LPP = Lean, Premixed & Prevaporized

Lean, Premixed, Prevaporized (LPP) Combustion for Gas Turbines

November 2017

The 16th Israeli Symposium on Jet Engines and Gas Turbines

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Michael S. Klassen, P.E., Ph. D.; Aharon David, B.Sc. MBA
LPP Combustions, LLC

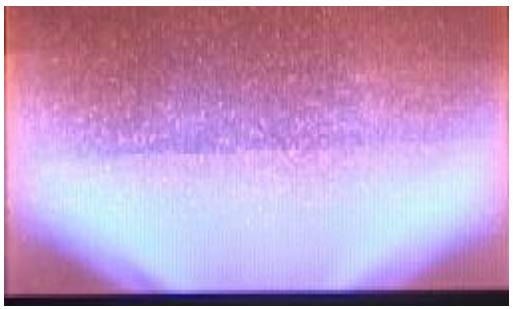
Outline

- Combustor Technology Review
- LPP Combustion Technology Solution
- 30 KWe Gas Turbine Experimental Results
- Centaur 50 Burner Experimental Results
- Suitable Fuels & Applications Spectrum
- Current Commercial Installation
- Oil & Gas Demo and Applications
- Utility-Scale Applications
- Interim Summary

Combustor Technology Review

- Traditional Combustion of Liquid Fuels in a Spray (Diffusion) Flame Creates High Levels of NOx, CO and Particulate Matter, even with Significant Water Injection to Reduce Emissions.

- Gaseous Fuel Combustion (with Natural Gas or LPP Gas) in a Lean, Premixed Burner Creates a Low-Emissions, Environmentally Friendly Blue Flame.

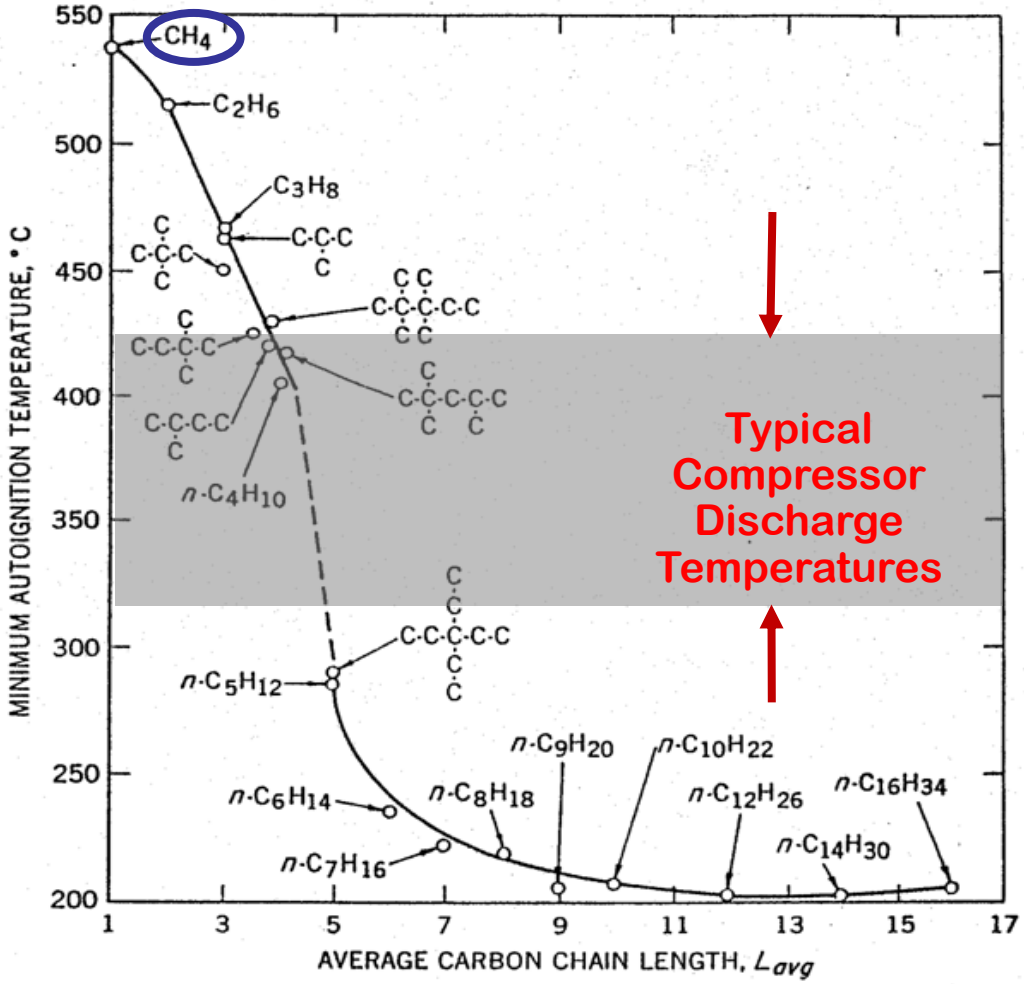


***LPP* = *L*ean, *P*remixed & *P*revaporized**

US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.

Fuel Autoignition Characteristics

- Autoignition becomes a problem for higher hydrocarbons, at higher inlet temperatures, where it is not a problem for natural gas



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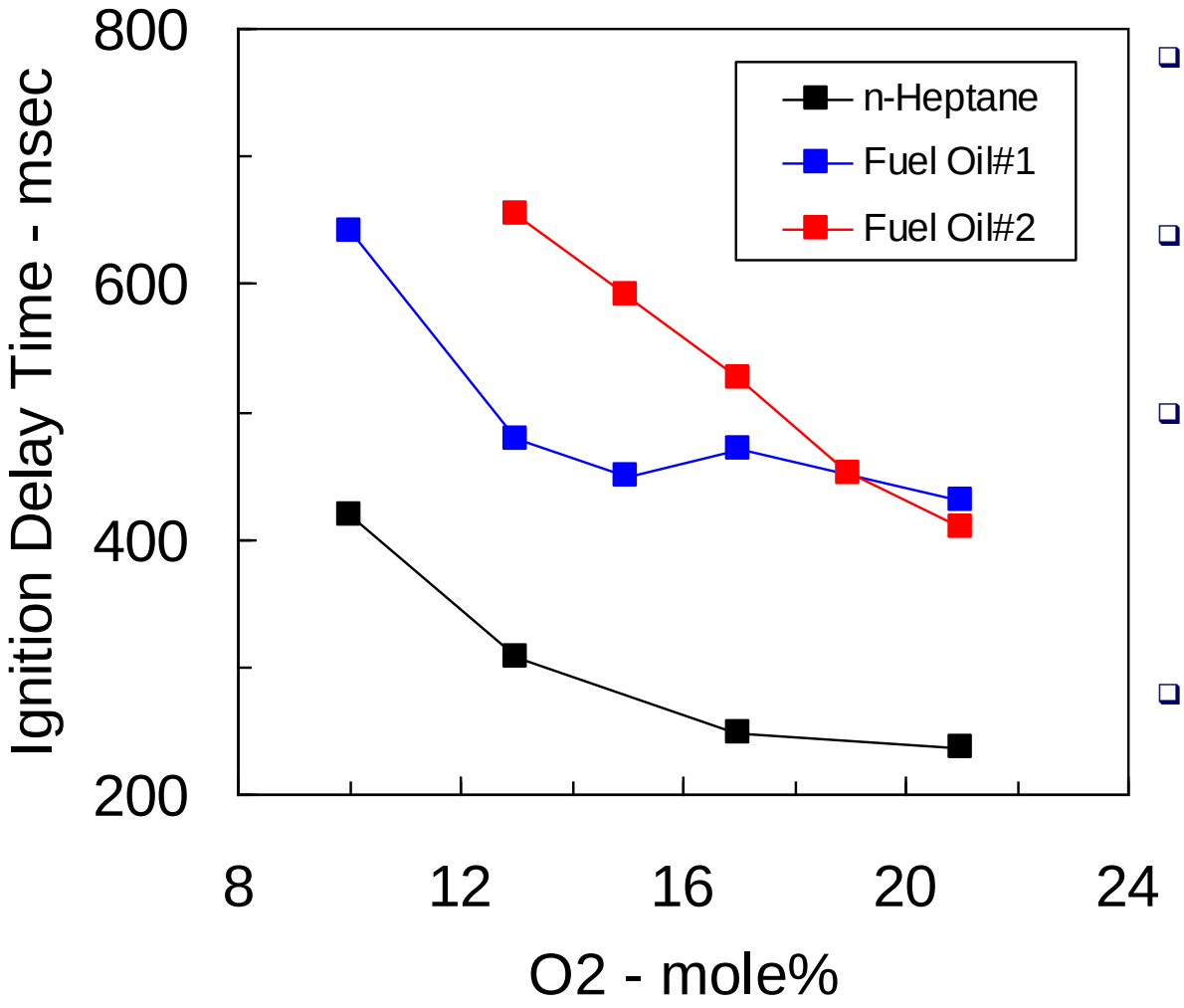
AFAPL-TR-75-70

