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INDUSTRIAL GAS TURBINE DEVELOPMENT AND OPERATING EXPERIENCE

K D Sinfield - IMIA Conference – September 1993

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SUMMARY

Widespread availability of natural gas, environmental pressures, and the need for greater efficiency and shorter lead times, have turned combined cycle generation into the preferred system of power supply for many utilities in the 1990s. This paper considers the rapid development of gas turbines by major manufacturers and highlights the salient design features necessary to enable operation under increasingly critical conditions. The varied experience of individual IMIA members is summarised and some alternative underwriting approaches indicated.

INTRODUCTION

By the mid 1990s there could be about 12,000 to 13,000 MW (megawatts) of gas fired power plant based on combined cycle gas turbine technology operating throughout the UK. Internationally, more than 7000 advanced technology units are either installed or on order. The short delivery cycle, the phased transition from simple cycle to combined cycle and, if necessary the addition of integrated coal gasification, makes power generation significantly more flexible.

It is therefore of little surprise that over the last decade there has been growing interest in the heart of the system – the industrial gas turbine – which has, unfortunately all too frequently, centred on the poor reliability of the sudden boost in output of certain machines. UK Engineering Insurers in particular recognise the potential for a similar scenario to the heavy losses experienced during the rapid development of power steam turbines in the 1960s and 1970s when outputs were increased in large steps from 250MW to 660MW.

There are however very significant technical differences in the current gas turbine programme which is firmly rooted in the heavy research and development spending on aerospace gas turbines, and where machines are protected by vastly improved condition-based monitoring and control equipment.

The feeling remains in some quarters that developments have been too rapid and that, consequently, the manufacturers have not had sufficient time to undertake in-depth research and development programmes specifically aimed at land based power applications before marketing new second and third generation machines.

Gas turbine manufacturers have been under pressure.

- To increase individual unit output.
- To increase unit efficiency.
- To meet the most stringent exhaust gas emission legislation.
- To achieve improved availability

In order to meet these demands the manufacturers have needed to:

- Aim for higher turbine inlet temperatures.
- Search for more sophisticated materials.
- Design complex low-NO_x systems.
- Design more sophisticated cooling systems.

This paper gives an overview of current developments, a summary of members operating experience and an assessment of the factors influencing alternative underwriting strategies.

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GENERAL CONSIDERATIONS

World-wide procurement

Very broadly there are five major manufacturers of high output gas turbines suitable for power generation:

1	General Electric (GE)	USA
2	Asea Brown Boveri (ABB)	Switzerland
3	Siemens	Germany
4	European Gas Turbines (EGT)	France/UK

5	Westinghouse/Mitsubishi	USA/Japan

Further joint ventures exist to serve specific markets and a world-wide network of potential sub-contractors are used to source components. As an example of the type of supply agreements currently being developed consider the following:

Licence agreements

The General Electric Company of USA (GE) have a long establish business in the design and manufacture of both aero and industrial gas turbines. The access of their products to the world-wide market has been further increased by GE's policy to licence a number of business associates for varying degrees of manufacture to GE designs.

GE associates	Country	Type of association
European Gas Turbines (EGT)	France UK	Full licensee with capability to manufacture and sell all 50Hz gas turbine models. Currently the frame 9F is co-designed and co-manufactured with GE but EGT will have full manufacturing capability in 1995. Manufacture of rotor assemblies for other GE European associates.
John Brown Nuovo Pignone Thomassen	UK Italy Netherlands	GE's European manufacturing associates. Capability to assemble and sell gas turbines up to frame 9E using rotor assemblies and combustion cans from EGT or GE.
Hitachi Toshiba	Japan	GE's Japanese manufacturing associates. Hitachi is producing 50 and 60 HZ models up to frames 9E and 7F, and may produce frame 9F in the future. Toshiba is currently limited to 50HZ models up to frame 9E. In all cases the rotors and combustion cans are supplied by GE.

The GE machines are known by their 'frame' number and within the individual frame types, there has been continual development as shown by the evolution of the Frame 9 machine.

