

MANUAL

CONDITION MONITORING AND SAFEGUARDING OF ROTATING EQUIPMENT

DEP 31.29.00.11-Gen.

December 2007

DESIGN AND ENGINEERING PRACTICE



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1. INTRODUCTION

1.1 SCOPE

This new DEP specifies requirements and gives recommendations for the condition monitoring and safeguarding of rotating equipment such as compressors, gas turbines, steam turbines, gas or liquid expanders, gearboxes, pumps, fans, electric motors and electrical generators. To maximise the benefits of current technology, it also covers the accessing of condition monitoring services such as Shell SmartConnect through remote connectivity.

Section 2 covers condition monitoring systems.

Section 3 covers safeguarding, which is implemented to maintain the integrity of the equipment. In emergency cases, the rotating equipment is shut down with minimum risk to operating personnel and to the equipment itself. Section 3 relates only to the safeguarding of rotating equipment and not to the interface between the subject machine and the associated production plant in which the rotating equipment is integrated

This DEP shall be applied to new construction projects and should be applied to the review of existing rotating equipment condition monitoring and safeguarding systems.

This DEP may be used as part of an integrated asset management plan, which will include tools for:

- Equipment Engineering/Design documentation and development of procedures.
- Saving and retrieving equipment history (including performance and repair history).
- Condition Monitoring, including tools to provide guidance for predictive maintenance or operational decision making (the subject of this DEP).
- Abnormal Situation Management (ASM) designed to diagnose incipient failures or deteriorating condition of the rotating equipment and to provide operational advice to prevent the condition from escalating.
- Aiding decision making with respect to: future operation, scheduling maintenance, replacement of rotating equipment and turnaround planning, all with account being taken of system constraints, trends and diagnosed faults.

These tools are primarily intended to provide information (from manned and unmanned locations) to operations, maintenance and engineering (both on-site and in remote locations). Therefore, they should be capable of being integrated into existing or future condition monitoring systems and other process equipment (e.g. heat exchangers, fired heaters, reactors) to provide an integrated tool to maximise asset performance.

Development of condition monitoring tools is ongoing. This DEP mentions new developments in order to drive the technology and to ensure Information Technology (IT) system design can accommodate advances in condition monitoring whenever systems are upgraded.

1.2 DISTRIBUTION, INTENDED USE AND REGULATORY CONSIDERATIONS

Unless otherwise authorised by Shell GSI, the distribution of this DEP is confined to Shell companies and, where necessary, to Contractors and Manufacturers/Suppliers nominated by them.

This DEP is intended for use in refineries, chemical plants, gas plants, exploration and production facilities, power generation plants and supply/distribution installations.

When DEPs are applied, a Management of Change (MOC) process should be implemented; this is of particular importance when existing facilities are to be modified.

If national and/or local regulations exist in which some of the requirements may be more stringent than in this DEP, the Contractor shall determine by careful scrutiny which of the requirements are the more stringent and which combination of requirements will be

acceptable with regards to the safety, environmental, economic and legal aspects. In all cases the Contractor shall inform the Principal of any deviation from the requirements of this DEP which is considered to be necessary in order to comply with national and/or local regulations. The Principal may then negotiate with the Authorities concerned, the objective being to obtain agreement to follow this DEP as closely as possible.

If the rotating equipment Manufacturer's requirements for the condition monitoring and safeguarding of his equipment are more stringent than the requirements in this DEP, the Contractor shall inform the Principal of this and shall provide a detailed proposal for the Principal's approval; this proposal shall include all deviations from this DEP in order to comply with the Manufacturer's requirements.

The Principal may then negotiate with the Manufacturer(s) concerned with the objective to reach an agreement to follow this DEP as closely as possible and to maintain the Manufacturer's warranty on the equipment.

1.3 DEFINITIONS

1.3.1 General definitions

The **Contractor** is the party that carries out all or part of the design, engineering, procurement, construction, commissioning or management of a project or operation of a facility. The Principal may undertake all or part of the duties of the Contractor.

The **Original Equipment Manufacturer (OEM)/Manufacturer/Supplier/Vendor** is the party that manufactures or supplies equipment and services to perform the duties specified by the Contractor.

The **Principal** is the party that initiates the project and is financially responsible for its design and construction. The Principal will generally specify the technical requirements. The Principal may also include an agent or consultant authorised to act for, and on behalf of, the Principal.

The word **shall** indicates a requirement.

The word **should** indicates a recommendation.

1.3.2 Specific definitions and abbreviations

Definitions of other terms used in this DEP but not mentioned below shall be in accordance with ISO 2041, ISO 13372 and API 670.

accelerometer	pick-up (transducer) that converts an input acceleration to an output (usually electrical) proportional to the input acceleration.
alarm (alert/warning) setpoint	pre-set value of a parameter at which an alarm is activated to warn of a condition that requires immediate evaluation or corrective action.
availability	measure of probability that a machine will, when used under specific conditions, operate satisfactorily and effectively when required to do so.
condition-based maintenance	maintenance governed by condition monitoring programmes.

condition monitoring	measurement and analysis of a number of machine parameters, which are used to determine the current health of the equipment and thus the correct timing/extent of equipment maintenance. NOTE: Continuous monitoring provides simultaneous, automatic and uninterrupted collection of all status conditions and measured and calculated variables. It is normally available in real time mode.
critical speed	characteristic shaft rotational speed at which resonances of a system are excited.
DACA (Data Acquisition and Control Architecture)	IT requirements for separation of data flow between the office domain and the process control domain. DEP 32.01.20.10-Gen. is the umbrella DEP for a series of DACA DEPs.
displacement	vector quantity that specifies the change of position of a body, or particle, with respect to a reference frame
displacement pick-up	pick-up (transducer) that converts an input displacement to an output (usually electrical) that is proportional to the input displacement (see also <i>proximity probe</i>).
FAR (Field Auxiliary Room)	room located next to or in the subject plant/unit.
failure	termination of the ability of an item to perform its required function.
flash point (of a liquid)	temperature at which its vapour ignites when exposed to a flame. A minimum flash point is normally specified for safety reasons.
FTM (Federal Test Method)	test method for oxidation and corrosion stability.
HAZOP	Hazard and Operability study.
IPF	Instrumented Protective Function.
keyphasor	signal used in rotating machinery measurements, generated by a transducer observing a once-per-revolution event, e.g. the passage of a keyway. The sensing device may be a magnetic, capacitive, eddy current, or photoelectric probe. The keyphasor signal is used for speed measurement and for phase measurements when analysing and balancing. NOTE: Keyphasor is a trademark of Bently Nevada Corporation.
machinery train	driver(s) and all of its associated driven pieces of equipment.
monitor system	system comprising signal processing, alarm/shutdown/integrity logic processing, power supply, display/indication, inputs/outputs, and protective relays.
off-line system	system that allows data capture on a periodic but not automatic basis. It is normally accomplished by manual data collection with time intervals that are typically daily, weekly, or monthly.

on-line system	system that automatically scans information at specific time intervals. The system performs signal processing, alarming, data storage, reporting, etc. This can be continuous or periodic.
OPC (Open Process Control)	set of seven open standards for connectivity and interoperability of industrial automation and enterprise systems.
parameter	measurable variable.
peak-to-peak (value of a vibration)	algebraic difference between the extreme values of the vibration in the units of measurement.
performance	machine efficiency and capacity.
periodic collection	collection of all status conditions and measured variables at discrete time intervals.
proximity probe	non-contacting sensor that consists of a tip, a probe body, an integral coaxial cable and a connector; used to translate distance (gap) to voltage. NOTE: See also displacement pick-up.
radial shaft vibration	vibratory motion of the machine shaft in a direction perpendicular to the shaft longitudinal axis.
RBVOT	Rotating Pressure Vessel Oxidation Test.
reliability	measure of the probability that a machine will perform its required functions without failure for a specified period when used under specific conditions.
RTD (resistance temperature detector)	temperature sensor that changes its resistance to electrical current as its temperature changes.
RIC	Reciprocating Internal Combustion.
rotating equipment	high-speed equipment used to provide plant compression (includes reciprocating compressors at all speeds), electrical power generation, process pumping and safety duties.
sensor	device (such as a proximity probe, thermocouple, accelerometer etc.) that detects the value of a physical quantity and converts the measurement into a useful input for another device. NOTE: See also transducer .
shutdown (danger/trip) setpoint	preset value of a parameter at which automatic or manual shutdown of the machine is required.
SIF	Safety Instrumented Function.
SIFPRO	Shell methodology used to carry out SIL assessments and define SIS requirements as well as to document and maintain all data relevant to a safety requirements specification.
SIL	Safety Integrity Level.
SIS	Safety Integrity System.

SmartConnect	Shell's integrated condition monitoring services delivery system utilising remote connectivity to sites.
TAN	Total acid number.
TBN	Total base number.
temperature sensor	thermocouple (TC) or resistance temperature detector (RTD) and its integral sensor lead.
thermocouple	temperature sensor consisting of two dissimilar metals so joined to produce different voltages when their junction is at different temperatures.
TOST (turbine oil stability test)	standard test to oxidise an oil resulting in the formation of acids.
transducer	device designed to receive energy from one system and supply energy, of either the same or of a different kind, to another in such a manner that the desired characteristics of the input energy appear at the output. NOTE: Also known as a sensor , a probe and a pick-up .
tribology	science and technology of interacting surfaces in relative motion, and of related subjects and practices. In the context of Triboscience or Tribotechnology it includes the study of lubrication, friction and wear.
trip	automatic or manual shutdown of a machine when a value of a monitored parameter exceeds a preset limit.
velocity pick-up	pick-up (transducer) that converts an input velocity to an output (usually electrical) that is proportional to the input velocity (also referred to as a velocimeter).
vibration	variation with time of the magnitude of a quantity which is descriptive of the motion or position of a mechanical system, when the magnitude is alternately greater and smaller than some average value or reference.

1.4 CROSS-REFERENCES

Where cross-references are made, the number of the part, section or subsection referred to is shown in brackets.

1.5 COMMENTS ON THIS DEP

Comments on this DEP may be sent to the DEP Administrator at standards@shell.com. Shell staff may also post comments on this DEP on the Surface Global Network (SGN) under the Standards folder.

2. CONDITION MONITORING STRATEGY

2.1 GENERAL

Section 2 provides guidelines and functional requirements for the justification, selection and configuration of condition monitoring systems for rotating equipment while Section 3 deals with their safeguarding. These systems can be applied to new and existing machinery installations but in all cases should be directed towards identifying and avoiding root cause failure modes as outlined in ISO 17359. Guidelines for establishing procedures for failure mode analysis are given in ISO 13379 and should be followed to ensure an effective implementation.

Condition monitoring is defined as the measurement and analysis of a number of machine parameters, which are used to determine the correct timing and extent of equipment maintenance, including the current health of the equipment.

The objectives of equipment condition monitoring are to achieve one or more of the following:

- plant safety improvement
- environmental safeguarding
- rotating equipment protection
- predicting maintenance interventions
- rotating equipment performance optimisation
- operating cost optimisation
- availability improvement
- mechanical integrity improvement
- maintenance cost optimisation

Although plant safety improvement and environmental protection are of the highest importance, condition monitoring plays only an indirect role in them. In the petrochemical industry it is the availability of critical rotating equipment which has the highest impact on the operation of the plant.

What determines equipment availability is largely dependent on the type of equipment, its failure modes and its application, although many common characteristics exist. The availability of reciprocating compressors, for example, is typically poorer than that of centrifugal compressors but keeping their lubricating oil cool, clean and dry applies to both equally. Parameters required for condition monitoring (based on known functional failure modes of each equipment type) are given in ISO 17359 and ISO 13373-1 and summarised in (2.6).

When applied systematically and consistently, condition monitoring of equipment provides additional synergistic benefits for a plant which result from closer cooperation between operations, maintenance and engineering departments. Condition monitoring tools, when available to appropriate staff, provide additional eyes and ears on the equipment, allowing earlier detection of developing faults and limiting their severity.

Condition monitoring requires capital investment and a commitment to operate and maintain a monitoring system throughout the lifecycle of the operating plant. A cost-benefit analysis shall be part of the process of deciding whether condition monitoring is justified for an item of equipment and the level of monitoring to be undertaken. Clear economic benefits shall be demonstrated before proceeding.

The condition monitoring to be applied in a plant shall be developed as part of the overall maintenance philosophy of the plant. A plant specific condition monitoring strategy shall be developed which identifies the equipment to be monitored and defines the appropriate type of monitoring,

2.2 CONDITION MONITORING

The extent and specifics of condition monitoring of rotating equipment should be defined for each installed machine and depend on the following characteristics:

a) Criticality.

As a first step in a condition monitoring program, the importance of the various equipment items and their impact on plant operation/availability shall be defined. For this purpose equipment items shall be individually classified. Experience has demonstrated that a "three category" classification provides adequate differentiation between the criticality of the relevant items. Appendix A provides a definition of the three categories, i.e. vital, essential spared and non-spared, and non-essential equipment.

b) Equipment complexity.

c) Types of failures (faults) expected to be detected for that equipment.

d) Type of maintenance scheme adopted for the subject equipment.

e) Availability, expertise and effectiveness of site personnel combined with staffing policy, namely in-house or outsourcing.

This DEP does not address the controls and measurements used for machinery control, specifically speed and anti-surge control and related safeguarding, but this information may be integrated into a common control and monitoring system.

As stated above, condition monitoring is defined as the measurement and analysis of a number of machine parameters, which are used to determine the correct timing and extent of equipment maintenance, including the current health of the equipment.

Condition monitoring consists of two types of monitoring:

- On-line monitoring (Section 2.3);
- Off-line monitoring (Section 2.4).

A condition monitoring system shall typically include, but not be limited to, the measurement of the following parameters:

- Vibrations, either shaft displacement and/or velocity/acceleration measurement of bearing housings, equipment casings and crank cases including phase angle
- Radial and axial shaft positions including phase angle
- Speed
- Bearing metal temperatures and/or bearing housing temperatures
- Bearing sump temperatures
- Lube and seal oil supply pressures and temperatures
- Seal oil consumption and lube oil leakages
- Lubricating oil condition by means of a number of parameters
- Lubricating oil exit temperatures at bearings (throw off temperature)
- Dry gas seal buffer gas and seal gas consumption and seal leakages
- Valve or valve cover temperatures of reciprocating compressors
- Pressure/volume diagrams of reciprocating compressors
- Rod position (rod drop) monitors for reciprocating compressors
- Piston rod packing leakage (flow, temperature, pressure or a combination of these)
- Hydraulic performance data of pumps and liquid expanders, including balance pressure

- Steam turbine steam data; including 1st stage steam pressure and steam valve position
- Compressor gas pressures, including reference gas and balance gas
- Gas turbine wheelspace and exhaust temperatures
- Thermodynamic performance data of compressors (head, flow, efficiency, power), steam turbines (steam flow, enthalpy drop, speed) gas turbines (compressor efficiency, speed, enthalpy), centrifugal pumps (polytropic head, flow, power, discharge pressure)
- Inlet air filtration quality of gas turbines and large process air compressors
- Electrical performance of electric motors and generators

Depending on the characteristics of the specific equipment, one or more of the above parameters will need to be monitored, either on-line or off-line. Recommended condition monitoring parameters by machine type are given in ISO 17359 and ISO 13373-1.

For a typical plant, a condition monitoring system for rotating equipment shall consist of an on-line system and an off-line system.

2.3 ON-LINE MONITORING

In an on-line monitoring system a number of equipment parameters are automatically measured, sampled, analysed and stored in a database (either continuously or periodically). The sampling can be conducted on a time basis, an alarm basis, when a pre-determined change in a measured value is detected, and during transient conditions. The parameters shall be analysed and stored in a database so that on a comparison basis a trend line of the machine condition can be established. This trend line will provide information to help determine whether the subject equipment will need to be taken out of operation for maintenance and/or overhaul.

On-line condition monitoring systems can either be a single system or a combination of distributed multiple systems. The main requirement for a combination of multiple distributed systems is that all information can be collected and analysed in one centralised database in order to facilitate the trending of relevant data over a minimum period of 10 years (two overhaul cycles minimum). For centralised server systems, data acquisition shall not be impaired by network communication disruption and hence shall provide temporary local storage (24 hours minimum). Either architecture shall enable the display and review of data in the FAR (or equivalent) to enable machine start up data to be captured and reviewed during commissioning, before and after turnarounds and in the event of network disruption.

An on-line system shall automatically sample, process and store the various parameters, as described above, with a resolution that can be adjusted to the specific needs of the measured parameter. Resolution may vary from milliseconds to hours or, in case of very slow changing parameters, to days. The final storage of data in the system shall be time based and event based. Both time and event based storage criteria shall be adjustable by the system user.

When a high end monitoring system is specified, it shall as a minimum meet the following requirements and shall provide instant information on:

1. The dynamic behaviour of each monitored machinery train component, including the various analysis techniques, both with current and with historical data. This includes all radial bearing vibration measurements, casing vibration measurements and rotor axial displacement measurements of all monitored rotors. Alarm and report facilities shall be provided in a programmable form, which can be adapted to the specific machinery needs. The system shall include, but not be limited to, the possibilities to trend sampled and calculated data and provide long term reporting on these. Transient waveform data captured during machine start-ups and coastdowns shall be used to provide high resolution analysis displays such as Bodé plots and Nyquist diagrams as well as frequency analyses of vibration. Waveform data shall be captured in real time and for all monitored channels simultaneously; multiplexing of transient data is not acceptable. Both real time and sampled data shall be included in the processing and reporting facilities.

Data storage shall extend to a minimum time span of 10 years (two overhaul cycles), either in total or compressed format, in order to serve as a database for assessments of maintenance requirements.

