Machinery and rotating equipment integrity inspection guidance notes

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Machinery and rotating equipment integrity inspection guidance notes

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The Machinery and Rotating Equipment Integrity – Inspection Guidance Notes provide guidance for Inspectors offshore. This document gives sufficient detailed guidance to enable informed and rational judgements to be made, during inspection visits to an offshore installation, on the state and general health of safety critical areas of machinery and rotating equipment.

This report covers the development of inspection guidance notes on major safety issues for process machinery and rotating equipment used on offshore installations.

This Inspection Guidance Note Report focuses on the equipment included within commonly applied machinery and rotating equipment packages for offshore installations.

These notes also provide a Review Process to be used to assess a complete installation, in order to help an inspector understand the impact of operating culture, and context on the safe operation of machinery and rotating equipment installations.

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SYNOPSIS

The Machinery and Rotating Equipment Integrity – Inspection Guidance Notes provide guidance for inspectors offshore. This document gives sufficient detailed guidance to enable informed and rational judgements to be made, during inspection visits to an offshore installation, on the state and general health of safety critical areas of machinery and rotating equipment.

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This issue of the Inspection Guidance Notes Report focuses on the equipment included within commonly applied machinery and rotating equipment packages for offshore installations.

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FOREWORD

This report covers the development of inspection guidance notes on major safety issues for process machinery and rotating equipment used on offshore installations.

This Inspection Guidance Notes Report focuses on the equipment included within commonly applied machinery and rotating equipment packages for offshore installations. The packages are grouped by typical process duties:

The report covers aspects of design, operation and maintenance which might contribute to a major incident and the ways in which the hazards might be designed out, risk level reduced, or the potential consequences minimised.

Section 1 introduces the Inspection Guidance Notes Report, providing a list of the contents of this report, and provides a map to aid navigation through the notes structure.

Section 2 covers the Package concept, outlines the features of the common packages found on offshore installations and discussing the key design issues and hazards related to the complete package.

Section 3 covers Machines (Drivers). Key design issues and relevant hazards are discussed.

Section 4 covers Rotating Equipment (Driven Equipment). Key design issues and relevant hazards are discussed.

Section 5 covers Ancillary Equipment & Systems. This report covers the significant support systems and equipment included within the package or as part of an equipment item.

Section 6 provides Operational Support Guidance identifying operational activities which will have an effect on the safety and reliable operation of the equipment.

Section 7 provides a Review Process that may be used to assess a complete platform, in order that an inspector may understand the operating culture. This may be of particular value as a training aid. The inspector can thus consider the potential effect of the operating environment on the equipment hazards.

The objective of the document is to aid understanding of the technology used and aspects of the equipment which might present seen or unforeseen major risks to operators of the equipment. In cases where concerns are identified which need to be amplified, then reference to a Topic Specialist Inspector should be considered to ensure all aspects of the concern are explored.

The last phase in the development process will translate the guidance into an interactive electronic version to improve accessibility of the information and evaluation processes.
SUMMARY

Inspection visits by safety inspection engineers to process plants operating major machinery have historically concentrated on dangers due to potential contact of operators or technicians with parts of the machine. These concerns are valid, and in some cases will pose a significant hazard to the operators and technicians. The contact dangers, however, are in general not the worst case event, loss of process fluid containment, loss of restraint of a high energy element within a machine, or dangers introduced from enclosures and service supplies can result in significant damage to the machine and anything or anybody near it.

The objective of the document is to aid understanding of the technology used and consider aspects of the equipment, which might present hidden major risks to operators of the equipment. The health of the equipment needs to be viewed both in terms of the context of the process integration of the equipment, and the operating and maintenance management.

USE OF THE GUIDANCE NOTES

These guidance notes provide background information on the machines and rotating equipment by duty and typical combinations or package of equipment in use offshore. The guidance does provide for a general evaluation of the operating on the machines and rotating equipment in use. The Sections are reference by the index, with the “Map” (fig 1-1) showing how the information and evaluation material can be integrated.

TECHNICAL SUPPORT GUIDANCE

A set of inspection guidance notes covering various packages of equipment in use offshore, supported by sections on the major equipment items, where these items contribute to the process hazards on the packaged machinery. The packages are grouped by typical process duties:

<table>
<thead>
<tr>
<th>Process and Export gas compression</th>
<th>Gas turbine driven centrifugal compressor</th>
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<tr>
<td></td>
<td>Electric motor driven centrifugal compressor</td>
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<td>Electric motor driven reciprocating compressor</td>
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<td></td>
<td>Expander driven centrifugal gas compressor</td>
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<tr>
<td>Crude oil handling and main oil export</td>
<td>Gas turbine driven large centrifugal pump</td>
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<td></td>
<td>Electric motor driven multistage centrifugal pump</td>
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<td>Electric motor driven vertical centrifugal pump</td>
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<tr>
<td>Water injection</td>
<td>Electric motor driven HP multistage pump</td>
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<td>Natural gas liquids</td>
<td>Electric motor driven high speed centrifugal pump</td>
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<tr>
<td>Chemical Injection</td>
<td>Air piston driven plunger and diaphragm pumps</td>
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<td>Fire water</td>
<td>Diesel engine driven extended shaft centrifugal pump</td>
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<td>Hydraulic motor drive for fire water centrifugal pump</td>
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<tr>
<td>Utilities</td>
<td>Diesel engine driven alternator</td>
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<td></td>
<td>Gas turbine driven alternator</td>
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<td></td>
<td>Electric motor driven screw compressor</td>
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<tr>
<td></td>
<td>Electric motor driven submersible pump</td>
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</tbody>
</table>
It is common practice to procure packages from a single supplier combining the driving and driven items from separate sources so that the supplier is responsible for designing, constructing and testing the package as a single entity. This minimises the physical size of the unit and the risk of problems during commissioning. It does require that the packager understands the full duty cycle of the system, and the associated risks. It has the great advantage of directly matching the drive unit to the driven unit, physically and in terms of load matching. The operator should ensure that the resulting system performance meets their requirements.

STRUCTURED REVIEWS

Developing a framework for reviewing the procedures, processes and practices on a facility will provide overall indication of the context, desired standards, and effectiveness of activities. Evidence gathered during a structured review provides the initial basis for technical consideration of the facility and will provide support for the conclusions reached by such analysis. The structured review provides the opportunity to probe sensitive areas to show the adequacy or otherwise of the systems, practices, and equipment.

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INTRODUCTION TO GUIDANCE NOTES

1.1 BACKGROUND

The aim of these Inspection Guidance Notes is to provide suitable technical background information on Machinery and Rotating Equipment. This will enable inspectors and specialist inspectors to make informed judgements during inspection visits to offshore installations about the state and general health of safety critical areas of machinery and rotating equipment.

These Inspection Guidance Notes aim to provide supportive information to assist in the understanding of potential safety issues for machinery and rotating equipment installations, highlighting the safety aspects of particular installation with guidance on detailed information gathering and evaluation structures.

These Inspection Guidance Notes have been developed in 2 parts, firstly Technical Guidance on particular machine and rotating equipment systems. Secondly, a Review Process giving generic guidance on information gathering and evaluation for a complete installation.

The guidance for inspectors addresses :-

- A top level process identifying and ranking the evidence that can be gathered on a general visit to support judgements on the apparent state of the unit.

- A structure for assessment of operating units by observations to allow deeper understanding of the machinery, leading to judgements on the requirements for action, or further investigation.

- Means by which machine related observations and auditable points, supported by additional information, can be used to evaluate the state of machine systems.

- Structured technical data to support the observations and assessments of the Inspector.
1.2 MAP OF GUIDANCE PROCESS

The Map provides the structure of the Guidance Notes, directing the user to the appropriate entry point.

Figure 1 – 1
1.3 APPLICATION OF GUIDANCE NOTE

- These Inspection Guidance Notes are split into two major parts, the Technical Guidance Notes on machinery and rotating equipment provided as a series of notes on specific systems, and the Review Process Guidance providing a structure for gathering and evaluating relevant information.

Technical Guidance

The technical guidance is written in a series of sections covering packaged machine systems, the specific machine and rotating equipment included in the package and the ancillary equipment installed to support the operation of the packaged equipment.

The technical guidance covers aspects of:

- General Description
- Main components
- Main sub systems (seal supply, lubrication)
- Safety systems
- Main services

with identification of :

- Hazards
- Operation
- Maintenance
- Control
- Key technical areas

Review Process Guidance

The map (Figure 1-1) shows the structure for a process which an Inspector might go through during a general visit. Documents have been prepared for training / reference purposes, suggesting topics and appropriate evidence of a satisfactory system. These have been split into 3 streams, being Induction / Meetings, Control Room, Plant Tour.

None of the above directly affects machine & rotating equipment safety, but taken as a whole is the background against which a machine incident may occur. In a good operating regime the potential incident will be recognised and controlled with no significant effect on the safety or operation of the platform or installation. In a poor operating regime an incident may reach a dangerous state before its effect is recognised.

It is intended that the observations made of the general state of the installation and manning be "filtered" through an evaluation matrix, with a view to identifying those issues / practices which raise sufficient concern to justify deeper investigation. Any particularly serious concerns may require immediate discussion with the OIM.
The "filtered" observations can then be used to aid in the planning of a structured review of those parts of the installation which give rise to concerns. The approach may equally be used to deal with non-machines issues.

Investigation

The material available as part of an incident investigation may be drawn into the "Map" at this point. The incident data may be compared with Inspector(s) general impression of an installation. The data may be used to help set up a structured review of the installation in question.

Planned Study

The Planned Study either for a structured visit with machines as a highlight or for a Safety Case also enters the "Map" at this point. The intentions of the Safety Case may be tested against actual experience on similar installations.

Support Information

For all of the above topics, support information is then available, both on the technical and operational fronts, to indicate how machine systems should reasonably be designed and operated. While this information, by its nature has to be generic, it provides a prompt of reasonable good practice, and some of the known problems & pitfalls.
SECTION 2.0  EQUIPMENT PACKAGES

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- Complete machine and rotating equipment systems are built as packages.
- One vendor is then responsible for design & build of the complete assembly
- Packages save weight and space but can be very congested
- Hazards are primarily related to the machine / rotating equipment items within the package
- Hazard assessment must take account of the proximity of other equipment and packages

2.0.1 PACKAGE CONCEPT

Equipment Packaging in this context describes the concept of providing a complete machine and rotating equipment system, or even a complete processing section, as a single entity or module. A "package" is designed and assembled as an operating entity, usually by the supplier of the most complex or most expensive machine item. It will comprise machine(s), rotating equipment, couplings, pipework, vessels and control system. The equipment will be mounted on one or more baseframes or skids, and will have been pre-wired, pre-piped and (as far as possible) tested prior to shipment.

Offshore installations have tight space constraints and are flexible. To provide a "foundation" rigid enough for machine alignment purposes, it is necessary to put equipment on self-contained skids or base-frames, which are rigid enough to maintain machine alignment, take up as little space as possible, and can be tested prior to delivery. It is normal practice for a skid or base-frame to be designed for "3-point" mounting to accommodate movement of the structure. In this way all necessary stiffness is contained within the skid, where some movement of mounting points is possible without affecting machine alignment.

Offshore installations such as FPSO's are subject to wave motion, which can be severe during adverse conditions. Equipment packages have safe operating limits, for the machines themselves and ancillary systems. The manufacturer will define these, and operators of equipment need to be aware of such limits, with procedures to avoid equipment operation when conditions outside the design capability are possible. The design of the equipment requires taking account of such conditions and will determine the specific limits that should not be exceeded.

2.0 – 1
2.0.2 ADVANTAGES OF PACKAGING

Packaging can reasonably be expected to yield the following benefits:

- Reduced weight.
- Reduced footprint area.
- Pre-testing at vendor's works reduces site installation, testing & commissioning time / cost.
- Package vendor develops expertise in producing "standard packages".
- Improved integration of machine, rotating equipment and control system.

2.0.3 POSSIBLE DIS-ADVANTAGES OF PACKAGING

Packaging may risk:

- Equipment which has not been designed to suit the real needs of the installation.
- Equipment which is very densely packed and difficult to maintain.
- Little or no commonality with other packages (particularly Control / Electrical).
- Hazards within the Package that have not been assessed by the overall Hazard Study process.
- Reduced flexibility for future process design changes.
- Dependence on vendor for expertise, records, and service.

2.0.4 TYPICAL PACKAGES

The following packaged units are typically located on Offshore Installations:

- Process and Export gas compression
  - Gas turbine driven centrifugal compressor
  - Electric motor driven centrifugal compressor
  - Electric motor driven reciprocating compressor
  - Expander driven centrifugal gas compressor
- Crude oil handling and main oil export
  - Gas turbine driven large centrifugal pump
  - Electric motor driven multistage centrifugal pump
  - Electric motor driven vertical centrifugal pump
- Water injection
  - Electric motor driven HP multistage pump
- Natural gas liquids
  - Electric motor driven high speed centrifugal pump
- Chemical Injection
  - Air piston driven plunger and diaphragm pumps
- Fire water
  - Diesel engine driven extended shaft centrifugal pump
  - Hydraulic motor drive for fire water centrifugal pump
- Utilities
  - Diesel engine driven alternator
  - Gas turbine driven alternator
  - Electric motor driven screw compressor
  - Electric motor driven submersible pump
2.0.5 TREATMENT OF PACKAGES WITHIN INSPECTION GUIDANCE NOTES

As there could be a very large number of possible machine / rotating equipment combinations suitable for packages, a number of typical packages are described and assessed within this report. The design and associated hazards of each package will be covered insofar as they relate to the package itself. This in particular will reflect the potential interaction of the driver and driven equipment in terms of proximity, drive train issues, common control and support services.

Each machine and rotating equipment type can be assessed separately as a piece of equipment in its own right, with associated design and hazard assessment. Similarly, Ancillary Equipment and Systems will be covered, relevant to the type of equipment supported.

Section 2 covers the selected range of packages, Section 3 the Machines (drivers), Section 4 the Rotating (driven) equipment. All common theme material on Ancillaries is gathered in Section 5.
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- **Gas Compressors** are used to increase the pressure of a process gas, in order to drive it into a pipeline system to an onshore process plant, to use on the producing well as gas lift, to re-inject gas for reservoir pressure maintenance or for use as a fuel gas.

- **Centrifugal compressors** are preferred for high mass flow systems because of their simplicity and reliability compared with screw or reciprocating compressors. In order to achieve the required pressure ratio, several compression stages may be required, in one or more casings. Each compression stage is carried out by a rotor in a matching diffuser.

- **Mechanically linked compressors**, working together with drive and support equipment, may be regarded as a single system for design and safety purposes.

- The major hazards relate to the inventory of flammable gas that can be released if there is an equipment failure. Hazard assessment must relate to the complete package and not just the compressor body. The injury risk from a mechanical failure is relatively low, as the robust casing will retain parts. Hot / moving parts may still cause injury local to the machine. Most compressors have gas seals on moving drive shafts or piston rods. These are safety critical items when handling hazardous materials.
It is often necessary to increase the pressure of a gas for processing, storage or transport reasons. There are two fundamentally different principles used to compress gases. Dynamic Compressors are continuous flow machines, they use rotating vanes or bladed discs to sequentially accelerate the gas (increasing its energy) then decelerate it (trading kinetic energy for increased pressure). This normally requires a number of stages, often within the same casing. Dynamic compressors always have an open gas route through the machine.

**Positive Displacement Compressors** are discontinuous flow machines, they induce a fixed volume of gas into a pocket, chamber or cylinder for compression. The size of this pocket is then reduced mechanically, compressing the gas. At the end of the compression cycle the pocket opens, discharging the high-pressure gas. Often only one or two stages of this compression process are required. There is never an open gas passage from delivery to suction (except for leakage through the clearances between moving parts.

**Dynamic Compressors** (as opposed to Positive Displacement) have relatively few moving parts, low vibration levels and thus high intrinsic reliability. Hence they are preferred over other compressor types where they can be used effectively. Compressor selection is a complex and subjective process, with similar duties resulting in quite dis-similar compressor choices. The most significant type of dynamic compressor used offshore are centrifugal compressors, as such are the focus of description and assessment within this report.

![Figure 2.1 - 1 Barrel Type Process Gas Compressor](image)

The materials of construction must be able to take the mechanical loads; in addition those parts in contact with the process gas must be chemically compatible. Non-metallic materials are often used in seals and valves.

It is common practice, for centrifugal compressors, to mount multiple compression stages on the same shaft within a common casing. For pressure ratios above perhaps 10 : 1, and for
discharge pressures above perhaps 20 barg, a Barrel Type Multistage Centrifugal Compressor would be a reasonable selection.

Where a high-pressure ratio is required, different sizes of compressor, running at different speeds, may be linked to a single common driver. Gearbox(es) match the various shaft speeds.

To achieve reasonably practical shaft alignment and permit thermal expansion, flexible couplings are used between co-axial shafts.

Compressors require robust base-plates to carry shaft torques and piping loads without excessive distortion. This is particularly true offshore with the baseplate having to provide the necessary stiffness for alignment and dynamic stability on the offshore installation where the structure itself is too mobile.

Compressors require suitable piping, interstage vessels and coolers with associated control systems. Together with baseplate and driver this forms the "Compressor System". The system may extend a long way beyond the package with elements of the system located in other parts of the installation.

The vast majority of compressors are shaft driven by a separate electric motor, gas turbine or diesel engine. Thus the compressor will require at least one shaft seal, which may have to contain hazardous gas.

The safety of compressors handling hazardous materials is dominated by their shaft sealing systems. These require appropriate design, maintenance and operator attention.
2.1.1 GAS TURBINE DRIVEN COMPRESSOR PACKAGE TECHNICAL SUPPORT

Gas Turbines are available in a range of sizes for power generation and as mechanical drives. They are supplied in package format, often with the driven equipment already mounted. Two fundamental designs, Aero-derivative and Industrial, are available. Due to the package approach the customer has little direct influence over design, although user groups have been set up to address common issues. A mechanical failure of the turbine may cause substantial mechanical damage within the acoustic enclosure, but is less likely to cause major injury / damage outside unless blades or other missiles are thrown. The greater risk is the uncontrolled release of fuel (gas or liquid); this may or may not be associated with a mechanical failure. There are well-understood risks to maintenance personnel during overhaul work; the greater safety risk is that a major failure is initiated by inadequate or incomplete maintenance work during subsequent operation.

Some specific pieces of terminology are used:

"Power Generation Package" comprises a packaged Gas Turbine and Alternator on a common base. The unit is intended for fixed speed operation for electricity generation, thus the gas turbine will have a common power turbine. There will be a load gearbox to match turbine and alternator shaft speeds.

"Mechanical Drive" comprises a packaged gas turbine and rotating equipment driven by it. The base frame will be a common single unit. For larger or on shore units this is often of two or more segments bolted together. The gas turbine may be of two distinct types as below:

"Single Shaft" turbine has all internal parts rotating at the same speed. This gives simplicity, but requires the driven equipment to be started at the same time as the turbine core. This design is normally applied to Power Generation.

