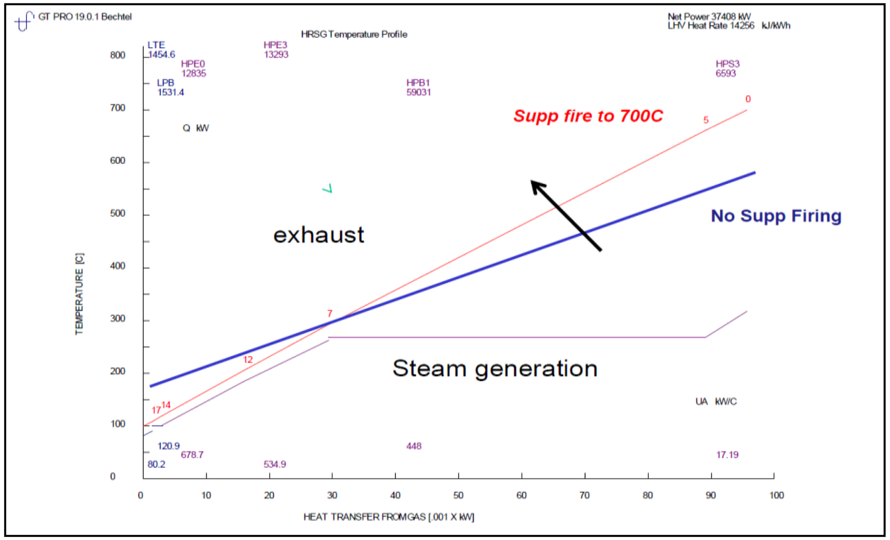




***(CHP more effective than CCS for GTCC)***

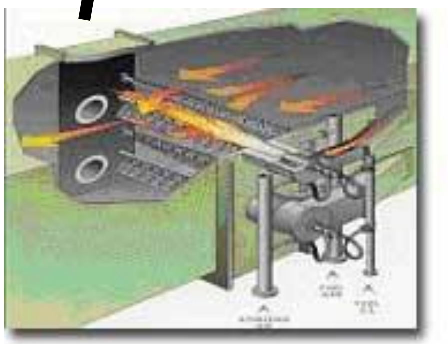
# Waste Heat and Duct Burners in CHP

- **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 Cogeneration Potential  2015-2040

**Replacing existing old industrial boilers with GT/HRSG Combinations;**

**Increasing Oil Sands Cogen to help phase out AB coal generation**

**Synthetic Gas,  Waste gases and Heat Recovery,  Polygeneration / CCS**

**-  total  5000 MWe,  12 Mt GHG reduction**

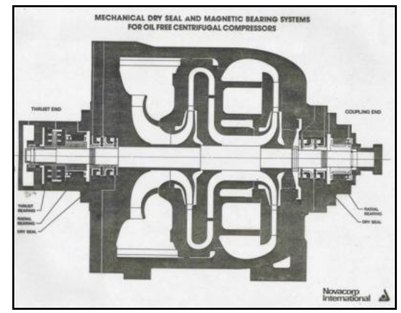
**New GT Cogen & CHP facilities;      15 000 MWe,  30 Mt GHG reduction**

- Oilsands Polygeneration
- Oil Refining and Upgrading
- Chemical Plants
- Forestry Sector
- Manufacturing
- Metals and Steel

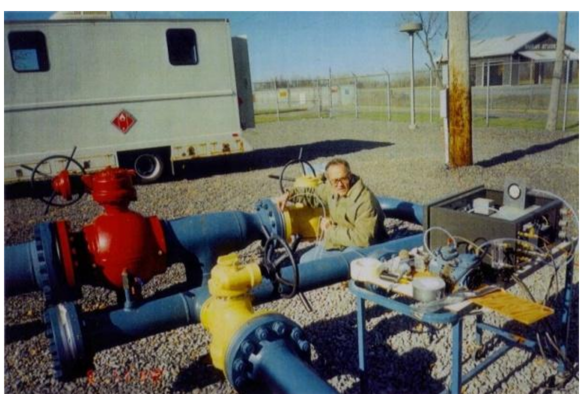
# Env'tl Solutions for Gas Pipeline Compression

