LNG TECHNICAL WORKSHOP

May 2014, Vancouver BC

Environmental Issues for Gas Turbine Energy Systems

- **Air Pollution and GHG Emissions**
- **Balancing Objectives**
- **System Interactions and Tradeoffs**
- **Gas Turbine Emissions Prevention**
- **Emission Standards**
- **LNG and Gas Pipeline Considerations**

RB211 dle (RR)

GT + HRSG (GE)

Manfred Klein

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Canadian Gas Turbine Energy Systems

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

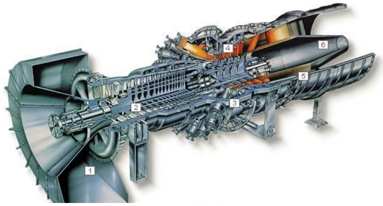
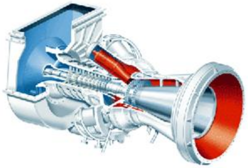
About 25 000 MW in Canada



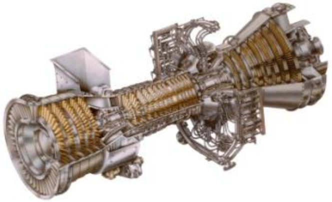
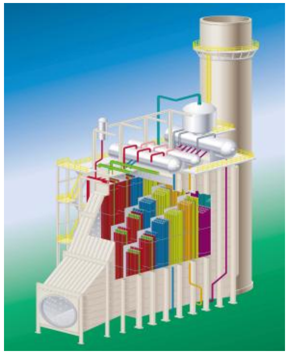
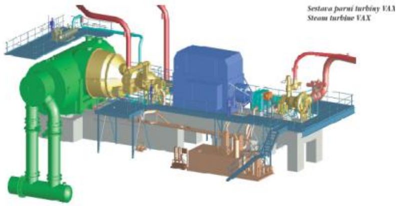



Many different types of units;

- Aeroderivative Gas Turbines
- Small & Large Industrial GTs
- BP & Ext'n. Steam Turbines
- Heat Recovery Steam Gen's
- Absorption Chillers
- Turboexpanders




Air Emissions

Air Pollution

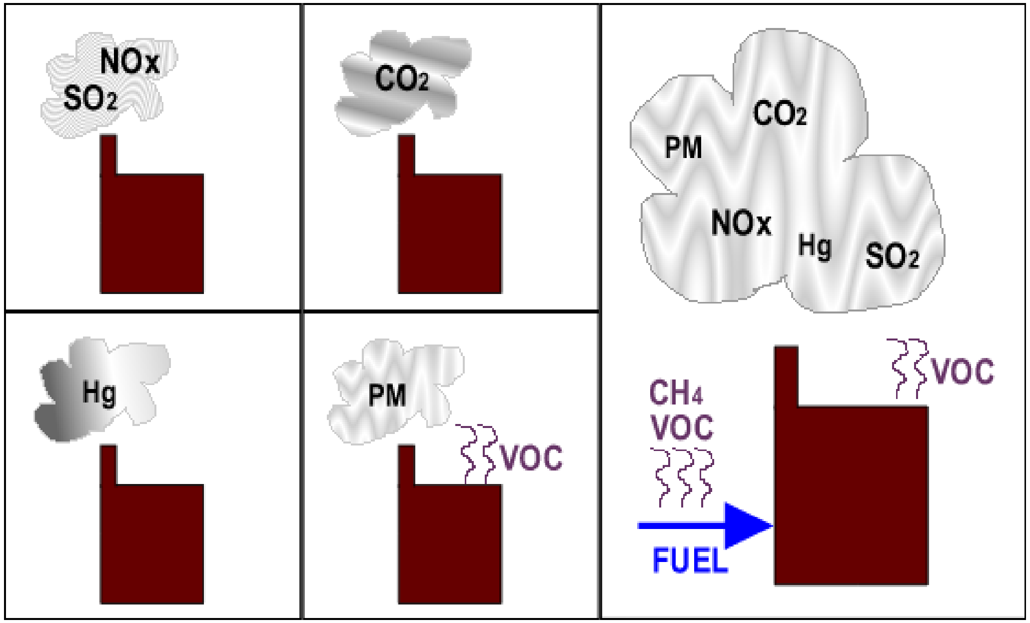
- Sulphur Dioxide SO_2
- **Nitrogen Oxides NO_2**
- Volatile Organics VOC
- Fine Particulates PM
- Mercury & Heavy Metals
- Ammonia NH_3
- Carbon Monoxide CO

Ozone Depletion

- CFCs

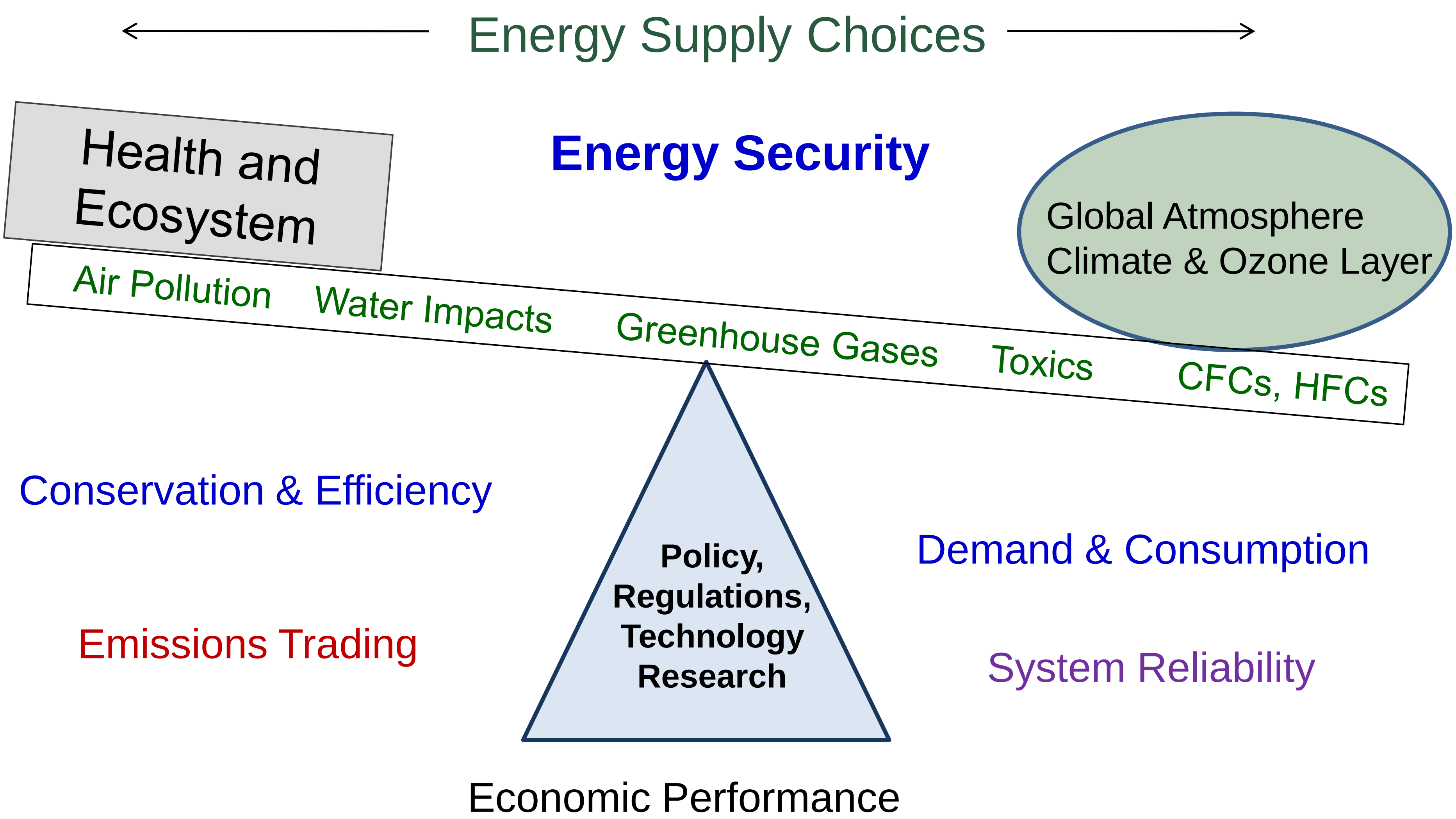
GHGs

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



Individual .. or … System

Clean Energy Balancing Act



Liquified Natural Gas Systems - EA Priorities

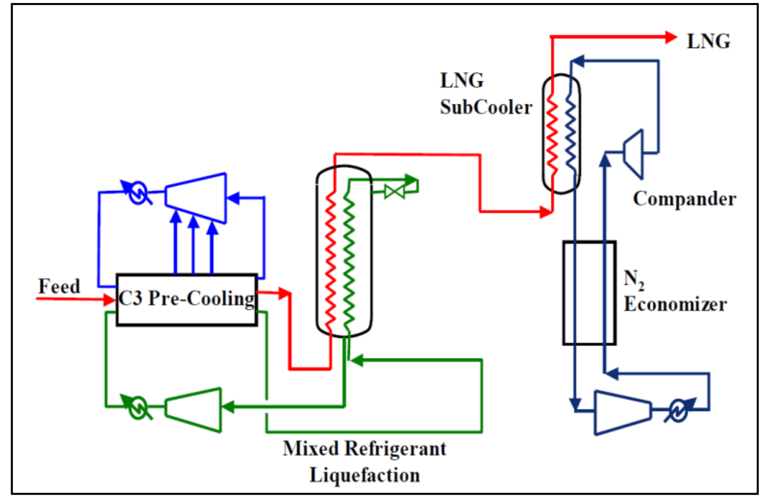
GHGs, Air Pollution, Water Impacts
LNG process choices, Flexibility
System Integration and Reliability

Refrigeration Compression;

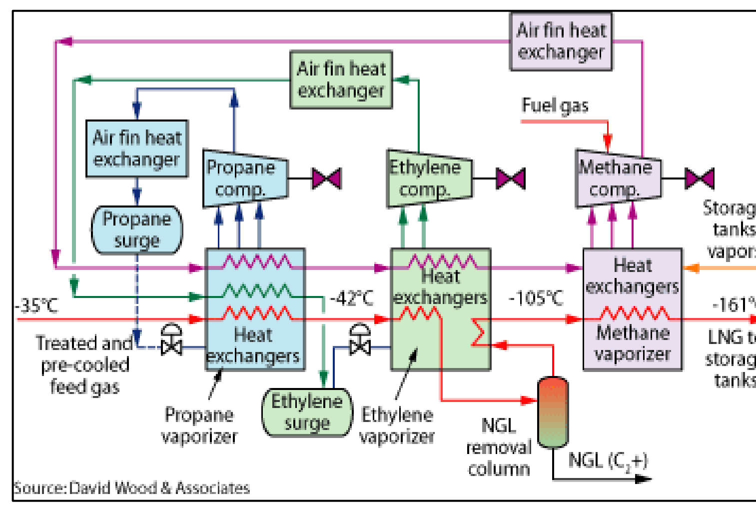
- Direct Mechanical, or Electric Drives
- GT Cogen & Combined Cycle systems
- DLN gas turbines; Frame or Aero
- Hydro Power Import (VSDs)
- LNG Compressor Types, speeds

Auxiliaries

- TurboExpanders, Absorption Chillers
- Gas Pipeline WHR, Inlet gas conditioning
- Fugitive Methane, Venting containment



AP-X Mixed Refrig. (Air Products)

