Operating Experience of GE’s LM6000 and LMS100 Gas Turbines

July, 2013
LM6000 Gas Turbine
LM6000 evolution continues
Proven, advanced technologies deliver greater value

40% higher output

1st Generation

2nd Generation

3rd Generation

HP攒LP Sprint

HP Sprint

HP & LP Sprint

Output (MW)


CF6-80C2 CF6-80E1

## LM6000 Experience

### LM6000 Products

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>SAC</th>
<th>DLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Engines Produced</td>
<td>1128</td>
<td>806</td>
<td>322</td>
</tr>
<tr>
<td>Total Operating Hours</td>
<td>26,100,097</td>
<td>19,309,923</td>
<td>6,785,700</td>
</tr>
<tr>
<td>High Time Engine</td>
<td>140,250</td>
<td>140,250</td>
<td>132,592</td>
</tr>
</tbody>
</table>

**>40 units have been converted to -PC, -PD or -PF configurations Engine count & operating hours have not been added to -PC/-PD numbers**

### LM6000 PA/PB

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>PA</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Engines Produced</td>
<td>161</td>
<td>141</td>
<td>20</td>
</tr>
<tr>
<td>Total Operating Hours</td>
<td>9,040,650</td>
<td>7,793,072</td>
<td>1,247,578</td>
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<tr>
<td>High Time Engine</td>
<td>140,250</td>
<td>140,250</td>
<td>132,592</td>
</tr>
</tbody>
</table>

### LM6000 PC/PD/PF

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>PC</th>
<th>PD</th>
<th>PF</th>
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</thead>
<tbody>
<tr>
<td>Total Engines Produced</td>
<td>957</td>
<td>658</td>
<td>216</td>
<td>83</td>
</tr>
<tr>
<td>Total Operating Hours</td>
<td>17,510,380</td>
<td>11,512,377</td>
<td>5,538,122</td>
<td>459,881</td>
</tr>
<tr>
<td>High Time Engine</td>
<td>115,543</td>
<td>115,543</td>
<td>100,544</td>
<td>60,204</td>
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</table>

### LM6000 PG/PH

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>PG</th>
<th>PH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Engines Produced</td>
<td>10</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Total Operating Hours</td>
<td>4,474</td>
<td>4,474</td>
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<tr>
<td>High Time Engine</td>
<td>1,856</td>
<td>1,856</td>
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</table>

<table>
<thead>
<tr>
<th>Equipped with Sprint</th>
<th>All</th>
<th>PC</th>
<th>PD</th>
<th>PF</th>
<th>PG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Engines</td>
<td>572</td>
<td>453</td>
<td>86</td>
<td>33</td>
<td>3</td>
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<tr>
<td>Total Operating Hours</td>
<td>8,626,508</td>
<td>7,314,618</td>
<td>969,364</td>
<td>342,526</td>
<td>4,474</td>
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<tr>
<td>High Time Engine</td>
<td>90,208</td>
<td>90,208</td>
<td>55,682</td>
<td>60,204</td>
<td>1,856</td>
</tr>
</tbody>
</table>

**Estimated data as of July 16, 2013**
**LM6000 Combustion System Experience**

**Dry Low Emissions**

- **PD**
  - 25 PPM NOx (gas)
- **PF**
  - 15 PPM NOx (gas)
  - 65 PPM NOx (liquid)

**Single Annular**

- **Water Injection**
  - 25 PPM NOx (gas)
  - 42 PPM (liquid)
- **Steam Injection**
  - 25 PPM NOx

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Dry</th>
<th>Gas</th>
<th>Liquid</th>
<th>Dual</th>
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<tbody>
<tr>
<td><strong>Gas</strong></td>
<td></td>
<td><strong>15</strong></td>
<td></td>
<td><strong>4</strong></td>
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<tr>
<td>25 ppm</td>
<td>226</td>
<td>6,325,819</td>
<td></td>
<td>126,313</td>
</tr>
<tr>
<td>15 ppm</td>
<td>70</td>
<td>258,905</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dual* 25 ppm</td>
<td>4</td>
<td>126,313</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dual 15 ppm</td>
<td>15</td>
<td>106,926</td>
<td></td>
<td></td>
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<tr>
<td><strong>Steam Injection</strong></td>
<td></td>
<td>49</td>
<td></td>
<td>258,905</td>
</tr>
<tr>
<td><strong>Water Injection</strong></td>
<td></td>
<td>414</td>
<td>8,604,014</td>
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<tr>
<td><strong>Dry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Liquid</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>628,235</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dual</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>279</td>
<td>6,093,607</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Includes hours from 2 Dual Fuel –PD (25ppm) prior to conversion to –PF (15ppm)

