Gas Turbines
Applications, Failures and Root Cause Analysis

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Lecture Contents

• 1. Gas Turbine Disassembly/Principles of Operation

• 2. Types of Gas Turbine and Applications

• 3. Potential Failure Considerations

• 4. Root Cause Analysis

• 5. Questions
Principle of Gas Turbine operation

All Gas Turbines are a continuous cycle 4 cycle (stroke) engine

Typical Four Stroke Cycle
Principles of Operation

• Air is accelerated in either a centrifugal or axial compressor.

• These gases are then slowed using a nozzle, also known as a diffuser; these processes increase the pressure and temperature of the flow.

• The air then pass from the compressor to a combustion chamber, where fuel is injected and ignited and the air converted into a super heated gas.

• As there is no change in pressure the specific volume of the gases increases.

• Finally, this larger volume of gases is expanded and accelerated by nozzle guide vanes before energy is extracted by the turbine.
Typical Gas turbine construction

- Compressor: Intake/Compression
- Combustion Chamber: Fuel/Ignition
- Turbine: Power/Exhaust

Westinghouse 701
Question

• From a purely mechanical point of view, a gas turbine has only 1 moving part and therefore should be ultimately reliable, so where do they fail?

• To answer that question, it is necessary to be aware of the types of gas turbine in use and their various applications.
Types of Gas turbine:-

1) **Aero derivative** – Originally designed for use in the aviation industry and converted for industrial applications

2) **Light Industrial** – Designed for military, marine or industrial use where weight is a primary factor

3) **Heavy Industrial** – Designed for continuous service in the Power Generation or Energy sectors
Aero derivative

Example – Rolls Royce Avon

• History – Originally designed in 1946 for use on the Hawker Hunter Fighter jet and other military aircraft.
Avon

- The first industrial version was the type 1533 adapted for use as a driver for a Turbo Generator with CEGB in the late 60’s and became very popular for use with offshore Oil and Gas companies because it’s power to weight ratio of 21800hp to 900kgs, is exceptional plus the generator package is compact and can be built to a modular design that allows it to occupy unusual spaces.
Example of Modular Design

- Steam Turbine
- Generator with Epicyclic Gearbox
- Lubrication Oil Module
- Control Oil Module
- Supervision Cubicle
Avon

• The Avon Gas generator has gone through a series of upgrades which increased power to over 30,000hp.

• Around 20,000 Avon driven packages remain in service today of which more than 70% are over 30 years old.

• The service interval is recommended at 24,000 hours (every 3 years) however there was one unit that gave 53,000 hours (6.5 years), more or less, continuous service, whereas, over units of the same specification disintegrated after 2,500 hours (3 months) service.

• As we go through this discussion we will explore why there can be such a dichotomy.
Light Industrial Turbine

- The Light Industrial Turbine is an “Armoured “ Aero, where, they have been designed specifically for industrial or marine applications.

- They have similar, but lower, power to weight characteristics, they can be modularised and the service intervals are between 35,000 to 50,000 hours.
Example – Solar Centaur

Gas Generator    Fuel system    Gear Box    Lube Oil System    Alternator    Compressed Air System
SOLAR Centaur

• The Centaur entered service in 1968 and produced 2700 hp

• Current units now produce over 4700 hp but the physical dimensions remain the same.

• Most of the development works were the incorporation new blades and nozzles made from exotic super alloys.