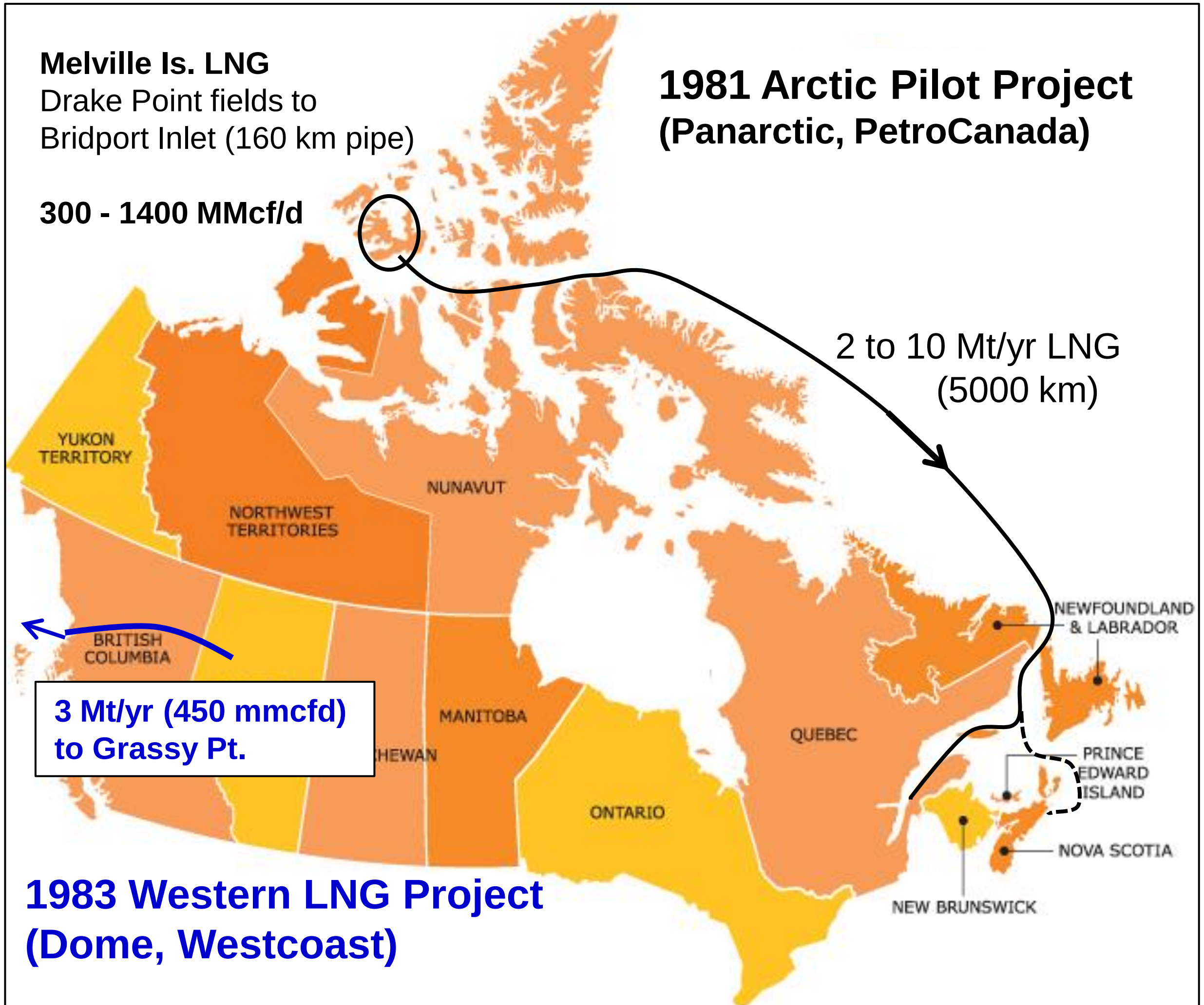


Optimized Cascade (Conoco Phillips)

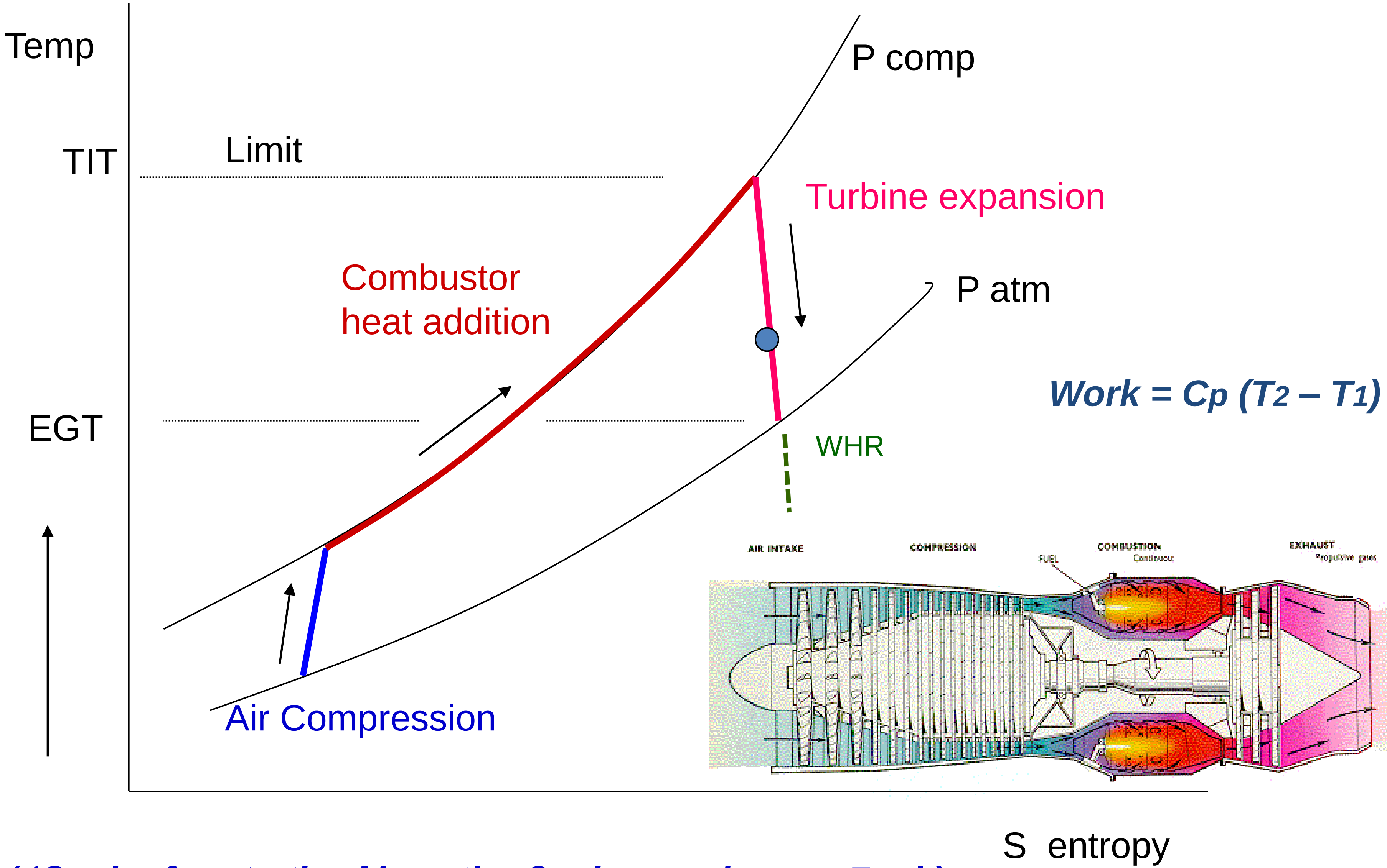
mafitrench.com

York Absorption chiller

Previous LNG Proposed Activities, 1980's



Brayton Air Cycle; T-S diagram for Gas Turbine



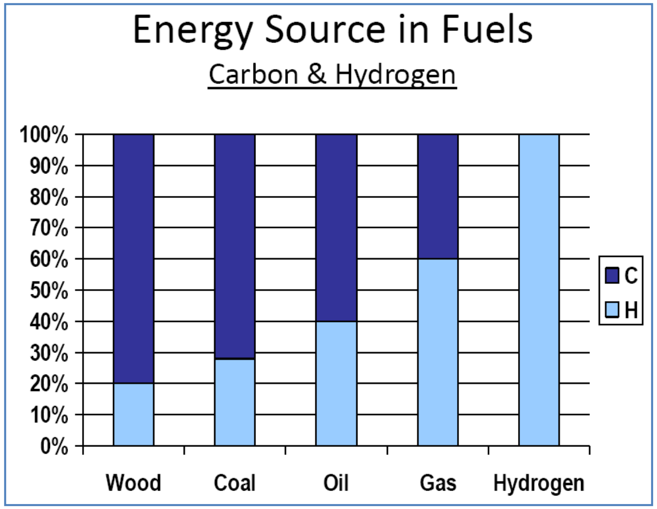
('Gas' refers to the Air or the Cycle, <u>not</u> the gas Fuel)

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



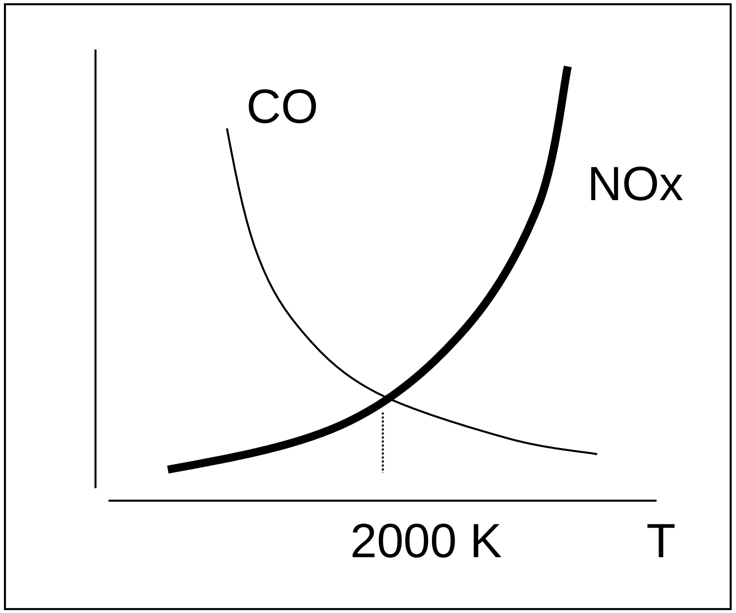
CO_2 Rate Examples (Heat $Rate_{HHV}$ x CO_2 factor)

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 ℓ/100km x 20000 km x 2.4 kg/ℓ =**	**4.8 t_{CO2}/yr**
LNG Prod'n	**$\frac{300\ kg_{CO2} / t_{LNG}}{55\ GJ/ t_{LNG}}$ x 6 GJ/MWhr =**	**33 kg_{CO2} per MWhr (10-15%)**

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



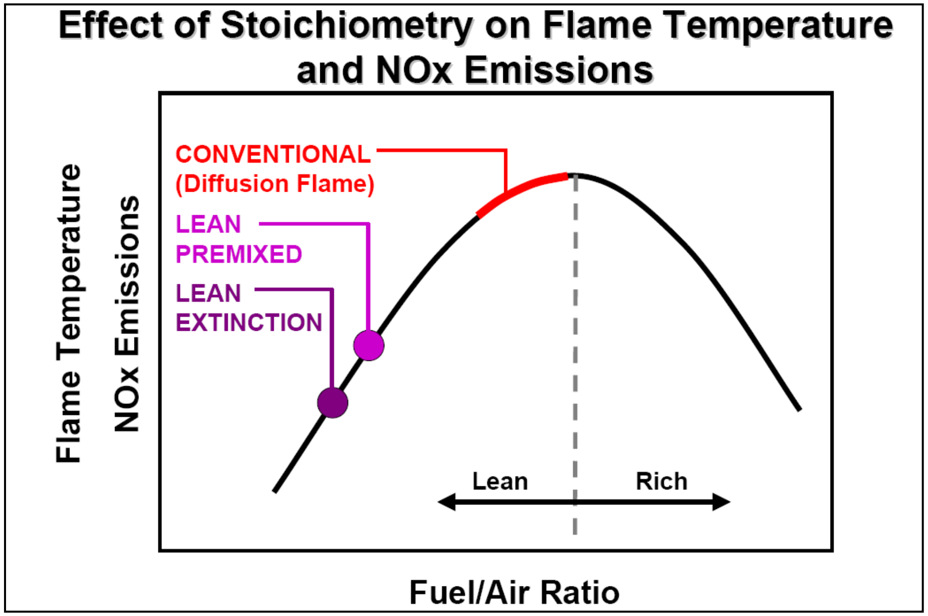
<u>Thermal NOx</u>:

High Temperature Combustion

$$NOx \longrightarrow T^{1.5},\ P^{0.5}$$

<u>Fuel NOx</u>:
From N_2 Content of Oil, Coal

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



(Solar Turbines)

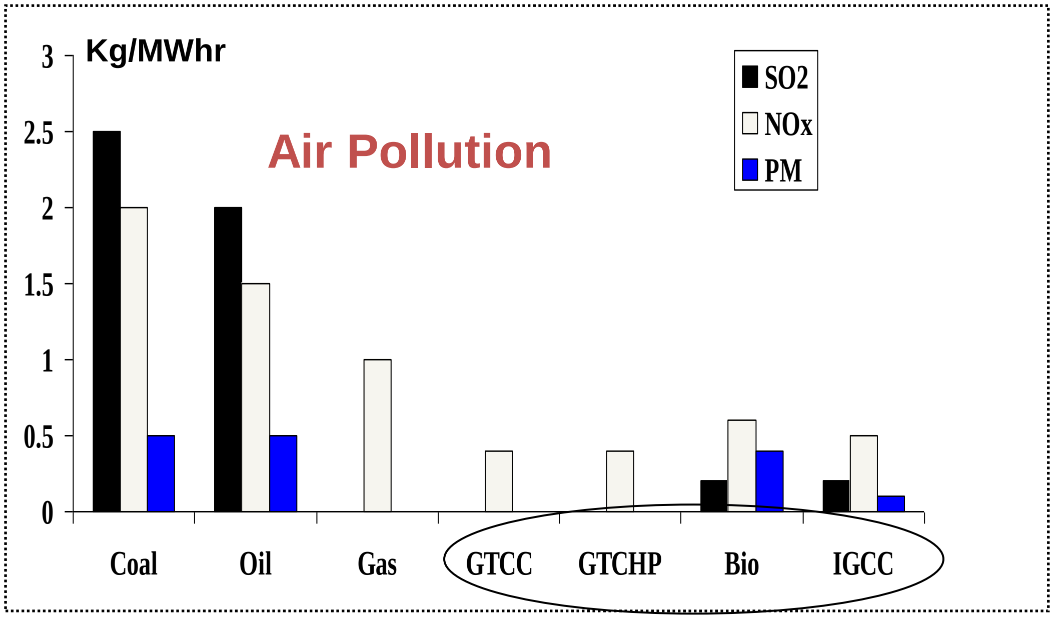
Comparing Emissions from Thermal Energy Systems