"Twin Shaft" turbines permit the core engine to be started without spinning the driven equipment, this is applicable to Mechanical Drive packages. As an example, 3 alternate Gas Turbine driven Packages are shown in outline below, showing the arrangement of the Turbine, Rotating Equipment & Ancillaries. For clarity, the Acoustic Enclosure, which is normally fitted over the turbine only, is not shown. Inlet and outlet duct systems are not shown.
2.1.1.1 Gas Turbine Driven Compressor Package - Description

The package comprises a twin shaft Aero-derivative Gas Turbine driving a Barrel Casing Centrifugal Compressor on hydrocarbon gas service, complete with Control System & Ancillary Equipment, all mounted on a 3-point mounting skid baseplate. The Gas Turbine is enclosed in an Acoustic Enclosure with its own Fire & Gas System. Ancillary Equipment & systems will include:

- Inlet Air System & Filter
- Fuel System
- Exhaust Duct
- Lubricating Oil System
- Compressor Dry Gas Seals & Support System
- Drive Gearbox (if required)
- Auxiliary Gearbox
The Process Schematic Diagram of such a system is shown below.

**Figure 2.1 – 4 Process Schematic Diagram - Gas Turbine Driven Gas Compression System**

### 2.1.1.2 Package Entity

Physically, the package is an enclosed gas turbine with one or two gas compressors co-axially on the end of the output shaft. All machine elements are mounted to a common baseframe that is sufficiently rigid to maintain machine alignment, despite movement of the supporting structure or vessel. The 3-point mounting system eliminates the transmission of twisting forces to/from the baseframe. In order to save space, and the weight of additional bases, as many as possible of the ancillary systems e.g. lubrication oil system, seal gas support system, are built into the main baseframe. The control panel may be built on to the end of the baseframe (which is convenient for pre-wiring) or mounted separately (which permits control panels for separate machines to be grouped together).

The Acoustic Enclosure for an Aero-derivative Gas Turbine will be close fitting, and fitted out with ventilation and Fire & Gas Detection Systems. The internal space will be tightly packed, making access to internal components quite difficult. Thus any problem on one component has the potential to affect adjacent components / systems, whether by release of material, vibration or over-heating. Similarly, it may be necessary to remove a component either to work on that component or to gain access to adjacent components.
The gas compressor and drive gearbox (if fitted) will be outside the acoustic enclosure, but still very closely packed with service pipework & cable trunking. Good design should permit ready access to compressor bearings, instruments and drive couplings.

The air inlet housing will be located separate from the turbine next to the external cladding of the process area.

2.1.1.3 Package Elements

2.1.1.3.1 Gas Turbine

The Aero-derivative Gas Turbine mounted within an Offshore Package will be centre-line mounted from the baseframe, ensuring internal alignment while permitting thermal expansion of the machine. The main drive shaft, which will be at the "hot" or exhaust end for a mechanical drive package, will be fitted with a flexible coupling, as will any auxiliary drive shafts. Flexible connections will link to the inlet and exhaust ducts. The turbine will have a fuel manifold wrapped around the middle of the machine, with multiple combustor fuel feeds.

Hot surfaces will be fitted with heat shields or thermal insulation. These must be in place for operator safety.

The gas turbine is dependent on various ancillary systems for safe operation, operating procedures and control system must ensure that these are operational prior to turbine start, and at all times during operation.

Any mechanical failure of the turbine, or an explosion within the acoustic enclosure, could disrupt fuel pipework, with the potential for a significant release. Missiles, in the form of ejected compressor blades or other high-speed components, may be thrown in a mainly radial direction, with the potential to damage people or critical systems at some distance from the turbine.

Technical and safety aspects of the Gas Turbine system are described in more detail in Section 3.1 of the Guidance Notes.

2.1.1.3.2 Multi-stage Centrifugal Gas Compressor

The Multi-stage Barrel Type Centrifugal Gas Compressor will be centre-line mounted on an extension of the common base-frame, ensuring shaft alignment. Where two compressors are required to achieve the required pressure ratio, the second compressor is likely to be driven from the first compressor shaft, by a mechanical gearbox. All shafts will require alignment within the tolerances of the shaft couplings. Process pipework will be connected to the barrel casings, normally by flanged connections, although fully welded assembly is possible. Thermal expansion of process pipework should be achieved by good pipe support and flexibility design, bellows are not preferred. The compressor casing and pipework may be lagged, as required by operating temperatures. The centre-line support system must not be lagged, as it has to remain at ambient temperatures, so far as is possible.

Multi-stage centrifugal gas compressors contain high speed moving parts within a robust casing. Mechanical failure can result in severe internal damage but this is not likely to pose a direct hazard to people who are not close to the equipment. The greatest potential threat is the uncontrolled release of a flammable hydrocarbon gas, particularly if the gas is then able to form an explosive mixture within a relatively enclosed space.

The risk is reduced by ensuring that compressors are competently operated and maintained, and that protective systems are regularly tested and in good order. The overall system design should provide suitable remote isolations, knockout pots and adequate vent routes.

Technical and safety aspects of the Centrifugal Gas Compressor system are described in more detail in Section 4.1 of the Guidance Notes.
2.1.1.3.3 Gearboxes

The inclusion of a drive gearbox within the machine package allows the manufacturer to optimise operating speeds of the Gas Turbine driver and Centrifugal Compressor separately. The technical disadvantages of additional skid length, equipment complexity, and weight being offset with benefits for the design of compressor and turbine.

Gas Turbine packages will include an Auxiliary Gearbox, normally integral to the "cold" end of the machine. This provides the necessary linkage for turbine starting, and mechanical drives where required for oil or fuel pumps.

There are a limited number of safety issues from inclusion of a gearbox within a machine package. The most serious are:

- The potential for accidental or failure engagement of auxiliary drives, used to rotate the compressor at low speed, leading to massive overspeed and usual disintegration of the drive.
- For bursting of the gear wheels (design or manufacturing flaws).
- For fires due to leakage of lubricating oil.

Technical and safety aspects of the gearbox systems are described in more detail in Section 5.5 of the Guidance Notes.
2.1.1.3.4 Main Drive Coupling

The use of flexible couplings within a machine package is essential to provide the necessary degrees of freedom to enable the machine elements to be aligned, and compensate for any flexibility inherent in the installation skid.

Misalignment of the coupling, even within its tolerance limits, puts increased loads on adjacent shaft bearings. It also reduces the service life of the coupling, as flexible elements are subjected to greater strains. Coupling lubrication (where required) and inspections must be proactively maintained as the coupling has significant mass and has the potential to become a dangerous missile if it fails. Loss of drive is not normally a safety-related incident; special design requirements apply if drive continuity is critical.

Technical and safety aspects of flexible shaft couplings are described in more detail in Section 5.6 of the Guidance Notes.

2.1.1.3.5 Lubrication System

The supply of oil for lubrication of bearings and couplings, support to sealing systems and hydraulic operation of actuators requires clean oil at appropriate pressures. For package units this can be delivered from a common system feeding all elements within the package.

The oil pumps may be driven by electrical power or by auxiliary mechanical drives from the turbine. Electrical drives are much simpler and make pump location much easier. Where the installation has reliable electrical supplies this option would be preferred. If the package is required to operate in "stand-alone" manner even after a total electrical failure, then shaft drives are required. Power requirements for control valves and other instruments must be considered, an UPS system may be required. As the package lubrication system will be very congested, and fairly inaccessible, oil leaks from pump seals or pipe joints will be difficult to detect and repair. The use of drip / drain trays and the least possible number of screwed fittings is advised.

Where a common lubrication system is fitted, in particular one which also provides compressor seal oil, there is a real issue of potential cross-contamination of the oil. Liquid fuel or the heavier fractions of hydrocarbon gases can dissolve in oil, reducing its viscosity and increasing its flammability. The fire hazard associated with this potential problem will be greatly reduced if the oil system operates under a nitrogen atmosphere.

The most serious issues for the supply of oil to a machine package arise from either failure of the supply that can lead to damage of the machines, or from oil spill or leakage resulting in a fuel source for potential fires.

Technical and safety aspects of lubrication systems are described in more detail in Section 5.2 of the Guidance Notes.

2.1.1.3.6 Control System

Machines within a package must be integrated to function as a complete system. Therefore control systems are designed to provide this essential control and protection for the machine elements. There will be key logical interlocks between the main control system, the turbine control and the compressor control. These will provide for start / run permits and sequence control, e.g. Control Room authorisation for turbine start. These logical signals must be of high integrity as they cannot be bypassed or ignored. There will then be numerical (possibly a mixture of analogue and digital) signals controlling e.g. compressor load, turbine set speed, and for data logging.

It may be permissible to operate with manual over-ride on some of these signals, for example during load changes. Alternately, the system may be intended to operate purely in fully automatic mode. This will require increased sophistication e.g. speed ramping, critical speed avoidance, operating temperature bands, load and speed matching during duty changes.
Although as much as possible of the Package will be tested onshore, prior to shipping, it will not be possible to fully test and tune the control system prior to commissioning. The interlocks, and to some degree the load control, might be tested by use of a computer model. The greater the degree of automation, the greater the demands on the commissioning team, who must set up and prove the system, knowing that in normal operation load changes will be done without close manual supervision.

Control software must be rigorously checked, subject to strict version and change recording and control. Pre-programmed cards can be fitted to the wrong machine; they may be physically identical (to Model and Serial Number) but carry different instructions.

Details of the requirements for the systems below are noted in the Guidance notes for each element.

2.1.1.3.7 Air Intake Filter & System

Air feed to the gas turbine will be filtered through a series of filtration elements to ensure cleanliness of combustion air. (Ref. Section 5.10)

2.1.1.3.8 Acoustic Enclosure

The gas turbine is enclosed in a acoustic enclosure – this reduces the risk from the noise hazard but introduces hazards of an enclosure possibly containing flammable gas. (Ref. Section 3.1)

2.1.1.3.9 Fuel System

The fuel system will take Gas Fuel and/or Liquid Fuel from the installation at the available pressure, filter the fuel(s) and raise pressure if necessary. The fuel system will control the rate of supply of fuel(s) and isolate the supply when necessary. See Section 5.1.1 & 5.1.2 for further details relevant to Gas Fuel and Liquid Fuel respectively.

2.1.1.3.10 Exhaust System

This system is specific to the Gas Turbine and is covered in Section 3.1.6.6

2.1.1.3.11 Compressor Dry Gas Seals & Support System

The compressor seals and support system are covered in detail in Section 5.3.4.

2.1.1.3.12 Process Coolers

Process coolers, e.g. Intercoolers, will typically be shell and tube heat exchangers built to a recognised code. ASME and BS 5500 are commonly used. Ideally, cooling will be against a closed fresh water cooling system, to minimise problems of corrosion, fouling and pollution. See Section 5.11 for further details.

2.1.1.3.13 Piping Systems

Piping systems are generally constructed to international standards, see Section 5.7 for details, special standards are required for fuel gas where double skinned piping is installed. (See Section 5.1.1)

2.1.1.3.14 Control and Anti Surge Valves

The gas compressor is likely to have discharge control, recycle and anti-surge control valves, the latter two duties may be combined. These valves are not necessarily provided by the
package vendor, but their specification, design, installation and control must be carefully integrated into the operation of the package. In particular, any changes in compressor duty or design must be allowed for in the valve design and set-up. See Section 5.13 for more detail.

2.1.1.3.15 Condition Monitoring

Condition monitoring on larger Machine Packages will be provided as part of the package. Vendors will offer their own preferred system, or will agree to tailor a system to suit the client's requirements. It is important to ensure that the system provided suits the proposed method of operating and maintaining the equipment. See Section 5.12 for more detail.

2.1.1.4 Integration Aspects

2.1.1.4.1 Hardware Matching

The design of the package must ensure that the operating capability of each element of the package matches or exceeds the greatest potential demand placed on it by the system.

For a Gas Turbine driven Centrifugal Compressor the major elements that must be considered are:

- Power rating
- Torque rating
- Speed
- Torsional critical speeds
- Lateral critical speeds

Details of the requirements for these systems are noted in the Guidance notes for the separate elements. Lateral & Torsional Critical Speed issues are covered in Section 5.6.1.

2.1.1.4.2 Operational Matching

The operation of a package unit requires that there are no conflicts within the system that would compromise safe operation of the system.

For a Gas Turbine driven Centrifugal Compressor the issues that must be considered are given in Operation Support Guidance Section 6.1.

2.1.1.5 Hazard Assessment

The hazards posed by the package are a combination of the hazards posed by the individual machine and rotating equipment items, with possibly some additional hazard due to potential interactions. Assessment of the hazards from the package should, however, be made easier at the design stage because one design team should be dealing with the complete package, and have all relevant information compiled together.

See Section 7.2.4 for a structured set of Hazard Assessment Tables.

2.1.1.5.1 Process Fluid Containment

The risk release of process fluid or fuel is described for each element in Sections 3.1 and 4.1 of this guidance. There is the hazard of one system affecting the other, however this is a specific case of hazards present on the facility and the guidance given for each element addresses such hazards.
2.1.1.5.2 **Equipment Hazards**

In practice, the equipment hazards of packaged equipment are the same as the individual units. There is a risk of an incident on one component of the system adversely affecting the other, but this applies to any multiple machine installation.

2.1.1.5.3 **Operational / Consequential Hazards**

Packaging should have no particular influence in this area; Mechanical, Process and Control interactions apply equally to Packaged and Non-packaged units. It can be argued that there is a reduction in risk, because the Package should have been designed as a whole to a consistent duty requirement.

2.1.1.5.4 **Maintenance / Access Hazards**

Maintenance on packaged units can be significantly more difficult because of very congested construction, this is not necessarily hazardous but can result in more sprains and similar injuries as people struggle to work in restricted spaces. Well-designed packaged units incorporate tailored lifting / slinging facilities. It is usually more appropriate to change out an assembly than to attempt to attempt a failed component in situ. There is a potential issue of isolation of electrical and other energy sources where isolation of part of the package may not isolate a closely adjacent part. This must be covered by Maintenance / Permit to Work procedures.

2.1.1.6 **Applicable Standards**

Selection of API Standards Relevant to Machinery in use in Refineries / Offshore

<table>
<thead>
<tr>
<th>Standard</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>API 11PGT 1992</td>
<td>Packaged Combustion Gas Turbines</td>
</tr>
<tr>
<td>API 2031 1991</td>
<td>Combustible-Gas Detector Systems &amp; Environmental / Operational Factors Influencing their Performance</td>
</tr>
<tr>
<td>API 616 1998</td>
<td>Gas Turbines for Refinery Services</td>
</tr>
</tbody>
</table>

General Standards for machinery can be found in Section 5.15
2.1.2 ELECTRIC MOTOR DRIVEN CENTRIFUGAL COMPRESSOR PACKAGE TECHNICAL SUPPORT

2.1.2.1 ELECTRIC MOTOR DRIVEN CENTRIFUGAL COMPRESSOR PACKAGE –

DESCRIPTION

The package comprises a High Voltage Electric Motor driving a Barrel Casing Centrifugal Compressor (or pair of compressors in series) on hydrocarbon gas service, complete with Control System & Ancillary Equipment, all mounted on a 3-point mounting skid baseplate. Ancillary Equipment & systems will include:

- Lubricating Oil System
- Compressor Dry Gas Seals & Support System
- Drive Gearbox (if required)
- Shaft Couplings
- Cooling System
- Piping Systems
- Condition Monitoring

Figure 2,1 – 6 Motor Driven Gas Compressor Package with Gearbox
2.1.2.2 PACKAGE ENTITY

Physically, the package is a High Voltage Electric Motor with one or two gas compressors co-axially on the end of the output shaft. All machine elements are mounted to a common baseframe – see Section 5.14 of the Guidance Notes for installation details. The control panel may be built on to the end of the baseframe (which is convenient for pre-wiring) or mounted separately (which permits control panels for separate machines to be grouped together).

The motor will be fairly accessible; the gas compressor and drive gearbox (if fitted) will be closely packed with service pipework & cable trunking. Good design should permit ready access to compressor bearings, instruments and drive couplings.

The package will require effective ventilation to ensure dilution of any leakage gas. An air cooled motor relies on this ventilation air for heat removal, a water cooled motor does not require air for cooling.

2.1.2.3 PACKAGE ELEMENTS

2.1.2.3.1 Electric Motor

The High Voltage Electric Motor will normally be foot mounted on the baseframe, ensuring support of the heavy stator and rotor. The motor shaft will be fitted with a flexible coupling, to accommodate thermal expansion and residual mis-alignment. Motors have a predictable thermal growth, which is allowed for in the alignment process.

The motor will be aligned to the compressor / gearbox.

The electric motor will require access to terminal box, access panels, bearings and air heat exchanger (normally mounted on top). Crane access will be required to lift the complete motor, also to remove the rotor (preferably without moving either the motor stator or the compressor).

Technical and safety aspects of the High Voltage Electric Motor are described in more detail in Section 3.5 of the Guidance Notes.

2.1.2.3.2 Multi-stage Centrifugal Gas Compressor

The Multi-stage Barrel Type Centrifugal Gas Compressor will be centre-line mounted on the common base-frame, ensuring shaft alignment. Where two compressors are required to achieve the required pressure ratio, the second compressor is likely to be driven from the first compressor shaft, by a mechanical gearbox. All shafts will require alignment within the tolerances of the shaft couplings. Process pipework will be connected to the barrel casings, normally by flanged connections, although fully welded assembly is possible. Thermal expansion of process pipework should be achieved by good design, bellows are not preferred. The compressor casing and pipework may be lagged, as required by operating temperatures. The centre-line support system must not be lagged, as it has to remain at ambient temperatures, so far as is possible.

Multi-stage centrifugal gas compressors contain high speed moving parts within a robust casing. Mechanical failure can result in severe internal damage but this is not likely to pose a direct hazard to people who are not close to the equipment. The greatest potential threat is the uncontrolled release of a flammable hydrocarbon gas, particularly if the gas is then able to form an explosive mixture within a relatively enclosed space.

The risk is reduced by ensuring that compressors are competently operated and maintained, and that protective systems are regularly tested and in good order. The overall system design should provide suitable remote isolations, knockout pots and adequate vent routes.
Technical and safety aspects of the Centrifugal Gas Compressor system are described in more detail in Section 4.1 of the Guidance Notes. The Process Schematic Diagram of such a system is shown below.

2.1.2.3.3 Gearboxes

Fixed speed A.C. motors on 60 Hz supply can only run at nominal speeds of 3600 rev/min, 1800 rev/min, or slower. The equivalent speeds for 50 Hz supply are 3000, 1500, etc. Centrifugal Gas Compressors, particularly for higher pressures, typically run at up to 7000 rev/min. To achieve speed matching, it is common to fit a drive gearbox between the motor and compressor, or between a Low Stage compressor running at motor speed, and a High Stage compressor running at a higher speed.

Typically, two types of gearbox are used:

Parallel shaft gearbox, using helical or herring bone pattern gears to increase the speed in one or two stages. This type of gearbox displaces the driven equipment laterally by typically 0.5 – 1 metre. It is easy to inspect and maintain, as the gearbox cover can be removed without disturbing the gear mesh.

