Offshore Gas Turbines and Dry Low NOx Burners

An analysis of the Performance Improvements (PI) Limited Database

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<td>October 2014</td>
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<tr>
<td>February 2015</td>
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Glossary
BAT          Best Available Techniques
CH₄          Methane
CO           Carbon Monoxide
CO₂          Carbon Dioxide
DLN / DLE    Dry Low NOₓ / Dry Low Emissions
GE           The General Electric Company
GT           Gas Turbine
IED          Industrial Emissions Directive
LCP BREF     Large Combustion Plant Best Available Techniques Reference Document
LHV          Lower Heating Value
NOₓ          Oxides of Nitrogen
OGUK         Oil & Gas UK
PI           Performance Improvements (PI) Ltd.
PPC          Pollution Prevention Control
SAC          Standard Annular Combustion technology
SO₂          Sulphur Dioxide
UKCS         United Kingdom Continental Shelf
UHC          Un-burnt Hydrocarbons
VOC          Volatile Organic Compounds
1. INTRODUCTION

Oil & Gas UK requested that Performance Improvements (PI) Limited compile a report on typical gas turbine operation in the UKCS and to specifically highlight issues concerning Dry Low NOx (DLE) burners. Oil & Gas UK will use this information to develop a position on whether DLE units can be considered as the Best Available Technique (BAT) for offshore operations.

The PPC baseline testing (for exhaust pollutants) and elsewhere, carried out since 2007 to present, has allowed PI to consolidate a large amount of information (concerning various aspects of gas turbine type, emissions and operation) in a large and probably unique database of knowledge regarding 192 gas turbines operating in the offshore environment.

All information in this Technical Note has been provided by PI in a non-attributable form.
2. EXECUTIVE SUMMARY

PI has used their extensive gas turbine database and PPC testing results for UKCS installations to compile this report. This information will allow Oil & Gas UK to comment on the IED directive (including the LCP BREF) legislation and provide evidence to support the belief that DLE units are not the Best Available Technique for existing offshore operations on the UKCS.

Hence the continued use of existing SAC gas turbine units is recommended in the foreseeable future.

The gas turbine data presented in this report shows:

- The analysis conducted shows that 66 out of 91 turbines were operating at <70% of the rated load and 45 out of 91 turbines were <60%. The average loading was 53%.
- N+1 (or load share) operation is normal operating practice. Out of the 192 units in the database, 187 (97%) of these were operating in load share.
- There are several examples where DLE engines under normal operation are outwith the BREF limits for NOx and CO. e.g. CO limit is 100 mg/Nm3 whereas measured values were in excess of 5,000 mg/Nm3 at low loads.
- The potential variability of fuel gas quality that is experienced on some platforms would be problematic for DLE operation. In the example quoted in the report, CH4 varied between 65% and 85% which is a significant range.
- Of the gas turbines studied, dual fuel machines were significantly more common than single fuel use machines. It was noted that 97% of power generation units were dual fuel. Power generation is by far the most common duty for GTs offshore, making up 66% of the units studied.
- It is estimated that at an average load (53%), no standard gas turbines would meet the BREF limits set for NOx (while they would meet the limits for CO).
- Of the 6 DLE units PI have knowledge of in the UKCS, 5 are loading <70% with only one being lightly loaded. At these high loads, the units would meet the proposed BREF limits for NOx and CO. However, if loaded below 60% it is likely that DLE units would not meet the BREF limits.
3. GAS TURBINE OPERATION ANALYSIS

Performance Improvements (PI) Ltd. consolidated their experiences from the conducted PPC tests into a single database which allowed for direct comparison of units. In the database, a total of 192 gas turbines from 45 offshore sites were analysed in terms of unit type, duty, fuels burned, burner type, typical loading and operating relationship with other units. The result of this analysis is presented in Table 1.

<table>
<thead>
<tr>
<th>Number of GTs in database</th>
<th>192</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of GTs with complete information</td>
<td>174</td>
</tr>
<tr>
<td>Power Generation Units</td>
<td>128</td>
</tr>
<tr>
<td>Mechanical Drive Units</td>
<td>64</td>
</tr>
<tr>
<td>Dual Fuel Units</td>
<td>126</td>
</tr>
<tr>
<td>Single Fuel units</td>
<td>66</td>
</tr>
<tr>
<td>DLE Units</td>
<td>6</td>
</tr>
<tr>
<td>Units operating in Load Share</td>
<td>187</td>
</tr>
<tr>
<td>Single Unit Operation</td>
<td>5</td>
</tr>
</tbody>
</table>

**Table 1 – Summary of Analysis**

The majority of gas turbines in the UKCS are dual fuel power generation units, with SAC (or cannular) standard combustors. These units are typically operated in load share (i.e. N+1 operation). Mechanical drive machines (where the GTs drive a compressor or a pump) are in the minority with only 64 of these units in the database.

