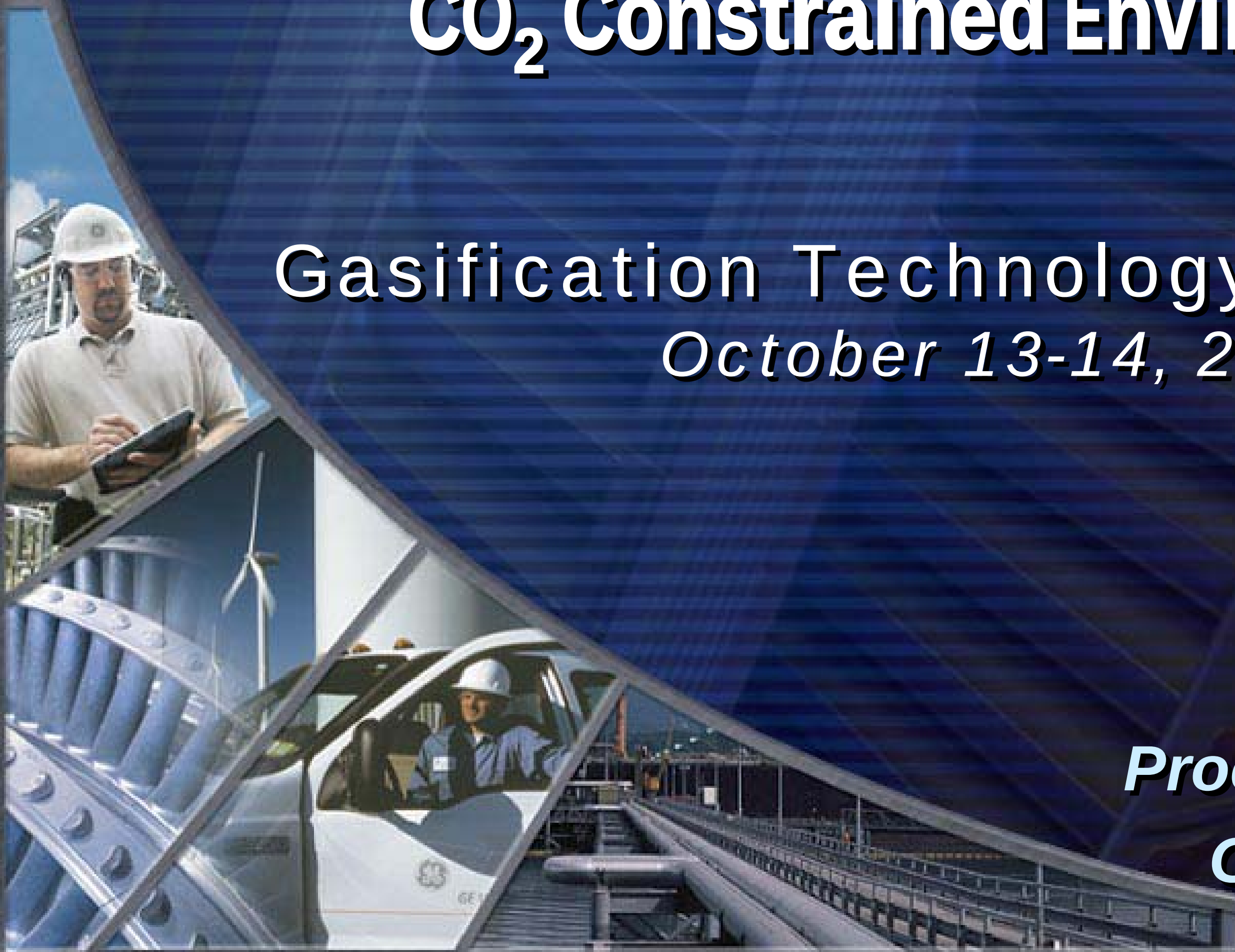
imagination at work

# The Response of Gas Turbines to a $CO_2$ Constrained Environment

## Gasification Technology Conference

*October 13-14, 2003*



***Norm Shilling***
***Robert M. Jones***
***Process Power Plants***
***GE Power Systems***

# Presentation Outline

Topics to be discussed

- Options for $CO_2$ Abatement
- $H_2$ GT performance implications
- Hydrogen combustion
- Total plant considerations
- Key tradeoffs and development needs
- Hydrogen experience in the process industry
- IGCC GT developments
- Summary

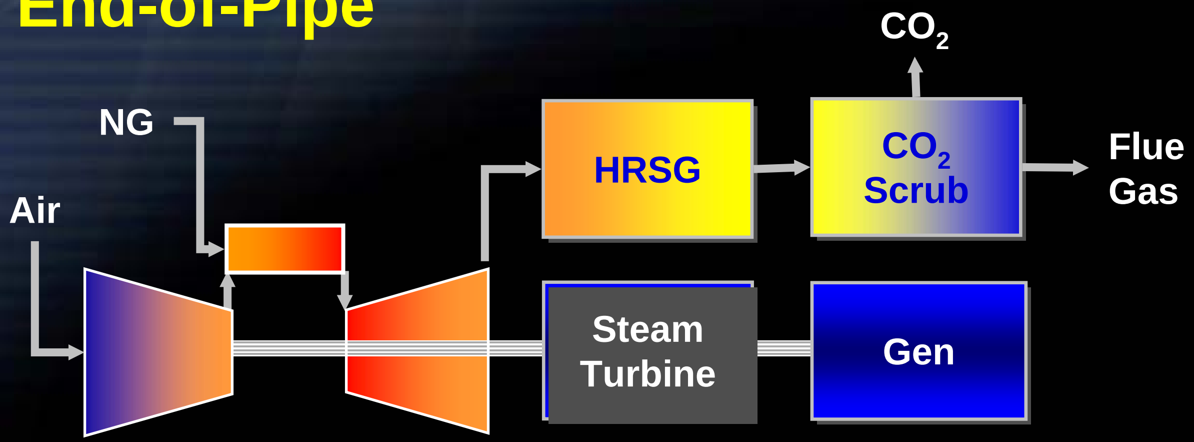
# Low $CO_2$ options for GTs

| *Process* | *Description* | *GT Fuel* | *Oxidant* | *Characteristics* |
|---|---|---|---|---|
| "End-of-Pipe" Capture | Open-cycle with Chemical or physical (adsorption) of $CO_2$ | NG | Air | Simple process<br>Large $CO_2$ plant<br>Poor economics for syngas |
| "Semi-closed" | Partial-recycle with Chemical or Physical $CO_2$ removal process | NG | Air | Simple process<br>Impact on GT performance<br>Smaller $CO_2$ plant |
| Pre-combustion Decarbonization | High hydrogen fuel from SG or NG Reform/Shift | $H_2$ | Air | Requires diffusion combustion<br>Steam or $N_2$ diluent to control $T_{fire}$ and NOx |
| Closed Post-Combustion "Oxy-Fuel" | Condensing heat exchanger to remove $H_2O$<br>Slip stream $CO_2$ removal<br>$CO_2$ recirculated as working fluid | NG/SG | $O_2$ | Smallest $CO_2$ plant<br>No NOx<br>Profound changes to GT with $CO_2$ working fluid |