• Fuel technology advances allowed the use of multiple types of fuel ranging from Crude Oil to plant based bio fuels such as palm oil and all types of combustible gasses ranging from flare gas to methane.
Heavy Industrial Turbines

• The Heavy Industrial Turbine is designed for continuous service

• Service intervals are about 100,000 hours (12.5 years)

• are designed to run continuously for periods of up to 8,000 hours (1 year) with only a small annual inspection

• From a construction point of view, the Power Station is built around the Turbo generator as opposed to the Turbo Generator being installed within a power Station.
Example – GE Frame 9
The GE Frame 9 was first introduced in the late 70’s but it’s design root dates back to the 1950’s with GE’s introduction of the classic Frame 5. In short the frame 9 is a Frame 5 multiplied by 4.
Food for thought...1

Specified life of stage 1 turbine blade is +50,000 hours ≈ 6 years! For six years the blade has to rotate continuously at 3000 RPM in a very harsh environment

• Local gas temperature of ~1527°C is ~200°C higher than alloy melting point of ~1350°C

• Power output per blade is ~850 horsepower i.e.~7 x typical family car
Food for thought…2

• Typical blade weight ≈ 9 lbs
• Centrifugal force ≡ weight of a dumper truck or 4 London double-decker buses
• Rotate continuously at 3000 RPM for ~6 years while also vibrating!
Potential failure considerations:
One of my responsibilities was to assess the warranty risks and over the years I found that the most effective way was to appraise the operation in terms of:

• Fuel

• Operations and Maintenance

• Competence

• Age and type of Equipment

• Location/environment
Fuel

- A gas turbine has the advantage of being a true multi fuel engine and as such can accommodate all type of combustible gases and all types of combustible liquids.
Operations and Maintenance

- **Ethos** – How is the unit operated on a daily basis- Constant load, standby, Peaking. What will be estimated equivalent hours in a 12 month period
- **Working Practices** – Do they follow recommended working practices and OEM recommendations
- **Workshop** – What equipment is available is it calibrated
- **Health and Safety** – A reliable indicator of working practice
- **Fire Prevention**
- **Are all lock out procedures observed**
- **Chain of command – who is in charge?**
- **Cleanliness** - Another reliable indicator of good working practice
- **Records** – Are all service records available and up to date
Hours-Based HGP Inspection

Maintenance Interval = \frac{24000}{\text{Maintenance Factor}} (Hours)

Where:
Maintenance Factor = \frac{\text{Factored Hours}}{\text{Actual Hours}}

Factored Hours = (K + M \times I) \times (G + 1.5D + A_f H + 6P)
Actual Hours = (G + D + H + P)

G = Annual Base Load Operating hours on Gas Fuel
D = Annual Base Load Operating hours on Distillate Fuel
H = Annual Operating Hours on Heavy Fuel
A_f = Heavy Fuel Severity Factor
(Residual A_f = 3 to 4, Crude A_f = 2 to 3)
P = Annual Peak Load Operating Hours
I = Percent Water/Steam Injection Referenced to Inlet Air Flow
M&K = Water/Steam Injection Constants

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Figure 43. Hot gas path maintenance interval: hours-based criterion
Starts-Based HGP Inspection

\[
\text{Maintenance Interval} = \frac{S}{\text{Maintenance Factor}}
\]

Where:

\[
\text{Maintenance Factor} = \frac{\text{Factored Starts}}{\text{Actual Starts}}
\]

\[
\text{Factored Starts} = 0.5N_A + N_B + 1.3N_P + 20E + 2F + \sum_{i=1}^{\eta} (a_{\eta_i} - 1) T_i
\]

\[
\text{Actual Starts} = (N_A + N_B + N_P)
\]

\[
S = \text{Maximum Starts-Based Maintenance Interval (Model Size Dependent)}
\]

\[
N_A = \text{Annual Number of Part Load Start/Stop Cycles (<60% Load)}
\]

\[
N_B = \text{Annual Number of Base Load Start/Stop Cycles}
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\[
N_P = \text{Annual Number of Peak Load Start/Stop Cycles (>100% Load)}
\]

\[
E = \text{Annual Number of Emergency Starts}
\]

\[
F = \text{Annual Number of Fast Load Starts}
\]

\[
T = \text{Annual Number of Trips}
\]

\[
a_{\eta_i} = \text{Trip Severity Factor} = f(\text{Load}) \text{ (See Figure 21)}
\]

\[
\eta = \text{Number of Trip Categories (i.e. Full Load, Part Load, etc.)}
\]

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<th>Model Series</th>
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Competence

• Do the operations and service personnel understand the operational principles or do they work to a predefined schedule?

