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ADVANTAGES OF AERODERIVATIVE GAS TURBINES: TECHNICAL & OPERATIONAL CONSIDERATIONS ON EQUIPMENT SELECTION

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1 Abstract

Technical, operational and commercial considerations play a major part in any large capital expenditure project, especially when those projects demand everything from daily single hour runs to continuous yearly operation. LNG trains may be offshore or land based and pipeline transmission projects are typically installed for generational use in remote and harsh locations. Power generation projects could have requirements of operation including base load, mid-merit or peaking, each with their own demands on the product.

These operations require flexibility, high levels of reliability and availability and operators need to convince themselves and investors that long term product integrity, product support and cost effectiveness are not only achievable but are proven capabilities of the OEM gas turbine supplier and long term supporter.

This paper will aim to highlight the fundamental differences between aero-derivative, light industrial, frame and hybrid machines and show the benefits in maintenance, operations and capability of choosing one over the other as the appropriate technology for a given application.

2 Applications

Industrial gas turbines are used across a wide range of environmental conditions, from arctic cold to desert heat. The power capability of these machines is generally defined on an ISA (15°C) day, but customers naturally expect the engine's performance to be provided at their own design point and operational extremes.

For example, on pipeline applications, typically the project will cover multiple sites which cover hundreds of miles or even be trans-continental, at a wide range of ambient conditions. As such, the power behind the pipeline must be flexible and as constant as possible regardless of ambient conditions.

Projects used to be assessed based on a single set of site conditions, however more recently the process involves assessing each station / site on an individual basis.

This allows more flexibility in equipment selection and operation in terms of power and capability.

3. Industrial Gas Turbine variations

Industrial gas turbines are generally divided into four main groups as described below:

3.1 Aeroderivative: (up to ~66MW in power)
This consists of an engine, or gas generator, which has been derived from existing aircraft engine technology and applied in an industrial application. Designed for small footprint and low weight, it utilizes advanced materials for high efficiency, ~41%, fast start up times with little or no cyclic life penalty and modular construction. They have been designed for quick removal and replacement allowing for fast maintenance and greatly reduced downtimes resulting in high unit availability and flexibility.

Aircraft engines are required to be the ultimate in turbine reliability, and this feature is carried over to the industrial counterpart. In a majority of cases, the gas flow path components used in both engines are identical in design and material. Minor changes may be required to coatings to accommodate operation on gas fuels rather than liquid (aero) as required by energy applications.

Rapid engine response is paramount to aircraft gas turbines, and their industrial derivatives also exhibit the same inherent flexibility to changing conditions. Typically they will have multiple shafts (2-3), which allows each mechanically independent compressive and turbine stage to operate at its optimal speed and efficiency.

As with all aeroderivative gas turbines, their higher pressure ratio mandates a higher fuel gas pressure at the skid edge than their heavy counterparts. This may require additional equipment to be purchased and installed by the end user to boost the available pressure sufficiently to meet their power and efficiency demands.

With a fast start and fast transient manoeuvre capability (ability to accommodate varying load quickly) fuel transfer capability (switching from gas to liquid or vice versa whilst running and at load) and ever increasing high nitrogen / carbon dioxide fuel flexibility capabilities, the overall operational flexibility of the machine is a considerable asset and customer advantage. DLE (dry low emissions) combustion systems used in aeroderivative tend to be smaller in size and more sensitive to either fuel composition or ambient conditions. As such, some systems may require seasonal emissions and performance tuning that can have an impact on unit availability; however this is not applicable to all DLE systems from all manufacturers.

Component accessibility for ease of service is important in minimizing aircraft downtime. Similarly, the aero-derivative industrials are ideally suited for ease of component inspection, repair or replacement.

