# Partial Oxidation Gas Turbine for Power and Hydrogen/Syngas Co-Production

Presented to **ICEPAG 2006**
by

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# Outline

> POGT development

> POGT for power generation

> POGT for hydrogen/syngas and electricity generation

> POGT for high-temperature industrial furnaces

> POGT-based CCHP

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# Project Sponsors and Partners

> California Energy Commission

> DOE NETL and DOE EERE

> SoCalGas

> Solar Turbines

> Siemens

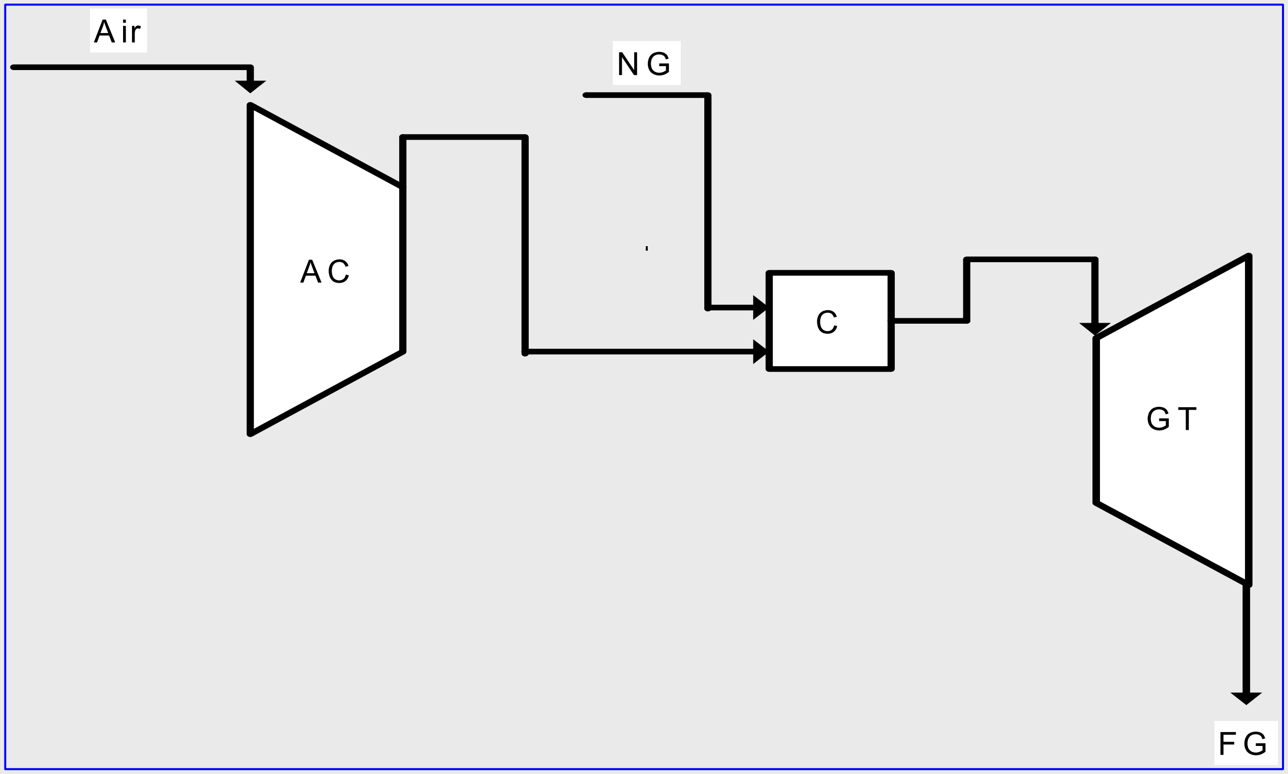
> Elliott Microturbine

> Alturdyne

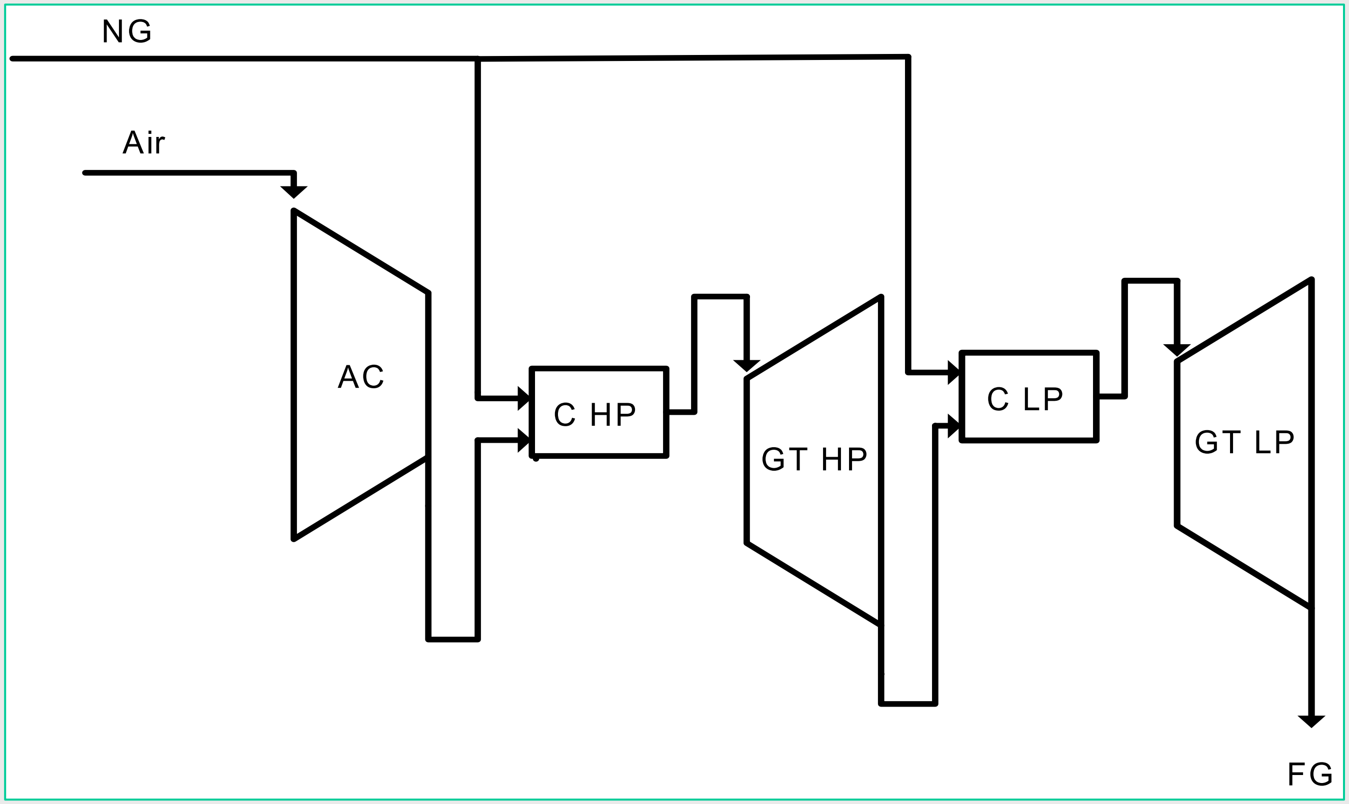
> GTI

# # 1
# Development of a Partial Oxidation Gas Turbine for Electricity and $H_2$-Enriched Fuel Production

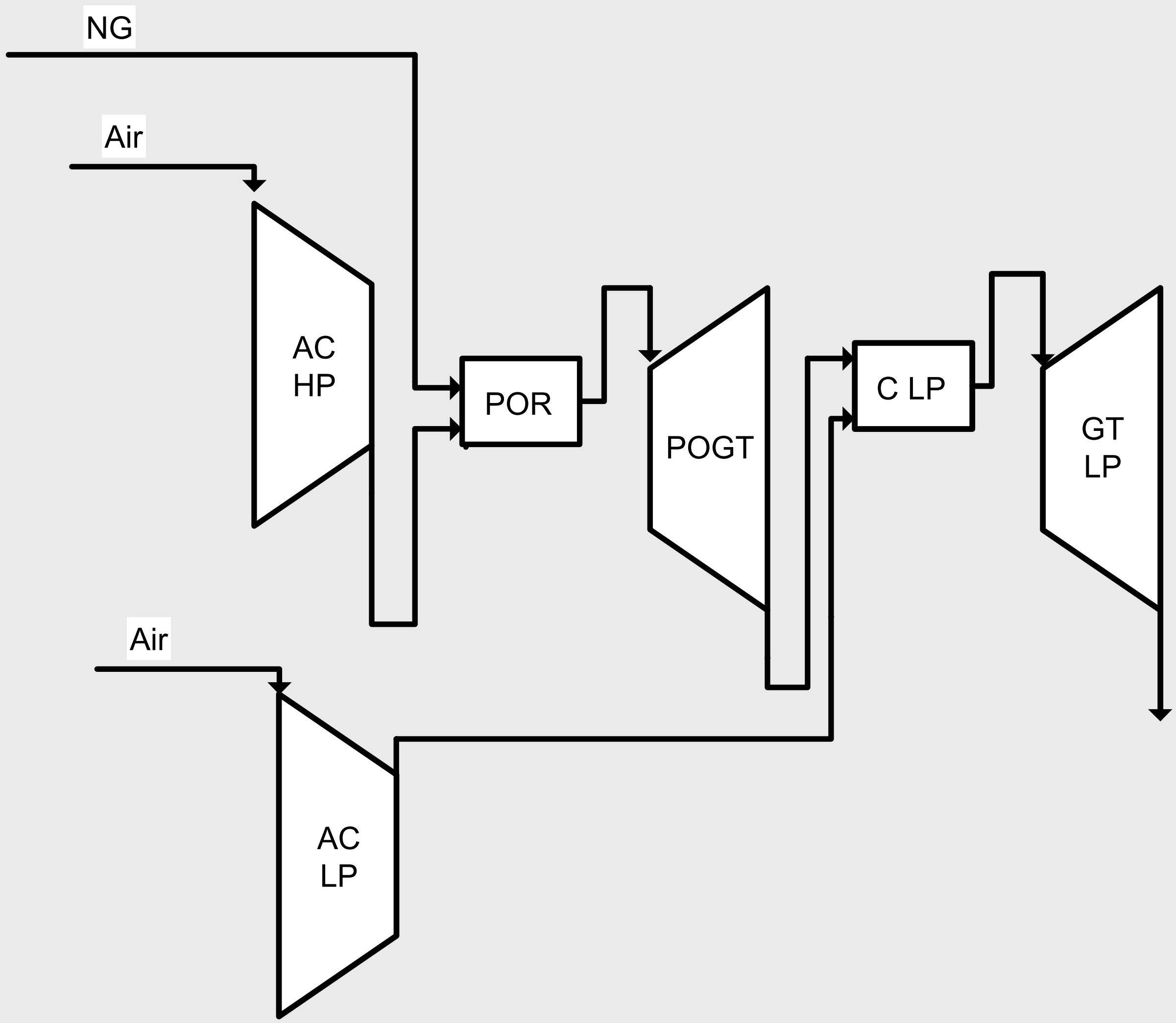
# Conventional Gas Turbine



# Reheat Gas Turbine



# Partial Oxidation Gas Turbine in a Two-Stage Gas Turbine



# IVTAN System Test Results

| | |
|---|---|
| > Power output, MWe | 60 |
| > Inlet pressure, atm | 4.8 |
| > Outlet pressure, atm | 1.2 |
| > Inlet rotor temperature, °C | 550 |
| > Flow rate, kg/s | 62.0 |

> Composition of working fluids, vol.%

| | |
|---|---|
| $H_2$ | 14 |
| CO | 21 |
| $CO_2$ | 21 |
| $H_2O$ | 2 |
| $N_2$ | 59 |
| Other | 1 |
| | 100 |

# Goals for Natural Gas Fired Partial Oxidation Gas Turbine Systems

- System Efficiencies (%LHV) up to:
  - 55% electrical efficiency for steam injection simple cycles
  - 75% electrical efficiency for POGT/FC hybrid
  - 88% fuel to electricity efficiency in cogeneration
  - 90% thermal efficiency for distributed multi-power generation