- High Operating Pressure (low$\Delta$P)
- Efficient and Reliable DLN Gas Turbine
- Minimizing Stops and Starts
- Waste Heat Recovery
- Gas-to-Gas Exchange, Aerial Coolers
- Dry Gas Seals to reduce Methane Venting
- Leak Monitoring, Better Valves & Regulators
- Air or Hydraulic Engine Starters
- Hot-Tapping Procedures, Gas Transfer Units
- System Optimization, Reliability


TCPL/Atlantic, Nipigon, ON



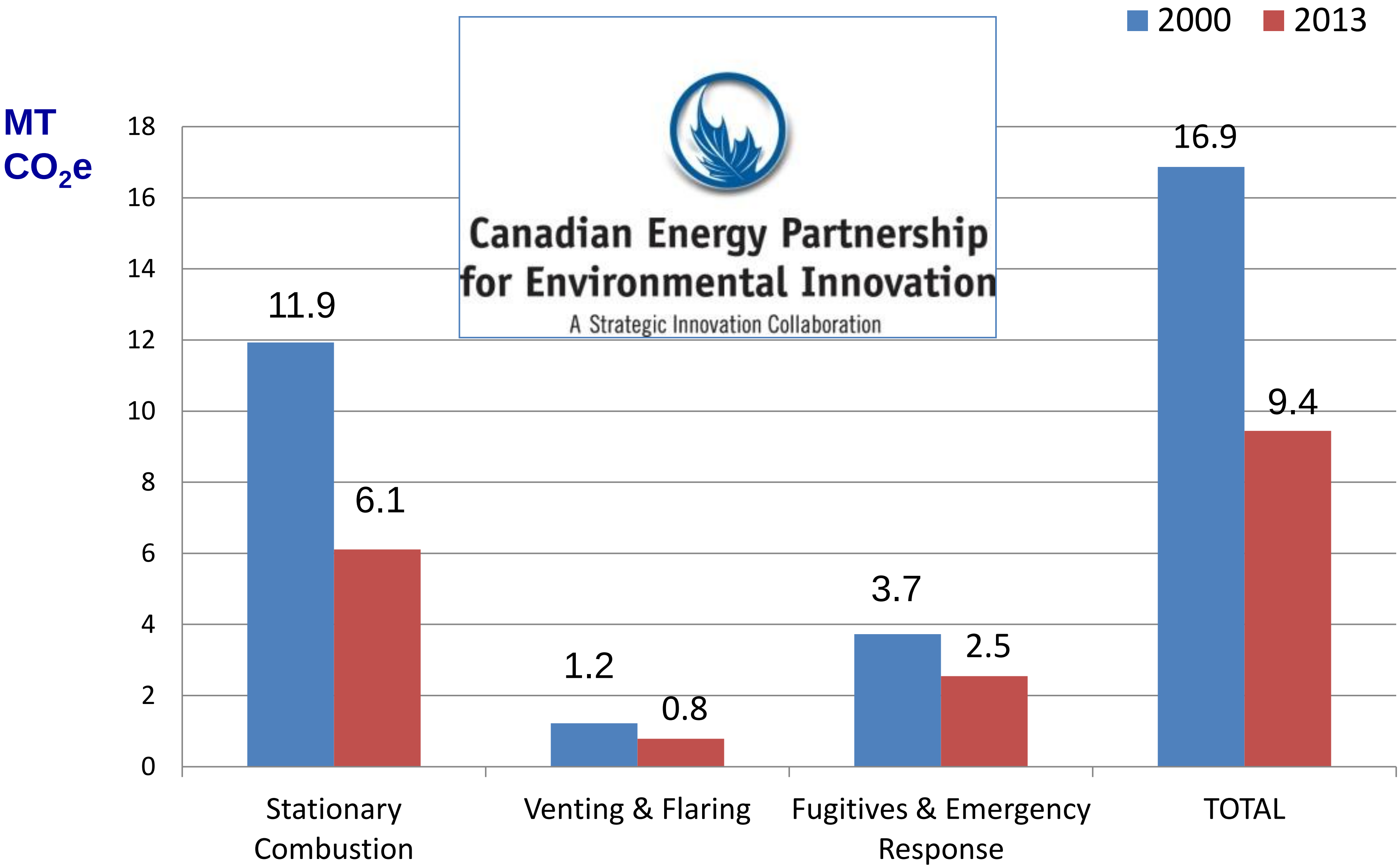

Gas Compressor Dry Gas Seals

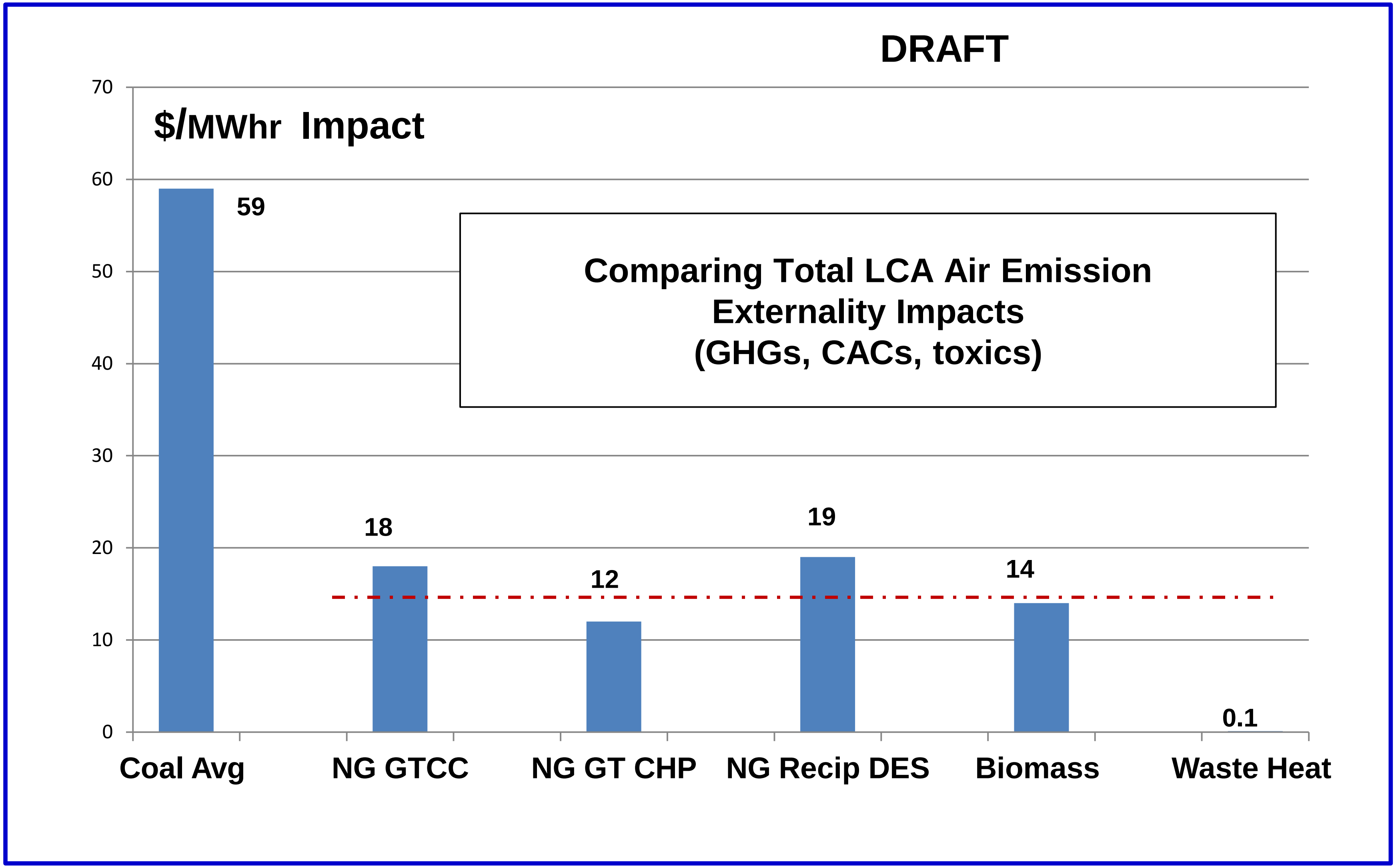



Crowsnest ORC


*Aerial coolers, Crowsnest BC*