2. The system shall collect all associated bearing temperatures of the machinery components and process and store them so that they can be related to the respective vibration and axial displacement data. If these data are measured in another system, such as plant DCS systems, they shall be imported from this system and correctly time stamped synchronously with the rotor-dynamic data collecting system. If they are also stored in the other system, they shall be available for analysis and reporting synchronously with the data of the condition monitoring system.
3. The system shall have two-way communication with the plant DCS system in which the connected machinery is located via OPC or an equivalent open system. It shall be able to import all necessary data and measured parameters from the plant DCS system to compute the performance of the connected machines. This includes, but is not limited to, all data necessary to automatically calculate the correct thermo-dynamic performance of compressors, gas turbines, steam turbines, and hot gas and cold gas expanders, and the hydraulic performance of centrifugal pumps and liquid expanders. Furthermore, it shall be able to calculate the performance of electric generators and motors shall be possible. The system shall have all these performance calculating facilities included in its programming and shall store these data for trending purposes.
4. As in point 3, in facilities where a Data Historian is used the system shall have two-way communication with the plant Data Historian.
5. All data shall be time stamped, synchronised with the plant master clock. This is required to enable correlation of equipment events with other plant events.
6. The system shall capture raw dynamic data when triggered by an event for subsequent analysis. The period of pre-event data shall be user definable and be at least 10 minutes. The storage capacity shall be sufficient to capture all monitored data, at programmable intervals, at least until the equipment comes to rest following a trip. Storage shall allow the capture and retention of alarm and transient data if network communication is disrupted. All channels shall be sampled simultaneously. The dynamic data capture system should be integrated within the condition monitoring system.
7. The system shall compare all new data against reference baseline data (including spectra) and against all configured Alert/Danger limits and automatically preset excursions.
8. The system shall be capable of storing the following static vibration data:
 - o Overall amplitude (direct)
 - o Gap Voltage
 - o 1x amplitude and phase angle
 - o 2x amplitude and phase angle
 - o 4 additional user-defined Nx amplitude and phase angle measurements
 - o 4 user defined frequency band measurements (including subsynchronous)
 - o Not 1x amplitude
 - o S_{max}
9. The system shall be capable of displaying at least the following plots:
 - o Spectrum (synchronous and asynchronous, full and half spectrum)
 - o Waterfall
 - o Cascade
 - o Campbell

- o Bodé
- o Nyquist
- o Polar
- o Timebase
- o Orbit/timebase
- o Shaft centreline
- o Acceptance region
- o X v. Y
- o Tabular lists
- o PV diagrams
- o Pressure v. crank angle
- o Vibration v. crank angle

10. Display of all measurements in SI or US Customary units.

The above requirements refer to applications where a high resolution on-line condition monitoring system (including spectral and timewaveform related data) is required. For applications where this is not the case, all requirements not related to spectral and timewaveform linked data shall still apply.

Vibration measurement probes and signal processors/pre-amplifiers, which are normally mounted on the machinery skids or base plates, shall be supplied by the rotating equipment Manufacturer for new machinery installations and shall be as indicated on the rotating equipment data/requisition sheets. All supplied systems shall comply with DEP 32.01.20.10-Gen. for communications infrastructure, API 670 for machinery protection systems, and DEP 32.31.00.32-Gen. and DEP 32.31.09.31-Gen. for instrumentation.

For new installations, the responsibility for this system and the integration of this system in the plant instrumentation shall be included in the scope of the main instrumentation Contractor/Vendor. As a result of this, ownership of and maintenance responsibility for the system shall be vested with the instrumentation maintenance/engineering discipline in the plant.

Because the plant Rotating Equipment Engineering Department (or equivalent RE Support Team) has first priority in the use of this system, the PC-based central data collecting and/or processing unit shall be connected to the Department's location for data access. System data for day-to-day operational personnel use shall be routed to the operations supervising panels in the Central Control Room (Plant Control Room). As access to instrumentation FARs (or equivalent) is frequently restricted, any FAR-installed parameter monitors shall be of the "blind type" and relay all data to the central processing and database of the system.

2.4 OFF-LINE MONITORING

Off-line monitoring differs from on-line monitoring in that the parameters are measured on an intermittent time basis and not collected automatically. The main reason for this intermittent measurement is that it is either not necessary for the parameters to be measured continuously or it is not economically viable to monitor the subject machines on a continuous basis. As an example, oil sampling on a given machine might be conducted on a monthly basis even though the vibration measurements are taken continuously on-line.

Off-line systems shall consist of a portable data collecting system and a central data processing and storage system. The supplied systems shall comply with the requirements of DEP 32.01.20.10-Gen. for communications infrastructure and data security and DEP 32.31.00.32-Gen. for instrumentation. The data collecting system shall consist of one or more portable vibration measurement and data collectors, which shall comply with the following general requirements:

1. They shall be programmable and flexible in their configuration of data points to be measured and the complexity of data to be taken.
2. They shall be suitable for all specified ambient conditions in which they are used and comply with all applicable electrical area classification requirements. The data collectors shall be intrinsically safe.
3. They shall be suitable for use by personnel equipped with appropriate PPE e.g. goggles, gloves etc. Their size should not restrict mobility of personnel.
4. They shall be resistant to ingress of dirt, rain and dust expected in the specified environment and ambient conditions (minimum IP 54).
5. The data collectors shall have provisions to collect data from process related parameters and to store such data for further processing. Manual inputting (keypad entry) of such data into the data collector shall also be possible.
6. The data collectors shall have provisions to allow on the spot analysis of the measured data without the need to connect to the central data processing and storage system.
7. The data collectors shall have facilities to download their collected data into a central processing and storage system directly and updated and re-loaded with additional programming automatically.
8. The central data processing and storage system for off-line condition monitoring shall have the same fundamental analysis features as the on-line system. This can be the same system as used for the on-line condition monitoring system although this is not mandatory.
9. For measurement repeatability, all machines identified for off-line condition monitoring shall have measurement locations clearly identified and appropriately prepared for the measurement type.

The off-line system's data collector shall also comply with the following specific requirements:

- a) Live display of current overall measurement values prior to acceptance for storage.
- b) Display of previous reading for comparison with currently collected value.
- c) Display of all valid Alarm values for a currently collected measurement.
- d) Battery life for continuous use for a nominal shift (8 hours minimum).
- e) Collection of vibration signals natively from accelerometers, velocity probes and displacement probes.
- f) Display of vibration readings in units of acceleration, velocity and displacement with values of r.m.s., peak and peak-peak.
- g) Display of all measurements in user selectable metric or imperial (US customary) units.
- h) Collection of process parameter signals from sensors with common voltage, current and charge outputs (e.g. 0 to 5 V, 4 to 20 mA, 0 to 24 V, -15 to 0 V, etc).
- i) Collection of data from on-line condition monitoring/safeguarding racks (via buffered outputs in accordance with API 670).
- j) Capability to connect auxiliary probes such as infra red temperature devices, oil monitoring probes, etc.
- k) Separate phase trigger input.
- l) Amplitude autoscale.
- m) Spectrum display (minimum 400 lines, maximum at least 6400 lines).
- n) Selectable frequency ranges up to at least 20 kHz.
- o) Selectable resolution.
- p) True zoom (10 x zoom around any cursor frequency selected).

- q) Waterfall plots.
- r) Phase angle.
- s) Time waveform display.
- t) Windowing functions.
- u) Averaging.
- v) Enveloping measurements.
- w) Band alarms.
- x) Point naming minimum 20 characters (capable of accepting standard tag numbering).
- y) Multiple route upload and download capability.
- z) All data to be time stamped, synchronised with the plant master clock.

In addition to the above, the off-line system's software shall also comply with the following specific requirements:

- Compatible with Microsoft Windows Operating System
- Capable of and compatible with data export to the Shell Group's standard DCS systems (Honeywell, Yokagawa, Emerson), data historians (OSI's PI, Honeywell's PHD) and SAP.
- Capable of and compatible with data import from the Shell Group's standard DCS systems (Honeywell, Yokagawa, Emerson) and data historians (OSI's PI, Honeywell's PHD).
- Capable of and compatible with data imports from 3rd party data sources e.g. Oil analysis lab data, Excel spreadsheets etc. (via suitable drivers if required).
- Trend plots including multiple parameters (at least 10) and trend extrapolation.
- Baselines.
- Comparison of data from different machines.
- Scalar and spectral data storage for minimum 10 years for all measurement points.
- Capable of structured hierarchical plant configuration to enable logical data retrieval.
- Data collection routes.
- Data collection route scheduling.
- Remote data collector upload and download via modem or similar.
- Automatic comparison of all new data against reference baseline data (including spectra) and against all configured Alert/Danger limits and automatic presentation of excursions.
- Auto report generation capabilities.
- All data to be time stamped, synchronised with the plant master clock.

2.5 TRIBOLOGY-BASED CONDITION MONITORING

2.5.1 General

A tribology-based condition monitoring program can provide important information about the mechanical health of rotating equipment. Such a monitoring program enables the detection of potential problems and forewarns the user to act prior to excessive mechanical damage or failure. Monitoring is performed by taking oil samples on a periodic basis, with analysis by competent in-house staff or an approved laboratory.

Tribology-based condition monitoring and diagnostics can be broadly categorised as consisting of two methodologies which are:

- particulate-based condition monitoring (also referred to as equipment condition monitoring)

based on oil debris analysis); and

- lubricant/working fluid condition monitoring (typically known as oil condition monitoring) .

NOTE: Condition monitoring by analysis of oil samples (tests, sampling methods, sampling frequencies, cleanliness levels etc.) should be conducted in accordance with ISO 14830-1 and ISO 17359.

2.5.2 Particulate-based condition monitoring

Should be conducted in accordance with ISO 14830-1 and ISO 17359.

2.5.3 Lubricant/working fluid condition monitoring

As a minimum for acceptable lubricant quality, the oil samples should be analysed for water content, flash point, wear metals (lead, copper, tin, iron etc.), colour / visual appearance, rust, foaming, viscosity at 40 °C and 100 °C, TAN, (TBN for diesel engines), RBVOT and degradation index. In the absence of suitable acceptance criteria in appropriate ISO standards, OEM guidelines shall be sought. Typical values for Turbo GT 32 and other Turbo oils are given in Appendix E.

2.6 CONDITION MONITORING PARAMETERS

According to the criticality ranking of specific equipment, on-line condition monitoring is required for equipment in essential non-spared service and other equipment deemed to require it. The objective of this monitoring is to obtain a detailed performance and mechanical behaviour database of the respective machinery to optimise planned maintenance and to maximise availability and reliability. Appropriate data shall be collected and stored for subsequent analysis and troubleshooting. Typical equipment monitored includes all axial and centrifugal compressors and their drivers (incl. gearboxes), gas turbines and steam turbines in mechanical drive applications as well as generator drive applications, reciprocating compressors, screw compressors, non-spared high pressure pumps (e.g. Hydrocracking Unit, Hydro De-Sulphurisation Unit process pumps, high-pressure boiler pumps, export pumps, water injection pumps) and electrical motors.

The **mechanical** and selected **process parameters** of the equipment shall be monitored in order to assess performance and mechanical integrity, and enable optimum equipment operation. Process parameters are shown in *italics*.

Unless otherwise specified, the minimum mechanical and process parameters to be monitored by the condition monitoring system are listed below for the main types of rotating equipment in accordance with the indicated standards:

Axial and Centrifugal Compressors: (DEP 31.29.40.10-Gen.)

Radial shaft vibrations

Axial thrust position (Axial displacement)

Phase angle (Keyphasor)

Journal bearing temperatures

Thrust bearing temperatures

Compressor speed (for variable speed drives)

Seal performance parameters

Lube oil pressure and level

Oil filter differential pressure

Tribology-based parameters

Compressor section inlet, interstage and outlet pressures, temperatures and flows

Recycle data such as surge parameters

Molecular weight of the process gas.

Liquid level in inlet separator(s)

Additional parameters for monitoring

Casing vibration

Torque (for mechanically driven compressors)

Power or current (for electrically driven compressors)

(If installed) Suction strainer differential pressure

Reference gas and balance gas pressure

Periodic performance assessments should be carried out to help determine the overall compressor condition, and thus the possible need for a scheduled overhaul and/or washing. Fouling of impellers and discharge volutes will reduce throughput, as will excess leakage across labyrinth seals. Monitoring of leakage rates across interstage labyrinths on back-to-back compressors is especially important, as excessive leakages can lead to significant performance losses. The best way to monitor this is to compare the current performance of the machine against the performance data of the machine in new condition and/or to rely on the Manufacturer's compressor test data. The primary indicators of oil film seal degradation are an increasing/decreasing oil flow and reducing seal oil flash point value. Flow and flash point values can be trended and give a good indication of the condition of seal performance, alerting the operator before the contaminated seal handling facilities become overloaded.

Reciprocating Compressors: (DEP 31.29.40.31-Gen.)

Main Bearing Temperatures

Crosshead Acceleration/Crankcase acceleration/Frame vibration

Rod position (rod drop) monitoring devices (for machines < 200mm stroke only if appropriate)

Provisions for P-V diagram analysis

Piston rod packing leakage

Suction and discharge valve temperature measurement (online)

Lube oil pressure and level

Oil filter differential pressure

Jacket water system failure

Tribology-based parameters

Cylinder pressure

Suction and discharge pressure and temperature per stage

Compressor flow per stage

Recycle flow rate

Liquid level in suction separator

Additional parameters for monitoring

Phase angle (Keyphasor)

Cylinder/packing lube oil flow

Gas turbines: (DEP 31.29.70.31-Gen. and DEP 31.29.70.11-Gen.)

Engine casing vibration

Radial shaft vibrations (where appropriate)

Axial thrust position/Axial displacement (where appropriate)

Journal bearing temperatures (where appropriate)

Thrust bearing temperatures (where appropriate)

Inlet air filter pressure drop (differential pressure)

Exhaust temperatures and exhaust temperature spread

Lube oil and hydraulic oil pressure

Tribology-based parameters

Power turbine 1st stage inlet nozzle temperature

Exhaust plenum pressure

Speed (GP and PT)

Power (via torque meter)

Compressor inlet and outlet pressure and temperature

Fuel gas flow and Wobbe index

Wheel space temperatures

Fuel control valve position

Fuel gas scrubber level

Lube oil tank level

Additional parameters for monitoring

Phase angle (Keyphasor)

Variable guide vane position (where applicable)

Hours run, number of starts and fired starts

Centrifugal pumps: (DEP 31.29.02.30-Gen.)

Radial shaft vibrations (plain bearing machines)

Axial thrust position (plain bearing machines)

Phase angle (Keyphasor)

Journal bearing temperatures (plain bearing machines)

Thrust bearing temperatures (plain bearing machines)

Tribology-based parameters

Suction and discharge pressure

Pump flow

By-pass flow

Additional parameters for monitoring

Pump speed

(If installed) Suction strainer differential pressure

Balance pressure (support thrust balance line flows for multistage high pressure pumps)

Liquid expanders:

Vibration

Tribology-based parameters

Speed

Inlet and outlet flow

Power generated

Inlet Guide Vane position (if applicable)

For both centrifugal pumps and liquid expanders, the purpose of monitoring the above parameters is to obtain information allowing the operator to assess performance, including efficiency losses, and thus provide input to the maintenance schedule.

Steam turbines: (DEP 31.29.60.30-Gen. and DEP 31.29.60.31-Gen.)

Radial shaft vibrations

Axial thrust position (Axial displacement)

Journal bearing temperatures

Thrust bearing temperatures

Tribology-based parameters

Steam inlet, extraction and outlet (exhaust) pressures and temperatures

Speed

Wheel chamber pressure

Steam flow

Bearing temperature and labyrinth seal leakage.

Additional parameters for monitoring

Phase angle (Keyphasor)

Casing vibration

Inlet valve position

Monitoring of the 1st stage wheel chamber pressure is important, as this provides information for assessing and planning overhaul intervals (e.g. loss of labyrinth clearances) and also provides details on the degree of fouling inside the steam turbine.

In a condensing steam turbine, monitoring of the steam condition at the outlet section is important, as erosion damage may lead to premature blade failures. Determining the actual outlet conditions, particularly the steam wetness, of the steam turbine is difficult. Trending of the inlet and exhaust conditions and comparing these to data taken under new and clean conditions at different operating points of the turbine is therefore the best method of monitoring any deterioration in performance.

Generators/Alternators/Motors: (DEP 33.66.05.31-Gen., DEP 33.65.11.32-Gen., NEMA MG 1, IEC 60034-1, IEC 60034-14)

Radial shaft vibrations

Axial thrust position (Axial displacement)

Journal bearing temperatures

Thrust bearing temperatures

Winding temperatures

Current

Voltage

Tribology-based parameters

Speed

Frequency

Additional parameters for monitoring

Phase angle (Keyphasor)

Winding high frequency discharge for motors/generators > 6.6kV (e.g. by Rogowski coils in switchgear)

RIC Diesel Engines: (DEP 31.29.80.30-Gen.)

Lube oil temperature and pressure

Engine coolant temperature

Pressure drop across lube oil filter and across air filter

Lube oil level and Engine coolant level

Air filter oil bath level

Fuel day tank level

Tribology-based parameters

Speed

P-V diagram

RIC Gas Fuelled Engines: (DEP 31.29.90.30-Gen.)

Lube oil temperature and pressure

Engine coolant temperature

Pressure drop across lube oil filter, air filter and fuel gas filter

Lube oil level and Engine coolant level

Air filter oil bath level

Fuel gas pressure

Tribology-based parameters

Speed

P-V diagram

Gearboxes: (DEP 31.29.00.32-Gen. and ISO 13691)

Radial shaft vibrations (plain bearing machines)

Axial thrust position/Axial displacement (plain bearing machines)

Bearing housing vibrations (rolling element bearing machines)

Journal bearing temperatures (plain bearing machines)

Thrust bearing temperatures (plain bearing machines)

Casing vibration (acceleration for Gear Mesh Frequencies)

Tribology-based parameters

For additional detailed information by machine type, refer to Appendix F.

For additional detailed information on SmartConnect implementation, refer to Appendix G.

For other types of rotating equipment in essential services the requirements for condition monitoring shall be discussed and agreed with the Principal.

3. ROTATING EQUIPMENT SAFEGUARDING PHILOSOPHY

3.1 INTRODUCTION

The prime reason for protecting and safeguarding rotating equipment is to prevent or limit the damage to this equipment in the event of malfunction. This approach also avoids or significantly limits consequential damage to the environment, minimises potential hazards for people, prevents damage to adjacent equipment and minimises significant lost revenue for the plant.