The majority of these mechanical drive machines are gas fired only, with only two machines being dual fuel. The percentage ratios of these figures are expressed in Table 2.
### Analysis Ratios

#### Unit Duty

<table>
<thead>
<tr>
<th>Power Generation</th>
<th>Mechanical Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>128</td>
<td>64</td>
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</table>

Ratio of Mechanical Drive units

33%

#### Power Generation Units

<table>
<thead>
<tr>
<th>Dual Fuel</th>
<th>Single Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>124</td>
<td>4</td>
</tr>
</tbody>
</table>

Ratio of Single Fuel units

3%

#### Mechanical Drive units

<table>
<thead>
<tr>
<th>Single Fuel</th>
<th>Dual Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>64</td>
<td>2</td>
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</tbody>
</table>

Ratio of Single Fuel units

97%

#### Gas Turbine Units

<table>
<thead>
<tr>
<th>SAC Combustion</th>
<th>DLE Combustion</th>
</tr>
</thead>
<tbody>
<tr>
<td>186</td>
<td>6</td>
</tr>
</tbody>
</table>

Ratio of DLE units

3%

Table 2 – Analysis Ratio results
4. GAS TURBINE LOADING

For reasons of both plant flexibility and security, load share operation (also known as spinning reserve and N+1 operation) is the normal operating philosophy in the UKCS and is considered best practice by the industry. In the event of an unplanned generator shutdown, the second unit will take up load, minimising risk to the workforce and production losses.

Single unit operation is seen as risky and undesirable. If the generator trips in single unit operation, a smaller emergency generator (normally a diesel engine) is started to prevent a “black out / lights out” scenario. As the emergency generator is normally of limited size, aggressive load shedding of the operational plant loads takes place in order to reduce the platform load to a level that can be handled by the smaller unit. As such, in the event of a generator trip, production from the platform will cease until the main unit can be restarted. If, of course, in the event that the standby unit fails to start, all power to the platform is lost which creates significant safety issues.

As gas turbine models are typically chosen to reflect the anticipated load on the platform, load share operation means that units are loaded less than 70% of gas turbine manufacturers rated load. In the gas turbines studied, PI has loading information for 91 units (out of the 192 units in our database). Out of these 91 units, 66 of them were loaded less than 70% and 45 units were loaded at less than 60%. Of these units, the average gas turbine load was only 53%.

Of the 6 DLE machines in the PI database only one unit was partly loaded at 44% with the average load being 71%, although, this is not a guarantee that these GTs will sustain such a load throughout the life of the field. As the fields mature electrical demands on the platforms may decline as production decreases, leading to these units become lightly loaded and out with DLE range of operation.

These findings are presented in Table 3 and graphically in Appendix A.
## Analysis Ratios

<table>
<thead>
<tr>
<th>GT Loading</th>
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</thead>
<tbody>
<tr>
<td>Number below 70% load</td>
<td>66</td>
<td>25</td>
</tr>
<tr>
<td>Percentage below 70% load</td>
<td>73%</td>
<td></td>
</tr>
<tr>
<td>Number below 60% load</td>
<td>45</td>
<td>54</td>
</tr>
<tr>
<td>Percentage below 60% load</td>
<td>49%</td>
<td></td>
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### DLE Units Loads

<table>
<thead>
<tr>
<th>Unit</th>
<th>Load</th>
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<tbody>
<tr>
<td>Unit 1</td>
<td>70%</td>
</tr>
<tr>
<td>Unit 2</td>
<td>70%</td>
</tr>
<tr>
<td>Unit 3</td>
<td>81%</td>
</tr>
<tr>
<td>Unit 4</td>
<td>89%</td>
</tr>
<tr>
<td>Unit 5</td>
<td>44%</td>
</tr>
<tr>
<td>Unit 6</td>
<td>72%</td>
</tr>
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</table>

### Table 3 Unit loads (SAC and DLE)

As DLE operation typically requires units to be loaded greater than 60%, DLE technology is **not considered BAT for existing turbines on the UKCS as most platforms would not be able to meet the operational criteria and maintain platform security from both a production and safety standpoint.**
5. SAC & DLE OPERATION

5.1. Description of Standard Annular Combustion (SAC) Operation

Gas Turbines are the most common type of power generation unit found offshore, both on fixed platforms and FPSOs. There are two general types of gas turbine; aero-derivative and industrial, the prime difference being the weight of the engine as industrial engines are heavier built. Both types operate in the same way.