Epicyclic gearboxes, which work on the "sun and planets" principle, have co-axial input and output shafts. Hence all machine shafts are in line, making alignment easier. Epicyclic gearboxes are also smaller, for a given power, than parallel shaft units. They have inspection covers, but full examination requires the gearbox to be removed and at least partially stripped.
There are a limited number of safety issues from inclusion of a gearbox within a machine package. The most serious are:

- The potential for unplanned engagement of auxiliary drives, used to rotate the compressor at low speed, leading to massive overspeed and, usually, disintegration of the auxiliary drive.
- For bursting of the gear wheels (design or manufacturing flaws).
- For fires due to leakage of lubricating oil.

Technical and safety aspects of the gearbox systems are described in more detail in Section 5.5 of the Guidance Notes.

### 2.1.2.3.4 Main Drive Coupling

The use of flexible couplings within a machine package is essential to provide the necessary degrees of freedom to enable the elements of the machine to be aligned, to compensate for thermal expansion and for any flexibility inherent in the installation skid.

Misalignment of the coupling, even within its tolerance limits, puts increased loads on adjacent shaft bearings. It also reduces the service life of the coupling, as flexible elements are subjected to greater strains. Coupling lubrication (where required) and inspections must be proactively maintained as the coupling has significant mass and has the potential to become a dangerous missile if it fails. Loss of drive is not normally a safety-related incident; special design requirements apply if drive continuity is critical. Note a failing drive may continue to operate for a limited time before further damage causes complete failure.

Technical and safety aspects of flexible shaft couplings are described in more detail in Section 5.6 of the Guidance Notes.

### 2.1.2.3.5 Lubrication System

The supply of oil for lubrication of bearings and couplings, support to sealing systems and hydraulic operation of actuators requires clean oil at appropriate pressures. For package units this can be delivered from a common system feeding all elements within the package.

Technical and safety aspects of lubrication systems are described in more detail in Section 5.2 of the Guidance Notes.

### 2.1.2.3.6 Control System

Machines within a package must be integrated to function as a complete system. Therefore control systems are designed to provide this essential control and protection for the machine elements.

Details of the requirements for these systems are noted in the Guidance notes for each element.

The overall description of package control systems is included in Section 5.13 of the Guidance Notes.

### 2.1.2.3.7 Compressor Dry Gas Seals & Support System

The compressor seals and support system are covered in detail in Section 5.3.4.
2.1.2.3.8 Process Coolers

Process coolers, e.g. Intercoolers, will typically be shell and tube heat exchangers built to a recognised code. ASME and BS 5500 are commonly used. Ideally, cooling will be against a closed fresh water cooling system, to minimise problems of corrosion, fouling and pollution. See Section 5.11 for further details.

2.1.2.3.9 Piping Systems

Piping systems are generally constructed to international standards, see Section 5.7 for details.

2.1.2.3.10 Control and Anti Surge Valves

The gas compressor is likely to have discharge control, recycle and anti-surge control valves, the latter two duties may be combined. These valves are not necessarily provided by the package vendor, but their specification, design, installation and control must be carefully integrated into the operation of the package. In particular, any changes in compressor duty or design must be allowed for in the valve design and set-up. See Section 5.13 for more detail.

2.1.2.3.11 Condition Monitoring

Condition monitoring on larger Machine Packages will be provided as part of the package. Vendors will offer their own preferred system, or will agree to tailor a system to suit the client's requirements. It is important to ensure that the system provided suits the proposed method of operating and maintaining the equipment. See Section 5.12 for more detail.

Figure 2.1 – 8 Barrel Casing Compressor In Service
2.1.2.4 INTEGRATION ASPECTS

2.1.2.4.1 Hardware Matching

The design of the package must ensure that the operating capability of each element of the package matches or exceeds the greatest potential demand placed on it by the system.

For an Electric Motor driven Centrifugal Compressor the major elements that must be considered are:

- Power rating
- Starting Torque/ Speed curve
- Speed
- Torsional critical speeds
- Lateral critical speeds

Details of the requirements for these systems are noted in the Guidance notes for the separate elements. Lateral & Torsional Critical Speed issues are covered in Section 5.6.1.

2.1.2.4.2 Operational Matching

The operation of a package unit requires that there are no conflicts within the system that would compromise safe operation of the system.

For an Electric Motor driven Centrifugal Compressor the issues that must be considered are given in Operation Support Guidance Section 6.

2.1.2.5 HAZARD ASSESSMENT

The hazards posed by the package are a combination of the hazards posed by the individual machine and rotating equipment items, with possibly some additional hazard due to potential interactions. Assessment of the hazards from the package should, however, be made easier at the design stage because one design team should be dealing with the complete package, and have all relevant information compiled together.

See Section 7.2.4 for a structured set of Hazard Assessment Tables.

2.1.2.5.1 Process Substance Containment Hazards

Containment hazards relating to the Compressor are covered in Section 4.1.3.1

See Section 3.5.3.1 for Ignition/ Explosion hazards within the H.V. electric motor.

The potential for the motor providing a source of ignition for releases from the compressor, other equipment in the area, or from the lubrication system, should be covered by the area hazard assessment and the electrical area classification studies. The motor will in any case be of Explosion Proof or Increased Safety design.

2.1.2.5.2 Equipment Hazards

In practice, mechanical hazards of packaged equipment are the same as the individual units.
The Mechanical Hazards associated with the elements are:-

Damage and loss of containment of machine elements due to high mechanical energy stored or transmitted within rotor shafts, gear box, couplings.

Electrical Hazards :-

Description of the source of the hazards and the protection / preventative measures necessary are given in Electric Motor Sections 3.3 (Generic A.C.) and 3.5 (High Voltage > 500 kW) of the Guidance Notes.

There is a risk of an incident on one component of the system adversely affecting the other, but this applies to any multiple machine installation.

2.1.2.5.3 Operational / Consequential Hazards

Packaging should have no particular influence in this area; Mechanical, Process and Control interactions apply equally to Packaged and Non-packaged units.

The Operational Hazards associated with the elements are :-

Loss of containment of process substances which are flammable and toxic

Description of the source of the hazards and the protection / preventative measures necessary are given in Centrifugal Gas Compressor Guidance Notes Sections 4.1.3, 4.1.4 and 4.1.5.

2.1.2.5.4 Maintenance / Access Hazards

Maintenance on packaged units can be significantly more difficult because of very congested construction, this is not necessarily hazardous but can result in more sprains and similar injuries as people struggle to work in restricted spaces. Well-designed packaged units incorporate tailored lifting / slinging facilities. It is usually more appropriate to change out an assembly than to attempt to attempt a failed component in situ. There is a potential issue of isolation of electrical and other energy sources where isolation of part of the package may not isolate a closely adjacent part. This must be covered by Maintenance / Permit to Work procedures.

2.1.2.6 APPLICABLE STANDARDS

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations ( Transposed Harmonised Standards ) can be found in Section 5.15 the specific standards relating to this package are:-

BS EN 1012-1 1996 Compressors and vacuum pumps – Safety requirements – Part 1: Compressors.

Selection of API Standards Relevant to Machinery in use in Refineries / Offshore :-


General Standards for machinery can be found in Section 5.15
2.1.3 ELECTRIC MOTOR DRIVEN RECIPROCATING COMPRESSOR PACKAGE TECHNICAL SUPPORT

2.1.3.1 ELECTRIC MOTOR / RECIPROCATING COMPRESSOR PACKAGE –

DESCRIPTION

The package comprises a High Voltage Electric Motor driving a Reciprocating Process Compressor on hydrocarbon gas service, complete with Control System & Ancillary Equipment, all mounted on a 3-point mounting skid baseplate. Ancillary Equipment & systems will include:

- Lubricating Oil Systems
- Compressor Seal Gas System
- Drive Gearbox (if required)
- Shaft Couplings
- Cooling System
- Piping Systems
- Pulsation Dampers
- Condition Monitoring

Figure 2,1 – 9 Motor Driven Reciprocating Gas Compressor Package (Open for Maintenance)
2.1.3.2 PACKAGE ENTITY

Physically, the package is a multi-cylinder Horizontal Reciprocating Process Gas Compressor driven by a High Voltage Electric Motor. All machine elements are mounted on a common baseframe - see Section 5.14 of the Guidance Notes for details. The control panel may be built on to the end of the baseframe (which is convenient for pre-wiring) or mounted separately (which permits control panels to be grouped together).

The motor will be fairly accessible; the gas compressor and drive gearbox (if fitted) will be closely packed with service pipework & cable trunking. Good design should permit ready access to compressor valves, piston rod packings, bearings and instruments. Due to the geometry of the compressor, and the physical size of the multi-pole motor typically used, the package is extremely wide, making access quite difficult.

The package will require effective ventilation to ensure dilution of any leakage gas. An air cooled motor relies on this ventilation air for heat removal, a water cooled motor does not require air for cooling.

2.1.3.3 PACKAGE ELEMENTS

2.1.3.3.1 Electric Motor

The High Voltage Electric Motor will normally be foot mounted on the baseframe, ensuring support of the heavy stator and rotor. In order to match the compressor speed, a multi-pole motor is the likely choice. For example, with a 60 Hz supply, a 16 pole motor will run at 450 rev/min (nominal) and a 12 pole motor at 600 rev/min. The motor shaft will be fitted with a flexible coupling, to accommodate thermal expansion and residual mis-alignment. Motors have a predictable thermal growth, which is allowed for in the alignment process.

It is possible to use a more conventional 4 or 6 pole motor with a speed reducing gearbox, this increases the length of the package but probably reduces weight.

The motor will be aligned to the compressor / gearbox, allowing for the predicted thermal growth of the casings.

The electric motor will require access to terminal box, access panels, bearings and air heat exchanger (normally mounted on top). Overhead crane access will be required to lift the complete motor, also to remove the rotor (preferably without moving either the motor stator or the compressor).

The distance between the front of the electric motor and the face of the compressor flywheel will be very short, restricting access to the bearings.

Technical and safety aspects of the High Voltage Electric Motor are described in more detail in Section 3.5 of the Guidance Notes.
2.1.3.3.2 Reciprocating Process Gas Compressor

The multi-cylinder Reciprocating Process Gas Compressor crankcase will be foot mounted on the common base-frame. The compressor crankcase will have a predictable thermal growth, which is allowed for in the alignment process. The compressor cylinders and distance pieces are solidly bolted to the crankcase extensions, but the weight of these components is supported from below to minimise the bending loads on this bolting. The baseframe must be stiff enough to provide rigid support at these mounting points. The mountings must be designed to expand vertically by a similar amount to the crankcase (by matching metal temperatures and dimensions) but to accommodate horizontal expansion by flexing or sliding.

Process pipework will be connected to the cylinders by flanged connections. Thermal expansion of process pipework should be achieved by good design, bellows are not preferred. The process piping may be lagged, as required by operating temperatures, but compressors are not normally lagged. The support systems must not be lagged, as they have to remain at ambient temperatures, so far as is possible. Some hot surfaces may have lagging or shielding for personnel protection only, although contact with surfaces of > 70 C is often still possible.

The Process Schematic Diagram of such a system is shown below:

![Process Schematic Diagram](image-url)

Figure 2.1 – 10 Process Schematic Diagram – Electric Motor Driven Gas Compression System

Reciprocating gas compressors contain a number of moving parts within an extended casing. Mechanical failure can result in severe internal damage but this is not likely to pose a direct hazard to people who are not close to the equipment. Parts do not move very quickly as average piston speed will be about 3 – 5 m/s. Mechanical failure can disrupt the pressure containment, thus the greatest potential threat is the uncontrolled release of a flammable hydrocarbon gas, particularly if the gas is then able to form an explosive mixture within a relatively enclosed space.
The risk is reduced by ensuring that compressors are competently operated and maintained, and that protective systems are regularly tested and in good order. Reciprocating compressors give the potential for fatigue failures, maintenance practices must recognise this. The overall system design should provide suitable remote isolations, knockout pots and adequate vent arrangements normally a route to flare.

Technical and safety aspects of the Reciprocating Gas Compressor system are described in more detail in Section 4.4 of the Guidance Notes.

2.1.3.3.3 Gearboxes

Fixed speed A.C. motors on 60 (50) Hz supply can only run at either 3600 (3000) rev/min nominal speed, or at speeds which are 3600 (3000) divided by 1,2,3,4, etc., Lower speed motors are referred to as multi-pole motors, and are very heavy and wide for their power. For very slow drives, or where for some other reason a multi-pole motor is not wanted, a speed reducing gearbox may be used. This does give the advantage that the compressor speed can be changed at some future time. Torsional pulsations from the compressor require the gearbox to be of a higher load rating than might otherwise be used, and an elastomer element flexible drive coupling will be preferred, particularly if the motor is of synchronous design. Gearboxes do provide a convenient location for auxiliary drives e.g. oil pump, low speed barring gear.

There are a limited number of safety issues from inclusion of a gearbox within a machine package. The most serious are:

- The potential for unplanned engagement of auxiliary drives, used to rotate the compressor at low speed, leading to massive overspeed and, usually, disintegration of the auxiliary drive.
- For bursting of the gear wheels (design or manufacturing flaws).
- For fires due to leakage of lubricating oil.

Technical and safety aspects of the gearbox systems are described in more detail in Section 5.5 of the Guidance Notes.

2.1.3.3.4 Main Drive Coupling

The use of flexible couplings within a machine package is essential to provide the necessary degrees of freedom to enable the elements of the machine to be aligned, to compensate for thermal expansion and for any flexibility inherent in the installation skid.

Misalignment of the coupling, even within its tolerance limits, puts increased loads on adjacent shaft bearings. It also reduces the service life of the coupling, as flexible elements are subjected to greater strains. Coupling lubrication (where required) and inspections must be proactively maintained as the coupling has significant mass and has the potential to become a dangerous missile if it fails. Loss of drive is not normally a safety-related incident; special design requirements apply if drive continuity is critical. Note that such a failed drive will only continue to operate for a limited time before further damage causes complete failure.

Technical and safety aspects of flexible shaft couplings are described in more detail in Section 5.6 of the Guidance Notes.

2.1.3.3.5 Lubrication System

The supply of oil for lubrication of bearings and couplings, support to sealing systems and hydraulic operation of actuators requires clean oil at appropriate pressures. For package units this can be delivered from a common system feeding all elements within the package.
The most serious issues for the lubrication system within reciprocating machines is the danger of crankcase explosion. Caused by the ignition of oil / air mixing within the crankcase being ignited by hot surface, packaged machines to included for protection system as described in Section 4.4.

Other issues from the supply of oil to a machine package arise from either failure of the supply that can lead to damage of the machines, or from oil spill or leakage resulting in a fuel source for potential fires.

The cylinder lubrication system is completely separate from crankcase lubrication, may well use a different oil which is injected into the cylinders and "lost" into the process. The two systems must not be cross-connected.

Technical and safety aspects of lubrication systems are described in more detail in Section 5.2 of the Guidance Notes.

2.1.3.3.6 Cooling System

Reciprocating Compressor packages require cooling, normally by closed circuit water, for lubricating oil system, cylinder jackets, intercoolers and aftercoolers as fitted. There may also be water cooling on the drive motor. Process coolers, e.g. Intercoolers, will typically be shell and tube heat exchangers built to a recognised code. ASME and BS 5500 are commonly used. Ideally, cooling will be against a closed fresh water cooling system, to minimise problems of corrosion, fouling and pollution. See Section 5.11 for further details.

2.1.3.3.7 Piping Systems

Reciprocating compressors are particularly sensitive to applied pipe loads on cylinders, these loads must be kept low under all operating conditions. The vendor is responsible for ensuring that pipe weight, thermal expansion and vibration effects are managed and that adequate expansion loops and supports are provided. Agreement is required as to what loads are permissible at the skid terminations. If any external connections go directly on to the compressor, not installed as part of the package build, these must be agreed with the vendor. Maintenance procedures must ensure that piping load limitations are recognised, and that suction and delivery pipework is reinstalled with the correct set-up and pre-loads, as defined by the vendor. Equally that the pipe supports are correctly set up and maintained. Excessive pipe loads can cause misalignment, piston, rod and seal wear, and joint leaks. Piping systems are generally constructed to international standards, see Section 5.7 for details.

2.1.3.3.8 Pulsation Dampers

Pulsation Dampers are integral to the Reciprocating Compressor. See Section 4.4.6.7 for details.

2.1.3.3.9 Control System

Machines within a package must be integrated to function as a complete system. Therefore control systems are designed to provide this essential control and protection for the machine elements. The overall description of package control systems is included in Section 5.13 of the Guidance Notes.
2.1.3.4 INTEGRATION ASPECTS

2.1.3.4.1 Hardware Matching

The design of the package must ensure that the operating capability of each element of the package matches or exceeds the greatest potential demand placed on it by the system.

For an Electric Motor driven Reciprocating Compressor the major elements that must be considered are:

- Power rating
- Starting Torque/ Speed curve
- Speed
- Torsional pulsations and their effect on the drive and power system.
- Torque limits

2.1.3.4.2 Operational Matching

The operation of a package unit requires that there are no conflicts within the system that would compromise safe operation of the system.

For an Electric Motor driven Compressor the issues that must be considered are given in Operation Support Guidance Section 6.

2.1.3.5 HAZARD ASSESSMENT

The hazards posed by the package are a combination of the hazards posed by the individual machine and rotating equipment items, with possibly some additional hazard due to potential interactions. Assessment of the hazards from the package should, however, be made easier at the design stage because one design team should be dealing with the complete package, and have all relevant information compiled together.

See Section 7.2.4 for a structured set of Hazard Assessment Tables.

2.1.3.5.1 Process Substance Containment Hazards

Containment hazards relating to the Compressor are covered in Section 4.4.3.1

See Section 3.5.3.1 for Ignition/ Explosion hazards within the H.V. electric motor.

The potential for the motor providing a source of ignition for releases from the compressor, other equipment in the area, or from the lubrication system, should be covered by the area hazard assessment and the electrical area classification studies. The motor will in any case be of Explosion Proof or Increased Safety design.

2.1.3.5.2 Equipment Hazards

In practice, mechanical hazards of packaged equipment are the same as the individual units. There is a risk of an incident on one component of the system adversely affecting the other, but this applies to any multiple machine installation.

The Mechanical Hazards associated with the elements are :-
Damage and loss of containment of machine elements due to high mechanical energy stored or transmitted within rotor shafts, gear box, couplings.

Electrical hazards :-

Description of the source of the hazards and the protection / preventative measures necessary are given in Electric Motor Sections 3.3 (Generic A.C.) and 3.5 (High Voltage > 500 kW) of the Guidance Notes.

Specific hazards can be generated due to large unbalance forces possible under certain failure conditions. Specific protection against these failure modes are given in Section 4.4, in addition the siting of controls and particular emergency stop controls needs to include for remote shut down in situations of major disruption and vibration.

2.1.3.5.3 Operational / Consequential Hazards

Packaging should have no particular influence in this area; Mechanical, Process and Control interactions apply equally to Packaged and Non-packaged units. It can be argued that there is a reduction in risk, because the Package should have been designed as a whole to a consistent duty requirement.

The Operational Hazards associated with the elements are :-

Loss of containment of process substances which are flammable and toxic

Description of the source of the hazards and the protection / preventative measures necessary are given in Sections 4.4.3 and 4.4.4 of the Guidance Notes.