The type of protection to be applied depends largely on the type of equipment. The main protection is against operating the equipment outside its integrity and performance design envelope, mainly in relation to process conditions; e.g. high discharge temperature. For several types of such equipment this protection is defined according to ISO and API standards. A safeguarding system shall be classified according to its SIL by means of an independent IPF/SIF analysis in accordance with DEP 32.80.10.10-Gen.

Vibration and bearing temperature protection forms a specific category of equipment protection. These types of protection serve the purpose of preventing severe equipment damage, costly repairs and unavailability of the equipment.

3.2 FUNCTIONAL REQUIREMENTS FOR SAFEGUARDING SYSTEMS - GENERAL

This part provides functional requirements for the design of safeguarding systems for essential rotating equipment, either spared or non-spared, in continuous operation, in refineries, chemical plants, exploration & production facilities, LNG & NGL plants, power generation plants and oil & gas services. The underlying presumption is that adequate operational attention is paid to machinery in service and that correct pre-start checks are carried out prior to putting machines into operation.

In contrast to the above, packaged units incorporate a dedicated control and safeguarding system instead of being integrated in the overall plant safeguarding and DCS systems. Typically, gas turbine driver packages are equipped with such dedicated systems, which often feature the "single start/stop button" design and, as such, need a different design approach for the inclusion of start permissive, alarm and shutdown functions. In plants with remote operation and/or operation by relatively unskilled personnel, the machines shall self-protect as far as is possible.

This part does not include the instrumentation hardware and software requirements for the actual execution of a machine safeguarding system. However, in general, safeguarding instrumentation should execute all necessary signal integrity checks to avoid incorrect alarming and/or shutdowns.

3.2.1 Machine Alarm and Shutdown Functions

Machine safeguarding shutdown functions or "trips" are required on rotating equipment to prevent serious failures of one or more of its components and the related potential hazard to personnel or environment. They also serve to limit consequential damage due to a component failure, such as rotor/stator damage as a result of a thrust bearing failure.

The decision to install trip functions shall be based on an IPF analysis and should include the recommendations of a HAZOP study and recommendations of the OEM. DEP 32.80.10.10-Gen shall be used to justify protective functions and to define their implementation and test intervals.

Machine trip functions are required for those measured parameters which, upon exceeding a certain pre-determined value, do not allow sufficient time and/or opportunity for corrective action by an operator to prevent a machine or component failure and damage. An example is the occurrence of low lube oil supply pressure, which requires an immediate shutdown of the equipment. Machine trip functions shall also be required if operating personnel will not be able to adequately assess the possible negative effects of a changing parameter.

If an IPF study allows, measured parameters other than the above shall be provided with an alarm function, indicating that corrective action is required. If this action does not restore acceptable conditions, operational personnel can then initiate a manual shutdown before the equipment is shut down by another trip function. As an example, high temperature of the lube oil supply to an equipment item will not cause immediate failure. A corrective attempt can be made to improve oil cooling before the decision is taken to shut down the equipment.

Use of the IPF methodology should avoid unnecessary machine trips. The number of trip functions of an equipment item has a direct impact on its total availability and reliability (the more trip functions, the more potential trips). Moreover, each trip function needs maintenance and attention, thus increasing costs. To mitigate risk of unwarranted trips (sometimes referred to as nuisance trips), trip voting and redundancy is applied (in US as recommended by a SIFPRO analysis).

Trip functions shall be active under all conditions and shall be cleared only by correcting the initiating parameter. As such, they automatically serve as start permissive. Exceptions to this rule should only be considered if trip functions cannot be cleared without the equipment or part of it being in operational condition. In this case, timed override functions may be applied, which, apart from facilitating a proper start, also ensure an automatic return of the overridden trip function to its normal active status. Alternative start up override functions shall be subject to the approval of the Principal.

The loss of a non trip related function and/or a status indication in a safeguarding logic shall not result in the equipment's shutdown, unless that loss jeopardises the integrity of the equipment which is served by the logic.

3.2.2 Start Permissive Functions

Start permissive functions are required for rotating equipment only if the equipment will immediately fail upon or during the start if certain pre-start conditions are outside the set values. As such, all trip functions are normally start permissive.

Alarm functions shall not be start permissive, as the measured parameter will not cause immediate equipment failure if it is outside the set value. In principle good operational practice and discipline require operating personnel to ensure that all alarms are cleared and corrected before machines are started. In this connection it is important that alarm values are set at realistic values in order to avoid false alarms as much as possible.

NOTE: In certain remotely installed and/or unmanned installations with minimum operational attention, the start-up sequence of rotating equipment shall include a number of start permissives based on various alarm functions in order to automatically verify that the equipment is ready to start.

Start permissive functions, which are not trip functions during operation of the equipment, shall be made inactive after start of the equipment. They shall never be allowed to cause a shutdown of the main equipment.

3.2.3 Requirements for Oil Supply Systems

Oil pumps, either lube/control/hydraulic oil or seal oil pumps, may be started automatically by the safeguarding logic and/or the DCS alarm system. However, they should never be stopped automatically as this could result in serious equipment damage. Only in dedicated, fully automated, start-up and shutdown systems for gas turbines may the automatic shut down of oil pumps be considered.

The start-up of oil pumps that are expected to start automatically upon an alarm signal from a measured parameter shall never be inhibited or prevented by other non-related functions, such as the running status of the equipment they serve. The only allowable start prevention is the physical lock-out of the electric motor RCU or the isolation of the electrical motor breaker in the electrical supply system.

Low oil pressure alarm and shutdown settings shall have a difference of at least 0.8 bar between the low alarm and shutdown. Lower differences are specifically subject to approval by the Principal.

Low oil pressure shutdown functions shall be activated immediately i.e., without any delay in the shutdown system.

The low level alarm and low temperature alarm of the main oil reservoir shall not be used as a permissive for starting the oil supply pumps. Any other start permissive for oil pumps, e.g. adequate nitrogen supply pressure to compressor dry gas shaft seals, shall be made inactive after the start of the main equipment and not return to active status until the main equipment has come to a full stop.

Lube/control/hydraulic and seal oil systems shall be in accordance with DEP 31.29.60.32-Gen.

3.3 MACHINE RELATED ALARM & SHUTDOWN FUNCTIONS, PHILOSOPHY & SETTINGS

3.3.1 Vibration measurement

Rotating equipment, mainly turbo machinery, is provided with vibration measuring devices for shaft displacement, casing or bearing housing velocity or acceleration measurements, primarily for the purposes of on-line condition monitoring. The mechanical integrity of the equipment can be monitored on-line, while the equipment is in operation. This will provide important information on the condition of equipment, whether a failure is developing and at what time in the future this may occur, i.e. trending of signals.

For major equipment in vital and essential service, i.e. equipment that is usually not spared and equipment for which repairs are costly and may require long downtimes, vibration alarms and trips are typically incorporated. Generally this applies to: gas turbine drivers, large steam drivers, centrifugal and axial compressors, expanders and high pressure pumps, and high speed or high shaft power gearboxes.

The transducer and monitor system accuracy shall be in accordance with API 670 Table 1 unless indicated otherwise.

3.3.2 Radial shaft displacement – Alarm setpoints (general)

Alarm settings shall be established in a similar fashion to radial shutdowns (see below). However, they are set at lower levels to indicate a significant change in the vibration state of a machine moving towards the shutdown state.

Alarms shall be raised and subsequent action taken to prevent machine damage.

A vibration alarm set point shall be at double the normal vibration levels when the machine is known to be in a good operating condition (or 25 μm above normal operating vibration levels, whichever is least). Alarms should be single voting. In order of preference, the normal vibration levels should be established by:

- 1) Historical data based upon equipment performance and integrity.
- 2) Test stand mechanical run data.
- 3) Allowable amplitude

$$A = 25.4 \sqrt{12000 / n}$$

where

A is the allowable amplitude (unfiltered peak to peak), in μm .

n is the maximum continuous speed, in r/min

- 4) Vendor data, e.g. for high speed integrally geared air compressors.

Alarm setpoints should be set sufficiently high that they are activated infrequently and indicate an unusual condition which an engineer knowledgeable about the machine would want to know about. Any change of alarm setpoints shall require a Management of Change process.

3.3.3 Radial shaft displacement – Shutdown setpoints (general)

Shutdown settings shall be established as a trade-off between protection against major incidents and the possibility of unwanted shutdowns.

Once the shutdown level is reached, the option to keep the machine running will no longer exist, in terms of protecting the machinery. Radial shutdowns should be dual voting as default, although single voting is acceptable where operational experience so indicates.

Shutdown settings should be selected to prevent failures. With appropriate shutdown settings the risk of the following types of incidents will be reduced to the minimum:

- Loss of containment in the machine or of the integrity of main casing/bearing housings.
- Potential safety related or environmental incidents.
- Secondary material damage to unit facilities from machine components.
- Failures that will keep the machine down for extended periods, e.g., those requiring rotor replacement or refurbishment, or entailing damage to the casing or stationary components.

A typical radial trip is established by API specifications. To prevent premature bearing failure, shutdown vibration levels should be limited to 75 % of the minimum diametrical bearing clearances.

3.3.4 Radial shaft displacement – Alarm and trip functions per machine type

3.3.4.1 Centrifugal compressors

Centrifugal compressors equipped with non-contact displacement probes are normally provided with dual alarm levels (high, H and high-high, HH) to alert operational personnel to take specific actions. Typical actions include, but are not limited to:

- On H alarm the rotating equipment engineer or maintenance department is alerted that a significant change in vibration level has occurred and that further analysis is required prior to a possible shutdown of the equipment. In addition, operating conditions may be changed (e.g. a lower speed or load) in an attempt to reduce the vibration level. If the levels continue increasing, preparatory action shall be taken for a controlled equipment and plant shutdown and appropriate staff shall be alerted (e.g. rotating equipment engineering department, maintenance department, asset support team, etc).
- HH level is used to trip the machine unless an IPF review has indicated otherwise.

Therefore:

Probes with alarm function:

- All centrifugal compressors

However, high radial vibration shutdown functions on centrifugal compressors shall be provided if one or more of the following conditions apply (irrespective of an IPF review):

- A compressor suction pressure of more than 200 bar.
- A compressor with an average power density of more than 5 MW per impeller.
- A remote not normally manned installation.
- An installation where the possibilities for operational intervention to assess and act on vibration alarms in a timely manner are minimal or non-existent.
- Existing installations, where historically auto shutdown functions are provided for machinery.

The shutdown function on radial vibration shall be triggered by a two out of two (2oo2) voting of the X and Y probes of the bearing or, if deemed necessary for the subject machine, a two out of four (2oo4) voting of radial probes, i.e. two X or two Y probes of both radial bearings or

an X and Y probe from each radial bearing.

High radial vibration shutdown functions on other centrifugal compressors should be provided. Trip voting configurations as above.

3.3.4.2 Rotary compressors

The same requirements as for centrifugal compressors apply for rotary positive displacement compressors if they are equipped with displacement probes for radial vibration measurement.

In general, however, these types of compressors are equipped with accelerometers or velocity pick-ups rather than displacement probes and hence such instruments only initiate alarms if vibration measurements are employed.

Probes with Alarm Function:

- all rotary compressors

Trip Function:

- generally not applied for accelerometers or velocity pickups

The allowable vibration limits shall be as given in Table 1.

Table 1 Allowable vibration limits

		Hydrodynamic journal bearings	Antifriction bearings
Measurement on bearing housing	Vibration at any speed within the operating range: Overall Discrete frequencies	$V_u < 5 \text{ mm/s RMS}$ $V_f < 2.8 \text{ mm/s RMS}$	$V_u < 8 \text{ mm/s RMS}$ $V_f < 4.5 \text{ mm/s RMS}$
	Increase in allowable vibration at speeds beyond operating speed but less than trip speed	20 %	20 %
Measurement on shaft adjacent to bearing	Maximum unfiltered peak-to-peak vibration at any speed within the operating range	63 μm	-
	1 x running speed component	30 μm	
	Increase in allowable vibration at speeds beyond operating speed but less than trip speed	20 %	
where: V_u = unfiltered velocity V_f = filtered velocity at discrete frequencies RMS = root mean square			

3.3.4.3 Axial compressors

For axial compressors in low-pressure air service, such as in Fluid Catalytic Cracking units, the same rules apply as for centrifugal compressors.

For axial compressors in LNG refrigerant service and for axial compressors of a size that is unprecedented in the Group, the radial vibration monitoring/protective functions are more restrictive during the initial period of operation. For these compressors the following requirements apply:

- During the start-up cycle of the compressor, the HH level of a single radial vibration

probe, either X or Y, will cause a shutdown.

- After the starting sequence has been completed, the shutdown function will remain. However, it shall be triggered by a two out of two (2oo2) voting of the X and Y probe per bearing or, if deemed necessary for the subject machine, a two out of four (2oo4) radial probes, i.e. two X or two Y probes of both radial bearings or an X and Y probe from each radial bearing.

3.3.4.4 Special-purpose steam turbine drivers

The same requirements as for centrifugal compressors apply for special-purpose steam turbines, if they are equipped with non-contacting displacement probes for radial vibration measurement.

Special purpose steam turbines are always equipped with vibration probes.

Probes with Alarm Function:

- All special purpose steam turbines

Trip Function:

- All special purpose steam turbines
- Radial vibration shutdown functions shall be applied in all situations

Radial vibration shutdown functions should be applied for all other steam turbines unless an IPF review has indicated otherwise.

3.3.4.5 Gearboxes

In accordance with ISO 13691, the same requirements as for centrifugal compressors apply for high speed gearboxes if they are equipped with non-contacting displacement probes for radial vibration measurement.

Vibration shutdown functions should be applied for all other high speed gearboxes unless an IPF review has permitted otherwise.

ISO 13691:2001, Clause 5.6.3.1, states allowable vibration limits for non-contacting probes as:

the overall unfiltered peak-to-peak amplitude of vibration, including run-out, in any plane measured on the shaft adjacent and relative to each radial bearing shall not exceed the following value, or 50 µm, whichever is the lower:

$$A = 25.4 \sqrt{12000 / n}$$

where:

A is the amplitude, in µm

n is the maximum continuous speed, in r/min.

If specified instead of displacement probes, accelerometers are fitted on the gearbox housing and shall be provided with alarm and shutdown functions. Limits for casing vibration (ISO 13691:2001, Table 9) are given below.

Measurement condition	Frequency range	
	10 Hz to 2.5 kHz	2.5 kHz to 10 kHz
	Vibration levels	
	Velocity [mm/s] (rms)	Acceleration (peak)

Unfiltered	4.0	$4 \times G$
Filtered component	2.5	-
NOTES: 1. These values shall apply for both horizontal and vertical off-set designs. 2. G is the gravitational constant.		

3.3.4.6 Centrifugal multi-stage pumps

Centrifugal multi-stage high power pumps (> 1 MW) and pumps in non-spared essential service, which are equipped with non-contacting displacement probes for radial vibration measurement, are subject to the same requirements as for centrifugal compressors.

Probes with Alarm Function:

- Multi-stage pumps in applications above 1MW

Trip Function:

- Should be applied unless an IPF review has indicated otherwise.

3.3.4.7 Integrally Geared Single & Multistage Compressors & Cryogenic Expanders

Integrally geared compressors and high speed cryogenic expanders feature high to very high pinion rotor speeds and can be vibration sensitive, such that serious component damage may occur in a short time upon the onset of high vibration. For this reason these machines shall be fitted with high radial vibration shutdown functions on the high speed rotor(s) and an alarm function only on the low speed rotor.

Because of size and design constraints, it may not always be possible to utilize dual radial probes on this class of machine. Dual probes are recommended but single probes may be used, subject to the approval of the Principal.

As the damage that can occur to this type of machinery may happen faster and be of more serious nature than in between-bearing machines, radial and axial alarm and shutdown levels are set at more conservative levels. The Manufacturer's recommended level is normally the acceptable level.

Probes with Alarm Function:

- On high and low speed rotor

Trip Function:

- On high speed rotors only

3.3.4.8 General-purpose steam turbines

There are few applications of general purpose steam turbines where displacement probes are provided. One such application is the integrally geared design steam turbine where the turbine wheel is directly mounted on the high speed shaft (HSS). For such applications it is common practice to equip the HSS with two probes, one near each radial bearing, with one probe providing the X-function and the other probe providing the Y-function. Although this installation does not provide the capability of performing a full vibration analysis it will provide the measurements for trending purposes.

Probes with alarm function:

- In general no probes, but if they are provided then alarm only
- Only for integrally geared designs

Trip function:

- Generally not applied unless indicated by an IPF review
- HH alarm levels apply as indicated below

The overall unfiltered peak-to-peak amplitude of vibration, including run-out, in any plane measured on the shaft adjacent and relative to each radial bearing shall not exceed the following value or 50 µm, whichever is the lower:

$$A = 25.4 \sqrt{12000 / n}$$

where:

A is the amplitude, in µm

n is the maximum continuous speed, in r/min.

Where casing vibration sensors are used, the unfiltered root mean square vibration velocity, measured on the bearing housing in any plane, shall not exceed 3 mm/s.

3.3.4.9 Hot gas expanders

Hot gas expanders are often part of a complete Power Recovery Train in a FCCU and, as such, shall be subject to the same requirements as the compressor and driver in the train. If they are in a separate power recovery configuration, they shall also follow the same requirements as set for the main compressor equipment in the plant.

3.3.4.10 Generator/alternators

Generators/Alternators equipped with non-contact displacement probes are normally provided with dual alarm levels (high, H and high-high, HH) to alert operational personnel to take specific actions. Typical actions include, but are not limited to:

- On H alarm the rotating equipment engineer or maintenance department is alerted that a significant change in vibration level has occurred and that further analysis is required prior to a possible shutdown of the equipment. In addition, operating conditions may be changed (e.g. lower load) in an attempt to reduce the vibration level. If the levels continue increasing, preparatory action shall be taken for a controlled equipment shutdown and appropriate staff shall be alerted (e.g. rotating equipment engineering department, maintenance department, asset support team, etc.).
- HH level is used to trip the machine unless an IPF review has permitted otherwise.

However, high radial vibration shutdown functions shall be provided where one or more of the following conditions apply (irrespective of an IPF review):

- A remote unmanned installation.
- An installation where the possibilities for operational intervention to assess and act on vibration alarms are minimal or non-existent.