# Pipeline Sector GHG Emissions (2000–2013)

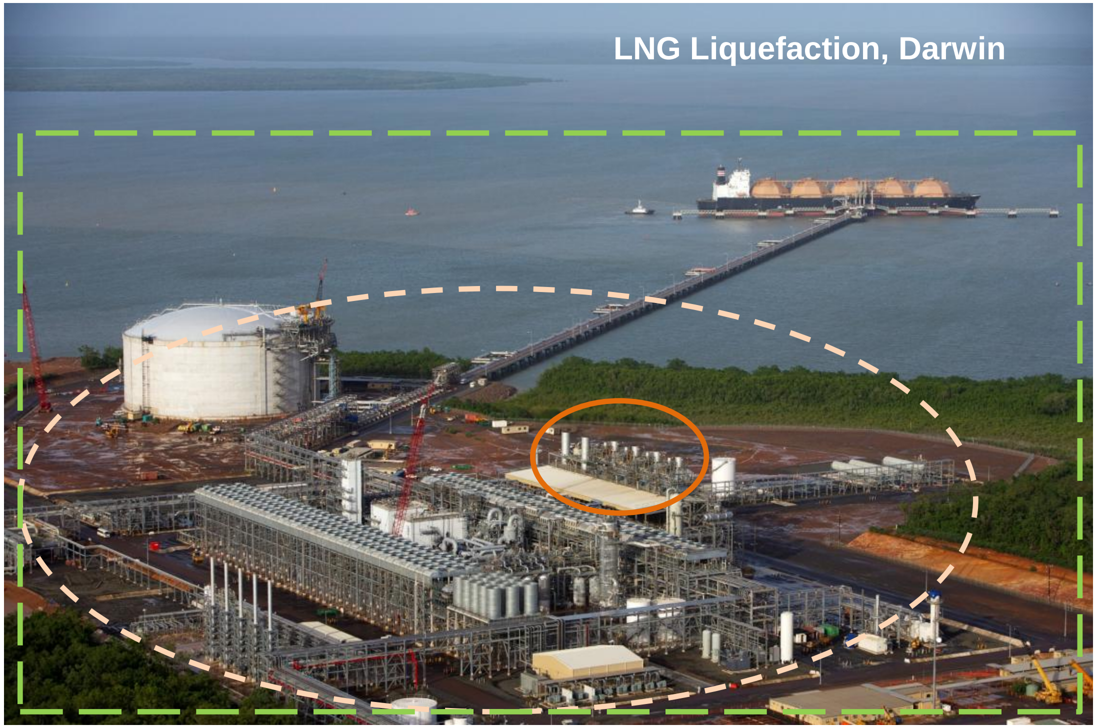





**Life Cycle Analysis;** Evaluating projects with low combined values (costs);

- $CO_2$ **$30** / tonne, NOx/$SO_2$ **$3000** / tonne
- particulates at **$5000** / tonne air toxics at **$0.5 million** / tonne