FRAME 9 EVOLUTION (MS 9001)					
Year	Output MW	Inlet Temp ^{O}C	Axial Flow Kg/s	Pressure Ratio	Efficiency
1976	84.7	1004	341.3	9.6	30.9%
1978	104.5	1068	393.7	11.6	31.5%
1981	108.8	1085	397.6	11.6	31.7%
1983	111.5	1093	401.6	11.9	31.8%

1987	116.9	1104	403.3	12.1	33.1%
1990	123.4	1124	409.5	12.5	33.8%
1992	212.0	1260	600.1	13.5	34.1%
1994	226.5	1288	600.1	15.0	35.5%

Operating experience – GE

The traditional measure of life of gas turbines is operating hours. Moreover since it is generally recognised that the cold end (compressor) components can operate much longer than the hot end components maintenance intervals and life limits are normally specified separately. The following is an overview of the known experience with GE machines.

<table>
<tr><th colspan="4">GE DESIGN HEAVY DUTY GAS TURBINES
INSTALLED AND ORDERED
AS OF FEBRUARY 1992</th></tr>
<tr><th>Frame Size</th><th>Number of units</th><th>Millions of fired hours</th><th>Number of units Over 100,000 fired hours</th></tr>
<tr><td>3-1</td><td>73</td><td>0.6</td><td>12</td></tr>
<tr><td>3-2</td><td>919</td><td>52.0</td><td>238</td></tr>
<tr><td>5-1</td><td>2201</td><td>72.5</td><td>323</td></tr>
<tr><td>5-2</td><td>423</td><td>10.0</td><td>29</td></tr>
<tr><td>6-1</td><td>366</td><td>1.8</td><td>0</td></tr>
<tr><td>7-1</td><td>561</td><td>8.8</td><td>10</td></tr>
<tr><td>9-1</td><td>182</td><td>1.5</td><td>0</td></tr>
<tr><td>Total</td><td>4725</td><td>147.2</td><td>612</td></tr>
</table>

Whilst the basis of operating hours can be used for base-load machines operating on good quality fuel in recent years, more sophisticated means of evaluating gas turbine life have been introduced, based on continuous measurement of machine performance parameters. With the complexity of the damage mechanisms, it is not surprising that experience has shown operating hours to be a relatively poor measure of life for machines subject to variable duties, frequent start ups and shut downs, or widely variable operating conditions, or poor quality fuels.

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TECHNICAL CONSIDERATIONS

Inlet temperature

A combined cycle plant combines the Brayton Cycle of the gas turbine with the Rankine Cycle of the steam turbine. At the lower end the steam exhaust already operates at its maximum available vacuum and therefore the major advances in efficiency are achieved by increasing the inlet temperature to the gas turbine. An increase in the firing temperature of 55°C (100°F) can provide corresponding increases of 10% to 13% in output and 2% to 4% in simple cycle efficiency.

Until about 1970 any rise in inlet temperature was dependant on the development of new alloys, particularly for the power turbine blades, capable of withstanding the increase. However during the 1970s manufacturing processes were developed which enabled air cooled blades to be produced so for the first time metal temperatures were independent of inlet temperatures.

Thus the development of cooling techniques, blade coating (to combat the effect of hot corrosion) and alloys resistant to corrosion (and creep) have enabled inlet temperatures, and hence the turbine output, to be steadily increased.

The following chart gives an indication of the development of the gas turbine in relation to output and turbine inlet temperature since 1970

Year	Maximum output	Turbine inlet temperature
1970	58 MW	850°C
1975	77 MW	900°C
1980	83 MW	1000°C
1985	96 MW	1100°C
1990	150 MW	1200°C
1993	200 MW+	1300°C

Conventional fossil fired power stations have efficiencies in the region of 35% to 40%, whereas the latest generation of gas turbines, in combined cycle applications, have efficiencies in excess of 50%.

Increase in gas turbine efficiency can also be achieved by reducing the running clearances of the compressor and power turbine blading, thereby reducing leakage losses. The reduced running clearances of the rotating components of these machines require careful monitoring, particularly during start up and shut down to ensure that controlled expansion is achieved. This is particularly relevant to the latest generation of high output machines with increasingly large physical dimensions yet operating with progressively reducing clearances.

