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Gas turbines — Data acquisition and trend monitoring system requirements for gas turbine installations

Turbines à gaz — Exigences relatives aux systèmes d'acquisition des données et de surveillance des tendances pour les installations à turbine à gaz

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Contents

Page

Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

ISO 19860 was prepared by Technical Committee ISO/TC 192, *Gas turbines*.

Introduction

The International Organization for Standardization (ISO) draws attention to the fact that it is claimed that compliance with this document may involve the use of a patent concerning data processing systems and diagnostic systems for technical/power plants.

The specific patents declared include the following:

EP 0 643 345:	Data processing device for the monitoring of the operating states of a technical plant
US 5,625,574	Method and data processing system for monitoring operating states of a technical plant
EP 0 667 013	Diagnostic system for a plant
US 5,734,567	Diagnosis system for a plant
KR 299811	Diagnostic system for a plant
IN 179026	Diagnosis system for a power plant

The ISO takes no position concerning the evidence, validity and scope of this patent right.

The holder of this patent right has assured the ISO that he is willing to negotiate licences under reasonable and non-discriminatory terms and conditions with applicants throughout the world. In this respect, the statement of the holder of this patent right is registered with the ISO. Information may be obtained from:

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Investors who acquire gas turbine engines insist more and more on having their installations equipped with trend-monitoring systems (TMS) of varying abilities. A rigorous employment of TMS in general allows projects to run with increased cost effectiveness as well as to improve the operation in the future. These statements are tempting enough to encourage retrofitting existing equipment with TMS in order to increase cost-effectiveness and reliability as well as to reduce maintenance intervals and risk of outages. The complexity of TMS can be determined by quoting chapters of this International Standard that are agreed by contract.

Trend-monitoring systems can also enable the following benefits:

— investigate reasons for outages;

— analyse the actual condition, enabling the preparation of maintenance in advance and only if the need arises.

Trends during recent years show that in the foreseeable future no gas turbine is likely to be sold without a TMS. There is also a tendency to integrate the TMS closely with the control systems of the gas turbines.

One reason for this lies in the use of the operating data available in the control system and needed for control as well as for the TMS. On the other hand, the control system can respond rapidly to critical situations detected by TMS. Therefore the direct connection of both systems offers the best solution.

Many independent, as well as integrated, systems are commercially available but they are based on different philosophies. Correspondingly, their performances can differ. Certain terms are often used with conflicting meanings and can mislead expectations.

TMS offers important benefits in the following areas:

— minimize fuel consumption;

— optimize maintenance costs in line with actual requirements (e.g. availability);

— minimize impact on the environment;

— predict possible failure and minimize subsequent damage and/or loss;

— improve reliability and availability.

Use of the same system will allow the manufacturer to

— determine the actual (not the theoretical) thermodynamic data;

— data and performance verification;

— determine gas-turbine ageing;

— improve service interval scheduling;

— optimize compressor cleaning.

Together, both operator and manufacturer will be able to

— interpret the short- and long-term trends established;

— perform a status analysis;

— identify and potentially reduce failures;

which in turn will enable future automated diagnostic systems to be extended still further.

As more and more new systems emerge, it is convenient to classify the technical terms and to define them. The intention is to set up certain guidelines on the subject of trend-monitoring systems to provide a basis for comparison of the various systems, their features, their performances and to help in the process of decision-making.

Gas turbines — Data acquisition and trend monitoring system requirements for gas turbine installations

1 Scope

This International Standard applies to data-acquisition and trend-monitoring systems for gas turbine installations and associated systems. It classifies and defines monitoring systems and their technical terms. It establishes a system for conversion and validation of measured quantities in order to enable a comparison of the various systems, their features and their performances.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2314:1989, *Gas turbines — Acceptance tests*

ISO 3977-2:1997, *Gas turbines — Procurement — Part 2: Standard reference conditions and ratings*

ISO 13373-1:2002, *Condition monitoring and diagnostics of machines — Vibration condition monitoring — Part 1: General procedures*

3 Terms, abbreviated terms and definitions

For the purposes of this document, the following definitions apply.

NOTE "Gas turbine" as used in this International Standard means the gas turbine and its associated systems.

3.1
combustion-monitoring system
CMS
equipment to acquire operating data and allow a judgement on the quality of the combustion process

3.2
data acquisition system
DA
equipment to collect and store a selection of data enabling a description of the condition of the gas turbine engine and its associated systems

3.3
diagnosis system
DS
equipment to determine the condition of the gas turbine installation using information acquired by DA and TMS

NOTE In addition, the DS can display the reason for the actual situation. In an advanced version, it can offer suggestions or guidance on actions required.

3.4
emission-monitoring system
EMS
equipment to store data, indicating the output of emissions that are produced by the combustion process of the gas-turbine installation

3.5
maintenance-on-condition
MOC
procedure whereby maintenance work is done only if requested by the monitoring system

3.6
mechanical-monitoring system
MMS
equipment to acquire data on the condition of the gas turbine installation that are of importance for the lifetime of the mechanical design

3.7
monitoring system
MS
equipment used in the same manner as for surveillance

NOTE This is considered as the generic term for all systems that perform a surveillance of the gas turbine and installations.

3.8
performance-monitoring system
PMS
equipment to take data and display the performance of the gas turbine

NOTE The parameters involved are essentially power, efficiency, exhaust-gas temperature and exhaust-gas flow and can include engine-component-condition assessment.

3.9
trend
approximation of an x-y correlation within an acceptable correlation coefficient on the basis of data that are eventually validated and normalized

NOTE The variable x is most often “time”, and trends are usually evaluated as functions of operating time or operating cycles.

3.10
trend-monitoring system
TMS
equipment to acquire operating data describing the condition of the gas-turbine installation that are used for the computation of short-term and long-term trends for selected parameters

3.11
validation
detection and elimination and/or replacement of wrong values among the measured data

3.12
vibration-monitoring system
VMS
equipment for monitoring the mechanical vibrations of the rotor(s) and the casing(s) of a gas turbine installation

4 Monitoring systems and their characteristics

4.1 General features

In applications where aspects of safety are extremely important (i.e. for aircraft engines), the analysis of the condition of complex systems has already attained a high level. The positive influence on the maintenance effort that accompanies the introduction of monitoring systems (MSs), as well as the possibility of preventing failures, more and more raises the interest in applying such systems to large power plants where the safety requirements are less stringent. The economic performance of a plant can be improved by such monitoring systems.

Projects carried out in recent years show trends in the operation of gas turbines that predict the need for the application of such a monitoring system. Furthermore, it can be observed that the values measured for the MSs are mostly those already being acquired by the available control system. To an increasing extent, MSs are combined with the control system of the gas turbine and the governing system leading an entire complex. MSs are considered as an integral part operating in the background.

Integration of the monitoring system and the control system has both advantages and disadvantages.

a) Joining control and monitoring systems is advantageous because

   1) the control system already contributes essential information on the condition of the cycle;

   2) the MS can use the control system to execute actions required in the process;

   3) the distributed systems and/or remote systems are becoming more popular.

b) The disadvantages include

   1) the system design and validation become much more complicated at the development phase;

   2) the possibility of introducing unexpected error to another system might be higher at a later modification phase.

There are already many independent, as well as integrated, systems commercially available, which differ in design concepts, operating philosophies and performance. As new systems emerge continuously, it is convenient to classify and define the technical terms. Beyond that, guidelines will be developed to allow comparisons among MSs in the future (see Annex A) and to enable decision-making according to requirements.

MSs may be grouped into three levels (see Figures 1 and 2 and Figure B.1), where the complexity and the information increase with the level. Depending on the application in the field, overlapping of the standards appears regularly.