**Does not include Spare/Lease/Exchange stats**

**Estimated data as of July 16, 2013**
LM6000 Availability and Reliability
Consistent World-Class Results

Aircraft engine & LM family experience
Extensive development testing
Every engine is factory full-load tested
Lease engine and rotatable component availability
Aircraft engine maintenance philosophy

Source: ORAP®; All rights to Underlying Data Reserved: SPS®

Gas Turbine Generator Set
50th percentile unit
328 units reporting

Source: ORAP®; All rights to Underlying Data Reserved: SPS®
Unique LMS100 advantage & value for LNG compression:

- Best GT simple cycle efficiency @ 44% & hot day performance
- 3 Shaft design, free PT, no gearbox & high starting torque
- No helper motor required saves $5MM capital and simplifies train
- Greater than 10 point efficiency advantage over other simple cycle machines at base or part power conditions
- Higher efficiencies yield over 55,000 tonnes less CO2 than competing gas turbines.
  - Less than 1% power loss at off speed conditions
  - Common driver for both generator and compressor
- On-condition maintenance, modularity and engine exchange capabilities yield an additional 10 days of production per year over alternative gas turbines
- Over 20% more power on hot day operation versus non-intercooled gas turbines.

Designs to meet ever evolving LNG industry
LMS100 operations growth

July 31st, 2013

Total Operating Hours 210,599
High-time Unit Hours 31,314
Total Starts 28,220

Fleet Hours Growth

49 Units

In Commercial Operation
- South Dakota 1 & 2
- Texas 1 & 2
- Argentina
- N. California 1 - 4
- New Jersey
- Connecticut
- Chile
- Canada 1 & 2
- Italy 1, 2 & 3
- Kentucky 1 & 2
- Turkey 1 & 2
- Montana
- New Zealand 1 & 2
- Colorado 1 & 2
- Australia 1 & 2
- S. California – 19 units
- New Mexico
- Venezuela
### LMS100 Fleet Operating Experience

#### All Operation (commissioning and post-COD)

<table>
<thead>
<tr>
<th>Unit Count</th>
<th>Unit Location</th>
<th>COD</th>
<th>Reported Through July 31st, 2013</th>
<th>Avg. Hrs/Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>South Dakota #1</td>
<td>Jun 2006</td>
<td>4,313 805</td>
<td>5.4</td>
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<tr>
<td>2</td>
<td>South Dakota #2</td>
<td>Jun 2008</td>
<td>2,387 495</td>
<td>4.8</td>
</tr>
<tr>
<td>3-4</td>
<td>Texas Units #1-2</td>
<td>Aug 2008</td>
<td>16,769 4,431</td>
<td>3.8</td>
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<tr>
<td>5</td>
<td>Argentina</td>
<td>Sep 2008</td>
<td>31,314 505</td>
<td>62.0</td>
</tr>
<tr>
<td>6-9</td>
<td>PEC, Firebaugh, Units 1-4</td>
<td>May 2009</td>
<td>16,254 4,114</td>
<td>4.0</td>
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<tr>
<td>10</td>
<td>New Jersey</td>
<td>Jun 2009</td>
<td>1,805 847</td>
<td>2.1</td>
</tr>
<tr>
<td>11</td>
<td>Connecticut</td>
<td>Jun 2009</td>
<td>2,972 1,158</td>
<td>2.6</td>
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<tr>
<td>12</td>
<td>Italy #1</td>
<td>Oct 2009</td>
<td>6,408 1,173</td>
<td>5.5</td>
</tr>
<tr>
<td>13</td>
<td>Chile</td>
<td>Oct 2009</td>
<td>10,569 787</td>
<td>13.4</td>
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<tr>
<td>14-15</td>
<td>Canada Units #1-2</td>
<td>Oct 2009</td>
<td>18,561 2,416</td>
<td>7.7</td>
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<tr>
<td>16-17</td>
<td>Kentucky Units #1-2</td>
<td>Dec 2009</td>
<td>16,335 1,832</td>
<td>8.9</td>
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<tr>
<td>18</td>
<td>Montana</td>
<td>Jul 2011</td>
<td>2,555 362</td>
<td>7.1</td>
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<tr>
<td>19-20</td>
<td>Turkey Units #1-2</td>
<td>Aug 2010</td>
<td>31,413 3,116</td>
<td>10.1</td>
</tr>
<tr>
<td>21</td>
<td>Italy #2</td>
<td>Oct 2010</td>
<td>5,337 1,052</td>
<td>5.1</td>
</tr>
<tr>
<td>22-23</td>
<td>New Zealand Units #1-2</td>
<td>Mar 2011</td>
<td>16,119 1,588</td>
<td>10.2</td>
</tr>
<tr>
<td>24</td>
<td>Italy #3</td>
<td>Jun 2011</td>
<td>4,467 743</td>
<td>6.0</td>
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<tr>
<td>25-26</td>
<td>Colorado Units #1-2</td>
<td>Dec 2011</td>
<td>4,999 694</td>
<td>7.2</td>
</tr>
<tr>
<td>27-28</td>
<td>Australia Units #GT2-GT3</td>
<td>Sep 2012</td>
<td>10,650 462</td>
<td>23.1</td>
</tr>
<tr>
<td>29-33</td>
<td>S. California 5-unit site</td>
<td>Jan-Mar '13</td>
<td>1,873 510</td>
<td>3.7</td>
</tr>
<tr>
<td>34-41</td>
<td>S. California 8-unit site</td>
<td>Mar-Apr '13</td>
<td>2,016 527</td>
<td>3.8</td>
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<tr>
<td>44-47</td>
<td>S. California 6-unit site</td>
<td>Feb-Jun '13</td>
<td>1,431 443</td>
<td>3.2</td>
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<tr>
<td>48</td>
<td>New Mexico (estimated)</td>
<td>May-13</td>
<td>684 114</td>
<td>6.0</td>
</tr>
<tr>
<td>49</td>
<td>Venezuela (interpolated)</td>
<td>Jul-13</td>
<td>1,368 46</td>
<td>29.7</td>
</tr>
</tbody>
</table>