These two factors are potentially major causes of concern for operators and their insurers.

The increased output of gas turbines by three manufacturers of power generating equipment – GE, Siemens and Asea Brown Boveri (ABB) – following increases in inlet temperature, is summarised as follows:

	Output (Approx.)	Inlet Temp. ^{o}C*	Year Introduced
GE			
FRAME 9E	100 MW	1085	1981
	123 MW	1124	1992
FRAME (7F)	(-60 HZ-) 135.7MW	1260	1990
FRAME 9FA	226 MW	1288	1994
SIEMENS			
Type V94.2	121 MW	970	.
	138 MW	1010	1986
	150 MW	1050	1988
V94.3	200 MW	1120	1992
ABB			
Type 13	98 MW	.	1973
Type 13E	150 MW	1070	1986
Type 13E2	165 MW	1100	1992

***Note:** Normally measured before inlet to stator 1 – but practice varies between manufacturers and quoted data. Only ISO 2314 measurements have common definition.*

Combusters

With higher inlet temperatures and increasing pressure for lower emissions much effort has been focused on the development of improved combustion systems. New combuster designs feature "swirlers" to create turbulence and reduce metal temperatures.

Uprating and Scaling

The main parameters affecting the output of a gas turbine are:

- Mass flow
- Compression ratio
- Firing temperature at turbine inlet (T Max)

- Speed

Where a major change to one or more of these parameters is undertaken the gas turbine should be considered a ‘prototype’ machine.

Uprating

If any of the above components are increased to boost output of the machine a corresponding increase in thermal/mechanical stresses will occur. In some cases it may be found that, despite the increased loadings the machine is still operating within its design limits and therefore this ‘spare’ capacity can be utilised. Only the closest attention to machine specification and operating experience however, permit such judgements to be made. If this is not the case and component limits are in doubt a design re-appraisal must be undertaken, and the inherent risk of the new machine will depend upon the extent of any modifications.

Scaling

Scaling is an accepted technique in the aero industry and is a method whereby in accordance with the laws of similarity, as applicable to flow mechanics, the linear dimensions of two geometrically similar (scaled) machines are inversely proportional to their rotational speeds. Materials and temperatures remain the same, as do mechanical stresses and aerodynamic performance. The combusters and bearings are not suitable for scaling and detailed design appraisal of these parts is required as output levels are increased. An illustration of development by two major gas turbine manufacturers using scaling and uprating techniques is shown.

SCALING							
Frame	Output MW	EFF %	Air flow	Press ratio	T/Inlet oC	T/Exh oC	Speed RPM
7001F	150	34.5	416	13.5	1260	583	3600
9001F	212	34.1	600	13.5	1260	583	3600

UPRATING							
Type	Output MW	EFF %	Air flow	Press ratio	T/Inlet oC	T/Exh oC	Speed RPM
13E	148	34.6	501	13.9	1070	516	3000
13E2	164	35.7	523	15.0	1100	525	3000

Prototype machines

Not surprisingly the definition of a "prototype" gas turbine varies between manufacturers and insurers. Manufacturers market their new machines extolling their virtues, new features, output etc. Yet they rarely consider them to be "prototype" machines. Major insurers however are somewhat more sceptical and generally consider a machine to be a "prototype" if a particular design type has not operated for 8000 hours without a major disruption, and not more than two emergency shutdowns.

In addition to the design type affecting the output of gas turbines as noted previously, other features may also need to be taken into consideration, ie:

- Is it operating in the same mode, ie simple cycle or combined cycle?
- Is it the first of an existing model to be built by a licensee?

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IMIA MEMBERS' FAILURE STATISTICS

As part of the preparation for this paper the IMIA members were asked for their experiences of Gas Turbine Failures. Energy policy varies considerably from country to country and where power generation is centred on fossil, nuclear or hydro plants members had little or no experience to report. Others have limited experience but have no readily available statistical information on breakdown history to date. However, some members do have many years experience and have been kind enough to provide information. We have now developed a database to collate and analyse this information in order to determine any common factors which may be of interest to all involved in the operation and insurance of this type of equipment.

