AGENDA

1. Introduction – Solar Turbines (Mahsima)
2. Small Scale LNG Market (Bruno)
3. EMD vs. Gas Turbine Economics (Bruno)
4. Typical Processes and Turbomachinery (Rainer)
5. Special Requirements (Min)
6. Drivers (Rainer)
7. Case Studies (Min)
8. Questions
SOLAR TURBINES

Who are we?

- Energy Solutions provider
- 90 Years in San Diego, California
- Global exporter to over 100 countries
- Subsidiary of Caterpillar Inc. since 1981
- Global Footprint: Customers, Products, People, Service
- Over 16,000 gas turbines and 6,500 gas compressors shipped

What do we do?

- Power and heat for hospitals, universities, industrial facilities...
- Power and compression for gas transmission, offshore platforms...

What do we make?

- Industrial gas turbines, compressors, electric motor drives, energy storage, digital solutions accompanied by service through the lifecycle

World's Largest Manufacturer of Industrial Gas Turbines

- Since 1981
- 16,000+ Gas Turbines Sold
- 6,500+ Gas Compressors Sold

Installations in 100+ Countries

Direct End-to-End Sales and Service

Global Workforce

- 8,000+ Employees

65 Sales and Service Locations
### Solar Turbines Gas Turbine Experience by Package

<table>
<thead>
<tr>
<th>Package</th>
<th>Units Sold</th>
<th>Estimated Hours (000's)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor Sets</td>
<td>4,930</td>
<td>1,050,000</td>
</tr>
<tr>
<td>Mechanical Drives</td>
<td>2,720</td>
<td>630,000</td>
</tr>
<tr>
<td>Generator Sets</td>
<td>8,350</td>
<td>1,320,000</td>
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<tr>
<td>Total</td>
<td>16,000</td>
<td>3,000,000</td>
</tr>
</tbody>
</table>

Jan 2020 © Solar Turbines Inc. | Note: Total includes >1,200 Spartans | Hours reflect new unit sales only

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**Product Overview**
Solar Gas Turbine Family

Saturn 20
1590 hp / 1210 kWe

Centaur 40 & 50
4700 - 6130 hp
3515 - 4600 kWe

Mercury 50
4600 kW

Taurus 60
7700 hp / 5670 kW

Taurus 65
6500 kW

Taurus 70
11,110 hp / 8180 kW

Mars 90 & 100
13,220 - 15,900 hp
9450 - 11,350 kW

Titan 130
23,470 hp / 16,530 kW

Titan 250
31,900 hp / 23,100 kW

Updated Apr 2019

Complete Package Systems

Compressor Sets

Generator Sets

Spartan™ EMD Compressor Sets

Powering the Future
Centrifugal Gas Compressors

- Match speed and power of Solar gas turbines
- First installed 1960
- Over 6500 units shipped
- Handle wide variety of applications and power requirements
- Modular rotor assembly

Small Scale LNG Market
LNG Market SEGMENTS

- Large Scale (>3 MTPA)
  - Selected Large Players
  - Global Market
  - Efficiency Focused
  - Transport via Shipping
- Mid Scale (1-3 MTPA)
  - CAPEX focused
  - Fragmented market dynamics
    - Local markets
    - Small players
  - Transport via ships/trucks
- Small Scale (<1 MTPA)

The LNG value chain

- SSLNG Liquefaction Plants
- LARGE SCALE LNG VALUE CHAIN
- Conventional chain
- Power Plant
- Distribution and End Users
- ISO Tanks
- LPG Carrier
- Bagas Terminal
- LPG Tanker
- LPG Fueled Truck
- LPG Fueled Vessel
- LNG Fueling Station
- Industrial End user
- Remote Mining, Drilling & Other Non-Road Operations
- Small Liquefaction
- Small Scale Power
- Remote Small Scale Power
- LNG Fueled Tractor
- LNG Fueled Forklift
- LNG Fueled Vessel
- LNG Powered Trailer
- LNG Fueled Truck
SSLNG MARKET SEGMENTS

SSLNG LIQUEFACTION PLANT

SSLNG LIQUEFACTION PLANT FROM 50K TO 1.0 MM TONS PER YEAR (TPA)

LNG

SSLNG LIQUEFACTION PLANT

CAPTIVE POWER PLANTS (~10/20 MW), INDUSTRIAL NEEDS, PIPELINE PEAK-SHAVERS, DE-BOTTLENECKING

BUNKERING SERVICES
CLEAN FUEL FOR DUAL FUEL VESSELS

VIRTUAL MARINE PIPELINE (SHORT DISTANCES)

ROAD TRANSPORTATION AND INDUSTRIAL/MINING

SSLNG LIQUEFACTION PLANT

Feed gas

Pre-Treatment

Liquefaction

STRANDED GAS

ASSOCIATE GAS FLARING

Pipeline Gas

Acid Gas Removal
Dehydration
Mercury Removal
NGL Extraction

CO₂
Water
NGL

Liquefaction Process
Cold Box
Expanders & Valves
GT Compressor

Storage & Distribution
SOLAR GT FOR SSLNG

Power (kW) vs MTPA LNG

- Single Train skidded solution
- Single Train stick-built
- Multi-train

Range of liquefaction process efficiency

Compressor Shaft Power kW

MTPA (Million Metric Tonnes per Annum)

Solar References:
- 16 Small Scale LNG trains running on Solar GT
- 1 EMD liquefaction train

Titan 130 & 230
15,000-23,790 kW
(Over 1100 Units)