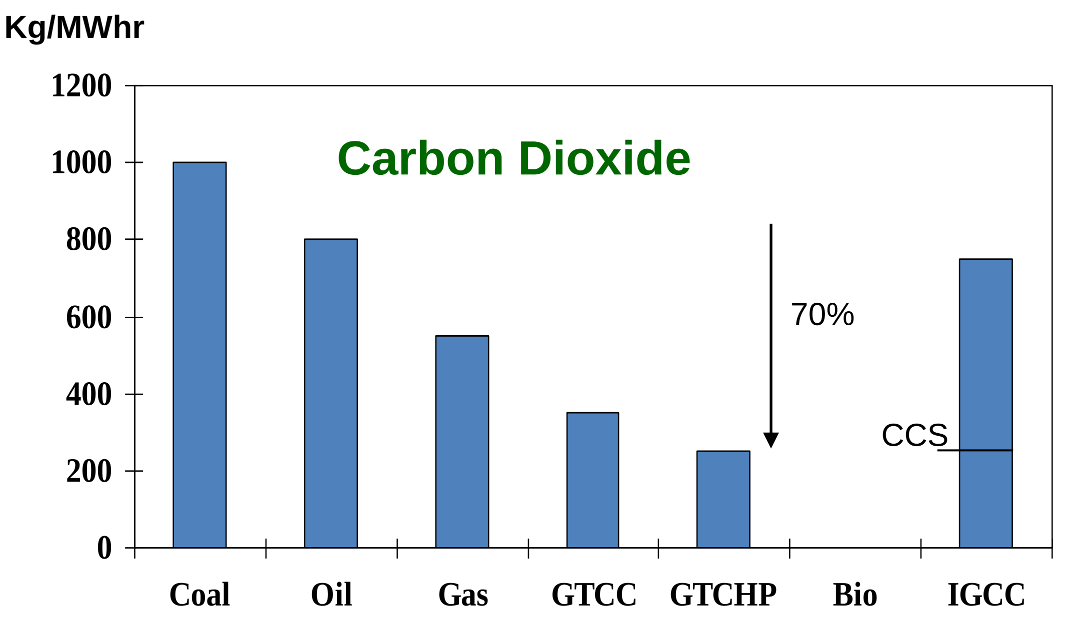
"Cannot produce Air Pollution without making CO_2"

- **Natural Gas**
- **Coal and Oil**
- **Biomass and Syngas**

'Integrated analyses for payback'

- ***Powerplants***
- ***Cogeneration and WHR***
- ***District Energy***
- ***Renewables***
- ***Vehicles and Trucking***





Gas Turbine Systems in Canadian Industrial Sectors

IAGT

2012 estimate (M.Klein)

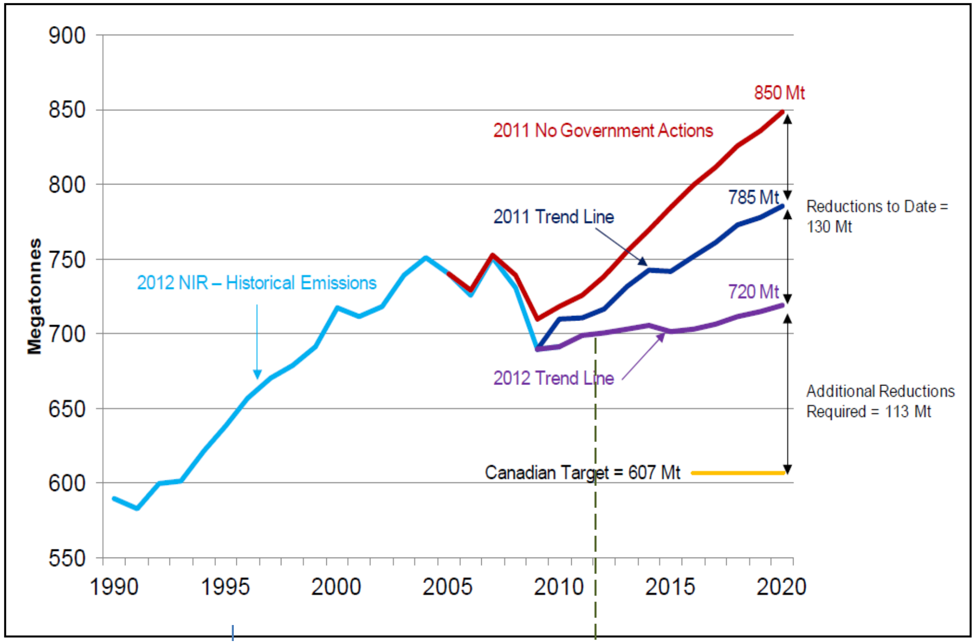
Installed MW	Simple Cycle	Combined Cycles	Comb. Cycle Cogen	Simple Cogen	Sector total
Electric Power	4640	7460			12100
Gas Pipelines	4970	140			5110
Upstream Gas	130		120	340	590
Oilsands & Refineries	115		575	1430	2105
Chemicals, Forestry, Metals			3175	400	3575
Manufacturing	40		1150	170	1360
Institutional			210	75	285
Est. Total	9895	7600	5230	2415	25140

- Not incl. retired units
- 21440 MW GTs, and 3700 MW of steam turbines

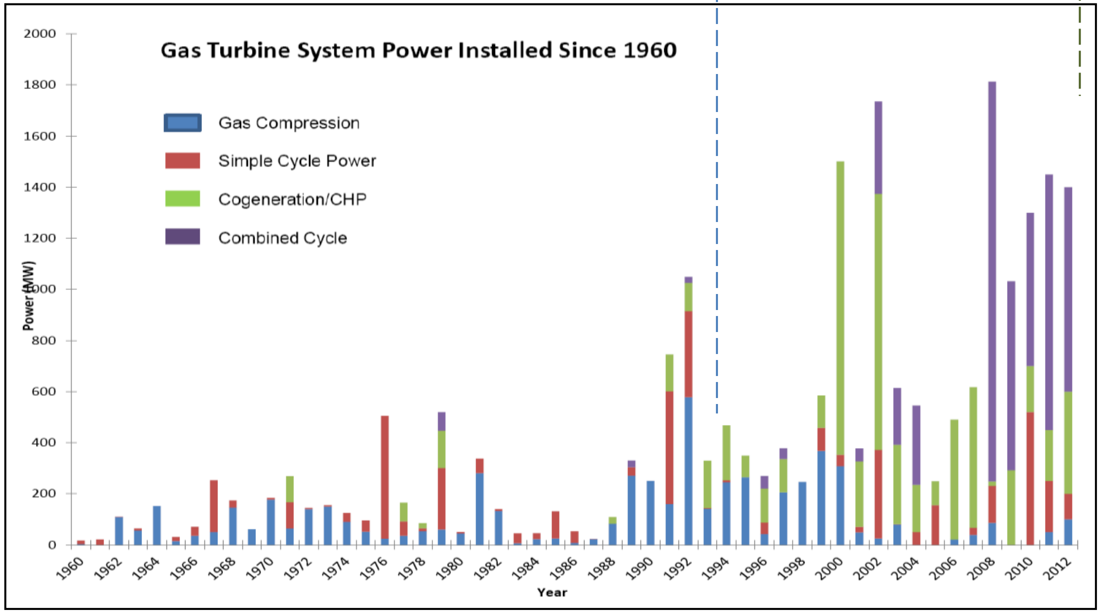
CLEANER ENERGY

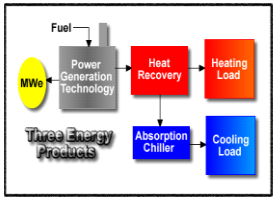
New GT systems with NG fuel have likely accounted for about 30% of Canada's GHG avoidance since 1995, plus 250 KT of air pollution reductions. About 70 TWhrs now generated from;

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



Canada's Emissions Trends 2012





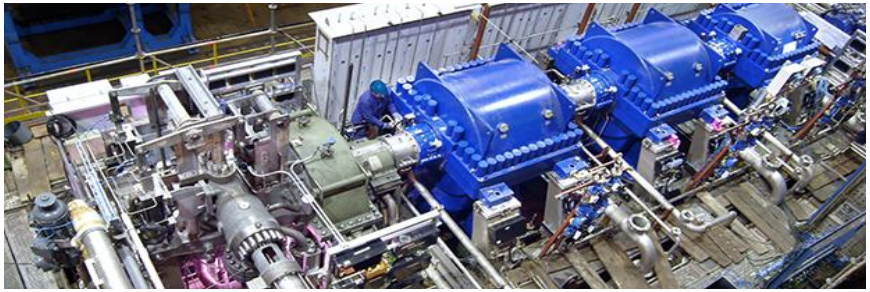
'Cleaner Energy'

Gas Turbine Emission Guidelines & Standards

Objectives

- *Prevention of Air Pollution, Toxics*
- *Minimize GHGs*
- *Energy Conservation*
- *System Efficiency*
- *Size and Location*
- *Minimize Water Impacts*
- *Noise*
- *Reduce CFCs*
- *Reliability, Energy Security*
- *Simplicity (HR, labour, skills)*

NOVA Chemicals, Joffre AB



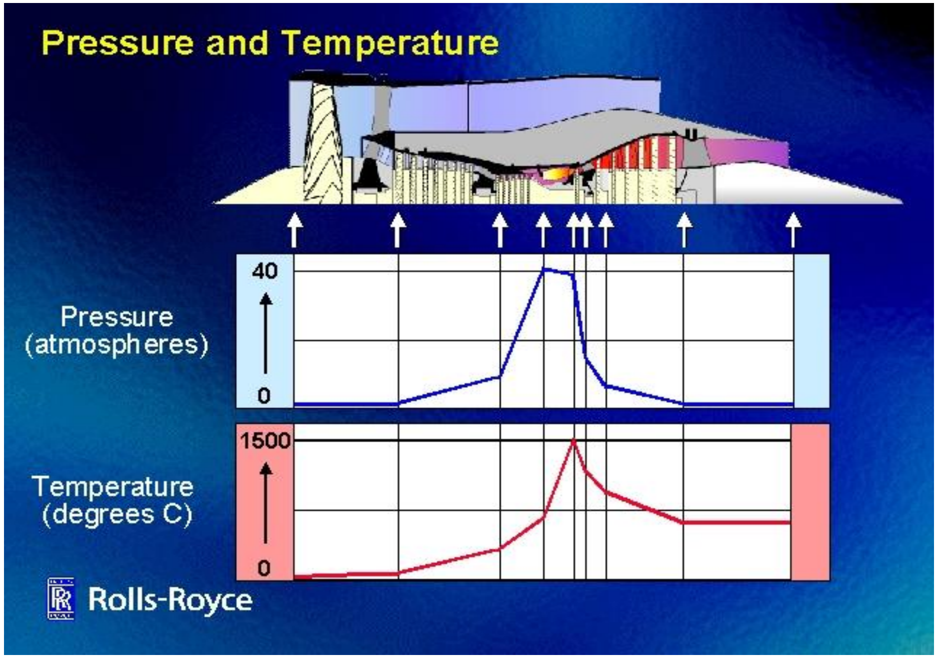
Look for solutions with;

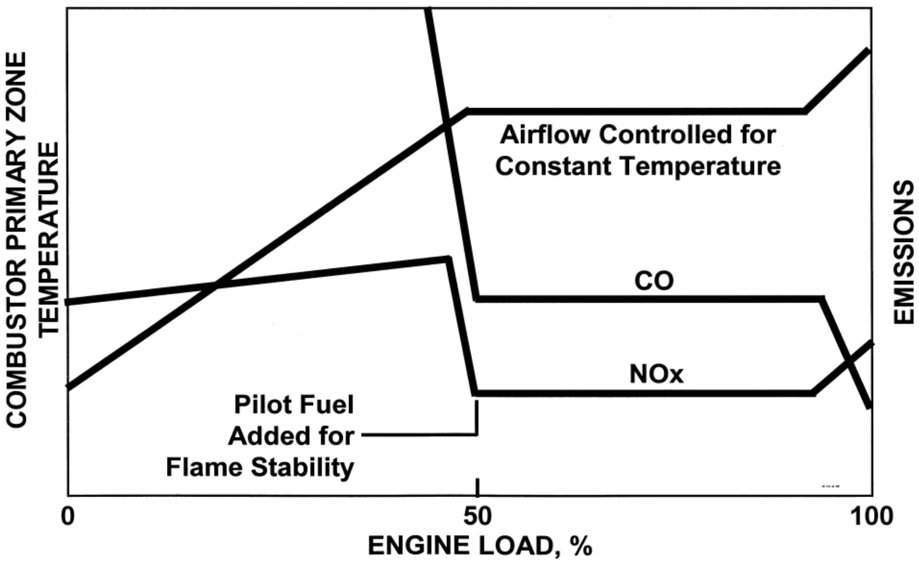
Clear Objectives
Multiple Economic Benefits
Systems Analysis
Balanced Approach

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
- Full & Part load operation, 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