The information collected came in many varying formats which has made the collation a little difficult. Many gave details of individual breakdowns and claims whereas others gave summary (statistical) information along with their own analysis and conclusions.

The results of this analysis of the *individual* case histories supplied by IMIA members can be seen in the following graphs, Figures 1 to 3. Given the relatively small number of incidents reviewed it would be premature to draw too many firm conclusions but some trends are already obvious. The information received detailed approximately 60 failure instances totalling some £44m in terms of claims. The average claim being in excess of £0.75m. Broadly the analysis covers the period from 1984 to 1992 and therefore includes some failures related to very large units.

Analysis of the number of failures by cause

Figure 1 below shows a relatively even spread of failures between the various causes of failure with design faults being the largest sector. Maintenance failures have been split into two groups; ie those caused by the actual maintenance function itself, (Maintenance Induced Faults or MIFS – an example of which would be a rag left in the machine) and those caused by a lack of maintenance such as blocked filters.

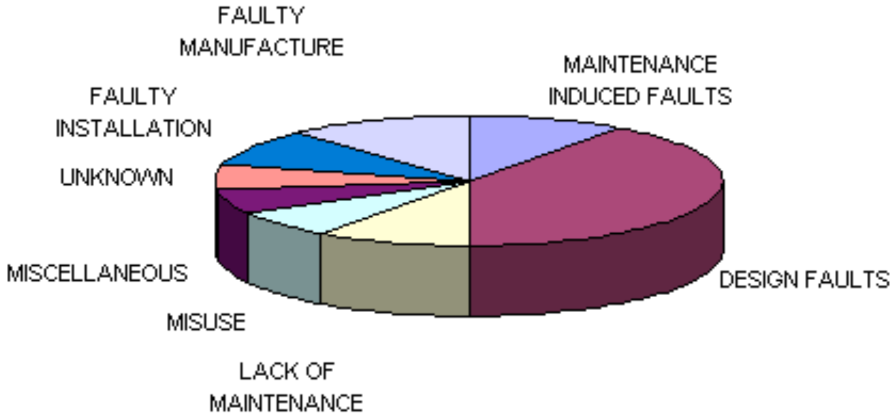

Figure 1 – Gas turbine failures by failure category (numbers of failures)

Analysis of failures by claims cost

Figure 2 below shows that when the claims were analysed with respect to costs, design based faults dominate the total claims cost for this type of business – confirming the need for close liaison with the manufacturers and where possible the desirability of a design exclusion.

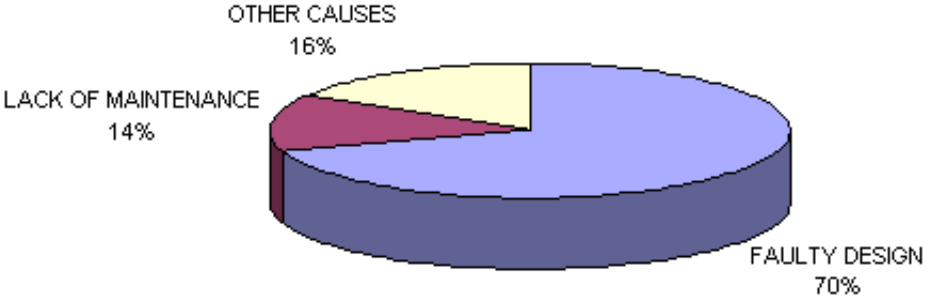

Figure 2 – Gas turbine failures by failure category (costs of failures)

In addition to looking at the failures by failure category we have also looked at the numbers and costs of failures by size, (MW). Figure 3 below shows how the increase in the average claim cost increases sharply when the units exceed 100MW.