2.1.3.5.4 Maintenance / Access Hazards

Maintenance on packaged units can be significantly more difficult because of very congested construction, this is not necessarily hazardous but can result in more sprains and similar injuries as people struggle to work in restricted spaces. Well-designed packaged units incorporate tailored lifting / slinging facilities. It is usually more appropriate to change out an assembly than to attempt to attempt a failed component in situ. There is a potential issue of isolation of electrical and other energy sources where isolation of part of the package may not isolate a closely adjacent part. This must be covered by Maintenance / Permit to Work procedures.

The Maintenance Hazards associated with the elements are :-

Loss of containment of process substances (flammable and toxic) not isolated during maintenance operations. Particularly cross feed from vent and sealing systems.

Explosions. Opening of the crankcase may lead to formation of an explosive mixture.

Weight and balance of components and tools used during maintenance.

Inadequate controls on maintenance can cause serious machine damage due to looseness in service for key components.

Description of the source of the hazards and the protection / preventative measures necessary are given in Sections 4.4.3 and 4.4.5 of the Guidance Notes.
2.1.3.5.5  **Pulsations / Vibration**

Pulsations and low frequency vibration can be transmitted from the compressor via the pipework (mechanically and as pressure waves), baseframe and even the electrical distribution network. It is the duty of the designers to block or damp out these effects as far as reasonably practical, and to provide suitable operating and maintenance instructions. These instructions should cover :-

- Anticipated effects, frequency and amplitude, route of transmission.
- Means taken to control the effects.
- How to check if controls are working.
- Actions to take to keep the controls working.
- Actions to avoid which may compromise the controls.

2.1.3.6  **APPLICABLE STANDARDS**

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations
( Transposed Harmonised Standards ) :-


Selection of API Standards Relevant to Machinery in use in Refineries / Offshore:-


General Standards for machinery can be found in **Section 5.15**
SECTION 2.1.4  EXPANDER DRIVEN CENTRIFUGAL GAS COMPRESSOR

TECHNICAL SUPPORT

The typical duty of this machine is as a power saving device on a Gas Conditioning Plant. The recovered power is used for any suitable gas compression duty.

The package comprises a single shaft with a single stage gas expander on one end of the shaft and a single stage centrifugal gas compressor on the other end. The unit and its control system will be mounted on a baseframe. Ancillary systems may include:

- Acoustic / Thermal Lagging
- Expander Inlet Gas System, Liquid Disengagement & Filter
- Expander Control & Trip Valves and Guide Vane unit
- Compressor Inlet Gas System, Liquid Disengagement & Filter
- Compressor Inlet Control Valve and Recycle / Surge Valve
- Compressor Discharge Non-return valve and Block Valve
- Lubricating Oil System
- Heat Exchangers
- Piping Systems
- Overspeed Monitoring & Protection System
- Condition Monitoring

Figure 2.1 – 11 Turboexpander – Compressor Package
Turboexpander-Compressors have become essential equipment in natural gas processing units, and other hydrocarbon processing operations, where effective use of gas pressure let down can be made to support other compression processes. Turboexpander- Compressors have a simple design with a short shaft and two overhung wheels. This design makes rigid body rotor design feasible and hence simplifies rotordynamics design and analysis. Furthermore, it eliminates high-speed coupling, reduction gear, and low-speed coupling. Auxiliary lubrication and sealing system designs are also simplified, and a totally closed system is possible avoiding emission of oil mist or hydrocarbon seal gas into the atmosphere, so the design is environmentally friendly.

Turboexpander-Compressor design is also an ideal application for active magnetic bearings. Since axial loads are inherently balanced, magnetic bearings Turboexpanders can operate in a wide range of process operations.

Turboexpanders- Compressors are designed for 100 - 15,000 kW and up to 120,000 rpm.

For further information see Section 3.1.11
Crude oil will be handled at a variety of pressures and flows, depending on installation and duty.

Duty requirements and the preferences of the operator and design contractor will dictate the selection of pump type.

The selection of the driver will be dictated by the pump duty and by the energy supply philosophy of the installation.

Large drives are likely to be Gas Turbines, below about 2 MW electric motors will be the normal choice.

Gas Turbines are inherently variable speed, electric motors can be made variable speed by integrating an inverter drive.

Hazard assessment must take account of the proximity of other equipment and packages.
Three representative packages have been chosen to demonstrate typical equipment selections for the Crude Oil / Main Oil Line duty.

Section 2.2.1  Gas Turbine driven Large Centrifugal Pump
Section 2.2.2  Electric Motor driven Multi-stage Centrifugal Pump
Section 2.2.3  Electric Motor driven Vertical Centrifugal Pump

The selection of the type of package is determined by the intended range of operating requirements. Crude oil is a generic term covering a wide range of oil mixtures dependent on the production fluid (oil/gas/water) from the wells served.

In general the major hazard that arises from this duty is the potential for the release of large volumes of volatile crude oil under pressure. The material itself is flammable and any release will result in evolution of flammable vapour cloud of the lighter fractions of the material being transferred.

Gas turbine centrifugal pump packages are used for larger installations above perhaps 2 MW. Electric motor driven centrifugal packages are used for other duties, though it is possible to use larger electric motors if required. A few emergency or standby duties can require use of diesel driven pumps; issues with diesel driven pumps are addressed in Section 2.6.
2.2.1 GAS TURBINE DRIVEN LARGE CENTRIFUGAL PUMP PACKAGE

TECHNICAL SUPPORT

2.2.1.1 GAS TURBINE DRIVEN LARGE CENTRIFUGAL PUMP PACKAGE – DESCRIPTION

The package comprises an Aero-derivative Gas Turbine driving a Large Horizontal Single Stage Centrifugal Pump on Crude Oil service, complete with Control System & Ancillary Equipment, all mounted on a 3-point mounting skid baseplate. The Gas Turbine is enclosed in an Acoustic Enclosure with its own Fire & Gas System. Ancillary Equipment & systems will include:

- Inlet Air System & Filter
- Fuel System
- Exhaust System
- Lubricating Oil System
- Pump Seals & Support System
- Drive Gearbox (if required)
- Auxiliary Gearbox
- Shaft Couplings
- Cooling System
- Piping Systems
- Condition Monitoring

Figure 2.2 – 1 Gas Turbine driven Pump Package
The Process Schematic Diagram of such a system is shown below.

Figure 2.2 – 2 Process Schematic Diagram - Gas Turbine Driven Pump System

2.2.1.2 PACKAGE ENTITY

Physically, the package is an enclosed gas turbine with one centrifugal pump co-axially on the end of the output shaft. A drive gearbox may be fitted to match pump and driver speeds. All machine elements are mounted to a common baseframe, the control panel may be built on to the end of the baseframe (which is convenient for pre-wiring) or mounted separately (which permits control panels to be grouped together).

The Acoustic Enclosure for an Aero-derivative Gas Turbine will be close fitting, and fitted out with ventilation and Fire & Gas Detection Systems. The internal space will be tightly packed, making access to internal components quite difficult. Thus any problem on one component has the potential to affect adjacent components / systems, whether by release of material, vibration or over-heating. Similarly, it may be necessary to remove a component either to work on that component or to gain access to adjacent components.

The pump and drive gearbox (if fitted) will be outside the acoustic enclosure, but still very closely packed with service pipework & cable trunking. Good design should permit ready access to pump bearings, seals, instruments and drive couplings.

The air inlet housing will be located separate from the gas turbine.
2.2.1.3 PACKAGE ELEMENTS

2.2.1.3.1 Gas Turbine

The Aero-derivative Gas Turbine mounted within an Offshore Package will be centre-line mounted from the baseframe, ensuring internal alignment while permitting thermal expansion of the machine. The main drive shaft, which will be at the “hot” or exhaust end for a mechanical drive package, will be fitted with a flexible coupling, as will any auxiliary drive shafts. Flexible connections will link to the inlet and exhaust ducts.

Technical and safety aspects of the Gas Turbine system are described in more detail in Section 3.1 of the Guidance Notes.
2.2.1.3.2 Large Centrifugal Pump

Figure 2.2 – 4 API 610 Axial Split Pump Option

The Single Stage Centrifugal Pump will be mounted on an extension of the common base-frame, ensuring shaft alignment. Centre-line mounting will be selected for “hot” service (above perhaps 100°C). Shafts will require alignment within the tolerances of the shaft couplings. Process pipework will be connected to the pump casing, normally by flanged connections, although fully welded assembly is possible. Thermal expansion of process pipework should be achieved by good pipe support and flexibility design, bellows are to be avoided. The pump casing and pipework may be lagged, as required by operating temperatures. The pump support system must not be lagged, as it has to remain at ambient temperatures, so far as is possible. The above notes apply equally to single, two or multi-stage pumps.

Technical and safety aspects of the Large Centrifugal Pump are described in more detail in Section 4.7 of the Guidance Notes.

2.2.1.3.3 Gearboxes

The inclusion of a drive gearbox within the machine package allows the manufacturer to optimise operating speeds of the Gas Turbine driver and Centrifugal Pump separately. The technical disadvantages of additional skid length, equipment complexity, and weight being offset with benefits for the matching of turbine and pump.

Twin shaft Gas Turbine packages will include an Auxiliary Gearbox, normally integral to the “cold” end of the machine. This provides the necessary linkage for turbine starting, and mechanical drives where required for oil or fuel pumps.

Technical and safety aspects of the gearbox systems are described in more detail in Section 5.5 of the Guidance Notes.
2.2.1.3.4 Main Drive Coupling

The use of flexible couplings within a machine package is essential to provide the necessary degrees of freedom to enable the elements of the machine to be aligned and compensate for any flexibility inherent in the installation skid. Technical and safety aspects of flexible shaft couplings are described in more detail in Section 5.6 of the Guidance Notes.

2.2.1.3.5 Lubrication System

The supply of oil for lubrication of bearings and couplings, support to sealing requiring clean oil at appropriate pressures. For package units this can be delivered from a common system feeding all elements within the package.

Technical and safety aspects of lubrication systems are described in more detail in Section 5.2 of the Guidance Notes.

2.2.1.3.6 Control System

Machines within a package must be integrated to function as a complete system. Therefore control systems are designed to provide this essential control and protection for the machine elements.

Details of the requirements for these systems are noted in the Guidance notes for each element.

Technical and safety aspects of flexible shaft couplings are described in more detail in Section 5.6 of the Guidance Notes.

2.2.1.3.7 Air Intake Filter & System

Air feed to the gas turbine will be filtered through a series of filtration elements (Ref. Section 5.10)

2.2.1.3.8 Acoustic Enclosure

The gas turbine is enclosed in a acoustic enclosure – this reduces the risk from the noise hazard but introduces hazards of an enclosure possibly containing flammable gas. (Ref. Section 3.1)

2.2.1.3.9 Fuel System

The fuel system will take Gas Fuel and / or Liquid Fuel from the installation at the available pressure, filter the fuel(s) and raise pressure if necessary. The fuel system will control the rate of supply of fuel(s) and isolate the supply when necessary. See Section 5.1.1 & 5.1.2 for further details relevant to Gas Fuel and Liquid Fuel respectively.

2.2.1.3.10 Exhaust System

This system is specific to the Gas Turbine and is covered in Section 3.1.6.6
2.2.1.3.11 Pump Dry Gas Seals & Support System

The pump dry gas seals and support system are covered in detail in Section 5.3.4. Note that this is new technology and not common offshore. They are included on this package as an example. Most pumps have liquid barrier mechanical seals, see Section 5.3.3.

2.2.1.3.12 Cooling System

Process coolers, e.g. Intercoolers, are not normally used on pump installations. However, recycle coolers may be fitted. The lubrication oil system will require a cooler. Such coolers will usually be shell and tube heat exchangers built to a recognised code. ASME and BS 5500 are commonly used. Ideally, cooling will be against a closed fresh water cooling system, to minimise problems of corrosion, fouling and pollution. See Section 5.11 for further details.

2.2.1.3.13 Piping Systems

Piping systems are generally constructed to international standards, see Section 5.7 for details, special standards are required for fuel gas where double skinned piping is installed. (See Section 5.1.1)

2.2.1.3.14 Control and Recycle Valves

The pump may well have discharge control and recycle control valves. These valves are not necessarily provided by the package vendor, but their specification, design, installation and control must be carefully integrated into the operation of the package. In particular, any changes in pump duty or design must be allowed for in the valve design and set-up. See Section 5.13 for more detail.

2.2.1.3.15 Condition Monitoring

Condition monitoring on larger Machine Packages will be provided as part of the package. Vendors will offer their own preferred system, or will agree to tailor a system to suit the client’s requirements. It is important to ensure that the system provided suits the proposed method of operating and maintaining the equipment. See Section 5.12 for more detail.

2.2.1.4 INTEGRATION ASPECTS

2.2.1.4.1 Hardware Matching

The design of the package must ensure that the operating capability of each element of the package matches or exceeds the greatest potential demand placed on it by the system. For a Gas Turbine driven Centrifugal Pump the major elements that must be considered are:
- Pressure Rating
- Power rating
- Minimum & Maximum Flows
- Speed
- Torsional critical speeds
- Lateral critical speeds

Details of the requirements for these systems are noted in the Guidance notes for the separate elements. Lateral & Torsional Critical Speed issues are covered in Section 5.6.1.
2.2.1.4.2 Operational Matching

The operation of a package unit requires that there are no conflicts within the system that would compromise safe operation of the system. For a Gas Turbine driven Pump the issues that must be considered are given in Operation Support Guidance Section 6.1.

2.2.1.5 HAZARD ASSESSMENT

The hazards posed by the package are a combination of the hazards posed by the individual machine and rotating equipment items, with possibly some additional hazard due to potential interactions. Assessment of the hazards from the package should, however, be made easier at the design stage because one design team should be dealing with the complete package, and have all relevant information compiled together. See Section 7.2.4 for a structured set of Hazard Assessment Tables.

2.2.1.5.1 Process Substance Containment Hazards

Containment hazards relating to the Large Centrifugal Pump are covered in Section 4.7.3.1. Hazards relating to the release/ignition of fuel within the Gas Turbine are covered in Section 3.1.3.1.

The potential for the turbine or its ancillaries providing a source of ignition for releases from the pump, other equipment in the area, or from the lubrication system, should be covered by the area hazard assessment.

2.2.1.5.2 Equipment Hazards

In practice, mechanical hazards of packaged equipment are the same as the individual units. There is a risk of an incident on one component of the system adversely affecting the other, but this applies to any multiple machine installation. Hazards which are specific to gas turbine driven pumps are:

Overspeed of the driven equipment; the gas turbine must be speed controlled with an appropriate speed monitoring, control and trip system to avoid overstressing the driven and transmission components. The pump and transmission system must be designed to have the capability to run at trip speed plus 5% margin. Requirements for protection are given in Section 3.1.

The gas turbine is dependent on various ancillary systems for safe operation, operating procedures and control system must ensure that these are operational prior to turbine start, and at all times during operation. Induction of a flammable gas release to the Gas Turbine enclosure to be avoided by appropriate positioning of intakes and monitoring of atmospheric hydrocarbon releases.

Crude oil pipework to and from such a large pump will itself be of a large diameter, particularly the suction piping which requires a low velocity and large radius bends to minimise pressure drop. This pipework takes up a significant amount of space and limits access and lifting arrangements. If at all possible, large pipework should not be dismantled for access, both the radial and axial split casing pump designs suit this intent. Any pipework to be removed should be within the pump isolation valves, both to avoid lifting heavy valves, and to aid control of any release.

Single stage pumps contain moving parts within a robust casing. Mechanical failure can result in severe internal damage but this is not likely to pose a direct hazard to people who are not close to the equipment. The greatest potential threat is the uncontrolled
release of a flammable hydrocarbon liquid, particularly if the liquid then evolves significant amounts of flammable gas within a relatively enclosed space.

The risk is reduced by ensuring that pumps are competently operated and maintained, and that protective systems are regularly tested and in good order. The overall system design should provide suitable duty matching, separators and remote isolations.

The Mechanical Hazards associated with the elements are:

- Damage and loss of containment of machine elements due to high mechanical energy stored or transmitted within rotor shafts, gear box, couplings.

Description of the source of the hazards and the protection / preventative measures necessary are given in Sections 4.7.3.2 and 3.1.3.2.

There is a risk of an incident on one component of the system adversely affecting the other, but this applies to any multiple machine installation.

**2.2.1.5.3 Operational / Consequential Hazards**

Packaging should have no particular influence in this area; Mechanical, Process and Control interactions apply equally to Packaged and Non-packaged units. It can be argued that there is a reduction in risk, because the Package should have been designed as a whole to a consistent duty requirement.

Relevant information for the machine elements is given in Sections 4.7.3.3 and 3.1.3.3.

**2.2.1.5.4 Maintenance / Access Hazards**

Maintenance on packaged units can be significantly more difficult because of very congested construction, this is not necessarily hazardous but can result in more sprains and similar injuries as people struggle to work in restricted spaces. Well-designed packaged units incorporate tailored lifting / slinging facilities. It is usually more appropriate to change out an assembly than to attempt to repair a failed component in situ. There is a potential issue of isolation of electrical and other energy sources where isolation of part of the package may not isolate a closely adjacent part. This must be covered by Maintenance / Permit to Work procedures.

Relevant information for the machine elements is given in Sections 4.7.3.4 and 3.1.3.4.

**2.2.1.6 APPLICABLE STANDARDS**

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations (Transposed Harmonised Standards) can be found in Section 5.15 the specific standards relating to this package are:

- BS EN 809 1998 Pumps and pump units for liquids – Common safety requirements.
- Selection of API Standards Relevant to Machinery in use in Refineries / Offshore:
  - API 610 1995 Centrifugal Pumps for Petroleum, Heavy Duty Chemical and Gas Industry Service
  - API 11PGT 1992 Packaged Combustion Gas Turbines
  - API 616 1998 Gas Turbines for Refinery Services

General Standards for machinery can be found in Section 5.15.
2.2.2 ELECTRIC MOTOR DRIVEN MULTI-STAGE CENTRIFUGAL PUMP PACKAGE TECHNICAL SUPPORT

2.2.2.1 ELECTRIC MOTOR DRIVEN MULTI-STAGE CENTRIFUGAL PUMP PACKAGE - DESCRIPTION

The package comprises a High Voltage Electric Motor driving a Horizontal Multi-Stage Centrifugal Pump on Crude Oil service, complete with Control System & Ancillary Equipment, all mounted on a 3-point mounting skid baseplate. The package does not include an Acoustic Enclosure. Ancillary Equipment & systems will include:
- Lubricating Oil System
- Pump Seals & Support System
- Drive Gearbox (if required)
- Shaft Couplings
- Cooling System
- Piping Systems
- Control System
- Condition Monitoring

![Motor Driven Multi-stage Pump – Final Assembly](image)

Figure 2.2 – 5 Motor Driven Multi-stage Pump – Final Assembly

2.2.2.2 PACKAGE ENTITY

Physically, the package is a large electric motor with one centrifugal pump co-axially on the end of the output shaft. A drive gearbox will often be fitted to match pump and driver speeds. All machine elements are mounted to a common baseframe the control panel may be built on to the end of the baseframe (which is convenient for pre-wiring) or mounted separately (which permits control panels to be grouped together).