Shutdown function on radial vibration shall be triggered by a two out of two (2oo2) voting of the X and Y probes of the bearing or, if deemed necessary for the machine, a two out of four (2oo4) voting of radial probes, i.e. two X or two Y probes of both radial bearings or an X and Y probe from each radial bearing.

3.3.5 Axial displacement philosophy and settings

For major equipment in vital and essential services, i.e. equipment that is usually not spared, and equipment for which repairs are costly and require long downtimes, shaft axial displacement alarms and trips shall be incorporated. Generally this is equipment with hydrodynamic type thrust bearings including gas turbines, large steam turbine drivers, centrifugal and axial compressors, expanders and high-pressure pumps.

Axial displacement probes with their respective alarms and trip functions protect against serious internal damage that could lead to even more extensive consequences if such

alarm/trip functions were not applied. At the value of the axial trip function it is accepted that some damage to the thrust bearing may already have taken place.

In order to ensure high integrity and to avoid unnecessary trips, axial displacement measurements are taken by three probes with a two out of three (2oo3) voting system applied in the safeguarding system. There are, however, systems that still apply a two out of two (2oo2) voting system using a two probe installation. These systems typically provide a lower reliability so should not be used on new equipment or in upgrades.

3.3.5.1 Shaft axial displacement

Shutdown settings are established to prevent contact between rotating and stationary parts that have the potential to cause major economic impact. With shutdown levels defined in this manner, moderate machine damage and in some cases serious machine damage may be experienced if an axial position shutdown takes place.

Shutdown levels should be selected to prevent the most serious failures, such as:

- Loss of containment in the machine or loss of the integrity of main casing/bearing housings.
- Potential safety or environmental incidents.
- Secondary material damage to unit facilities from machine components.
- Failures that will keep the machine down for extended periods, e.g., those requiring rotor replacement or refurbishment, or entailing damage to the casing or stationary components.

Axial displacement measurement of rotors shall be implemented so that adequate redundancy is obtained and on-line changing of alarm and shutdown trip settings is possible (upon completion of a Change Management process). On equipment which has its own thrust bearing and thrust collar this shall be achieved by a two out of three (2oo3) trip voting system.

Two out of two (2oo2) voting systems for axial displacement shutdown functions need the specific approval of the Principal.

Alarm and shutdown settings shall be in accordance with the Manufacturer's recommendations, however the following shall be observed;

- The shutdown setting shall be aimed at preventing major damage to internal components of the equipment and loss of containment.

The preferred method of setting axial position shutdowns is the point at which no more than 50 % of Babbitt thickness is lost on either the active or inactive shoes. In addition, shutdown should occur prior to internal axial contact, e.g., of turbine nozzles or diaphragms (axial alarms shall be set at, or below, where 25 % of the Babbitt has been lost on either side of the thrust pads).

- The axial displacement shutdown shall **not** be delayed beyond the machine shutdown system's minimum unless indicated otherwise by an IPF review.

If the preferred method of setting axial shutdowns does not fall within the linear range of the probe system [usually 2 mm (0.08 in)], an alternative method shall be used.

Appendices B-D summarise the above sections, giving typical examples for plant safeguarding of main rotating equipment at various installations.

3.3.6 Bearing temperature alarm and shutdown philosophy

Bearing temperatures shall be measured by means of thermocouples (TCs) or RTDs in the white metal of the hydro-dynamic bearing of the equipment (journal and thrust bearings) in accordance with standards and DEPs appropriate for that equipment. These measurements are provided with a single or double (H and HH) alarm unless indicated otherwise by an IPF review. Settings shall be provided by the equipment Manufacturer, but shall be realistic

values. Bearing temperatures should be measured (at least one measurement) in or near the loaded zone of the bearing.

Shutdown functions on high bearing temperature shall not normally be installed. An exception to this is the high bearing sump temperature shutdown function in aero-derivative gas turbines, where the measured temperature serves as an indicator of anti-friction bearing distress or failure.

RTDs and TCs are easily damaged during maintenance activities leading to low reliability and, therefore, trip functions are normally not provided. However, thrust temperatures are a particularly valuable protection method, much more sensitive than axial position, so should be applied wherever reliability is not an issue or where indicated by an IPF review.

3.3.7 Overspeed Protection

Expanders, gas turbines and steam turbine drivers shall be equipped with an independent overspeed protection system. A SIL review shall be carried out according to DEP 32.80.10.10-Gen. to determine the appropriate level of protection. A two out of three (2oo3) voting logic shall be applied on electronic overspeed detection systems unless indicated otherwise by the SIL review.

The applied overspeed protection shall be guaranteed and verified by the equipment Manufacturer.

The overspeed protection shall be a separate safeguarding system, and shall not be integral with the speed control system in accordance with DEP 31.29.60.31-Gen. and DEP 31.29.70.31-Gen.

The overspeed protection system shall have an integral gear wheel on the shaft for measurements and shall be monitored from the energy input shaft.

In accordance with DEP 31.29.60.31-Gen. and DEP 31.29.70.31-Gen., multiple shaft turbines shall have individual overspeed protection for each shaft.

The equipment Manufacturer shall outline his overspeed test philosophy (including test facilities up to the expander inlet valve, and/or to the fuel gas trip valve and/or to the main steam trip valve).

3.3.8 Seal protection systems

Overspeed protection described in the section above combined with surge control provides the mechanical containment element of technical integrity of the machine system. The process containment element of technical integrity of the machine system is provided by seal systems which contain and limit any process fluid release. Lube/control/hydraulic and seal oil systems shall be in accordance with DEP 31.29.60.32-Gen. and DEP 31.29.40.30-Gen.

3.3.9 Reciprocating compressors

Due to the reciprocating nature of this compressor, alarm and shut down functions differ widely from normal centrifugal rotating equipment as described above, and as such no similarities can be directly drawn.

Reciprocating compressors shall be protected for the following parameters:

Description	Alarm	Trip
Lube oil low pressure.	yes	yes
Lube oil high temperature	yes	no
Lube oil low level	yes	no
Lube oil filter differential pressure	yes	no
Main bearing temperatures.	yes	no

Rod position (rod drop) monitoring for rider ring wear.	yes	no ⁽¹⁾
Cross-head / crank case vibrations (accelerometers).	yes	yes, with a 5 s delay
Suction temperature.	yes	no
Discharge temperature.	yes	yes
Suction pressure low	yes	yes
Discharge pressure high	yes	no
Differential pressure per stage	yes	yes, after initial stage first at alarm
For cylinder lubricated compressors: cylinder lubricator low pressure or level.	yes	no
Suction and discharge valve cover temperatures (optional)	yes	no
Leakage from packing/ stuffing box (optional)	yes	no
Coolant flow low	yes	no
Gas scrubber level high (if applicable)	yes	yes
⁽¹⁾ "yes" in exploration and production facilities		

4. COMPETENCE AND QUALIFICATIONS OF ANALYSIS STAFF

Using vibration analysis to monitor condition and diagnose faults in machinery is a key activity in predictive maintenance programmes for most industries. Other non-intrusive technologies, including lubricant analysis, infrared thermography, acoustic emission and motor current analysis, are generally used as complementary tools. Companies which have diligently and consistently applied these techniques have experienced a return on investment far exceeding their expectations. However, the effectiveness of these programmes depends on the capabilities of individuals who perform the measurements and analyse the data.

ISO 18436-2 specifies requirements for the training and certification of personnel involved in condition monitoring and diagnostics of machines, both on-line and off-line using the above monitoring techniques. ISO 18436-2 details requirements for personnel involved with vibration data classified in 4 categories of competence (Categories I to IV).

All personnel involved with collecting, monitoring and analysing vibration data shall be competent to a standard of at least Category I (Category II preferred). Senior personnel involved in decisions requiring a machine to continue running in the presence of suspected faults shall be competent to a standard of at least Category II (Category III preferred). Certification of such competence shall be sought.

NOTE: These qualification requirements are not intended to be applied retroactively. Existing staff may be fully competent without the need for such qualifications and those staff may continue to perform these activities if approved by the Principal.

ISO 18436 Parts 3, 4, 5, 6 and 7, specifying requirements for personnel involved in the other technologies (lubricant analysis, infrared thermography etc.), are in preparation by ISO. When these parts are published, they shall also apply. Personnel involved in collecting, monitoring and analyzing such data shall be competent to do so, to a standard equivalent to that of personnel involved with vibration data. Certification of such competence should be sought.

5. REFERENCES

In this DEP, reference is made to the following publications:

- NOTES:
1. Unless specifically designated by date, the latest edition of each publication shall be used, together with any amendments/supplements/revisions thereto.
 2. The DEPs and most referenced external standards are available to Shell staff on the SWW (Shell Wide Web) at <http://sww05.europe.shell.com/standards>.

SHELL STANDARDS

Petroleum and natural gas industries – High-speed special-purpose gear units (amendments/supplements to ISO 13691)	DEP 31.29.00.32-Gen.
Centrifugal pumps (amendments/supplements to ISO 13709)	DEP 31.29.02.30-Gen.
Compressors - selection, testing and installation	DEP 31.29.40.10-Gen.
Centrifugal and Axial Compressors (amendments/Supplements to API 617)	DEP 31.29.40.30-Gen.
Reciprocating compressors (amendments/supplements to API 618)	DEP 31.29.40.31-Gen.
General-purpose steam turbines (amendments/supplements to API Std 611)	DEP 31.29.60.30-Gen.
Special-purpose steam turbines (amendments/supplements to ISO 10437)	DEP 31.29.60.31-Gen.
Lubrication, shaft-sealing and control oil systems and auxiliaries for petroleum, chemical and gas industry services (amendments/supplements to API 614)	DEP 31.29.60.32-Gen.
Combustion gas turbines – Selection, testing and installation	DEP 31.29.70.11-Gen.
Combustion gas turbines (amendments/supplements to API 616)	DEP 31.29.70.31-Gen.
Diesel engines	DEP 31.29.80.30-Gen.
Spark-ignited gas fuelled engines	DEP 31.29.90.30-Gen.
Data Acquisition and Control Architecture (DACA)	DEP 32.01.20.10-Gen.
Instruments for measurement and control	DEP 32.31.00.32-Gen.
Instrumentation for equipment packages	DEP 32.31.09.31-Gen.
Classification and implementation of instrumented protective functions	DEP 32.80.10.10-Gen.
Electrical machines – Cage-induction types (amendments/supplements to IEC 60034-1)	DEP 33.66.05.31-Gen.
Packaged unit a.c. generator sets	DEP 33.65.11.32-Gen.

AMERICAN STANDARDS

Machinery protection systems	API 670
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Issued by:
American Petroleum Institute
Publications and Distribution Section
1220 L Street Northwest
Washington DC 20005
USA

Standard test methods for flash point by pensky-martens closed cup tester	ASTM D 93
Standard test method for kinematic viscosity of transparent and opaque liquids (and the calculation of dynamic viscosity)	ASTM D 445
Standard test method for rust-preventing characteristics of inhibited mineral oil in the presence of water	ASTM D 665
Standard test method for foaming characteristics of lubricating oils	ASTM D 892
Standard test method for acid and base number by color-indicator titration	ASTM D 974
Standard test method for water separability of petroleum oils and synthetic fluids	ASTM D 1401
Standard test method for oxidation stability of steam turbine oils by rotating pressure vessel	ASTM D 2272
Standard test method for determination of water in petroleum products, lubricating oils, and additives by coulometric karl fischer titration	ASTM D 6304

Issued by:
American Society for Testing and Materials
100 Barr Harbor Drive, West Conshohocken
PA 19428-2959
USA

Motors and generators	NEMA MG 1
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Issued by:
NEMA
1300 North 17th Street
Suite 1752
Rosslyn, Virginia 22209
USA

INTERNATIONAL STANDARDS

Rotating electrical machines – Part 1: Rating and performance	IEC 60034-1
Rotating electrical machines – Part 14: Mechanical vibration of certain machines with shaft heights 56 mm and higher – Measurement, evaluation and limits of vibration severity	IEC 60034-14

Issued by:
Central Office of the IEC
3, Rue de Varembe
CH 1211 Geneva 20
Switzerland

Copies can also be obtained from national standards organizations.

Vibration and shock – Vocabulary	ISO 2041
Hydraulic fluid power – Fluids – Method for coding the level of contamination by solid particles	ISO 4406

Condition monitoring and diagnostics of machines – Vocabulary	ISO 13372
Condition monitoring and diagnostics of machines – Vibration condition monitoring - Part 1: General Procedures	ISO 13373-1
Condition monitoring and diagnostics of machines – General guidelines on data interpretation and diagnostics techniques	ISO 13379
Petroleum and natural gas industries – High-speed special-purpose gear units	ISO 13691:2001
Condition monitoring and diagnostics of machines – General guidelines	ISO 17359
Condition monitoring and diagnostics of machines – Tribology-based monitoring and diagnostics – Part 1: General guidelines	ISO 14830-1
Condition monitoring and diagnostics of machines – Requirements for training and certification of personnel	
– Part 2: Vibration condition monitoring and diagnostics	ISO 18436-2
– Part 3: Requirements for training bodies	ISO 18436-3 *
– Part 4: Lubrication management and analysis	ISO 18436-4 *
– Part 5: Thermography	ISO 18436-5 *
– Part 6: Diagnostics and prognostics	ISO 18436-6 *
– Part 7: Condition monitoring specialists	ISO 18436-7 *

* In preparation

Issued by:
ISO Central Secretariat
1, ch. de la Voie-Creuse
Case postale 56
CH-1211 Genève 20
Switzerland

Copies can also be obtained from national standards organizations.

APPENDIX A DEFINITIONS AND EXAMPLES OF VITAL, ESSENTIAL AND NON-ESSENTIAL SERVICES

	SAFETY EQUIPMENT	OTHER EQUIPMENT		
	SERVICE CATEGORY			
	VITAL	ESSENTIAL		NON-ESSENTIAL
		Non-spared equipment	Spared equipment	
Definition	A service in which failure of equipment causes an unsafe condition of the plant or installation resulting in jeopardy to life and/or major damage (fire, explosion etc.).	A service in which failure of equipment renders a plant or process unit inoperable or reduces performance to a level unacceptable to the Principal.	A service in which failure of equipment renders a plant or process unit inoperable or reduces performance to a level unacceptable to the Principal.	All other services.
Selection Criteria	Equipment shall be adequately spared to ensure 100 % availability of the service under all circumstances	A decision not to install spare equipment is based upon economic considerations and proven equipment availability. Non-spared equipment availability may be upgraded by means of additional Capex to match required plant availability.	Installed spare equipment is normally selected where potential losses due to equipment outage greatly outweigh equipment Capex. Sparing philosophy shall be economically evaluated and is typically 2x100 % or 3x50 %.	Economic evaluation required to justify spared equipment.
Driver Selection Criteria	Independent power sources shall be selected to ensure 100 % service availability		Independent power sources may be selected, for start-up and utility availability reasons	
Examples	- <i>firewater pumps with diesel and motor drives;</i> - <i>ESD systems;</i> - <i>Emergency Instrument Air compressor.</i>	- <i>Hydrocracking Unit feed pump;</i> - <i>Hydrocracking Unit recycle compressor;</i> - <i>Fluid Catalytic Cracking Unit main air compressor;</i> - <i>Feed Draught and Induction Draught fans;</i> - <i>Export gas compressor.</i>	- <i>Boiler Feed Water pumps;</i> - <i>fractionator bottom pumps;</i> - <i>fresh gas compressors (Hydrocracking Unit);</i> - <i>Main oil line pump.</i>	- <i>drinking water pumps;</i> - <i>sewage pumps.</i>

**APPENDIX B TYPICAL VIBRATION AND TEMPERATURE BASED SAFEGUARDING
APPROACH FOR THE MAIN ROTATING MACHINERY IN THE REFRIGERANT
COMPRESSOR TRAINS OF AN LNG INSTALLATION**

Gas turbine mechanical drives	Radial Vib. probe		Axial disp. probe Z	Velocity meter std. seismic protection	Thermocouple in bearing pad
	X	Y			
Alarm setting	2 levels	2 levels	2 levels	2 levels	2 levels
Trip setting***	N.A.	N.A.	N.A. *	Yes	N.A.
Trip logic	N.A.	N.A.	N.A. *	2oo2	N.A.

Gas turbine power generation	Radial Vib. probe		Axial disp. probe Z	Velocity meter std. seismic protection	Thermocouple in bearing pad
	X	Y			
Alarm setting	2 levels	2 levels	2 levels	2 levels	2 levels
Trip setting***	N.A.	N.A.	N.A.	Yes	N.A.
Trip logic	N.A.	N.A.	N.A.	2oo2	N.A.

Axial compressors (LP compressors)	Radial probe X	Radial probe Y	Axial disp. probe Z	Thermocouple in bearing pad
Alarm setting	2 levels	2 levels	2 levels	2 levels
Trip setting ***	Yes	Yes	Yes	N.A.
Trip logic	2oo2 ****		2oo2/2oo3	N.A.

Centrifugal compressors	Radial probe X	Radial probe Y	Axial disp. probe Z	Thermocouple in bearing pad
Alarm setting	2 levels	2 levels	2 levels	2 levels
Trip setting ***	Yes	Yes	Yes	N.A.
Trip logic	2oo2 *****		2oo2/2oo3	N.A.

Helper steam turbines / motors & electric generators	Radial Vib. probe X and Y		Axial disp. probe Z	Thermocouple in bearing pad
Alarm setting	2 levels		2 levels	1 or 2 levels
Trip setting ***	N.A.		Yes	N.A.
Trip logic	N.A.		2oo3	N.A.

Load gearboxes; mech. drive and generator drive **	Vib. probe	Accelerometer	Thermocouple in bearing pad	This column <u>only</u> for auxiliary gearboxes. Accelerometer probe
Alarm setting	2 levels	2 levels	1 level	1 or 2 levels
Trip setting ***	N.A.	Yes	N.A.	N.A.
Trip logic	N.A.	2oo2	N.A.	N.A.

* This only applies to gas turbines coupled to an equipment which has its own thrust bearing. If the equipment coupled to the gas turbine does not have its own thrust bearing, then 2oo2 or 2oo3 trip logic shall be used on the gas turbine.