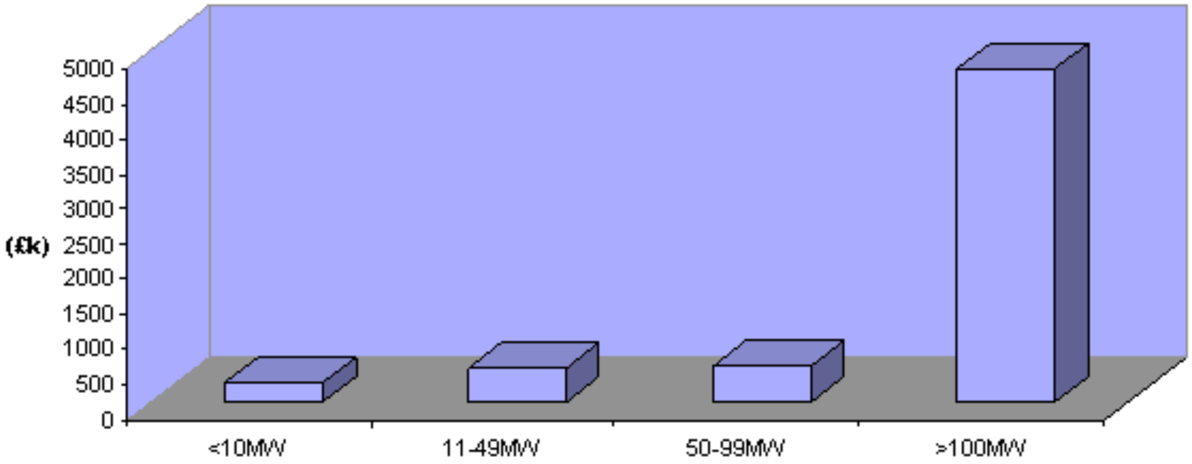

Figure 3 – Gas turbine failure costs (£k) by size of unit (MW)

USA Experience

In addition to the information summarised above we have also received detailed information and analysis from members in the USA which has probably the most experience of all in terms of insurance/losses relating to gas turbines.

- The Hartford Steam Boiler Co provided information extracted from a much larger database which monitors loss experience on an ongoing basis. For the period 1986-91 their conclusions were that gas turbines were more reliable than most plant, ranking number 25 in their rankings by loss frequency with a %age of total loss frequency of 0.25%, (boilers came top with 22.12%). However when the losses were ranked by cost, gas turbines come out clearly on top with 21.98% of total payout.

- Allendale Insurance also provided extensive data on a study for the Factory Mutual System covering the period 1988 to 1992. During this period they covered 194 losses where the gas turbine was the originating object of the loss. Total gross losses were approx. £90m. From their study they concluded an anticipated 4/5 losses annually for every 100 gas turbines covered with an average loss of approx. £0.5m. From their data they confirmed that the failures were most likely to occur within the first 3 years of operation.

The above confirms the foregoing general analysis that most losses are due to design faults and indicating that perhaps further ‘proving’ of newer and more complex designs was required. Throughout all of the above surveys the predominant items of failure were the blades, vanes and bearings.