Many Other Variations

# Gas Turbine Considerations

## End-of-Pipe



## GT Impact

**Simple – Low GT Impact**

**$CO_2$ concentrations in exhaust:**

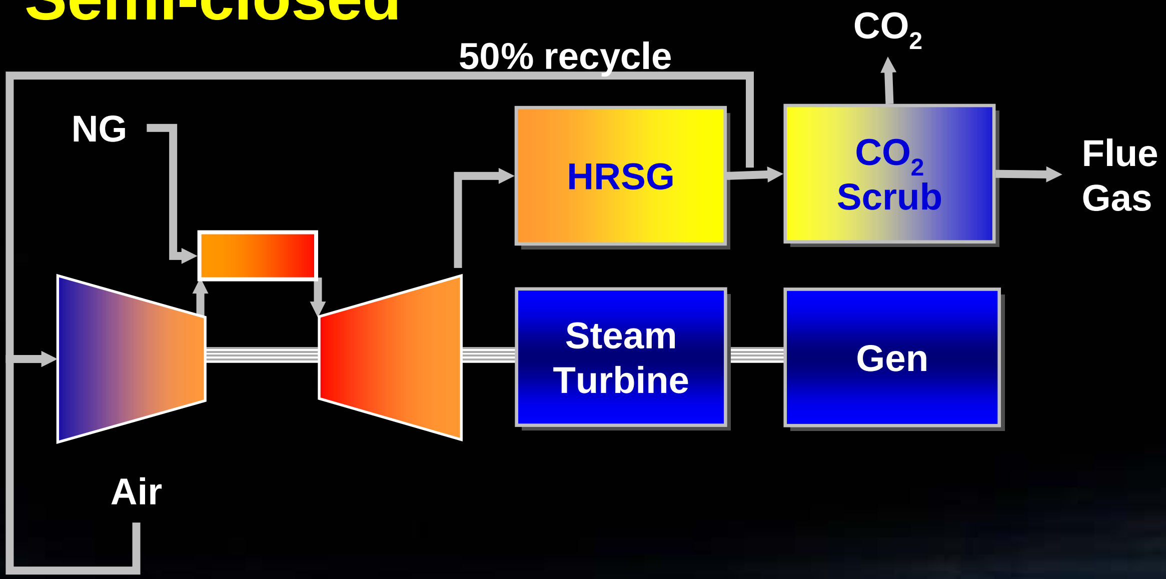
**3.5% for NG**

**7.7% for coal syngas[1]**

***Low concentrations & high volume drives high scrubber capital and operating costs***

[1] 1.5 lb Dry $N_2$ diluent /lb syngas

## Semi-closed



**Doubles $CO_2$ concentration but impacts GT performance:**

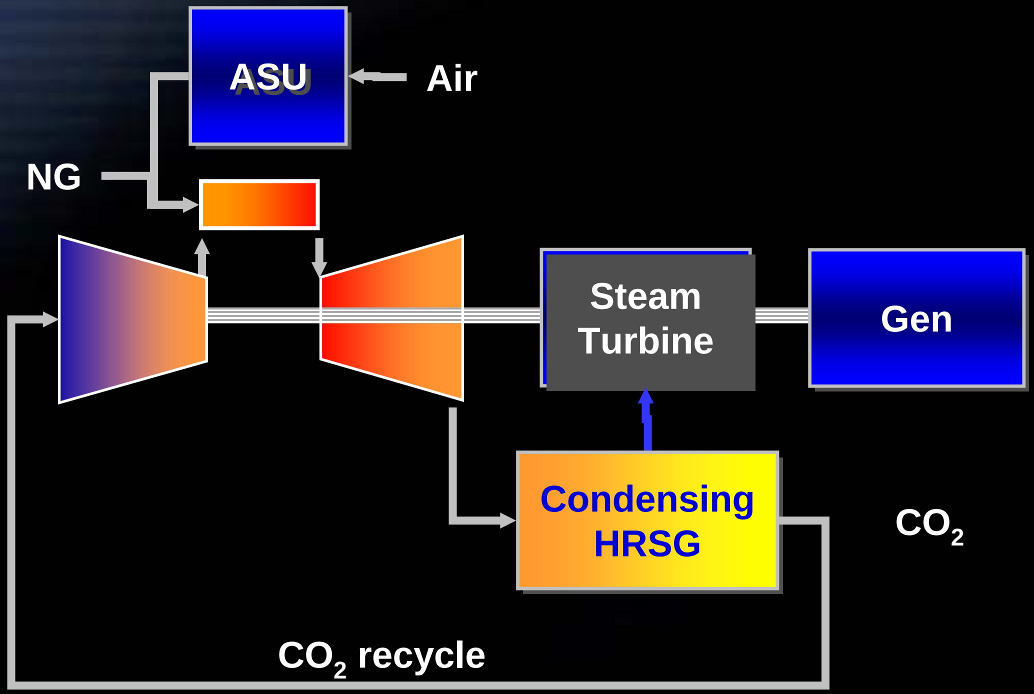
***Theoretical impact of working fluid on GT performance***

| | $C_p$ | $C_v$ | $k$ | $\eta_{Max}$[1] |
|---|---|---|---|---|
| $N_2$ | 0.27 | 0.19 | 1.38 | 53% |
| Air | 0.27 | 0.20 | 1.34 | 50% |
| $CO_2$ | 0.28 | 0.24 | 1.19 | 35% |

[2] Isentropic expansion efficiency at 15.5 PR with 100% working fluid

# Gas Turbine Considerations

## Oxy-Fuel



## Impact on current GTs

Operation at normal synchronous speed will choke compressor

*$CO_2$ Speed of sound of 80% of air*

*$CO_2$ Density 50% higher than air*

*Challenging compressor design problem*

Significant combustor development needed

*Significant aerodynamic change with operating fluid*

*Acoustic feedback potential with lower Mach number*

Hot gas path

*Mach number limitations in back end*

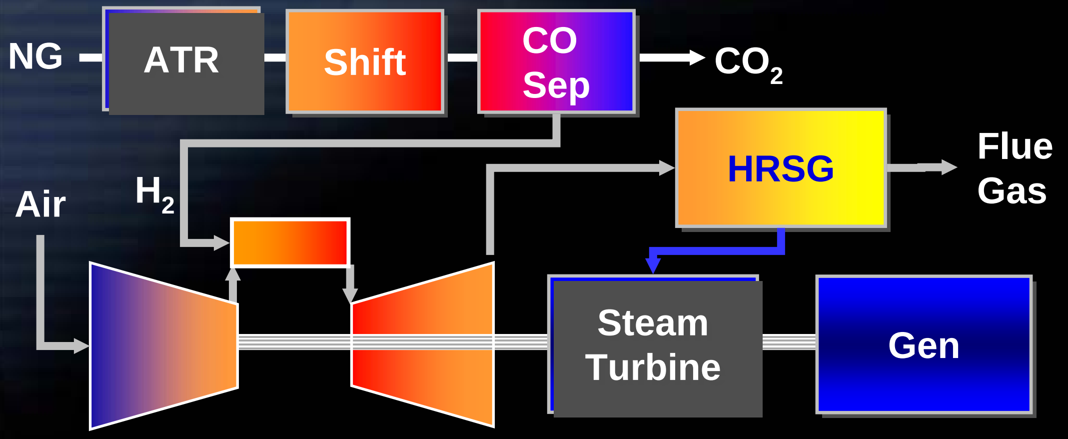
*Modified heat and mass transfer*

No experience database for large industrial turbines

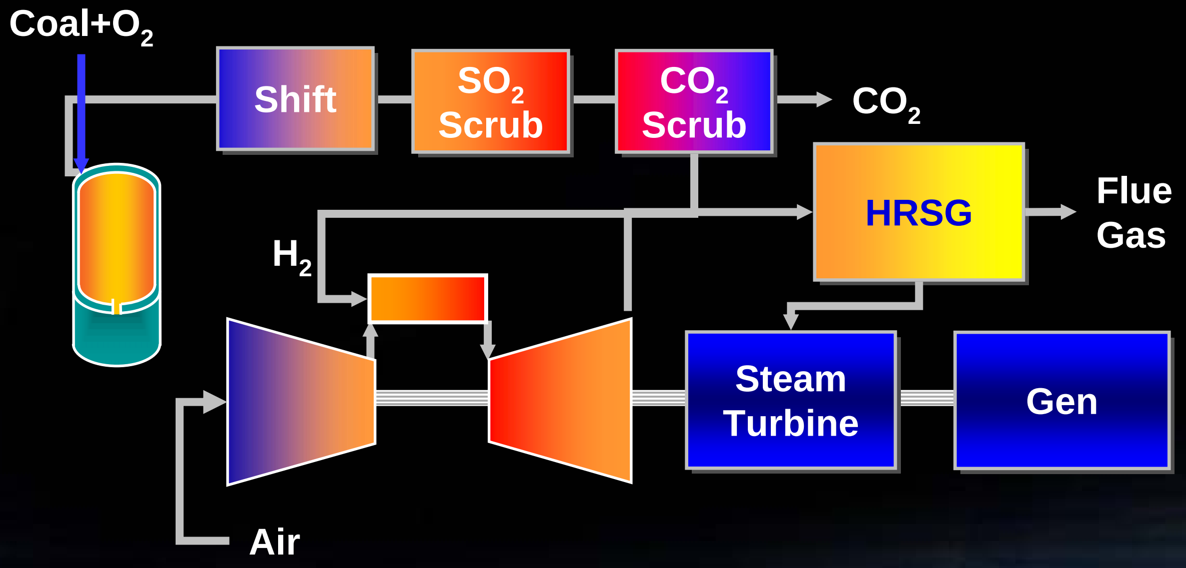
**Completely New Turbine**

# Basic Gas Turbine Considerations

## NG Pre-combustion De-carbonisation


NG
ATR
Shift
CO Sep
$CO_2$
HRSG
Flue Gas
Air
$H_2$
Steam Turbine
Gen

## IGCC Pre-Combustion De-carbonisation


Coal+$O_2$
Shift
$SO_2$ Scrub
$CO_2$ Scrub
$CO_2$
HRSG
Flue Gas
$H_2$
Steam Turbine
Gen
Air