Ignition Delay Time (IDT) Varies with O_2



- Atmospheric Pressure
- 900 K inlet temperature
- IDT increases by factor of 1.5 to 2 with decreasing O_2 level
- Presence of aromatic hydrocarbons in fuel oils leads to longer IDT

LPP = Lean, Premixed & Prevaporized

Gokulakrishnan, GT2007-27552

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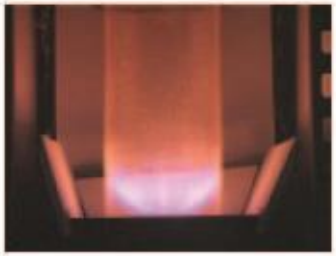
The Problem, Solved by LPP

Burn Liquid Fuels at or Below Natural Gas Emission Levels

Conventional Liquid Fuel Flame

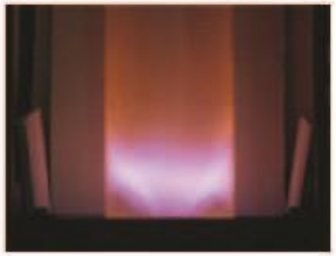
The Problem

Natural Gas Flame



The Goal

Liquid Fuel (Biodiesel) Using the LPP System



The Solution

- Many firms have attempted to solve the problem (e.g. GE, Siemens, United Technologies), but have traditionally concentrated on modifying the combustor hardware.

- LPP Combustion solved this problem by focusing on modifying the fuel, allowing it to be cleanly burned in combustor hardware designed for burning gaseous fuels.

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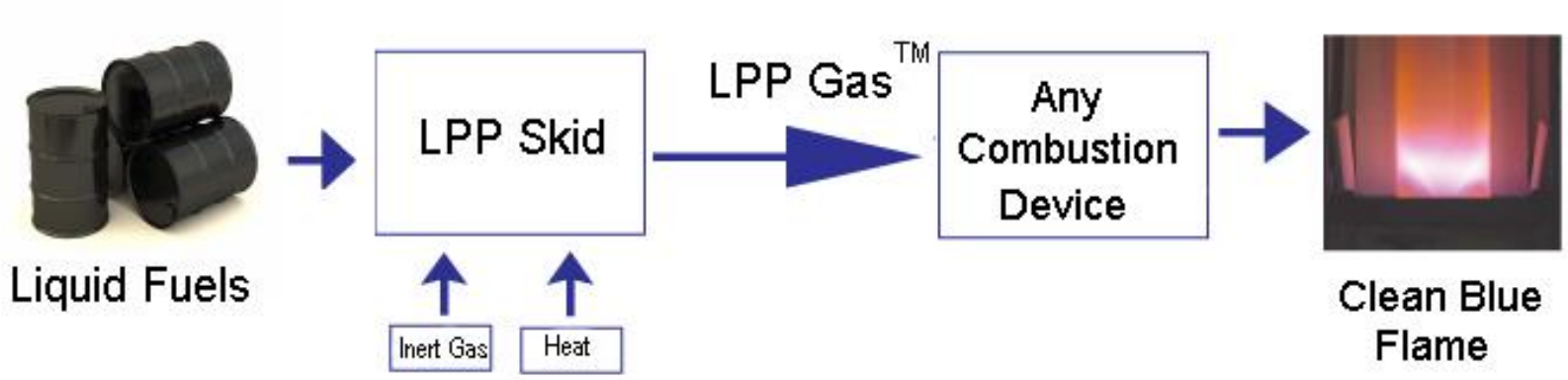
The Patented Solution

LPP = Lean, Premixed & Prevaporized

- The LPP Combustion System Vaporizes Liquid Fuels Into a Reduced-Oxygen Background Gas (diluent), Creating a Substitute Natural Gas -> ***LPP Gas™***

- This LPP Gas™ Can Then Be Burned With Low Emissions In Place Of Natural Gas In Virtually Any Combustion Device: Turbine, IC Engine, Boiler, Duct…



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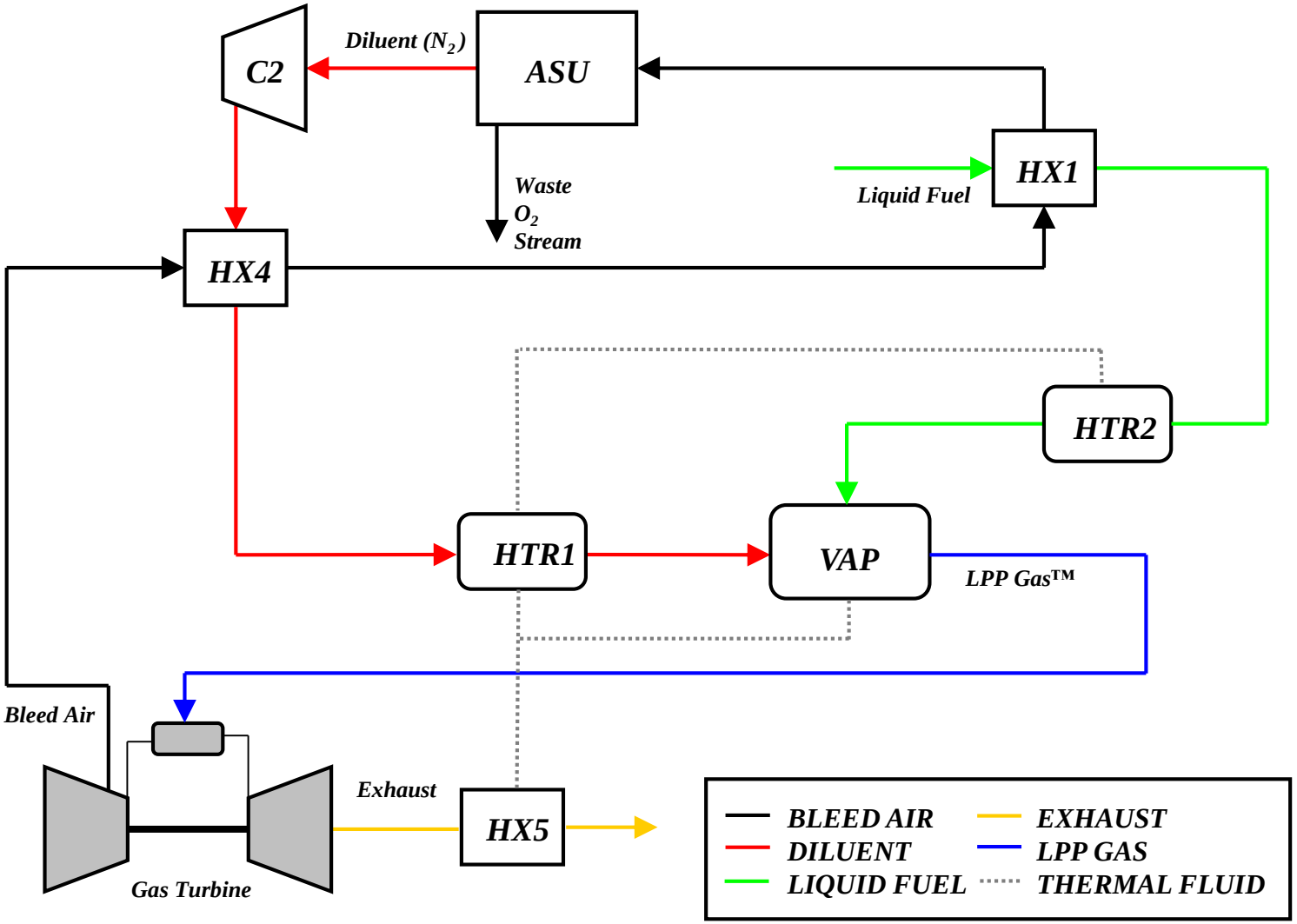
Gas Turbine/LPP Process Flow Diagram