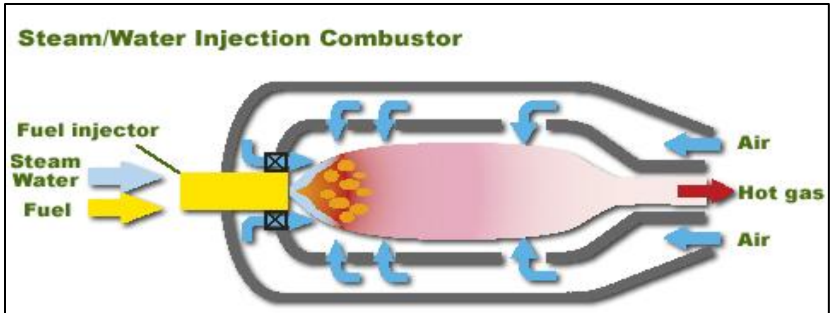




NOx Reduction Methods

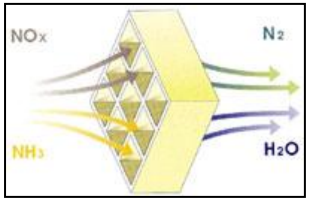
Steam/Water Injection

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

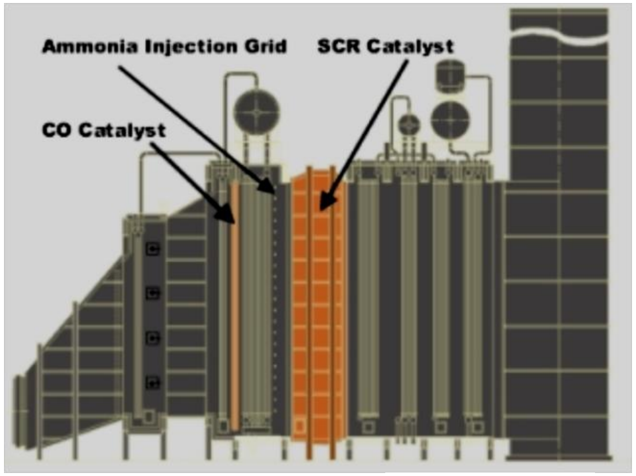


(Kawasaki)

Selective Catalytic Reduction (SCR)



- NH3 injection in HRSG catalyst, ~ 80% NOx Red'n
- **Backend Control**
  - Ammonia emissions & handling (toxic)
  - transport risk, rail & truck
  - fine PM, N_2O ?
  - Cold Weather, Cycling duty - ammonia slip
  - Efficiency loss in HRSG … CO_2
  - Full Fuel Cycle impact – NH_3 Prod'n, Delivery



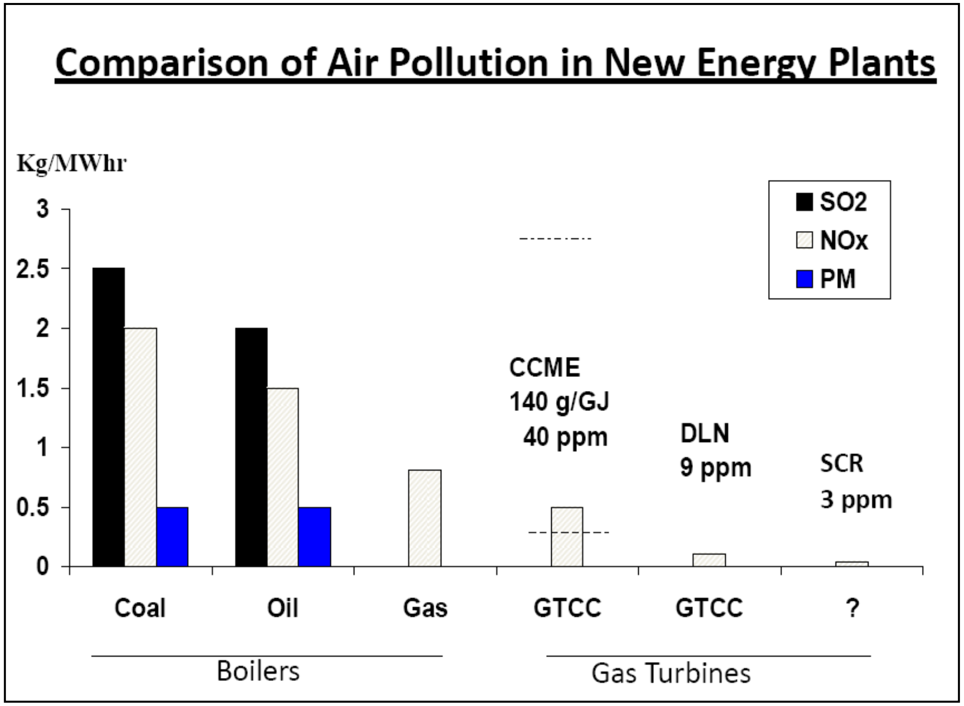
IST Aecon

EA Assessments of Gas Turbine Plants

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

- **Companies may be required to install NH_3-based SCR after DLN**
- **Ammonia transportation & handling - serious local health & safety issue**
- **Collateral impacts;**

$PM_{2.5}$ NH_3 GHGs



"Given the capital & operating costs and collateral impacts associated with SCR, the env'tl benefits do not justify the economic expense"

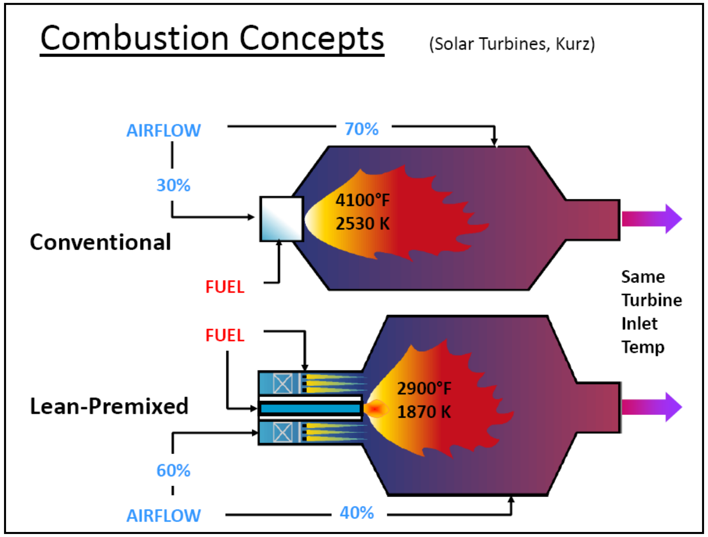
(T. McCann, B. Howard, M. Klein)

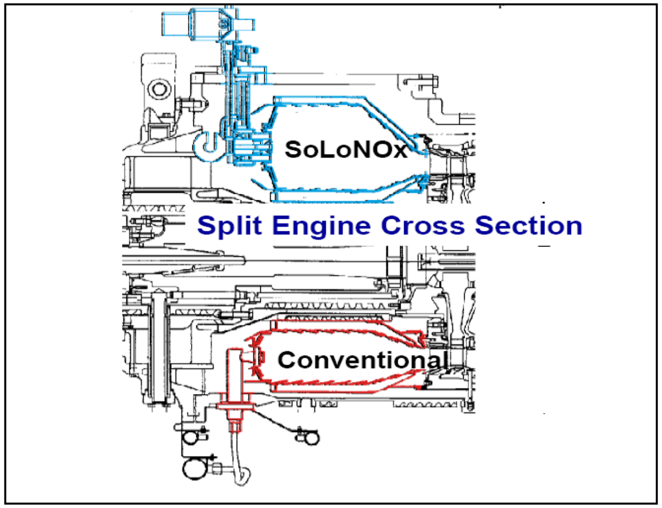
Marginal, low $/tonne benefit after DLN

Dry Low Emissions Combustion

- <u>Preventative</u> 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
- Applied to LNG fuel combustion

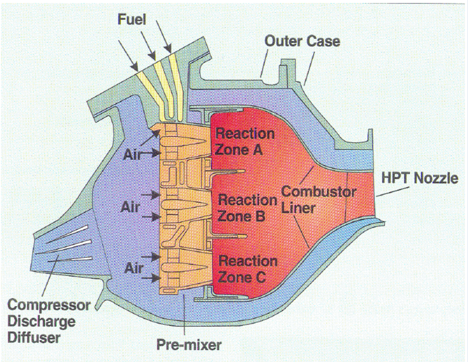
  (wider Wobbe range ?)

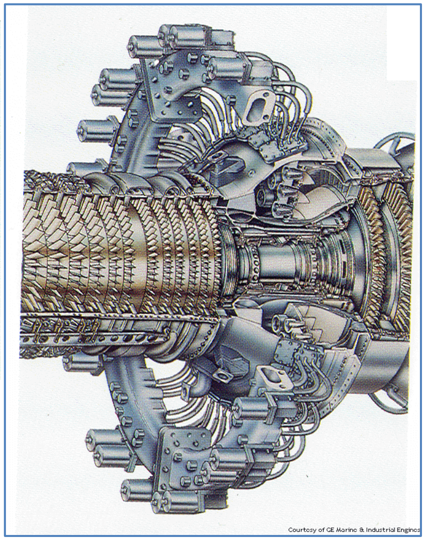




Solar SoLoNox

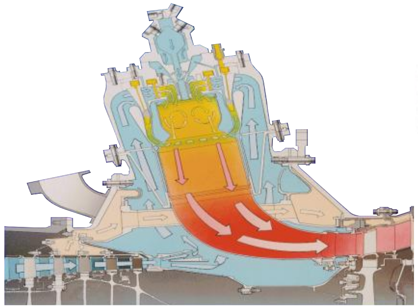
Aero-Derived DLN Systems

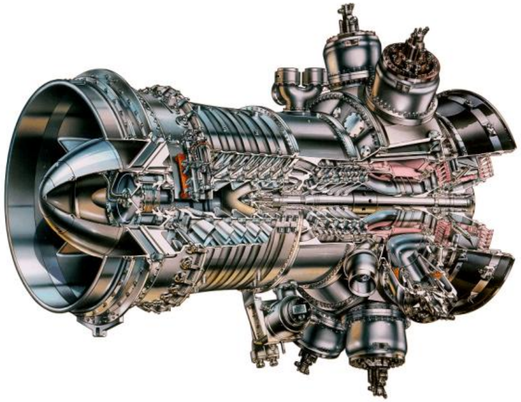




General Electric LM6000 DLE

Triple Annular Dome

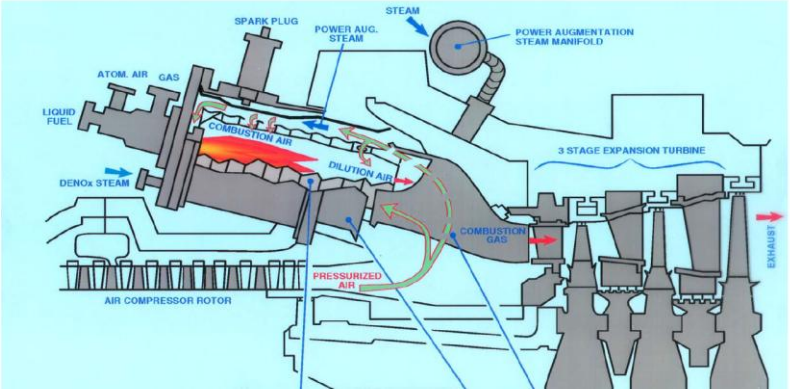




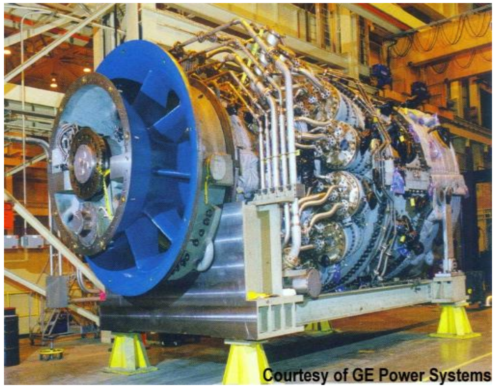
Rolls Royce RB211 DLE

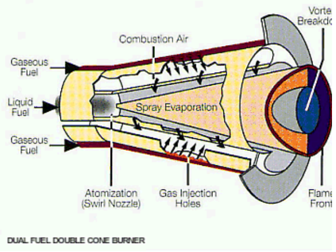
(Series staged)

Large Frame Unit DLN



GE Frame 7 DLN2

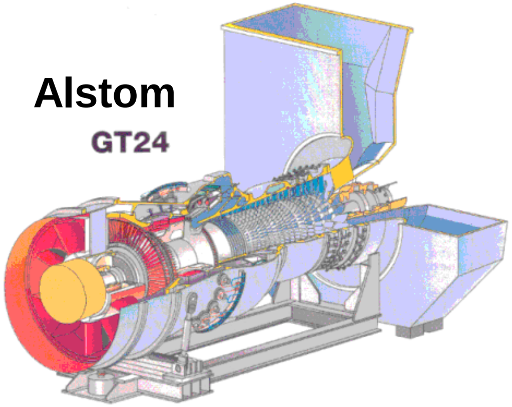




Annular EV burner

Alstom

GT24



Emissions Valuation; 300 MWe GTCC Plant

2 TWhrs	DLN + SCR System		DLN Without SCR	
	tpy	$000/yr	tpy	$000/yr
NOx	100	200	400	800
Ammonia (5 ppm)	50	250	0	0
PM	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
		$15452 K		**$15200 K**

Air Pollution @ $2000 & $5000/tonne GHGs @ 20/tonne

Examples of International Standards – 2005

(for GT Units Larger than ~ 10 MWe, gas fuel)

United States	**2 - 42 ppm**
United Kingdom	**60 mg/m^3**
Germany	**75 mg/m^3**
France	**50 mg/m^3 ***
Japan	**15 - 70 ppm**
Canada	**140 g/GJ_{out} ***
Australia	**70 mg/m^3**
EU LCPD	**50 - 75 mg/m^3 ***
World Bank	**125 mg/m^3**

- **Facility Cogeneration Incentives (Values Subject to Change)**
- **Uncontrolled NOx levels were 100-300 ppm (200-600 mg/m^3)**

How do these standards view GHGs and efficiency ?