## GT Impact

**Requires gas turbines to use 90%+ hydrogen fuel**

*E-class GTs already in service with 65%-95% $H_2$*

*Demonstrated acceptable combustion at F-class conditions*

**Requires diffusion combustor with diluent injection**

*DLN limited to 10% $H_2$*

*IGCC combustors suitable at 45%-50% net $H_2$*

**$N_2$ diluent preferred vs. steam**

*Heat transfer increase from steam:*

| | $c_p$ | $\mu$ | $k$ | $\Phi$[1] |
|---|---|---|---|---|
| $N_2$ | 0.28 | 2.80 | 0.04 | 0.06 |
| $H_2O$ | 0.56 | 2.47 | 0.06 | 0.09 |
| $CO_2$ | 0.30 | 2.86 | 0.04 | 0.06 |

[1] Fluid property heat transfer factor for turbulent flow over a tube

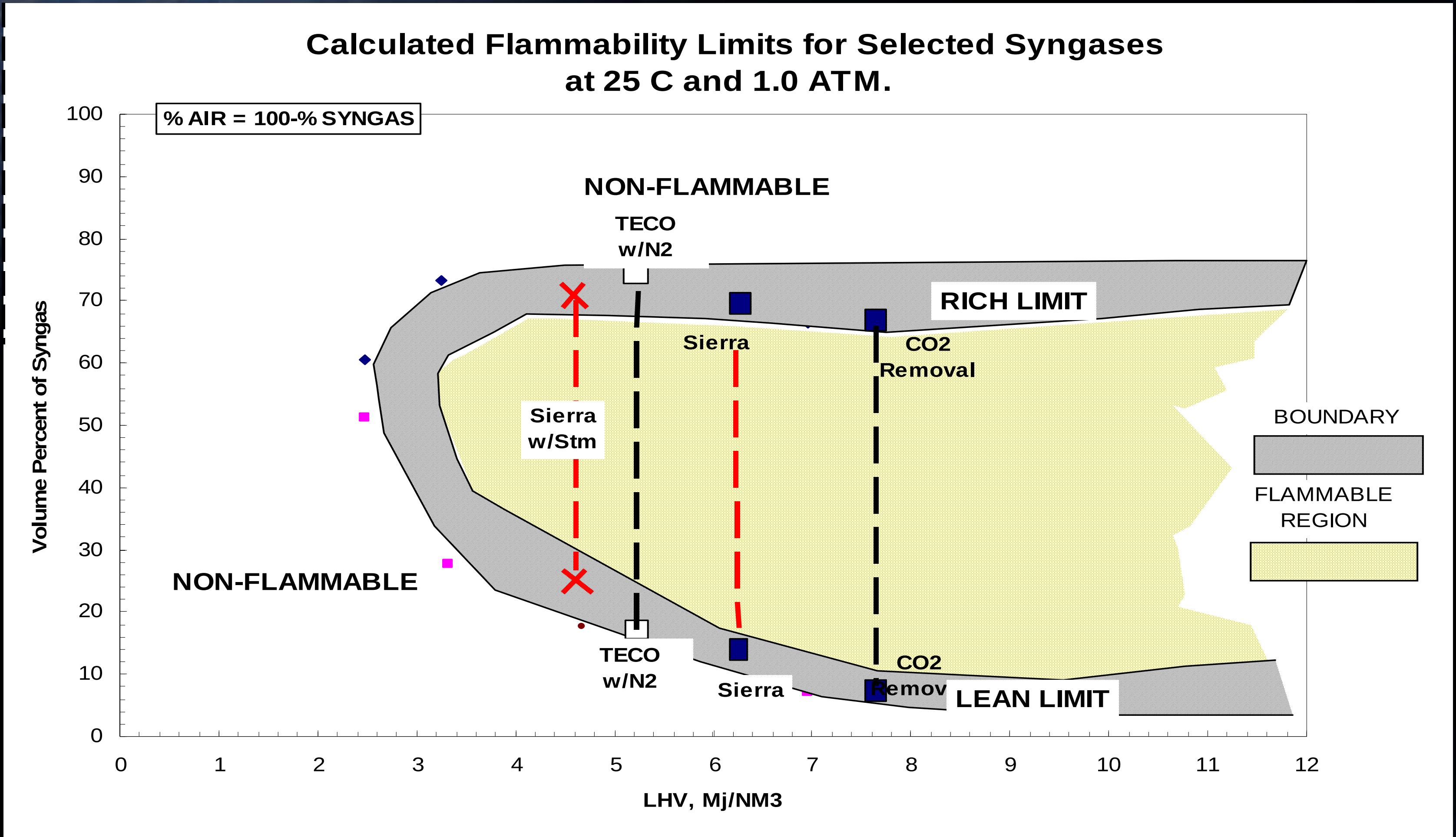
# Experience with $H_2$ in Process Plants

| Site | Country | G.T. Model | No. | Commission Year | Gas Type | LHV (kJ/Nm3) | Main Design Features |
|---|---|---|---|---|---|---|---|
| Geismar | US | MS 6000B | 1 | 1998 | PG | 11,138 | Up to 80% $H_2$ |
| Daesan 2 | Korea | MS 6000B | 1 | 1997 | RG | 16,500 | Up to 95% $H_2$ |
| Schwarze Pumpe | Germany | MS 6000B | 1 | 1996 | SG | 12,492 | 65% $H_2$ |
| Cartagena | Spain | MS 6000B | 1 | 1993 | RG | 25,100 | 66% $H_2$ |
| Tenerife | Spain | MS 6000B | 1 | 1994 | RG | 29,000 | 70% $H_2$ |
| San Roque | Spain | MS 6000B | 2 | 1993 | RG | 24,000 | 70% $H_2$ |
| Antwerpen | Belgium | MS 6000B | 1 | 1993 | RG | 20,700 | 78% $H_2$ |
| Puertollano | Spain | MS 6000B | 2 | 1994-1994 | RG | 16,700 | Up to 60% $H_2$ |
| La Coruna | Spain | MS 6000B | 1 | 1991 | RG | 25,000 | Up to 52% $H_2$ |
| Rotterdam | Holland | MS 6000B | 1 | 1990 | RG | 28,000 | 59% $H_2$ |
| Zarqa Refinery | Jordan | PGT10 | 1 | 1997 | RG | 15,258 | 82% $H_2$ |
| Donges | France | GE10 | 1 | 2001 | RG | 16,788 | 76% $H_2$ |

Gas types: RG=refinery gas; PG=process gas; SG=syngas

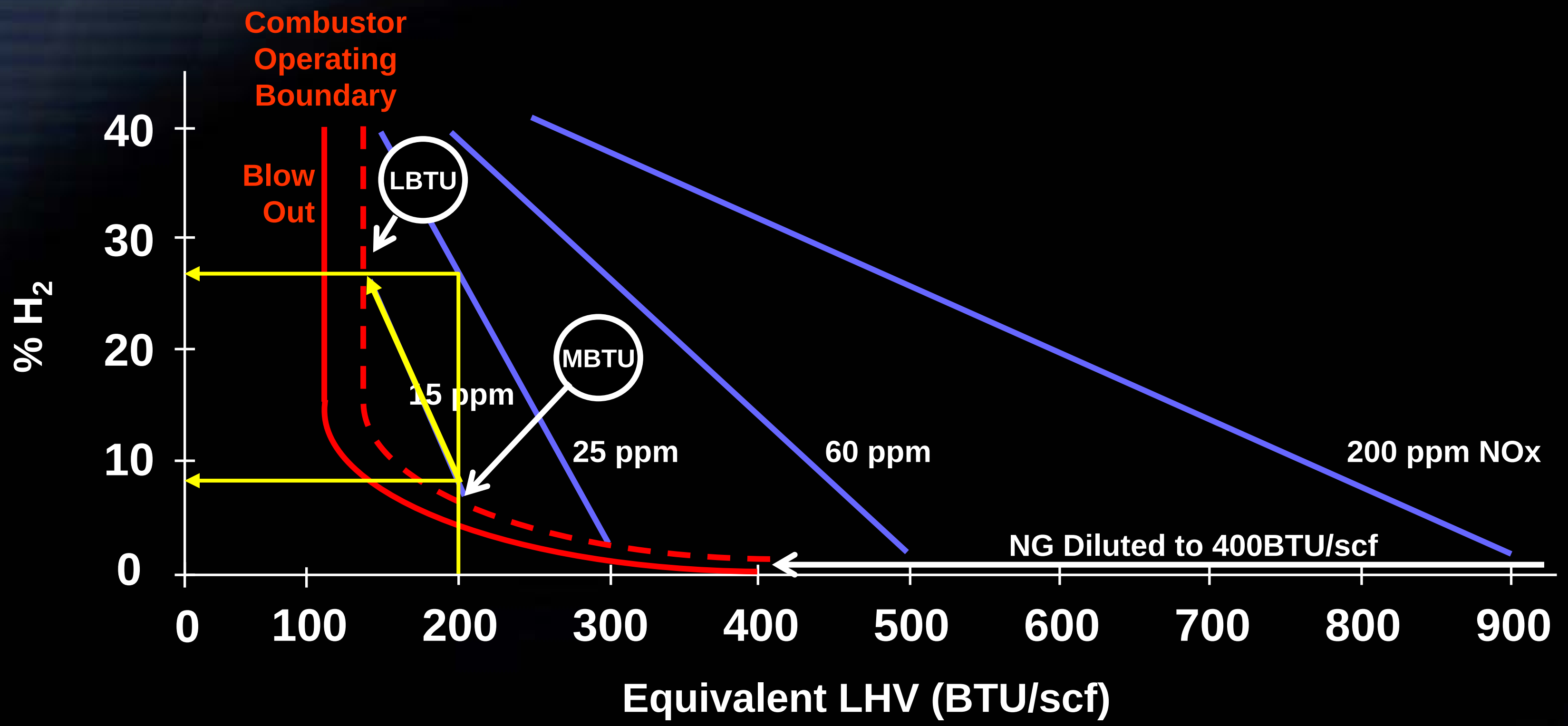
**450,000 Hours on High Hydrogen Gases**