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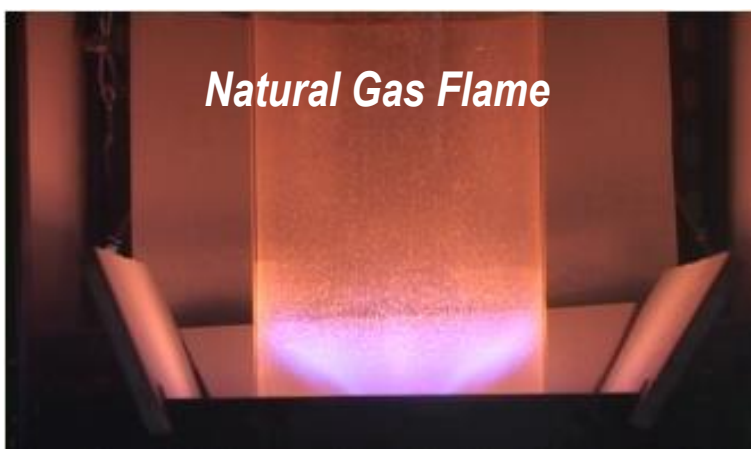
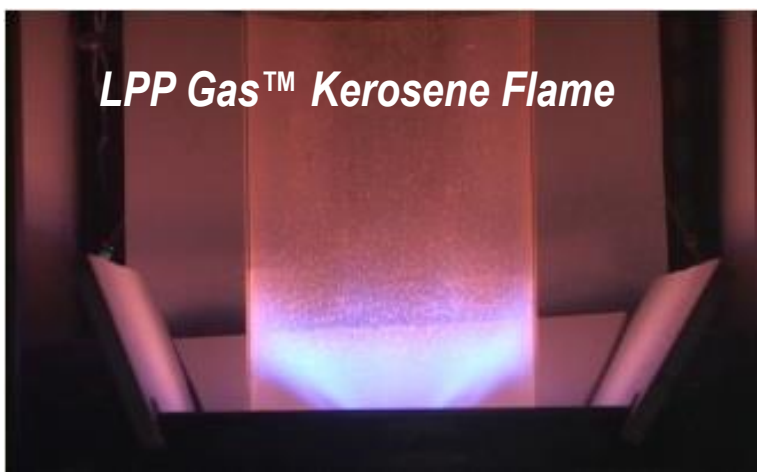
Gas Turbine LPP Effect

Same Gas Turbine Combustion System as Natural Gas

The LPP System Provides Clean Energy from Liquid Fuels:

- Provides Flexible Liquid/Gaseous Fuel Source While Reducing Emissions
- Uses Existing Power Generation Equipment and Infrastructure
- Enables wide spectrum Fuel Flexibility
- Reduces Fuel Cost due to "Physical Fuel Arbitrage"
- Reduces Equipment Maintenance Cost – lower corrosion, etc.





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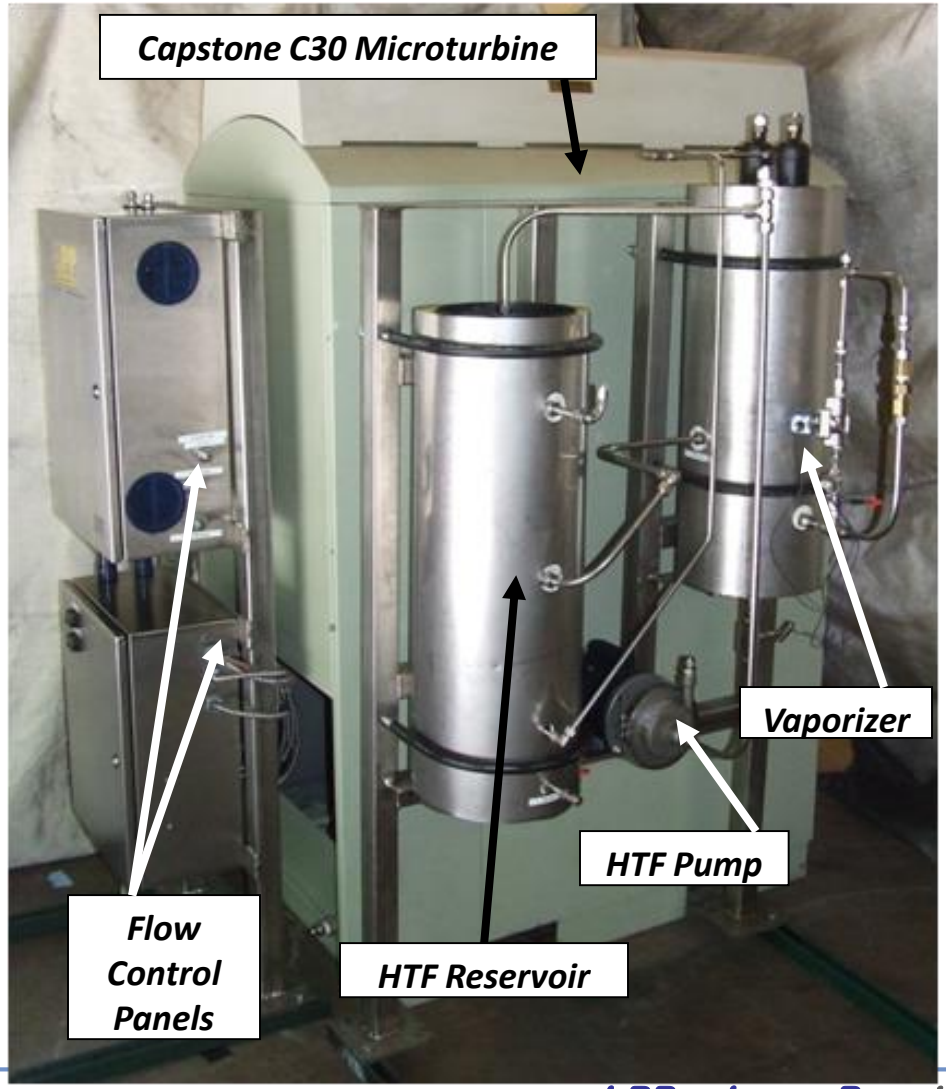
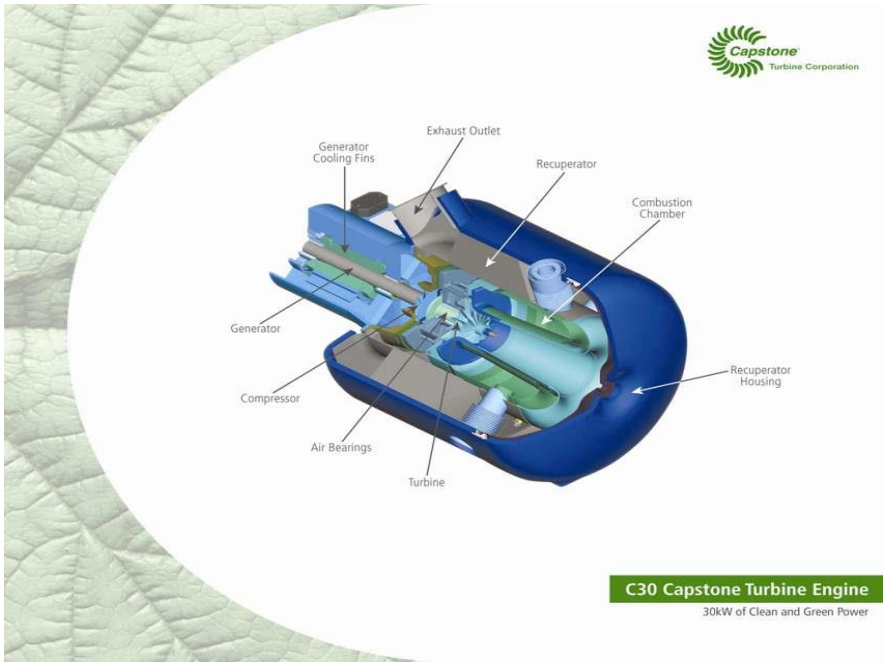
Capstone C30 Gas Turbine with LPP Combustion Fuel Processing Skid





