Introduction of the Solar Turbines Titan 250 Gas Turbine System

Design, Development and Validation Testing a New 22.4 MW Gas Turbine

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- **History**
  - Founded in 1927 as Prudden Airplane Company
  - Full transition to industrial gas turbines in 1970’s
  - Caterpillar subsidiary since 1981
  - 6000 employees in 96 countries worldwide

- **Products**
  - Over 12,500 units installed worldwide (3100 in EAME)
  - Over 5,900 compressor sets and mechanical drive units
  - More than 1.2 billion operating hours (350 million in EAME)

- **Titan 250 Timeline**
  - Program Kick-Off - 2004
  - Hardware Delivered - 2008
  - New Test Cell Commissioned - 2008
  - First Light-Off – 2008
  - Customer Delivery - 2009
Leveraging Proven Technology

- Taurus 65
- Titan 130
- Mercury 50
- Titan 250
SYSTEM DESIGN GOALS

- Highest-Efficiency Gas Turbine in Class
- Design for Long-Life Industrial Applications
- Common Modular Design Throughout
- Minimum Package Footprint
- Advanced Aerodynamics, Optimized Cooling
- High Availability, Maximum Life-Cycle Benefits
- Wide Application Range for Compressors
- Packaged Generator Set for High Efficiency
- Simple Cycle and Heat Recovery Installations

Overall Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CS/MD</th>
<th>GS</th>
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</thead>
<tbody>
<tr>
<td>Power Output</td>
<td>22,400 kW</td>
<td>21,745 kWe</td>
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<tr>
<td>Heat Rate</td>
<td>8993 kJ/kW-hr</td>
<td>9259 kJ/kW-hr</td>
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<tr>
<td>Efficiency</td>
<td>40.0% (shaft)</td>
<td>38.9% (generator)</td>
</tr>
<tr>
<td>Exhaust Flow</td>
<td></td>
<td>245664 kg/hr</td>
</tr>
<tr>
<td>Exhaust Temperature</td>
<td></td>
<td>463 °C</td>
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<tr>
<td>Pressure Ratio</td>
<td></td>
<td>24:1</td>
</tr>
<tr>
<td>Power Turbine Speed</td>
<td></td>
<td>6,300 rpm (optimum) 7,000 rpm (maximum)</td>
</tr>
</tbody>
</table>
Titan 250 General Arrangement

- 16-STAGE ACE COMPRESSOR
- 2-STAGE GAS PRODUCER TURBINE
- DRY LOW EMISSIONS (DLE) COMBUSTOR
- 3-STAGE POWER TURBINE ALL-SHROUDED BLADES
COMPRESSOR FEATURES

PERFORMANCE
• “Clean Sheet” Design
• 16-Stages of High-Efficiency Aerodynamics
  • 2 Stages More Than Titan 130
  • Built on Taurus 65 Success
• 6 Stages of Variable Guide Vanes
  • Optimized Airflow For Full Operating Range
• Sets New Standard for Compressor Efficiency
  • Within Experience Base
  • Unsurpassed Attention to Detail
• Multi-Stage CFD Code
  • Validated by Rig Testing
  • Mercury 50, Centaur 50 and Taurus 65
• Optimized for Wide Range of Operation
• Low-Loss, Minimum Distortion Inlet
• Compressor- Discharge and Inter-Stage Bleed

INLET
• $\Delta p/p = 0.75\%$
• Blockage < 1.5\%
• Minimum Distortion

DIFFUSER
• $\Delta p/p = 1.6\%$
• $C_p > 0.70$
• $Ma < 0.10$
• $\alpha = +/- 3.0$ deg
COMRESSOR FEATURES

DURABILITY
• Welded Drum Design for Rigidity, Long Life
• Modular Annular Design
• Bearing Support Optimized - Rotor Dynamics
• Extensive Vibration Analyses
• Latest Variable Guide Vane Bushing Design
  • Based on In-House Corrosion Testing
  • Prevent Lock-up in Field

MAINTAINABILITY
• Designed for Long Life and Maintainability
• Anti-Corrosion Aluminide Coating (Stages 1-12)
• In-Situ Two-Plane Trim Balancing
• All Airfoils Individually Field Replaceable
• 4-Piece Compressor Case (Mars, Titan 130)
COMBUSTOR FEATURES

