THE DEVELOPMENT OF COST EFFECTIVE GAS TURBINE INSTALLATIONS OFFSHORE

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ABSTRACT

The paper describes the application and development of the offshore gas turbine from its infancy on Lake Maracaibo, Venezuela up to the current mature technology. North Sea developments are described, particularly in the Norwegian sector which was an important contributor to advancing the state of the art.

The first application of the second generation aero engine and of the very high pressure centrifugal gas compressor were important milestones which have made significant contributions to the economic recovery of North Sea hydrocarbons.

The author describes the current efforts to further optimise gas turbine installation, and operating costs. Cheaper and lighter gas turbine facilities require, not only increases in specific power, but also considerable innovation from the Engineers responsible for the application of this machinery.

For the future, fewer units of even larger ratings are foreseen, applied as high efficiency simple cycles with limited heat recovery.

INTRODUCTION

During the last 25 years, substantial offshore hydrocarbon reserves have been discovered and developed. Many of these developments would not have been possible without the ideal offshore prime mover - the gas turbine. The processing and transportation of hydrocarbons from offshore installations requires significant amounts of Power which needs to be generated by equipment requiring low space/weight. The evolution of the gas turbine offshore from it's early origins on Lake Maracaibo, Venezuela has been progressively developed from 2MW Industrial type 'H' units up to the currently installed 34MW second generation aero-engines and a 41MW GE LM6000 is planned for a future UK offshore installation.

The following description traces the important milestones of the development during the last 25 years. It also describes the current challenges of the applications engineer to make gas turbine packages of even greater ratings and specific power. Efficiency, safety and reliability are also important concerns.

EVOLUTION OF THE OFFSHORE GAS TURBINE

Early Offshore Gas Compression 1960 - 1972

Large offshore reserves in the Gulf of Mexico and Venezuela's Lake Maracaibo were found in the 1960's. The first early offshore prime movers for main power and gas compressor were diesel generator sets and integral gas engine compressor sets. This was typical onshore machinery taken offshore and whilst main power was never really a problem due to extensive marine experience, gas compression with integral gas engine compressors most certainly was. Vibration, pre-ignition explosions, were not an uncommon experience. As more offshore oil was found, particularly on Lake Maracaibo, it became apparent that large numbers of these machines would be necessary for gas compression. The Venezuelan oil companies showed considerable initiative and foresight in adopting new technologies and this led to Lake Maracaibo becoming the most important offshore oil province at the time of the 1973 oil crisis.

The particular development of relevance was the first use of the Avon to drive large gas compressors.

This was one of the largest technical advances in the development of offshore gas Compression. The Avon and Olympus jet engines had been used on land by the then Central Electricity Generating Board as peak shaving units and the idea of using the jet engine for Industrial Power was not new.

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The use of these gas turbine trains in Venezuela made dramatic reductions in installed weights and costs of facilities (See Fig 1). However the transition to operating high technology equipment was not smooth and it took several years before the sets were reliable.

The North Sea Developments 1972 - Present Day
The discovery of the Ekofisk, Forties, Brent and Statfjord Fields in the late sixties/early seventies heralded a new era for large offshore platforms requiring vast amounts of Power. This time however, Waters were deep and the environment harsh, unlike the comparative calm of Lake Maracaibo.

The Companies in the Norwegian Sector took a leading role in advancing the state of the art in the application of large offshore gas turbines. The Phillips Petroleum Company made the single decisive step in changing the course of offshore gas compression. They selected all centrifugal compression for the Ekofisk Field Complex. The Elliot re-injection compression train had a final discharge pressure of 640 barg. Bearing in mind, at that time, that maximum discharge pressures offshore had not exceeded 200 barg, this was indeed a progressive decision.

However, just like the Avons on Lake Maracaibo, technological advancement is always accompanied by set-backs. For Ekofisk, the problem of sub-synchronous compressor vibration took about 2 years to resolve and this phenomenon occupied the Worlds top experts for many years to come. This development provided a quantum leap forward in technology and was to make future facilities cheaper and lighter.