It is not normal to fit an acoustic enclosure to such packages. Individual machines, particularly the drive gearbox, may have a close-fitting acoustic box. Good design should permit ready access to pump bearings, seals, instruments and drive couplings.

The available space on the package will be tightly packed, making access to internal components quite difficult.
2.2.2.3 PACKAGE ELEMENTS

2.2.2.3.1 Drive Motor

Figure 2.2 – 6 High Voltage Electric Motor – Frame Construction

The High Voltage Motor described is typical of motors of 3.3 kV to 11 kV, rated around 0.5 to 20 MW. It will be of fabricated frame construction, foot mounted on the baseframe. The motor shaft will be fitted with a flexible coupling, linking it to the pump or drive gearbox. The motor will be provided with lubricating oil supply and return to the bearings, and an available supply of cooling water or air to integral heat exchanger(s). Mechanically, the motor is otherwise self-contained. Three-phase power supply cables will link the motor terminal box to the starter cabinet (fixed speed motors) or inverter (variable speed motors). Some special electric motors have resistor boxes and similar large items of control equipment mounted locally. Many have Exp Protections (Expo Systems) coolers and instrumentation local to the motor. Technical and safety aspects of the High Voltage Electric Motor are described in more detail in Section 3.5 of the Guidance Notes.
2.2.2.3.2 Multi-stage Centrifugal Pump

The Multi-stage Centrifugal Pump will be mounted on the common base-frame, ensuring shaft alignment. Centre-line mounting will be selected for “hot” service (above perhaps 100 C), or may simply be standard for the pump model. Shafts will require alignment within the tolerances of the shaft couplings. Process pipework will be connected to the pump casing, normally by flanged connections, although fully welded assembly is possible. Thermal expansion of process pipework should be achieved by good design, bellows are to be avoided. The pump casing and pipework may be lagged, as required by operating temperatures. The pump support system must not be lagged, as it has to remain at ambient temperatures, so far as is possible.

It is assumed that a pump for Crude Oil service will be of Barrel Casing (radially split) or Axial Split design to API 610. Other equivalent Oil & Gas specifications may be applied instead, but National Standards do not generally contain valuable Oil & Gas experience. Experienced operators have their own standards, typically applied as complementary to API 610. Ring section or novel construction pumps are not suitable.

Barrel casing pumps normally have the suction and delivery pipework connected vertically to the top of the barrel casing. Axial split casing pumps, by contrast, normally have the piping connected horizontally to the lower casing. This pipework takes up a significant amount of space and limits access and lifting arrangements. If at all possible, pipework should not be dismantled for access, both the barrel and axial split casing pump designs suit this intent. Any pipework to be removed should be within the pump isolation valves, both to avoid lifting heavy valves, and to aid control of any release.

Multi-stage pumps contain high speed parts within a very robust casing. Mechanical failure can result in severe internal damage but this is not likely to pose a direct hazard to people who are not close to the equipment. The greatest potential threat is the uncontrolled release of a flammable hydrocarbon liquid, particularly if the liquid then evolves significant amounts of flammable gas within a relatively enclosed space.

The risk is reduced by ensuring that pumps are competently operated and maintained, and that protective systems are regularly tested and in good order. The overall system design should provide suitable duty matching, separators and remote isolations.
Technical and safety aspects of the Multi-stage Centrifugal Pump are described in more detail in Section 4.8 of the Guidance Notes.

2.2.2.3.3 Gearboxes

- The inclusion of a drive gearbox within the machine package allows the manufacturer to optimise operating speeds of the Electric Motor and Centrifugal Pump separately. The technical disadvantages of additional skid length, equipment complexity, and weight being offset with benefits for the matching of motor and pump.

Figure 2.2 – 8 High Voltage Electric Motor and Drive Gearbox on Package

A drive gearbox is often fitted as the motor will typically run at 3600 rev/min (for 60 Hz supply) while multi-stage pumps often run at around 5000 - 7000 rev/min. It would be normal to use a parallel shaft foot mounted gearbox, fitted with helical or “herringbone” toothed gears. The gearbox extends the length of the package by about 2 m. Drive gearboxes are noisy and are often fitted with metal-clad lagging boxes as the most effective acoustic protection. Large gearboxes require a pumped and cooled oil supply to the bearings and gears. Technical and safety aspects of the gearbox systems are described in more detail in Section 5.5 of the Guidance Notes.

2.2.2.3.4 Main Drive Coupling

See Section 2.2.1.3.4
2.2.2.3.5  Lubrication System

See Section 2.2.1.3.5

2.2.2.3.6  Control System

See Section 2.2.1.3.6
For an electric motor driven package, particularly if it runs at a fixed speed, the local control will be primarily motor stop-start and driven equipment control and protection. Control of process control valves will be from the central DCS (Distributed Control System).

2.2.2.3.7  Pump Mechanical Seals & Support System

The pump mechanical seals and support system are covered in detail in Section 5.3.3 (Liquid barrier) & Section 5.3.4 (Gas barrier). Note that dry gas seals are new technology and not common offshore.

2.2.2.3.8  Cooling System

See Section 2.2.1.3.12.

2.2.2.3.9  Piping Systems

Piping systems are generally constructed to international standards, see Section 5.7 for details.

2.2.2.3.10  Control and Recycle Valves

See Section 2.2.1.3.14.

2.2.2.3.11  Condition Monitoring

See Section 2.2.1.3.15.
2.2.2.4 INTEGRATION ASPECTS

2.2.2.4.1 Hardware Matching

The design of the package must ensure that the operating capability of each element of the package matches or exceeds the greatest potential demand placed on it by the system. For a Motor driven Centrifugal Pump the major elements that must be considered are:

- Pressure Rating
- Power rating
- Minimum & Maximum Flows
- Speed (fixed or within design range)
- Torsional critical speeds
- Lateral critical speeds

Details of the requirements for these systems are noted in the Guidance notes for the separate elements. Lateral & Torsional Critical Speed issues are covered in Section 5.6.1.

2.2.2.4.2 Operational Matching

The operation of a package unit requires that there are no conflicts within the system that would compromise safe operation of the system. For a Motor driven Pump the issues that must be considered are given in Operation Support Guidance Section 6.

2.2.2.5 HAZARD ASSESSMENT

The hazards posed by the package are a combination of the hazards posed by the individual machine and rotating equipment items, with possibly some additional hazard due to potential interactions. Assessment of the hazards from the package should, however, be made easier at the design stage because one design team should be dealing with the complete package, and have all relevant information compiled together. See Section 7.2.4 for a structured set of Hazard Assessment Tables.

2.2.2.5.1 Process Substance Containment Hazards

Containment hazards relating to the Multi-stage Pump are covered in Section 4.8.3.1

See Section 3.5.3.1 for Ignition/Explosion hazards within the H.V. electric motor.

The potential for the motor providing a source of ignition for releases from the compressor, other equipment in the area, or from the lubrication system, should be covered by the area hazard assessment and the electrical area classification studies. The motor will in any case be of Explosion Proof or Increased Safety design.

2.2.2.5.2 Equipment Hazards

In practice, mechanical hazards of packaged equipment are the same as the individual units. The Mechanical Hazards associated with the elements are:

- Damage and loss of containment of machine elements due to high mechanical energy stored or transmitted within rotor shafts, gear box, couplings.
For guidance specific to the Multi-stage Pump see Section 4.8.3.2

Electrical Hazards :-

Description of the source of the hazards and the protection / preventative measures necessary are given in Electric Motor Sections 3.3 (Generic A.C.) and 3.5 (High Voltage > 500 kW) of the Guidance Notes.

There is a risk of an incident on one component of the system adversely affecting the other, but this applies to any multiple machine installation.

2.2.2.5.3 Operational / Consequential Hazards

Packaging should have no particular influence in this area; Mechanical, Process and Control interactions apply equally to Packaged and Non-packaged units.

The Operational Hazards associated with the elements are :-
Loss of containment of process substances which are flammable and toxic.

For the Multi-stage Pump, descriptions of the source of the hazards and the protection / preventative measures necessary are given in Sections 4.8.3 & 4.8.4

For the HV Electric Motor, see Section 3.5.3.3

2.2.2.5.4 Maintenance / Access Hazards

Maintenance on packaged units can be significantly more difficult because of very congested construction, this is not necessarily hazardous but can result in more sprains and similar injuries as people struggle to work in restricted spaces. Well-designed packaged units incorporate tailored lifting / slinging facilities. It is usually more appropriate to change out an assembly than to attempt to attempt a failed component in situ. There is a potential issue of isolation of electrical and other energy sources where isolation of part of the package may not isolate a closely adjacent part. This must be covered by Maintenance / Permit to Work procedures.

2.2.2.6 APPLICABLE STANDARDS

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations ( Transposed Harmonised Standards ) can be found in Section 5.15 the specific standards relating to this package are :-

BS EN 809 1998 Pumps and pump units for liquids – Common safety requirements.

Selection of API Standards Relevant to Machinery in use in Refineries / Offshore :-

API 610 1995 Centrifugal Pumps for Petroleum, Heavy Duty Chemical and Gas Industry Service
API 541 1995 Form-Wound Squirrel Cage Induction Motors – 250 HP and larger
API 546 1997 Form-Wound Brushless Synchronous Motors – 500 HP and larger

General Standards for machinery can be found in Section 5.15
2.2.3 ELECTRIC MOTOR DRIVEN VERTICAL CENTRIFUGAL PUMP PACKAGE TECHNICAL SUPPORT

2.2.3.1 ELECTRIC MOTOR DRIVEN VERTICAL CENTRIFUGAL PUMP PACKAGE - DESCRIPTION

The package comprises a High Voltage Electric Motor driving a Vertical Caisson Type Centrifugal Pump on Crude Oil service, complete with Control System & Ancillary Equipment, all mounted on a 3-point mounting skid baseplate. The package does not include an Acoustic Enclosure. Ancillary Equipment & systems will include:
- Lubricating Oil System
- Pump Mechanical Seals & Support System
- Drive Gearbox (if required)
- Shaft Couplings
- Cooling System
- Piping Systems
- Control System
- Condition Monitoring

2.2.3.2 PACKAGE ENTITY

Physically, the package is a multi-stage centrifugal pump, fitted vertically into a cylindrical pressure vessel, and with a vertical electric motor mounted on the top end of the pump shaft. A drive gearbox may be fitted to match pump and driver speeds. As the machine elements are integrated together, they do not strictly require to be mounted to a rigid baseframe. It is not normal to fit an acoustic enclosure to such packages. Individual machines, particularly the drive gearbox, may have a close-fitting acoustic box. Good design should permit ready access to pump bearings, seals, instruments and drive couplings.

The available space on the package will be tightly packed, making access to internal components quite difficult. Thus any problem on one component has the potential to affect adjacent components / systems, whether by release of material, vibration or over-heating. Similarly, it may be necessary to remove a component either to work on that component or to gain access to adjacent components. For pump installations it is important that there is sufficient access to remove the shaft or cartridge (which can be very long) up. Special tools, may be required.
Vertical clearance, and headroom, is required for removal of components and complete items of equipment. Although the pump caisson protrudes below deck level for several metres, there is normally no access, nor process connections, to the caisson from below.

2.2.3.3 PACKAGE ELEMENTS

2.2.3.3.1 Drive Motor

The High Voltage Motor described is typical of motors of 3.3 kV to 11 kV, rated around 0.5 to 20 MW. It will be of fabricated frame construction, flange mounted to an extension stool on top of the pump bearing housing. The stool contains the flexible coupling linking the motor shaft to the pump shaft. The motor will be provided with lubricating oil supply and return to the bearings, and an available supply of cooling water or air to integral heat exchanger(s). Mechanically, the motor is otherwise self-contained.

If the motor is of TEFC construction (possible up to about 2 MW), it will be a standard motor with flange mount and modified bearings to suit vertical installation. If of Frame or fabricated construction, it will be specially made for vertical mounting, in particular the bearing and lubrication systems will be different to ensure adequate shaft support, and to keep oil out of the motor.

Three-phase power supply cables will link the motor terminal box to the starter cabinet (fixed speed motors) or inverter (variable speed motors). Some special electric motors have resistor boxes and similar large items of control equipment mounted locally.

Technical and safety aspects of the High Voltage Electric Motor are described in more detail in Section 3.5 of the Guidance Notes.

2.2.3.3.2 Caisson Type Centrifugal Pump

Caisson type pumps are special in that a complete multi-stage pump assembly is suspended inside a pressure vessel below working deck or floor level. The pump itself is therefore inaccessible in service except for the top bearing housing and shaft seal. The shaft seal may also work at pump discharge pressure.

It is assumed that the pump will be to API 610 construction, and that the pressure vessel will be to an appropriate code e.g. ASME or BS 5500.

The suction and delivery pipes are connected horizontally to branches on the top part of the caisson, which protrudes up through the deck or floor. As the complete weight of pump, pump contents, caisson and motor are carried on the caisson mountings, these must be designed for this, not just for the vessel weight. These mountings, and the relevant part of the baseframe, must be strong enough to take the fatigue loadings imposed by the heavy motor if the installation is subjected to wind and wave motion.

Figure 2.2 – 10

Vertical Caisson Pump Cut-away
The rotor of a caisson type pump is effectively double contained, firstly by the stator housing and then by the caisson. Mechanical failure can result in severe internal damage but this is not likely to pose a direct hazard to people who are not close to the equipment. The greatest potential threat is the uncontrolled release of a flammable hydrocarbon liquid, particularly if the liquid then evolves significant amounts of flammable gas within a relatively enclosed space. The risk is reduced by ensuring that pumps are competently operated and maintained, and that protective systems are regularly tested and in good order. The overall system design should provide suitable duty matching, separators and remote isolations. Technical and safety aspects of the Vertical Caisson Type Centrifugal Pump are described in more detail in Section 4.9 of the Guidance Notes.

2.2.3.3.3 Gearboxes

- A drive gearbox is not normally required for Caisson Pumps, as these pumps do not normally operate at high speeds.

A drive gearbox is not normally required for Caisson Pumps, they are selected for low NPSHa duties for which pump speeds of 1800 or 3600 rev/min are ideal. The head requirement is made up by selecting the appropriate number of pump stages, or by using the Caisson Pump as a suction lift or suction booster pump, feeding a higher pressure main pump. Technical and safety aspects of the gearbox systems are described in more detail in Section 5.5 of the Guidance Notes.

2.2.3.3.4 Main Drive Coupling

See Section 2.2.1.3.4

Additionally, since the motor is flange mounted by a spigot, the coupling alignment should be pre-defined by the build quality. It is best to check, if possible. Some vertical machines may have a common thrust bearing in the motor only. Pump shaft weight / thrust is then carried via a rigid shaft coupling.

2.2.3.3.5 Lubrication System

See Section 2.2.2.3.5

Additionally, vertical shaft machines require special lubrication arrangements for bearings. This normally takes the form of a well or weir surrounding the bearing, preventing the oil from running down the shaft. If the drain port or pipe should be restricted, oil will spill down the shaft into the machine. Technical and safety aspects of lubrication systems are described in more detail in Section 5.2 of the Guidance Notes.

2.2.3.3.6 Control System

See Section 2.2.2.3.6

2.2.3.3.7 Pump Mechanical Seals & Support System

The pump mechanical seals and support system are covered in detail in Section 5.3.3 (Liquid barrier) & Section 5.3.4 (Gas barrier). Note that dry gas seals are new technology and not common offshore.
2.2.3.8 Cooling System

See Section 2.2.1.3.12.

2.2.3.9 Piping Systems

Piping systems are generally constructed to international standards, see Section 5.7 for details.

2.2.3.10 Control and Recycle Valves

See Section 2.2.1.3.14.

2.2.3.11 Condition Monitoring

See Section 2.2.1.3.15.

2.2.3.4 INTEGRATION ASPECTS

See Section 2.2.2.4

2.2.3.5 HAZARD ASSESSMENT

See Section 2.2.2.5

Additionally, because of the potential for oil to be lost into the motor if the lubricating oil return pipe is restricted, unexplained oil loss should be recognised as the potential for an oil soaked motor.

Because the pump and motor are generally so inaccessible, it must be recognised that faults may go unrecognised for a longer time than might apply for more conventional equipment.

2.2.3.6 APPLICABLE STANDARDS

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations
( Transposed Harmonised Standards )
BS EN 809 1998 Pumps and pump units for liquids – Common safety requirements.
Selection of API Standards Relevant to Machinery in use in Refineries / Offshore
API 610 1995 Centrifugal Pumps for Petroleum, Heavy Duty Chemical and Gas Industry Service

General Standards for machinery can be found in Section 5.15
High pressure sea water is used for re-injection into wells, at pressures dictated by the formation and injection rate.

Duty requirements and the preferences of the operator and design contractor will dictate the selection of pump type.

The selection of the driver will be dictated by the pump duty and by the energy supply philosophy of the installation.

Large drives are likely to be Gas Turbines, below about 2 MW electric motors will be the exclusive choice.

Gas Turbines are inherently variable speed, electric motors can be made variable speed by integrating an inverter drive.

Hazard assessment must take account of the proximity of other equipment and packages.

Injection water may be handled at different duties and pressures, depending on the installation and on the formation pressures and injection rates required. Even apparently similar duties may have different pump systems, dictated by operator preferences and the history of the installation. Generally it is preferable to have a smaller number of large pumps, as this gives the best reliability. This choice may not be practical if the duty flow has wide variations.

Water pumps need not be to Oil & Gas standards e.g. API 610, although operator preference may be to do so.

Pump driver selection is in practice limited to electric motors for drives of less than about 2 MW. For larger drives it is possible to use Gas Turbines, although electric motors are cheaper, simpler and more compact if sufficient electric power is available. For drives above about 10 MW, the Gas Turbine is likely to be preferred.
Gas Turbines are inherently variable speed, this is of great benefit for high power pumping duties where pump speed variation is part of the preferred control philosophy. Electric motors are inherently fixed speed, but can be supplied with a matched inverter drive system to drive variable speed equipment. Such equipment is available (currently) to about 12 MW but this rating will increase.

Each pump package can and should be assessed by the vendor for hazards, and designed accordingly. The overall hazard assessment is the responsibility of the operator/ main contractor. In particular, the location and orientation of the high hazard packages will have a significant effect upon the potential for an incident to be contained and controlled, or to escalate uncontrollably.

While Gas Turbine driven packages may apparently offer greater hazards, Gas Turbines are at least relatively easy to stop. Electric motors can deliver a very large amount of energy for their size, have a high inertia rotor and thus can take a long time to stop. In addition, switchgear faults can make a motor continue to run even if the emergency stop buttons have been pressed. This could be through faults in the stop button, or the control circuit, or because switchgear contacts have welded closed. In this event the motor must be stopped from the switch-room. It may be possible to trip the incoming circuit breaker from the control room.
2.3.1 ELECTRIC MOTOR DRIVEN HIGH PRESSURE MULTI-STAGE CENTRIFUGAL PUMP PACKAGE TECHNICAL SUPPORT

- This package will be similar to the crude oil pump in Section 2.2.2
- As the process fluid is non-flammable, there is no fire / explosion risk.
- The discharge pressure is higher, increasing the pressure-related risks.
- High pressure water is dangerous at short range and should be treated accordingly.
- High pressure salt water containing oxygen is corrosive, requiring the use of stainless steels.