4.2 Data-acquisition systems

All systems are based on DAs and therefore they shall be considered as the basic component leading to all further extensions. DA is essentially restricted to measurement or acquisition and limited storage of system and operating conditions.

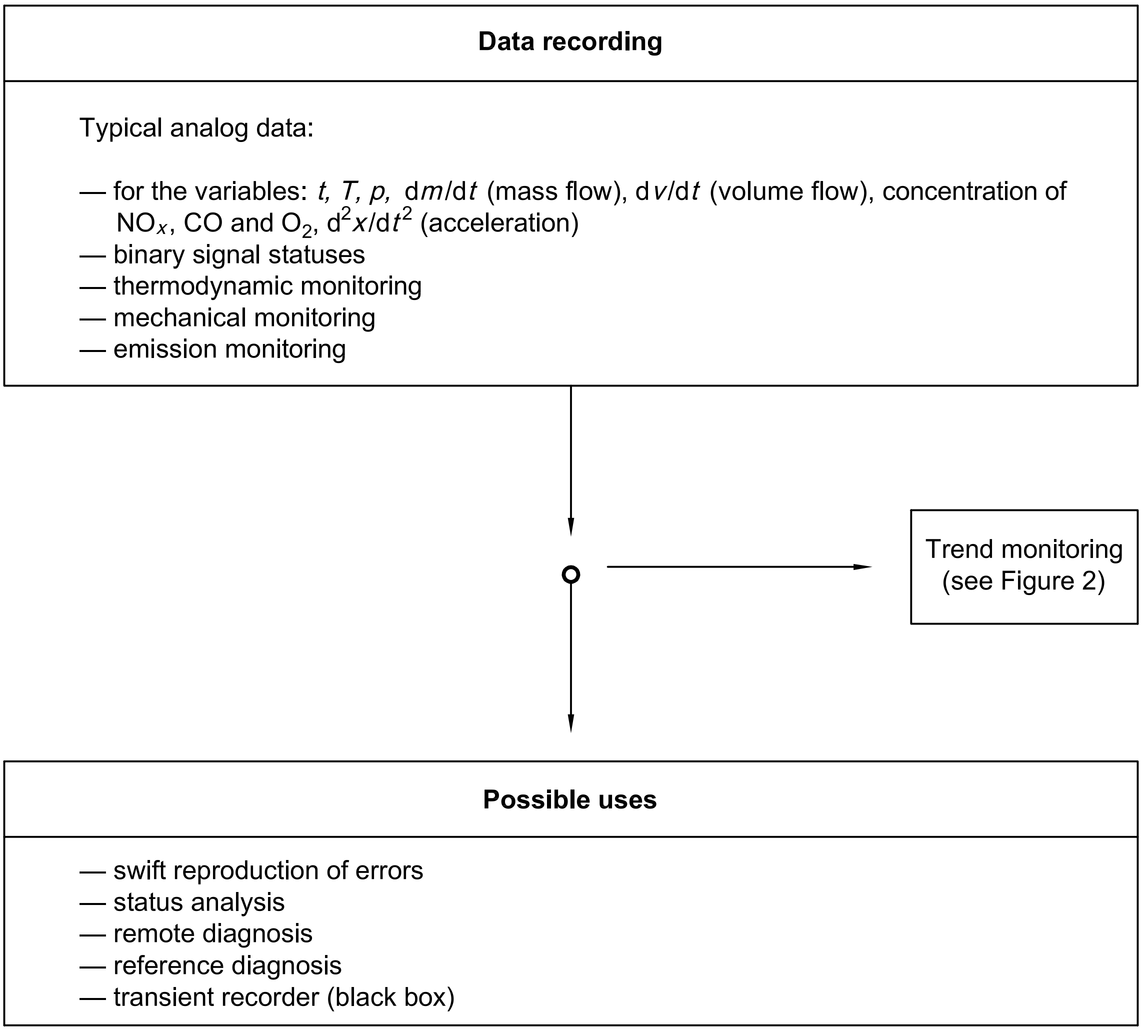

Figure 1 — Data acquisition

DAs usually require a high level of technical knowledge and experience as well as knowledge of the system. Therefore, their use remains restricted to experienced personnel.

4.3 Trend-monitoring systems

TMSs (Figure 2) evaluate short-term and long-term trends in the performance, the exhaust emissions and the mechanical behaviour of gas turbine installations. In contrast to DAs, the data the variables corresponding to the thermodynamic state are normalized to ISO standard conditions[1)] (see ISO 3977-2) and can be archived in long-term storage.

Intentional deviations of the reference conditions from the ISO standard conditions shall be agreed upon between the contract partners. Often, when the measured values do not correspond to standard conditions (ISO 3977-2), TMSs do not give the usual analysis of trends (e.g. deviation of specific fuel consumption) and do not extrapolate for upcoming consequences (e.g. NO_x emissions).

TMSs shall also provide validation of the experimental data as well as the logic for the selection of elements from the acquired data and the numerical algorithms from which to construct the trends. Wrong measurements shall be eliminated and spurious data shall be identified and discarded.

1) $p = 101{,}3$ kPa; $T = 288{,}15$ K; $\varphi = 60$ % relative humidity in the ambient air.