- Very high power density
- Low weight & small footprint
- High efficiency resulting in significant fuel cost savings

- High cycle flexibility
- Fast start and transient capability
- Short downtimes for maintenance

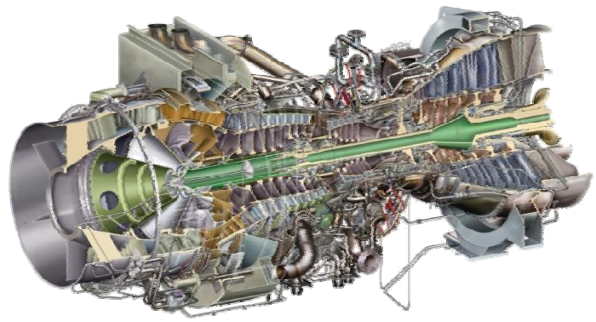

Figure 1. Rolls-Royce Trent 60 WLE

3.2 Frame / Heavyweight: (up to 340MW in power)
Casings and rotatives are designed purely for land operation with little consideration as to weight or footprint, and are derived from steam turbine technology. Main design differences are that most frame are single shaft machines and operate at a single fixed speed and thus require more stages of variable blades for airflow management and surge control during start up and shutdown. The mainline bearings are hydrodynamic (vs. anti-friction for aero derivative) and they typically use less advanced but more commercially available materials in their construction. The physical size of the combustion systems allow for lower pressure ratios which can aid in lower emissions (single digit) and high fuel flexibility.
As they are field erected with all maintenance completed in on site, maintenance times for the plant as a whole are typically longer and more manpower intensive.

- High Power output
- High Combined cycle efficiency
- Lower emissions
- Lower initial capital expenditure cost
- Has higher tolerance to lower quality fuel at the cost of reduced thermal efficiency
- Single shaft machines tend to have quick reaction times to large step load changes.

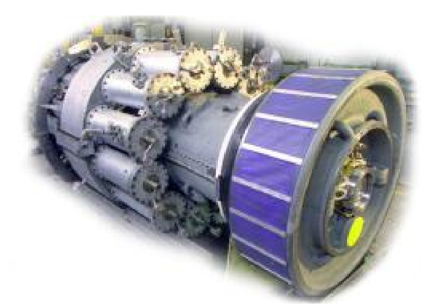

Figure 2. MS5002 – Frame 5. Courtesy GE Energy

3.3 **Hybrids**: (up to 100MW in power)

Uses an aeroderivative at the heart of the machine, but adds on an industrial compressor and intercooling system for an increase in power in efforts to combine the best attributes between aero and heavy.

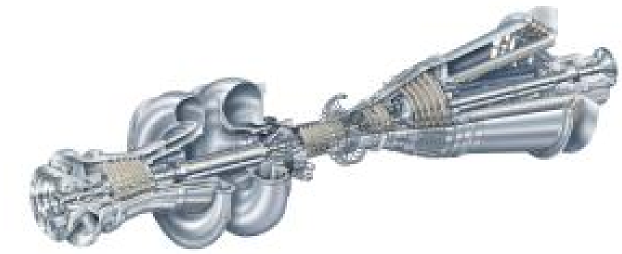

Figure 3. LMS100 - Courtesy GE Energy

3.4 **Light Industrials**: (up to 50MW in power)

Designed specifically for the energy market - power generation / oil and gas mechanical drive. Although they are designed to maintain some aeroderivative characteristics, they have no aero operational experience or heritage meaning that the experience or lessons learned in aero can no longer be applied to the fleet for operational improvements. The design intention is to keep some of the advantageous aspects of Frame / Heavyweights such as material cost and life, and combine them with the footprint and flexibility attributes of an aeroderivative gas turbine.

Figure 4. SGT750 - Courtesy Siemens

4 Derivation of the Aeroderivative

Because aero-derivative gas turbines are derived from their corresponding aircraft power plant models, they benefit from the extensive technological development and experience of jet propulsion aircraft gas turbine engines (see Figure 5). Today, aircraft engines lead the development of turbine technology in the drive for higher efficiency components and performance. The extension of this technology from aircraft to their industrial counterparts provides many significant advantages to the user.