** If the load gearbox is equipped with its own thrust bearing the gearbox shall also be protected as follows ; Alarm setting 2 levels, Trip setting Yes, and Trip logic 2oo3.

*** As indicated by an IPF review.

**** See also (3.3.4.3).

***** See also (3.3.4.1).

**APPENDIX C TYPICAL VIBRATION AND TEMPERATURE BASED SAFEGUARDING
APPROACH FOR THE MAIN ROTATING MACHINERY IN A REFINERY OR
CHEMICAL PLANT OR GTL INSTALLATION**

Gas turbine mech. drives (normally NA)	Radial Vib. probe		Axial disp. probe Z	Velocity meter std. seismic protection	Thermocouple in bearing pad
	X	Y			
Alarm setting	2 levels	2 levels	2 levels	2 levels	2 levels
Trip setting ***	N.A.	N.A.	N.A. *	Yes	N.A.
Trip logic	N.A.	N.A.	N.A. *	2oo2	N.A.

Gas turbine power generation	Radial Vib. probe		Axial disp. probe Z	Velocity meter std. seismic protection	Thermocouple in bearing pad
	X	Y			
Alarm setting	2 levels	2 levels	2 levels	2 levels	2 levels
Trip setting ***	N.A.	N.A.	N.A.	Yes	N.A.
Trip logic	N.A.	N.A.	N.A.	2oo2	N.A.

Axial compressors (LP compressors)	Radial probe X	Radial probe Y	Axial disp. probe Z	Thermocouple in bearing pad
Alarm setting	2 levels	2 levels	2 levels	2 levels
Trip setting ***	Yes	Yes	Yes	N.A.
Trip logic	2oo2 ****		2oo2/2oo3	N.A.

Centrifugal compressors	Radial probe X	Radial probe Y	Axial disp. probe Z	Thermocouple in bearing pad
Alarm setting	2 levels	2 levels	2 levels	2 levels
Trip setting ***	Yes	Yes	Yes	N.A.
Trip logic	2oo2 *****		2oo2/2oo3	N.A.

Helper steam turbines / motors & electric generators	Radial probe X and Y		Axial disp. probe Z	Thermocouple in bearing pad
Alarm setting	2 levels		2 levels	1 or 2 levels
Trip setting ***	Yes		Yes	N.A.
Trip logic	2oo2.		2oo3	N.A.

Load gearboxes; mech. drive and generator drive **	Vib. probe	Accelerometer	Thermocouple in bearing pad	This column <u>only</u> for auxiliary gearboxes. Accelerometer probe
Alarm setting	2 levels	2 levels	1 level	1 or 2 levels
Trip setting ***	Yes	Yes	N.A.	N.A.
Trip logic	2oo2	2oo2	N.A.	N.A.

* This only applies to gas turbines coupled to an equipment which has its own thrust bearing. If the equipment coupled to the gas turbine does not have its own thrust bearing, then 2oo2 or 2oo3 trip logic shall be used on the gas turbine.

** If the load gearbox is equipped with its own thrust bearing the gearbox shall also be protected for axial displacement as follows ; Alarm setting 2 levels, Trip setting Yes, and Trip logic 2oo3.

*** As indicated by an IPF review.

**** See also (3.3.4.3).

***** See also (3.3.4.1).

**APPENDIX D TYPICAL VIBRATION AND TEMPERATURE BASED SAFEGUARDING
APPROACH FOR THE MAIN ROTATING MACHINERY IN AN UPSTREAM E&P
INSTALLATION**

Gas turbine mechanical drives	Radial Vib. probe		Axial disp. probe Z	Velocity meter std. seismic protection	Thermocouple in bearing pad
	X	Y			
Alarm setting	1 level	1 level	1 level	1 level	1 level
Trip setting	Yes	Yes	Yes	Yes	Yes
Trip logic	1oo2	1oo2	1oo2	1oo2	2oo2

Gas turbine power generation	Radial Vib. probe		Axial disp. probe Z	Velocity meter std. seismic protection	Thermocouple in bearing pad
	X	Y			
Alarm setting	1 level	1 level	1 level	1 level	1 level
Trip setting	Yes	Yes	Yes	Yes	Yes
Trip logic	1oo2	1oo2	1oo2	1oo2	2oo2

Axial compressors (LP compressors)	Radial probe X	Radial probe Y	Axial disp. probe Z	Thermocouple in bearing pad
Alarm setting	1 level	1 level	1 level	1 level
Trip setting	Yes	Yes	Yes	Yes
Trip logic	1oo2	1oo2	1oo2/2oo3	2oo2

Centrifugal compressors	Radial probe X	Radial probe Y	Axial disp. probe Z	Thermocouple in bearing pad (radial & thrust)
Alarm setting	1 level	1 level	1 level	1 level
Trip setting	Yes	Yes	Yes	Yes
Trip logic	1oo2	1oo2	1oo2/2oo3	2oo2

High Energy Pumps	Radial probe X	Radial probe Y	Axial disp. probe Z	Thermocouple in bearing pad (radial & thrust)
Alarm setting	1 level	1 level	1 level	1 level
Trip setting	Yes	Yes	Yes	Yes
Trip logic	1oo2	1oo2	1oo2/2oo3	2oo2

Large Electric motors and generators	Radial probe X an Y	Axial disp. probe Z (if fitted)	Thermocouple in bearing pad	Winding Temperatures
Alarm setting	1 level	1 level	1 level	1 level
Trip setting	Yes	Yes	Yes	Yes
Trip logic	1oo2	1oo2/2oo3	2oo2	2oo2

Load gearboxes; mech. drive and generator drive	Vib. probe	Accelerometer	Thermocouple in bearing pad	This column <u>only</u> for auxiliary gearboxes. Accelerometer probe
Alarm setting	1 level	1 level	1 level	1 level
Trip setting	Yes	No (Yes if no vibration probes)	Yes	N.A.
Trip logic	1oo2	N.A.	2oo2	N.A.

APPENDIX E GUIDELINES FOR CONDITION MONITORING ACCEPTANCE CRITERIA FOR TURBO OILS

Table E.1 Typical monitoring values for Turbo GT 32

Property	Test method	Units	Typical values for Turbo GT 32	Condemning limits	Remarks
Viscosity at 40 °C	ASTM D 445	mm ² /s	32	±10 %	±10% is ISO viscosity grade range
Water content	ASTM D 6304	% v/v	0	>0.1	Free water if > ~150 ppm
TAN	ASTM D 974	mg/KOH/g	0.2	0.15 alarm 0.4 condemn	Deviation from value for unused oil
Flash point	ASTM D 93	°C	228	< 190 alarm < 160 condemn	Pensky –Martens
RPVOT	ASTM D 2272	Minutes	1250	50% of original - alarm 25% of original - condemn	Determine rest- oxidation stability of the oil
Foaming (air separation)	ASTM D 892	Seq. I, mL Seq. II, mL Seq. III, mL	30/nil 15/nil 30/nil	Max 400 Max 100 Max 400	24 °C 93.5 °C 24 °C
Emulsion (water separability)	ASTM D 1401	mL oil-water-emulsion			
Rust prevention	ASTM D 665	Pass/Fail	Pass	Fail	
Particle count	ISO 4406				
Trace metals		ppm	Nil	Max 50	Iron, copper, lead, chromium, aluminium, etc.

Table E.2 Typical monitoring values for Turbo GT 46

Property	Test Method	Units	Typical Values for Turbo GT 46	Condemning Limits	Remarks
Viscosity at 40 °C	ASTM D 445	mm ² /s	46	±10 %	±10% is ISO viscosity grade range
Water content	ASTM D 6304	% v/v	0	>0.1	Free water if > ~150 ppm
TAN	ASTM D 974	mg/KOH/g	0.2	0.15 alarm 0.4 condemn	Deviation from value for unused oil
Flash point	ASTM D 93	°C	228	< 190 alarm < 160 condemn	Pensky –Martens
RPVOT	ASTM D 2272	Minutes	1250	50% of original - alarm 25% of original - condemn	Determine rest- oxidation stability of the oil
Foaming (air separation)	ASTM D 892	Seq. I, mL Seq. II, mL Seq. III, mL	30/nil 15/nil 30/nil	Max 400 Max 100 Max 400	24 °C 93.5 °C 24 °C
Emulsion (water separability)	ASTM D 1401	mL oil-water-emulsion			
Rust prevention	ASTM D 665	Pass/Fail	Pass	Fail	
Particle count	ISO 4406				
Trace metals		ppm	Nil	Max 50	Iron, copper, lead, chromium, aluminium, etc.

Table E.3 Typical monitoring values for Turbo CC 32

Property	Test method	Units	Typical values for Turbo CC 32	Condemning limits	Remarks
Viscosity at 40 °C	ASTM D 445	mm ² /s	32	±10 %	±10% is ISO viscosity grade range
Water content	ASTM D 6304	% v/v	0	>0.1	Free water if > ~150 ppm
TAN	ASTM D 974	mg/KOH/g	0.2	0.15 alarm 0.4 condemn	Deviation from value for unused oil
Flash point	ASTM D 93	°C	228	< 190 alarm < 160 condemn	Pensky –Martens
RPVOT	ASTM D 2272	Minutes	2500	50% of original - alarm 25% of original - condemn	Determine rest- oxidation stability of the oil
Foaming (air separation)	ASTM D 892	Seq. I, mL Seq. II, mL Seq. III, mL	30/nil 15/nil 30/nil	Max 400 Max 100 Max 400	24 °C 93.5 °C 24 °C
Emulsion (water separability)	ASTM D 1401	mL oil-water-emulsion			
Rust prevention	ASTM D 665	Pass/Fail	Pass	Fail	
Particle count	ISO 4406				
Trace metals		ppm	Nil	Max 50	Iron, copper, lead, chromium, aluminium, etc.

Table E.4 Typical monitoring values for Turbo T 32

Property	Test method	Units	Typical values for Turbo T 32	Condemning limits	Remarks
Viscosity at 40 °C	ASTM D 445	mm ² /s	32	±10 %	±10% is ISO viscosity grade range
Water content	ASTM D 6304	% v/v	0	>0.1	Free water if > ~150 ppm
TAN	ASTM D 974	mg/KOH/g	0.2	0.15 alarm 0.4 condemn	Deviation from value for unused oil
Flash point, closed cup	ASTM D 93	°C	228	< 190 alarm < 160 condemn	Pensky –Martens
RPVOT	ASTM D 2272	Minutes	1100	50% of original - alarm 25% of original - condemn	Determine rest- oxidation stability of the oil
Foaming (air separation)	ASTM D 892	Seq. I, mL Seq. II, mL Seq. III, mL	30/nil 15/nil 30/nil	Max 400 Max 100 Max 400	24°C 93.5°C 24°C
Emulsion (water separability)	ASTM D 1401	mL oil-water-emulsion			
Rust prevention	ASTM D 665	Pass/Fail	Pass	Fail	
Particle count	ISO 4406				
Trace metals		ppm	Nil	Max 50	Iron, copper, lead, chromium, aluminum, etc.

APPENDIX F CONDITION MONITORING PARAMETERS BY MACHINE TYPE

F.1 CENTRIFUGAL COMPRESSORS

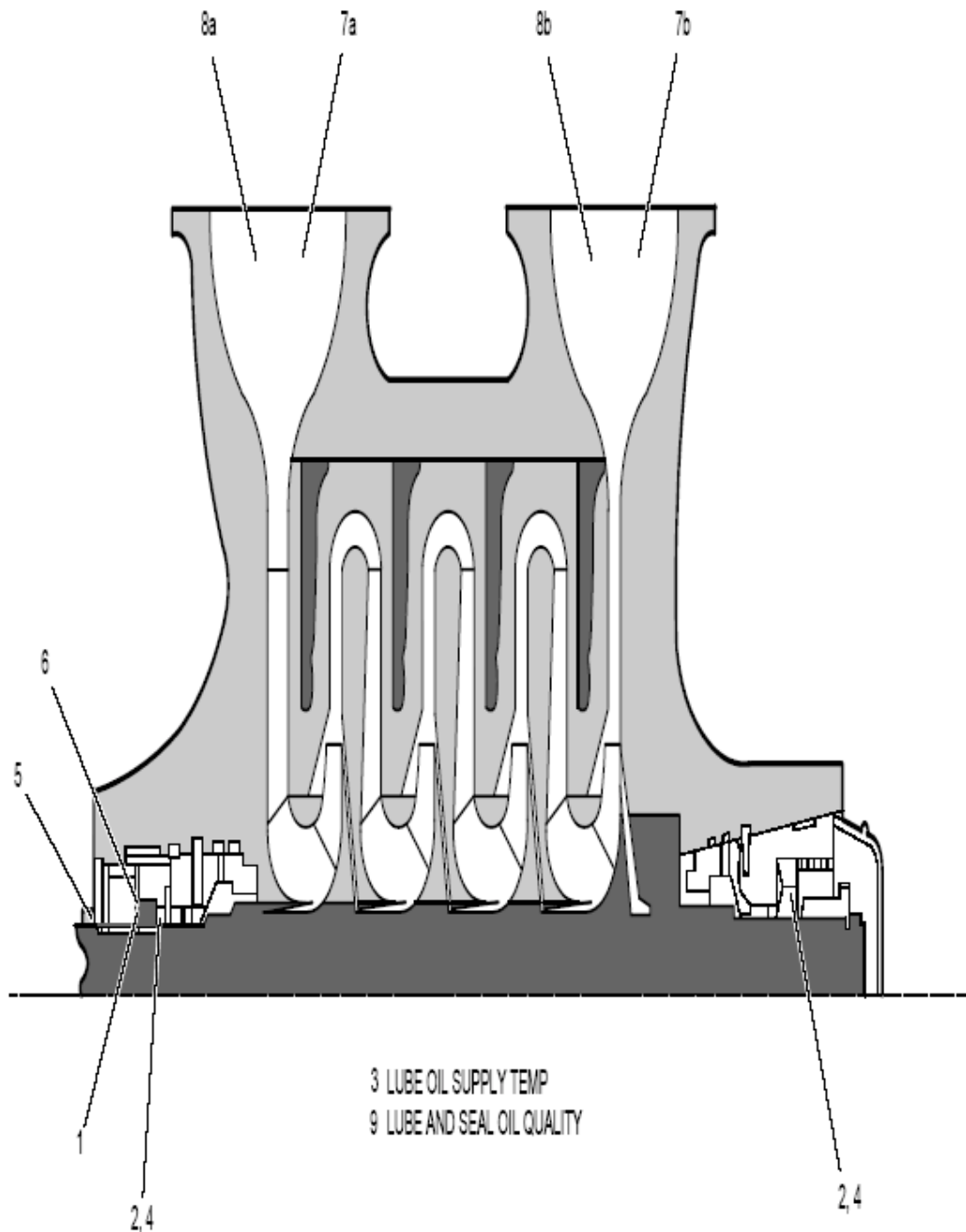


Figure F.1 Condition monitoring for centrifugal compressors

Table F.1 Condition monitoring for centrifugal compressors

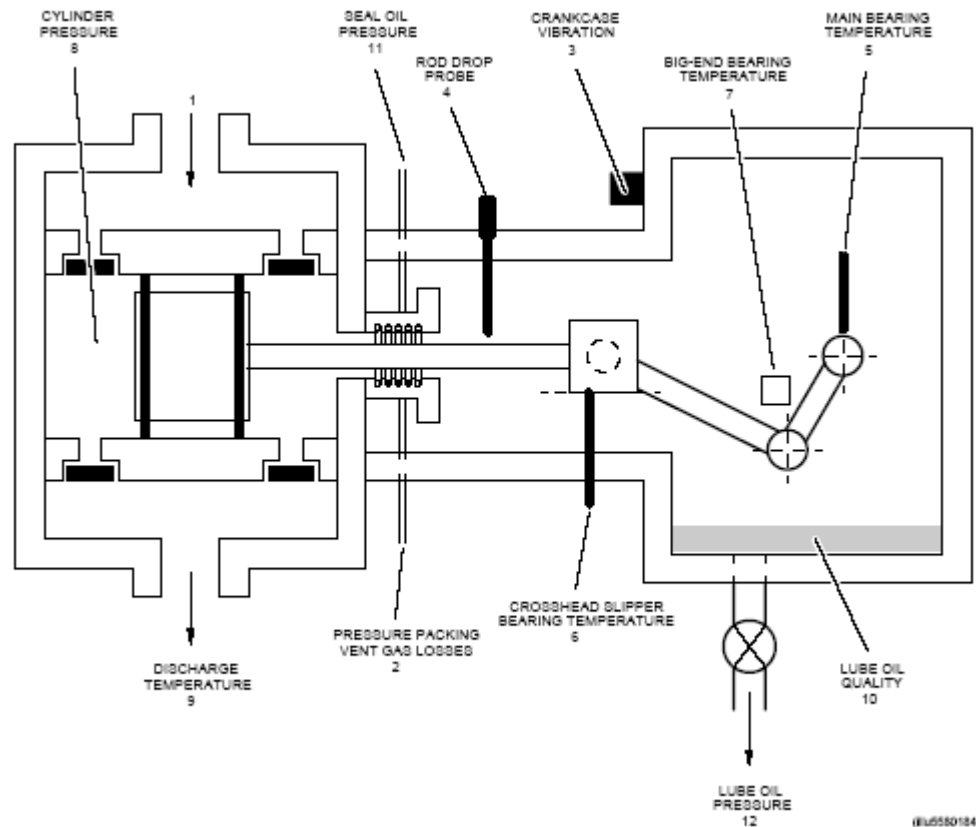
Ref # on Fig. F.1	Monitored parameter	Location (minimum)	Sensor and instrument type	No. of sensors	Monitoring equipment, analysis and other requirements
1	Temperature of metal adjacent to bearing surfaces	Thrust bearing	Resistance temperature detector (RTD) or Thermocouple (TC)	As: Tilting Pad Type Thrust Bearings Fixed-Geometry Hydrodynamic Thrust Bearings	Continuous monitoring for bearing temperature rise (metal minus lube oil supply temperature). Alarm (and trip for EP applications).
2	Temperature of metal adjacent to bearing surfaces	Radial bearing	RTD or TC	In accordance with API 670 Non Contacting Vibration and Axial Position Monitoring Scheme	Alarm and trip functions when maximum permissible temperature is exceeded
3	Temperature of lube oil	Supply line, downstream cooler	RTD or TC	One	Trending against bearing temperature
3 (a)	Lube oil pressure	Supply line	Pressure	One	Trending with alarm and trips
4	Vibration (Compressor rotor displacement)	Adjacent to bearing journals	Eddy current proximity probes	Two per bearing	Continuous vibration displacement monitoring in accordance with API 670 Non Contacting Vibration and Axial Position Monitoring Scheme
5	Rotor unbalance (keyphasor)	Rotor, forward or aft	Magnetic sensor or Eddy current proximity probe	One per rotor	Access to sensor and balance holes/planes to be provided
6	Axial shaft displacement	Thrust bearing	Eddy current proximity probes	In accordance with API 670 Non Contacting Vibration and Axial Position Monitoring Scheme	Trend axial shaft position at common operating modes, periodically with alarm and trip

Table F.1 Condition monitoring for centrifugal compressors (continued)

Ref # on Fig. F.1	Monitored parameter		Location (minimum)	Sensor and instrument type	No. of sensors	Monitoring equipment, analysis and other requirements
7	Performance monitoring	Gas Pressure	(a) Compressor inlet (b) Compressor discharge (c) Balance pressure	Pressure transducers or ports for portable test	(a) Two (b) Two	Plot operating point and compressor efficiency on the compressor base line characteristics to check for performance degradation Balance pressure against thrust position
8		Gas Temperature	(a) Compressor inlet (b) Compressor discharge	RTD or TC	(a) Two (b) Two	
8 (a)		Flow	Suction or discharge depending on application	Venturi flowmeter or orifice plate flowmeter or turbine flowmeter	One	Trending and transmittal to DCS/historian for Performance Monitoring calculations
8 (b)		Gas Composition	Suction	Chromatograph or Gas Analyser	One	Needed for Performance Monitoring
9	Lubricating and seal oil quality		Lube and seal oil discharges	Oil sampling kit		Oil deterioration analysis applied and trended periodically for problem diagnosis and oil change scheduling.
10	Gas seal leakage rate Oil seal leakage rate		Seal panel Seal oil rundown	DP or flow elements Sight glass or manual drain	One per seal One per seal	Trending with alarm and trips Trending with alarm

NOTE: For accurate performance monitoring, all pressure, temperature and flow sensors shall be high quality, precision devices.