Gas Turbine 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**

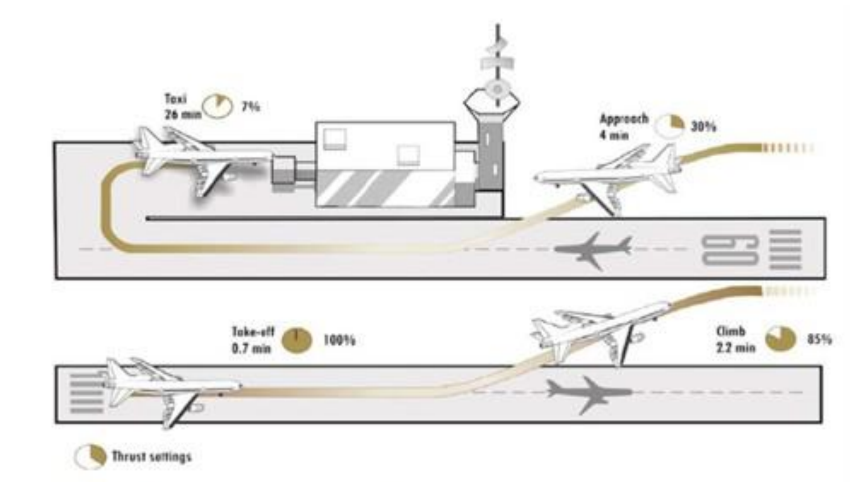


Figure 1 - Illustration of ICAO Emissions Certification Procedure LTO Cycle.
Source: ICAO.

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

Output-based Rules;

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

tonnes/yr

$/tonne

$/MWhr

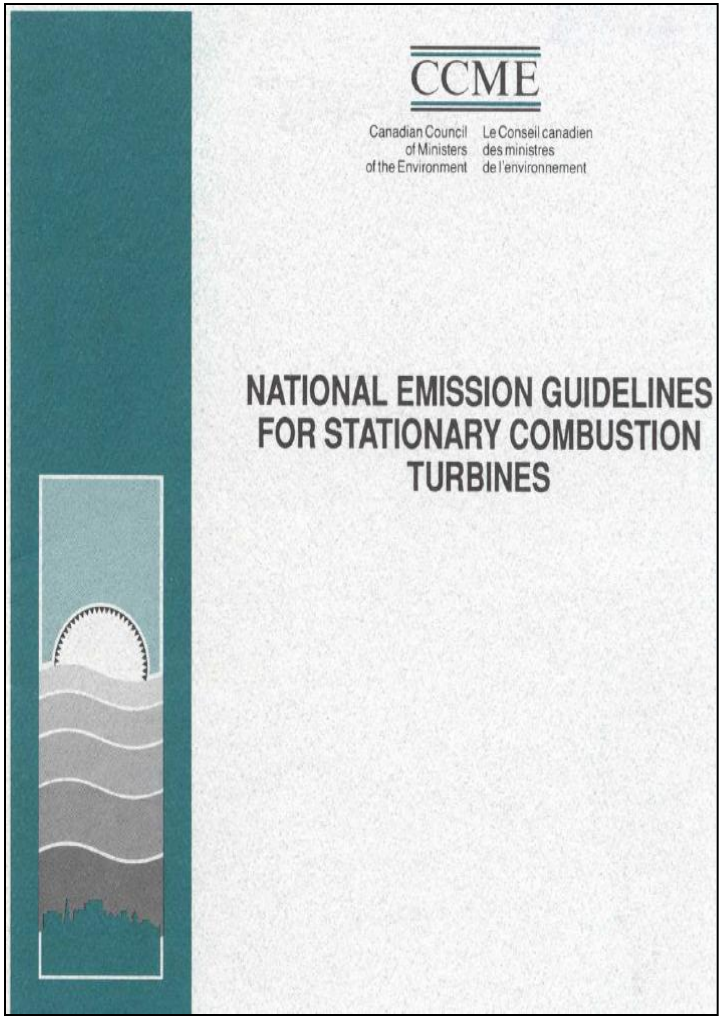
Lbs/HpHr

Canadian GT Emission Guidelines (1992)

- Guideline Reflects National Consensus
- Balanced NOx Prevention & Efficiency
- Regulatory Clarity

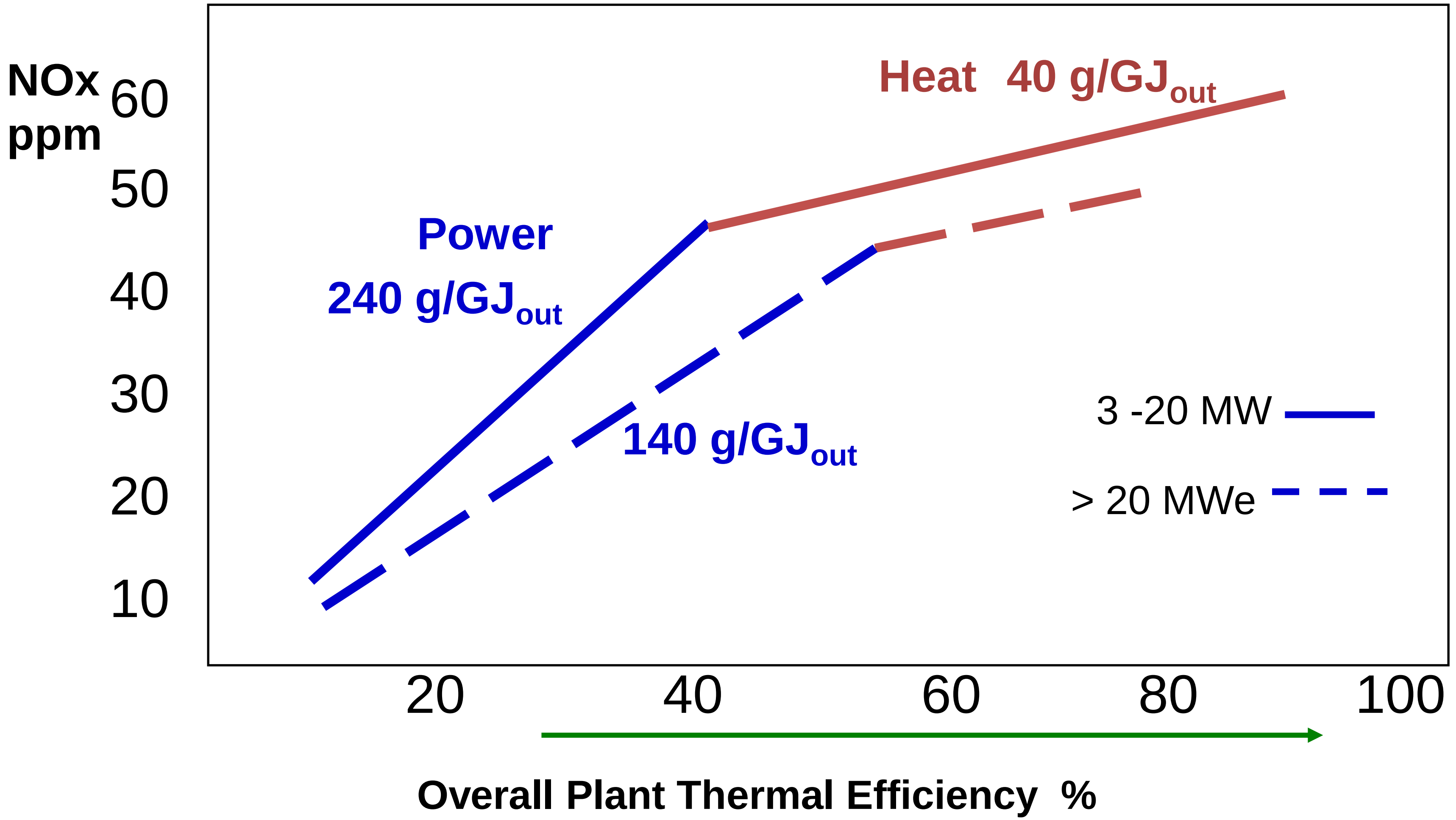
- Output-Based Standard for Efficiency ($140\ g/GJ_{out}$ Power + 40 g/GJ Heat)

- Engine Sizing Considerations
- Promotes Cogeneration and low CO_2
- Peaking units (<1500 hrs/yr)
- CO emissions at 50 ppm
- Flexible Emissions Monitoring
- Energy Output reporting (?)
- Cold Weather considerations



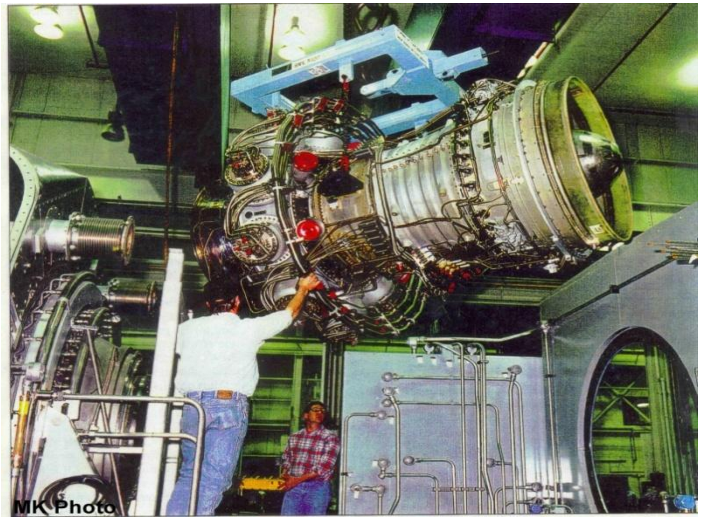
Canadian CCME Gas Turbine Guideline, 1992

Energy Output-based Guideline allows higher NOx for smaller units, which can have higher system CHP efficiency (H:P ratio, Energy Quality)



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

TCPL Nipigon Waste Heat Recovery, 1991



Rolls Royce RB211 DLE

TransAlta Ottawa Hospital CHP, 1991

GE LM6000 steam injection

New US EPA Rules for Gas Turbines

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

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*

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/m^3 = 24 ppmv

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

25 ppmv NOx = 0.099 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 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?

- Remote O&M capabilities

- Can an Output-based GT design contribute to solutions?

TCPL Northern Ontario

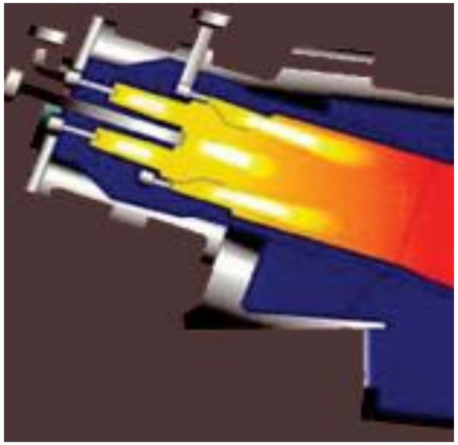
Rolls Royce RB211dle

Stittsville ON (MK)

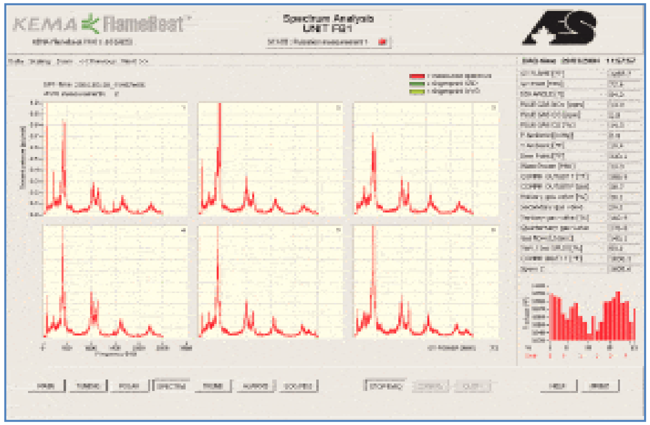
Combustor Dynamics "Humming"

Acoustic Oscillations Under Transient Conditions, caused by;

- Ultra-Low NOx ppm Design
- CO and turndown req'ts
- Cyclic GT Unit Loading
- Ambient Temp, Pressure Ratio, Fuel properties (Nat Gas, LNG, Syngas ...)



