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

November 2017

The 16th Israeli Symposium on Jet Engines and Gas Turbines

Richard J. Roby, P.E., Ph. D.; Leo D. Eskin, Ph.D.; Michael S. Klassen, P.E., Ph. D.; Aharon David, B.Sc. MBA

LPP Combustion, 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

*LPP = Lean, Premixed & Prevaporized
US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.*
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.
Autoignition becomes a problem for higher hydrocarbons, at higher inlet temperatures, where it is not a problem for natural gas.
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

$LPP = \text{Lean, Premixed & Prevaporized}$

Gokulakrishnan, GT2007-27552

US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
The Problem, Solved by LPP

Burn Liquid Fuels at or Below Natural Gas Emission Levels

- 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.

LPP = Lean, Premixed & Prevaporized

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

---

**LPP = Lean, Premixed & Prevaporized**

US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
Gas Turbine/LPP Process Flow Diagram

ظهير الرسم: نموذج تدفق العملية لمحرك توربيني/نفايات LPP

**LPP** = Lean, Premixed & Prevaporized

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

**LPP = Lean, Premixed & Prevaporized**

US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
Capstone C30 Gas Turbine with LPP Combustion Fuel Processing Skid

LPP = Lean, Premixed & Prevaporized
US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
C30 Gas Turbine NOx Emissions Data

LPP = Lean, Premixed & Prevaporized
US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
C30 Gas Turbine CO Emissions Data

**Capstone C30 CO Emissions**

**LPP = Lean, Premixed & Prevaporized**

US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
Solar Centaur 50 Combustor
Prototype LPP Skid

LPP = Lean, Premixed & Prevaporized
US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
Solar Centaur 50 Combustor NOx (1 Atm)

**CENTAUR 50 DATA (1 ATM)**

- **NOx - ppmvd (at 15% O2)**
- **Exhaust Temperature (F)**

**Fuels Tested:**
- Fuel Oil #2
- Fuel Oil #1
- Natural Gas
- Biodiesel B100 (SME)
- Ethanol (ASTM D-4806)
- Naphtha (Petroleum)
- S-8 (FT-GTL)
- JP-8 (4-12-07)

**LPP = Lean, Premixed & Prevaporized**

US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
Solar Centaur 50 Combustor CO (1 Atm)

### CENTAUR 50 DATA (1 ATM)

<table>
<thead>
<tr>
<th>Exhaust Temperature (F)</th>
<th>CO - ppmvd (at 15% O2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>0</td>
</tr>
<tr>
<td>1600</td>
<td>2</td>
</tr>
<tr>
<td>1700</td>
<td>4</td>
</tr>
<tr>
<td>1800</td>
<td>6</td>
</tr>
<tr>
<td>1900</td>
<td>8</td>
</tr>
<tr>
<td>2000</td>
<td>10</td>
</tr>
</tbody>
</table>

- **Fuel Oil #2**
- **Fuel Oil #1**
- **Natural Gas**
- **Biodiesel B100 (SME)**
- **Ethanol (ASTM D-4806)**
- **Naphtha (Petroleum)**
- **S-8 (FT-GTL)**
- **JP-8**

**LPP = Lean, Premixed & Prevaporized**

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

- **Biodiesel**
  - ASTM spec
  - Non-ASTM spec

- **Bioethanol**
  - Anhydrous (<0.5% water)
  - Hydrous (5% water)

- **Biobutanol**

- **Biomass Derived Liquids**
  - ..............

- **No. 2 Diesel/Heating Oil**
- Recycled Industrial Solvents
- Kerosene/Gasoline
- Coal Derived Liquids
  - ..............
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

LPP = Lean, Premixed & Prevaporized
US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
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

*LPP = Lean, Premixed & Prevaporized*

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

**LPP = Lean, Premixed & Prevaporized**

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

LPP = Lean, Premixed & Prevaporized

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

LPP = Lean, Premixed & Prevaporized
US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
# Bakken Flare Gas Composition

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

**CALCULATED SPECIFIC GRAVITY** 1.0073 (Air = 1.0000)

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

**REMARKS**

*LPP = Lean, Premixed & Prevaporized*

US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
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 = Lean, Premixed & Prevaporized

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

**LPP** = Lean, Premixed & Prevaporized

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

LPP = Lean, Premixed & Prevaporized

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

We can help you turn off the flare and turn on the power

Turning your flares into clean power

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

LPP = Lean, Premixed & Prevaporized

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

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


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

LPP = Lean, Premixed & Prevaporized

US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
Trailer-Mounted 30 kW LPP System

Site Visit and Demonstration:
PGP Ethanol Plant
Clearfield, PA

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

LPP = Lean, Premixed & Prevaporized

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

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 kW</td>
<td>Capstone C200</td>
</tr>
<tr>
<td>400 kW</td>
<td>Capstone C200 X 2</td>
</tr>
<tr>
<td>600 kW</td>
<td>Capstone C200 X 3</td>
</tr>
<tr>
<td>1.0 MW</td>
<td>Capstone C1000</td>
</tr>
<tr>
<td>3.4 MW</td>
<td>Solar Turbines Centaur 40</td>
</tr>
<tr>
<td>5.6 MW</td>
<td>Solar Turbines Taurus 60</td>
</tr>
<tr>
<td>30 MW</td>
<td>GE TM2500+</td>
</tr>
</tbody>
</table>

## 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 = Lean, Premixed & Prevaporized*

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

LPP = Lean, Premixed & Prevaporized
US Patents: 7,089,745; 7,322,198; 7,770,396; 8,225,611. Other Patents Pending.
The LPP 3000 Power System operates on C1-C8 fuels to provide 3400 kW of electric power with natural gas emission levels. The LPP 3000 can optionally be configured as a Combined Heat & Power (CHP) system to also produce hot water or steam.

LNG 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 LPP 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 = Lean, Premixed & Prevaporized*

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