- Ultra-low emissions:
  - NOx < 2 vppm @ 15% $O_2$, no catalytic treatment

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# Major Characteristics and Issues of POGT System

> Operation on sub stoichiometric combustion products
> Production of $H_2$-enriched fuel / syngas
> Low air compressor power required
> Utilization of non-oxidizing media (steam, flue gases, etc.) for combustor and turbine cooling
> Soot formation
> Hydrogen embrittlement

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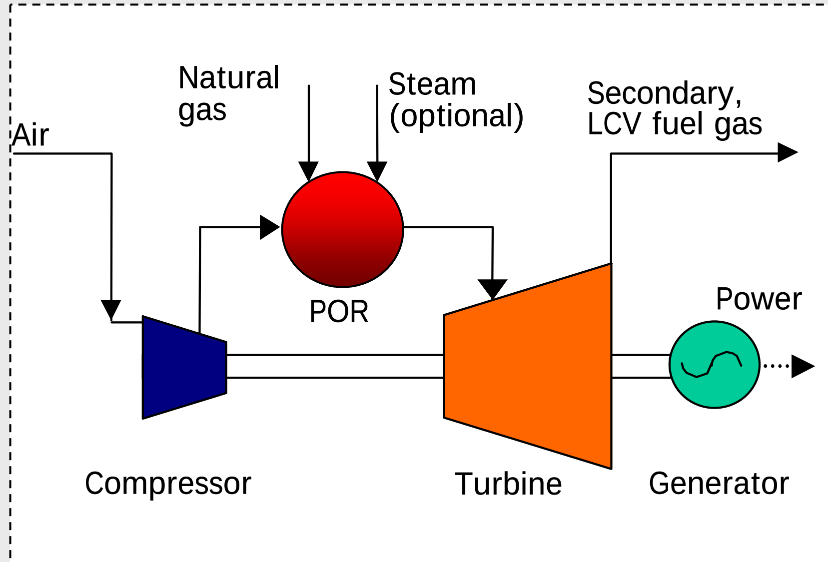
# POGT Overview




> An advanced gas turbine-based systems for on-site co-production of:

- Power
- A hydrogen-rich fuel gas, syngas
- Compressed air
- Hydrogen (where needed, after additional downstream processing and purification of the exhausted fuel gas)

> Platform provides a flexible ratio of generated power and fuel gas production in highly efficient and cost effective manner for different applications

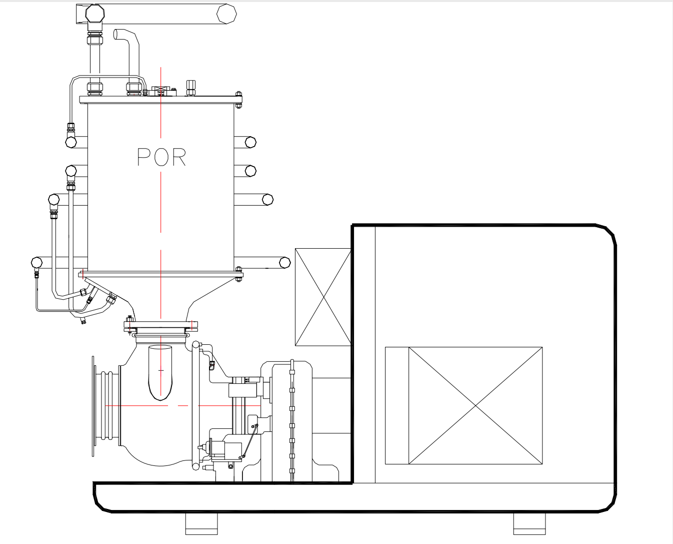
# POGT Development Status

- Construction of POGT Test Cell at GTI's Energy Campus - *completed*
- Design, Fabrication & Installation of a 7 MWth Prototype POR Unit - *completed*
- Design & Conversion of a Prototype 200 kW Spartan Generator Unit for POGT Operation – *completed*

(continued)

# POGT Development Status

- POR Unit Parametric and Start-up Testing – *finishing*
- Design and Integrate POR with converted Spartan Turbine Unit – *ongoing*




- POGT-Spartan unit installation, shakedown and parametric testing – *1st Qtr of 2007*
- Feasibility Design Study of retrofit an existing gas turbine to POGT duty – *ongoing*