2.3.1.1 ELECTRIC MOTOR DRIVEN MULTI-STAGE H.P. PUMP PACKAGE - DESCRIPTION

The package comprises a High Voltage Electric Motor driving a Horizontal High Pressure Multi-Stage Centrifugal Pump on Water Injection service, complete with Control System & Ancillary Equipment, all mounted on a 3-point mounting skid baseplate. The package does not include an Acoustic Enclosure. Ancillary Equipment & systems will include:

- Lubricating Oil System
- Pump Seals & Support System
- Drive Gearbox (if required)
- Shaft Couplings
- Cooling System
- Piping Systems
- Control System
- Condition Monitoring

2.3.1.2 PACKAGE ENTITY

Physically, the package is a large electric motor with one centrifugal pump co-axially on the end of the output shaft. A drive gearbox will often be fitted to match pump and driver speeds. All machine elements are mounted to a common baseframe that is sufficiently rigid to maintain machine alignment, despite movement of the supporting structure or vessel. The 3-point mounting system eliminates the transmission of twisting forces to / from the baseframe. In order to save space, and the weight of additional bases, as many as possible of the ancillary systems e.g. lubrication oil system, seal gas support system, are built into the main baseframe. The control panel may be built on to the end of the baseframe (which is convenient for pre-wiring) or mounted separately (which permits control panels to be grouped together).
It is not normal to fit an acoustic enclosure to such packages. Individual machines, particularly the drive gearbox, may have a close-fitting acoustic box. Good design should permit ready access to pump bearings, seals, instruments and drive couplings.

The available space on the package will be tightly packed, making access to internal components quite difficult. Thus any problem on one component has the potential to affect adjacent components / systems, whether by release of material, vibration or over-heating. Similarly, it may be necessary to remove a component either to work on that component or to gain access to adjacent components. For pump installations it is important that there is sufficient access to remove the shaft or cartridge (which can be very long) in the appropriate direction. Special tools, e.g. slide frames, may be required. Similarly large electric motors are serviced by removing the rotor axially, using special lifting equipment.

Packages with a mix of foot-mounted and centre-line mounted drives, particularly if they include a gearbox, are difficult to align. The manufacturer should provide alignment instructions but it is valuable to understand how the various thermal expansions have been allowed for. “Hot” alignment is a valuable check but can be difficult and frustrating in practice as the equipment is moving while being measured. It may be possible to fix sensors to machines and monitor the alignment during a working run. Machine vibration readings give a good guide to alignment quality and can be analysed to look for the cause of a problem.

High pressure Multi-stage pumps can also be installed vertically, with the vertical-shaft motor on top. This saves deck space and reduces alignment and baseframe stiffness issues. Access for inspection and maintenance is severely restricted. Vertical installation requires modified design, particularly of the motor; it is not done simply by tipping units on end.
2.3.1.3 PACKAGE ELEMENTS

2.3.1.3.1 Drive Motor

The High Voltage Motor described is typical of motors of 3.3 kV to 11 kV, rated around 0.5 to 20 MW. It will be of fabricated frame construction, foot mounted on the baseframe. The motor shaft will be fitted with a flexible coupling, linking it to the pump or drive gearbox. The motor will be provided with lubricating oil supply and return to the bearings, and an available supply of cooling water or air to integral heat exchanger(s). Mechanically, the motor is otherwise self-contained.

Three-phase power supply cables will link the motor terminal box to the starter cabinet (fixed speed motors) or inverter (variable speed motors). Some special electric motors have resistor boxes and similar large items of control equipment mounted locally.

Technical and safety aspects of the High Voltage Electric Motor are described in more detail in Section 3.3 of the Guidance Notes.

2.3.1.3.2 High Pressure Multi-stage Centrifugal Pump

See Section 2.2.2.3.2

Additionally, for sea water handling, unless all oxygen and solids have been removed prior to pump, the fluid will be both corrosive and abrasive. This will require the use of stainless steels for product contact parts, probably with the use of exotic materials in the mechanical seals and support systems.

The higher pressures and smaller flows of the H.P. compared to the standard Multi-stage pump will result in a thicker casing, heavier bolting, but a smaller diameter pump cartridge.

As non-toxic fluids are being handled, and the pump is built of corrosion-resistant materials, preparation for, and protection during, maintenance are much simpler.

Technical and safety aspects of the High Pressure Multi-stage Centrifugal Pump are described in more detail in Section 4.10 of the Guidance Notes.

2.3.1.3.3 Gearboxes

See Section 2.2.2.3.3

Technical and safety aspects of the gearbox systems are described in more detail in Section 5.5 of the Guidance Notes.

2.3.1.3.4 Main Drive Coupling

See Section 2.2.1.3.4

2.3.1.3.5 Lubrication System

See Section 2.2.2.3.5

Technical and safety aspects of lubrication systems are described in more detail in Section 5.2 of the Guidance Notes.
2.3.1.3.6 Control System

See Section 2.2.1.3.6

For an electric motor driven package, particularly if it runs at a fixed speed, the local control will be primarily machine operation and protection. Control of process control valves will be from the central DCS (Distributed Control System).

2.3.1.3.7 Pump Mechanical Seals & Support System

The pump mechanical seals and support system are covered in detail in Section 5.3.3 (Liquid barrier) & Section 5.3.4 (Gas barrier). Note that dry gas seals are new technology and not common offshore.

2.3.1.3.8 Cooling System

See Section 2.2.1.3.12.

2.3.1.3.9 Piping Systems

Piping systems are generally constructed to international standards, see Section 5.7 for details.

2.3.1.3.10 Control and Recycle Valves

See Section 2.2.1.3.14.

2.3.1.3.11 Condition Monitoring

See Section 2.2.1.3.15.

2.3.1.4 INTEGRATION ASPECTS

See Section 2.2.2.4

2.3.1.5 HAZARD ASSESSMENT

See Section 2.2.2.5
2.3.1.6 APPLICABLE STANDARDS

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations (Transposed Harmonised Standards) can be found in Section 5.15; the specific standards relating to this package are:

- BS EN 809 1998 Pumps and pump units for liquids – Common safety requirements.

Selection of API Standards Relevant to Machinery in use in Refineries / Offshore:

- API 610 1995 Centrifugal Pumps for Petroleum, Heavy Duty Chemical and Gas Industry Service
- API 541 1995 Form-Wound Squirrel Cage Induction Motors – 250 HP and larger
- API 546 1997 Form-Wound Brushless Synchronous Motors – 500 HP and larger

General Standards for machinery can be found in Section 5.15.
Natural Gas Liquids will be handled at a variety of pressures and flows, depending on installation and duty.

Duty requirements and the preferences of the operator and design contractor will dictate the selection of pump type.

Natural Gas Liquids handling will generally be with relatively small pumps, driven by electric motors.

Drives of about 250 kW or less will be Low Voltage motors, above this High Voltage motors are generally used.

If the pump discharge pressure is reasonably constant, a fixed speed drive is practical. Variable speed can be achieved using inverters.

Hazard assessment must take account of the proximity of other equipment and packages.

Although the selected package of a vertical high speed pump is typical of those handling low viscosity clean fluids, it is also possible to use canned motor pumps for these types of duty. Canned motor pumps avoid the use of a mechanical seal by combining the pump and motor rotors into a single component within a hermetically sealed pressure containment. Such pumps are commonly used in the chemical industry on hazardous fluids, less commonly used in the oil and gas industry.
2.4.1 ELECTRIC MOTOR DRIVEN HIGH SPEED VERTICAL CENTRIFUGAL PUMP PACKAGE TECHNICAL SUPPORT

2.4.1.1 ELECTRIC MOTOR DRIVEN VERTICAL PUMP PACKAGE - DESCRIPTION

The package comprises a Low Voltage Electric Motor driving a Vertical High Speed Centrifugal Pump on Natural Gas Liquids return service, complete with Control System & Ancillary Equipment, all mounted on a 3-point mounting skid baseplate. The package does not include an Acoustic Enclosure. Ancillary Equipment & systems will include:

- Integral Lubricating Oil System
- Pump Mechanical Seals & Support System
- Integral Drive Gearbox
- Shaft Couplings
- Cooling System
- Control System
- Piping System
- Condition Monitoring
2.4.1.2 PACKAGE ENTITY

Physically, the package is a single stage vertical in-line centrifugal pump, driven by an integrated speed increasing gearbox, and with a vertical electric motor mounted on the top of the gearbox. As the machine elements are integrated together, they do not require to be mounted to a rigid baseframe. The control panel may be built on to the end of the baseframe (which is convenient for pre-wiring) or mounted separately (which permits control panels to be grouped together).

It is not normal to fit an acoustic enclosure to such packages. Individual machines, particularly the drive gearbox, may have a close-fitting acoustic box. High speed pumps are very noisy in the high frequency ranges, and benefit from partial acoustic shielding; this protects working locations rather than enclosing the machine. Good design should permit ready access to pump bearings, seals, instruments and drive couplings.

The available space on the package will be tightly packed, making access to internal components quite difficult. Thus any problem on one component has the potential to affect adjacent components / systems, whether by release of material, vibration or over-heating. Similarly, it may be necessary to remove a component either to work on that component or to gain access to adjacent components. Vertical clearance, and headroom, is required to remove the pump, gearbox and motor.

![LMV/BMP Series](image)

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Figure 2.4 – 1 High Speed Vertical Pumpset – Vendor Data
2.4.1.3 PACKAGE ELEMENTS

2.4.1.3.1 Drive Motor

The Low Voltage Motor described is typical of motors of 400 - 650 V, rated around 0.5 to 300 kW. It will be of cast or cast/ fabricated construction, flange mounted to an extension stool on top of the integral gearbox housing. The stool contains the flexible coupling linking the motor shaft to the pump shaft. The motor will be cooled by air circulated over the casing fins by the built-in fan. Vertical L.V. motors should include a rain/ dirt shield as part of the fan cowl. The bearings will be grease lubricated and are self-contained.

Three-phase power supply cables will link the motor terminal box to the starter cabinet (fixed speed motors) or inverter (variable speed motors).

Technical and safety aspects of the Low Voltage Electric Motor are described in more detail in Section 3.4 of the Guidance Notes.

2.4.1.3.2 High Speed Centrifugal Pump

High speed pumps are special in that a complete single stage pump and a sophisticated drive gearbox are integrated. The pump shaft is slender are supported purely by the gearbox output shaft bearings. The pump impeller and radial diffuser are designed to minimise radial shaft loads. The gearbox has a 2-part cast aluminium housing, with internal oil pump and lubrication system. The only external components are the oil filter and oil cooler.

As the pump is mounted into the pipework, only a simple base is required to carry the pump weight.

Technical and safety aspects of the High Speed Centrifugal Pump are described in more detail in Section 4.12 of the Guidance Notes.

2.4.1.3.3 Gearbox

- **The drive gearbox is an integral part of the pump and is key to its safe operation.**

The integral gearbox is required to drive the small impeller at high speed to achieve the required pump head with one stage. This permits a standard drive motor to be used.

The gearbox is built from precision cast and machined sections, located by spigots and dowels. Vertical gearboxes require a pumped system to lubricate the gear teeth and upper bearings, and a well arrangement to prevent oil leakage from the bottom bearing. The oil pump is internal, as is the oil reservoir. Oil passages are drilled in the castings, minimising the use of internal pipes.

As the gearbox is mounted above the pump, and there is an air gap between the pump mechanical seal and the gearbox bottom bearing, there should be no risk of pumped product contaminating the gearbox oil.

Technical and safety aspects of the gearbox systems are described in more detail in Section 5.5 of the Guidance Notes.
2.4.1.3.4 Main Drive Coupling

See Section 2.2.1.3.4

Additionally, since the motor is flange mounted by a spigot, the coupling alignment should be pre-defined by the build quality. It is best to check the alignment, if possible.

2.4.1.3.5 Lubrication System

Gearbox lubrication is completely self-contained, the only external service is a small cooling water supply to the oil cooler; this is mounted on the outside of the gearbox. As there is no pre-start oil pump, oil pressure is not reached until a few seconds after pump start. To permit starting, the oil pressure trip switch is bypassed by a timer.

As the pump itself has no bearings, it does not require lubrication.

Technical and safety aspects of lubrication systems are described in more detail in Section 5.2 of the Guidance Notes.

2.4.1.3.6 Control System

See Section 2.2.2.3.6

2.4.1.3.7 Pump Mechanical Seals & Support System

The pump mechanical seals and support system are covered in detail in Section 5.3.3 (Liquid barrier) & Section 5.3.4 (Gas barrier). Note that dry gas seals are new technology and not common offshore.

2.4.1.3.8 Cooling System

See Section 2.2.1.3.12.

2.4.1.3.9 Piping Systems

Piping systems are generally constructed to international standards, see Section 5.7 for details.

2.4.1.3.10 Control and Recycle Valves

See Section 2.2.1.3.14.

2.4.1.3.11 Condition Monitoring

See Section 2.2.1.3.15.
2.4.1.4 INTEGRATION ASPECTS

See Section 2.2.2.4

2.4.1.5 HAZARD ASSESSMENT

See Section 2.2.2.5

Where the electric motor is referenced, the relevant sections are 3.4.3.x

2.4.1.6 APPLICABLE STANDARDS

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations (Transposed Harmonised Standards) can be found in Section 5.15 the specific standards relating to this package are:

- BS EN 809 1998 Pumps and pump units for liquids – Common safety requirements.

Selection of API Standards Relevant to Machinery in use in Refineries / Offshore:

- API 610 1995 Centrifugal Pumps for Petroleum, Heavy Duty Chemical and Gas Industry Service
- API 541 1995 Form-Wound Squirrel Cage Induction Motors – 250 HP and larger
- API 546 1997 Form-Wound Brushless Synchronous Motors – 500 HP and larger

General Standards for machinery can be found in Section 5.15
Additives are injected into various process streams, in order to alter the behaviour of the fluid.

Typical desired effects are reduced viscosity, corrosion, foaming, bacterial growth, hydrate formation.

The additive may act by dispersing in the fluid, or by coating pipe or vessel walls.

Additives are normally introduced as pulsed flows, adjustable in volume and frequency.

The normal method of introduction is to use a metering pump, delivering at a pressure significantly higher than the system pressure.

Additives may be toxic, flammable and/or corrosive in the concentrated form, but usually pose little hazard once dispersed in the process.

Failure of additive injection can create an indirect hazard e.g. corrosion of process pipework.

Many liquid process streams have undesirable properties in the raw or untreated state. They may have a high viscosity, corrode pipework, foam, promote bacterial growth or deposit solids. In many cases the undesirable properties can be reduced or eliminated by the addition of special additives. Additives tend to work either by coating or reacting with the pipe wall, to reduce corrosion or deposition, or they work by dispersing in the fluid, killing bacteria or altering flow properties. It is normally found that additives are most effective when introduced as a steady, small, flow, well dispersed in the process fluid. Typically, the flow is adjusted to achieve maximum benefit (assessed by sampling or other process measurement) for the least additive usage (additives are often expensive, or over-dosing can reduce the benefit). In some duties, e.g. chlorination, there may be a requirement for periodic “shock” dosing at high levels for a short time, reverting to continuous low dosing in between “shock” doses.

The most effective way to introduce additives is to use a small positive displacement pump, operating at a high enough pressure to ensure accurate delivery at any system pressure within the duty range. Adjustable flow rate is achieved within the pump, not by recycling part of the...
flow to the suction tank. This is partly because the measuring of small flows is difficult, unreliable and expensive.

One other, apparently cheaper, method is to bleed a chemical from a manifold or tank at high pressure, via a flow meter, into the process line. This can give problems as it is often difficult to control and measure such small flows, particularly if the downstream pressure is variable.

Another method is to add "slugs" of chemicals periodically. This is very effective and the preferred method if the system can tolerate variable concentrations, or in some way recycles most of the additives. Chlorination of large cooling systems may be done this way.

In most cases, however, the additive works best / most economically is delivered constantly at just high enough concentration to have the desired effect. Variable concentration can trigger chemical reactions which quickly destroy beneficial protective layers.

The most effective way of achieving continuous injection has been found to be by the use of positive displacement pumps. These all work on the same basic principle but the operating power may be :-

- Electrical (via an electric motor and gearbox).
- Electrical (via electronic timer and actuating solenoid)
- Pneumatic (via pneumatic or electronic timer)

Because of their reliability and low operating cost, pneumatic drives are chosen offshore as well as not providing a source of ignition.

Additive chemicals come from a wide range of chemical sources, although there are generic solutions to problems, there is often a considerable element of trial and error, and "improved" chemicals are constantly coming on the market. These are often proprietary and the supplier is very reluctant to reveal the formulation. Broadly, simple chemicals are used to neutralise or remove undesirable trace chemicals e.g. oxygen, acids, and as biocides. Surfactants (detergents) are used to alter surface properties, reducing foaming, deposition of solids, viscosity. Complex salts, e.g ferrocyanides, are used to react with metallic pipe walls and reduce corrosion. Additives may interact, particularly in the concentrated form, and are thus usually injected at separate locations, using separate pumps. Concentrated additives may be very toxic, flammable and/or corrosive, and are usually handled in Intermediate Bulk Containers (IBC’s) which permit pumping direct from the IBC to process without any handling. Larger quantities may even require the shipping of ISO tank containers. Handling of drums or similar containers should be avoided because of the difficulty, cost and risk involved. Once dispersed in the process fluid, additives usually pose no significant hazard.

Many potentially hazardous conditions e.g. corrosion of carbon steel are controlled by additives. Since the failure of the additive to be effective is seldom immediately obvious, it is normal and good practice to monitor for the presence of the additive, or even better for its effect, in the systems being treated. Measuring at several points, including the least well treated, or most vulnerable, would be sensible. A good treatment policy would then adjust the treatment level to maintain the desired effect, triggering alarms at apparently high or low levels of addition or effect.

It is sensible to independently monitor the usage of the additive, and compare results periodically.

Each additive package can and should be assessed by the vendor for hazards, and designed accordingly. The overall hazard assessment is the responsibility of the operator/ main contractor. In particular, the location of the additive storages will have a significant effect upon the hazards that they pose.
2.5.1 AIR PISTON DRIVEN PLUNGER & DIAPHRAGM PUMPS
TECHNICAL SUPPORT

- Chemical additives are usually handled by small positive displacement pumps.
- Plunger or diaphragm pumps are the normal choice.
- Offshore installations often use air-driven pumps to reduce hazard.
- The primary hazard to personnel is the additive, this is often toxic and at high pressure.
- There are minor hazards from mechanical handling, compressed air.
- Secondary hazards e.g. from Too Much, Too Little, Incorrect Additive should be assessed by the Hazard Study process.