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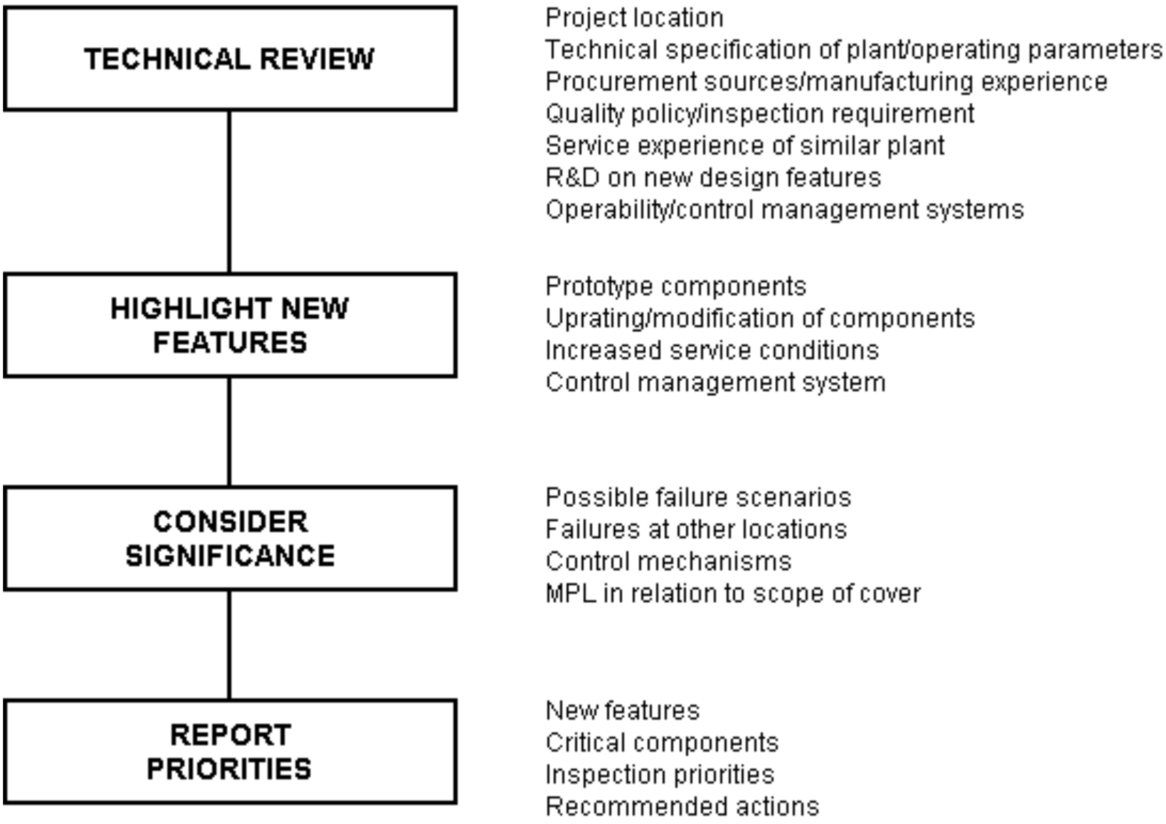
UNDERWRITING CONSIDERATIONS

Technical Review

GE claim that more than 300 man-years have gone into the design of their latest turbine unit – excluding support work. The complexity and pace of gas turbine development therefore necessitate a fundamental technical review of any major projects demanding clear communication between the underwriters and the specialist engineers. The following sequence indicates the probable steps necessary to undertake such a review.



Following the technical review the specialist underwriter must then consider in detail the commercial options available when underwriting such complex risks, ie:

MPL considerations

Fortunately total disruptions of turbines are relatively rare occurrences but the potential exists for total destruction of the unit itself and for considerable surrounding property damage as a result. Repair or replacement times are very significant, particularly when the demand for new equipment is high. Relatively minor repairs typically cost two to three times the original component cost and access and delays for critical spares are common.

Maintenance effects

Strict adherence to the manufacturers maintenance schedule is paramount for reliable operation of gas turbines. From our own experience we are aware of machines that have operated trouble free for many years yet similar machines are prone to failure due to lack of adequate maintenance. Maintenance of modern machines designed to operate under severe conditions will be even more critical.

The main factors affecting the maintenance programme are:

- Starting frequency
- Type of fuel
- Load cycle
- Environment

These factors will result in:

- Thermal fatigue cracking due to thermal stresses as a result of cyclic operation of the machine
- Deterioration of the hot gas parts caused by the effects of corrosion, vibration and creep

General

The risks associated with gas turbine installations fall within three main headings:

- the installation risk including advanced loss of profits;
- the operation and site risk;
- the consequential loss risk following damage to the plant during operation.

Two additional risks are also associated with the installation risk and the operation/site risk:

- loss of or damage to surrounding property;
- legal liability for loss of or damage to third party property and/or persons.

Erection/Machinery breakdown

There are the usual hazards associated with the physical erection and construction of the plant. Generally they would be independent of the reliability and degree of sophistication of the machine itself.

Gas turbines are sensitive machines and expensive to repair and so as far as the machinery breakdown risk is concerned a high deductible should always be applied. Whilst this will vary according to the type and size of machine and other risk factors it will typically represent 1% to 3% of the new replacement value of the machine.