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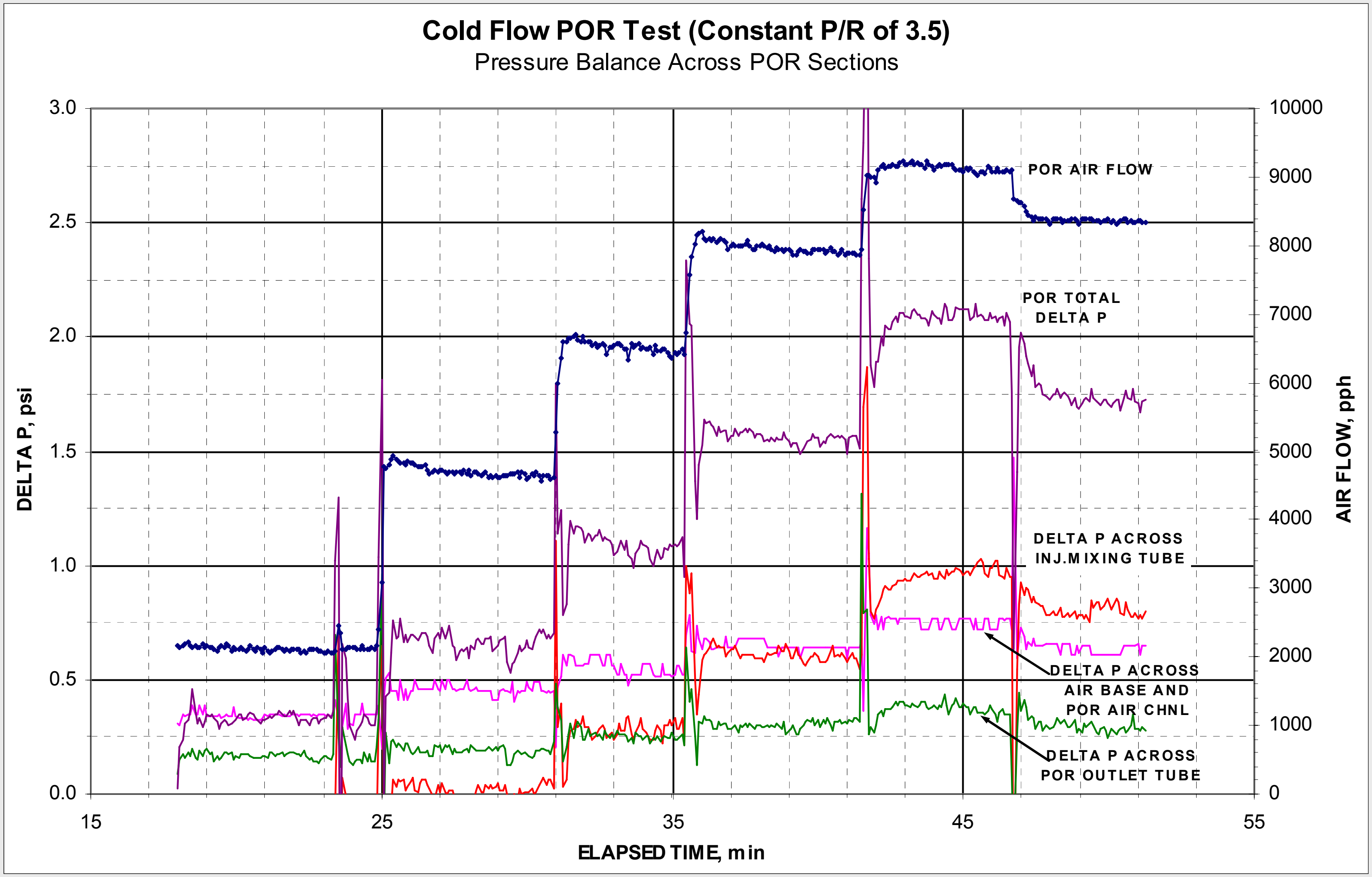
# POR Testing
## Outline

- > Cold tests
- > Torch ignition
- > Light-off
- > Lean operation up to 6 MMBtu/h
- > Conversion from lean to rich
- > Rich operation up to 16 MMBtu/h

# POR Testing
## Cold Tests



# POR Testing
## Torch Ignition

- Torch ignition was tested at the following conditions:
  - With and w/o air flow through POR
  - Air/inert gas ($N_2$ and/or steam) mixture in the POR
  - Inert gas only($N_2$ and/or steam, and no air) in the POR
- Stable ignition and operation was achieved at all above conditions
- Torch flame heat input ~120 kBtu/h at selected air and NG parameters

# POR Testing

## Light-Off

> Stable light-off was achieved at the following conditions:

- Air flow rate 15 – 40 ppm
- NG flow rate 0.8 – 1.5 ppm
- Fuel/air ER 0.4 – 0.9
- Inert gas ($N_2$ and/or steam) flow rate 2 – 10 ppm

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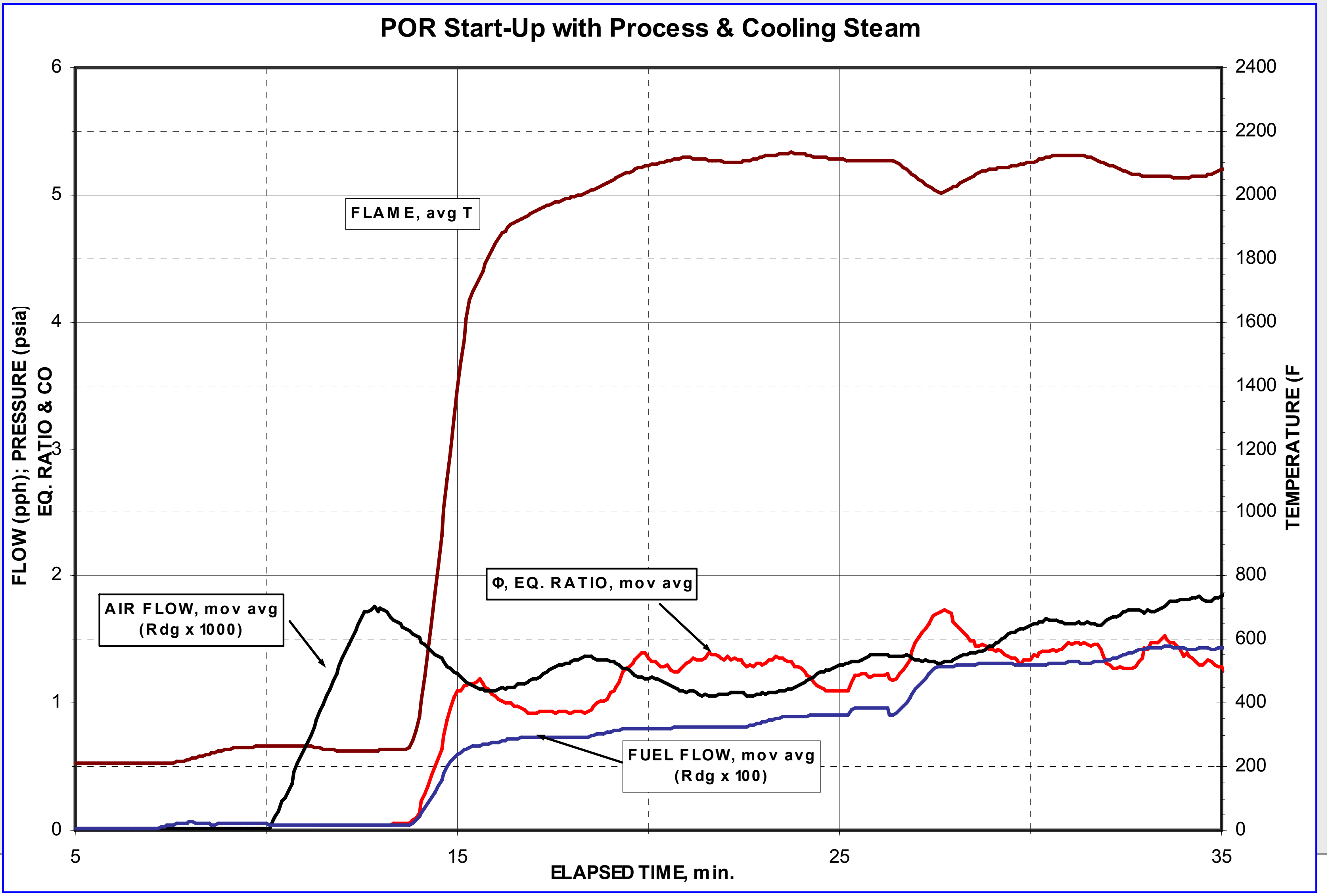
# POR Start-Up



POR Start-Up with Process & Cooling Steam
FLAME, avg T
Φ, EQ. RATIO, mov avg
AIR FLOW, mov avg
(Rdg x 1000)
FUEL FLOW, mov avg
(Rdg x 100)
FLOW (pph); PRESSURE (psia)
EQ. RATIO & CO
TEMPERATURE (F
ELAPSED TIME, min.
0
1
2
3
4
5
6
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
5
15
25
35

# POR Testing
## Lean Operation

> Lean operation was tested at the following conditions:

- Air flow rate 20 – 70 ppm
- NG flow rate 1.0 – 4.5 ppm
- Fuel/air ER 0.4 – 0.9
- Inert gas (N2 and/or steam) flow rate 3 – 30 ppm

> Lean operation before conversion to rich :

- Air 35 ppm; NG 1.5 ppm; Steam 25 ppm;
  ER 0.95

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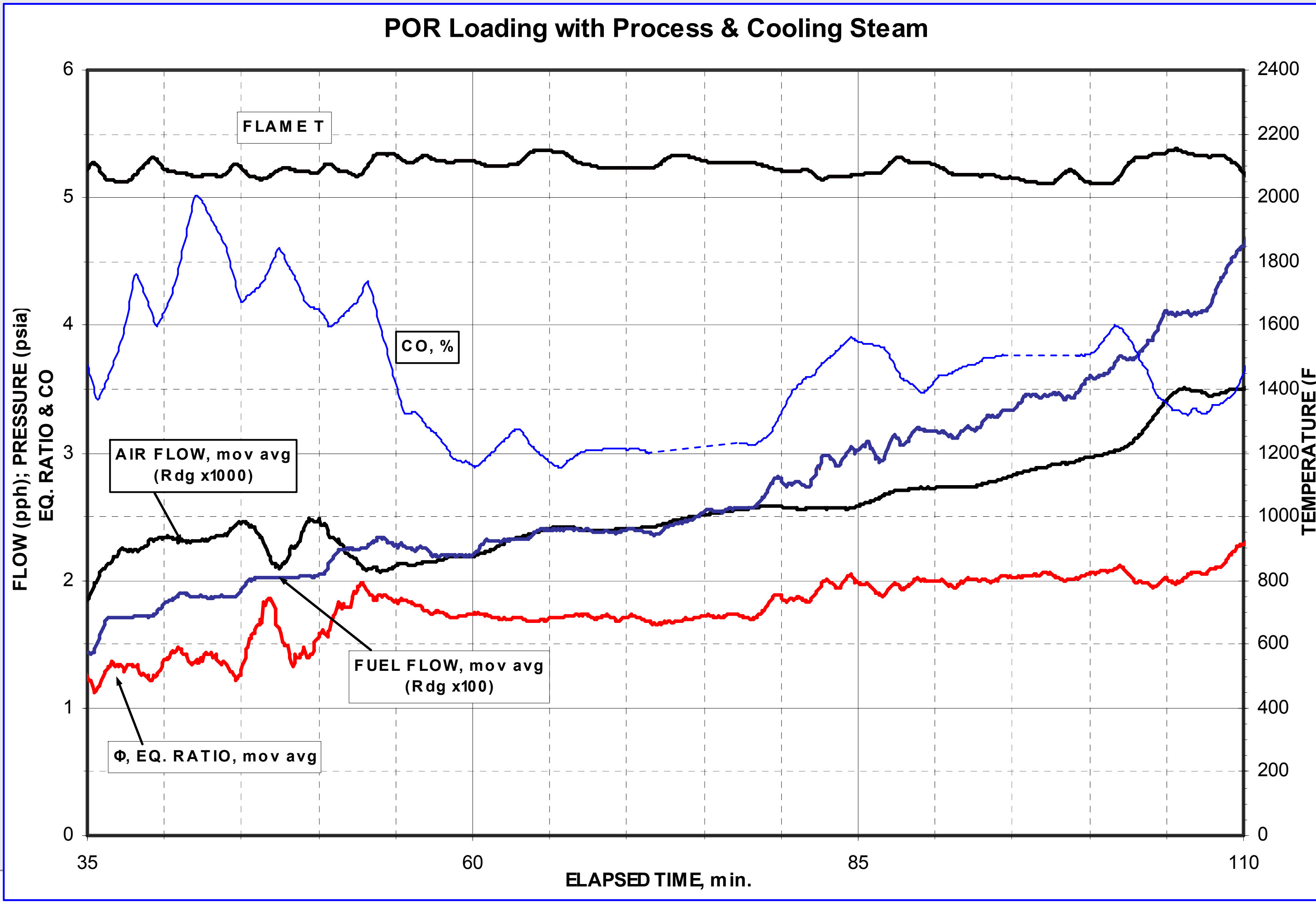
# POR Testing
## Rich Operation

> Rich operation was tested at the following conditions:

- Air flow rate 30 – 85 ppm
- NG flow rate 2.0 – 12 ppm
- Fuel/air ER 1.5 – 4.3
- Inert gas (N2 and/or steam) flow rate 5 – 40 ppm

# POR Loading



POR Loading with Process & Cooling Steam
FLAME T
CO, %
AIR FLOW, mov avg
(Rdg x1000)
FUEL FLOW, mov avg
(Rdg x100)
Φ, EQ. RATIO, mov avg
FLOW (pph); PRESSURE (psia)
EQ. RATIO & CO
TEMPERATURE (F
ELAPSED TIME, min.
0
1
2
3
4
5
6
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
35
60
85
110

# POR Exhaust Gas Composition

| | Mol% | Mol% | Mol% |
|---|---|---|---|
| Hydrogen ($H_2$) | 5.70 | 8.18 | 11.14 |
| Oxygen/Argon | 2.15 | 2.49 | 0.99 |
| Nitrogen ($N_2$) | 77.30 | 73.98 | 69.30 |
| Carbon Monoxide (CO) | 4.76 | 6.86 | 8.81 |
| Methane ($CH_4$) | 2.21 | 2.23 | 6.06 |
| Carbon Dioxide ($CO_2$) | 7.64 | 5.98 | 2.71 |
| Ethylene ($C_2H_4$) | 0.141 | 0.058 | 0.161 |
| Ethane ($C_2H_6$) | 0.024 | 0.043 | 0.011 |
| Propane ($C_3H_8$) | | | 0.125 |
| Acetylene ($C_2H_2$, ethyne) | 0.119 | 0.178 | 0.672 |
| i-pentane ($C_5H_{10}$) | | | 0.009 |
| hexane ($C_6$+) | 0.004 | | |
| Total | 100.0 | 100.0 | 100.0 |
| | | | |
| HHV, Btu/cf (calc) | 60.9 | 75.7 | 142.5 |
| | | | |
| EQ. RATIO (Φ) | 1.34 | 2.62 | 3.45 |
| PR | 2.5 | 3.20 | 3.01 |
| Flame Temperature, °F | 1901 | 1998 | 2009 |
| Firing Rate, MMBtu/h | 5.14 | 8.84 | 8.40 |

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# POR Testing
## Findings

- Confirmed POR test rig mechanical integrity and operation readiness for required air, fuel, steam and N2 flow rates
- Determined process conditions and protocol for reliable light-off at different air, fuel, steam and/or N2 flow rates
- Achieved stable lean operation up to 6 MMBtu/h firing rate
- Transitioned from lean to rich combustion mode in POR and achieved stable operation at ER of 1.5 – 4.3
- Achieved stable rich operation up to 16 MMBtu/h