# LNG System Environmental Performance




## Process Efficiency

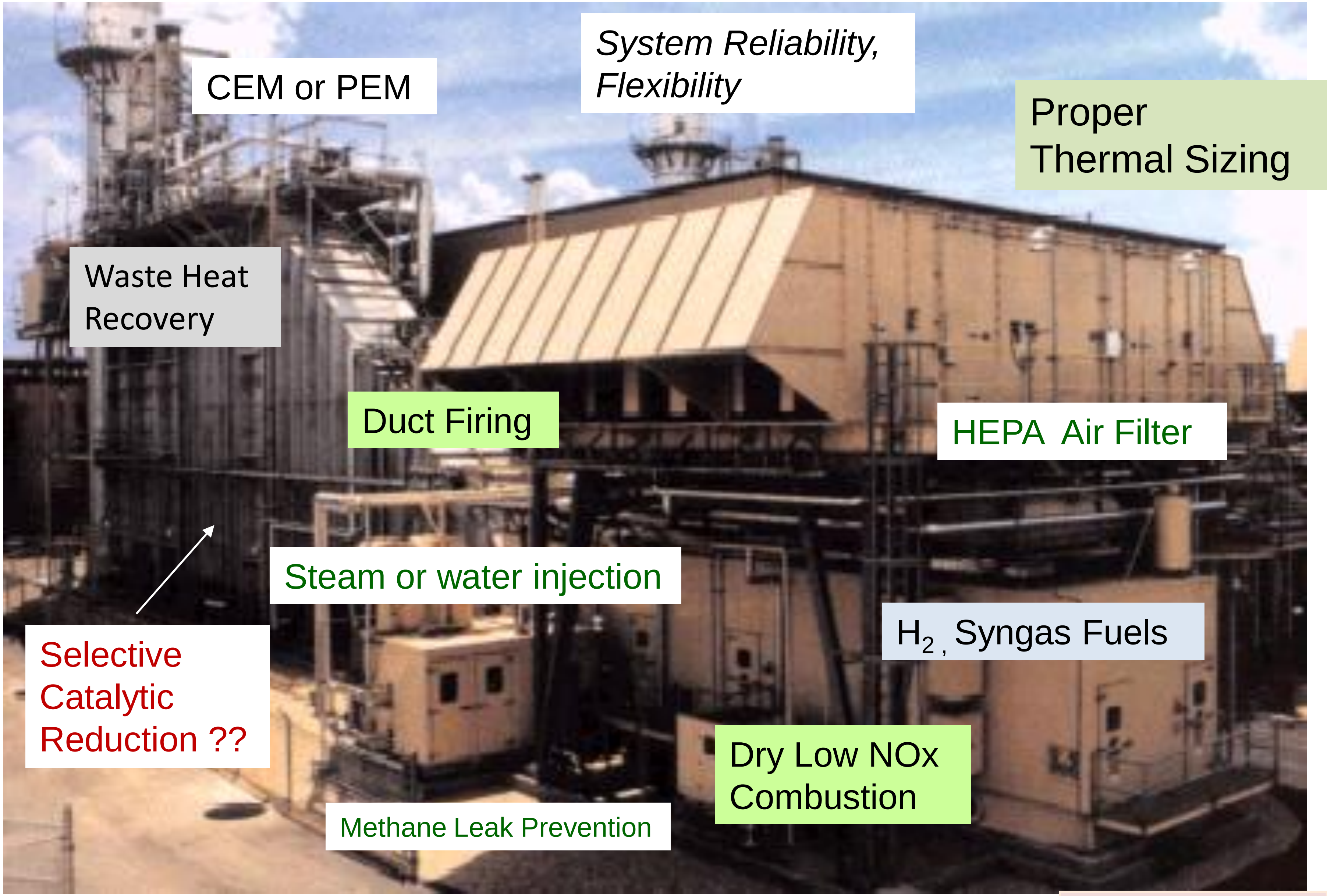
- Liquefaction design choices
- Feed conditions
- Precooling methods
- Compressor speeds, Axial Inlet
- Variable Speed Electric Drives
- TurboExpanders, Abs.Chillers
- Flaring red'n, use BOG fuel