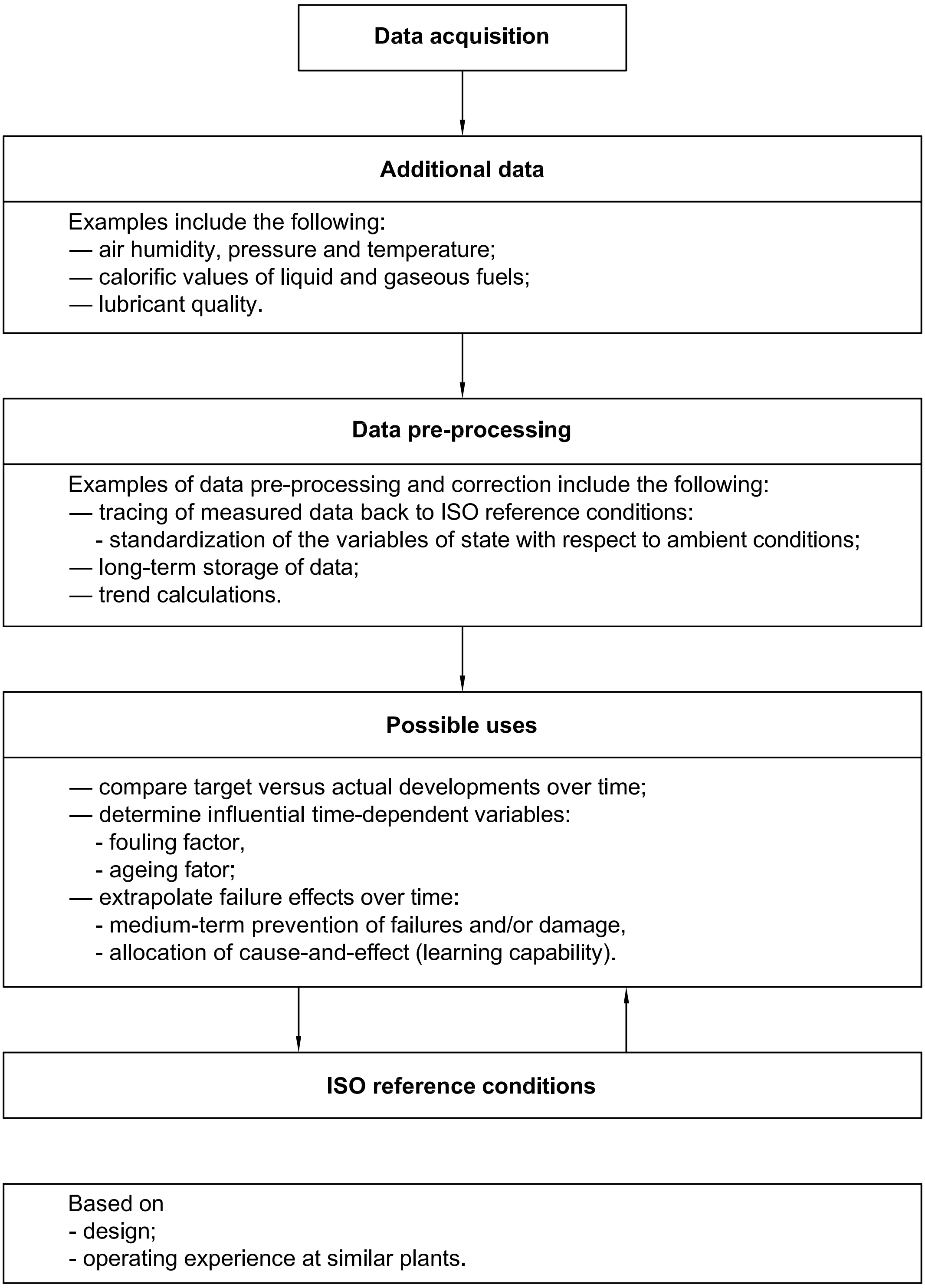

Figure 2 — Trend-monitoring system (TMS)

Normalizing the thermodynamic state of the plant requires the acquisition of all ambient operating parameters, including the following:

— ambient pressure;

— temperature;

- humidity;
- heating value;
- exhaust-gas pressure loss.

It is convenient to compare actual values with target values that can be provided by the cycle analysis for actual conditions from integrated systems. The cycle is computed analytically from measured parameters, or, if data are missing, empirically through the use of the charts or tables that are provided by the manufacturer of the plant. Performing a cycle analysis requires data that might not always be known to the operator of the plant.

In this way, it is possible to determine deviations from the design or reference values which are persistent over time (e.g. for efficiency), to check values related to operating costs (e.g. specific fuel consumption) and to follow the evolution of disturbances or failures.

Advanced systems might also be able to provide diagnosis and advice to non-specialist maintainers and operators.

Key areas for application in connection with gas turbines are as follows:

a) all properties of DAs and, in addition, trend-monitoring over medium and long periods of
   - performance results,
   - emissions-monitoring and reporting,
   - mechanical operating parameters;

b) analysis of trends for
   - identification of developing faults,
   - prediction of failures,
   - optimization of operating and maintenance,
   - improvement of availability by maintenance-on-condition (MOC).

4.4 Comparison of the systems

TMSs are capable of performing the same tasks as DAs, but also validate and normalize measured data. In addition, information to date is stored in a databank from which all values are extracted to determine short- and long-term trends.

When using a DA, the personnel can compare formerly registered data with current registered data and decide whether values are abnormal and might, eventually, lead to difficulties. More advanced systems analyse the trends and predict when the parameters will reach an established range limit. Appropriate alerts can be signalled to the operator.

The TMS performs this task and indicates values that might be abnormal and that might lead to disturbances or failures that could damage the plant. On top of that, the TMS might contain the necessary rules as well as experience to recommend necessary precautions as an output.

Finally, a very sophisticated MS will be similar to a DS, which indicates risks, consequences of failures and the required action to be taken to change a situation identified as being unfavourable. At this level of development, all functions indicated in Figure B.1 are available.

5 Detailed examination of trend-monitoring systems

5.1 The tasks of a trend-monitoring system

5.1.1 As a rule, a modern TMS for gas turbine can monitor the following:

- thermodynamic data,
- combustion, including emissions to the environment,
- mechanical behaviour, including vibrations of a gas turbine.

And as a result of this, the tasks that a TMS can carry out include the determination, indication and prediction (with relevant confidence factors) of the short- and long-term trends of all variables monitored.

5.1.2 Accordingly, TMS should comprise the following:

- performance-monitoring system (PMS);
- combustion-monitoring system (CMS);
- emission-monitoring system (EMS);
- mechanical- and vibration-monitoring system (MMS and VMS).

5.1.3 Finally, it is also the TMS's task to assess trends, to prepare data for future diagnosis for the plant or component (see Annex B), to issue recommendations for actions, and in critical situations, to initiate these directly.

This puts the operator in a position to

- have good insight into the condition of the plant at all times;
- to quickly initiate the necessary responses to current conditions.

5.1.4 The TMS findings can also indicate the necessity of an inspection or overhauls [maintenance-on-condition (MOC)].

The following operations can then be performed when required:

- combustor inspections,
- inspections of components in the hot-gas path,
- major inspections.

5.2 Performance-monitoring systems

5.2.1 PMSs essentially monitor the following:

- shaft and/or electrical power output;
- gas turbine rotor speeds in case of mechanical drives;
- calculated efficiency and/or performance of the gas turbine;
- flow rates (fuel, inlet air, water and/or steam) including exhaust gas of the gas turbine,
- exhaust gas temperature.

5.2.2 Significant ambient conditions, such as the following, are also monitored for the purpose of converting the performance data to the standard reference conditions (ISO 3977-2).

— atmospheric pressure;

— temperature of the intake air;

— air humidity.

5.2.3 The following operating conditions shall also be recorded.

— load and power factor;

— pressure loss at the compressor inlet;

— temperature at the compressor inlet;

— pressure loss at the outlet (possibly also the back pressure caused by downstream plant components).

5.2.4 One major aim of the PMS is to establish the overall process efficiency, together with the associated uncertainty; the evolution of these values over time facilitates decisions concerning operational responses, such as compressor washing or maintenance and the generation of business-related data (e.g. specific fuel costs).

In this way, the gas turbine can always be maintained in the best possible condition and so minimize the specific fuel consumption.

Table 1 lists typical direct and indirect variables of the gas turbine from which trends can be developed.

Table 1 — Parameters for trend development — Performance-monitoring

Direct or indirect variables	Sensor application	Measured data for trend analysis	Fault detection and/or analysis
Power output	Generator terminals Power turbine shaft Compressor shaft	Power output Torque and/or speed measurement Compressor shaft speed	Incomplete combustion Compressor fouling, blading corrosion and/or erosion
Fuel consumption	Measurement of fuel mass flow	Total fuel flow Partial fuel flows	Fuel supply, uniform distribution to the individual nozzles
Thermal efficiency	Indirect determination from power output, heating value, fuel flow	Thermal and/or electrical efficiency	Compressor fouling; blading corrosion and/or erosion Incomplete combustion
Exhaust temperature	Exhaust duct downstream from the turbine diffuser	Mean exhaust temperature (individual values, mean values, maximum deviations)	Correct starting point for subsequent utilization of waste heat Intact combustion system problems
Exhaust flow	Indirect determination	By energy and mass balances	With HRGS: less steam production, more supplementary firing
NOTE Additional parameters are listed in Table 5.			

5.3 Combustion- and emission-monitoring systems

5.3.1 General

The combustion- and emission-monitoring tasks both monitor

— conditions of the combustion process (Table 2);

— exhaust gases, including pollutants (Table 3).

5.3.2 Combustion-monitoring system

The combustion-monitoring system (CMS) monitors those variables that characterize the combustion process because monitoring the combustion process itself is not practicable at the current time.

Essentially these variables include

— exhaust temperature,

— distribution of the exhaust temperature immediately downstream of the gas turbine or the gas generator,

— pressure fluctuations in the combustion system,

— metal temperatures.