• Are they interested?
Age

• Most of the Turbines in operation in the UK are over 30 years old

• Young engineers are introduced to equipment that is antique by their standards and unusual

• Ancillary material outside the turbine starts to randomly become problematic. Pipe work starts to leak, false reading occur in monitoring equipment so the operators lose confidence in the readings

• The risk potential increases with age.
Location/Environment

• Location and environment are crucial considerations in terms of risk.
• The perfect environment is somewhere in Alaska where the air quality is perfect and the fuel is sweet natural gas.
• In desert locations where the air carries high volumes of sand there is a high potential for erosion on the leading edge of all parts in the gas path.
• In an oil refinery where there are high volumes of sulphur location of the turbine in relation to prevailing wind direction is important because the risk of sulpheration corrosion increases.
• A shoreline location for an electrical generation plant where the air is humid and contains high levels of salt increases the risk of leading edge erosion and general corrosion of all steel.
Root Cause Analysis

• Worked with Braemar for just over a year and the one thing that has grabbed my attention is the findings given on root cause analysis reports.

• There is no suggestion that the assured has tailored these reports as the facts given are in all cases correct, however the findings do not necessarily agree with the facts.
Case Study 1

• Foreign Object damage to a two stage power turbine causing irreparable damage to both the Buckets and Nozzles.

• Object identified as a gas seal that interfaces the 1st Nozzle and outer case

• The reports and dimensional checks confirm Heavy Distortion of the casing But none on the nozzle? This means the gap between the nozzle and casing has changed

• The report concludes the seal needs to be redesigned?

• So the casing did not damage the seals?
Findings (Define): Possible Failure mode 4
Failure mechanism considering inaccurate assembly and/or parts out of spec

1. Due to bad stacking or to parts geometry out of spec, 1 locking seal is liberated
2. Angel wings collide and parts are rubbed and smashed together
3. Sudden liberation of nearby lock seals and catastrophic damaging
4. Debris hit the balancing weights of the 1st stage wheel.
5. Rotor is unbalanced, and high vibrations are detected
6. Once rotor is stopped, all debris fall downward
7. Rotor is jammed by debris

- Nozzle support ring groove ("c" seal housing) is inside design tolerances.
- Possibility of inaccurate assembly cannot be evaluated on failed seals because the parts are heavily damaged

Probable Root Cause
Corrective Actions (Improve)

- **Actions proposed/performed to solve the issue on failed unit**
  Failed unit is under refurbishment

- **Implementation plan for existing installed fleet**
  No other issue detected up to now in the 200 units fleet.

- **Actions for units under procurement**
  No changes in the assembly procedure is necessary, since the current procedure is still correct.

Additional checks during BSI are strongly recommended for units under the same operating limits.

**Additional checks:**

*It is recommended to perform additional checks throughout boroscope inspection, to make sure no other engine is damaged.*

*Additional inspection should focus on the status of the angel wings between 1st stg nozzle and 1st stg rotor. Anomalies must be reported, so to keep the status under control.*

*At first available opportunity, when GG is removed from the enclosure, proceed with removing the elliptical shield and perform a boroscope inspection of the area between 1st stg disk and nozzle support ring, to verify the status the locking system of the 1st stg nozzle.*

**Long term corrective Action:**

Investigative and evaluate alternative nozzle lock seals system.
• Results of the inspection:
  - The casing is in general poor conditions for heavy distortion
    - Owing to the entity of defects the item is scrap

• Proposed repair workscope:
  - Replacement of the item with new one
Photo 3 – Unit during disassembling
CONTROLLO DIMENSIONALE E RUNOUT - DIMENSIONAL & RUNOUT CHECK

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<th>SURF.</th>
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