Not to be outdone by this breakthrough in compressor technology on Ekofisk, Mobil and Statoil had set up their own task force to find the most cost effective prime mover for the giant Statfjord Field. As on Ekofisk, the economics of scale were completely appreciated and the prime mover size was therefore seen as paramount. Gas turbines in the 20-30MW class were then considered.

The G.E. Frame 5 as used on Ekofisk, The Rolls Royce Olympus and Pratt and Whitney's FT4 were examples of first generation jet engines and the second generation G.E. LM2500. The second generation engines being those advanced engines being developed for the high Thrust, high efficiency by-pass engines for airliners such as the 747, DC10 and Lockheed 1011.

The Statfjord platforms had power requirements of over 100MW/platform and low weight and space were vital to reduce costs. The Mobil/Statoil team selected the second generation LM2500 which was to ensure that Norway held its place as the most efficient producer of power for many years to come. The Statfjord LM2500's were unique at that time in that they also incorporated the lightweight/high efficiency aero power turbine as well.

Shortly afterwards, Elf selected the Worlds largest offshore gas compressor with the 30MW Pratt and Whitney FT4C engines for its Frigg development and Norsk Hydro selected the RB211C for Oseberg. Currently the Norwegian Sector has over 70 gas turbine trains in the 20-30MW class of which more that 50 are of the advanced second generation jet engine type. This, together with the strict environmental legislation will mean that Norway will continue to set the standards for high efficiency offshore power and minimum flaring.

Development of large offshore gas turbines in the UK Sector lagged behind the Norwegian sector in the 1970's up-to oil price collapse of 1986. Post 1986, The UK has been in the forefront of technical innovation to reduce topsides weights and costs. The large gas turbine has played a significant role in making marginal developments economic. The Marathon E. Brae Field for example, has the largest offshore gas compression trains in the world at 34MW with the RLM5000 and Nuovo Pignone Compressors and Shell's Brent redevelopment will feature the uprated RB211G driving a Cooper Rolls Power turbine of 28MW. Fig. 2 and Table 1 (Appendix I) illustrates the development of offshore gas turbines in terms of unit rating and specific power.
DESIGN CONSIDERATIONS IN REDUCING INVESTMENT AND OPERATING COSTS

The following subjects need to be examined in the early conceptual studies:
- Energy Demand/Prime Mover
- Energy Strategy
- Choice of Cycle/Prime Mover
- Number and size of Trains
- Operating Costs
- Gas Turbine Type
- Standardisation
- Packaging Optimisation

Energy Demand
Total Energy Requirement is a logical starting point in any prime mover selection study where on the large platforms 100MW is typical and a field complex may require 250MW. The objective is to use as few prime movers as possible in view of the specific power and maintenance costs, providing the availability/reliability goals can be achieved.

Energy Prime Mover Strategy
Strategy involves the choice of fundamentals with particular regard to the split of Electric power and Mechanical drive prime movers. The strategy might be one of maximising electric power and using large Electric Motors. Alternatively the use of mechanical drive gas turbine driven compression trains is attractive if the gas compression load is of the order of 40-60MW which requires two or three 20MW + trains.

The strategy to maximise Central Electric Power generation has the disadvantage of reducing specific power but has real advantages in increasing operational flexibility/availability and reduces offshore manning. Moreover, future flexibility is enhanced by making it relatively easy to add Motor driven gas compression, water injection or electro submersible pumps. In view of this, small/mechanical medium mechanical drive gas turbines (<10MW) would appear to have limited future application offshore North Sea. The new Amerada Hess Scott platform which utilises 3 x LM5000 Power generators is a good example of this maximum electric power strategy.

Choice of Cycle/Prime Mover
Several basic options have been studied during recent years:
1. Simple open cycle gas turbines
2. Simple cycle gas turbines with exhaust heat recovery
3. Steam Generation
4. Electricity from Shore
5. Combined Cycles

About 99% of current installations belong to classes 1) or 2). Steam cycles may have a future for offshore heavy oil reserves requiring steam injection for assisted hydrocarbon recovery.

Electricity from shore via high voltage cables looks very attractive in view of the current goals of low offshore manning and low pollution. Large variable speed electric motors have now been shown to be viable up to 40MW, and such large units have been ordered for the sales gas compressors for Shell’s Troll Onshore production facility.