# Flammability Characteristics



## Low Lean Limit with Low $CO_2$ Fuel

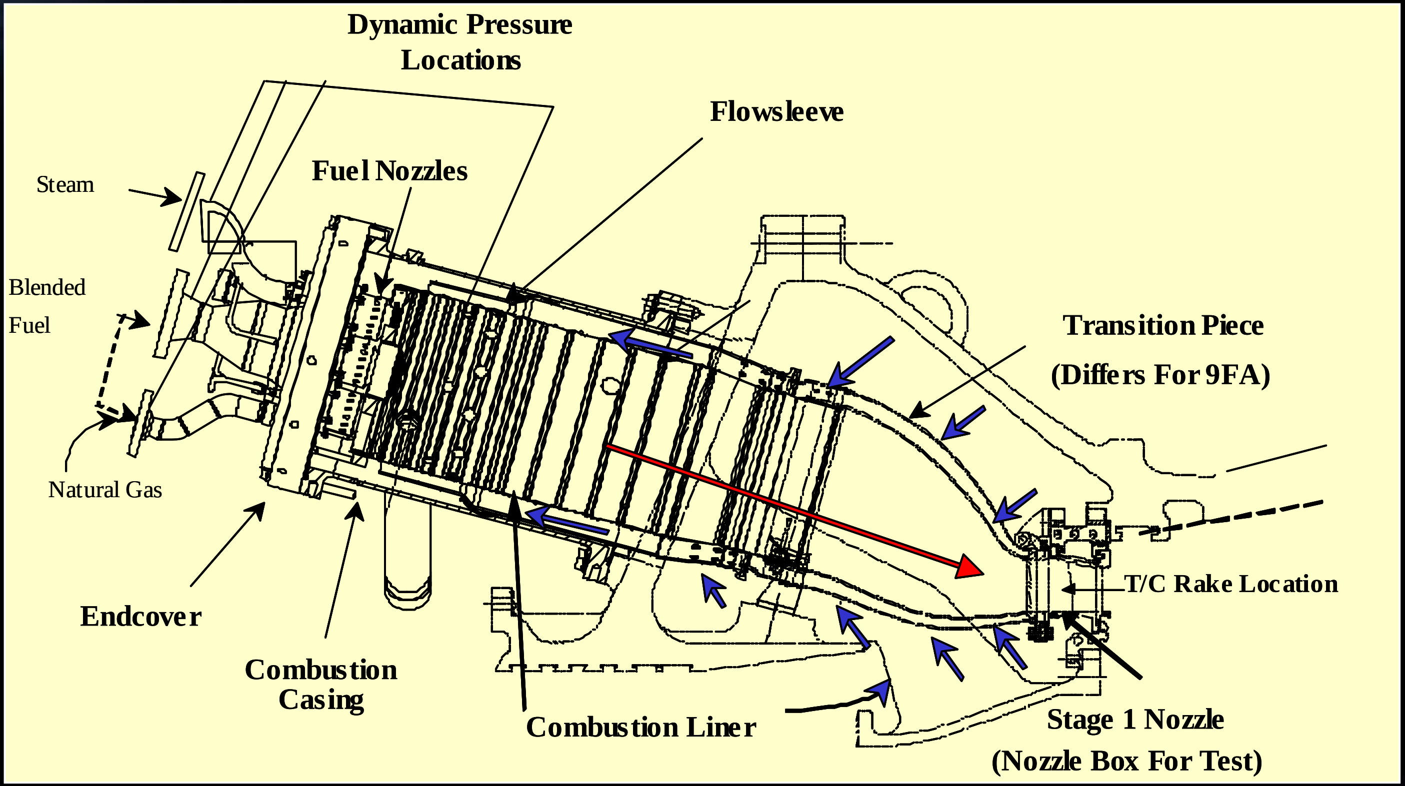
# Hydrogen Effect



**$H_2$ Extends Lower LHV Capability**

# $H_2$ Combustion for Advanced Machines

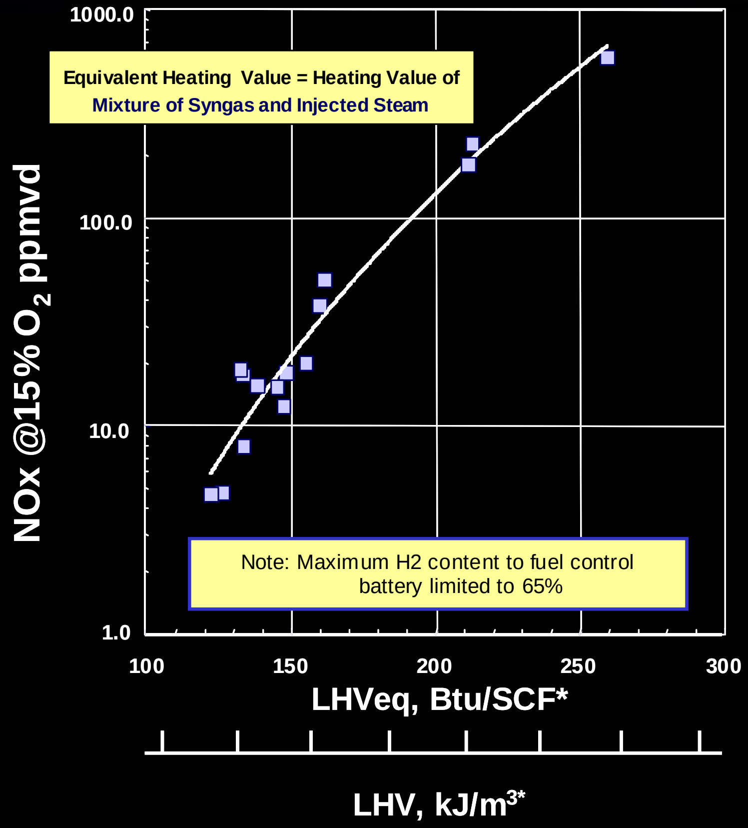
## Modified Diffusion Combustor for Low Heating Value Fuels with High Hydrogen Content