## 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**

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



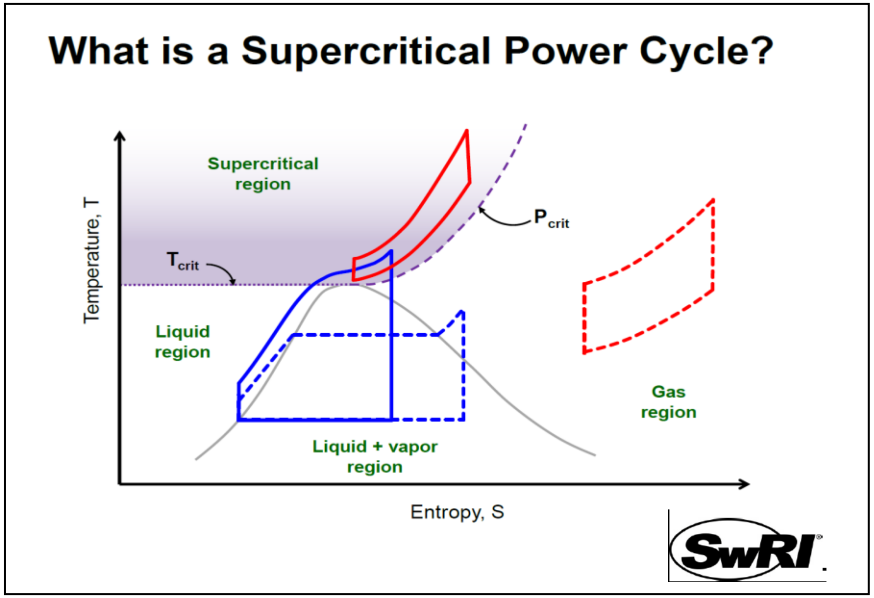

GE Power Systems

**Maximizing System Output CHP Efficiency**

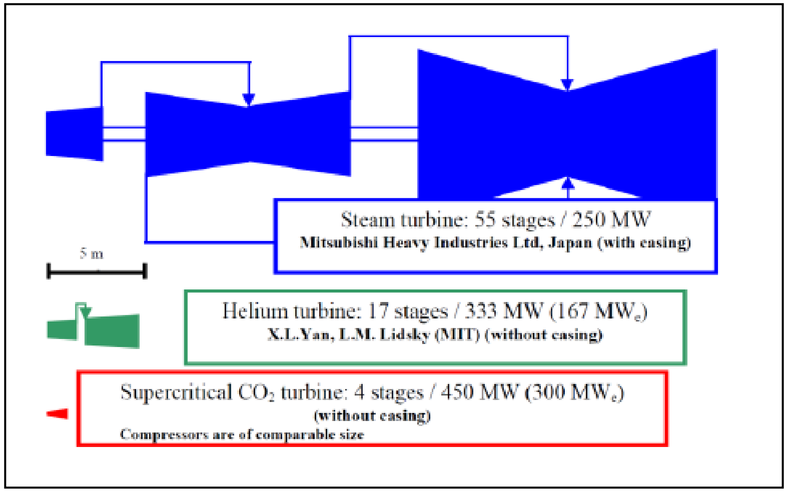
# Waste Heat for Supercritical $CO_2$ Power Cycle

$sCO_2$ has;

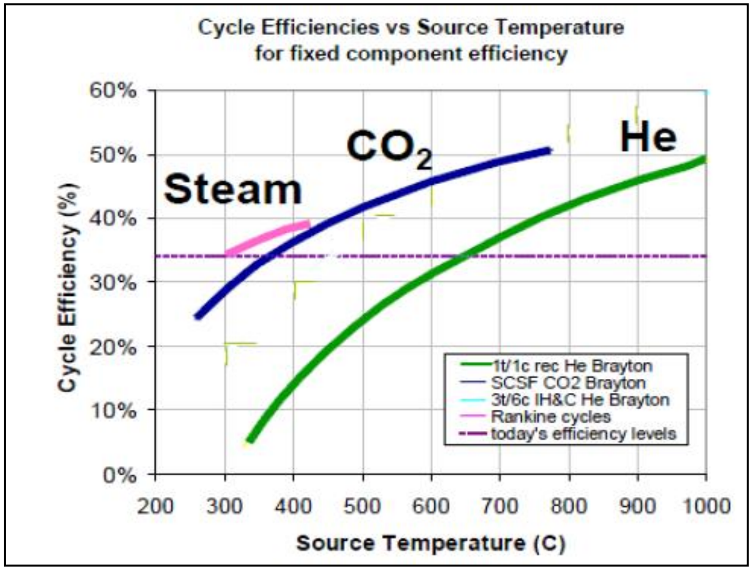
- High pressure working fluid
- No phase change loss
- Small footprint for turbine
- High efficiency for pipeline WHR
- Water not required
- Needs research and demo sites




www.geothermal.uq.edu




SwRI



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IGTI

CRITICAL ISSUES

# IS LOWER PPM BETTER?

by Manfred Klein
Chair, IGTI Environmental and Regulatory Affairs Committee

**It is likely that the reduction of $CO_2$ and fugitive methane emissions will overtake NOx and other pollutants as the major new challenge of the next century**

**GT DLE … this 90 % reduction through cost-effective pollution prevention is unmatched in most other industrial sectors**

**… the ecosystem will likely not notice the difference between GTs emitting a moderate 25 ppm and those forced to further limit emissions to the ultra-low single digit levels of 2-9 ppm.**

**Modern cogen plants are not a cause of significant regional air pollution.**

**… why are gas turbines still designed and regulated on the basis of NOx ppm standards? … regulations requiring simply a lower ppm NOx emission level are not necessarily better for the environment.**

**… antiquated systems be replaced by future systems that use renewable energy and high-efficiency natural gas CHP and district energy.**

# Concluding Remarks

- ***A gas turbine*** **is an** ***engine*** **in a system*****, uses Air for power***
- ***Natural Gas - $CH_4$ is a hydrogen-based fuel***
- **Maximize Energy Conservation, System Efficiency, Innovation**
- **Clean Energy: Gas Turbine Systems ⟷ Renewable Energy**
- **Combustor Reliability & Operating Range are a Challenge**
- **Output-based Standards can be Superior**
- **Integration & Balance; Air Pollution ⟷ Greenhouse Gases**