Selection of number and size of trains
Early offshore experience on Lake Maracaibo proved that two large aero derivative trains, although troublesome, provided less combined problems than 8 series gas compressors with small gas turbines of 2-3MW. So apart from the advantage of high specific power and low weight, a small number of large units requires less total manning. Furthermore, if a standby train is provided, the investment and operations costs increase significantly. For small marginal fields, provision of a standby could even make the development uneconomic.

In the high oil price regime of the 1970’s, standby trains were almost invariably provided for gas turbine driven main power and gas compression. Since the collapse of the oil price in the mid 1980’s, the standby facility has been very carefully examined.

Where several platforms provide gas to a common pipeline, the idea of a field standby, rather than a standby for each platform, makes good sense. Statoil also employed innovative technology on its Sleipner Platform by employing the spare pipeline compressor for alternative Re-injection service thereby reducing the number of compression trains from six to five.

These innovations provided considerable savings.

Operating Costs

Maintenance Costs
The costs are best evaluated on a cost per fired hour basis including major overhauls at 25,000 - 32,000 hours to restore mechanical and thermodynamic performance to the "as-new" condition. Long term data of the 16 LM2500’s during the first 6 years on the Statfjord Field gave average maintenance costs of 52 USD fired hour.

Equivalent Industrial Frame 5’s costing an average of 10-15 USD fired hour. The aero-derivative is therefore seen to be extremely costly to maintain with a differential maintenance cost of 42 USD fired hour. The LM2500 is now a mature engine with optimum costs. Any new engine like the LM5000 will have a typical early life costs of at least twice that figure.
Fuel Costs

In early North Sea Installations, before sales gas contracts and pipelines, etc. were in place, associated gas was mostly reinjected. The Wellhead price of such gas was very low. Only for "sales gas only" platforms was the price of gas ever seriously considered. Environmental issues/constraints started in the Mid 1980's prompting the first Energy taxes. Energy efficiency is now paramount and favours the aero derivative as Table 2 illustrates, the reduced maintenance costs of the heavy duty machines can be easily lost by the increased fuel consumption and energy tax.

<table>
<thead>
<tr>
<th>OPTION TYPE</th>
<th>TYPE H. INDUSTRIAL</th>
<th>2ND GENERATION AERO DERIVATIVE</th>
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<tr>
<td>AVG. SFC (KJ/KW-HR)</td>
<td>13.000</td>
<td>10.200</td>
</tr>
<tr>
<td>AVG LOAD (KW)</td>
<td>20.000</td>
<td>20.000</td>
</tr>
<tr>
<td>GAS FUEL LHV (KJ/KG)</td>
<td>40.000</td>
<td>40.000</td>
</tr>
<tr>
<td>FUEL CONSUMPTION (SM'/HR)</td>
<td>6.500</td>
<td>5.100</td>
</tr>
<tr>
<td>△ FUEL (SM'/HR) COMPARED TO OPTION B</td>
<td>1.400</td>
<td></td>
</tr>
<tr>
<td>DIFFERENTIAL OPERATING COSTS £/FRED HOUR</td>
<td>£280/HR</td>
<td></td>
</tr>
<tr>
<td>△ CO2 TAX</td>
<td>158</td>
<td></td>
</tr>
<tr>
<td>△ FUEL</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>△ MAINTENANCE</td>
<td>(37)</td>
<td></td>
</tr>
<tr>
<td>△ TOTAL</td>
<td>£280/HR</td>
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</tr>
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</table>

Differential Cost of running a heavy duty type H Turbine compared with an Aero-derivative is £1.43 Million/year based on 95% use.

TABLE 2
OPERATING COSTS FOR A 20MW GT

Costs

For large trains, recent bids and feasibility budget bids, indicate the costs per MW to be approximately equal.

Weight

Studies of actual on installations regarding weights is shown on Fig. 2 and Table 1.