F.2 RECIPROCATING COMPRESSORS



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Figure F.2 Condition monitoring for reciprocating compressors

Table F.2 Condition monitoring for reciprocating compressors

Ref # on Fig. F.2	Monitored parameter	Location (minimum)	Sensor and instrument type	No. of sensors	Monitoring equipment, analysis and other requirements
2	Pressure packing vent gas losses	Downstream of packing on horizontal pipe run	V-Cone Flowmeter	One per cylinder	Venturi type flowmeter with mechanical pressure gauge giving constant readout
3	Crankcase vibration	Where good transmission of vibration occurs Dependent on machine design	Accelerometer to API 670	Two per crankcase	Primarily used for protection, with alarm and trip levels set locally. May give more information in association with keyphasor
4	Rod Drop	Crankcase distance piece in vertical plane (can be below or above rod depending on system)	Displacement probe to API 670	One per piston rod	Trend rod to probe clearance related to specific position of piston (use keyphasor). Periodic measurements. If used for protection set alarm and shut down to 50% and 95% clearance.
5	Main bearing temperature	Main bearing caps	Resistance temperature detector (RTD) or thermocouple (TC) in accordance with API 670		Trend temperature related to required power
6	Crosshead bearing temperature	Lower crosshead slipper bearing guide	RTD or TC	One or two per bearing	Also used for protection purposes. Alarm and shutdown levels set by operator experience
7	Big end bearing temperature	Big end bearing cap	AMOT Switch	One per bearing	Used for protection only if potential problems are likely. (Reliability not high)
8	Cylinder Pressure	Cylinder tapping	Pressure transducers	One per cylinder	Take PV diagrams periodically. Acceptable performance operator dependent.
9	Gas discharge Temperature	Discharge line	RTD or TC	One per location	Trend temperature related to required power
10 (a)	Lube-oil quality	Upstream of filter	Oil sampling kit		Analyse periodically for chemical analysis / flash point / water content/ additives / viscosity / corrosiveness
10 (b)	Lube-oil debris				Analyse periodically for wear particles and metals
11	Mini lube pressure	Between lubricator and compressor	Pressure gauge or transducer or sight glass	One per high pressure line	Also used for protection
12	Lube-oil pressure Minimum lube-oil flow	In lube-oil supply line In lube-oil supply line	Pressure transducer Sight glass	Two per system	Also used for protection. Alarm and trip functions

F.3 ELECTRIC MOTORS

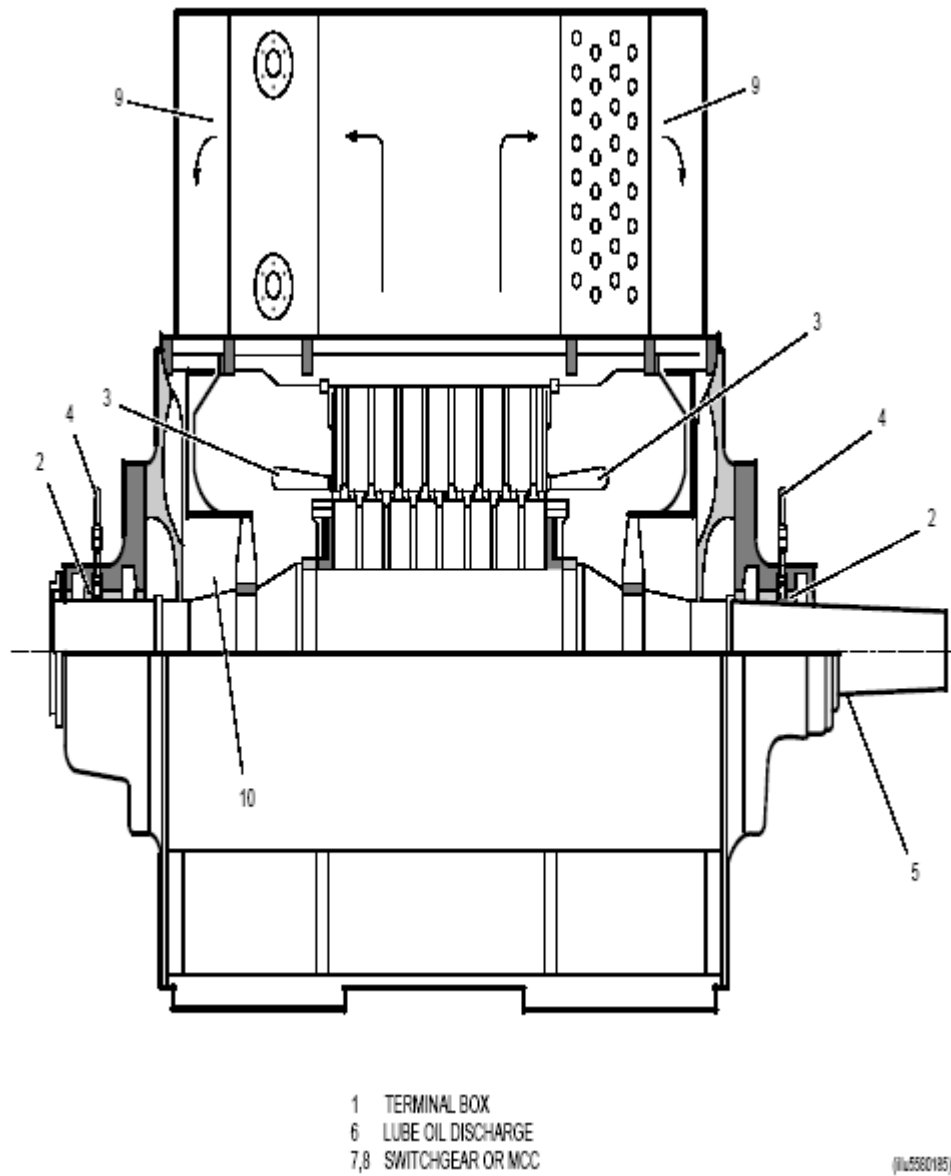
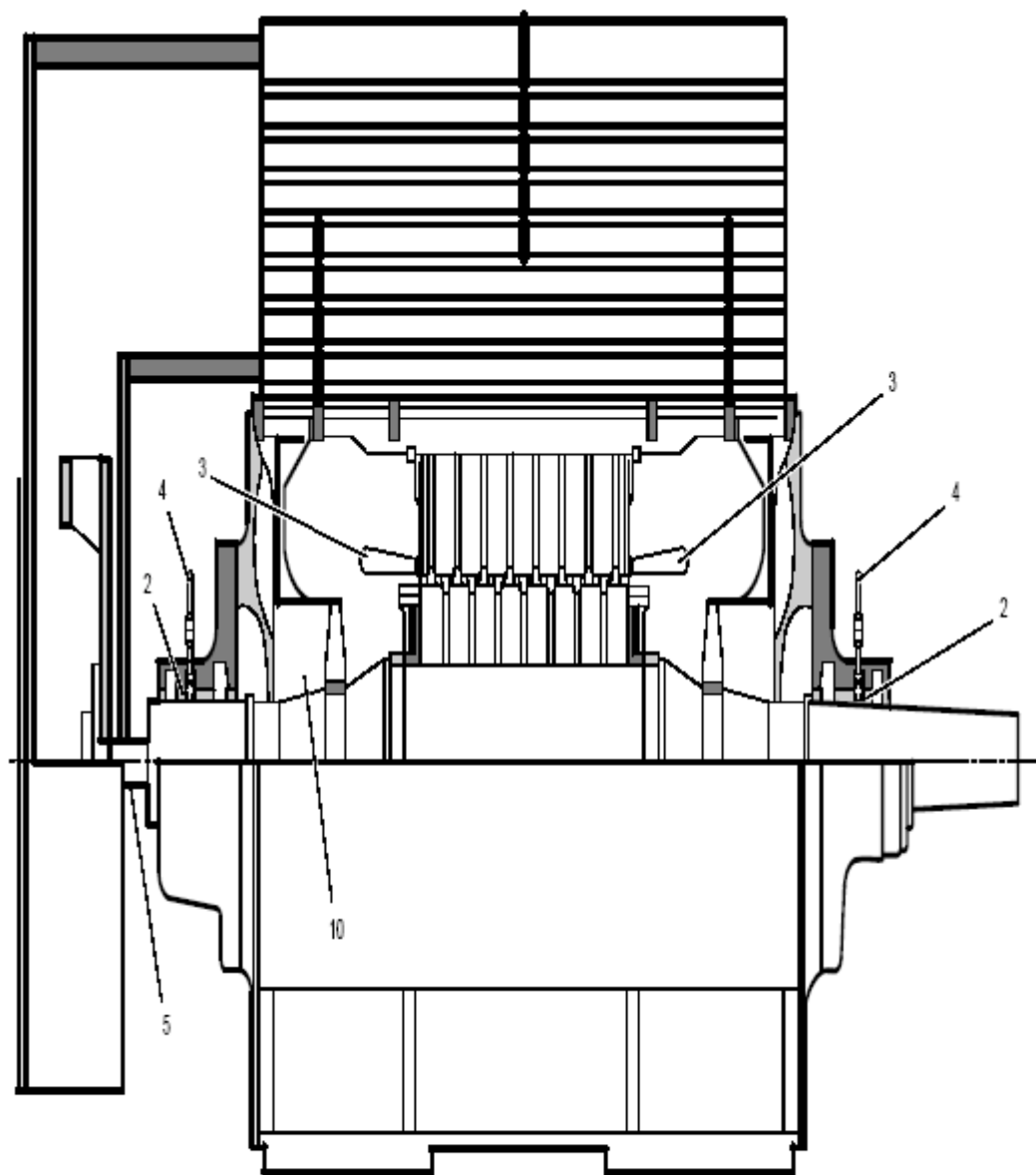


Figure F.3a Condition monitoring for electric motors - CACW



- 1 TERMINAL BOX
- 6 LUBE OIL DISCHARGE
- 7,8 SWITCHGEAR OR MCC

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Figure F.3b Condition monitoring for electric motors - CACA

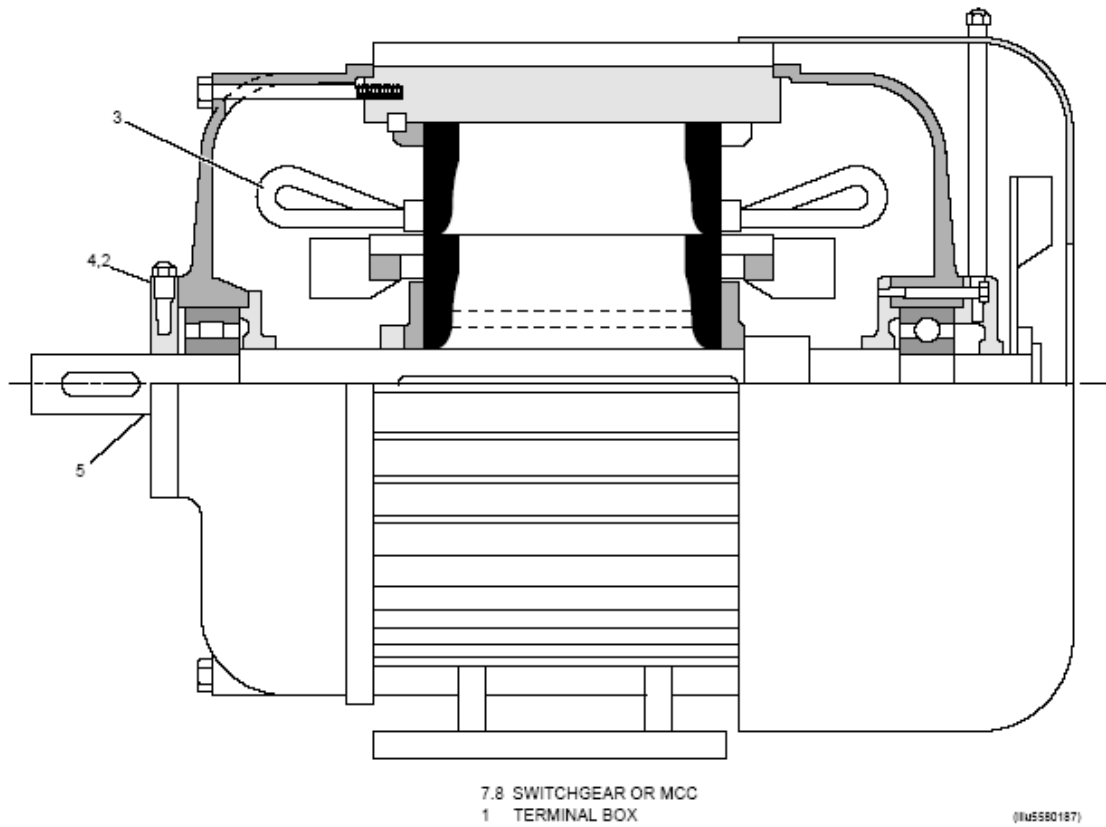


Figure F.3c Condition monitoring for electric motors - TEFC

Table F.3 Condition monitoring for electric motors

Ref # on Fig F.3 a/b/c	Monitored parameter	Location (minimum)	Sensor and instrument type	No. of sensors	Monitoring equipment analysis and other requirements
1	High frequency discharge	Motor Terminal box	Rogowski coil	One per phase (may be portable if required)	Monitor and trend average and peak repetitive discharge levels periodically. Specialist examination needed for diagnosis
2	Bearing shell temperature (journal bearings)	Radial bearing	Resistance Temperature Detector (RTD) or Thermocouple (TC)	One or two per bearing in accordance with API 670	C.M. - Trend temperature protection-alarm (and shutdown levels for EP applications)
or	Bearing temperature (rolling element bearings)	Radial bearing	RTD or TC	One per bearing	C.M. - Trend temperature protection-alarm level only
3	Stator winding temperature	Embedded between coil sides in stator slots	RTD or TC	Two per phase	Continuous monitoring of winding temperature. Alarm and trip.
4	Bearing vibration (Journal bearings)	Adjacent to bearing journals	Eddy current proximity probe	Two per bearing	Continuous vibration displacement monitoring in accordance with API 670
or	Bearing vibration (Rolling element bearings)	On bearing housing	Accelerometer in accordance with API 670	As Shaft Vibration	Continuous vibration monitoring in accordance with API 670
5	Keyphasor	At accessible end of rotor	Eddy current proximity probe	One	Primary use for diagnostic purposes
6	Lube-oil quality and debris	Sample point at lube-oil discharge	Oil sampling kit		Effectiveness depends on layout of lubrication system and sample point
7	Stator current	Switchgear	Ammeter/Current transformer	One	Used for driven equipment performance monitoring
8	Current spectrum Analysis	Switchgear	Current transformer	One (portable)	Normal monitoring using portable equipment typically at 6 monthly intervals
9	Water leakage (CACW motors only)	Below cooler	Capacitive detector	One per cooler	No routine monitoring. Protection - alarm on activation
10	Internal air temperature	In airflow before and after cooler	RTD or TC	Two	Occasional monitoring needed. Protection - alarm only