(turbinetech.com)

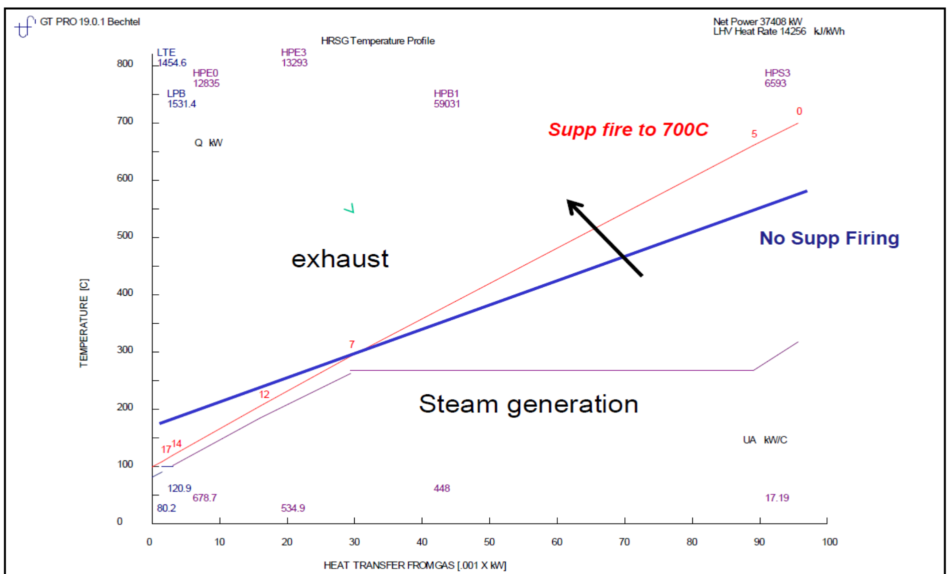


(KEMA)

1. Natural Frequencies and Resonance
2. Vibration, Trips & Shutdown
3. 'Zero' GT emissions ⟶ use ??? Instead ?

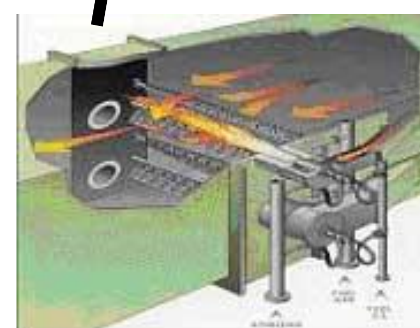
Waste Heat and Duct Burners in CHP

- 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



JOHN ZINK COMPANY

Nooter



Coen

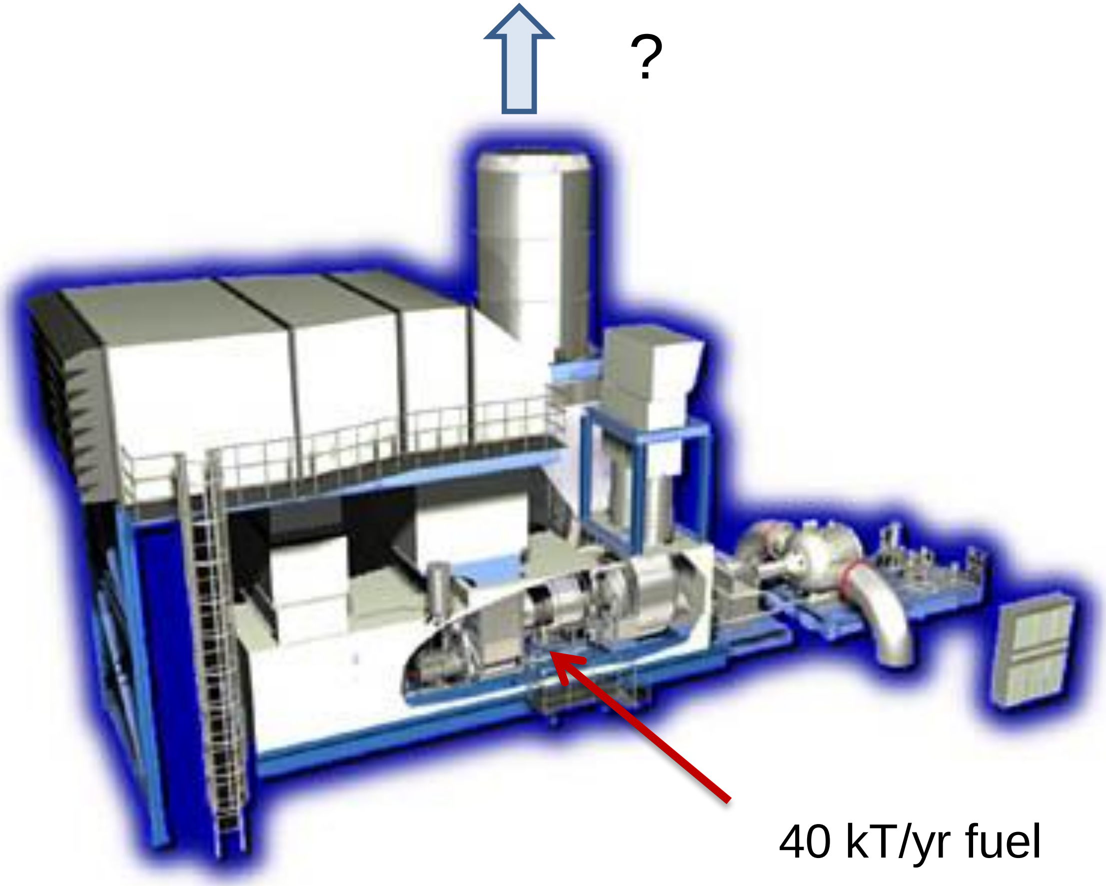
C. Meher-Homji, Bechtel

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

(AP42 - 0.07 lb/MWhr ?)

2 million t/yr Air

Air Filter 99.8%

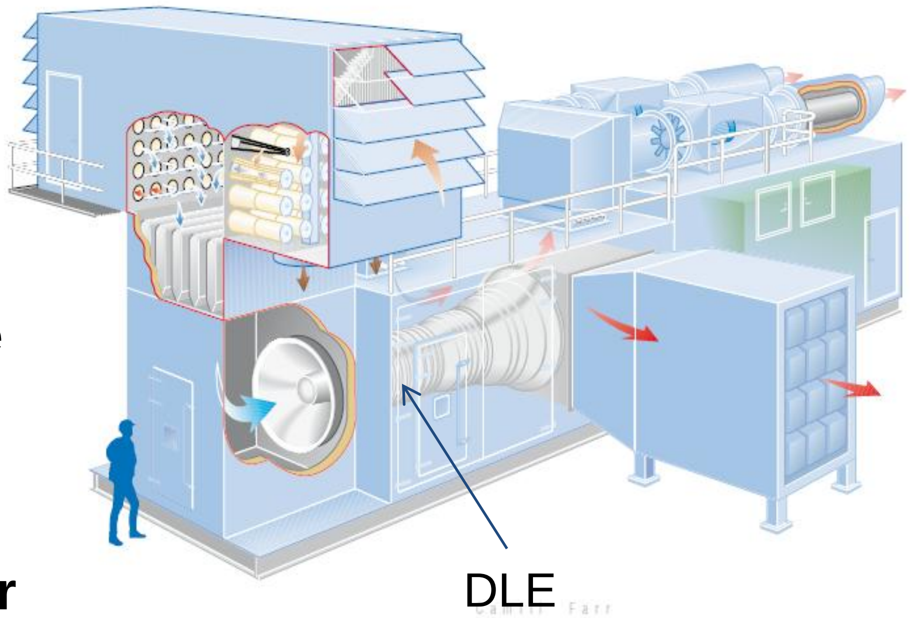


Does dry NG combustion produce fine PM emissions?

What is the Inlet-Exhaust mass balance ?

Are there any Air Toxics ?

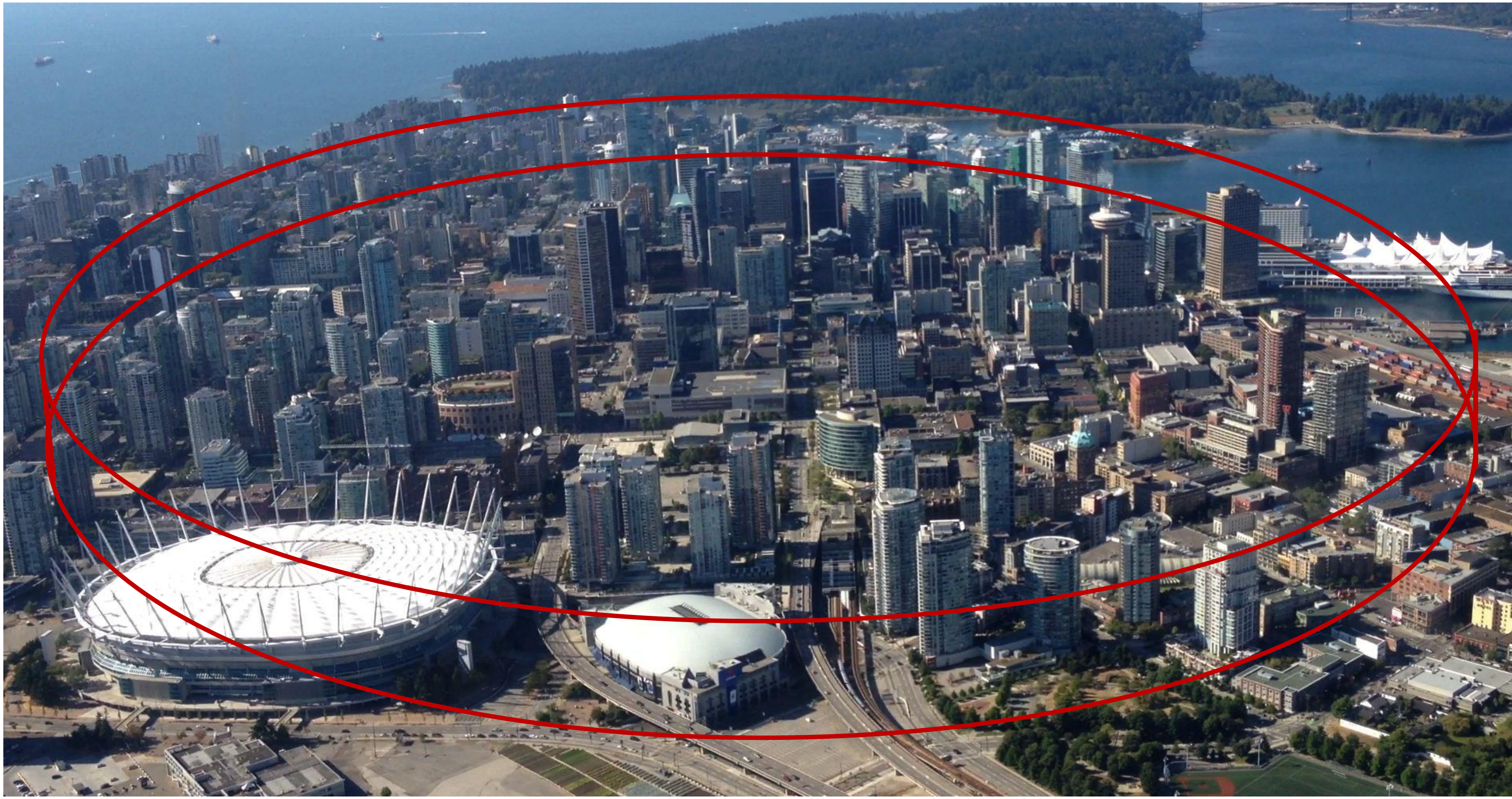
New Gas Turbine Systems



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



<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)

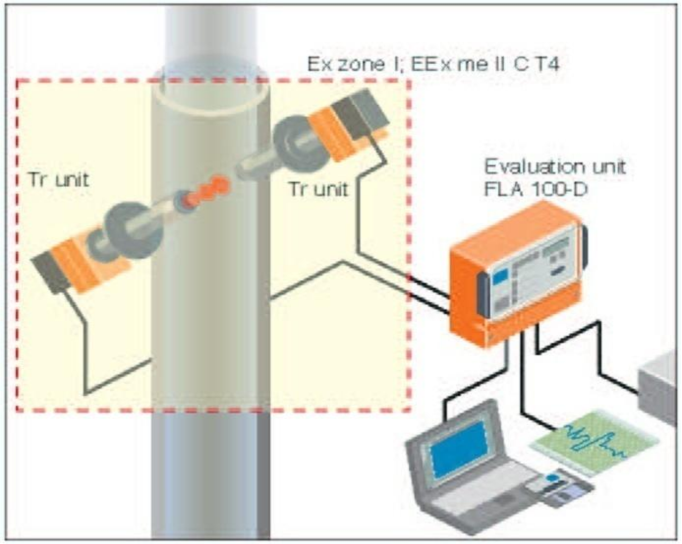
Ambient PM_{10} @ 40 ug/m^3 = 100 kg of PM_{10} ingested (incl. 10 kg of $PM_{2.5}$)