In the Mid 1970's the aero-derivative trains had a specific Power advantage of 66% i.e. For a given power requirement, the aero derivative train was 66% lighter. Fig. 1 illustrates how both types have been developed significantly and in fact the present advantage in Specific power is reduced to about 44%. Nevertheless there is still a large incentive in favour of the aero-derivative especially with each ton of topsides for Northern North Sea installations requiring and expenditure of about 15,000 USD to provide support steelwork etc.

Space

The 1975 Stafford Prime mover study indicated that the equivalent type H Industrial gas turbine required 118% more volume of platform space than the LM 2500. The Equipment density of aero derivative trains can be very high (see Fig. 3) It would have been possible to install only one industrial type unit in the space occupied by the 2 x LM 2500 aero derivatives.

The additional space requirement to install Industrial type H turbines on Statfjord A would have been approximately 5000m³. The present day cost of each m³ is approx. USD 1,000/m³ and consequently the aero-derivative has a big advantage over the Industrial Type "H".

FIGURE 3
STATFJORD A - RECOMPRESSION TRAINs

Availability

The Industrial type H turbines are extremely reliable and typical offshore availabilities better than 97% can be achieved. By contrast, early aero derivative installations were unreliable. Nevertheless the situation has improved significantly and current availabilities in the Norwegian Sector are in the range 90-97% with an average of about 93%, with most of the fuel firing being on natural gas.
**Fuel Flexibility**

Fuel flexibility can be a big advantage for the Industrial Type H gas turbine if only crude oil or heavy fuel are the only fuels available. For most North Sea installations however, clean sweet Natural gas is available and consequently the aero-derivative is not at a disadvantage. Most power generation turbines are dual fired whilst mechanical drive applications are gas fuel fired.

**Operating Flexibility**

Operating Flexibility of the aero engine is excellent and a unit can operate successfully and with good efficiencies even at 40% load. The Industrial type particularly as a single shaft Unit is not so flexible as a compressor driver.

**Performance Degradation**

In the past much has been said about rapid performance degradation of second generation aero derivative engines like the LM 2500 and it is therefore important to be objective. The highly complex aero derivative operating at higher pressure ratios and firing temperatures is far more sensitive to fuel and air quality. Early North Sea installations in the late 1970's with the Rolls Royce RB 211 and LM 2500 encountered problems of high salt levels in the diesel fuel.

Another significant factor in the reduced performance of the Statfjord LM 2500 engines was extensive drilling mud burning. These very fine muds produced clouds of fine particulates which quickly fouled the compressor and blocked blade cooling holes resulting in higher bulk material temps for the same firing temperatures.

Fig. 4 shows Power loss and increased fuel consumption for the second generation LM2500 versus typical heavy industrial units. The LM2500 seems to lose about 17.5% in power and consume an extra 4-5% fuel at 25,000 hours. The performance loss is of little significance providing a power margin is included to cater for degradation. 12% is a typical average for a gas fired LM2500 and 5% for typical heavy duty turbine like the Frame 5. The increase in SFC is almost insignificant. Performance degradation therefore is a factor that can be virtually excluded as a selection parameter for proven second generation engines.

These engines have already been well tested in flight where fuel burn is absolute critical to range and operating cost margins. Differential degradation between such engines as the RB211, LM2500 etc. is small particularly the all important fuel consumption.

**FIGURE 4**

PERFORMANCE DEGRADATION

Degradation therefore is no deterrent to the selection of advanced aero derivative engines providing the power margin and the criticality of fuel and air quality, are taken into account.

**Standardisation**

The early Mobil/Statoil study of the Statfjord A platform resulted in the selection of the LM 2500. Subsequently, for the B and C platforms, the option was open to select a different engine. Studies however highlighted the additional operator costs in spares inventory and onshore/offshore support. The LM 2500 was thereby selected, not only for Statfjord B&C, but also for Statoil's subsequent platforms Gullfaks, Vestlefrikk and Sleipner. The Company now has 33 LM 2500's installed and is able to optimise spares inventory and onshore support costs.

Offshore personnel became familiar and experienced with one engine type which enhances availability and has been a significant factor in the long engine lifetimes. Which enhances availability and has been a significant factor in the long engine lifetimes. The benefits of Standardisation cannot be over emphasised, however the initial gas turbine selection studies are even more vital.