**Shared for 6FA, 7FA & 9FA**

# 6FA $H_2$ Combustion Testing

## Video Capture of Flame Structure - 85-90% $H_2$



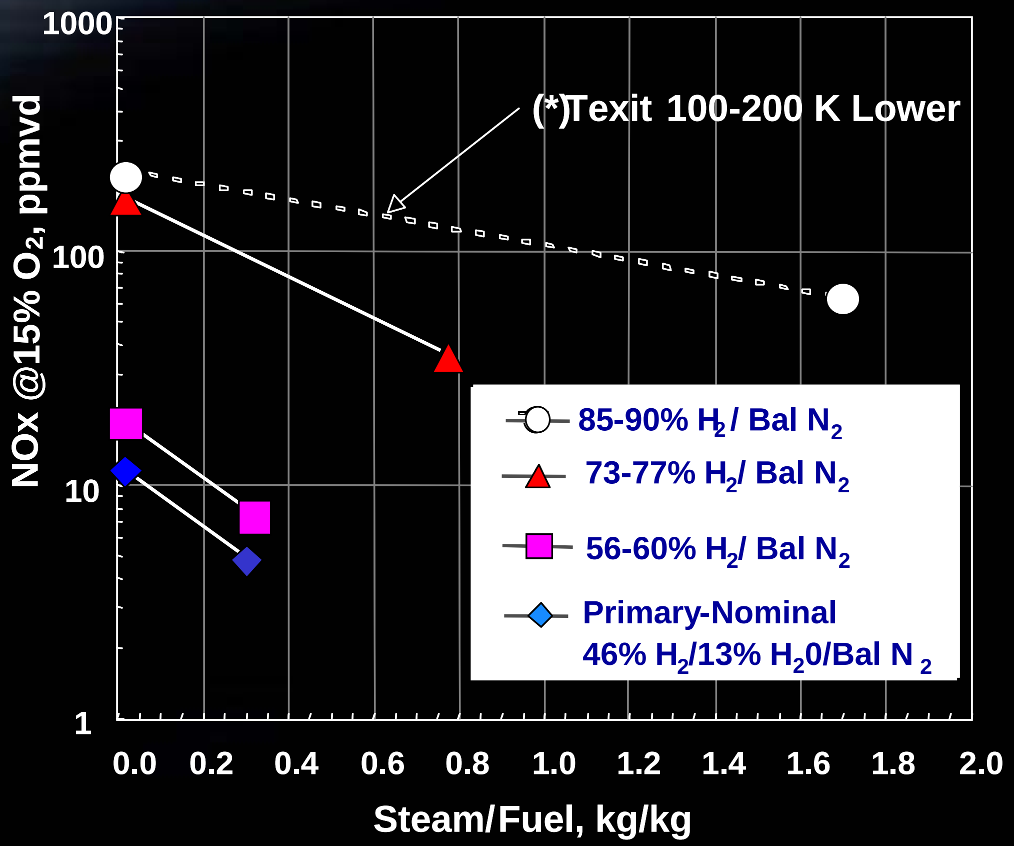
Equivalent Heating Value = Heating Value of Mixture of Syngas and Injected Steam

Note: Maximum H2 content to fuel control battery limited to 65%

50 - 95% $H_2$ By Volume, Bal. $N_2$, $N_2$ + $H_20$

**Combustion Capability for Low $CO_2$**

# Emissions Characteristics of $H_2$



**45%-50% Net $H_2$ Best for GT Emissions**

# Comparative $H_2$ Properties

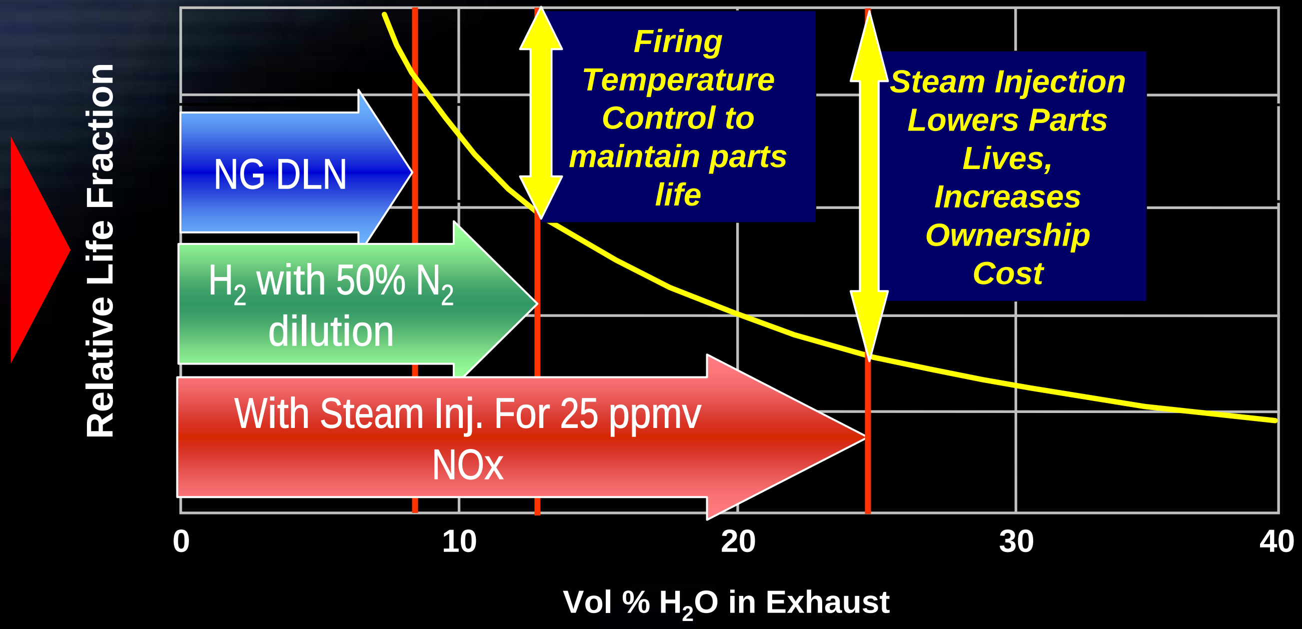
| | Typical Fuel Properties | | | | | Combustion Products |
|---|---|---|---|---|---|---|
| Fuel | LHV Btu/lb | LHV Btu/scf | Density lb/scf | Specifc Volume (scf/lb) | Mass Ratio $N_2$/ Fuel | $H_2O$ % Vol |
| 100% $H_2$ [1] | 51,495 | 273.5 | 0.0053 | 188.68 | --- | 16.94 |
| 50% $H_2$/ 50% $N_2$ | 3,457 | 137.0 | 0.0396 | 25.25 | 13.90 | 12.30 |
| Medium BTU Syngas (Neet) | 4,671 | 249.3 | 0.0534 | 18.73 | -- | -- |
| Syngas Post-Dilution ($N_2$ to 15ppm NOx) | 1,776 | 114.6 | 0.0645 | 15.50 | 1.63 | 6.01 |
| NG DLN | 18,507 | 873.0 | 0.0472 | 21.19 | -- | 8.30 |

[1] Hypothetical only -- would not be fired at 100% $H_2$

**Recommended Split of $N_2$ Injection and Blend**

# Hydrogen RAM

## Control Response to moisture to maintain HGP life



- Alternative to Lower Life: Reduced Firing Temp to Maintain Design Metal Temp/ 100% Life

**Total Cost Tradeoff**

# Example: Diluent Impact from IGCC

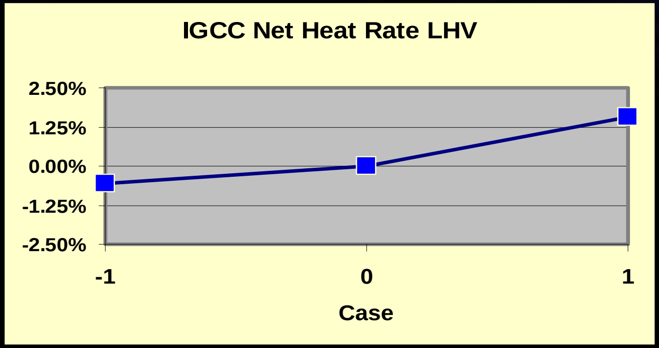
## Net impact of NOx control and ASU integration

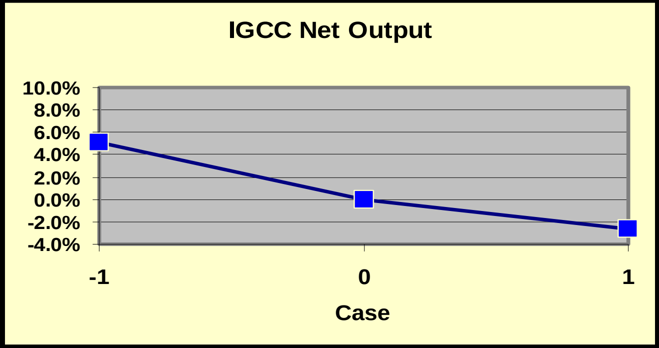
**Configuration:**

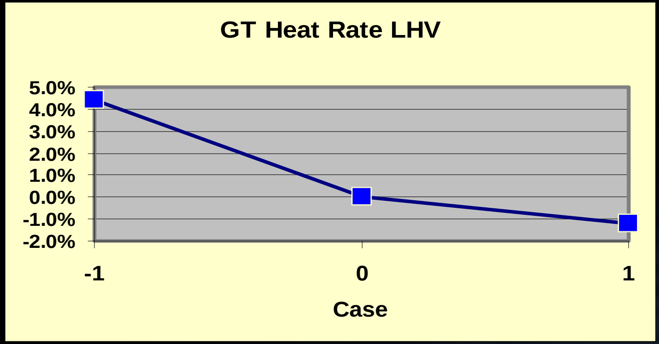
- PG7241 IGCC
- Syngas expander
- ISO operation at torque limit
- ChevronTexaco Quench
- GT Integration with Elevated Pressure ASU
- 3PRH - 1815psia/1000 - 1050F/1000 - 1050F; 1x40" LSB
- Diluent injection to 15 ppm NOx