F.4 ELECTRIC GENERATORS

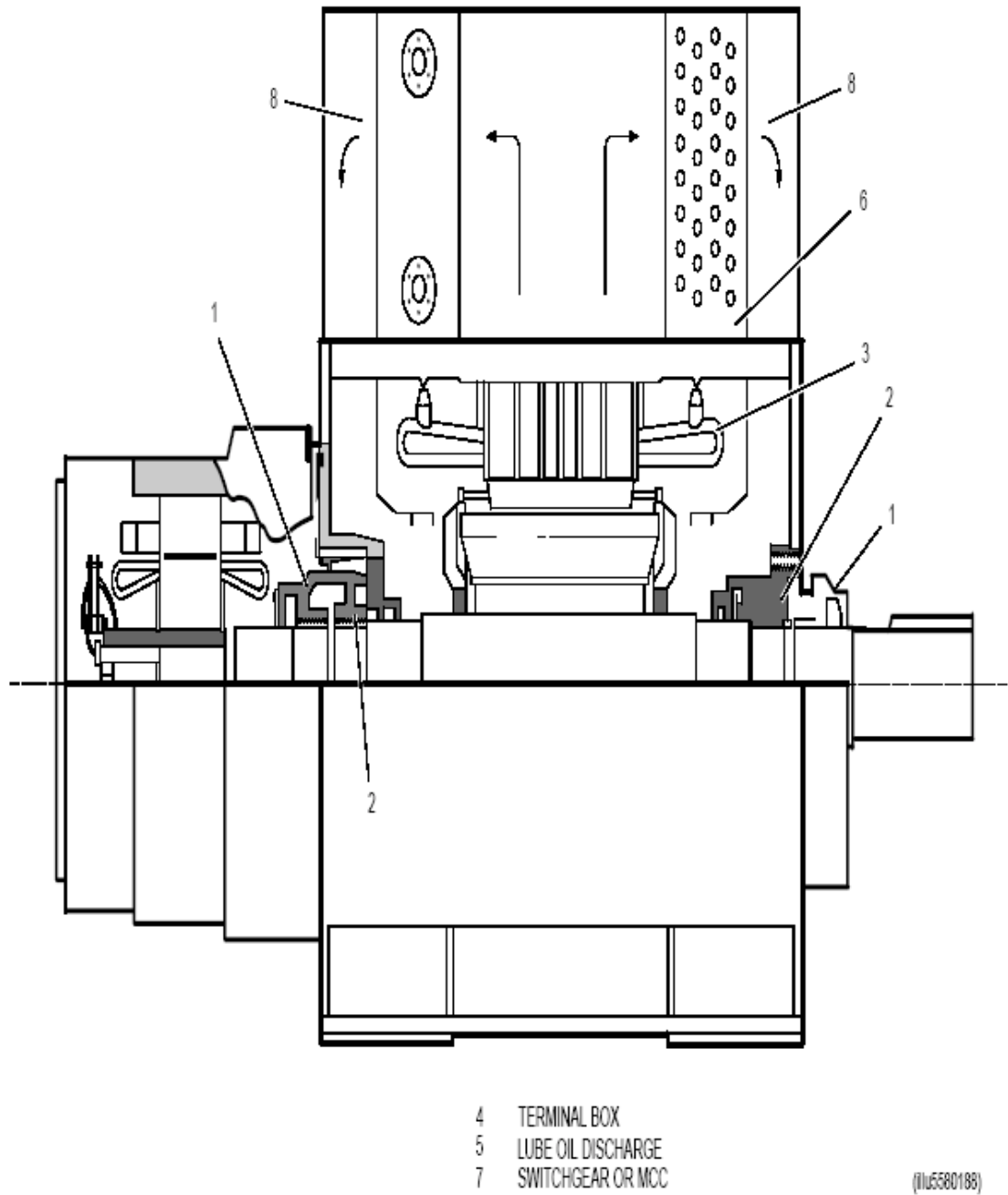


Figure F.4 Condition monitoring for electric generators

Table F.4 Condition monitoring for electric generators

Ref # on Fig F.4	Monitored parameter	Location (minimum)	Sensor and instrument type	No. of sensors	Monitoring equipment, analysis and other requirements
1	Bearing Vibration (Journal bearings)	Adjacent to bearing journals	Eddy current proximity probe	Two per bearing	Continuous vibration displacement monitoring in accordance with API 670
or	Bearing Vibration (Rolling element bearings)	On bearing housing	Accelerometer to API 670	As Shaft Vibration (Step 3) of this Spec.	Continuous vibration monitoring in accordance with API 670
2	Bearing shell temperature (Journal bearings)	Radial bearing	Thermocouple (TC) or Resistance Temperature Detector (RTD)	In accordance with API 670	C.M. - Trend temperature. Protection- Alarm (and shutdown levels for EP applications)
or	Bearing temperature (Rolling element bearings)	Radial bearing	RTD or TC	One per bearing	C.M. - Trend temperature. Protection- Alarm only
3	Stator winding temperature	Embedded between coil sides in stator slots	RTD or TC	Two per phase	Continuous monitoring of winding temperature. Alarm and trip levels.
4	High frequency discharge	Generator terminals	Rogowski Coil	One per phase (may be portable if required)	Monitor and trend average and peak repetitive discharge levels periodically. Specialist examination needed for diagnosis
5	Lube-oil quality and debris	Sample point in return line (before filter)	Oil sampling kit		Effectiveness depends on layout of lubrication system and sample point
6	Water leakage	Below cooler	Capacitive detector	One per cooler	No routine monitoring. Protection - alarm on activation
7	Electrical protection	Switchgear	Overcurrent / Earth fault relay.		Differential protection relay. Impedance relay. No routine monitoring. Trip on activation
8	Internal air temperature	In airflow before and after cooler	RTD or TC	Two	Occasional monitoring needed. Protection - alarm only.

F.5 CENTRIFUGAL PUMPS

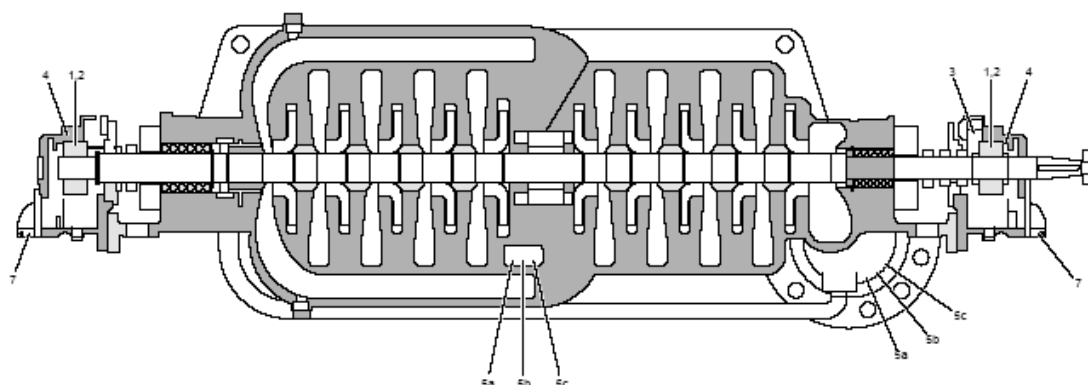


Figure F.5a Condition monitoring for centrifugal pumps (journal bearings)

Table F.5a Condition monitoring for centrifugal pumps (journal bearings)

Ref # on Fig. F.5a	Monitored parameter	Location (minimum)	Sensor and instrument type	No. of sensors	Monitoring equipment, analysis and other requirements
1	Temperature of metal adjacent to bearing surfaces	Thrust bearing	Thermocouple (TC) or Resistance Temperature Detector (RTD)	Two embedded in each bearing	Continuous monitoring for bearing temperature rise (metal minus lube oil supply temperature) per bearing
2	Temperature of metal adjacent to bearing surfaces	Journal bearing	(TC) or (RTD)	Two embedded in each bearing	Alarm (and trip for EP applications) functions when maximum permissible temperature is exceeded
3	Axial shaft displacement	Thrust bearing	Proximity probes	In accordance with API 670	Trend axial shaft position at common operating modes periodically
4	Radial shaft displacement	Adjacent to each bearing journal	Eddy current proximity probe	Two per bearing (as API 670	Vibration displacement monitoring in accordance with API 670
5	Pump performance	(a) Inlet or discharge flow (b) Inlet and discharge temperature (c) Inlet and discharge pressures (d) Balance pressure	(a) Orifice flow meter (b) RTDs or TCs (c) Ports for portable test gauge or sensors for permanent system pressure gauge or transmitter		Ensure suction orifice is suitable for full flow (inc recirculation). Speed measurement required for variable speed pump. For trending of thrust bearing load.
6	Lubricating oil pressure	Lube-oil supply line	Pressure transducer		Used for protection only
7	Lubricating oil quality	Lube-oil discharge	Oil sampling kit		Oil deterioration analysis performed and trended periodically for problem diagnosis and oil change scheduling

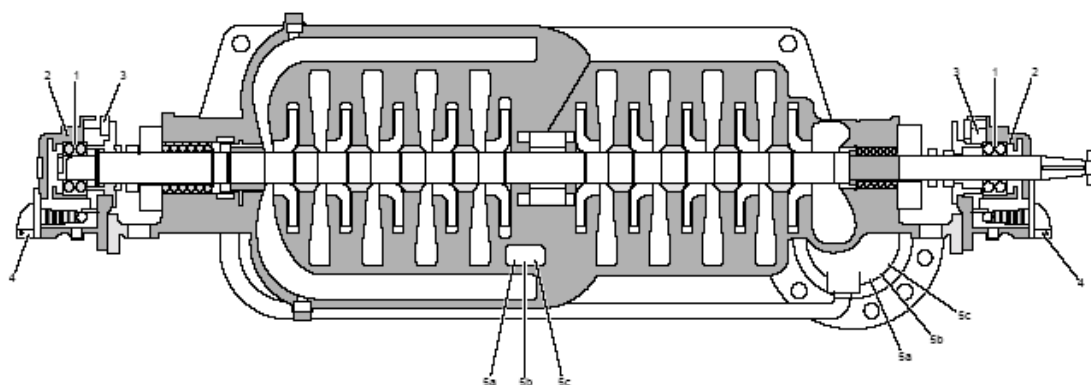
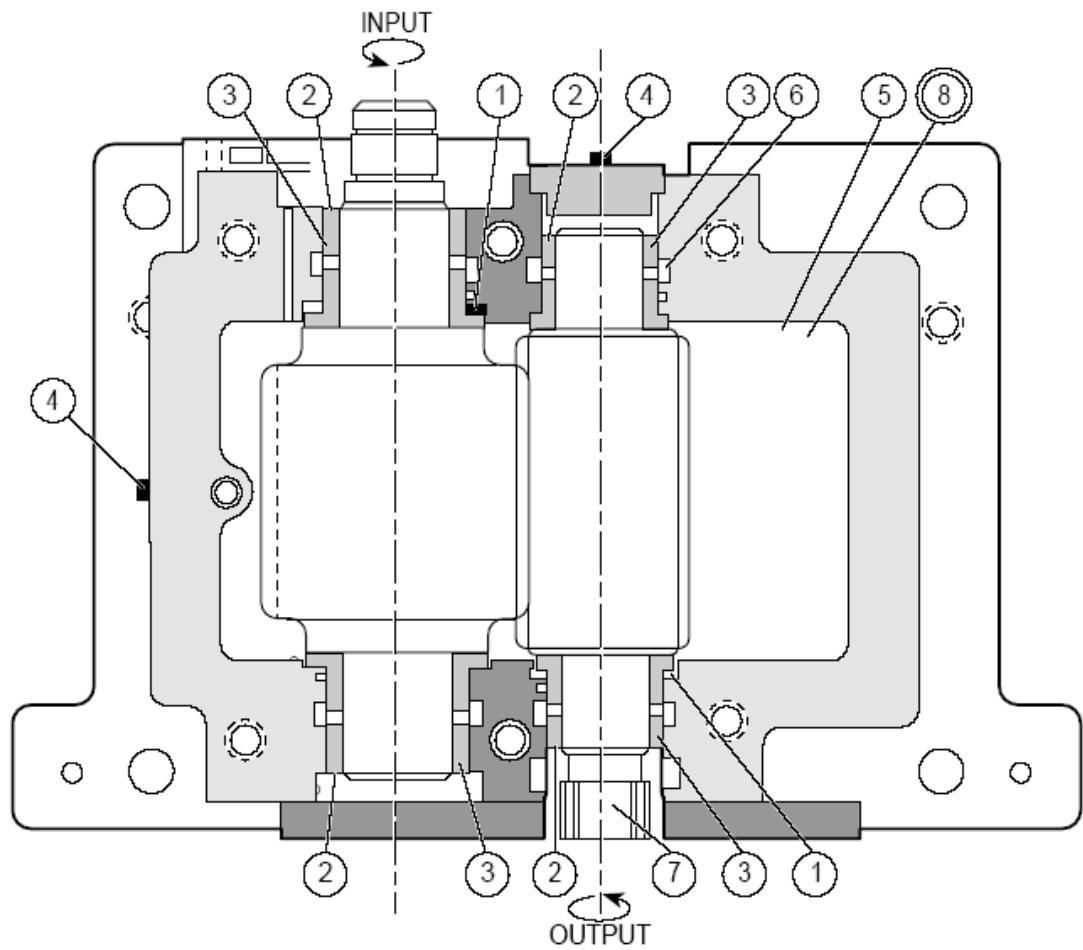


Figure F.5b Condition monitoring for centrifugal pumps (rolling bearings)

Table F.5b Condition monitoring for centrifugal pumps (rolling bearings)

Ref # on Fig. F.5b	Monitored parameter	Location (minimum)	Sensor and instrument type	No. of sensors	Monitoring equipment, analysis and other requirements
1	Bearing temperature	Radial bearing	Thermocouple (TC) or Resistance Temperature Detector (RTD)	One per bearing	C.M. - Trend Temperature. Protection - alarm level only.
2	Bearing vibration	Radial bearing	Accelerometer in accordance with API 670	As Shaft Vibration	Continuous vibration monitoring in accordance with API 670
3	Lubricating oil pressure	Supply line	Pressure transducer	One	Used for protection only
4	Lubricating oil quality	Lube-oil discharge	Oil sampling kit		Oil deterioration analysis applied and trended periodically for problem diagnosis and oil change scheduling
5	Pump performance	(a) Inlet or discharge flow	(a) Orifice flow meter		Ensure suction orifice is suitable for full flow (inc. recirculation). Speed measurement required for variable speed pump
		(b) Inlet and discharge temperature	(b) RTDs or TCs		
		(c) Inlet and discharge pressures	(c) Ports for portable test gauge or sensors for permanent system		
		(d) Balance pressure	Pressure gauge or transmitter		For trending of thrust bearing load

F.6 GEARBOXES



Note: The gearbox shown in this drawing has journal bearings.
On appropriate sizes/speeds of gearbox rolling element
bearings may be used.

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Figure F.6 Condition monitoring for gearboxes

Table F.6 Condition monitoring for gearboxes

Ref # on Fig. F.6	Monitored parameter	Location (minimum)	Sensor and instrument type	No. of sensors	Monitoring equipment analysis and other requirements
1	Temperature of metal adjacent to bearing surfaces function	Thrust Bearing	RTD or TC	2 embedded in each bearing (1 spare)	Continuous monitoring for bearing temperature rise. Alarm/ (and trip for EP applications)
2	Temperature of metal adjacent to bearing surfaces	Journal Bearings	RTD or TC	2 embedded in each bearing (1 spare)	Continuous monitoring for bearing temperature rise. Alarm (and trip for EP applications)
3	Radial shaft Displacement (Journal Bearings)	Gearbox bearing journals	Eddy Current proximity probes	Two per bearing (As API 670)	Vibration displacement monitoring in accordance with API 670
3A	Bearing Vibration (Rolling Element Bearings)	Bearings	Accelerometer in accordance with API 670	As API	Vibration monitoring in accordance with API 670
4	Casing Vibration	Gearbox casing	Accelerometer (Ensure response covers gear mesh harmonics)	Two	In axial and vertical/horizontal planes for alarm and trip
5	Lubricating Oil Quality	Lube-oil discharge	Oil sampling kit		Oil deterioration analysis applied and trended periodically for problem diagnosis and oil change scheduling
6	Lube-oil temperature	Supply line	RTD or TC	One	
7	Keyphasor	Output shaft (In order to determine speed and related phase angles Keyphasor may be installed on driver and driven)	Proximity probe	One (or two)	Where suitable, keyphasor from driven equipment may be used
8	Oil Debris Analysis	Gearbox Oil Drain	Magnetic plug or Oil Sampling Kit		Periodic analysis based on equipment criticality

F.7 Gas turbines

The aim of this section is to give some guidance on the preferred methods of condition monitoring for gas turbines. Information is given for both the gas generator and power turbine components. The data given here is necessarily generalised, since the turbines used vary considerably in design and construction. As a result, the sensors required, their positions, and the access available for fitting them vary significantly. The construction may therefore limit the monitoring possible.

Preferred methods of monitoring:

In the monitoring of gas turbine units, two aspects need to be considered. Firstly, experience suggests that condition monitoring techniques may have more limitations for a gas turbine than for some other equipment types. The techniques that can be applied with the turbine running do not give clear indications of the presence of many possible faults. A shutdown and inspection (e.g. by boroscope) is needed to detect them. Secondly, much of the unplanned downtime comes from faults in auxiliaries such as the fuel supply, lubrication or control and starting systems. Some characteristics of these (e.g. lube oil pressure) are measured to provide protection functions. The relationship between variables in these systems is related to the operating point of the gas turbine, so for critical systems the auxiliaries should also be monitored. With these points in mind, the suggested techniques are indicated below.

(1) Casing vibration – 'Aero derivative' gas turbines

On most 'aero derivative' gas turbines, access to the rolling element bearings for fitting of monitoring devices is limited or impossible. Measurement of vibration is, therefore, limited to casing accelerometers. The transmission paths for vibration from the bearings to the casing may be long and indirect. While overall casing vibration level is used as part of the machine protection, this limited access restricts the use that can be made of vibration monitoring as a diagnostic tool. Each model of turbine should be assessed individually, and monitoring points on the casing used where specified by the Vendor for protection purposes and where otherwise safely accessible. One location sometimes used is on auxiliary gearboxes, to monitor these components as well as the main turbine.

For twin shafted aero derivatives, two high temperature accelerometers are typically applied. The signal of a single accelerometer is filtered and monitored against the speed of both shafts, HP compressor and LP compressor

(2) Shaft displacement – 'Industrial' gas turbines

Most industrial gas turbines use sleeve bearings, and in a number of designs there is sufficient access to these bearings to fit displacement probes. In these instances standard monitoring procedures for sleeve bearings should be used.

(3) Bearing temperature

This applies mainly to industrial turbines with sleeve bearings, where there may be access to fit thermocouples as well as vibration probes. This can give both monitoring and protective functions.

(4) Lube-oil quality

The sampling location shall be upstream of any filters in the oil system. This technique is primarily useful for determining when the oil should be changed.