Mars 90 & 100
9450-11,350 kW
(Over 1200 Units)

Taurus 60 & 70
5070-8250 kW
(Over 2000 Units)

Centaur 40 & 50
3500-4570 kW
(Over 2700 Units)

Gas Turbine and EMD Economics

- a) EMD connected to the GRID
- b) EMD Powered by ICE
- c) Gas Turbine

EMD

VFD

SUBSTATION

HV

MV

ICE

GT

Fuel Gas

Powering the Future

Powering the Future
Gas Turbine and EMD Economics

a) EMD connected to the GRID

b) EMD Powered by ICE
Typical Processes and Turbomachinery

Refrigeration Process

- 2 Phase systems
  - SMR, DMR, Cascade,C3-MR etc.
- Reverse Brayton (single phase) systems
  - Nitrogen
Turbomachinery

- Compressors
- Drivers
Compressors

• SMR: typically 2 section compression, discharge pressures relatively low (40 to 50 bar), pressure ratio per section 3 to 5.
• N₂: Single Shaft or Integral Gear type Centrifugal
• For the very small LNG plants:
  - Reciprocating Compressors
  - Screw Compressors

Compressors

• Relatively Low Pressure
• Sidestreams for some processes
• Benign, clean Gases (Mixed refrigerant, Nitrogen).
• Moleweight moderately high
• Gas Leakage is a cost factor
• Efficency and Range
Compressors

• Rotordynamics
  - Stability impacted by
    • Pressure Ratio
    • Gas Density/Discharge Pressure/Avg. Density
    • Compressor Speed
    • Rotor Length
  - LNG Compressors are pretty benign

• Seal Systems:
  - N2 Compressors: Cost of Seal vs Cost of lost refrigerant (DGS or Carbon Ring)
  - SMR: Always DGS since refrigerant is flameable

Compressors

• Typical N2 Train
  - Single shaft
  - Integral Gear Type
Compressors

- Typical SMR Trains
  - Often two section or 2 body

Process Control
Process Control

- N2 process can be controlled by refrigerant charge (ie density)
  - significant turndown capability
  - Secondary control by expander vanes.

Compressors - Aerodynamics

- Compression of heavy Gas: S.G. = 0.9673 for expansion cycle, S.G. = 1.1 ~ 1.3 for SMR cycle;
- Relatively high machine Mach numbers due to low speed of sound and high compression ratio;
- High-subsonic flow near design condition, but passage shock may appear near choke condition.

Primary design variable:

\[
M_{n,\text{Tip}} = \frac{U_{\text{Tip}}}{\sqrt{\gamma R Z T / S.G.}}
\]

\[
U_{\text{Tip}} = \frac{\pi D_{\text{Tip}} N}{60}
\]
**Impeller Aerodynamics Design Strategy**

- Maintain appropriate passage area ratio between inducer and exducer to achieve optimal diffusion ratio;
- Increase throat area through splitter-type blade for design condition approaching sonic choke;
- Choose appropriate family of impellers to achieve design with optimal efficiency.

\[ \text{Specific Speed: } NS = N \times \left( \frac{Q_{\text{inlet}}}{H_{\text{isen}}} \right)^{\frac{1}{3}} \]

**Evaluate Mach Number effect through CFD**

- Simulation of impeller-stator flow field with CFD analysis;
- Impeller design is responsible for the performance variation from flow choke to near surge along the speed line.
**Impeller flow field**

- Passage flow near choke at different level of $M_{n,\text{Tip}}$
- Sonic choking appears at high $M_{n,\text{Tip}}$

**Multi-stage design of Centrifugal Compressor**

Rotor speed inverse to wheel count;
- Design impeller flow at high subsonic to achieve wide operating Range.
- Increased wheel count means mild pressure ratio per stage;
- Stability concern of longer rotor design.
Drivers

• Gas Turbine
  - Typically two shaft
• Electric Motor
  - Constant Speed or Variable Speed
• Starting
• Availability of Fuel/Electricity
• Control via speed needed
Compressor Drivers

- Electric
  - Constant speed
  - Variable Speed
- Gas Turbine
  - Single Shaft
  - Two Shaft

Decision Points

- Fuel Cost
  - Electricity
    - CAPEX and OPEX
  - Gas fuel might be opportunity fuel
- Availability
  - Equipment Availability
  - Electricity outage
EMD

- Motor Starting
  - Inrush Current
  - Softstarter
  - VFD
Brayton Cycle (Simple Cycle Gas Turbine)

Drivers-Speed-Power Relationships

Comparison of GT and Various EMD Output Power vs Speed Characteristics - Input HP - GT-10,000 104 F (40C), VFD-EMD - 10,347 (10,864 @95.2% RPM Design), Constant Speed EMD - 10,772 (11,418 w/TV), VSHD - 10,785
Gas Turbine Fuel

• Changes in Fuel Composition can be significant
• Gas Turbine Combustion:

LNG Processing—Where does the fuel come from?
Case Studies: Plants

Applied LNG Topock AZ
Design Strategy: Full Load vs Partial Load Operation

- Plant Turndown is limited by surge control of turbo-compressor along with maintaining heat-exchanger performance;
- Dropping pressure to avoid flow recycle through releasing refrigerant inventory can extend the partial load production but being limited by heat-exchanger performance.
- Fair comparison of partial load performance may not be attainable between expansion cycle and SMR since expansion cycle consumes more power than SMR.

Conclusion: Variable speed capability and wide performance range are key technical advantages of turbine driven barrel compressors.
Conclusions

• Major issues and processes for small scale LNG explained.