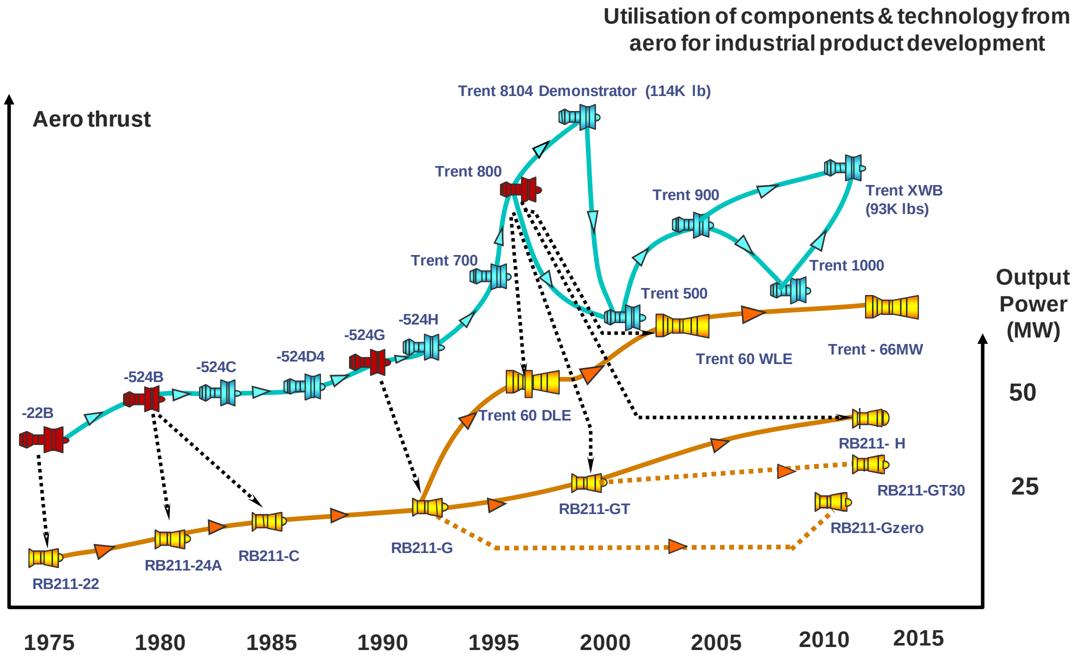

Figure 5. Shows the derivation of energy gas turbines from their aero power plants

5 Modifications required

Modifications must be made to an aircraft gas turbine to render it suitable for any industrial application.

From Aircraft engine	To Industrial Gas Turbine
Intermittent operation over short periods	Continuous operation over long periods
Wide Range of altitudes experienced	Narrow range of altitudes experienced
Only high grade aviations fuels used	Wide range of liquid and gas fuels used
Both high & cruise power used every flight cycle	Base or part load operation over long periods

To convert an aircraft gas turbine for industrial use, some design changes are introduced. In addition to modifying the fuel system to operate on differing fuels, engineering work has been largely concentrated in:

- Strengthening of main line bearings and lubrication for continuous operation at relatively low elevations.
- Development of combustion systems to improve life, give a cleaner exhaust and lower emissions for lower grade fuels.
- Modification of components to extend inspection and servicing intervals.
- Rating of engines to give three years, (25,000 hours), of service before gas generator removal is required for overhaul.

25,000 hours is an expected industry standard. Aero-derivative gas turbine engines are generally not “hard lifed”, and time for overhaul is recommended based on the condition of the unit during routine inspections. Some engines may need to be overhauled sooner than others due to its condition, or more likely due to operational requirements so as to not have two GT’s removed for overhaul at the same time. Some engines are cleared for further running and additional inspections are carried out. Factors that affect an engines condition can include site conditions / location, inlet air quality, fuel quality, power loads and start cycles etc.

6 Characteristic comparisons

A direct comparison of an aero-derivative gas turbine with a heavy frame type reveals several significant advantages of the aeroderivative unit which are of major importance to the end user. The following table summarizes the relative typical characteristics for each of the two turbine types and indicates the impact on the user in each case.