#### Summary of Total Operations

<table>
<thead>
<tr>
<th>Unit Count</th>
<th>Unit Location</th>
<th>COD</th>
<th>Reported Through July 31st, 2013</th>
<th>Avg. Hrs/Run</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>210,599 28,220</td>
<td>7.5</td>
</tr>
</tbody>
</table>

**49 units in operation**  
**Fleet >210,000 hours**  
**High time unit**  
**>31,000 hours**  
**High starts unit**  
**>2,300 starts**  

[As of 31 July 2013]
Modular Exchange

NEW CONCEPT FOR MAJOR OVERHAUL ... Exchange Gas Turbine Engine instead of opening GT at site

- Speeds-up major overhaul activities
  ... down to **11 days** for Major Overhaul

- Removed modules may be **overhauled in service shop**
  ... highest quality standards & best tools available

- **Quick recovery** from catastrophic failure / emergency shutdown
  ... maximize uptime

- **Best benefits with sites with high costs from loss of production**

- **Spare MS5002 engine to be purchased**
MS5002C lifting sketch

Single lift ... ~ 73 ton

~2.2 m
~3.4 m
~2.2 m
~2.4 m
~2.9 m
~3.1 m
~1.8 m
~0.8 m
~5.0 m
~2.9 m
~3.1 m
~2.9 m
~3.1 m

~49.5 ton
~23.5 ton
Modular Replacement
Replacing GT Tube ... restore efficiency and reliability

- Replacing existing GT tube with **same** model
  - Rejuvenate **avoiding** re-permitting
  - Restore original **efficiency and reliability**
  - GT tube Rejuvenation to **new life** (30+ years)
- **Zero** plant impact ... **Short downtime**
- Introduce latest design change / CM&U

**MS3002A thru G**
- Re-industrialize MS3002F to fit all
- Regen or Simple cycle
- DLN Could be investigated

- New life to aged equipment... parts commonality and availability
- Available for MS3002H & J, MS5001 and MS5002 all models
- Can be developed for MS3002A...G
Modular Replacements

Contacts

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Nuovo Pignone S.p.A.
GE Oil & Gas

Compression technology for LNG applications

GE imagination at work
25 years of compression evolution for LNG

1988

Single Compressor Train (size 1000)
FR5 Driver
<80% efficiency
~30MW

2013

3 Compressor Train (Size 1400)
FR7 Driver
~85% efficiency
~80MW

Increased 2x train capacity with higher efficiency, reliability and flexibility
LNG drivers ... technology enablers