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

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**

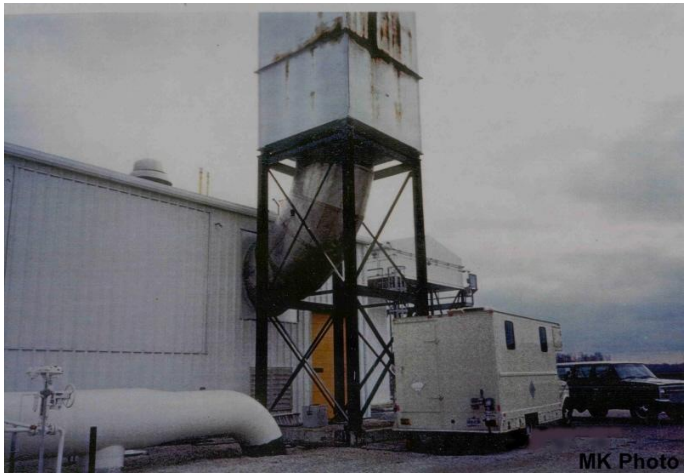


(CEM Specialties)

PEMs;

- ***good predictability of GT operation***
- ***cost-effective emissions reporting***
- ***process efficiency optimization***
- ***a good solution for DLN facilities***

Emissions Averaging Time is Important

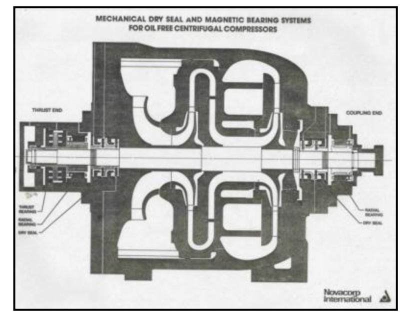


EnvCan CEM van, 1996 (TCPL 1217)

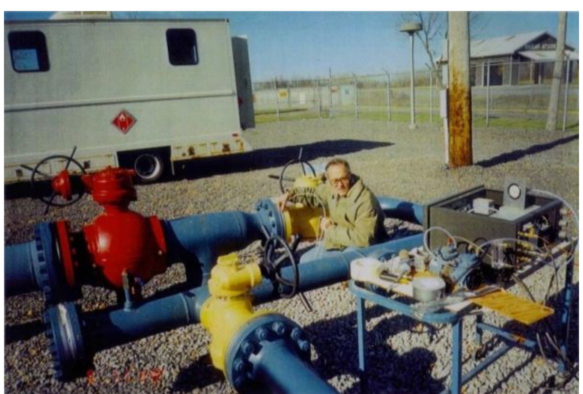
Env’tl Solutions for Gas Pipeline Compression

- **High Operating Pressure (low ΔP)**
- **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

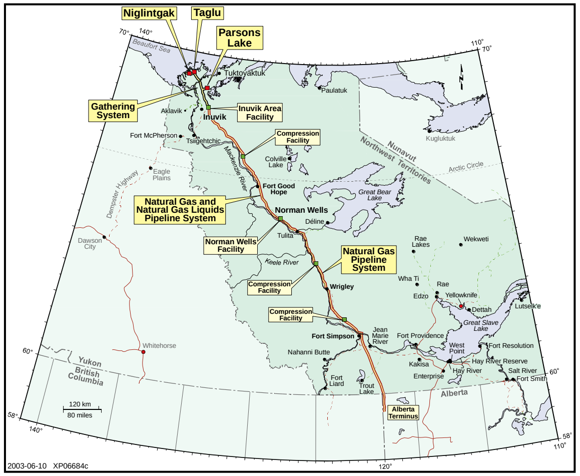


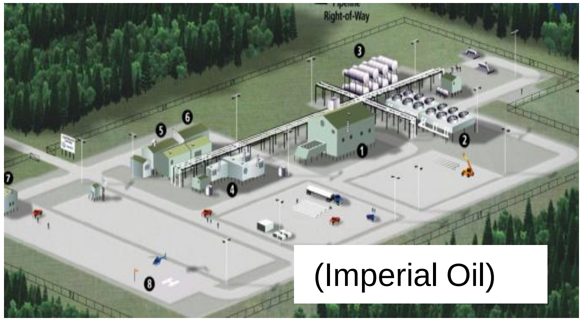

Aerial coolers, Crowsnest BC

Env’tl Assessments;   Example, Mackenzie Gas P/L (2006)

95% of GHG & NOx emissions were from gas turbine units (270 MW) and small recips (13 MW)

- NOx combustion levels which are too low will cause engine instability.
- CCME Guideline balances NOx prevention to moderate level, with low GHGs
- Cold weather, O&M considerations





(Imperial Oil)

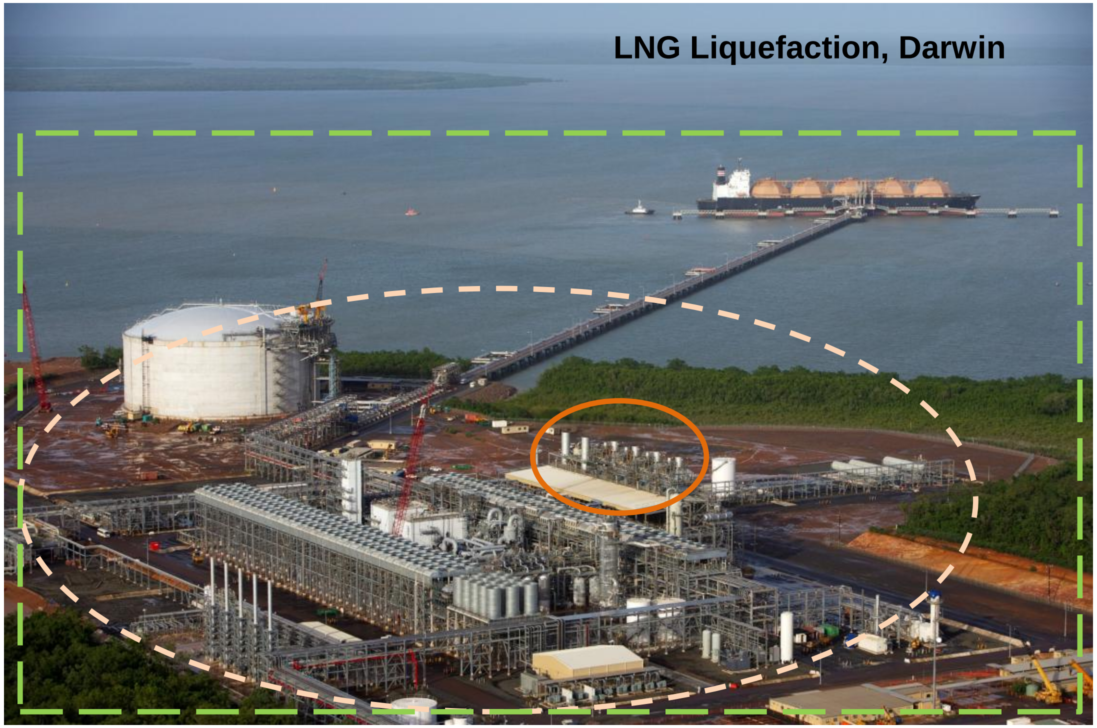
BAT =

- Dry Low NOx burners, Waste Heat Recovery
- Best Practices; Fugitive Leak monitoring
- Minimize Flaring, vented methane
- BMPs in CEPEI / CGA Handbooks (1997-99)
- Maintain system reliability

Canadian Energy Partnership for Environmental Innovation

A Strategic Innovation Collaboration

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

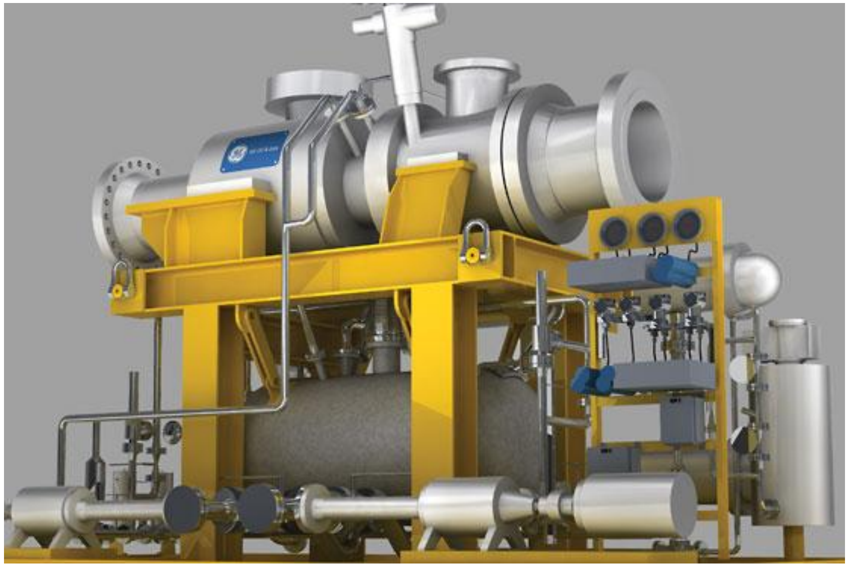
"Cleanest LNG" ?
< 0.3 t_{CO2} per t_{LNG}
- other impacts

‘Zero Emissions’ Energy

Prevents <u>both</u> GHGs and CACs
(like Renewable Energy …)

Pressure Recovery with TurboExpanders

- Pipeline pressure reduction
  for re-compression, onsite MWe
- for Process Cooling



Turboexpander - compressor (GE Oil&Gas)

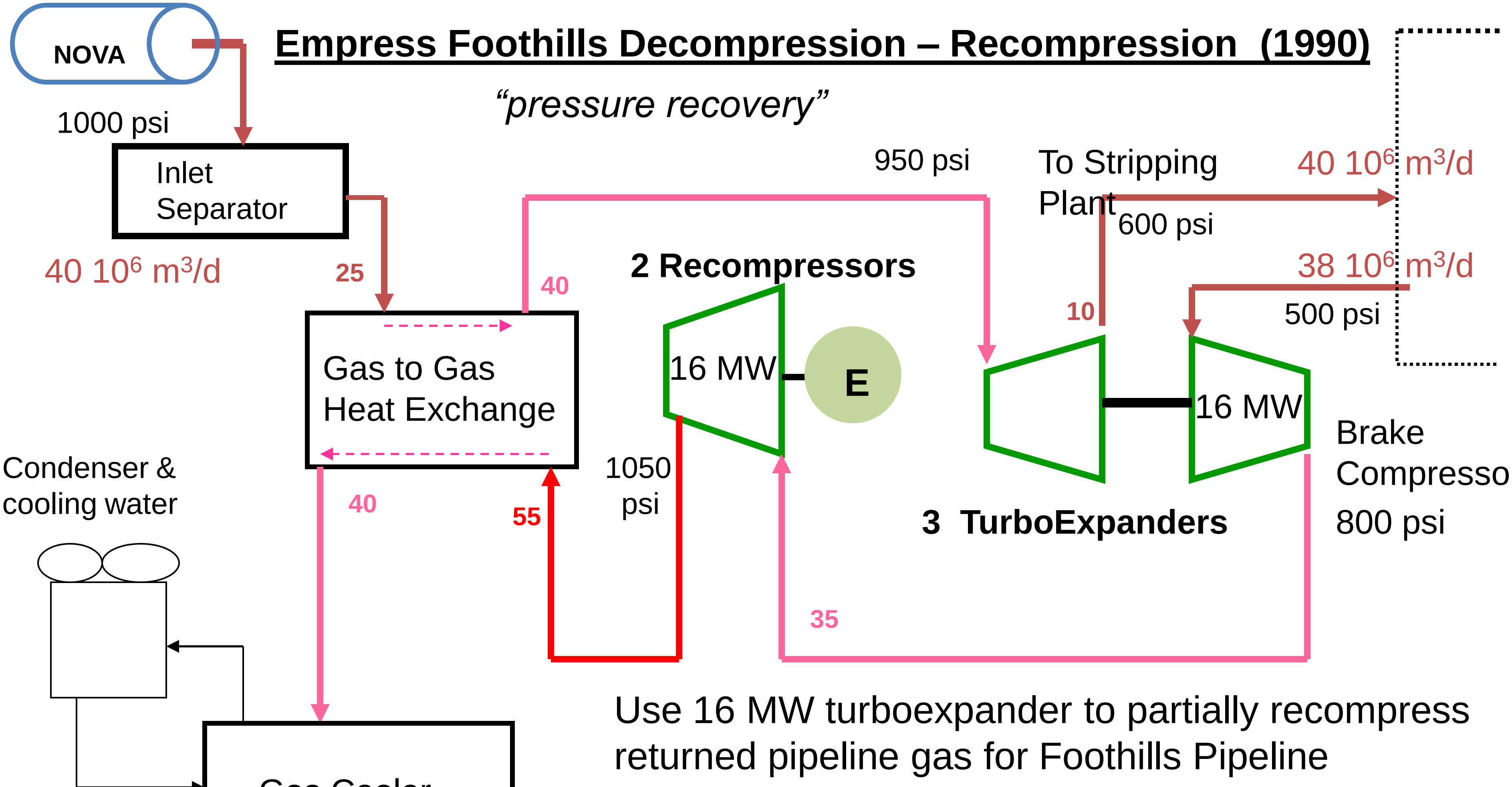
Waste Heat Recovery (HRSG, ORC)