The mixing conditions of the partial fuel flows (primary, secondary, pilot and pre-mix amounts) are also of great importance.

Table 2 — Parameters for trend development — Combustion-monitoring

Direct or indirect variables	Sensor application	Measured data for trend analysis	Fault detection and/or analysis
Exhaust temperature	Control cross-section in the exhaust duct downstream from the turbine	Mean exhaust temperature Maximum exhaust temperature Minimum exhaust temperature Exhaust temperatures at all points registered	Incomplete combustion in all burners Uniform fuel supply to all burners Mechanical integrity of the combustion system (burners, nozzles, …)
Spread of the exhaust temperatures	Control cross-section in the exhaust duct downstream from the turbine	Spread of the exhaust temperature and the corresponding position of the control cross section	Definition of the module responsible
Pressure fluctuations in the combustion system	Combustor or transition piece to the turbine	Amplitude of the pressure fluctuations Frequency of the pressure fluctuations	Flame pulsations with the danger of excessive mechanical stress leading to the particular danger of mechanical resonance and combustion problems such as lean flame

5.3.3 Emission-monitoring system

The emission-monitoring system (EMS) continuously determines the pollutant content in the exhaust, i.e. essentially the

— NO_x emissions;

— CO emissions;

— total organic compounds;

— oxygen content (oxygen is also usually measured to adjust the concentrate to a specific reference condition);

— particulate matter or dust (liquid fuel).

NOTE The limits for some or all of these pollutants depend on local requirements.

In case of wet reduction, EMS can also determine the injection (water or steam) conditions.

With this information, it is possible to monitor the emission system effectively. This, in turn, promotes operation and maintenance regimes that minimize the gas turbine's environmental impact.

Table 3 — Parameters for trend development — Emission-monitoring

Direct or indirect variables	Sensor arrangement	Measured data for trend analysis	Fault detection and/or analysis
NO_x emissions	Representative locations in the flow cross-sectional area in the exhaust duct and/or the stack	NO_x content in the exhaust (NO content in the exhaust) (NO_2 content in the exhaust)	Faults in the combustion and/or NO_x reduction process resulting in excessive environmental pollution
CO emissions	Representative locations in the flow cross-sectional area in the exhaust duct and/or the stack	CO content in the exhaust	Incomplete combustion resulting in excessive environmental pollution
O_2 content	Representative locations in the flow cross-sectional area in the exhaust duct and/or the stack	O_2 content in the exhaust	—
Total organic compounds	Representative locations in the flow cross-sectional area in the exhaust duct and/or the stack	TOC	Incomplete combustion resulting in excessive environmental pollution

5.4 Mechanical- and vibration-monitoring systems

The MMS and the VMS monitor the mechanical condition based on different mechanical parameters of the gas-turbine plant (see example in Table 5).

The monitoring of mechanical parameters should include couplings, gears and auxiliary systems (Table 4) when appropriate.

This makes it possible to detect and as a result reduce (but by no means completely) possible problems and damage to a large extent. Maintenance work (maintenance-on-condition) can be performed depending on the actual condition of the system.

5.5 Measured parameters

Table 5 provides a typical data list for a simple-cycle gas turbine. The exact scope and any contractual system shall be agreed between the supplier and the customer.

Some important parameters are not recorded directly, but can be derived from others (e.g. air flow by energy balance and thermal efficiency from fuel consumption and power).

The parameters in Table 5 are listed in functional groups. The notation is in accordance with ISO 2314. The location of sensors is based on relevant acceptance test procedures.

Table 4 — Parameters for trend development — Mechanical- and vibration-monitoring

Direct or indirect variables	Sensor arrangement	Measured data for trend analysis	Fault detection and/or analysis
Casing and/or shaft vibrations (structure-borne sound)	Casing and/or shaft vibration sensors (acceleration, speed probes) located and type specified according to the measurement tasks they perform on representative sections of the casing and/or shaft (temperature resistance, measuring range for amplitudes and frequencies, resonance range)	Trend monitor assigned to a machine area, including rotating speed information Summary level of defined frequency range; overall level Amplitudes of defined orders of harmonics (e.g. for vibrations generated by blading, gears, monitoring roller bearing) Recording of the amplitudes or spectra during start-up and coast-down of shafts Overall spectrum (“water-fall diagram”) Time signal display when a limit value is exceeded (“flight data recorder”)	Bearing problems (ball, inner or outer roller ring) Balancing changes Loose components Combustor vibrations Rubbing, blade fracture Changes to the clearance of tooth flanks Extremely fast (millisecond) time-monitoring of acceleration signals in the selected frequency range with corresponding limit value processing for the machine trip can serve as an additional safety-monitoring system with the aim of preventing or limiting blade damage. Event-controlled data records facilitate the subsequent analysis of the damage.

Table 5 — Summary of possible measured parameters dependant on type, operating conditions and scope of supply

Measured parameter	Represented by:[a]		
	PMS	EMS	MMS and VMS
Time and date	X	X	X
Environment			
barometric pressure	X	X	—
ambient air temperature	X	X	—
relative humidity	X	X	—
Air inlet ahead of the compressor			
temperature for the PMS, EMS and MMS and VMS	X	X	X
indication of inlet air heating and/or bleed heating in operation, or malfunctioning	X	(X)	—
air filter pressure loss	X	(X)	—
silencer pressure loss	X	—	—
static pressure ahead of the compressor (resulting in total inlet pressure loss)	X	(X)	—
Compressor blade duct			
static pressure			
ahead of inlet guide vanes	X	—	(X)
at bearing seal-air tapping location	—	—	X
at cooling-air tapping locations	(X)	—	X
at blow-off locations	(X)	—	X
behind blading and/or diffuser	X	—	X
temperatures			
at cooling-air tapping locations	X	—	X
behind blading and/or diffuser	X	(X)	X
Combustion chamber			
static pressure			
ahead of combustion chamber	(X)	X	(X)
combustion chamber pressure loss	X	—	(X)
pressure oscillations and/or pulsations	—	(X)	X
Cooling system air and/or water			
air cooling temperatures	X	—	X
static pressure of air cooling flows	X	—	X
Metal temperatures (direct or indirect)	—	—	X
combustion chamber	—	—	X
transition elements	—	—	X
turbine blades	—	—	X

Table 5 (*continued*)

Measured parameter	Represented by:[a]		
	PMS	EMS	MMS and VMS
Exhaust gas diffuser			
static pressure in diffuser	X	—	(X)
exhaust gas temperature	X	X	(X)
Fuel system	—	—	—
fuel mass flow	—	—	—
fuel pressure	(X)	X	—
fuel temperature	X	(X)	—
fuel composition (resulting in lower heating value of fuel)	X	X	—
control valve lift	—	(X)	X
water for injection (if available) (mass flow, temperature pressure)	X	X	(X)
steam for injection (if available) (mass flow, temperature, pressure)	X	X	—
Recuperator (if available)			
air temperature			
inlet	X	X	(X)
outlet	X	X	(X)
exhaust gas temperature			
inlet	X	—	(X)
outlet	X	—	(X)
Pressure loss			
air side	X	—	(X)
exhaust gas side	X	—	(X)
Instrumentation & controls			
position of control systems:			
vanes	X	(X)	X
bleed valves	X	—	X
various valves	—	—	X
anti-icing system on/off	X	—	(X)
Performance data			
gross power output or torque	X	—	X
grid frequency	X	—	—
power factor	X	—	—
Mechanical data			
speed	X	—	X
axial shaft position and/or axial thrust	—	—	X

Table 5 (*continued*)

Measured parameter	Represented by:[a]		
	PMS	**EMS**	**MMS and VMS**
Bearings			
metal temperatures of sleeve-type bearings	—	—	X
static pressure of sealing air	—	—	X
Vibrations			
bearing block vibrations	—	—	X
shaft vibrations	—	—	X
housing vibrations	—	—	X
Oil lubrication system			
lube oil temperatures	—	—	X
lube oil supply pressure	—	—	X
differential pressure of lube oil filters and coolers	—	—	X
chemical-physical examination of oil condition (metal particles, abrasion analysis)	—	—	X

[a] (X) indicates allocation to the corresponding monitoring system, if only this system is used.