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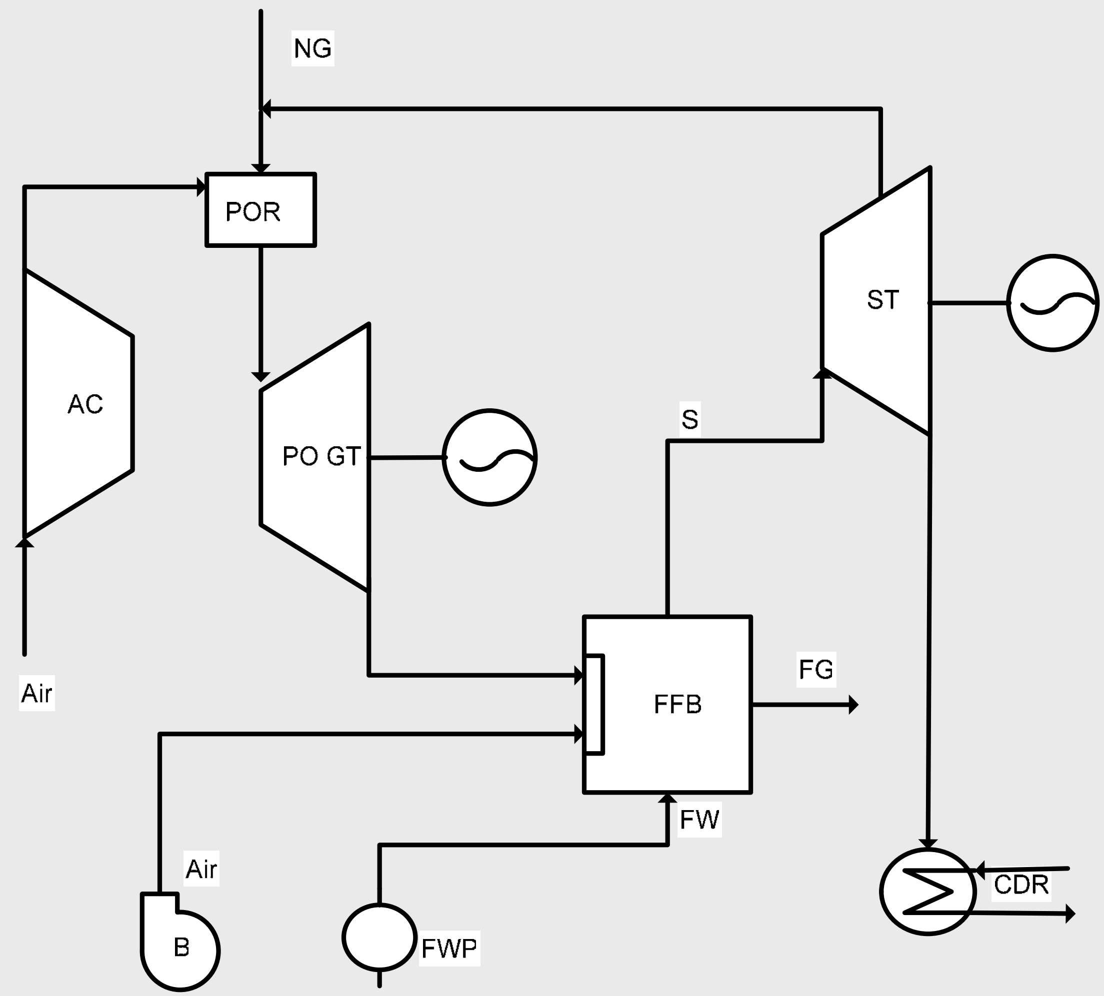
# Areas of POGT Applications

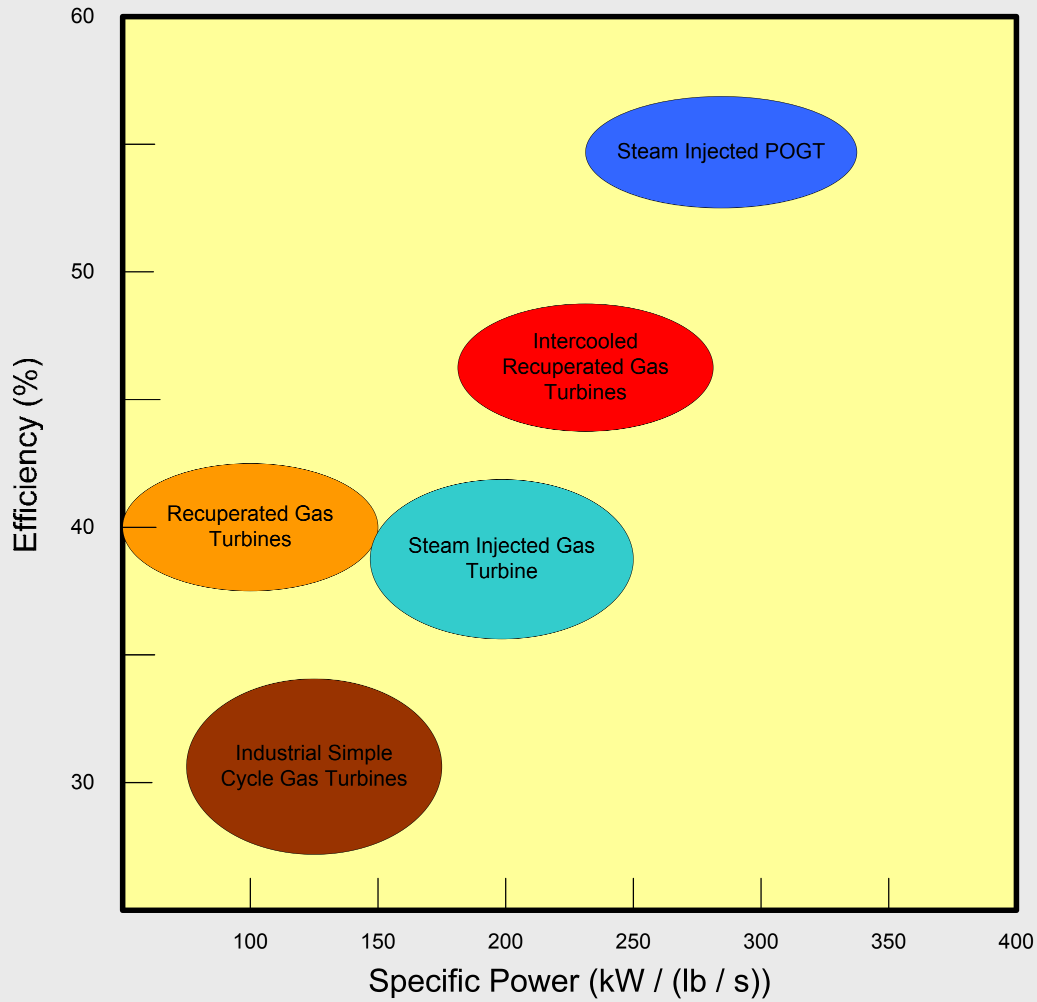
> Power generation, cogeneration, multi-power generation utilizing
  - —Gas turbines
  - —Internal combustion engines
  - —Fuel cells: POGT/SOFC Hybrid
> Co-Production of Power and Hydrogen/Syngas
  - —Remote self-powered units
  - —Distributed Hydrogen and Power generation
> Industrial cogeneration
  - —High temperature (glass, cement, chemicals, pyrometallurgy, incineration, etc.)
  - —Medium temperature (aluminum, direct ore reduction, heat treatment, etc.)
  - —Boilers, process heaters, chillers

# #2
# POGT for Power Generation

# Single Stage POGT in a Combined Cycle with a FFB

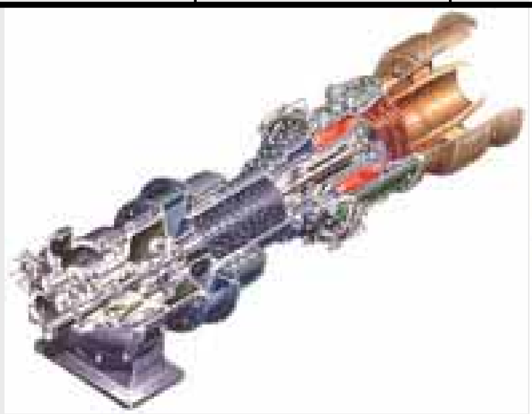
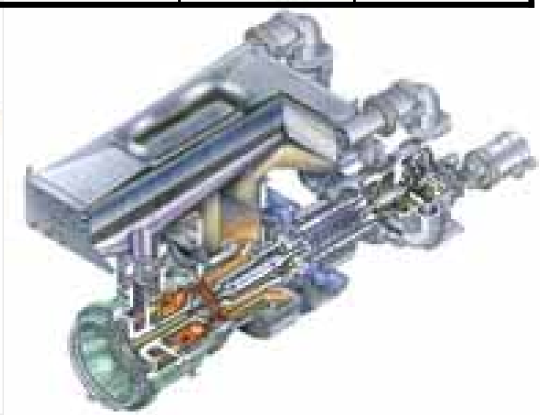


# Performance Comparison of Steam Injected POGT and Other Advanced Cycles



# Solar's Product Line Turbines to be Operated in POGT Mode

| Engine Model | Power $kW_e$ | Compr-r Work, kW | Turbine Power kW | Exh. Flow, lb/h | Exh. T,°F | Eff., % |
|---|---|---|---|---|---|---|
| Spartan 350 | 200 | 518 | 734 | 20,860 | 1,165 | 15.5 |
| Centaur 40 | 3,520 | 5,960 | 9,750 | 147,720 | 820 | 27.9 |
| Mercury 50 | 4,600 | 4,980 | 10,100 | 139,710 | 725 | 38.0 |

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# Efficiency Comparison of Solar's Turbines Operated in Design Condition and POGT Mode

| Engine Model | Eff., % | Eff. POGT, % |
|---|---|---|
| Spartan 350 | 15.5 | 25.0 |
| Centaur 40 | 27.9 | 42.9 |
| Mercury 50 | 38.0 | 52.0 |

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# POGT /SOFC Hybrid Application, Combined Cycle