***Main effects chart:***

| Case –1 | Case 0 | Case 1 |
|---|---|---|
| Dry $N_2$ | Dry $N_2$ | Steam |
| $T_{fire}$ at NG level | $T_{fire}$ control curve | $T_{fire}$ control curve |







**Complex GT-IGCC System Interactions**

# Fuel Management Challenges

### *$H_2$ vs. Natural Gas*

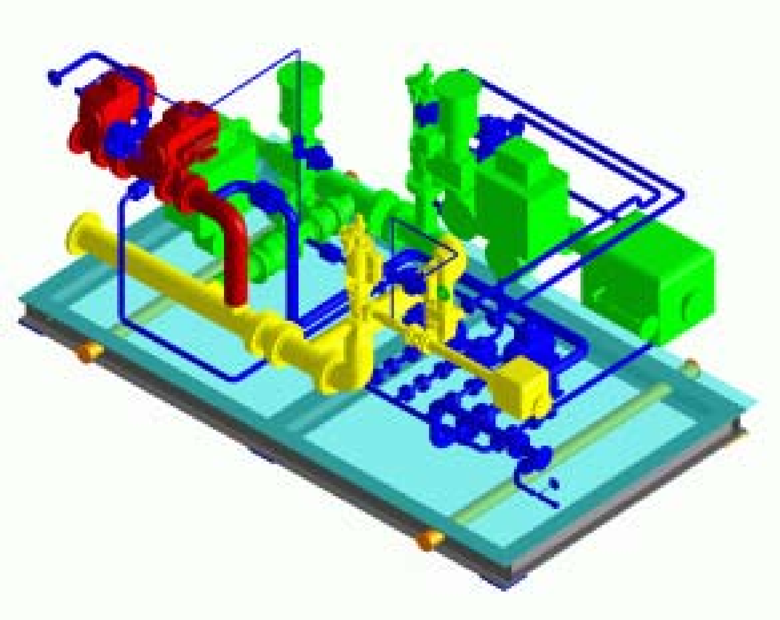
- Very Low Ignition Energy
- ~3 x More Volume Per BTU
- Non-luminous Flame
- Material Compatibility
- Buoyant + Rapid Dissipation

### *Fuel Control*

- $H_2$ Free Start-up Fuel
- Ignition-Free Purge & Transfer

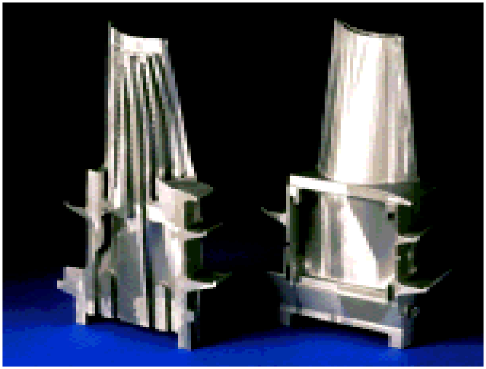
### *Safety*

- Codes & Standards Compliance
  - Sealing
  - Explosion Proofing
  - Ventilation
  - Leak Detection
  - Protection Algorithms

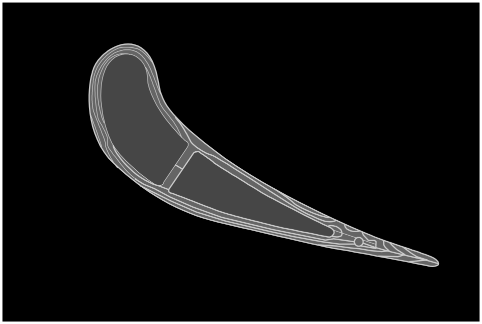


**Operability and Safety Require Development**

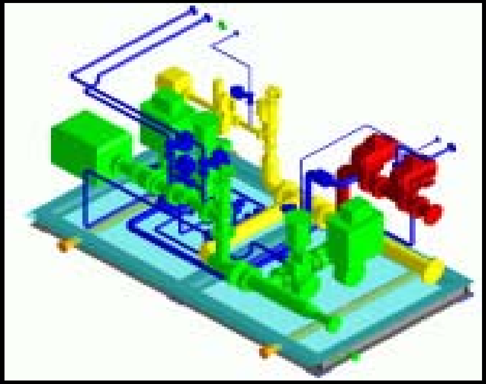
# Development Needs



Understanding of advanced materials & TBC interactions with high moisture/high temp gas

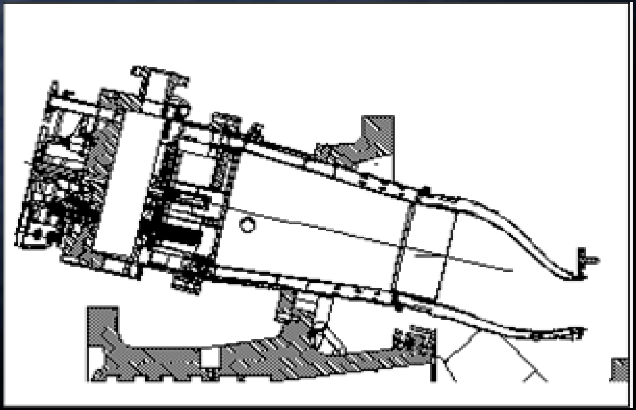


Aero-thermal studies and experimental validation to optimize tradeoffs between efficiency and RAM

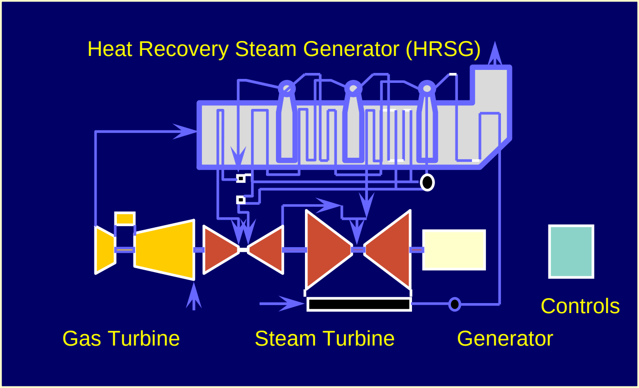


Assessment and definition of fuel control and balance-of-plant safety requirements

# Development Needs (Continued)



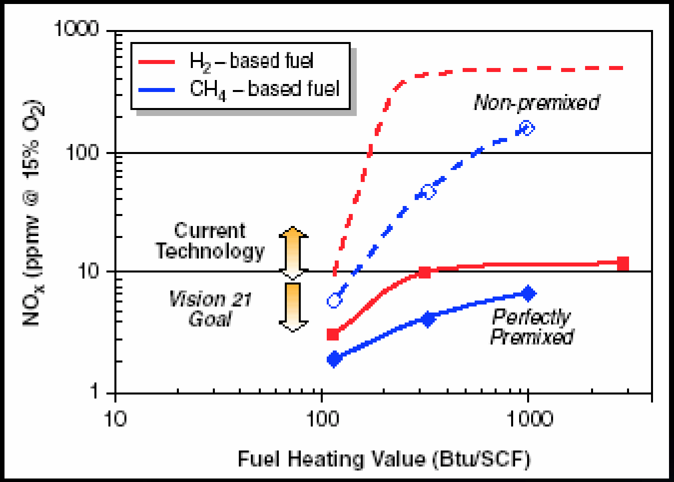
**Feasibility assessment and development of lean-premix hydrogen combustion**

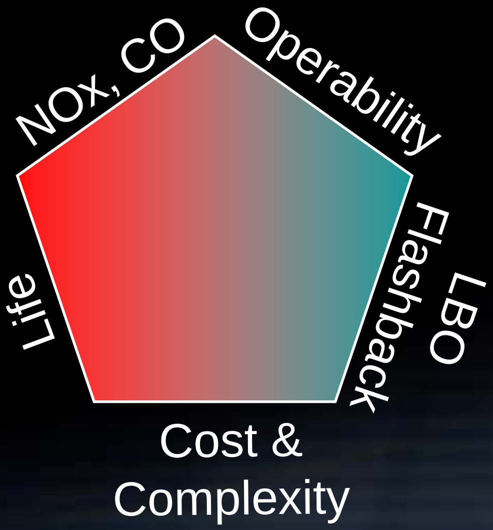


**Process evaluations for optimal gas turbine integration and demonstration to validate concepts**

# Future Combustion Approaches

- Present combustors rely on 30 yr old diffusion flame technology
- NOx control requires significant diluent
  - *Performance issue where $N_2$ is not available as diluent*
- Modern approach: increase efficiency and decrease $NO_x$ using advanced technology
  - *Provide reliable data for hydrogen combustion*
  - *Design, evaluate and optimize sub-scale combustors*
  - *Provide technology for GT integration in hydrogen economy*
  - *Provide technology that can be used in various gas turbines*