- For onsite Power
- For thermal energy in Inlet Gas
  Conditioning (Cogeneration)

ORMAT WHR Cycle, Savona BC (Spectra/Chinook)

Empress Foothills Decompression – Recompression (1990)

"pressure recovery"



Use 16 MW turboexpander to partially recompress returned pipeline gas for Foothills Pipeline

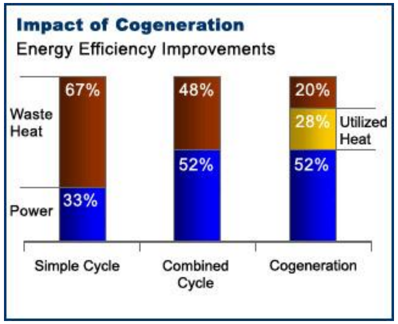
mafitrench.com

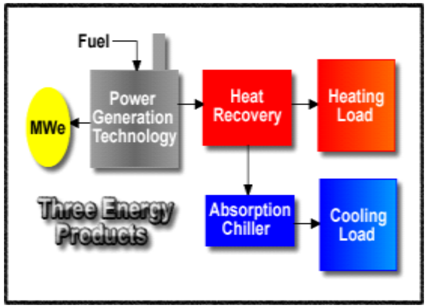
Critical Elements for Cogen (CHP) Systems

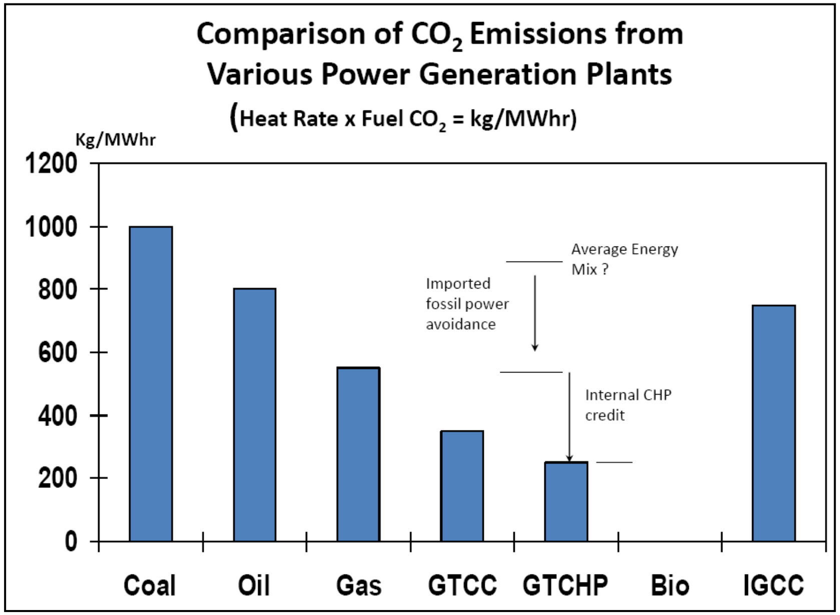
CHP - Producing 2-3 forms of energy from the same fuel, in same process

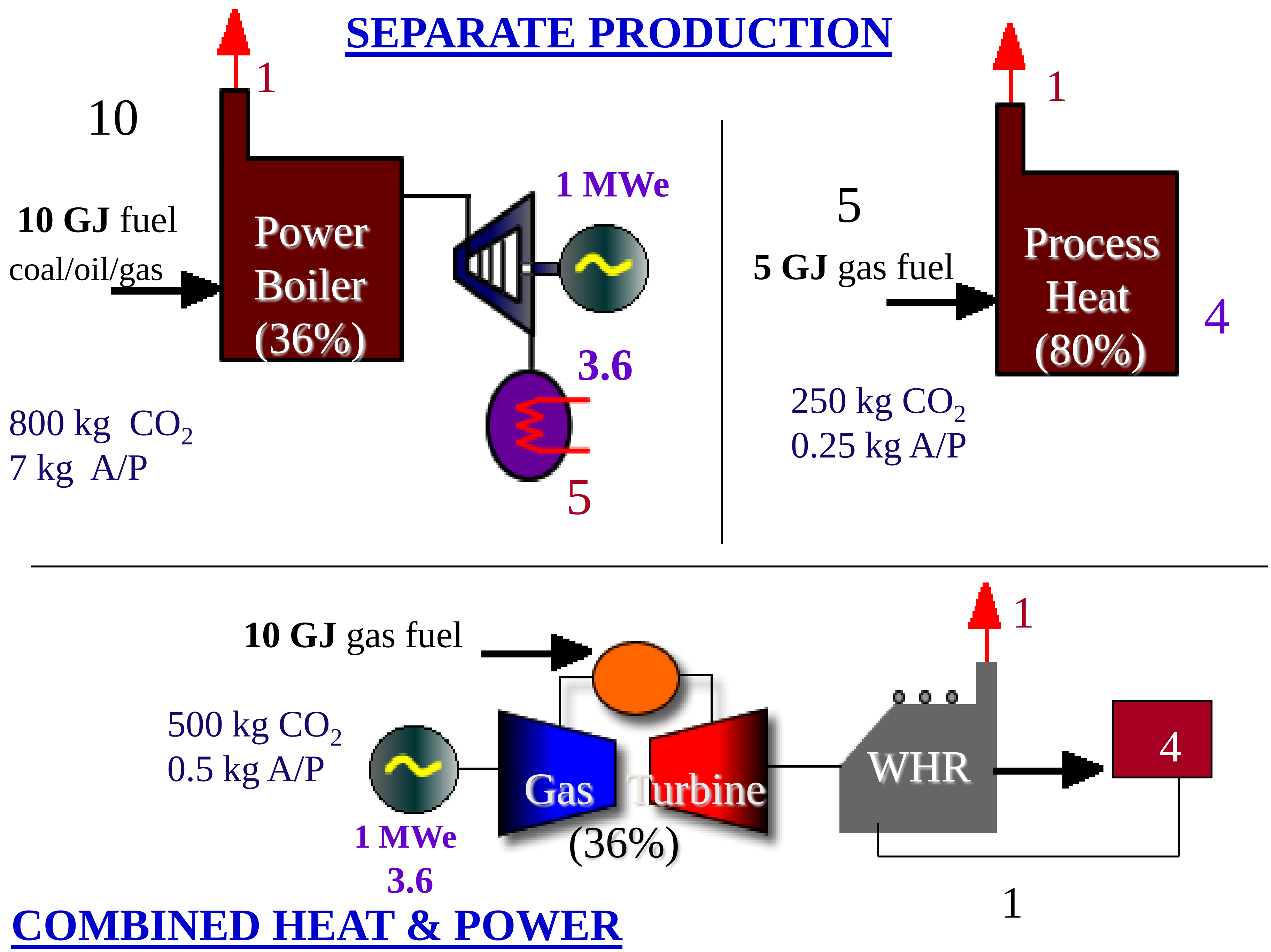
- **Awareness of Opportunities**
- **Site, Sizing to Match Thermal Load**
- **Seasonal Heat/Cooling Design**
- **Electrical Utility Interconnection**
- **Energy Quality, Heat:Power ratio**
- **Low Air Pollution, Local Impacts**
- **Greenhouse Gases & Allocation**
- **Output-based Emission Rules**
- **Integrated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

(CHP more effective than CCS for GTCC)

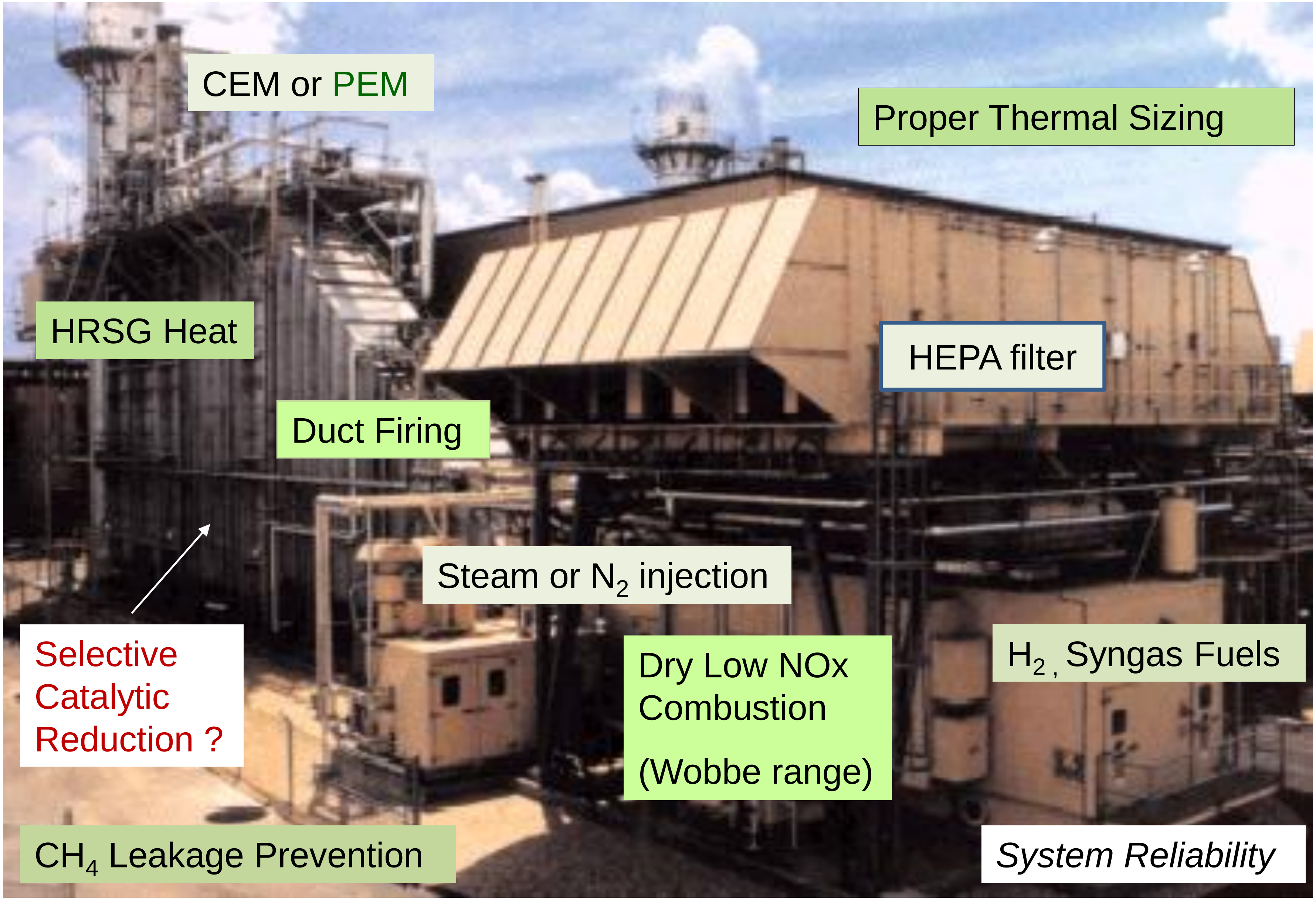







SEPARATE PRODUCTION
10
1
10 GJ fuel
coal/oil/gas
Power
Boiler
(36%)
1 MWe
3.6
5
800 kg CO_2
7 kg A/P
5
1
5 GJ gas fuel
Process
Heat
(80%)
4
250 kg CO_2
0.25 kg A/P
10 GJ gas fuel
1
500 kg CO_2
0.5 kg A/P
Gas
Turbine
(36%)
1 MWe
3.6
WHR
4
1
COMBINED HEAT & POWER

Gas Turbine Emission Prevention & Control (NOx, GHGs)



Maximizing System Output CHP Efficiency

GE Power Systems

Air Emissions; System Synergies and Tradeoffs

- CAC, toxic & CO_2 emissions must occur simultaneously in combustion
- All power from fuels generated originally from a 'Heat' system
- Small & medium sized gas turbines - high CHP efficiency
- Duct burners in HRSGs – good for cogeneration
- Renewable energies, with the integration of GTs
- GT power from high Inlet Airflow – reduce ambient PM ?

- Small HP Dry Low NOx combustor - reliability ?
- CO emissions; potential brown plumes during long startups
- SCR systems and collateral impacts - net $ cost per tonne reduction
- Pipeline system upsets from unreliable DLN - more fugitive GHGs
- Large GTCC systems, require steam condensers - Water impacts
- Plant cycling can affect efficiency and 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

<u>Concluding Remarks</u>

- Gas Turbine power is based on ‘Air’, <u>not</u> gas fuel
- All types of Emissions can be prevented with System Integration
- LNG Synergies & Tradeoffs - Balancing of priorities, ‘Clean Energy’ ?
- *BAT* = Waste Heat, DLN Combustion, CH_4 mitigation, Turboexpanders
- System Efficiency and Combustion Reliability are important
- Tech Issues; Integration, Refrig. Choices, Air Filtration, SCR ?
- Advantages of ‘Output-based’ analyses and emission rules
- HR issues; workers & remote sites; Need Training, Site Visits

GTAA Pearson Airport Plant Tour, IAGT 2006

TCPL Carseland, 2012