Gas turbine operation is best expressed by the typical Brayton engine cycle where air entering the engine intake is compressed by an axial compressor (thereby reducing its volume and increasing its pressure) and is then mixed with fuel and combusted. The explosive action adds heat and the expansion drives a turbine stage allowing work to be done, typically driving an item of rotating equipment such as a compressor or an alternator for power generation.

The most common type of combustion system is the Standard Annular combustor. Annular combustors do away with the separate combustion zones (found on the older Cannular type) and combustion nozzles are located around a continuous liner and casing in a ring (the annulus of the gas turbine). There are many advantages to annular combustors, including more uniform combustion, shorter size (therefore lighter), and less surface area. A typical example is shown in Figure 1.

![Figure 1 – Annular combustor ring](Ref 3)

Annular combustors tend to have very uniform exit temperatures. They also have the lowest pressure drop of existing burner designs. The annular design is also simpler making them desirable for offshore operation.
5.2. Description of Solar Dry Low NOx operation

The formation of NOx and CO occurs in different temperature regimes. NOx is formed mainly through the thermal NOx route, which becomes significant at combustion temperatures above 1850 K. CO is present at lower temperatures, due to lower reaction rates and less oxidation of CO to form CO₂, which is a function of combustion efficiency and residence time. Hence, the window of technological opportunity to achieve low NOx and CO lies in a narrow range for both equivalence ratio and thus combustion temperature, as shown in Figure 2.

![Diagram showing emissions characteristics](image)

**Figure 2 – Emissions Characteristics**

Emissions of UHC are a result of local fuel-rich zones. All of the fuel will not be combusted and UHC will occur in the combustion gases. In gas turbines it is seen that UHC emissions in general follow the same pattern as CO emissions.

The concept of DLE technology focuses on controlling the flame temperature within a narrow band to minimise both the NOx and CO emissions. Normally this involves making a lean air/fuel mix, which reduces the flame temperature, and is often based on premixing in an initial chamber. Additional air is then added in a subsequent chamber to complete the combustion process and to provide a cooling function.

The disadvantages of running in lean conditions are the marginal blowout limit and the risk of high CO/UHC emissions at low combustion temperatures, due to incomplete combustion. Hence, operation of a low emission combustion system requires accurate fuel control, which is particularly vulnerable to small disturbances that may result in combustion instabilities. A major problem when designing combustors with lean premixing has been keeping the combustion generated noise levels at a satisfactory low level.
In practice it is not possible to keep within the low emissions window across the full operating range. For example, Solar Turbine’s SoLoNox technology low emissions operation is restricted to the range between 60 – 100% load on gas fuel and 65 – 100% load on liquid fuel.

At operating loads below 60% (gas fuel) and below 65% (liquid fuel), the guide vanes are fully opened. Terminating the temperature control causes the system to lean out, so the pilot fuel is increased to a higher level to maintain flame stability. The result of the two control changes is the increase of NOx and CO emissions. Typical emissions characteristics across the turbine load range are shown in Figure 3.

![Figure 3 – SoLoNox Emissions and T5 Characteristics](image)

NOx emissions contribute to acid deposition and may also contribute to ozone formation when mixed with volatile organic compounds in sunlight.

Hence, engine manufacturers now offer modified combustion systems known as DLE (Dry Low Emissions). These turbines can be very effective as they can reduce NOx production by up to 90%. This effect is achieved by operating in a fuel lean configuration mode using a complex burner system, which reduces the combustion temperature. The designs differ slightly but they usually have several different combustion modes with the main combustor having several sub-sections. The use of the different sections varies as fuel flow increases, and their operation is optimised along with air flow control (e.g. air bleed) to maintain air/fuel pre-mix and lean burn conditions.
5.2.1. Operational Issues

There are numerous issues associated with DLE combustion technology when used in offshore oil and gas production.