NOx, CO

Operability

Flashback

LBO

Cost & Complexity

Life

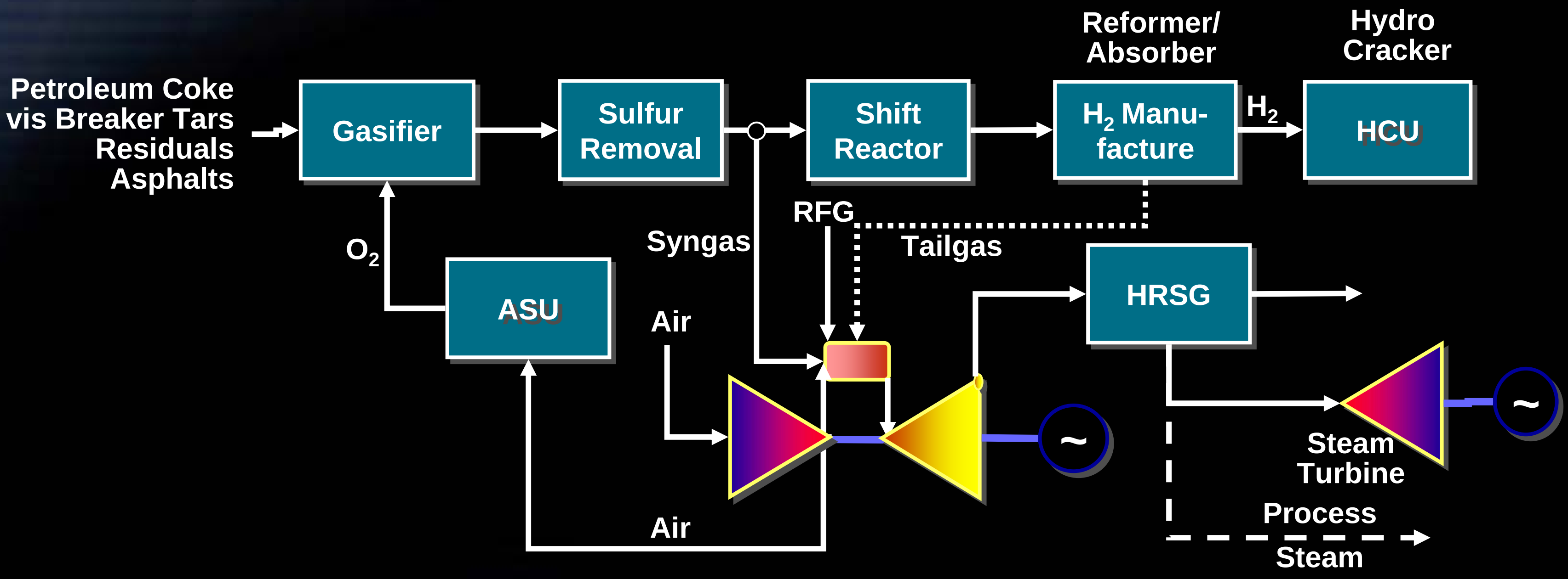
# Combustion Test Capability

## GE Investment in IGCC

- State-of-the-art combustion development facility at Greenville, S.C.
- Standard machines for optimal integration of turbine and gasification plant
- Full scale, pressure and temperature validation of combustion performance
- At GE's Global Research Laboratory - Advanced concepts for low emissions combustion for LHV fuels