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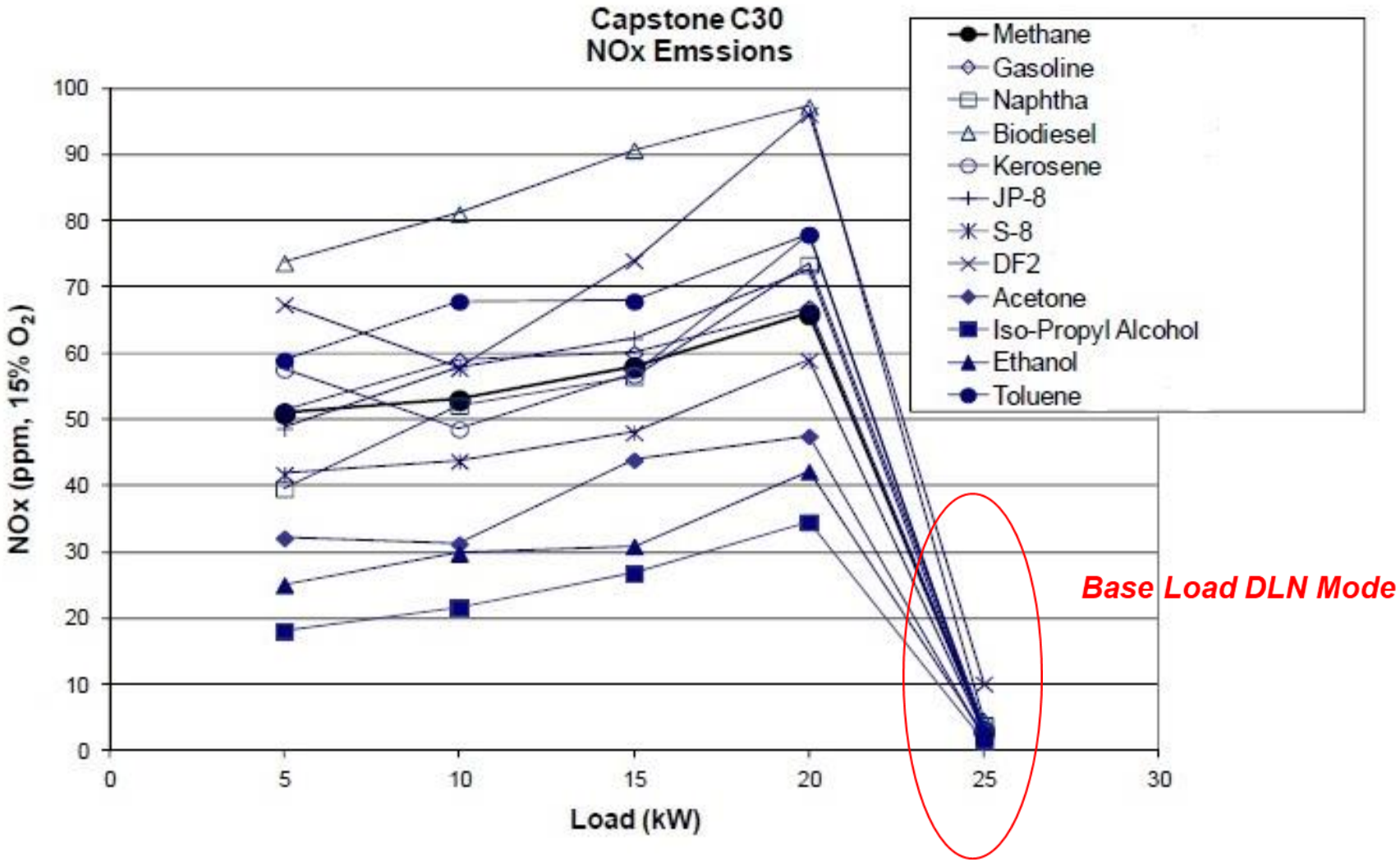
C30 Gas Turbine NOx Emissions Data



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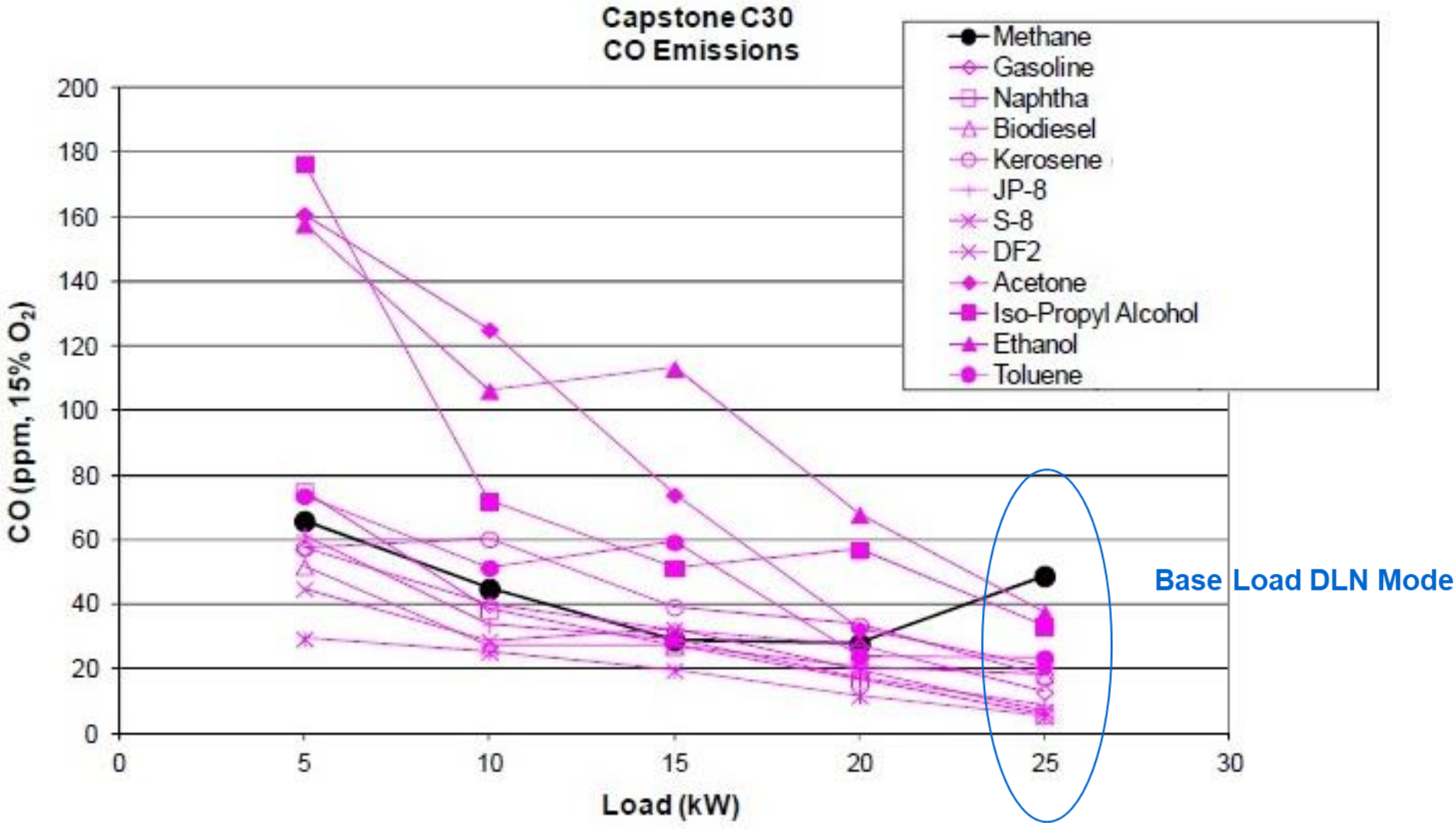
C30 Gas Turbine CO Emissions Data



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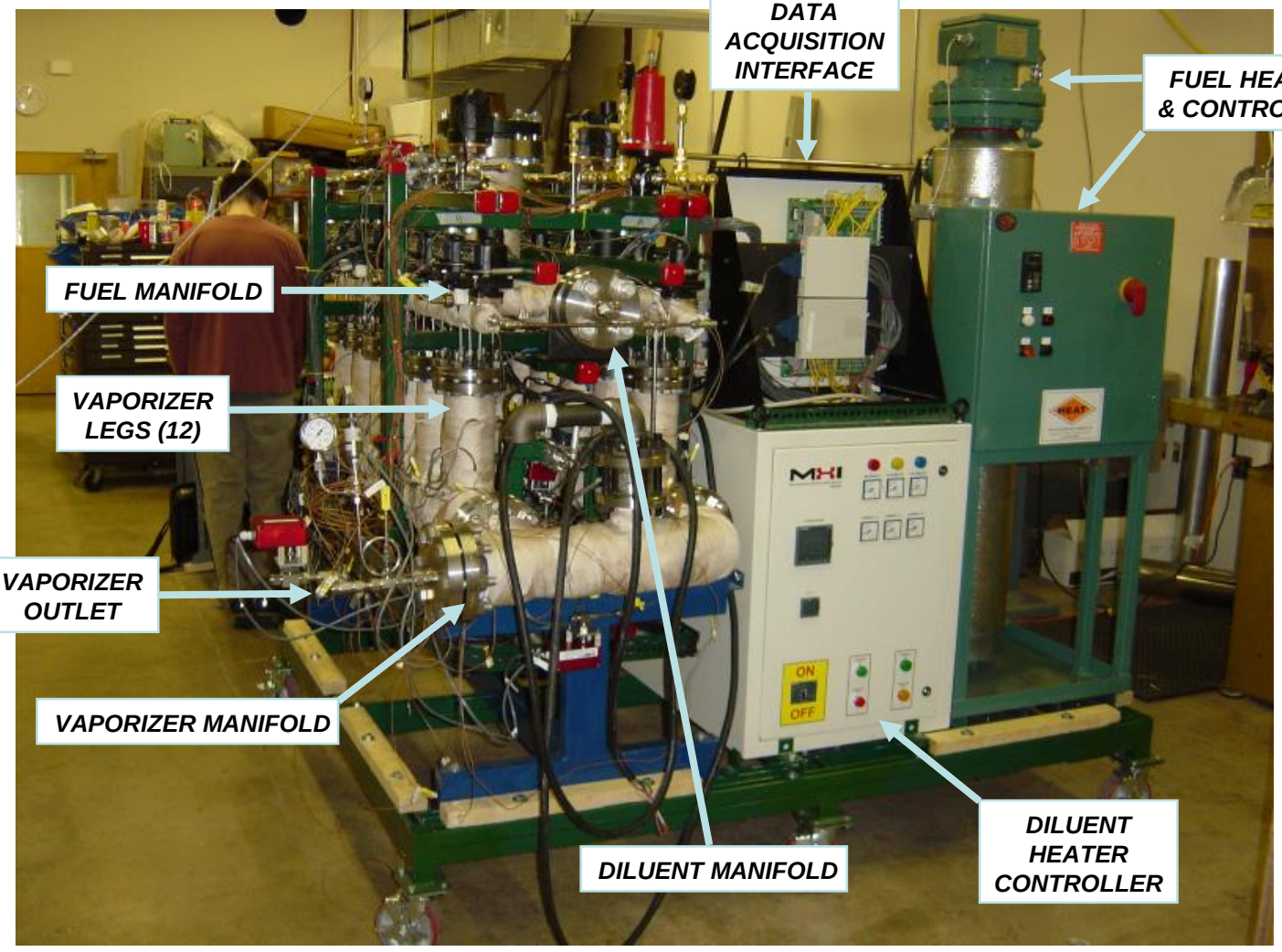
Solar Centaur 50 Combustor Prototype LPP Skid