(5) Lube-oil debris

The detectors used are:

- a. Magnetic plugs. These require shut-down of turbine for examination.
- b. Detectors monitoring the presence of debris in oil flow. These shall be placed upstream of any filters and are used for on-line monitoring.

(6) Performance monitoring

For meaningful gas generator performance monitoring, a simple trending procedure of a

small number of basic performance parameters is generally what is required. The preferred monitoring parameters are:

- o Ambient pressure, temperature and humidity.
- o Air inlet (filter) differential pressure.
- o Gas generator and power turbine speeds.
- o Compressor inlet and exit pressures.
- o Compressor inlet and outlet temperatures.
- o Exhaust temperatures and spread.
- o Fuel flow, pressure, temperature, dew point and quality (calorific value etc).
- o Variable inlet guide vane angle.

A more limited assessment of performance can be made provided the following minimum data is available:

- o Air intake temperature.
- o Barometric pressure.
- o Gas generator speed.
- o Exhaust gas temperature.
- o Compressor delivery pressure.
- o Variable Inlet guide vane angle.

(7) Borescope Inspection

This is a key condition monitoring activity on gas turbines and should be used to verify integrity as well as to define planned maintenance interventions.

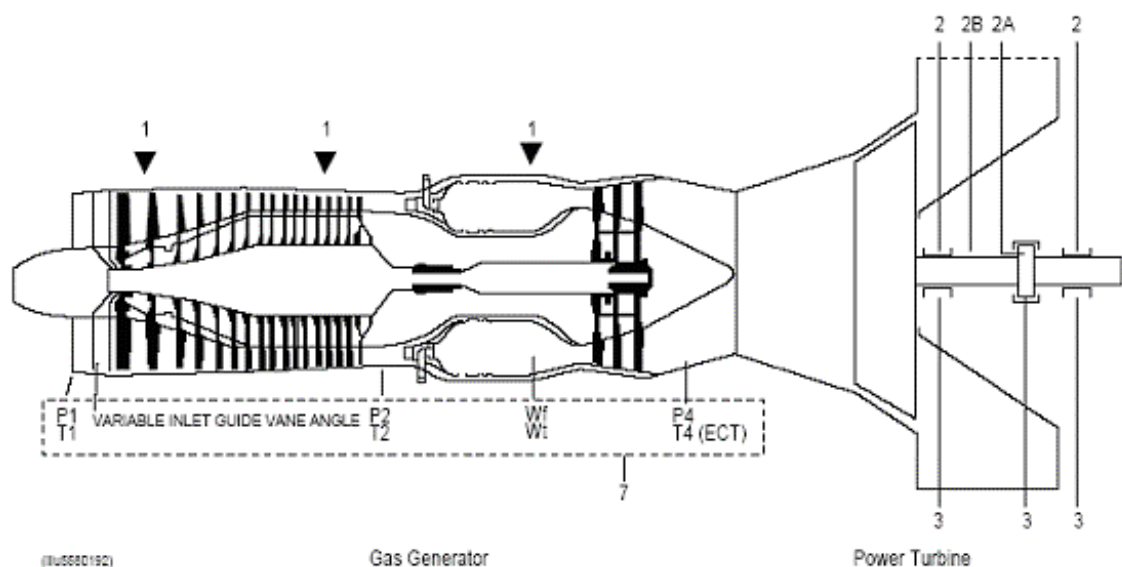


Figure F.7a Condition monitoring for “aero derivative” gas turbines

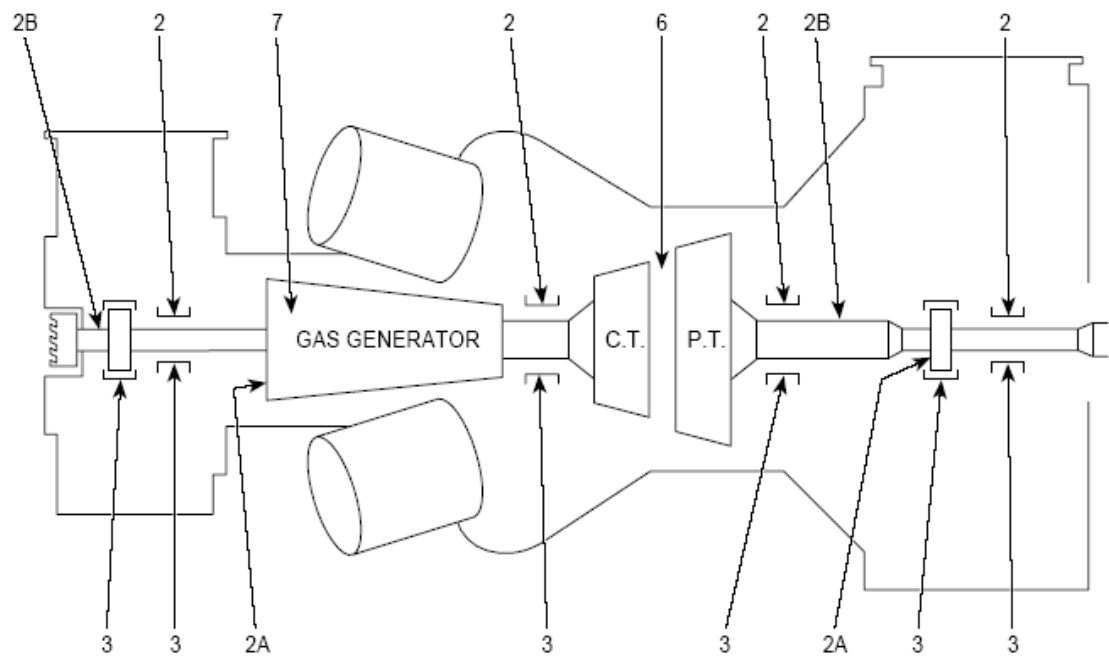


Figure F.7b Condition monitoring for “industrial” gas turbines

APPENDIX G SHELL SMARTCONNECT IMPLEMENTATION REQUIREMENTS

G.1 INTRODUCTION

G.1.1 Shell SmartConnect overview

Shell SmartConnect is a Shell GSI initiative to improve condition monitoring and process optimization for a wide variety of equipment including both stationary and rotating machinery. It aims to optimize the use of condition data and make the data available to key technical staff, whether these staff are in the plant, in a central engineering or production office, in Shell GSI offices or at the equipment OEM premises. One aspect of this is remote access to the data and bringing the data to centres where experts in various disciplines can work together towards solutions. This is accomplished in Remote Monitoring and Diagnostic (RMD) centres. This section focuses on condition monitoring techniques for rotating machinery.

If the instrumentation and systems are installed in accordance with this DEP, then all of the required information is available for the Shell SmartConnect modules to be implemented. Shell SmartConnect modules are a combination of Shell technology and 3rd party tools. It is essential to install the Shell baselayer tools and supplement them with the 3rd party tools to ensure the widest commonality of methodology throughout Shell. All critical machine data as identified in this DEP will be stored in the site data historian from which the Shell SmartConnect tools collect their data for analysis. If there is a higher frequency collection of data, a subset will still be stored in the data historian and appropriate high-speed analysis tools from the relevant 3rd party will be installed.

Results of all monitoring tools will be stored in the site data historian. 3rd party tools will also store the results in their own database as required. The site data historian will store data typically on a one-minute scan time.

G.1.2 Condition Monitoring approaches supported

Shell SmartConnect recommends a modular approach to the monitoring so that, depending on the machine criticality and instrumentation, the appropriate condition monitoring approach can be taken. For most non-vital pieces of equipment, vibration analysis by high-speed data acquisition is usually not performed. If a modular approach is not taken, then these pieces of equipment will not have appropriate monitoring.

1. Status indication.

The lowest level of condition monitoring is simple status indication. A common example would be a status indicator that the machine is either running or shutdown, perhaps along with a running hours calculation, or an availability calculation. This can be achieved by means of standard data that is usually available in a data historian.

2. Performance monitoring.

Pressures, temperatures, and flows that are stored in the data historian can be used along with a first principles thermodynamic model to trend performance. Absolute accuracy of the performance calculation will be a function of instrument accuracy, however it is usually more useful to trend and identify performance deviations rather than working towards a high level of accuracy in the measurement (high accuracy flow measurement and gas properties are very important for accurate performance measurement).

3. Condition parameters, rules and operator advisories.

The data tags in the historian associated with the measurement parameters required by the main body of this DEP (e.g. vibration, temperature, pressures, flows, etc.) can be used together to assess the condition of a machine. One approach to this is to use rule sets, based on experience in Shell, to evaluate machine condition and the actions to be taken to prevent malfunctions or improve operation. These rules are then programmed into a calculation engine and interfaced to an operator advisory program so that the operator receives actionable information on machine condition.

4. High speed data acquisition vibration and condition analysis systems.

The main body of this DEP recommends high speed vibration and condition data acquisition and analysis systems for some classes of vital machinery and these systems are typically provided by Vendors that specialize in this type of data acquisition system. This type of data shall be made available to qualified professionals for condition assessment and diagnosis/prognosis in the event of machine malfunctions. Remote access is usually required, unless qualified professionals reside on site.

5. Statistical and benchmarking analysis.

Sophisticated statistical data analysis tools are available for processing data from a variety of sources, including data historians or OEM data acquisition systems. These tools can be used to run optimization or diagnostic and condition assessment routines.

If the Shell SmartConnect baselayer tools are installed in a uniform way, benchmarking and reliability analysis will be made possible.

G.1.3 Remote monitoring and diagnostic centres and analytical support

1. RMD collaboration centres

Shell Global Solutions operates RMD centres at various locations including The Hague, Bangalore, Kuala Lumpur, and Houston. These centres provide IT infrastructure, data management, data visualization and collaboration services for the remote monitoring and diagnostics of machinery malfunctions.

2. Analytical/fleet management support

RMD centres have qualified staff to provide diagnostic analysis for problem machines as well as condition assessment. One important aspect of remote access to data from a central location is that the machinery fleet across the Shell Group can be evaluated and trends indicating common design or maintenance problems identified. Statistical analysis of data on a fleet basis can then be used to address design or maintenance issues with machinery OEMs.

3. Training.

The RMD centres have also been equipped to provide training in condition monitoring and diagnostic assessment.

G.2 DATA FLOW

All the condition monitoring approaches discussed in the introduction require appropriate IT infrastructure and access to the data. Condition data usually either resides in the data historian, or in specialized vibration/condition data acquisition systems, which generally reside in the process control domain (PCD) at a location. With regard to data acquisition and control architecture, DEP 32.01.20.10-Gen. describes the appropriate IT infrastructure and security process to access the PCD from the office domain. Figure G.1 provides a summary of this while Figure G.2 and Figure G.3 are flow charts showing the data flow from the machine through to access for remote monitoring for various IT architectures.

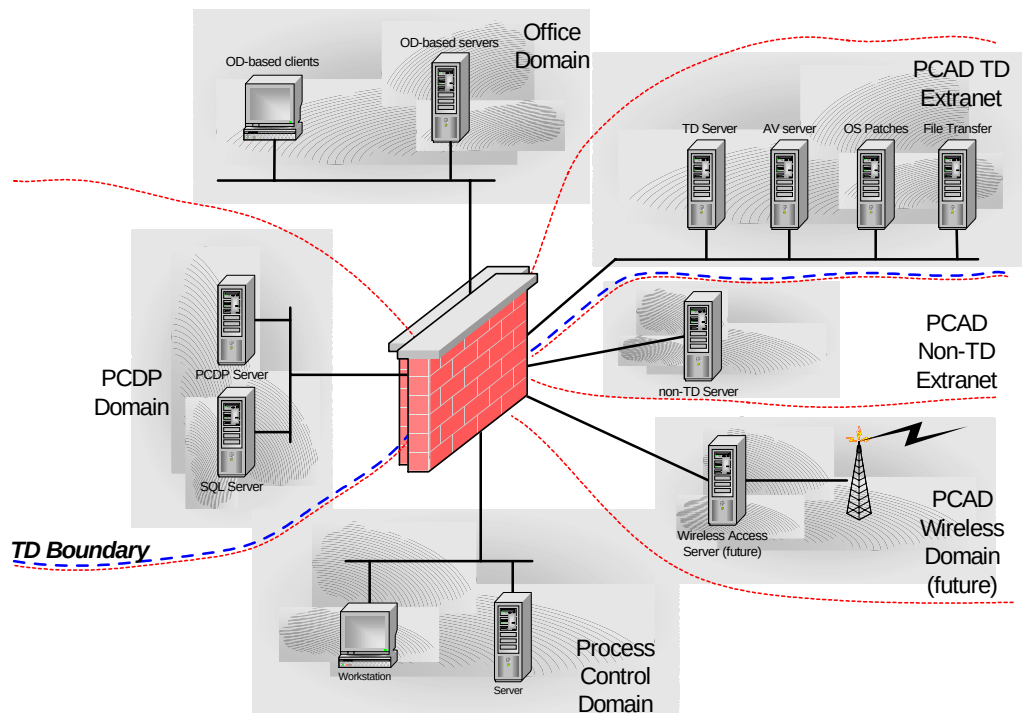


Figure G.1 DACA compliant access to the Process Control Domain (PCD)

Historian on Business Network (BIZ), not the PCD, therefore, calculation engine is on the BIZ either local or remote.

- Local is preferred option
- Remote/central is fallback if the site does not have facilities to host the engine

Fallback: No Local server, use remote server in one of the central RMD centres (HAG, WTC, KL, BANG)

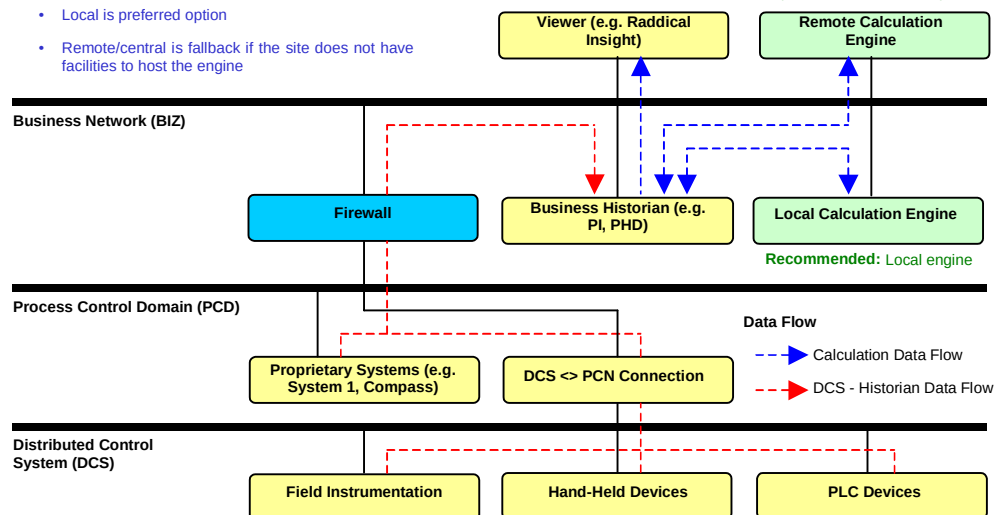


Figure G.2 Shell SmartConnect data flow – Architecture 1

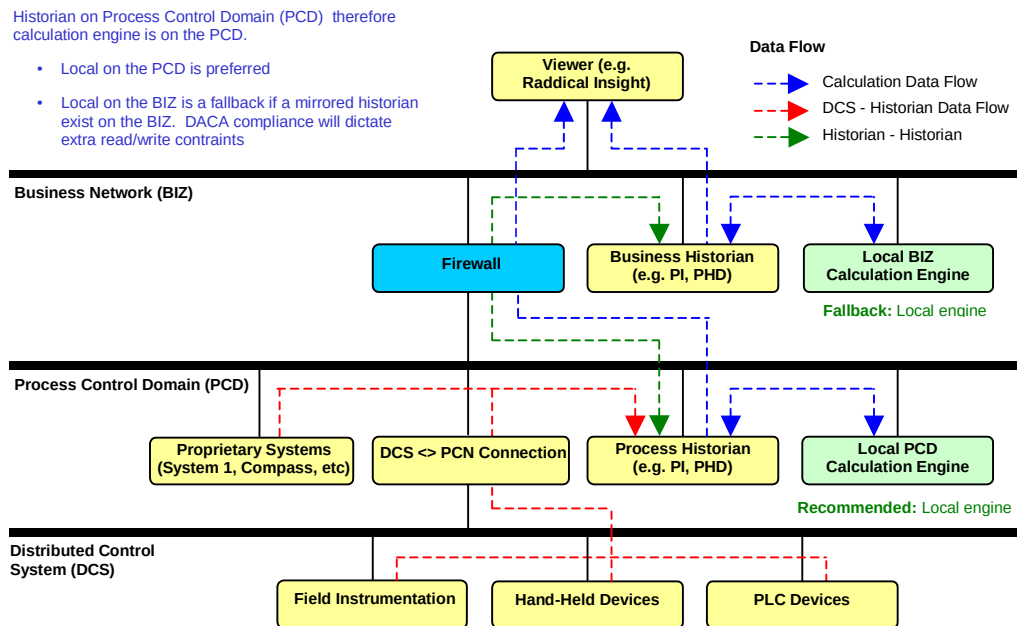


Figure G.3 Shell SmartConnect data flow – Architecture 2

G.3 RMD SUPPORT

Remote monitoring and diagnostic support requires appropriate IT infrastructure to be in place for DACA compliance, and access to be available through the firewall into the process control domain at the site. Secure access to the process control domain is achieved through a Citrix server on the process control access domain (PCAD) allowing workstations on the office domain, or VPN connected to the office domain, to view servers on the process control domain. Servers that need to be accessed include the data historian and any specialized vibration or condition data acquisition servers.

It is also possible to set up access credentials so that only certain data servers can be accessed through the remote link, allowing access to the condition monitoring systems, while restricting access to the plant controls. This methodology can also be used to give 3rd parties such as machinery or vibration data acquisition system OEMs access to their installations, allowing the RMD centres to collaborate with the OEMs.

Data historians can also be mirrored to the office domain so that access to the data historian does not require access through the PCAD and into the process control domain (PCD). High speed vibration/condition monitoring systems are typically interfaced to the site DCS and so those data servers reside on the PCD. In this case, access to that data remotely requires secure access through the PCAD.