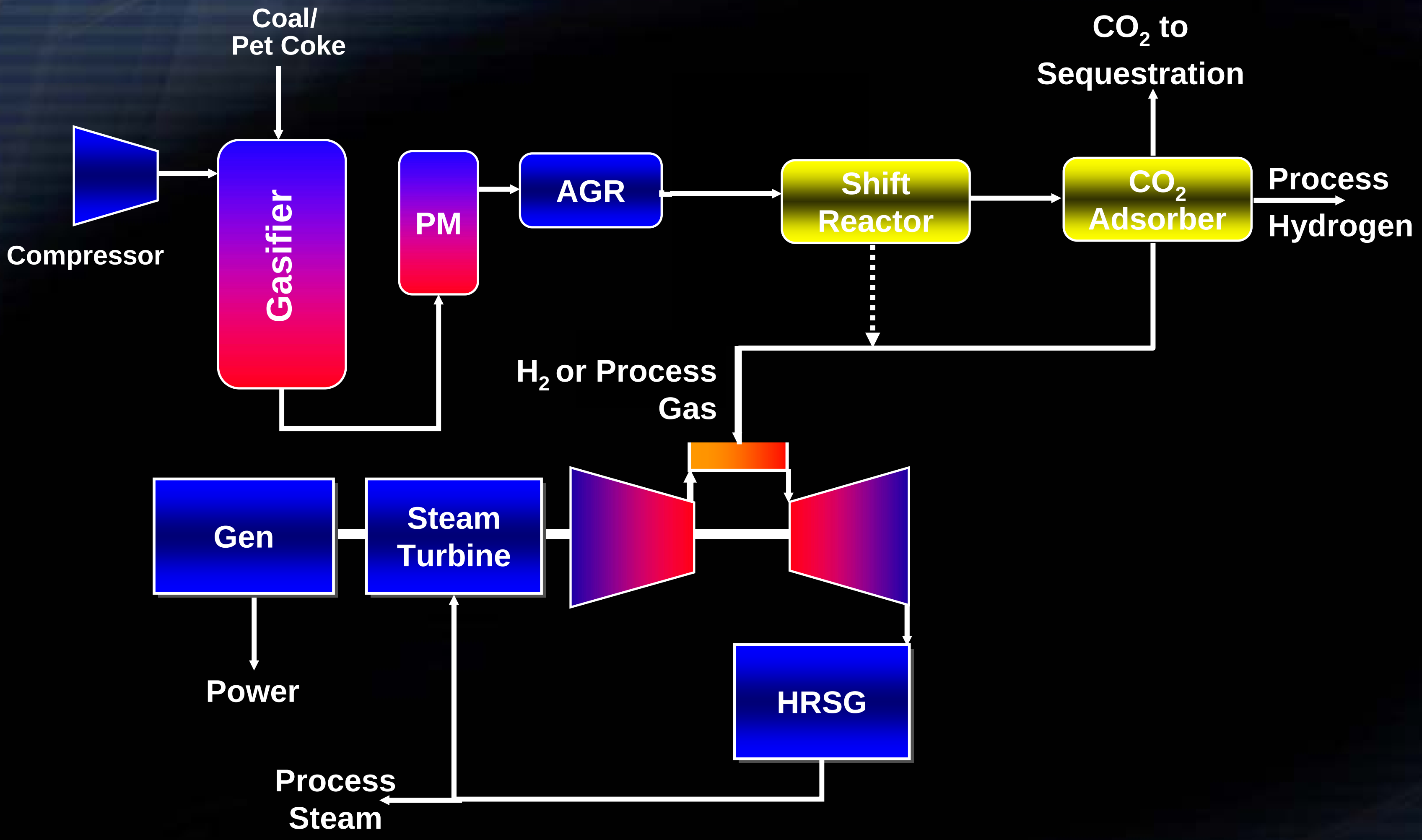
**Full-Scale Performance Validation**

# $H_2$ in Refinery IGCC



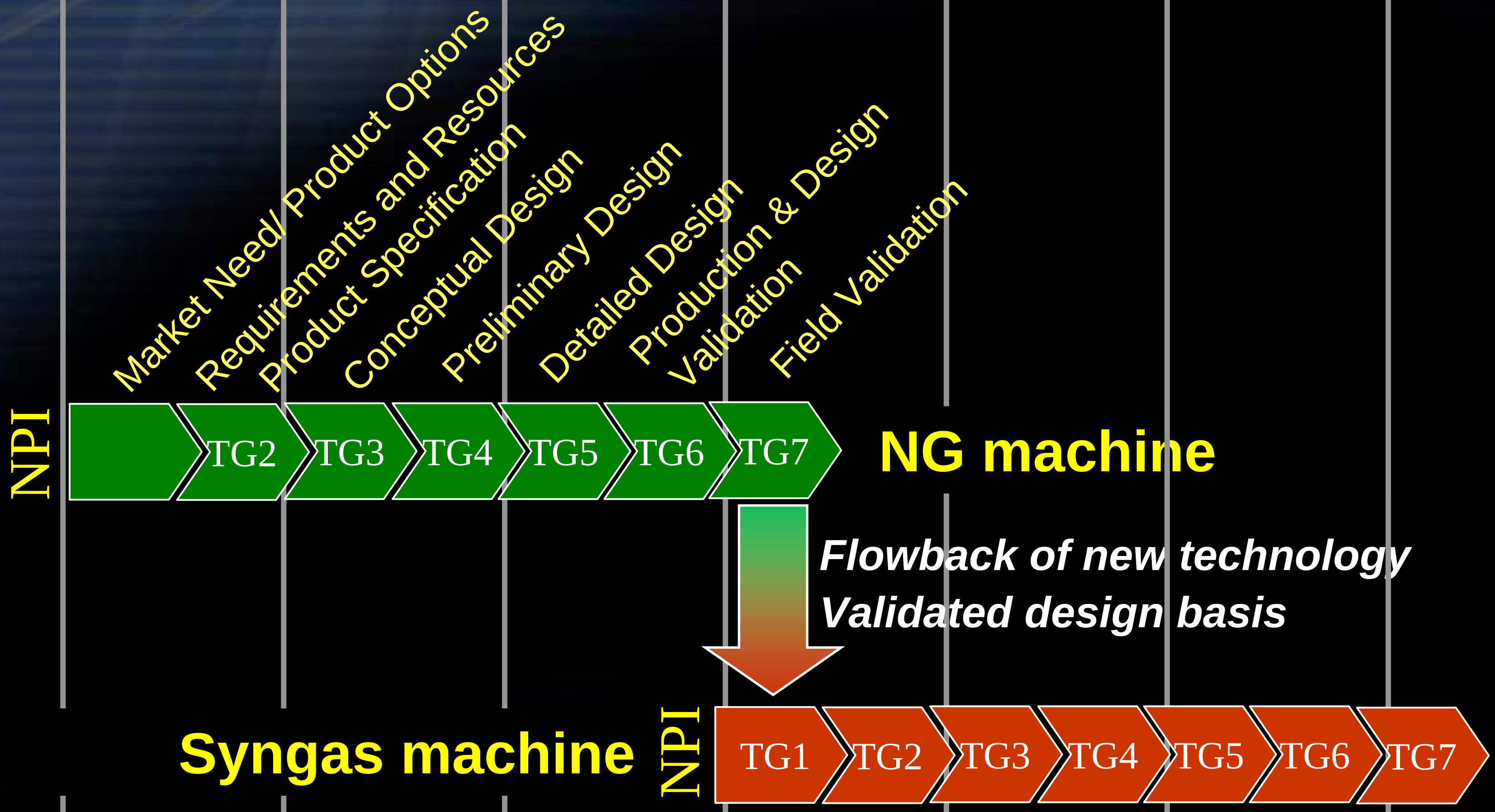
**$H_2$ for Increased Refinery Yield**

# Multi-Generation Process Concept



**Flexibility to Meet Changing Process Demands**

# Design Evolution of IGCC GTs



Market Need/ Product Options

Requirements and Resources

Product Specification

Conceptual Design

Preliminary Design

Detailed Design

Production & Design Validation

Field Validation

NPI

TG2 TG3 TG4 TG5 TG6 TG7

**NG machine**

***Flowback of new technology***

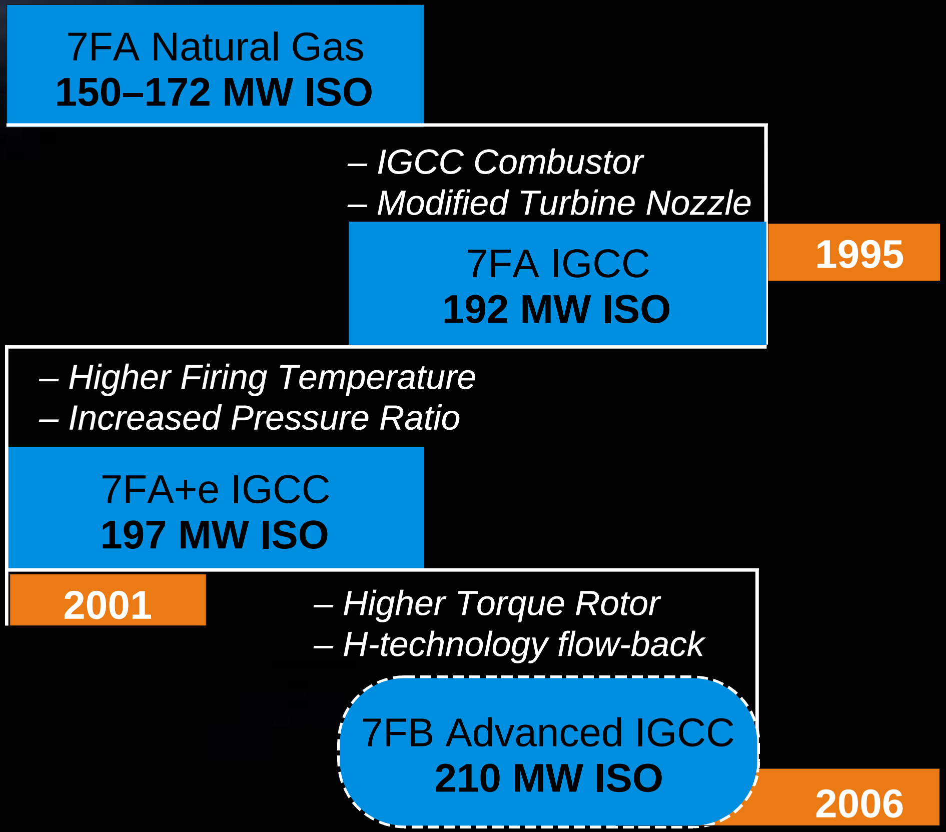
***Validated design basis***

**Syngas machine**

NPI

TG1 TG2 TG3 TG4 TG5 TG6 TG7

# GT IGCC Evolution



7FA Natural Gas
**150–172 MW ISO**

– *IGCC Combustor*
– *Modified Turbine Nozzle*

7FA IGCC
**192 MW ISO**

**1995**

– *Higher Firing Temperature*
– *Increased Pressure Ratio*

7FA+e IGCC
**197 MW ISO**

**2001**

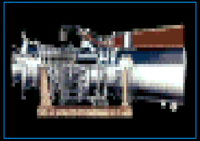
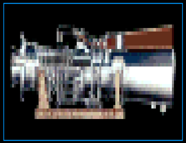
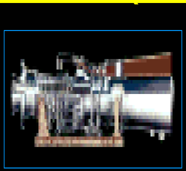
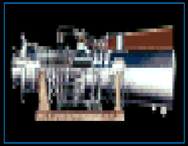
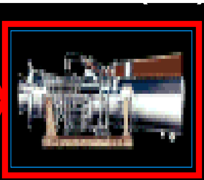
– *Higher Torque Rotor*
– *H-technology flow-back*

7FB Advanced IGCC
**210 MW ISO**

**2006**

**Advancements Enhancing IGCC Economics**

# MS7001FB – Latest Air-Cooled 60 Hz Gas Turbine

| | PG7211(F) | PG7221(FA) | PG7231(FA) | PG7241(FA) | PG7251(FB) |
|---|---|---|---|---|---|
| |  |  |  |  |  |
| Turbine SC Output, MW | 150 | 159 | 167.8 | 171.7 | 184.4 |
| 1X CC Output, MW | - | 253.4 | 258.8 | 262.6 | 280.3 |
| 1X CC Efficiency, LHV | - | 55.0 | 56.0 | 56.0 | 57.3 |
| Firing Temperature, C | 1260 | 1287 | 1316 | 1327 | 1370+ |
| Pressure Ratio | 13.5:1 | 15:1 | 15:1 | 15.5:1 | 18.5:1 |
| Compressor Stages | 18 | 18 | 18 | 18 | 18 |
| Turbine Stages | 3 | 3 | 3 | 3 | 3 |
| Combustion Chambers | 14 | 14 | 14 | 14 | 14 |
| Year of First Shipment | 1989 | 1992 | 1996 | 1999 | 2001 |

**7FB – 6 Units in Commercial Operation July '03**

# Summary

- Hydrogen / $N_2$ fuel is an acceptable fuel for gas turbines using IGCC Combustors
- Excellent experience record on high Hydrogen process gases
- Reliability, Availability and Maintainability can be equivalent to natural gas
- NG-based ATR as basis for $H_2$ power challenged to deal with steam diluent impact
- Many candidate hydrogen generation processes – optimum GT process integration will be critical to economics
- Feasibility and benefits of pre-mix hydrogen combustion need to be studied