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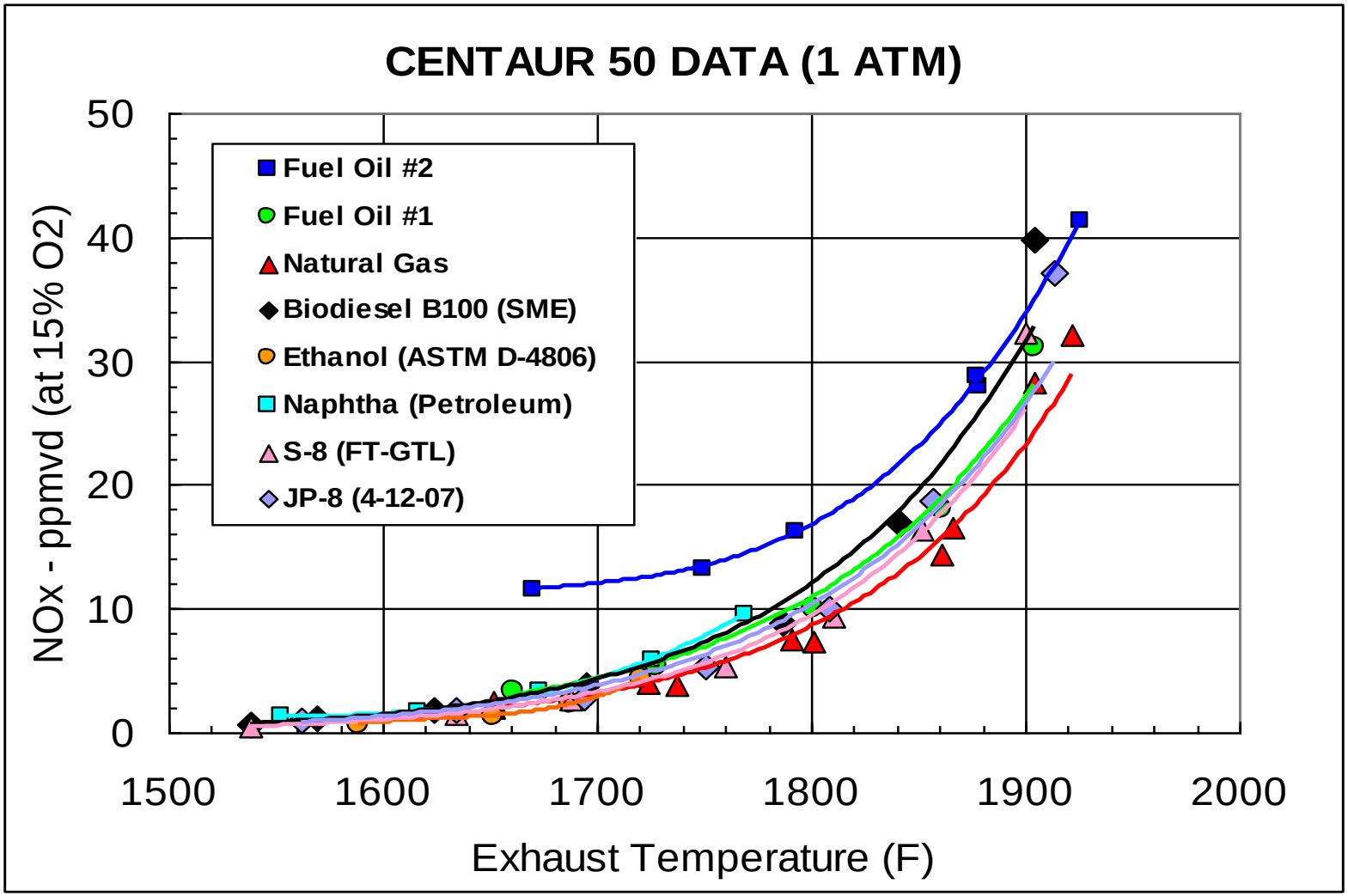
Solar Centaur 50 Combustor NOx (1 Atm)



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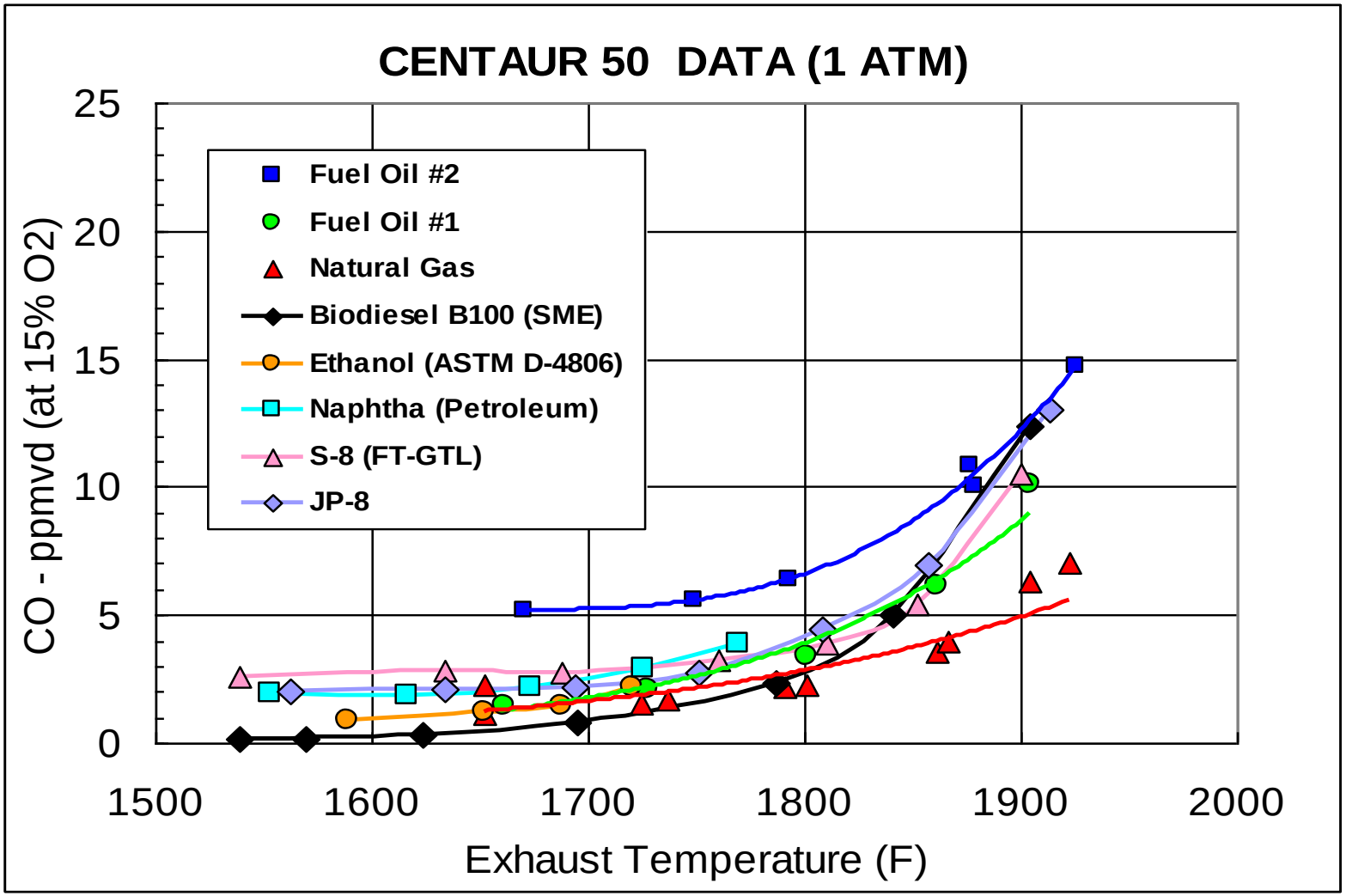
Solar Centaur 50 Combustor CO (1 Atm)