**Packaging/Optimisation**

Optimising topsides weight/space requirements is fundamental to provide cost effective offshore installations. The cost of supporting each ton of topside equipment being typically USD 15,000 ton for a northern North Sea installation.
Although the 22MW aero engines weigh only 3-5 tons, the total packaged train weight could be over 200 tons. In the 1980's, efforts were therefore concentrated on smaller and lighter packages. Table 3 illustrates the weight savings that were achieved by Statoil on the Gas Compression Module for Sleipner which amounted to a weight reduction of over 20%. The Sleipner trains made by Kongsberg Dresser Power also featured 3 point mounted Torque tube base plates which were the first to be integrated into the deck steelwork.

<table>
<thead>
<tr>
<th>Modification</th>
<th>Weight saving</th>
</tr>
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<tbody>
<tr>
<td>Aluminium Inlets</td>
<td>7.7 T</td>
</tr>
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<td>Centralised Lube Systems</td>
<td>8.0 T</td>
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<td>Common Hydraulic Starters</td>
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</tr>
<tr>
<td>Plate Lube Oil Coolers</td>
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</tr>
<tr>
<td>Double Helical gears</td>
<td>1.1 T</td>
</tr>
<tr>
<td>Torque Tube baseplate</td>
<td>12.0 T</td>
</tr>
<tr>
<td>Compound Compressor Casings</td>
<td>4.0 T</td>
</tr>
<tr>
<td>Total Weight Savings/Train</td>
<td>39.3 T</td>
</tr>
<tr>
<td>Optimised Train Weight</td>
<td>129.0 T</td>
</tr>
<tr>
<td>% Weight Savings:</td>
<td>221</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modification</th>
<th>Weight saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use a single train for dual service of Gas Sales and Re-injection</td>
<td>129.0 T</td>
</tr>
<tr>
<td>INTEGRATE Torque tube 3 point baseplates into the Module Steelwork</td>
<td>110.0 T</td>
</tr>
<tr>
<td>Module Weight Savings</td>
<td>229.0 T</td>
</tr>
<tr>
<td>Train Weight Savings (5 x 39.3)</td>
<td>196.5</td>
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<tr>
<td>Total Weight Saving</td>
<td>425.0 T</td>
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**TABLE 3**

**SLEIPNER GAS COMPRESSION OPTIMISATION**

Secondary steelwork weight was reduced by about 100 tons and the train centre line dropped by about 600 mm. High train centre-lines were a disadvantage of early 3 point mounted skids.

Space is also vital because a larger space requires a larger amount of secondary steelwork which adds to the total topside weight. The new gas compression module for Shell Brent also included several innovative weight/space reductions. A "back to back" layout and "offskid" common lube-oil system which together reduced space requirement by 35% (see Fig 5) with significant financial savings.

**FIGURE 5**

**BRENT COMPRESSION TRAIN LAYOUTS**

**SUMMARY AND THE FUTURE FOR THE OFFSHORE GAS TURBINE**

The gas turbine has proven itself as being the ideal offshore prime mover in almost all offshore installations. Indeed, without the gas turbine, the development and extraction of vast volumes of offshore hydrocarbons would not have been possible.

The Statfjord prime mover/selection study was a significant turning point in the use of aero derivatives offshore in the Norwegian sector which is now the largest and most efficient user of large gas turbines offshore.

The development of the gas turbine offshore has been very significant but there are still challenges ahead. The higher reliability, reduced manning and reduced fuel consumption are paramount considerations in making the future marginal fields economic. The gas turbine represents a significant proportion of maintenance, offshore manning and energy costs (where environmental legislation exists).
The trend to even larger and more efficient simple cycle machines looks set to continue. The use of combined cycles looks unlikely especially in the goal to low manning. The use of small gas turbines <5MW looks likely to decrease significantly for North Sea installations.