Characteristic	Typical Aero	Typical Heavy	Aero Benefit
Skid dimension	395 sq.ft	515 sq.ft	30% less floor space. More transportable. Reduced foundation requirements. Faster Installation times
Thermal Efficiency	37-42%	28-34%	High efficiency machines provide added protection against fluctuations in fuel price.
Operational Flexibility	Multiple lower power units	Single high power unit	Greater operational flexibility with ability to split or share load whilst maintaining fuel efficiency.
Driver skid weight	60 tonnes	120 tonnes	Half the weight. Reduced foundation civil works required.
Single heaviest maintenance lift	~5 tonnes	10-15 tonnes	Requires lower lifting capacity onsite.
Starting	Cold iron to full load in 10 mins possible depending upon configuration, without impact to cyclic life. For some engines, this is the standard time period for a start.	Fast starts not possible without adverse impact to cyclic life, and therefore component life. No fast start capability at all on larger heavy weights.	Higher response times to customer power demand. Smaller footprint and easier starting

	Start with only ~350kW.	Helper motors required to get engine rotating	Ability to break away large levels of torque with small starter motor.
Acceleration to load	Rapid – Idle to full load in 2 mins.	Slower – 10-15 mins, meaning time spent at first critical speed.	Ready to accept load faster. Standby turbine on line when needed. Heavy can experience critical dynamic thermal stressing during acceleration.
Deceleration	5-15 mins depending on configuration.	Approximately 30-60 mins.	Ready for maintenance faster.
Cooling	Rapid - gas generator can be cooled down in less than one hour.	Due to mass, cool down is 10-24 hours on a turning gear to prevent shaft bowing.	Ready for maintenance or inspection faster. Less downtime. Less Cost
Immediate re-start	Yes. Depending on engine type, if initiated within 3 hours of the shutdown, a reduced power turbine warm-up is required. For some machines, no hot lockout at all is required.	If not restarted within 10 mins, a full machine cool down must be allowed to occur (see above)	Higher start availability along with a fast start capability means more responsive to customers' needs and less time idling on standby as rolling reserve.
Hot section inspection	Inspection through borescope holes of entire gas generator and power turbine. Incorporated into annual inspections and is not a separate shutdown.	Inspection requires removal of fuel nozzles and combustors. Borescope ports only available for critical parts and not the whole engine.	Faster inspections. Less downtime Less cost due to loss of availability.
Turbine Inspection (hot gas path).	Incorporated into annual inspections and is not a separate shutdown.	Inspection in approx 160 hours not including cool down time.	Faster inspections. Less downtime Less cost due to loss of availability.

Annual Inspection	Takes approximately 30 hours or 3 x 10 hour shifts. Heavy lift equipment not necessary. 2 Reps from OEM, 2 from Customer.	Takes approximately 6-15 Days depending on engine and scope. 4 Reps from OEM, 4-6 from Customer.	Faster inspections. Less downtime Less cost due to loss of availability. Less logistical and planning requirements
Detailed Compressor Inspection (not normally required by aero)	Not normally required by aero-derivatives regardless of manufacturer. Inspection by borescope.	10 Days. If more than 2-3 complete blade rows need to be replaced, can be longer due to in-situ re-balancing requirements. Some newer machines have adapted to the aero philosophy of not re-blading in-situ. Heavy lift equipment is required. 2 Reps from OEM, 2 from Customer.	Less downtime Less cost due to loss of availability.
Gas Generator Change out	From engine stop command to full load, 48 hours or 4x12 hour shifts. Includes Power Turbine Inspection. 2 Reps from OEM, 2 from Customer.	Very limited. A 28 day shutdown has been proven to be carried out in 20 days, but requires significantly higher manpower and logistical resources. 4-10 Reps from OEM, 4-6 from the customer minimum.	Significantly less downtime Less cost due to loss of availability. Less personnel logistical and planning requirements.
Power Turbine Overhaul	Once every 6-12 years / 50-100K operation depending on product. ~180 hours See figure 5.1 2 Reps from OEM, 2 from Customer.	Would be a part of the Gas Generator change out scope.	Less downtime Less cost due to loss of availability.

Parts Logistics	Gas Generator sent to site as a single unit. Only minimal spares and consumable items required.	Parts required will not be fully known until engine strip has occurred. Time taken to get parts shipped from OEM to site represents additional downtime, which means maintaining a full team of personnel at site waiting for parts may prove prohibitive meaning. Multiple mobilisations may be required	Significantly less downtime Less cost due to loss of availability. Cost of engines changes known in advance.
Maintenance location alternatives	Either on site or at an off-site facility as requirements dictate	On-site maintenance only practical alternative. Requires large lay down area's.	Flexibility to suit location, timescales for maintenance requirements.