5.6 Scaling and validation

5.6.1 Conversion of measured parameters

Operating performance strongly depends on the air-inlet conditions. For an independent comparison of the measured parameters, data shall be normalized according to the empirical correction curves from the manufacturers or standard reference conditions in accordance with ISO 3977-2.

5.6.2 Validation of measured parameters

During acquisition of performance data for gas turbines, incorrect measurements, failures of transducers and accumulation of data in the upper or lower tolerance zone sometimes occur. If these incorrect values are not recognized and eliminated from the trend basis, the derived trends can be incorrect and ultimately result in wrong conclusions. In a modern TMS, this is avoided by data validation.

Different methods, such as the following can be applied, in some cases simultaneously, for data validation:

— straight numerical data validation;

— physical data validation;

— voting system selection of signal validation;

— statistical elimination methods;

— plausibility check.

The direct numerical data validation recognizes and eliminates measured data that are out of the tolerance zone. Trends are smoothed by fitting polynomials through the sets of recorded data points.

With the physical data validation, the measured thermodynamic data are validated by calculations for subsets of the process. For this, the unit is subdivided into a series of closed balance areas. A set of equations for the mass and the energy balances is solved by fitting a least-squares line through the data. The measured data can be corrected and outliers eliminated from the trends. Characteristic parameters like efficiency and effectiveness are determined after the data validation.

When a voting-system selection is used, normally 2 out of the 3 systems are used for validation of measured signals.

If large quantities of data are already available for a specific system, incorrect values can be excluded by statistical elimination methods, but only after the measured parameter is incorporated back into the statistical trend. Therefore, statistical elimination methods should be used for data sets only after a certain amount of data has been accumulated.

Finally, plausibility checks are available, but like the diagnostic systems, these depend on continuous acquisition of knowledge.

Iterative methods are often used for data validation. Measured data are correlated using trends, and values outside the given tolerance are eliminated. The trend is then recalculated with the new set of data. This procedure is repeated until the trend is stable within a certain bandwidth.

6 Example of a trend-monitoring system

The schematic of a modern trend-monitoring system is shown in Annex C. All three main components of the TMS (performance-monitoring, combustion- and/or emission-monitoring and mechanical- and/or vibration-monitoring) as described above are integrated.

The schematic also includes access to a database where measured data are stored or new descriptions of characteristics are generated from previously acquired data. Data can be used for statistics and trends as well as to support decisions for intervention. The actual raw data should be stored for objective documentation of operations. Rules for access to these data shall be established.

From the database, the fouling factor (contamination) and the ageing factor of the gas turbine can be derived and, therefore, the behavior of a unit as it ages under different operating conditions can be predicted.

The database can also fulfill tasks in addition to monitoring trends. It is possible, for instance, to store the data from other units in the same construction series, in order to determine values averaged over multiple units. The data compiled for multiple units can also be used for the supplementation or correction of the owner's or even the manufacturer's documentation. On the other hand, data can be collected, stored and subsequently used to predict the behavior under different conditions (i.e. new facility, before or after overhaul or exchange of major parts, etc.).

Annex A
(informative)

Status and further development of trend-monitoring systems

A.1 General

Today in many applications only single elements of a trend-monitoring system (TMS, as it is described in this document) are used. That is, often only the vibration pick-ups offered by the suppliers are used in the vibration-monitoring systems (VMSs). In other cases, thermodynamic data are monitored (PMS) to operate the unit at the highest achievable efficiency.

Because of overlapping objectives, the mechanical-monitoring system (MMS) is often combined the vibration-monitoring system (VMS) while the combustion-monitoring system (CMS) is often combined with the emission-monitoring system (EMS).

The current tendency is to combine all elements of the described systems and to use the combined system as a standardized TMS.

The different monitoring systems are thus more and more

— combined into one system which interacts with the control system;

— integrated in the control system;

— automated;

— permanently operating.

It is advantageous to distinguish the operational parameters that have to be monitored at short intervals (e.g. rotor-shaft and bearing-block vibration, pressure oscillations and pulsations in combustion system) from those that are monitored on a long-term basis (e.g. efficiency). Consequently, in the modern automated TMSs that are integrated into the control system of the gas turbine and that run in the background, the acquisition of data for the operational parameters is partitioned into high- and low-frequency.

The incoming sets of data are stored in databanks and transformed by software tools.

The TMSs enable the generation of different intervals to examine the various aspects of the data. Concerning the efficiency, the short-term trends indicate the need for compressor washing and long-term trends reflect the ageing of the unit.

Even performance improvement and/or deviations can be analysed by means of collected data before and after a refurbishment, overhaul or repair. More and more, cumulative experience is integrated into the system, enabling a diagnosis. The scope of the messages, or rather the recommendations, is increasing steadily. By comparing and logically combining messages, the TMS can be turned into an expert system.

A.2 Status and further development of performance-monitoring systems

The simplest level of monitoring of the thermodynamic parameters of gas turbines is to take single readings at more or less regular time intervals. Evaluation of measured data is done manually using the correlations (e.g. curves, tables) of the manufacturer.

Normally, only the following parameters are compared with target values and trends are determined at full load:

- power output of gas turbine (directly);
- thermal efficiency (indirectly through fuel consumption);
- exhaust gas temperature;
- exhaust gas flow (indirectly through energy balance of gas turbine).

Monitoring of analogous data at partial load is basically limited to thermal efficiency and exhaust-gas temperature, which depend strongly on power output and the position of guide vanes. Under partial load, power is only a specified setting.

All measured thermodynamic data for the gas turbine have to be converted to standard reference conditions (see ISO 3977-2) to enable comparisons among these. Guarantee conditions or ISO conditions can be used as a reference.

Modern performance-monitoring systems (PMS) record the thermodynamic data of the gas turbine at given regular time intervals and automatically convert them to standard reference conditions (see ISO 3977-2). Algorithms for conversion are integrated in the system. The converted data are stored and can be output as a function of time on request (statistics only) showing the more or less distinct trends.

Furthermore, development of PMSs is such that mathematical methods are used for trends and validation.

For trend generation, thermodynamic data are correlated with data at standard reference conditions, preferably those specified in ISO 3977-2. Standard data can be selected for

- analogous data for a gas turbine in new and clean condition, or
- data after overhaul or repair of the gas turbine.

A.3 Status and further development of combustion- and emission-monitoring systems

A.3.1 Combustion-monitoring systems

In most cases, combustion-monitoring systems track only those parameters that are significant for indirect control of combustion. These include exhaust-gas temperature spread and distribution in the controlled cross-section of the exhaust duct, in addition to the exhaust gas temperature or turbine exit-temperature spread.

Pressure oscillations are monitored in the combustion system, especially for Dry Low NO_x reduction. Under certain operating conditions, excessive pressure oscillations can occur in these systems. At distinct frequencies, these oscillations lead to resonances, resulting in high mechanical loads and finally causing damage.

Monitoring of the frequency and amplitude of pressure oscillations and pressure amplitudes contributes significantly to avoiding damage and therefore to ensuring effective operation of the unit.