Performance Summary for Conceptual POGT-SOFC System

| | Competitive GT-FC | POGT-SOFC |
|---|---|---|
| System electrical efficiency, % LHV | 70 | 78 |
| $NO_x$ emissions, @15% $O_2$, vppm | <9 | <2 |
| Excess air, % | 260 | 15 |
| Lean premixed combustion | required | not required |
| GT and FC size for comparable power output | 1.00 | 0.83 |
| Power output split between GT and FC | 30/70 | 45/55 |
| Pre-reformer required for FC stack | Yes | No |
| Production of $H_2$-enriched gas | No | Yes |

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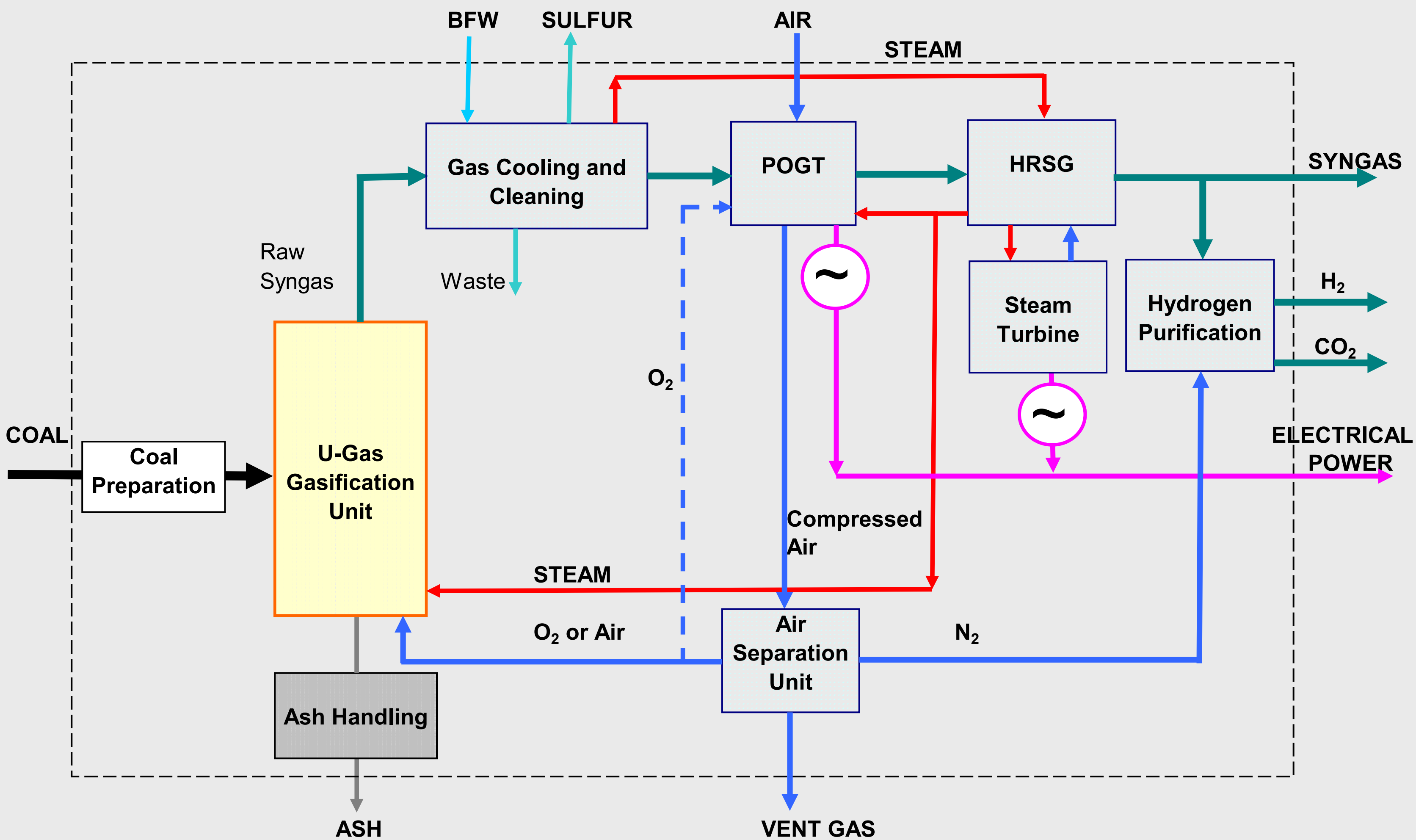
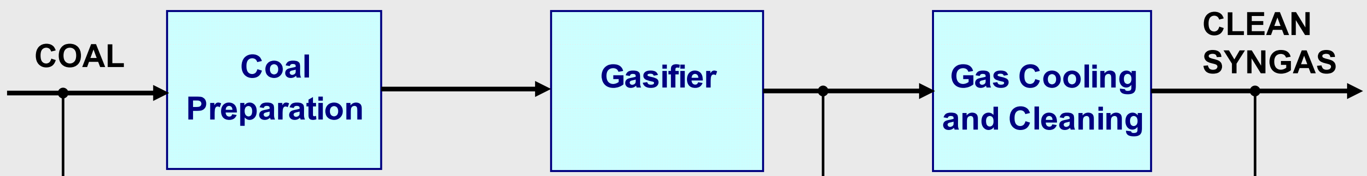
# #3
# POGT for Combined Hydrogen and Electricity Generation

# IGCC-POGT Plant Scheme for Power and Syngas/Hydrogen Co-Production from Coal



# IGCC-POGT Coal and Syngas Gas Composition




| Ultimate Analysis, wt% | As-Received |
|---|---|
| C | 68.38 |
| H | 5.3 |
| N | 1.41 |
| S | 3.04 |
| Ash | 5.41 |
| O | 8.06 |
| Moisture | 8.40 |
| HHV, Btu/lb | 12,448 |

| Syngas Composition | % mole |
|---|---|
| $H_2$ | 12.09 |
| CO | 20.72 |
| $CH_4$ | 4.25 |
| $CO_2$ | 6.88 |
| $H_2O$ | 6.39 |
| $N_2$ | 48.97 |

| | |
|---|---|
| $H_2S$ | 0.52 |
| COS | 0.02 |
| $NH_3$ | 0.15 |
| CHN | 0.02 |

| Impurity Requirements, ppmw | |
|---|---|
| Na+K | 0.06 |
| V | 0.06 |
| Ca | 1.18 |
| Pb | 0.06 |
| Ba | 0.24 |
| Mn | 0.24 |
| P | 0.24 |
| S | 588.9 |
| HCN+$NH_3$ | 17.7 |
| Cl | 0.71 |

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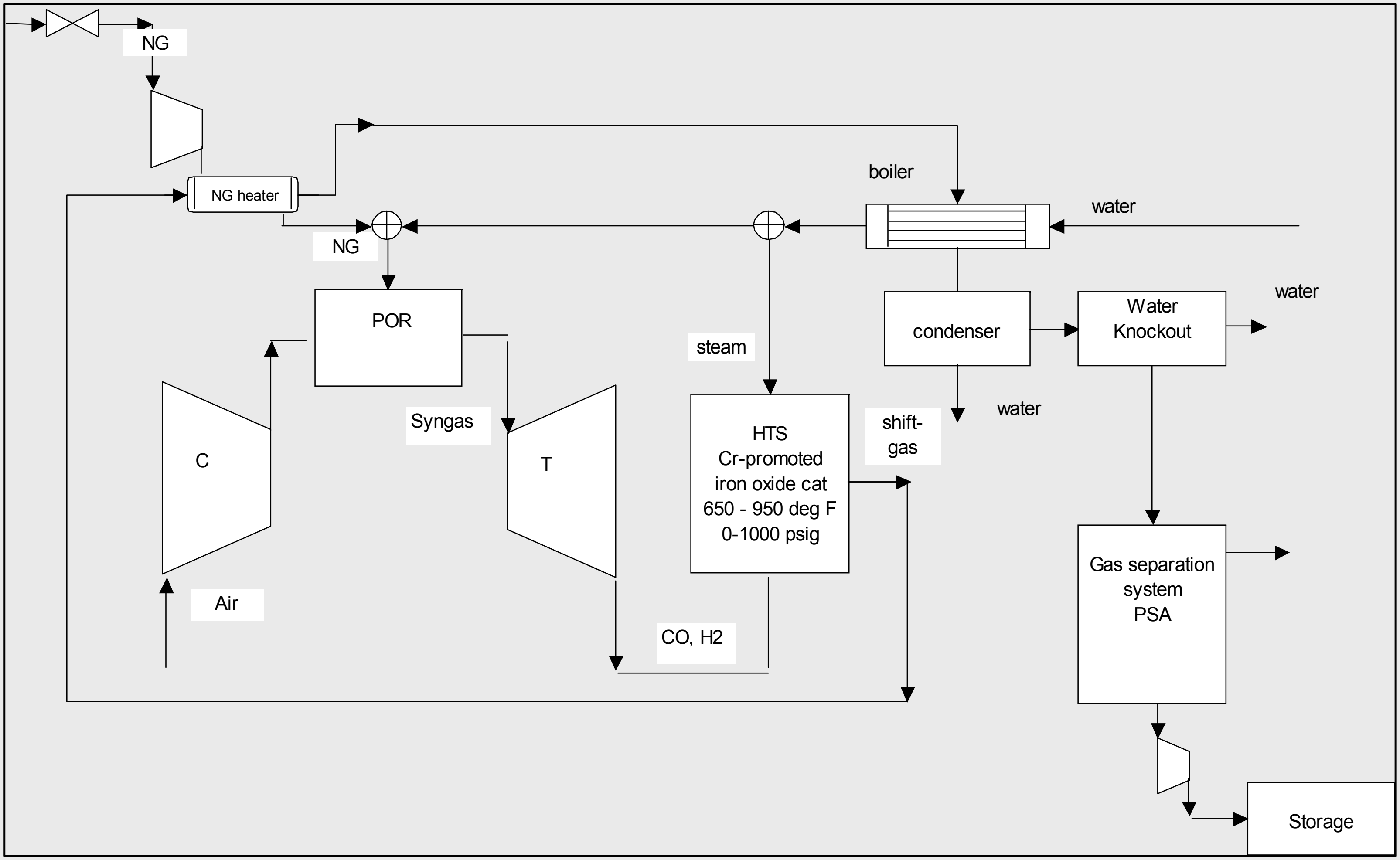
# POGT Based Hydrogen and Electricity Generation