- In general, DLE technology is not yet fully mature compared to SAC, leading to reduced reliability.

- Effective DLE air/fuel control has narrow tolerances, and it does not work well in situations where the properties of the fuel gas can change quickly, as can occur on offshore installations. The consequences are a loss of DLE performance with a potential for flame failure (‘flameout’) with subsequent production trip and increased flaring. One operator in particular experienced many flameouts.

- The fuel systems are intolerant of heavy ends in the fuel gas (C10+).

- Combustion “rumble” was an initial issue leading to premature failure of components. Detailed post overhaul/repair testing procedures have now been developed to identify combustion component ‘noise islands’ which match the natural resonant frequencies of combustion components. The fuel control system is uniquely tuned on an ‘engine by engine’ basis to avoid these islands during operation to prevent premature degradation of the combustor.

- The load generally has to be above 60% for the DLE system to work effectively. Below this value, combustion performance can be compromised, particularly with excessive quantities of carbon monoxide being produced. Furthermore, because most DLE fuel control systems focus on limiting flame temperature (and hence controlling NO\(_x\)) they are prone to high CO and UHC in instances where incomplete combustion or internal leakage paths between burner rings go undetected / uncontrolled.

- DLE systems require additional air bleed at various loads, which increases the CO\(_2\) emissions marginally (2% to 3%). Effective control is very sensitive to correct operation and feedback of air flow control / variable geometry mechanisms including bleed valves and guide vanes.

- The engines require frequent “fuel mapping” to re-tune fuel control to thermodynamic and physical tolerances (e.g. performance degradation and fuel valve replacement respectively) that requires additional expertise, thus increasing the numbers of personnel offshore and cost of additional OEM intervention due to ‘black box’ technology.

- The need for a more detailed maintenance regime requiring additional training of personnel.

DLE machines are less likely to offer extended time between overhauls and generally cost more to overhaul e.g. typical DLE overhaul costs are increased by up to £300,000 when compared to SAC type machines. Overhaul cost increase is per major overhaul i.e. approximately every 24,000 fired hours.
In PI’s experience, DLE units do not have a good reputation in the UKCS. Out of the 192 units in our database only 6 units are fitted with DLE combustors. Of these 6 units:

- 3 units belonging to one operator have already been changed back to SAC combustors due to combustion rumble issues

- 2 units belonging to another operator have experienced frequent issues with burner cracking (due to “caking” of the diesel nozzles). This operator is considering changing the units back to SAC combustion.

- A third operator with a dual fuel power generation unit found that they are unable to run on diesel for any significant amount of time.

Of the units known to PI, only the single fuel mechanical drive DLE units have been known to operate with any reasonable success but units with these specific demands are in a minority.

DLE units when operated at a lower load may still not meet the Best Available Techniques BREF limits for NO\(_x\) and CO production. Figures 4 & 5 show results from a recent test on a DLE unit.

As may be seen, the DLE units when loaded below 60% have:

- NO\(_x\) emissions that are greater than the BREF limit of 50mg/Nm\(^3\)

- CO emissions which increase dramatically to over 5,000mg/Nm\(^3\) at low load. This is far greater than the BREF Limit of 100 mg/Nm\(^3\) and could represent a health hazard. Anecdotal evidence from USA indicates numerous DLE units are not allowed to run with these emissions at low load.
For a gas turbine fitted with standard combustors (SAC or the older cannnular style) the typical emissions characteristics can be seen, with NO\textsubscript{x} increasing in a linear fashion with load and CO being...
negligible with the exception of low loaded units where typically CO values increase to >150 mg/Nm³.

Figure 6 & 7 below shows a comparison between SAC and DLE engines for NOx and CO emissions. These results are taken from a selection of the emissions tests carried out by PI in the UKCS. They show:

- Across all load ranges DLE engines do emit less NOₓ and have a “flatter” emissions profile.
- While at low loads, CO emissions are in general far greater than typical SAC engine and considerably above the LCP BREF limit of 40 mg/Nm³.