Direct monitoring of combustion is also possible with today's state-of-the-art technology, but it is normally not used because the sensors in the high-temperature areas of the gas turbine do not have sufficient endurance for continuous operation. Resulting failures of sensors could easily have a negative influence on the operation of the complete unit. Therefore, this type of monitoring is limited to test runs and sometimes to commissionings.

Modern combustion-monitoring systems enable the identification of the burner that is responsible for the established exhaust-gas temperature spread. The relationship of the burners to the thermocouples is provided by the manufacturer. An appropriate message is output to indicate those combustion chambers or burners which are responsible for bigger deviations.

A.3.2 Emission-monitoring systems

The monitoring of emissions is limited today to the measurement of NO_x and CO values, as well as a determination of oxygen content of the exhaust gas to convert the measured emissions to the required ISO standard conditions of 15 % O_2 in dry condition. Emissions are normally measured in dry condition by cooling the probes and separating the condensed water (see ISO 11042). The content of unburned hydrocarbons is normally not monitored, since these values are very low (negligible) in general.

Like the performance-monitoring systems (PMSs), monitoring of emissions is limited in most conventional systems to full load. For systems with dry NO_x reduction, emission peaks can occur at partial load as well. In these applications, emission monitoring at partial load is meaningful.

The target values for emissions are also determined in modern systems. So far, these systems rely on

— empirical data, or

— stored curves based on the measurements during development of the system,

— position of fuel distribution control elements,

although reliable semi-empirical procedures are already available.

A.4 Status and future development of mechanical- and vibration-monitoring systems

A.4.1 General

See also International Standards ISO 13372, ISO 13373-1, ISO 13373-2, ISO 13374-1, ISO 13379, ISO 13380 and ISO 13381-1.

A.4.2 Mechanical-monitoring systems

Mechanical-monitoring systems can be applied to the following:

— measurement and registration of speeds of all rotor systems:

two-speed pick-ups for each rotor;

— measurement and registration of the axial position of rotors with sleeve-type bearings:

proximity probe for each shaft to monitor the shaft axial position;

— measurement and registration of axial (thrust) and radial bearing temperatures of rotor systems;

— sleeve-type bearings:

direct measurement of bearing-pad temperatures (bearing metal) through thermo-elements;

— anti-friction bearings:

measurement and registration of differential temperature between oil supply and return for each bearing and each oil sump. One measuring location in supply, further measuring locations in returns;

— oil-lubrication system;

- measurement and registration of oil pressures:

  pressure-measuring points in oil system;

- measurement and registration of differential pressures of oil filters and coolers:

  differential pressure measuring points at filter elements and coolers;

- metal particle detector for anti-friction bearings:

  monitoring of metallic abrasion for localizing the wear of components in the oil circuit. In aero-derivative gas turbines, the metal particle detector is arranged in the oil return as a rule (per each oil sump);

- performance of analytical oil investigations[2];

- chemical-physical investigation of lubricant for ageing:

  examination for thermal resistance and corrosiveness through thermo-mechanical loads;

- abrasion analysis and/or oil purity:

  analysis of lubricant abrasion elements with the objective of localizing wear of the machine components, avoiding erosive damage through solids dissolved in the oil circuit;

- measurement and registration of combustor vibrations and/or pulsations (humming of gas turbines with Dry Low NO_x combustion chamber systems and/or DLN/DLE combustors);

  recording of dynamic pressure in combustion chambers by piezoelectric pressure pick-ups with the objective of assessing the uniformity of the combustion process while also avoiding inadmissible component stressing for the combustor components;

- measurement and registration of positioning of control systems (e.g. variable guide vanes, bleed valves etc.):

  measuring the position of variable guide vanes on the compressor and/or turbine by way of transducers such as linear variable displacement transducers (LVDTs) or rotational variable displacement transducers (RVDTs), recognizing sluggish motion and/or blockage by design/actual-value comparison;

- measurement and registration of torque and/or machine power:

  installation of torque-measuring coupling (only applicable when compressor and pump are driven) between gas turbine and driven machinery.

A.4.3 Vibration-monitoring systems

Any mechanical changes of rotating parts, bearings and casings are liable to modify the vibrational response of turbo-machinery in almost every instance. Often, this change in the vibration behavior cannot be detected directly from standard vibration monitors as a function of the adjusted monitoring parameters. Therefore, it is necessary to use more detailed vibration-analysis systems based on fast Fourier transformation (FFT) analyzers, filtering systems, phase-angle detectors, etc.

As a rule, it is necessary to consider other operating parameters for the analysis.

Variations in the operating or environmental parameters, such as speed, power, temperatures, will cause changes in the measured vibration values. A direct comparison of measurements is possible only if the other operating conditions are identical. Therefore, relations can be established between as-measured amplitudes or spectra and speeds or loads or other marginal conditions (i.e. position of blow-off valves and/or guide vanes, oil and/or bearing temperatures) for measuring blade, casing and shaft vibration.

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2) Lab-based analysis equipment required.

Reference data shall be redefined after any mechanical alterations as a result, for instance, of a basic overhaul.

It is not possible to detect all potential defects on all gas turbine types to the same extent.

The installation of vibration pick-ups and monitors, as well as the use of the analysis processes involved, shall be in accordance with ISO 13373-1.

Annex B
(informative)

Diagnostic systems

B.1 Diagnostic systems

Diagnostic systems are not a topic considered by this International Standard, but are considered as a future option for enhancing trend-monitoring systems. This annex is intended to provide some useful general information about diagnostic systems.

The DS (see Figure B.1) acquires the information generated by TMS and uses it to derive overall conditions of the whole system, e.g. the extent of maintenance intervals of certain sub-systems. Statements may be issued on the remaining risk in the case of impending disturbances and the reasons leading to undesirable states of the system.