7 Maintenance Downtime

The below chart highlights the typical down time required only for the major inspections of aero derivative industrial gas turbines. For the same period, expected downtime for a heavy weight machine is expected to be between 110 and 140 days resulting in reduced unit availability. For both types, there may be other inspections required either by the operator, individual manufacturer or local authority for regulatory requirements and compliance, such as the installation of emissions monitoring equipment. During these times, other maintenance procedures may be completed simultaneously.

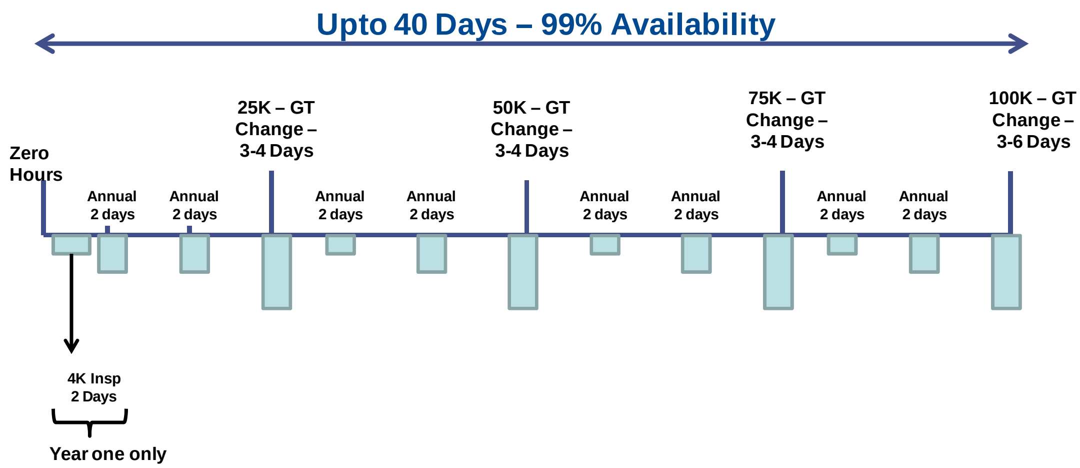

Figure 6. Typical Aero downtime over 100,000 hours

8 Average Heavy industrial maintenance requirements

8.1 Combustion Inspection 2-5 days (extending to weeks if parts unavailable)

It is recommended for heavy industrial turbines that a combustion inspection is undertaken between 800 hours and 8,000 hours dependent upon the application and total number of starts the machine completes.

Step	Notes
1.	Remove gas piping, fuel nozzles, spark plugs and flame detectors.
2.	Remove combustion covers, combustion liners, transition pieces and crossfire tubes.
3.	Inspect combustion liner, discharge casing, flow sleeve welds, fuel nozzles for lock tip safety, spark assembly plus all other combustion system components.
4.	Boroscope turbine buckets to establish wear. This allows the schedule for hot gas path inspection to be calculated.
5.	Boroscope compressor. Inspect the IGV's and associated components. Inspect last stage buckets and exhaust system.
6.	Inspect and check the proper operation of the purge and check valves and calibration of combustion controls.

It also assumes that:

- All parts requiring repair are immediately replaced from an available stock – responsibility of the operator.
- Most parts cannot be seen until disassembly has taken place; therefore time to complete could take significantly longer due to logistics of getting parts from OEM to site.
- Does not include cool down period (10-24 hours).
- The inspection is pre-planned.

- The inspection/replacement is conducted under the technical direction of a Manufacturers Field Service Representative.

For aero derivatives, combustion inspection is completed once every 4000-8000 hours depending upon unit availability, and is combined with a complete gas generator borescope inspection. This borescope inspection takes ~10 hours to complete and is combined with other yearly maintenance activities.

8.2 Hot Gas Path Inspection – Time ~5 Days

Heavy industrial manufacturers recommend this inspection is undertaken after one year (8760 hours). It is normally combined with a combustion inspection, and consists of a detailed inspection of the turbine nozzles, stationary stator shrouds and turbine buckets.