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LPP is Fluid Fuel Agnostic

- **Byproduct Streams –**
  100% gaseous –> 100% liquid:
  - Ethane
  - Associated ("Flare") gases/liquids – mostly gaseous
  - Natural gas condensate (Y-Grade) – mostly liquid
  - Naphtha
  - ……
- **No. 2 Diesel/Heating Oil**
- **Recycled Industrial Solvents**
- **Kerosene/Gasoline**
- **Coal Derived Liquids**
- ……

- **Biodiesel**
  - ASTM spec
  - Non-ASTM spec
- **Bioethanol**
  - Anhydrous (<0.5% water)
  - Hydrous (5% water)
- **Biobutanol**
- **Biomass Derived Liquids**
- ……

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LPP Combustion Main Applications

Utility Gas Turbine Power Generation Fuel Flexibility

Replace Natural Gas/LNG with liquid fuels e.g. ethane, NGCs, naphtha

Clean Power Generation for Islands / Isolated Regions

Replace dirty diesel generator sets with clean LPP Gas™ for gas turbines

Electric Power for Oil & Gas Sites from Flares and NGCs

Shale oil/gas, Off-shore Oil & Gas Platforms

Utility Gas Turbines Dispatchable Renewable Power

Bio-ethanol and biodiesel

Power Generation from Recycled Industrial Solvents

Low value liquid side stream available for combined heat & power

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Current Commercial Installation – Recycling

- **Envirosystems Canada/Atlantic Industrial Services**

  Hydrocarbon Reclamation and Disposal Facility –
  Debert, Nova-Scotia, Canada

- **Use of Waste Oil for Power Generation**
  - Use LPP Combustion skid integrated with a commercial 65kW Capstone C65 gas turbine to produce power
  - Waste liquid fuels: mixture of **reclaimed hydrocarbons previously incinerated**
  - Designed to ultimately produce ~1MWe to meet entire facility power needs
  - Savings of ~$.12/kW-hr to be realized

- **Remote Command & Control**

  System is **monitored & controlled from remote location** –
  LPP facility, Columbia, MD, USA

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Installation On Site

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LPP for Oil & Gas

- **Use raw, untreated gas from the well-head for electric power generation**
  - No need to separate liquids from the fuel stream
  - Use total energy content of the available NGLs on-site
  - No need to truck away NGLs
  - Flare gas reduction
- **Accommodate varying fuel-stream composition & heating value**
  - Handles hot-burning higher-hydrocarbons (C2 – C8)
- **Portable power systems can be moved from well to well**
- **Wide range of system sizes for various applications:**
  - Drilling – 2 MW to 10 MW
  - Hydraulic Fracturing – 20 MW to 40 MW
  - Enhanced Oil Recovery (EOR) – 60 Kw to 1000 kW
- **Low emissions power generation with liquid fuels**
- **Produce hot water / steam on-site**

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Oil Field Flare Applications

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Bakken Flare Gas Composition

COMPONENT	MOLE %	GPM
Nitrogen	3.00	0.000
Methane	50.73	0.000
Carbon Dioxide	0.58	0.000
Ethane	19.92	5.319
H2S	0.00	0.000
Propane	14.83	4.066
i-Butane	1.82	0.593
n-Butane	5.00	1.570
i-Pentane	0.95	0.346
n-Pentane	1.16	0.418
Hexanes+	2.01	0.880
Oxygen/Argon	0.00	0.000
Total	100.00	13.191

CALCULATED SPECIFIC GRAVITY 1.0073 (Air =1.0000)

CALCULATED GROSS BTU/ft³ 1627 (Saturated) 1656 (Dry) at 14.73 psi and 60°F

REMARKS

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LPP for Associated Petroleum Gas (APG)

- **Methane only systems:**
  - Can use ~50% of APG
- **"Natural Gas" systems = ~85% Methane:**
  - Can use ~60% of APG, ~40% more HV than pure Methane
- **"All Gas" systems = C1-C3:**
  - Can use ~85% of APG, ~150% more HV than pure Methane
- **"All hydrocarbon + diluents" systems (=LPP):**
  - Can use almost 100% of APG, ~250% more HV than pure Methane

LPP Bakken Demo

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Utility/"Island" Applications

Examples:

Ethane .vs. Natural Gas/LNG

100% ethane as an alternative to ***natural gas***

Natural Gas Condensates (Y-Grade) .vs. Oil

NGCs (a.k.a. NGLs) as an alternative to ***oil***

… and more "opportunistic" options…

Utility: Ethane vs. Natural Gas

Scenario: US Oil & Gas fracking has produced unprecedented volumes of ethane which are often being flared. High ethane content makes natural gas "too hot" for GTs. Use an LPP skid to utilize ethane in a 2x1 F-class power plant (~500MW) in place of natural gas

Locations: Near fracking sites:

PA; WV; MD; VA; OH; ND; SD; CO; UT; TX; LA

Benefits:

- ❑ Ethane trades at less than half the price of natural gas
- ❑ No reopening of Title V permit
  - Ethane pollutant emissions same as those from natural gas
  - $3M to $5M savings not included in analysis

Payback period: ~**6 months** compared to convectional NG use

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"Island" Utility: NGCs vs. Oil

Scenario: Large quantities of natural gas condensates (NGCs) are generated from oil & gas wells, particularly fracking sites. With an LPP skid, these NGCs can be used to substitute for DF2 in a 2x1 7FA CCGT Power Plant, total installed capacity = ~500MW

Benefits:

- LPP system provides fuel flexibility for use of a variety of liquid fuels
- Heat rate improvement of ~2% when using exhaust stream to heat NGCs
- O & M Costs substantially reduced compared to burning oil
  - Maintenance Reduced by 3x (maintenance intervals lengthened from 1 year to 3 years)
  - 4% increased availability

Payback period: ~3 months compared to conventional DF2 use

Interim Summary

- LPP Combustion technology has been developed and has demonstrated the ability to burn a range of liquid & gaseous fuels using unmodified, natural gas combustion hardware.
- Emissions measurements have shown that in the absence of fuel-bound nitrogen, the LPP criteria pollutant (NOx, CO, PM) emissions are equivalent to those for natural gas for DLE combustion equipment.
- Lab tests, factory proof of concept, field demonstration and commercial installation achieved.
- Broad application range for LPP Combustion: Utilities, Islands/Isolated Regions, Oil & Gas Industry, Renewables and more.
- Work In Progress…

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Thank You!

Proven gas turbine power generation using Bakken flare gases, Y-grade and other NGLs.

LPP Combustion, LLC

Wellsite power systems available for sale or lease in mobile units from 65 kW to 30 MW.

Turning your flares into **clean** power

Chris Broemmelsiek or Elizabeth Zelley | 410-884-3089 | info@LLPCombustion.com

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Backup

Extensive Peer-Reviewed Validation

LPP Combustion Technology has been accepted and presented at international technical meetings and published in the peer-reviewed literature:

- Leo D. Eskin, Maclain M. Holton, Brent A. Turner, Richard G. Joklik, Michael S. Klassen and Richard J. Roby, "ong-Term Demonstration of a Lean, Premixed, Prevaporized (LPP) System for Gas Turbines," ASME 2012 Power Conference, ICONE20-POWER2012, July 30 – August 3, 2012, Anaheim, California, USA
- R. Joklik, L. Eskin, M. Klassen, R. Roby, M. Holton, and T. Mallinson, "Low Emissions Power Generation Using Natural Gas Condesates." Proceedings of ASME Turbo Expo 2011 GT2011-46674, June 6-10, 2011, Vancouver, Canada.
- Gokulakrishnan, P., Ramotowski, M. J., Gaines, G., Fuller, C., Joklik, R., Eskin, L. D., Klassen, M. S. and Roby, R. J. (2008), "A Novel Low NOx Lean, Premixed, and Prevaporized Combustion System for Liquid Fuels", Journal of Engineering for Gas Turbines and Power, Vol. 130, pp. 051501:1-7.
- Ramotowski, M.J., Roby, R.J., Eskin, L.D., and Klassen, M.S., "Fuel Flexibility for Dry Low Emission Gas Turbines – Cleanly Burning Biofuels, Coal Liquids and Petroleum Fuels", to be presented at PowerGen International, New Orleans, December 2007.
- Eskin, L.D., Roby, R.J., Klassen, M.S., and Ramotowski, M.J., "A Novel Approach for 'Clean' Power Generation Using Coal Liquids and the LPP Combustion Process in an Integrated Gasification Combined Cycle (IGCC) System", presented at the 24th Annual International Pittsburgh Coal Conference, Johannesburg, South Africa, September 2007.
- Roby, R.J., Klassen, M.S., Eskin, L.D., Ramotowski, M.J., and Gaines, G.C, "Development of a System for Lean, Prevaporized, Premixed Combustion", presented at the 36th Turbomachinery Symposium, Houston, September 2007.