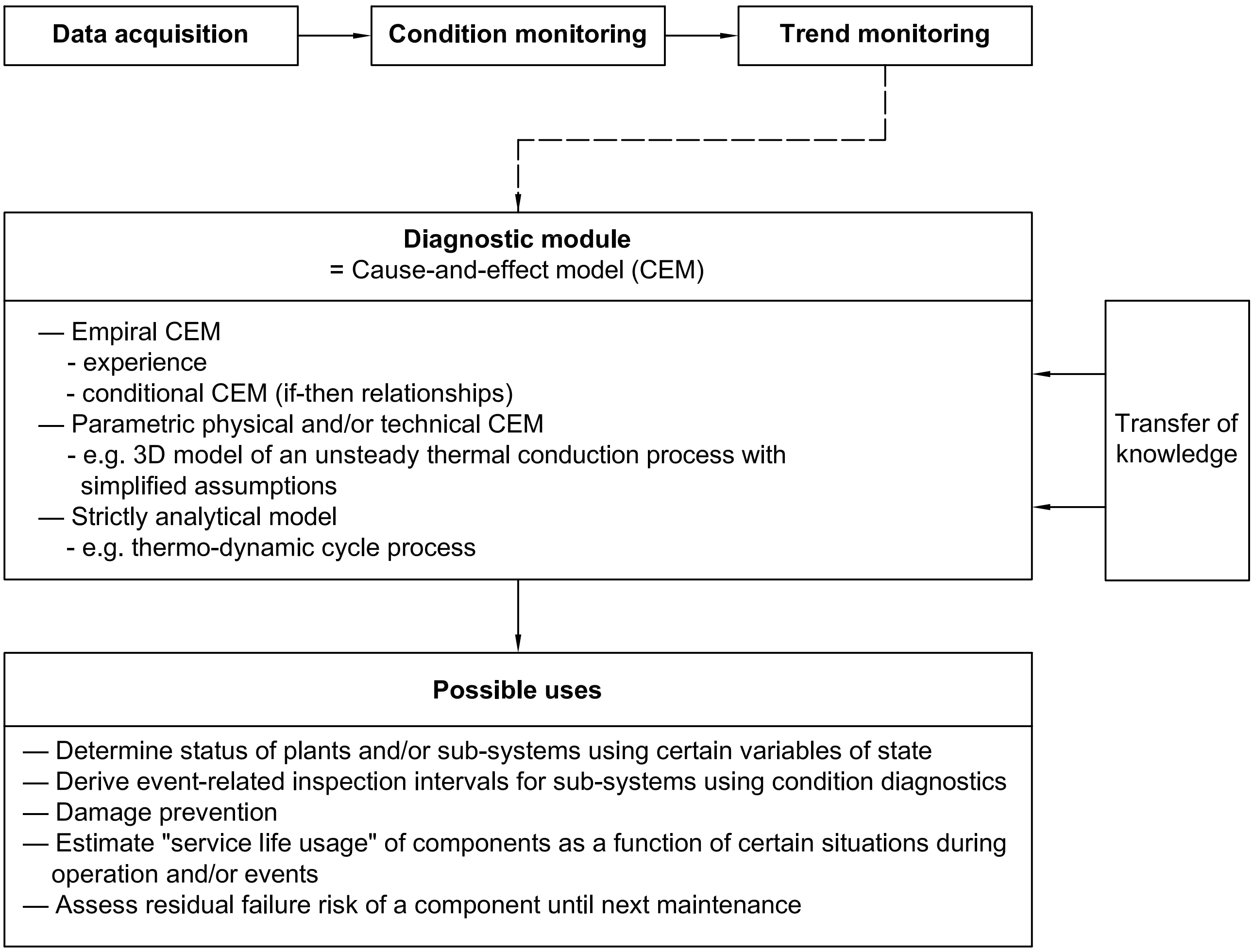


Figure B.1 — Diagnostic systems (DS)

The prerequisite for these capabilities is a knowledge base that allows the quantification of the cause-and-effect relationships (such as those for temperatures, forces, attack by corrosion or the resulting consequences such as fatigue, wear, corrosion).

These cause-and-effect models (CEMs) represent an essential feature of a monitoring system, enabling it to formulate a diagnosis and to function as a knowledge-based system (Figure B.1).

A general practical problem with CEMs is that they have a strongly empirical character. Therefore, they do not adapt to changing situations (e.g. new developments, changes in the field and operating conditions).

Thus, there exists a real need to develop theoretically based CEMs that are able to make statements that are more widely applicable with respect to cause and effect.

EXAMPLE Application to a sufficiently well performing CEM relative to the effects of ageing of components exposed to the hot gas:

Cause	Effect
Transient stress by temperature	Measurement of temperature distributions
Temperature variation and its cycles	Computer simulation of the unsteady temperature distributions in the component (input of knowledge) Statements of time- and space-dependent stresses in the material Description of the contribution to fatigue, e.g. by a trip acting on a certain component and reducing its lifetime respectively

Principle applications in connection with gas turbines are as follows:

— scheduling condition-based maintenance;

— optimization of investments in maintenance;

— prevention of failures;

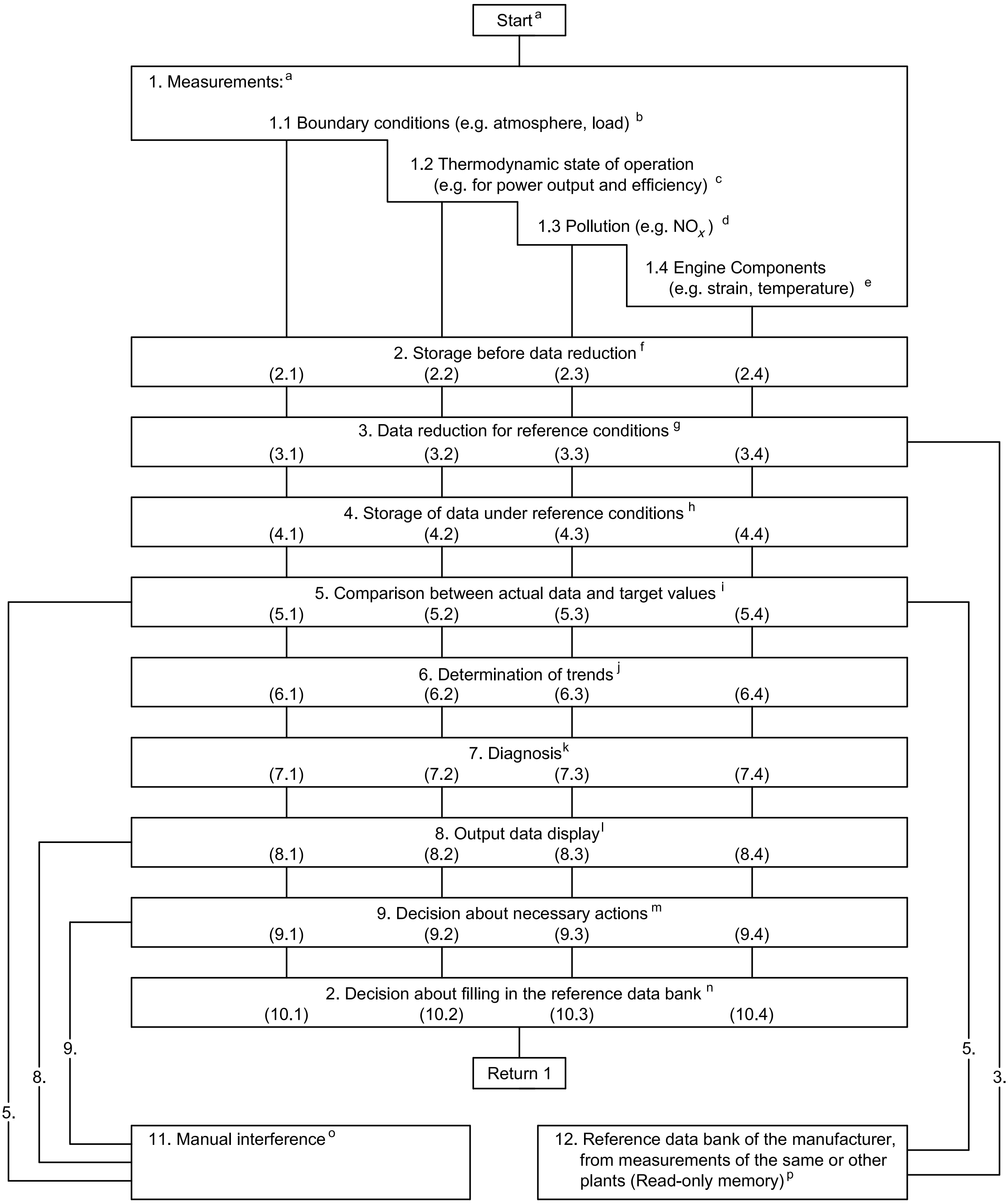
— evaluation of the remaining risk in operating a plant under progressive ageing and/or anticipated disturbances;

— localization of an identified failure.

Annex C
(informative)

Flow chart of the trend-monitoring system

C.1 Flow chart of the trend-monitoring system



Key

- [a] See C.2.1.
- [b] See C.2.2.
- [c] See C.2.3.
- [d] See C.2.4.
- [e] See C.2.5.
- [f] See C.2.6.
- [g] See C.2.7.
- [h] See C.2.8.
- [i] See C.2.9.
- [j] See C.2.10.
- [k] See C.2.11.
- [l] See C.2.12.
- [m] See C.2.13.
- [n] See C.2.14.
- [o] See C.2.15.
- [p] See C.2.16.