In order for this inspection to be completed, the top half of the turbine casing has to be removed. This demands the use of a 10-ton mobile crane which has a 15-foot reach and 30-foot lift. Secondly, the machine centerline must be maintained and supported with the use of mechanical jacks. This is required to ensure correct alignment of rotor and stator and prevent twisting of the stator casings.

In comparison the aero-derivative unit can be borescoped in ten hours without the removal of major components or the use of heavy lift equipment.

8.3 Major (Overhaul) Inspection – Time 3+ weeks

Depending on engine manufacturer, heavy industrial companies state these inspections should be scheduled every 25-40K hours depending upon the load, duty and operating requirements.

8.4 Major (Overhaul) Inspection Work Scope

Step	**Notes**
1	Same as for combustion and hot gas path inspections
2	Remove remaining upper half casing and bearing covers
3	Remove both rotors

During this major reconditioning of the turbine, and in fact during the combustion and hot gas path inspections, certain designated accessories in need of repair or replacement would be returned to the factory on either a repair and return basis or exchange basis.

The reconditioning process can take several weeks even if no serious deterioration of turbine components has taken place. The service estimate does not include time for blade replacement, and possible field balancing of the rotor. Tooling required for this procedure include engine driven welding kit, oxyacetylene cutting gear, 3-15 ton hoists and wrenches upto 16 inches. During this shutdown period the unit is completely non-operational.

In contrast, on an aero-derivative turbine, 4-6 persons can remove and replace the gas generator using a manual hoist and standard tools in 72-96 hours depending upon both the combustion system type and other inspection requirements completed at the same time.

9 Average aero maintenance requirements

Period	Activity	Work Hours Required	OEM Personnel	Customer Personnel
8,000 hrs or Annual	**Gas Generator** ✓ Tests ✓ Inspections ✓ Borescope **Power Turbine** ✓ Evaluation ✓ 'A' Class Inspections ✓ Measure clearances **Package** ✓ Controls/Instrumentation system functional check & calibration. ✓ Fuel & Oil System checks & filter change ✓ Air intake system inspection & filter change ✓ Anchor system ✓ Enclosure checks ✓ Driver to Driven Gearbox alignment check	48 hrs	1-Mech FSR 1-Ctrls FSR	2-3
25,000 hrs	**Gas Generator** ✓ Gas Generator removal for mid-life overhaul / refurbishment **Power Turbine** ✓ 'A' Class Inspection ✓ Evaluate vibration – inspect bearings condition ✓ Externally inspect exhaust seals ✓ Check mounting **Package** ✓ 'A' Class Inspection ✓ Inspect oil coolers	72 hrs	2-Mech FSR 2-Ctrls FSR	4
50,000 hrs	**Gas Generator** ✓ Gas Generator removal for full-life overhaul **Power Turbine** ✓ 'B' Class Inspection ✓ Inspect bearings ✓ Inspect aero-dynamics in situ **Package** ✓ 'C' class inspection	72 hrs	2-Mech FSR 2-Ctrls FSR	4

	✓ Check package bearings, gears and other components			

It should be noted that rotating assemblies and hot gas path components can be replaced upon aero-derivative turbines in the field with comparatively simple tools and that operators have undertaken to maintain their turbines at their own facilities. However, an overhaul at the aero-derivative central support facility reduces the stock levels of required spares and enables the gas generator to be completely overhauled.

For a midlife, hot section refurbishment (typically 25,000 hours) or full life overhaul (typically 50,000 hours) it is recommended a gas generator be returned to the central support facility on the same basis as heavy industrial turbine components requiring reconditioning. The gas generator would be returned to the operator in "as new" condition in 8-10 weeks or re-allocated into the spare pool. This process extends the gas generator life indefinitely.

Power turbine overhaul of aero-derivative turbines is only required "on condition." Units have completed more than100,000 hours without major overhaul. Bearing inspections can be completed without the removal of major components. The maximum maintenance weight is the turbine rotor is typically less than two tons.
Maintenance of turbine auxiliaries also favours the aero-derivative turbine as starting and lubricating systems are smaller and less complex.

10 Fuel treatment effect on overhaul life

Fuel quality is directly related to the cost and frequency of repair and life of gas turbine components. Poor fuel quality or even a good quality fuel gas that is poorly understood and managed can result in detrimental effects to unit operability, performance, availability, emissions and life.