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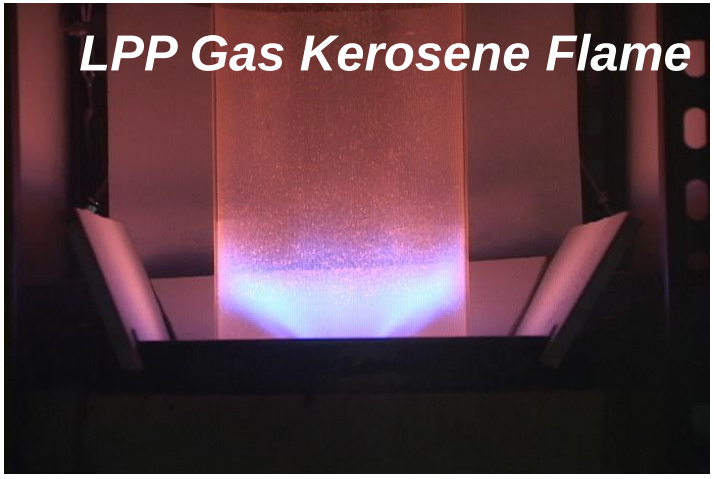
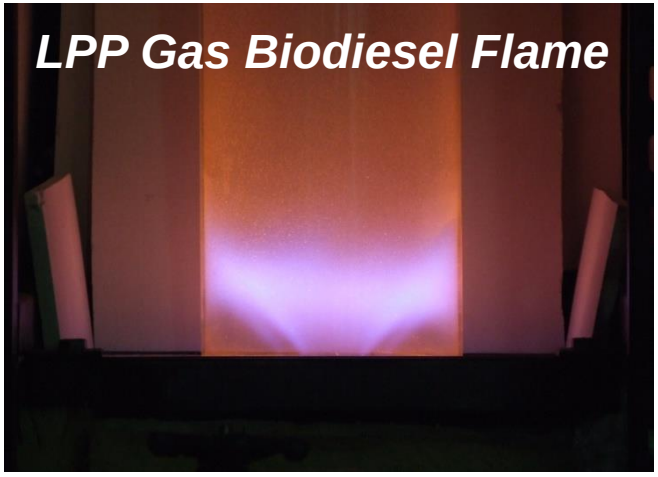
Natural Gas vs LPP Gas™ Visual Flame

- Commercial, Swirl-Stabilized, Lean, Premixed, Dry-Low-Emissions Burner at Atmospheric Pressure
- Equivalence Ratio = 0.6
- Combustion Air Temperature = 650° F





No Combustor Hardware Modification Required

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Trailer-Mounted 30 kW LPP System

Site Visit and Demonstration:

PGP Ethanol Plant
Clearfield, PA

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System In Place

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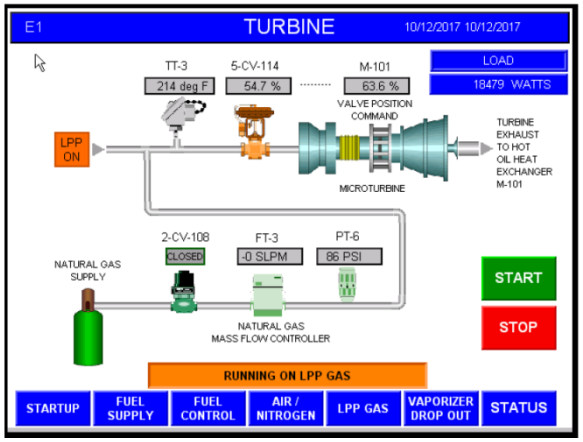
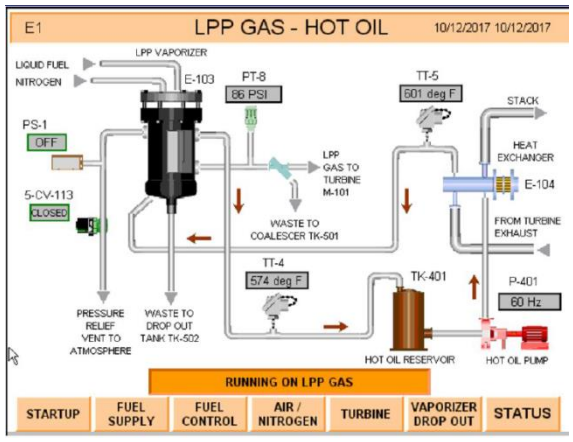
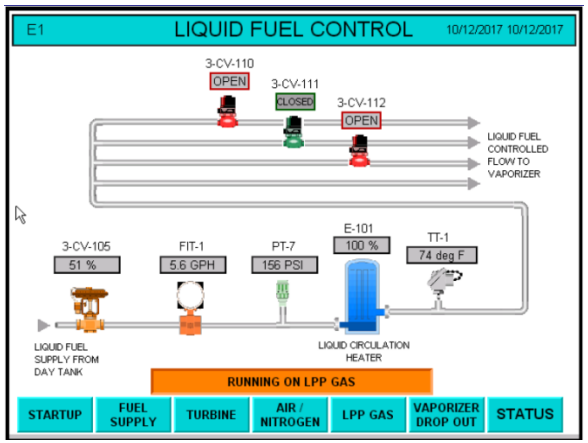
LPP Remote Monitoring/Control Computer Screen Shots



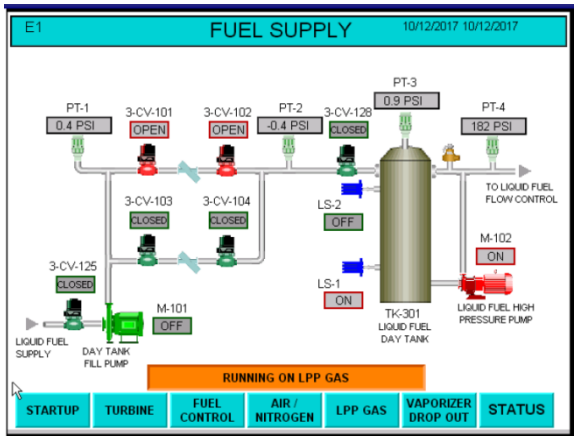
Turbine Operating Conditions



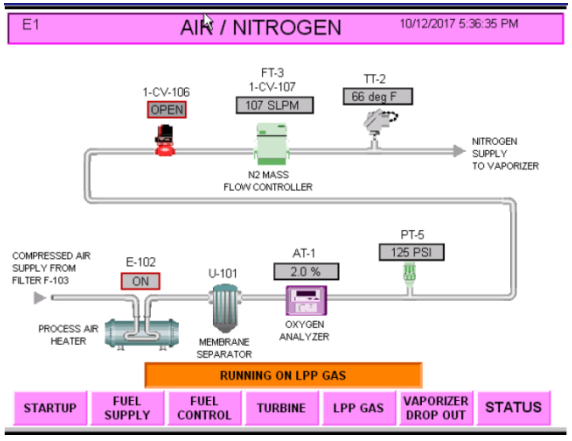
LPP GasTM Generation and Hot Oil Loop



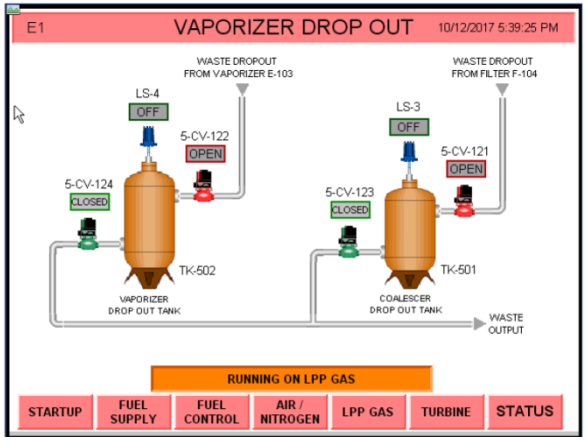
Liquid Fuel Control into Vaporizer



Liquid Fuel Supply to and from Skid Day Tank



Air Separation and Nitrogen Generation



Vaporizer Liquid Dropout Monitoring

LPP = Lean, Premixed & Prevaporized

US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.