PERFORMANCE
• Proven SoLoNOx Technology
• Canted Diffuser for Optimized Airflow
• Optimized Outer Dome For Good Swirler Flow
• Extensive CFD Used to Design
  • Diffuser
  • Liner
  • Injector
• Emissions (NOx/CO/UHC) ppm
  • Natural Gas: 15/25/10
  • Liquid Fuel: 60/30/15
  • Associated Gas (900–1600 WI) / 25/50/10
• Operating Range
  • 40 thru 100% Load
  • –29°C to 49°C (Gas/Liquid)
COMBUSTOR FEATURES

DURABILITY
• Modular Annular Design
• Augmented Backside Cooled (ABC) Liner
• Simple Supported Pins
  • Reduce Dome Stress
• Independently controlled fuel flows
  • Main Primary, Main Secondary, Pilot
• Extensive Experience with HAST-X Material
• Modal Frequencies Per Design Criteria
• Injector Barrel Features Helmholtz Resonator
  • Oscillation Abatement

MAINTAINABILITY
• Designed for Long Life and Maintainability
• 14 Radial-Inflow Injectors – Offset Stems
  • Proven Taurus 65 Experience
  • Easy Installation
  • Field Replaceable and Repairable
GAS PRODUCER TURBINE

PERFORMANCE
- Two-Stage Design, Similar to Titan 130
- Leveraged Taurus 65 Experience
- High Aspect Ratio Airfoils
- Optimized Work Split, High Stage Loading
  - Designed for Uncooled 2nd Blade
- Jump Cooling Experience Applied
- Extensive Application of Advanced CFD
  - Airfoil Design
  - Combustor Interface
  - Cooling Support
- Passive Tip Clearance Control
GAS PRODUCER TURBINE

DURABILITY
• Advanced 1st Stage Nozzle and Blade Cooling
  • Showerhead Film Cooling
• 2nd Nozzle Cooled for Minimum Performance Impact
  • Internal Convection Cooling
• Optimized Cooling Passages (Advanced CFD)
• Under-platform Dampers
• Advanced Materials
  • Nozzles - MAR-M-247
  • Blades - SCRY-4
  • TBC Pt-Al Coatings (1st Stage Airfoils)

MAINTAINABILITY
• In-Situ Repair and Replacement Capability
• Borescope Access
• 2-Plane Trim Balance in Field
• Low-Speed Turning Gear (Cool down)
  • Avoid Rotor-Lock-up Issues
POWER TURBINE

PERFORMANCE

• Three-Stages
• Low RPM Design (6300 / 7000)
• Moderate Endwall Slope
• All Blades Shrouded
  • Reduced-Leakage Geometry
  • Increased Knife-Count
• High Efficiency, 3-D Airfoils
• Optimized Axial Gaps
• High Fidelity, Detailed CFD Models Used
  • Tip Gap Analysis
  • Purge Cavity Effects Captured

• Flat Power Curve across Speed Range
• Highest Efficiency Solar PT
**POWER TURBINE**

**DURABILITY**
- Shrouded Blade Experience
  - Titan-130, Taurus-65
  - Low to Moderate AN^2 Levels
  - Clearances Set for Durability
- Extensive Experience with Materials
  - Nozzles: IN 939
  - Blades: IN792
- Vibration Testing on Shrouded Blades
- Proven, Reliable High-Time Bearings
  - Field-Retrofittable

**MAINTAINABILITY**
- Modular Design for Field Maintenance
  - Advanced Rail System
  - Dedicated Lubrication System
- Borescope Access
VALIDATION

• New Test Cell Commissioned in 2008
• Test Program Initiated in Sep-08
  • >250 Hours of Operation
  • Advanced Instrumentation
• Start Power Minimized
  • Guide Vane Optimization
• Component Performance Validated
  • Compressor Mapping
  • Power Turbine Mapping
  • Load Modulation
• Emissions Verified
SUMMARY

• Methodology
  • Lean, Interactive Processes
  • State-of-the-Art Design Tools
  • Experience From Prior Designs
  • Industry Design Experience
  • Maximum Commonality

• Design
  • Advanced Technology
  • Detailed Analyses
  • Highest Efficiency, Durable Components
  • Focus On Ease of Maintenance

• Validation
  • Attained Performance
  • Verification With Calibrated CFD
  • Extensive Engine Testing