![Figure 6 – DLE & SAC NOx Emissions Vs GT Load](image1)

![Figure 7 – DLE & SAC CO Emissions Vs % GT Load](image2)
A selection of results from SAC engines are shown in Appendix B and should be regarded as typical. At average GT loading (being 60%) it would be expected that all units would not meet the proposed BREF limits for NO$_x$ but likely meet the limit for CO in the short term.
6. FUEL GAS VARIABILITY

Offshore installations frequently have several sources of fuel gas which are taken from different points in the production system. Depending on the level of gas conditioning/processing, the composition of the gas can vary significantly. One such installation (taken from a PI survey) has three such sources as shown in Figure 6.

![Schematic of Fuel Gas Flow](image)

**Fig 8 Schematic of Fuel Gas Flow**

On this particular site the wide range of fuel gas properties is due to the following:

- Change in the number of wells that are on line which is a consequence of regular well testing or reservoir management requiring wells to be taken off line. Even platforms with only one fuel gas source experience changes in fuel gas quality as a result of changes to the well configuration.

- Variation in mix from the different sources due to temperature and pressure changes in the process.

- Changes to overall process following a plant or equipment trip.
Figures 9 & 10 show the variation in methane content and LHV following a shutdown.

Figures 9 and 10 - Variation of Methane Content and LHV vs Hrs since Shutdown
Even for a Standard Annular Combustor (SAC) these variations in gas compositions can be problematic, especially for dual fuel gas turbines where the tuning for the fuel controls must match both gas and diesel so that the system can automatically handle a fuel trip and transfer to diesel fuel seamlessly. Often, this does not happen, as mechanical lag can occur (where the actuators in the control valve do not respond quickly enough) resulting in a gas turbine trip. In PI’s experience during the PPC testing, it was very common for a gas turbine to trip on a gas/diesel changeover. Operators were often wary of implementing the fuel change for the purposes of an emissions test explaining that it added significant risk to the process.

For a DLE gas turbine the consequences are even more marked. Often an on line chromatograph is installed which has a response time of several minutes. Again the gas turbine controls cannot handle the mechanical lag and the unit is tripped as a consequence of the safety provisions. Hence, the uptimes for DLE gas turbine units are lower than their SAC counterparts.

The cost and feasibility of providing a more consistent fuel gas quality has been evaluated on numerous occasions. Frequently this involves a separate gas import line or a major change to the system design involving an extensive shutdown. At all times, the costs have been proved uneconomic.
7. SUMMARY

SAC gas turbines are by far the most common type of gas turbine in the UKCS. Nonetheless, operators are aware of the availability of DLE machines and prepared for possible upgrade by adopting a “DLE ready” strategy. This involves installing high efficiency fuel gas treatments units and ensuring gas turbine enclosures are sufficiently large to allow gas turbine change-outs to DLE version.

However, it can be seen that the offshore operating environment presents a unique challenge to DLE gas turbines due to:

- Variability of gas composition
- Low loads due to use of spinning reserve which gives high CO levels magnitudes in excess of the proposed limit.
- Poor reliability due to mechanical issues, especially with dual fuel units
- Frequent engines tuning / mapping requires significantly more contractor/OEM input to the operation of the units.
- Simplicity of Standard Annular Combustors is ideal for offshore operations due to lower maintenance requirements and higher reliability
- Standard Annular Combustion engines are more suited to dual fuel operation which is the most common and desirable operation
8. REFERENCES

1. PPC permits from various installations. Issued by DECC to Oil and Gas Operators. 2007 to present day.


3. JAXA, Japan Aerospace Exploration Industry, Clean Engine Technologies, 2003
Appendix A

Subject: Gas Turbine Loading

![Typical GT Loading graph]

![DLE Loading graph]
Appendix B

Subject: Typical NOx and CO Results from SAC Machines
R.R. Data = 174 mg/Nm³ @ 15% O₂ 
at nominal 16.5 MW design rating. 
Calculated from values of 85 ppmv at 15% 
O₂, 26,000 GGE GCHP, and 65% Power 
Turbine Efficiency.
Graph showing CO Concentration (mg/Nm³ @ 15% O₂) vs. Load (MW).

- Maximum Process Operating Load at ~4.3 MSm³/day Export Flow (November 2012 well availability).
- Maximum Rated Output 16.6 MW (as shown on PPC Permit).
- Turbine at idle (No process load).
- R-R Data = 31 mg/Nm³ @ 15% O₂ at nominal 16.5 MW design rating. Calculated from values of 25 ppmv at 15% O₂, 26,000 GGE, and 85% Power Turbine Efficiency.