<table>
<thead>
<tr>
<th>Enablers</th>
<th>Design and manufacturability</th>
<th>Aerodynamic</th>
<th>Test capabilities</th>
<th>Rotordynamic</th>
<th>Predictability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>• Large casings</td>
<td>• Large impellers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• NEMA</td>
<td>• CFD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Large impellers, flow capabilities</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Efficiency</td>
<td>• Large impellers, performance</td>
<td>• Large impellers</td>
<td>• Side streams</td>
<td></td>
<td>Model test</td>
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<tr>
<td></td>
<td>• CFD</td>
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<td></td>
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<td>Thermodynamic test</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pre-referenced impeller</td>
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<tr>
<td>Reliability</td>
<td>• Aeromechanics</td>
<td>• String test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Large impellers robust design</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Availability</td>
<td>• Robust design</td>
<td></td>
<td>• Stability test</td>
<td>• Torsional analysis test</td>
<td></td>
</tr>
</tbody>
</table>

DEGLOG: 0.1113  
Res. Freq : 52.7Hz  -  Res. Speed : 3159.3rpm  -  AF: 28.2178  -  Zeta: 0.0177
Start: 38.7Hz (2323.2rpm)  -  Stop: 64.6Hz (3877.0rpm) (04/03/2013 14:03:30)  -  (04/03/2013 14:05:13)
Propane Centrifugal Compressor Efficiency

- Single Casing Propane
  - 3 side streams arrangement
  - 100 MW reached in single casing

- Radial Side stream arrangement
  - Optimized Discharge volute
  - Optimized Mach Stages
  - Optimized casing to increase DR

Focus on Capacity/Power
Focus on Performance
Focus on Predictability

Continuous Casing Optimization
Continuous Stator Optimization
Return Channel Optimization
Abradable seals

Full path CFD analysis
Optimization of stators
Full Multistage CFD analysis
Optimization of stators

Validation Model Test
MR Compressor Efficiency

Focus on Performance
- Optimized Discharge volute
- 3d, 2d Stage introduction
- Larger casing to increase DR

Focus on Predictability
- Continuous Stator Optimization
- Return Channel Optimization
- Continuous Casing Optimization
- Abradable Seals

- Full path CFD analysis Optimization of stators
- Full Multistage CFD analysis Optimization of stators

Validation Model Test Validation Model Test Validation Model Test Validation Model Test
Aerodynamic - Impellers

Impeller geometry

High Volumetric Flow Capability
High Inlet Tip Diameter (High Mach)
Aerodynamic - Impellers

- Head coeff limits pushed beyond
- Increased head per impeller (4,500m / 44,145 J/Kg / 14,770 ft)
- Need of high head stages to increase flow and reduce machine length
- Mixed flow impellers introduced
- Constant performance in whole range

Head coefficient per stage in LNG application

Polytropic Efficiency per stage in LNG application

8800m @ Surge
8700m @ SCL - 1.4% HRTS
8510m @ DP - 3.3% HRTS
Aerodynamic – Side Streams

Side Loads

- Tangential
- Radial

Mixing Ratio

- Tangential still valid to reduce bearing span or for revamps
- Optimization to reduce losses: from 3 to 0.5 pressure loss coefficient
Aerodynamic

Technology Milestones

- Max Machine Mach No : 1.20
  1.24 in Model Test
- Max Inlet Mach N : 0.98
  1.05 in Model Test
- Flow Coefficient : 0.1800 \( \text{flow coeff} = \frac{Q}{(u^2 A)} \)
- Head Coefficient : >0.54 per stage
- Polytropic head : > 4,500 m / 44,145 J/Kg / 14,770 ft
- Power per Impeller: >25 MW
- Head rise to surge : < 5
- Inlet Volume Flow: 350,000 m³/h single flange
- SideLoad losses: <1
- Discharge Volute : <0.5
Optimization analysis to increase production

Analysis

New impeller design for 10% reduced power
OEM experience enables reduced plant margins

Configuration approach

- 12 Full “blue print” PR design
- 11 Full “blue print” MR train
- AN200 + 2BCL806
- 9 ‘derived’ PR design

- 50+ propane compressors & 160+ propane impellers in operation
- New propane PJ... all impeller already fully tested
- Proven experience for a step up innovation with low risk

Low tolerances to optimize plant design and boost profitability
Thank you!