LPP NGL Power Systems

Power Generation Capacity

- 200 kW Capstone C200
- 400 kW Capstone C200 X 2
- 600 kW Capstone C200 X 3
- 1.0 MW Capstone C1000
- 3.4 MW Solar Turbines Centaur 40
- 5.6 MW Solar Turbines Taurus 60
- 30 MW GE TM2500+

Fuel Cost

- $0 (Flare Gas)
- $8 - $40/bbl (Y-grade) = $0.20 - $1.00/gallon
  - **Y-grade @$10/bbl is half the cost of natural gas**
  - **$1.75 MBTU (Natural Gas = ~$3.50 Henry Hub + transport costs)**

Combined Heat and Power (CHP) Configuration

- Produce process heat / hot water /steam

LPP NGL 200 Power System

LPP Combustion, LLC
8940 Old Annapolis Road
Suite K
Columbia, MD 21045-2129

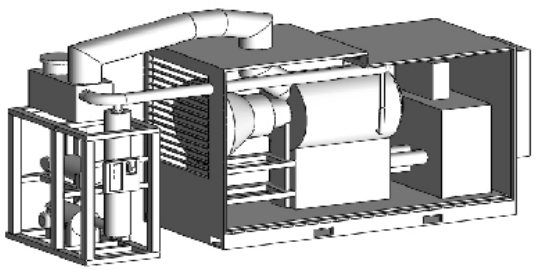
NGL 200

Multi-Fuel, Mobile Power for the Oil & Gas Industry

The NGL 200 Power System operates on C1-C8 fuels to provide 200 kW of electric power with natural gas emission levels. The NGL 200 can optionally be configured as a Combined Heat & Power (CHP) system to also produce hot water.

NGL Power Systems use industry standard, robust gas turbines configured to generate power using well-head gas, natural gas, and natural gas liquids (NGLs) ranging from ethane and Y grade to natural gasoline without the need for diesel fuel. The NGL Power Systems can be deployed in stationary applications or truck-mounted for mobile applications and ruggedized for severe weather.

NGL 200 Turn-Key Power System



System features include:

- Up to 200 kW continuous electric power
- Combined Heat & Power (CHP) option for hot water
- Capstone C200 Gas Turbine
  - Lower maintenance cycles & cost
  - High performance
  - Rapid load-following
- 100% operation on wellhead gas, NGLs, Y grade
- On-the-fly fuel switching & blending
- No diesel fuel required
- Natural gas level emissions across fuel blends
- Mobile & Stationary installations
- Ruggedized option for severe weather

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Suite K
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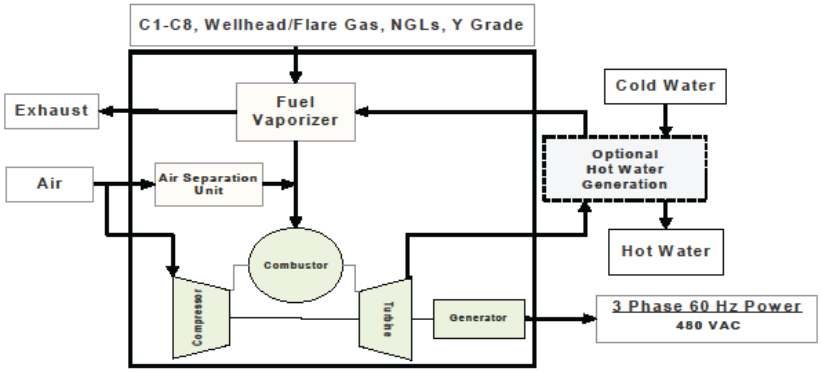
NGL 200

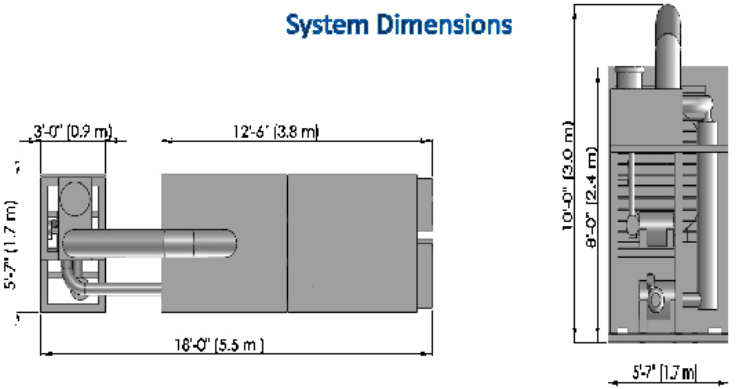
Multi-Fuel, Mobile Power for the Oil & Gas Industry

Simplified Process Flow Diagram



- Electric Output: 200 kW
- Fuel Type: C1 - C8, wellhead/flare gas, NGLs, Y Grade
- Inlet Water Temperature: 55F
- Hot Water Temperature: 180F
- Hot Water Flow Rate: 50 gpm

System Dimensions



***LPP* = *L*ean, *P*remixed & *P*revaporized**

US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.

LPP NGL 3000 Power System

LPP Combustion, LLC
8940 Old Annapolis Road
Suite K
Columbia, MD 21045-2129

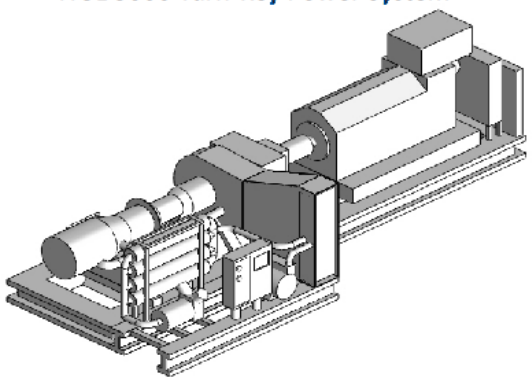
NGL 3000

Multi-Fuel, Mobile Power
for the Oil & Gas Industry

The NGL 3000 Power System operates on C1-C8 fuels to provide 3400 kW of electric power with natural gas emission levels. The NGL 3000 can optionally be configured as a Combined Heat & Power (CHP) system to also produce hot water or steam.

NGL Power Systems use industry standard, robust gas turbines configured to generate power using well-head gas, natural gas, and natural gas liquids (NGLs) ranging from ethane and Y grade to natural gasoline without the need for diesel fuel. The NGL Power Systems can be deployed in stationary applications or truck-mounted for mobile applications and ruggedized for severe weather.

NGL 3000 Turn-Key Power System



System features include:

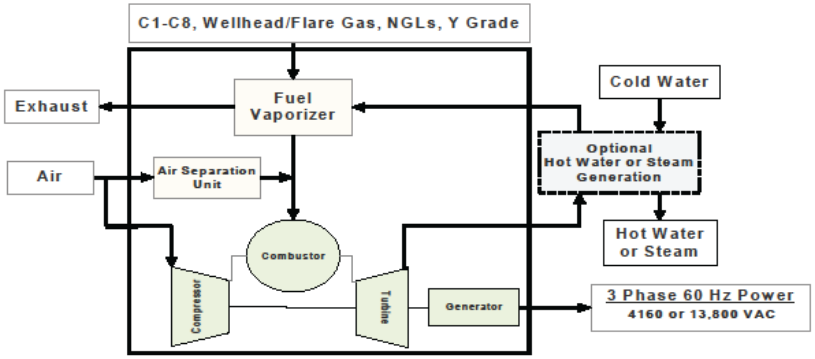
- Up to 3400 kW continuous electric power
- Combined Heat & Power (CHP) option for hot water or steam
- Solar Centaur 40 Gas Turbine
- Lower maintenance cycles & cost
  - High performance
  - Rapid load-following
- 100% operation on wellhead gas, NGLs, Y grade
- On-the-fly fuel switching & blending
- No diesel fuel required
- Natural gas level emissions across fuel blends
- Mobile & Stationary installations
- Ruggedized option for severe weather

LPP Combustion, LLC
8940 Old Annapolis Road
Suite K
Columbia, MD 21045-2129

NGL 3000

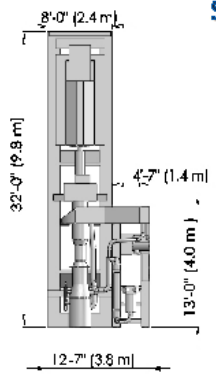
Multi-Fuel, Mobile Power
for the Oil & Gas Industry

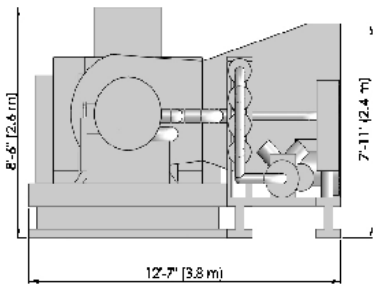
Simplified Process Flow Diagram



- Electric Output: 3400 kW
- Fuel Type: C1 - C8 wellhead/flare gas, NGLs, Y Grade
- Steam: 18,000 lbs/hr., 150 psig/sat.
- Inlet Water Temperature: 55F
- Hot Water Temperature: 180F
- Hot Water Flow Rate: 500 gpm

System Dimensions





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