# POGT Based Hydrogen and Electricity Generation

## Performance for Spartan and Centaur 40

| | Spartan | Centaur |
|---|---|---|
| NG, SCFH | 32,430 | 349,805 |
| Air, SCFH | 106,955 | 1,153,658 |
| NG, LHV, mmBtu/hr | 30 | 319 |
| POGT power, kW | 427 | 6,944 |
| Hydrogen produced, Lb/hr | 452 | 4,879 |

## Estimated costs for Spartan and Centaur 40

| | | Spartan | Centaur |
|---|---|---|---|
| Costs in $/kg H2 | ATR/PSA | POR/PSA | POR/PSA |
| H2 cost | 3.59 | 2.57 | 2.12 |
| Capital recovery | 1.5 | 0.90 | 0.76 |
| Natural gas | 1.17 | 1.11 | 0.83 |
| electricity | 0.41 | 0.10 | 0.07 |
| O&M | 0.31 | 0.26 | 0.26 |
| Taxes and Insurance | 0.2 | 0.2 | 0.20 |

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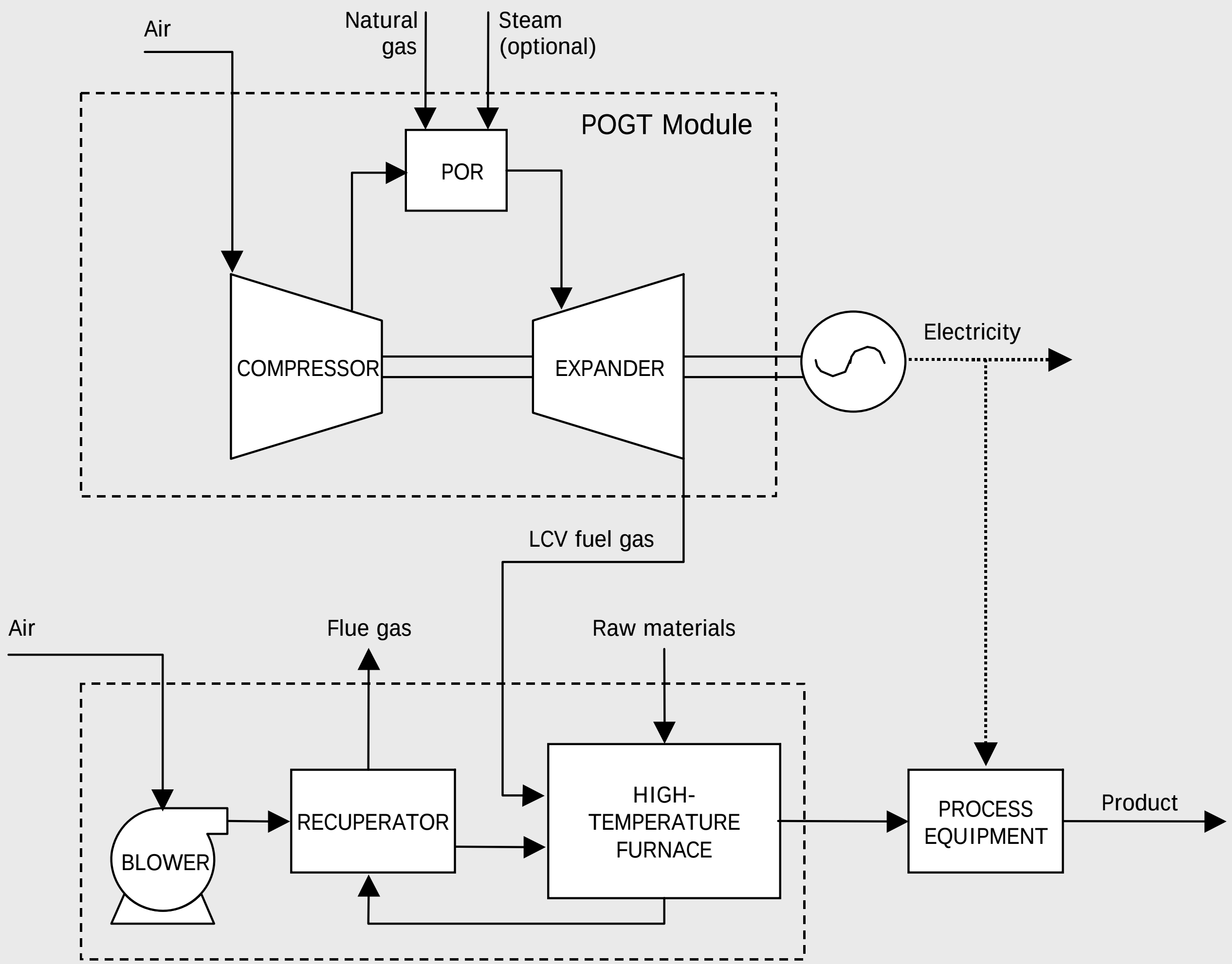
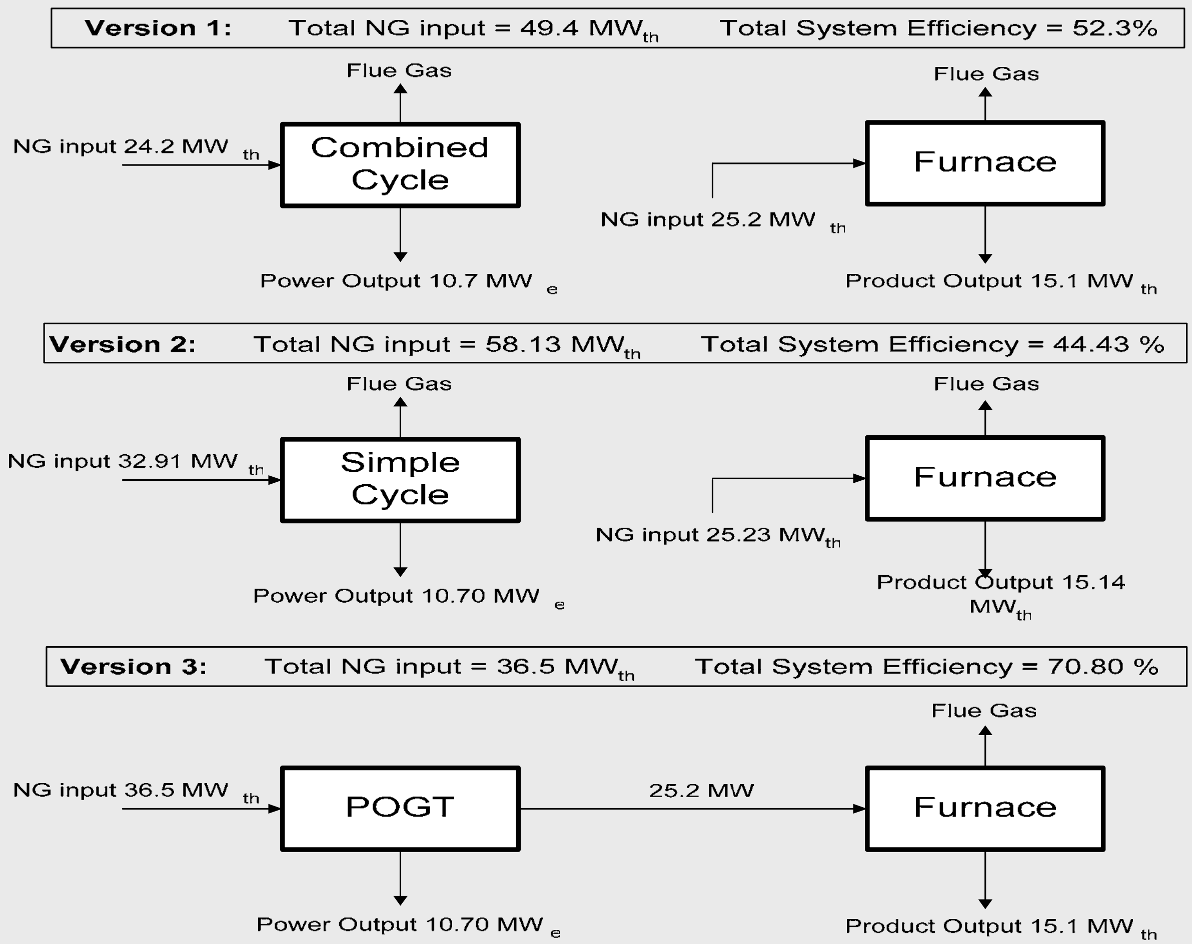
# #4
# POGT Cogeneration with High-Temperature Industrial Furnaces