The electric motor and particularly the variable speed electric motor in sizes up to 40MW looks very attractive for mechanical drivers. These large motors require the use of large central Power plants of 100-200MW which then makes 40-50MW Electric Power Generators feasible. The gas turbine could then be either an advanced second generation aero derivative like General Electric’s LM6000 or the advanced Industrial heavy duty turbine might also come back into favour. The applications for large mechanical drivers in the 40MW range are going to be very few. There still remains many very inefficient gas turbines offshore. With subsea electrical power distribution becoming relatively economic, it would make good sense to provide large efficient energy blocks of 100-300MW and distribute to an existing platform complex. Semi-submersibles could be economically converted to mobile power generators.

This idea is not new, a power barge was used on Lake Maracaibo for emergency power supplies. High efficiency power generation and use are essential in countries which impose taxes on energy usage and this trend is likely to continue.

CONCLUSION

The future of the offshore gas turbine is therefore assured for many years forward albeit with fewer machines of larger ratings. Whether the developments however can match the existing progress during the last 25 years remains to be seen.

APPENDIX 1

<table>
<thead>
<tr>
<th>YEAR</th>
<th>LOCATION</th>
<th>FIELD</th>
<th>ENGINE</th>
<th>ISO</th>
<th>TRAIN</th>
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<td>1968</td>
<td>VENEZUELA</td>
<td>UNIGAS.</td>
<td>AVON</td>
<td>9.8</td>
<td>40-60</td>
<td>30</td>
<td>I MP</td>
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<td>1971</td>
<td>&quot;</td>
<td>&quot;</td>
<td>AVON</td>
<td>9.8</td>
<td>175T.</td>
<td>56</td>
<td>ADI MP OF</td>
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<tr>
<td>1973</td>
<td>NORWAY</td>
<td>EKOFISK</td>
<td>MS5001</td>
<td>18.7</td>
<td>250T</td>
<td>75</td>
<td>H MP OF</td>
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<tr>
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<td>&quot;</td>
<td>&quot;</td>
<td>MS5002</td>
<td>24.2</td>
<td>&quot;</td>
<td>97</td>
<td>H OF</td>
</tr>
<tr>
<td>1989</td>
<td>&quot;</td>
<td>&quot;</td>
<td>MS5002A</td>
<td>27.6</td>
<td>&quot;</td>
<td>110</td>
<td>HA</td>
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<td></td>
<td></td>
<td>STATFJ.</td>
<td>LM2500FC</td>
<td>20</td>
<td>160</td>
<td>125</td>
<td>AD2 OF</td>
</tr>
<tr>
<td>1982</td>
<td>&quot;</td>
<td>FRIGG</td>
<td>FT4C</td>
<td>31</td>
<td>-</td>
<td>-</td>
<td>AD1 OF</td>
</tr>
<tr>
<td>1985</td>
<td>&quot;</td>
<td>OSEBERG</td>
<td>RB211C</td>
<td>24.6</td>
<td>215</td>
<td>114</td>
<td>AD2 MP OF</td>
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<tr>
<td>1993</td>
<td>&quot;</td>
<td>SLEIPN.</td>
<td>LM2500PE</td>
<td>22.7</td>
<td>129</td>
<td>176</td>
<td>AD2 MP OF</td>
</tr>
<tr>
<td>1993</td>
<td>&quot;</td>
<td>BRAGE</td>
<td>LM2500PE</td>
<td>22.7</td>
<td>119</td>
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<tr>
<td>1993/4 U.K.</td>
<td>E.BRAE</td>
<td>LM5000</td>
<td>-</td>
<td>-</td>
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<td>FUTURE NORWAY</td>
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<td>162</td>
<td>AD2 MP  3P</td>
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<tr>
<td>FUTURE NORWAY</td>
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<td>42</td>
<td>205</td>
<td>205</td>
<td>AD2 MP  3P</td>
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<tr>
<td>FUTURE &quot;</td>
<td>FEASIBILITY</td>
<td>MS6000</td>
<td>34</td>
<td>206</td>
<td>133</td>
<td>HA MP</td>
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**Key:**
- **H:** Type H Industrial
- **ADI:** First generation Aero derivative
- **AD2:** Second generation Aero derivative
- **I:** Integral
- **MP:** Multipoint
- **OF:** Oil film
- **3P:** 3 Point
- **DG:** Dry Gas

**Table 1**

GAS TURBINE SIZE AND SPECIFIC POWER DEVELOPMENT