2.5.1.1 AIR DRIVEN PUMP ADDITIVE PACKAGE - DESCRIPTION

The package comprises a pair of Air Piston driven Plunger or Diaphragm Pumps on Chemical Injection service, complete with Control System & Ancillary Equipment, all as part of an Additives Module. The package does not include an Acoustic Enclosure. Ancillary Equipment & systems will include:

- Additive Storage (typically IBC & lifting system)
- Air supply filtration and regulation
- Bunding and containment
- Pressure and flow regulation
- Injection lances
- Control System
- Piping Systems
- Condition Monitoring
2.5.1.2 PACKAGE ENTITY

Physically, the package is a complete system for injecting the chosen chemical additive into one or more process pipes. Each duty would typically be served by a pair of pumps (one working, one standby) although several pumps on similar duties plus a common standby, or a single pump for a less critical duty, are all possible. The pumps will be mounted close to the IBC or storage tank to keep the suction pipe as short as possible. There may be room for two adjacent IBC’s to permit convenient manual change-over when one is empty, or there may be some form of automatic change-over. IBC’s will require some form of safe handling system that can be used in any weather. The pumps will have a delivery manifold with flow and pressure regulating valves, to ensure forward flow only, at the correct rate and pressure. The pipework will often be in small-bore plastic, which should be fully supported and protected. Pumps are driven by integral air piston units, the air supply will require local filters and regulation. The complete unit should have bunding or other containment to hold the contents of local storages, in the event of a release. This containment will have to be resistant to the chemical being handled. The control panel may be built on to the end of the baseframe (which is convenient for pre-wiring) or mounted separately (which permits control panels to be grouped together).

The available space on the package will be tightly packed, making access to internal components quite difficult. Thus any problem on one component has the potential to affect adjacent components / systems, whether by release of material, vibration or over-heating. Similarly, it may be necessary to remove a component either to work on that component or to gain access to adjacent components. For pump installations it is important that there is sufficient access to remove assemblies.
2.5.1.3 PACKAGE ELEMENTS

2.5.1.3.1 Air Piston Unit and Air Supply

Air pistons are a convenient means of operating small reciprocating pumps. They are only suitable for very low power applications, due primarily to the cost of compressed air. Air piston and air motor drives avoid the potential ignition risk from electric motors.

Air piston units are simple air cylinders fitted with a timing valve; at the end of each stroke the air supply is vented, or switched to the opposite side of the piston. The piston is returned pneumatically or by a return spring. The air supply should be clean & dry, thus instrument air quality. The pressure should be regulated to suit the duty, this inherently limits the maximum pressure achieved by the pump, and should avoid the requirement for liquid side pressure relief. The air supply to the regulator should be filtered, to protect the regulator and piston unit. A filter with a clear plastic bowl, if permitted on the installation, will display any dirt, rust or water in the air, giving some advance warning of problems. Wet air, in particular, is likely to freeze in the regulator or timing valve. Depending on design, the air may require lubrication, in which case a small lubricator bottle is fitted after the filter & regulator. The oil in this bottle must be topped up regularly.

The normal arrangement is to use a timer valve to provide one pulse of air for each pump stroke required. There is no inherent method of checking that the pump has actually worked.

Air piston units should be protected from the weather, otherwise atmospheric moisture and salt can enter.

Technical and safety aspects of the Air Piston Unit are described in more detail in Section 4.13 of the Guidance Notes (as part of the associated pump).
2.5.1.3.2 Reciprocating Plunger or Diaphragm Pump

In order to handle small flowrates, accurately, a metering type pump is required. The most common type is the plunger or diaphragm pump. In these pumps a single acting reciprocating plunger displaces a measured volume of liquid with each stroke. The rate of flow can often be controlled by altering the stroke travel or rate. Forward flow is ensured by the use of suction and delivery non-return valves. Where the fluid to be handled is toxic, corrosive or contains abrasive solids, the plunger displaces an oil which then displaces a flexible diaphragm. The diaphragm then pumps the hazardous fluid.

Onshore, the pump is typically operated by an internal crankshaft, driven by a close-coupled gearmotor unit.

On critical service, two pumps may be installed to provide redundancy. Where several systems are to be dosed at the same time, it is normal to install one pump per duty, to ensure accurate metering. It may then be practical to install a single common standby unit.

Technical and safety aspects of the Reciprocating Plunger or Diaphragm Pump are described in more detail in Section 4.13 of the Guidance Notes.

2.5.1.3.3 Instrument Air Supply

It is assumed that the instrument air supply to the additives system is at least as reliable as the pump systems. Dosing systems are seldom sufficiently critical that their loss is instantly felt. Where it is necessary to maintain pressure on a system, pressure-maintaining valves and a local air receiver may be called for. It is important that the system can provide the appropriate quality and pressure of air, otherwise the pumps could suffer internal damage or stall.

The air quantities required are too large for the use of compressed air cylinders to be of any benefit, except for testing or commissioning, when the instrument air supply may not be available.

Local filtration, pressure regulation and moisture checking are advisable. Simple air filter/regulators are available with transparent bowls as a check for dirt or moisture. The aluminium/plastic construction normally adopted may not be acceptable in the environment, and special units may be required.

2.5.1.3.4 Additive Storage & Bunding

Normally, each pump will handle a single additive, drawn from a local reservoir, typically an IBC. Bulk storage is possible, depending on the quantity of additive handled. IBC’s have to be changed when empty, so it is normal for the pump to draw up the fluid through a flexible plastic pipe. It is quite good practice to mount the pump higher than the IBC, where possible, this reduces the risk of syphoning the contents out of the IBC if the suction pipe leaks. IBC’s require a proper and safe handling system, ideally with room to hold 2 IBC’s within the additives package. This permits one IBC to be fully emptied, and the pump changed over, with the empty IBC removed at a convenient time.

Work on and around the IBC’s will often require full PPE for protection until all openings are capped and the unit is safe to handle. This requires adequate room, lighting, washdown and drainage points as applicable. The Permit To Work system should ensure the use of the correct PPE, the connection & disconnection of the correct IBC to the correct pump, and the labelling and segregation of empty from full IBC’s. Damaged IBC’s to be marked.

Since the additives are often hazardous, bunds or containment are required to hold the largest realistic spillage, from storage, pumps and pipework. The containment may be segregated if additives do or may react adversely when mixed. Special design and precautions apply if any of
the additives should not contact water or be washed into the drains. These chemicals should be handled in a separate unit with additional containment and specific procedures.

The storages and containment should have a means to check levels, preferably level switches linked to alarms. IBC’s may sit on load cells for control and low level alarm purposes.

2.5.1.3.5 Pressure and Flow Regulation

Additive systems normally require a controlled rate of addition irrespective of downstream pressure, but often controlled by system parameters e.g. flow, residual additive as detected downstream. To achieve stable flow, the normal arrangement is to have a relatively high nominal pump delivery pressure, with a spring loaded back pressure valve to regulate the flow. The flow rate will then be relatively insensitive to the system pressure. It is not normal to feed more than one pipe system from each pump, as it is difficult to control the split flows.

With air piston pumps the rate can be adjusted by altering the timing valve frequency, and often by adjusting the stroke. The pumping rate can be measured by counting the pulse rate of the timing valve. If continuous dosing is not required, the pump can be stopped and started as required to maintain the desired average rate.

If the system being dosed operates under partial vacuum, or the additive is fed to the pump at a higher pressure than the dosed system, particular care is required as the additive can be sucked into the system even when the pump is not operating.

2.5.1.3.6 Injection Lances

It is normally important that additives are well mixed into the process fluid. Additionally, some additives are corrosive until well mixed. Thus tailor made injection lances are often used to inject the fluid into the process stream. Typically, the process pipe is fitted with a proprietary injection manifold, mounted on a branch. This manifold carries isolation valves and a lance insertion system. High pressure systems will require a more robust system e.g. a bypass insert that can be isolated and removed.

The delivery pipework from the pump(s) may well be small bore and in plastic. This would require continuous supporting and protection, with consideration given to containment, at least at joints and fittings.

2.5.1.3.7 Control System

The simplest systems require a continuous pre-set flow, this might just be by hand set timer valves / stroke length, periodic level checks in the IBC or sampling of the process.

The most sophisticated will be continuous adjustment based on process flow rate and in-line measurement of the effect of the additive at one or more downstream points.

One control unit will probably manage several dosing systems, including alarms and automatic pump change-over, as appropriate.

2.5.1.3.8 Piping Systems

Piping systems are generally constructed to international standards, see Section 5.7 for details.
2.5.1.3.9 **Condition Monitoring**

Simple condition monitoring may be appropriate, as part of the control system. Monitoring of the process system to which the additive is being introduced is the most valuable check, followed by storage level, pump operation and spillage checking. For maintenance purposes a record of the number of strokes or amount injected since the pump was last overhauled, would be convenient. For more general comments on condition monitoring see **Section 5.12**.

2.5.1.4 **INTEGRATION ASPECTS**

The pumps will be selected to handle the appropriate chemical at pressures high enough to ensure accurate delivery to the process. As chemicals may change, and interchangeability of pumps can be useful, it is best to have a small number of pump types/ materials of construction. The dosing rates may not be fully established at the design stage, and may change during operation, so pumps should be selected with a reasonable rate turn-down (or up) and modular design permitting plunger size changes.

Reciprocating pumps create pulsations, particularly with a single plunger operation. Suction side pulsations are best dealt with by using the shortest possible suction line. Delivery side pulsations may well require a pulsation damper. These dampers are notorious for creeping deterioration, leading to gradually increasing pulsation levels. Short, flexible pipework minimises the requirement for dampers.

Contamination of the instrument air by additives would be a serious problem. Hence there should be absolutely no possibility of cross-connection, to the extent of using segregated pipe routes. Similarly, it would be good practice to let down the air supply, via a regulator and relief valve, into a small local air receiver operating at a lower pressure than the air supply. Any new pumping device or unit should be checked out to ensure that an internal fault cannot cross-connect air and additive flows – due to the pressure multiplying effect the additive will probably be at a higher pressure than the supply air.

2.5.1.5 **HAZARD ASSESSMENT**

Primary hazards relate to the release of toxic, flammable or corrosive additives in their concentrated form, or operator contact with additives during IBC change or pump maintenance. Operators are reliant on the additive supplier to provide the mandatory hazard data sheet, and to provide updates when the formulation or chemical is changed. The operators should also assess risks from mixing of additives with other additives, process fluids or lubricants likely to be present in the area. The quantities to be stored, the size of containers to be used, and the storage conditions, are important. Fluids which react with water, or should not be disposed of to the sea, are or particular concern.

Note that failure of the delivery pipework could result in a release of additive (as the pump continues to operate) and process fluid (unless a carefully located NRV works).

There are minor but well understood hazards from mechanical handling and the use of compressed air.

The secondary process hazards to be considered relate to the consequences of inadvertently supplying too much or too little additive, or the wrong additive, at an injection point. Some of these consequences could take a long time to become apparent. These are Hazard Study issues. The consequent question is “How do we know we have got it wrong ?”.

See **Section 4.13** for the hazard assessment for the Reciprocating Pump.
2.5.1.6 APPLICABLE STANDARDS

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations (Transposed Harmonised Standards) can be found in Section 5.15 the specific standards relating to this package are:-

BS EN 809 1998 Pumps and pump units for liquids – Common safety requirements.
BS EN 983 1996 Safety of machinery – Safety requirements for fluid power systems and their components – Pneumatics.

Selection of API Standards Relevant to Machinery in use in Refineries / Offshore :-

API 674 1995 Positive Displacement Pumps – Reciprocating
API 675 1994 Positive Displacement Pumps – Controlled Volume

General Standards for machinery can be found in Section 5.15
SECTION 2.6 FIRE WATER

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- Fire water is an emergency service, effective operation on demand is the prime requirement.

- The system will be highly independent of other systems.

- The system will have a small number of running hours, but a relatively large number of test starts.

- The chosen system will be a vertical submerged pump driven by a dedicated diesel engine. The pump drive may be mechanical, electrical or hydraulic.

- The system must be able to operate for a few hours in the midst of a major platform fire. Survival for that period is paramount, condition thereafter irrelevant.

- Extreme simplicity is preferred as the route to reliability, although twinned support and starting systems, using different technologies, can be of benefit.
Section 2.6.1 Diesel Engine driven Extended Shaft Centrifugal Pump
Section 2.6.2 Hydraulic Motor drive for Fire Water Centrifugal Pump

For Pump and Driver information refer to :-

Section 4.11 Centrifugal Pump – Vertical Long-shaft or Submersible Driver Type
Section 3.6 Diesel Engine

For any fire pumped sea water will be applied from hosepipes and fixed deluge systems triggered automatically. Deluge systems, using distributed spray nozzles, are the best way to tackle a fire as cooling of surrounding equipment and steel structure is at least as important as tackling the actual fire. Since there is no reliable external source of pressurised water, an onboard system is required. There will already be multiple sea water service pumps powered by the main power system, but these may have been compromised by a fire or explosion in the power generation or distribution system. Hence the requirement for a number of fully independent, black start (start with no external energy supply), fire water pump sets. These are normally not running during normal operation, but can be brought on line quickly by a very simple automatic or manual action. The prime requirement is that the operators are confident that the set(s) will start on demand.

To achieve independence, each Fire Water Pump set is a separate package with all its own systems, with the minimum possible linkage to each other or to the main platform systems. Fuel, stored energy for starting, and batteries for lighting and control, will all be mounted local to the set, within a fire-resistant housing. Since no emergency system can be truly relied on without testing, routine test starts, under realistic conditions, must be made by the actual operators who will call on the set(s) in an emergency. The design of such safety critical elements should comply with the Offshore Regulations (Prevention of Fire and Explosion, and Emergency Response) Regulations 1995 [PFEER] and associated performance standards. The set must then be run for long enough for all systems to settle down, temperatures to stabilise. The preferred run time would be significantly longer than the guaranteed time set out in the Safety Case. The set must then be shut down in such a way as to assure its availability for re-start in emergency. These test starts must be logged to confirm that such a vital system is being tested properly. Hence the number of starts will be relatively high, and the number of hours run, low. These units are not suitable for continuous operation, running hours exceeding 10 % of platform operating hours would suggest inappropriate use of the system.

The chosen system will be a submerged multi-stage seawater lift pump, driven by a dedicated diesel engine. The pump will be located in its own conductor tube, and the engine in its own enclosure. Several units will be installed, in at least two well separated locations. This minimises the risk that a single event will disable most or all of the fire pumps. The drive system might be by mechanical shaft, dedicated electrical drive or dedicated hydraulic drive. The latter two are somewhat simpler, and give the potential advantage that the engine does not have to be vertically above the pump.

The entire system and location of equipment will be chosen to ensure, as far as possible, its survival and continued operation through a major platform fire. It is accepted that on-board systems cannot be expected to run indefinitely, and that either the fire will be out, the platform destroyed, or external fire-fighting resources in play, after a few hours. In any event, time will have been gained to evacuate personnel and shut down as many fuel sources as possible. The system will be designed to operate for a period with an enclosure specification of A60 under fire conditions, any design work, tests or simulations must bear this in mind and demonstrate a reasonable safety margin. It is more important that the system continue to run, than to protect it from damage, hence no trips will be fitted, and the system is considered to run to destruction (or until the fuel runs out) if the operators do not stop it.

Reliability is achieved by having several independent pump systems, each system is then kept as simple as possible. There will be one driver, one drive system and one pump. There is merit
in having duplicated support systems using different technologies e.g. starting by compressed air and batteries, oil pumping by shaft drive and battery supply. Cooling water should be obtained from the platform main and from the fire pump delivery.

The unit will have no trips, although alarms will be required, primarily to avoid damage during test runs, and to confirm that energy storage and charging systems are in top condition. There will be some form of control room indication that the system is healthy and ready for automatic and/ or manual start. Disabling of part of the system e.g. for maintenance or for diving operations near intakes, must be subject to risk assessment and Permit to Work. Disabling must not be prolonged beyond the minimum necessary duration.
2.6.1 DIESEL ENGINE DRIVEN EXTENDED SHAFT CENTRIFUGAL PUMP PACKAGE

TECHNICAL SUPPORT

Figure 2.6.1 – 1 Diesel Engine Drive Unit with Gearbox and Pump Discharge Branch

2.6.1.1 DIESEL ENGINE DRIVEN EXTENDED SHAFT PUMP - DESCRIPTION

The package comprises an Industrial Diesel Engine driving an Extended Shaft Multi-stage Submerged Centrifugal Pump on Fire Fighting Sea Water service, complete with Control System & Ancillary Equipment, all mounted on a 3-point mounting skid baseplate. The Diesel Engine and Ancillaries are enclosed in an Fire-resistant Acoustic Enclosure with its own Fire-fighting System. Ancillary Equipment & systems will include:

- Inlet Air System & Filter
- Fuel System
- Starting Systems(s)
- Exhaust Pipe and Silencer
- Lubricating Oil System
- Right Angled Drive Gearbox
• Shaft Couplings
• Shaft Mechanical Seals
• Cooling System
• Piping Systems
• Control System
• Batteries and Emergency Lighting

The Schematic Diagram of such a system is shown below.

![Schematic Diagram – Diesel driven Fire Water Pump System](image)

**Figure 2.6.1 – 2**  Schematic Diagram – Diesel driven Fire Water Pump System

### 2.6.1.2 PACKAGE ENTITY

Physically, the package is an enclosed diesel engine with a close-coupled gearbox and pump drive. This is linked by a long vertical drive shaft to a submersible pump. All machine elements except the drive shaft and pump are contained in a fire-resistant acoustic enclosure mounted on a common baseframe that is sufficiently rigid to maintain machine alignment, despite movement of the supporting structure or vessel. The 3-point mounting system eliminates the transmission of twisting forces to/from the baseframe. In order to protect them from fire/explosion, all of the ancillary systems e.g. fuel system, lubrication oil system, cooling system, are inside the enclosure. The control panel will also be inside the enclosure. There will be energy storage e.g. diesel fuel, compressed air, batteries, to provide for starting and running the system for in excess of the guaranteed time without outside support or service. Within the enclosure equipment will enable injection through venturi suction for foam additives with a store of such additives held.

The Fire-resistant Acoustic Enclosure will be large enough for personnel to work inside, and fitted out with lighting, ventilation and Fire Detection systems. The internal space will be tightly
packed, making access to internal components quite difficult. There must be enough room to permit servicing and system testing in the minimum time without removing access panels from the enclosure. The interior of the enclosure will be very hot and noisy in operation, the insulation of the enclosure, while primarily for fire purposes, will limit noise transmission and heat loss.

The pump will be at the bottom of a conductor tube leading from the underside of the enclosure. Access to the pump is only possible by removing access covers and parts of the drive system, then lifting the complete pump assembly out onto the deck.

The air inlet filter will be located inside the enclosure, the air intake will be from a low fire risk area, probably below the platform adjacent to the conductor tube.

2.6.1.3 PACKAGE ELEMENTS

2.6.1.3.1 Diesel Engine

The Industrial Diesel Engine mounted within the Fire Pump Package will be foot mounted from the baseframe, in order to carry the considerable weight of the machine. The main drive shaft, which is horizontal, will connect the engine flywheel to the right-angle gearbox via a flexible coupling. Auxiliary Drives within the engine will typically be mounted on the front (opposite from flywheel) end and driven by chains or belts. Flexible connections will link to the inlet and exhaust ducts, and cooling water pipes.

Hot surfaces will be fitted with heat shields or thermal insulation. These must be in place for operator safety.