# POGT-HTF Cogeneration Cycle



# Efficiency Advantage of POGT-HTF Cycle

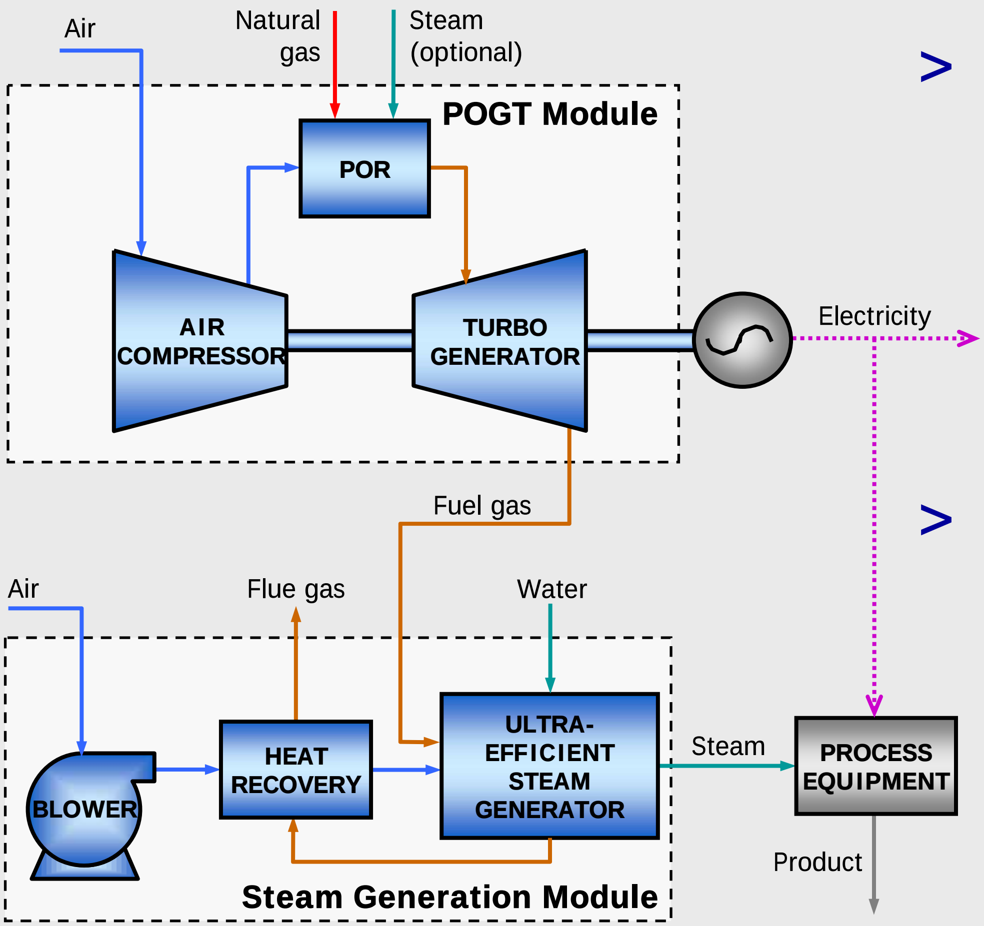


# #5
# POGT Cogeneration with Steam or Hot Water Boilers, and/or Absorption Chillers

# POGT-CCHP Benefits

- Partial Oxidation Gas Turbine (POGT) integrated with ultra-efficient boiler
- Superior potential
  - Efficiency: up to 89% (HHV)
  - Emissions: less than 5 ppmv (@3% $O_2$) $NO_x$ and CO
  - Flexibility: power/heat ratio from 0.2 to 1.2
  - Packaging: focus on pre-engineered packages in 0.4 to 15.0 MWe range

# POGT-CHP Cycle with Advanced Steam Generation




- POGT module
  - Non-catalytic POR
  - Reduced compressor demand
  - Extremely low NOx formation
- Steam gen module
  - POR exhaust gas burned to raise steam
  - Low excess air
  - Advanced heat recovery system

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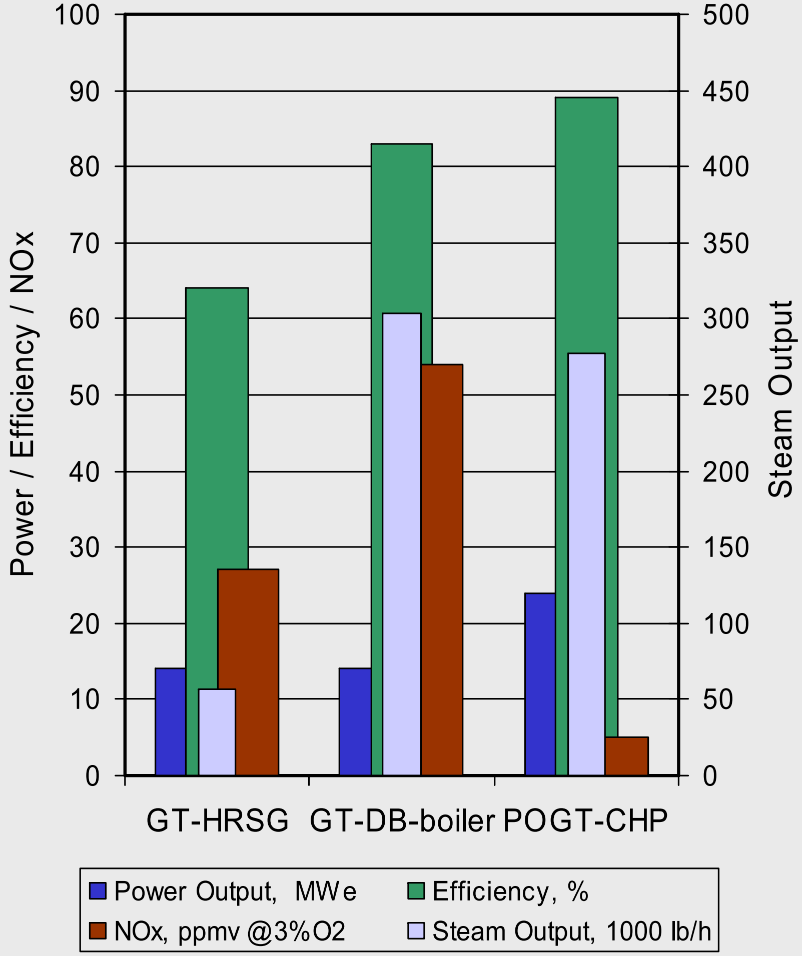
# POGT-CHP Comparison with Competing CHP Cycles




> Comparison based on nominal 14-MW turbine
  - Efficiency
  - Emissions
  - Flexibility

> Annual savings*:
  - 35 trillion Btu
  - 2.0 million tons $CO_2$
  - 11,000 tons NOx
  - $238 million total cost savings

* Based on 10% penetration of predicted CHP market by 2015