Figure C.1 — Flow chart of the TMS

C.2 Explanations for the flow chart of the trend-monitoring systems

C.2.1 Measurements (Figure C.1, item 1)

The acquisition of experimental data for physical quantities in and near the gas turbine is the first step towards a trend-monitoring system for the surveillance of the condition and the detection of time-dependent distributions of values of the important operation parameters. Usually the measurements are acquired automatically, but the data (e.g. visual control to consider direction of wind, fouling, corrosion, replacement of components, etc.) may also be manually input by the operators. An extension even to the level of image processing might be useful in some cases.

C.2.2 Boundary conditions (Figure C.1, item 1.1)

The open-cycle gas turbine installation is an air-breathing propulsion system. For this reason, the temperature, pressure and humidity of the surrounding atmosphere, through their influence on the air density, influence the efficiency and the available operating range in the charts. Depending on the field of application of the gas turbine, additional physical quantities might be needed to get an indication of the state of the plant. Eventually, these values are not measured directly at or in the gas turbine. The power output, for example in an electricity-generating plant, may be taken at the points of the generator. Thus, the experimental data for the power output may be taken from the points of the generator. The rotor speed may be determined at the shaft train outside the gas turbine. When the gas turbine drives a compressor or pump, a pressure measurement can provide information on the power output derived from the load.

C.2.3 Thermodynamic state of operation (Figure C.1, item 1.2)

Beside the boundary conditions imposed by the atmosphere and the load, the thermodynamic state of the turbine cycle yields information on the level of the load, with the hot-gas temperature determining the lifetime of engine components and the hot-gas path. The temperature at the inlet of the turbine is derived from the exhaust-gas temperature and pressure, the temperature at the compressor exit, the fuel mass flow and its temperature. The power output is derived from thermodynamic considerations of the turbine pressure ratio, the mass-flow consumption and the efficiency.

C.2.4 Pollution (Figure C.1, item 1.3)

Pollution from the gas turbine can be minimized through a control or feedback system as a function of the emissions measured in the exhaust gases. In general, this is achieved by an adequate quantity of fuel injection into the combustion air in the region of the burner (controlled by switching off burners, changing the amount of fuel, adjusting of compressor guide vanes, etc.). Water injection and exhaust-gas cleaning may be added as additional means to reduce pollution.

C.2.5 Engine components (Figure C.1, item 1.4)

Apart from the thermodynamic state of the flow in the gas turbine, a number of other quantities shall be checked to guarantee reliability. These include, among other things, the limiting values for lubrication in the bearings (temperature and pressure of the oil, axial thrust), bearing vibrations, cooling-air temperature, sealing pressures to prevent undesired leakages, strain and temperatures of structural parts.

C.2.6 Storage before data reduction (Figure C.1, item 2)

The data acquired from local and temporal situations should be available to users in the form of a read-only file that provides a basis for the analysis of structural safety. Comparative statements with respect to power and efficiency can be made only after reducing the data to standard reference conditions (see ISO 3977-2). In certain situations, the operator of a plant might be interested in the raw data without normalization. This allows, for instance, converting the data to other standard reference conditions (see ISO 3977-2) at a later date. For example, the mechanical speed and the corresponding ambient temperature can be stored to examine the harmonics in the mechanical vibrations before normalizing the values to standard reference conditions (ISO 3977-2 or other).

C.2.7 Data reduction for standard reference conditions (Figure C.1, item 3)

Operating conditions related to power output and efficiency require conversion to standard reference conditions (ISO 3977-2). In general, ratings are based on ISO standard conditions ($p = 101{,}3$ kPa; $T = 288{,}15$ K; $\varphi = 60$ % relative humidity in the ambient air).

Other reference conditions can be meaningful for a comparison of several engines of the same type or other data from the same engine under off-design conditions. The time lapse after shutdown for hot-start capability or low ambient temperature because of axial thrust can be mentioned in this context.

NOTE See also ISO 3977-2.

C.2.8 Storage of data under standard reference conditions (Figure C.1, item 4)

In order to avoid repeated recalculation of data, the results may be stored as reference data (e.g. power, thermal efficiency under ISO conditions). This may reduce computer time for future comparisons.

NOTE See also ISO 3977-2.

C.2.9 Comparison between actual data and target values (Figure C.1, item 5)

The measurements taken while the engine is running describe the actual condition of the machine. Relating the values under normalized conditions allows a determination of the offset from the expected target values. Loss of power due to compressor fouling, pressure rise due to turbine fouling and drop in inlet pressure due to clogging of the filter may serve as examples. This provides not only the basis for the trend monitoring but also indicating upcoming requirements for maintenance.

C.2.10 Determination of trends (Figure C.1, item 6)

The data acquired may now be compared with stored historical information. The comparison allows a determination of gradients over time, over operating hours, ambient temperature, power or other quantities (e.g. power loss over operating hours as a consequence of fouling).

C.2.11 Diagnosis (Figure C.1, item 7)

The diagnosis is derived from a comparison of the computed result from the actual data and from the reference-library data; these should be expanded with increasing experience into an expert system.

C.2.12 Data output and display (Figure C.1, item 8)

Increasing automation of the data processing reduces the volume of data on paper files (e.g. tables with numbers, diagrams). With the aim of more easily accessing the database for subsequent computer treatment, the development is directed towards storage in digital format.

C.2.12.1 Surveillance

The display of results and the surveillance of operating conditions can be called upon request for a selection of values in digital or analog form as diagrams on-screen, or as plotted or printed paper copies. Under these circumstances, quantities important for the fail-safe operation of the plant shall appear automatically in a continuous or intermittent manner to transmit decisive information to the operators. Alarms should be given optically and perhaps also acoustically.

C.2.12.2 Display of the results

The representation of the computational results can be called upon by the personnel (e.g. by selections from menus) or, for special purposes, can be programmed in special formats.

C.2.12.3 Security of data

In order to guarantee the security of the data for customers or manufacturers, the law may impose redundancy in the filing and documentation (e.g. archiving in both paper and electronic form).

C.2.13 Decision about necessary actions (Figure C.1, item 9)

C.2.13.1 Automatic action

A diagnostic system monitoring the evolution of a situation (gradient) may ask for decision-making in automated form to implement programmed decisions into actions automatically (e.g. bearing vibration triggers a trip of the engine, exhaust-gas emissions lead to a change in the setting of compressor guide vanes).

C.2.13.2 Proposed actions

The diagnostic system may conclude that certain actions are economically desirable but not absolutely required. In these cases, the operating personnel can decide about the actions in light of the diagnostic results (e.g. increase of efficiency by compressor cleaning).

C.2.14 Decision about filing in the reference databank (Figure C.1, item 10)

After completion of the analysis, it shall be decided whether the raw data or the rated values should be incorporated in a databank. They can be useful as a reference at a later date or simply document the historical events. The decision about filing in the databank may be taken by the operating personnel.

C.2.15 Manual interference (Figure C.1, item 11)

Beside start and stop of the TMS, manual intervention in the programmed sequence may be needed in the following steps:

— comparison between actual data and target values (Figure C.1, item 5);

— data output and display (Figure C.1, item 8);

— decision about actions (Figure C.1, item 9);

— decision about filing in the reference databank (Figure C.1, item 10).

These day-to-day decisions may need to be documented with remarks.

C.2.16 Reference databank (Figure C.1, item 12)

A comparison is made of the actual situation with reference data that originate either from the manufacturer, from the initial conditions when new (or after revision), or from other comparable plants. (The reference data should be archived in read-only files.) Manufacturers' data are stored before initial runs, and data from the actual operations are added during the course of exploitation of the installation.

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