The most critical and expensive parts are the rotors and all parts in contact with the hot gas path. All hot gas parts have a limited life and the insurance cover should incorporate a clause which in the event of a loss restricts liability to the unexpired portion of the rated life of such components, ie an amortisation clause. Serious damage can also be caused by careless handling or fires occurring during welding etc.

The advantage of a fast construction period can work in reverse should an incident occur as there is a shorter period to effect repairs and this is a consideration should Advanced Loss of Profits cover be given.

Commission and testing

When the construction and erection has been completed the commissioning and testing phases commence. This is when the previous experience associated with specific machines must be considered very carefully. Is it a true "standard" model? Have any modifications been incorporated, and if so why? (eg to uprate the machine or to improve reliability). What problems were being experienced? Have any modifications been field tested?

Even with a proven machine the testing and commissioning periods represent major risk exposure. Faults that may have been introduced during the building/erection of the plant will usually manifest themselves during this period. A specific problem associated with the high output machines is that manufacturers do not have facilities for full speed/full load trails. The point here is that in effect the manufacturer's risk is transferred to the insurance market. It is for this reason that high excesses and rates are justified for this period.

Following satisfactory completion of commissioning, the plant will be under warranty from the manufacturer, which is normally insured under a separate policy. It is worth noting that should this cover be requested experience indicates that this also represents major exposure. The latest generation of machines in particular are often working to the limits of current technology and are often under constant development. Experience indicates that failures are most likely to occur during the first 36 month operating period with the highest proportion being the first 12 months. It is therefore preferable for a trouble free period to be established before insurance commences. This is not always practical however and, where inception of cover coincides with operational running, it is recommended that higher deductibles and exclusion periods should apply during the period of initial operation, ie for the initial 2500 hours. Insurers should also take into account usage factors, eg peak loading or base load operation.

Consequential Loss

The consequential loss risk including increased cost of working can follow on the back of the operational material damage covers. When consideration is being given to this type of cover, it is essential to ensure the comments above concerning the material damage risks have been fully evaluated. Very pertinent to this risk is the availability of spares, and with the event of the latest generation of high output machines, production is relatively limited. Clients should maintain spares as recommended by the manufacturer, but obviously it is not in the client's commercial interest to hold expensive items which may never be needed, eg rotor assemblies. It is therefore essential for insurers to obtain substantial premiums and lengthy exclusion periods. These will vary for individual risks but would perhaps amount to a small fraction of the actual sum insured (or the indemnity period sum insured, if greater) and an appropriate exclusion period. The monetary excess levels and exclusion periods apply to each and every loss and, therefore, careful thought should be given to requests for aggregate deductibles.

The availability of major spares should be ascertained as well as establishing the lead times. Components under construction for alternative contracts may be may be made available, although this obviously depends on the manufacturer's ability to maintain the contract programme. From our own experience it should be noted that the manufacturers are reluctant to confirm this course of action is available, and will generally quote the time required for the construction of a new component.

With the latest generation of high output gas turbines being used exclusively for base load generation, a major disruption will result in a hard loss as no alternative working will be available.

Surrounding property and third party risks are normally only considered in respect of large projects due to the number of contractors involved during the construction phase as part of the contract works cover. It is considered cover should be limited to 5% - 10% of the total contract value.

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CONCLUSIONS

- Gas turbines either as part of single or combined cycle units will be key players in the power supply industry of the 1990's and beyond.

- The scale and complexity of individual units will increase significantly and test the limits of materials, designers and insurers.

- The current failure data with individual IMIA members is varied in depth of detail and clearer definitions of technical features, ie cause of failure, and commercial details, ie claims by class of business are needed if meaningful market trends are to be identified.

- Turbine failures are not a frequent occurrence but the potential material damage and consequential losses are substantial.

- It remains a challenge for machinery insurers to provide adequate cover in response to the market demand for more powerful and efficient machines. Policy wordings need to be drafted to encourage the fullest implementation of current technology which can significantly minimise losses and reduce claim repair costs.

- Only those insurers who keep pace with the technical developments can expect to provide the cover industry needs and those who ignore such developments should not be surprised by the very large losses inherent in this technology.

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