If a gas fuel is well understood and monitored, it can be correctly heated and treated prior to combustion, and reliable operation is more easily gained, unit expectations are met, and life cycle costs and management more easily tracked and predicted.

Good fuel handling practice should always be followed to avoid contamination. As either a secondary measure or in cases where fuel contamination has occurred, fuel treatment should always be considered and put in place as necessary to meet the appropriate manufacturer fuel requirements and recommendations.

Most operational problems experienced with fuel gas are with regards to a poor understanding of the entire fuel gas composition which, in turn, leads to both incorrect fuel treatment in terms of cleanliness and heating and results in liquid formation within the gas.

Causes of liquids on the fuel gas:

- Insufficient fuel heating
- Well degradation over time

- Contamination after fuel analysis taken, e.g. water, oil during transport
- Liquids are unlikely to be in 'intermittent slugs', but most probably in continuous 'aerosol' form.
- They would not be found by a site investigation, nor by examination of filter bowls, as the liquids evaporate at ambient temperatures.

Example of effect on dewpoint:-

Assuming = C1, C2, C3, C4, C5, N2 and C02 are constant;

Example 1: C6+ is **0.062** % volume, **assumed as C6** for dew point calculation
Example 2: C6+ is **0.062** % volume, **assumed as C7** for dew point calculation
Example 3: C6=0.031, C7=0.013, C8=0.007, C9=0.005, C10=0.003, C11=0.002, C12=0.001 % volume (**total C6+ = 0.062 % volume**)

Calculated hydrocarbon dew points at fuel pressure of 495 psia are : -16 ºC, -5ºC and +29ºC.
The presence of liquids in the fuel gas results in an outboard traverse of the exhaust heat profile: figure 6.

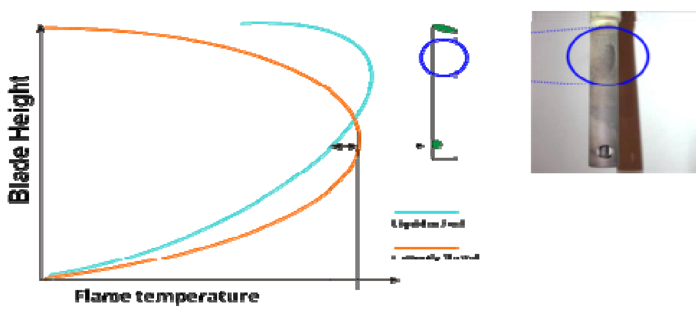

Figure 7: Diagram showing outboard traverse effect of liquids in the fuel gas

Rather than exhaust temperature thermocouples picking up the correct heat for engine control, the hottest part of the profile is no longer in the correct position. This has the adverse effect of engine over firing, hence the reduction in overhaul life.

This difference in fuel dewpoint, which is based on a given understanding of the fuel gas can have serious commercial and operation impacts if they are not properly dealt with in the fuel treatment options during project definition and procurement stages.

11 Summary

The aeroderivative industrial gas turbine offers the end user advantages in terms of unit availability via reduced maintenance requirements where run time is money earned.
Although the heavy weight gas turbine has advantages in its capability to burn low quality fuels, this comes at the price of much reduced thermal efficiency and therefore a much increased lifetime fuel cost over a project life cycle.

Similarly demands of starting and stopping offer a benefit by using only the fuel and hours needed to meet operational demand rather than having to run for hours or days on stand-by.

The extended service on heavy industrial turbines has the effect of dramatically reducing availability, which without a multi-unit redundancy philosophy, would only be acceptable for seasonal operations. On the basis of a normal scheduled maintenance, heavy industrial turbines can expect to be non-operational for several weeks every year in comparison a few days for aero-derivative machines.

Each project, whether power generation or mechanical drive, will have its own demands for power output and must be judged on those requirements, however projects should be assessed on more than just capital expenditure and should involve long term operations in the model.

The modern aeroderivative, regardless of manufacturer, has the capability to be flexible enough to meet changing project conditions, demands and constraints with high levels of reliability, availability and efficiency.

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