The engine is dependent on various ancillary systems for safe operation, operating procedures and control system must ensure that these are operational prior to engine start, and at all times during operation. Note that on an emergency duty the failure of a service will not trip the engine, but should instead raise an alarm. Hence the reason why test runs should be monitored by the operator. This emergency duty requirement is a major inversion of normal design philosophy, correctly designed systems may be intended to operate in or fail to a “danger” mode.

Any mechanical failure of the engine, or an explosion within the enclosure, could disrupt fuel pipework, with the potential for a release. Missiles, in the form of bits of turbocharger or other components, may be thrown in a mainly radial direction, with the potential to damage people or critical systems within the enclosure. With the exception of the turbocharger, diesel engine parts are low speed and very unlikely to penetrate the enclosure. There are several energy storage systems in close proximity to the engine. During servicing, these systems are still “live” and have the potential to cause major injury.

Technical and safety aspects of the Diesel Engine system are described in more detail in Section 3.6 of the Guidance Notes.

2.6.1.3.2 Submersible Centrifugal Pump

The Multi-stage Centrifugal Pump is mounted at the bottom of the Conductor Tube, which can easily be 40 m long. There will be a certain amount of flexing of the tube, especially during storms. The pump discharge pipe, containing the drive shaft, runs up the centre of the conductor tube and must, if necessary, flex with it. There may well be flexible elements in the drive shaft, particularly at the ends.

The pump is lowered down the tube, guided by “spiders” until it hangs in the correct location, close to the intake grilles at the bottom. These grilles are to stop the entire pump or large components from falling out of the tube if dropped, and to prevent large objects e.g. fish, plastic debris, from being drawn in. The pump is guided but not supported at the bottom, the weight continues to hang on the discharge pipe.
Submersible pumps contain moving parts within a robust casing. Mechanical failure can result in severe internal damage but this is extremely unlikely to pose a direct hazard to people, due to the under-sea location of the pump. The risk during normal operation entirely relates to maintenance and inspection activities, perhaps in difficult locations under the platform or whilst lifting awkward pump components.

The real safety risk posed by the pump is that it will not work when it is required in an emergency. Due to its location, it is barely possible to be sure that the pump is still there, still less that is will work as required. Some condition monitoring / slow roll testing may be possible but the only realistic check is a regular full power test run exercise, with the pumped water dumped through an orifice plate to simulate system load.

Technical and safety aspects of the Multi-stage Submersible Pump are described in more detail in Section 4.11 of the Guidance Notes.

2.6.1.3.3 Right Angle Gearbox

Since the diesel engine will have a horizontal shaft and the pump a vertical one, the shaft drive requires a right angle gearbox. This can also conveniently contain the clutch, brake and any speed matching required. The gearbox is very compact and sits on top of the pump discharge branch. Unfortunately, this means that it must be lifted aside to access the pump drive shaft.

There are a limited number of safety issues from inclusion of a gearbox within a machine package. The most serious are:

- The potential for unintended engagement of auxiliary drives, used to rotate the pump at low speed, leading to massive overspeed and usually the disintegration of the drive.
- For bursting of the gear wheels (design or manufacturing flaws).
- For fires due to leakage of lubricating oil.

The right angle gearbox has a few special features:

- It has top and bottom bearings in the same way as a vertical gearbox, requiring appropriate lubrication systems.
- It tends to be noisier than a parallel shaft gearbox. This may give the impression of wear to someone used to standard gearboxes.
- Setting up of thrust bearings is critical to correct operation, otherwise excessive gear wear will occur. This is offset by the low operating hours.
- The gearbox must be designed and laid out for easy removal and re-installation, thus service pipes etc., should not be damaged by this process.
- The output shaft will be aligned by the gearbox mounting spigot but the input shaft from the motor will require an alignment check after re-installation. The input shaft may be set up as a cardan shaft, with large alignment tolerances, to facilitate this.

As with the pump, the true requirement is that the unit works when required. Observation/monitoring during test runs will give the best check on condition. Oil heaters etc., may be fitted to ensure easy starting. There may be a barring/slow roll drive.

Technical and safety aspects of the gearbox systems are described in more detail in Section 5.5 of the Guidance Notes.

2.6.1.3.4 Main Drive Coupling

The use of flexible couplings within a machine package is essential to provide the necessary degrees of freedom to enable the elements of the machine to be aligned and compensate for thermal expansion and any flexibility inherent in the installation skid. This is particularly the case for a diesel engine with its large torsional fluctuations and general vibration level. The pump drive shaft, however, will act as an ideal torsion spring.
Misalignment of the coupling, even within its tolerance limits, puts increased loads on adjacent shaft bearings. It also reduces the service life of the coupling, as flexible elements are subjected to greater strains. Coupling lubrication (where required) and inspections must be proactively maintained as the coupling has significant mass and has the potential to become a dangerous missile if it fails. A maintenance check that the coupling is not in the part-failed condition is advisable.

Technical and safety aspects of flexible shaft couplings are described in more detail in Section 5.6 of the Guidance Notes.

2.6.1.3.5 Lubrication System

In Diesel Engine drives the engine oil has different requirements from gearbox oil, and can also become contaminated with fuel. The engine normally has a self-contained oil system (manufacturer’s standard with, possibly, a battery driven pre-start/standby pump which can be tested without starting the engine). The gearbox and pump top shaft bearing can sensibly have a shared oil system, provided by the gearbox manufacturer, having one shaft driven pump and, again, possibly a battery driven pump.

The diesel engine is inevitably going to suffer from fuel contamination of the crankcase oil, the large plain bearings used are reasonably tolerant of this and the carbon that also tends to accumulate in the oil. Gear drives are not tolerant of these contaminants.

Shaft driven oil pumps may well be internally mounted and inaccessible, this should not be a problem for the limited running hours required. They can easily be tested in service by checking the oil pressure, and perhaps the flow if sight glasses or flow meters are fitted. Bearing temperature monitoring will confirm satisfactory lubrication. For reliability, the systems should be simple, accessible, robust, easily understood. Thus designs based on manifold blocks, welded/flanged connections, are much preferred to lengths of small bore screwed pipe. Where flexible connections are required, they should use hydraulic type hose with appropriate fittings, and be laid out logically and with ample clearance for tool access and inspection. Drip trays should be fitted to keep the floor clean and to monitor for any oil leaks. Labelling will be required to ensure that the correct oil and filters are used in each system.

The oil level, oil pressure, oil temperature, and the availability of main/standby pump, should be monitored by the alarm system, with fault alarms as appropriate. For simplicity, standby pumps will probably be set up on a “both running” basis with non-return valves to control back-flow. Oil sampling can be a valuable non-invasive check on the condition of the oil. In order to get a representative sample, it should be taken from pumped flowing oil between the pump and the filter. Sampling from sumps or level devices may not give a fair sample. Regular testing of oil condition can warn of issues like water contamination and gear or bearing wear. See Section 5.12 for available condition monitoring techniques.

The submersible pump and its drive shaft guide bearings are sea water lubricated from the pumped water. There is no lubrication system as such. The shaft thrust bearing, as mentioned above, is probably oil-lubricated. This is at the top of the shaft for simplicity and also to ensure that the shaft is in tension rather than compression, for stability.

The most serious issues for the supply of oil to a machine package arise from either failure of the supply that can lead to inoperability of the machines, or from oil spill or leakage resulting in a fuel source for potential fires. In either case this would be a major failing, the pump drive system must be operable at any time and cannot survive a fire inside the enclosure.

Technical and safety aspects of lubrication systems are described in more detail in Section 5.2 of the Guidance Notes.
2.6.1.3.6 Control System

Machines within a package must be integrated to function as a complete system. Therefore control systems are designed to provide this essential control and protection for the machine elements.

The control system is required to monitor the system as closely as practicable when not in use, to confirm availability and starting mode(s). Once running, the control system provides alarm and monitoring only. Even if cables and pipes are burned through or otherwise destroyed, the pump should still run. Hence the “fail to danger” philosophy may be appropriate, with live signals preventing the engine from starting. For example, a “System Safe” signal from the installation Fire & Gas system may inhibit automatic pump start. Loss of this signal will trigger the automatic start sequence. It should only be possible to stop the engine locally i.e. from within the fire-resistant enclosure. It is accepted that in a real fire, the fire pump will run to destruction. There will be provision for manual or automatic start, according to operating requirements. It is vital that the operators know which status applies to each system.

Automatic start will have to be disabled e.g. for diving operations, and the complete system disabled for maintenance. In such cases alternative or temporary systems will be required to ensure continuity of fire system cover. Maintenance may also require the isolation or draining of all stored energy systems which could result in injury to personnel. After maintenance or inspection, all systems must be restored and some form of system test (not necessarily a start) performed. Any Permits must be cleared to confirm that the unit is ready for instant operation.

Control software must be rigorously checked, subject to strict version and change recording and control. Pre-programmed cards can be fitted to the wrong machine; they may be physically identical (to Model and Serial Number) but carry different instructions.

Details of the requirements for these systems are noted in the Guidance notes for each element.

2.6.1.3.7 Diesel Engine Fuel and Air Systems

The diesel engine will be supplied with its own fuel tank, pumps and filters, in order to operate independently of the platform fuel supplies. The tank will be inside the enclosure to benefit from the fire protection, and probably mounted high up to provide a gravity feed to the fuel pumps. There will be provision to manually check the liquid level (e.g. a full height sight glass) and to check for and drain off any water in the fuel. The fuel level, in particular high and low levels, will be monitored by the control system, in such a way that any failure of the system cannot affect engine operability. Re-filling of the tank from the platform main supply will be under operator control to ensure clean fuel is supplied up to the correct level. The system should be designed to prevent over-filling, and should be isolated at the enclosure wall when not in use. Fuel leakage or spillage within the enclosure could lead to destruction of the fire pump driver.

All fuel pumps / heaters will be powered from the diesel engine and its batteries, to preserve complete isolation from main systems. See Section 5.1.3 for further details on Diesel Engine Fuel Systems.

The intake air for the engine will be filtered locally to remove dust/ dirt/ salt. This filter should be located inside the enclosure. The combustion air must be drawn from a “safe” location which is at low risk of being subject to fire or significant amounts of flammable gas. Ingestion of flammable gas can cause diesel engines to overspeed and self-destruct. See Section 5.10 for further details on Air Inlet Filter Systems.

Cooling of air within the enclosure will be required for A60 enclosures where external ventilation will be closed in case of fire. In other cases the ventilation air for the enclosure can be drawn from the same location, although some silencing will be required to reduce the engine suction
noise transmission to the enclosure. The exhaust air does not necessarily have to go to a “safe” location provided that fire cannot enter the duct. The ventilation system is intended to provide a working environment within the enclosure. It will pressurise the enclosure to prevent gas ingress, and will remove fumes e.g. from battery charging, and heat from exhaust pipes and hot surfaces.

2.6.1.3.8 Engine Starting Systems and Energy Storage

Emergency diesel engines require a self-contained starting system or systems. These may include battery start, compressed air start, “pony motor” start, or manual start.

A battery start system requires a starter motor, large lead-acid storage batteries, a battery charging system and a control system to de-compress the engine cylinders until the engine is running fast enough to start. The starting batteries should be independent, to prevent power drain. The battery charge condition should be monitored constantly and reported to the control room. The routine maintenance must include regular checks on the battery electrolyte level and strength. Note that lead-acid batteries contain sulphuric acid and generate hydrogen during and after charging.

Compressed air starting is used because it is effective and simple. In the commonly used design, stored compressed air is fed to valve gear on the engine, where it is bled directly into the engine cylinders to rotate the engine. When the engine has reached its starting speed, fuel is introduced and normal valve gear restored. An alternate, very simple, design uses an air motor as a starter motor. The compressed air storage receiver(s) must be located inside the enclosure, for fire protection, but the re-filling can be from the normal instrument air supply or from a dedicated compressor; this can be located outside the enclosure.

“Pony motor” is the term used for a small diesel engine which can be used to rotate the main engine at its starting speed. The pony motor is first started by batteries and run up to full speed, an automatic clutch or hydraulic drive is then used to spin the main motor, decompressed. Finally the main motor is started, again automatically. The pony motor drive must then disconnect or over-run safely, for the main motor to run up to full speed. Typically, such clutches include a sprag or over-run device. If the drive does not disconnect, e.g. because it has seized, the drive or pony motor will be destroyed. Pony motor start is inevitably slower than direct starting.

For a large engine, a combination of air starting (for speed) and pony motor (as backup) might be used. The pony motor would be a convenient driver for a slowroll system, and for recharging compressed air storage tanks.

Battery charging systems will be supplied from the platform main supply. A separate set of batteries should be used for lighting and other support functions, failure of this system should not affect system operation. If battery powered pumps, fans etc., are used during the pump operation, the main engine should carry an alternator rated to support these loads, to minimise battery drain.

Once the main engine is up to a working speed (not necessarily full speed), the pump can be brought into service by engaging the drive clutch or drive system, again automatically on such an emergency system. Smooth engagement is required as the pump drive shaft is long and flexible. It must be assumed that the pump delivery line is empty, it will start filling as the pump accelerates. For effective operation, the trapped air must be vented from the line. This can be done with the use of an orifice plate matched to the anticipated fill rate. Once the line fills and the pressure rises, a non-return valve allows the fire water into the distribution main. The water now being released from the orifice plate can be used for local fire sprays e.g. to deluge the outside of the enclosure, or dumped over the side. A water bleed will be required for engine cooling.

Details of the requirements for the systems below are noted in the Guidance notes for each element.
2.6.1.3.9 Acoustic Enclosure

For further information on Acoustic Enclosures see Section 5.4.

2.6.1.3.10 Exhaust System

This system is specific to the Diesel Engine and is covered in Section 3.6.6.7

2.6.1.3.11 Cooling Systems

The Diesel Engine cooling system will be proprietary, see Section 3.6.6.11. For more general notes on cooling systems and equipment see Section 5.11.

2.6.1.3.12 Piping Systems

Piping systems are generally constructed to international standards, see Section 5.7 for details.

2.6.1.3.13 Condition Monitoring

Condition monitoring on larger Machine Packages will be provided as part of the package. Vendors will offer their own preferred system, or will agree to tailor a system to suit the client’s requirements. It is important to ensure that the system provided suits the proposed method of operating and maintaining the equipment. See Section 5.12 for more detail.

2.6.1.4 INTEGRATION ASPECTS

2.6.1.4.1 Hardware Matching

The design of the package must ensure that the operating capability of each element of the package matches or exceeds the greatest potential demand placed on it by the system.

For a Fire Pump System the major elements that must be considered are:

- Pressure Rating
- Flow demands
- Sea water levels and wave action
- Delay from start signal to full delivery flow
- Manual / automatic starting
- Location of equipment and fire protection
- Number of installed systems vs. number required to run for full protection

2.6.1.4.2 Operational Matching

The operation of a package unit requires that there are no conflicts within the system that would compromise effective operation of the system.
It is expected that the system will function with one or all fire pumps running, maintaining an effective pressure in the fire mains by a combination of pump selection and dumping excess water. A minimum flow will be required to satisfy the pump design and to provide enough load to keep the engine governor loaded.

In the event of rupture or damage to the fire main, the pump and engine speeds must not exceed safe limits, again by use of the engine governor.

The system must be able to start up and pump into a pressurised fire main.

For more general Operation Guidance see Operation Support Guidance Section 6.1.

2.6.1.5 HAZARD ASSESSMENT

Fire and other emergency systems require a somewhat different approach to hazard assessment, as they pose little or no hazard when not in use, and must work reliably for a specified period on demand. The risks posed by energy storage systems, automatic starts and probably some unguarded hot surfaces, must be set against the paramount requirement for a fast and trustworthy start. The design and integration of the complete package by a specialist fire system supplier then makes complete sense, they can then buy in specialist items e.g. pump, engine, specified for the rigours of fire service. A conventional packager of equipment will not normally have the experience or the right philosophy to get this right. See Section 7.2.4 for a structured set of Hazard Assessment Tables.

2.6.1.5.1 Process Substance Containment Hazards

Since the pump discharge, and cooling water pipes, pass inside the enclosure, a failure of the pipework could release a significant amount of water inside the enclosure. This could flood the enclosure to sufficient depth to compromise the operation of the engine. The fire-resistant design of the enclosure will limit the amount of water drainage. Personnel hazard is unlikely, as the access doors will be open when people are inside.

Containment hazards relating to the Submersible Pump are covered in Section 4.11.3.1

See Section 3.6.3.1 for Ignition/ Explosion hazards from the Diesel Engine.

2.6.1.5.2 Equipment Hazards

In practice, mechanical hazards of packaged equipment are the same as the individual units. There is a risk of an incident on one component of the system adversely affecting the other, but this applies to any multiple machine installation.

All moving and hot parts should be guarded, the risks will relate to the stored energy/ automatic start systems and thus the potential for unexpected starting. The noise level in the enclosure during a start will be very high.

For information specific to the package elements see Sections 3.6.3.2 & 4.11.3.2

2.6.1.5.3 Operational / Consequential Hazards

Packaging should have no particular influence in this area; Mechanical, Process and Control interactions apply equally to Packaged and Non-packaged units. It can be argued that there is a reduction in risk, because the Package should have been designed as a whole to a consistent duty requirement.
For information specific to the package elements see Sections 3.6.3.3 & 4.11.3.3

2.6.1.5.4 Maintenance / Access Hazards

Maintenance on packaged units can be significantly more difficult because of very congested construction, this is not necessarily hazardous but can result in more sprains and similar injuries as people struggle to work in restricted spaces. Well-designed packaged units incorporate tailored lifting / slinging facilities. It is usually more appropriate to change out an assembly than to attempt to repair a failed component in situ. There is a potential issue of isolation of electrical and other energy sources where isolation of part of the package may not isolate a closely adjacent part. This must be covered by Maintenance / Permit to Work procedures.

The Fire Pump package should have a little more access room than most, servicing must be done quickly and in particular without removing or disturbing other items. Energy sources must be disabled or drained prior to access, and restored thereafter. As this can be complex, risk assessments and sensible procedures are required to identify logical packages of servicing work. These packages must be followed through to completion, not altered in mid-stream.

In particular, major personnel hazards can be introduced during the lifting out of either the pump (with its delivery pipe and drive shaft) or major diesel engine parts. Here, heavy or awkward parts are being lifted from a confined space, often with people in close attendance at the bottom of the lift. The crane operator will not be able to see these people, but relies on instructions from a trained banksman. Lifting procedures must be good, e.g. no lifting without positive & continued instructions, dedicated radio channel, instructions by nominated and trained banksman only.

For information specific to the package elements see Sections 3.6.3.4 & 4.11.3.4

2.6.1.6 APPLICABLE STANDARDS

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations ( Transposed Harmonised Standards ) can be found in Section 5.15 the specific standards relating to this package are :-

BS EN 809 1998 Pumps and pump units for liquids – Common safety requirements.
BS EN 1037 1995 Safety of machinery – Prevention of unexpected start-up.

Selection of API Standards Relevant to Machinery in use in Refineries / Offshore :-

API 610 1995 Centrifugal Pumps for Petroleum, Heavy Duty Chemical and Gas Industry Service
API 14G 1993 Fire Prevention & Control on Open Type Offshore Production Platforms

General Standards for machinery can be found in Section 5.15
2.6.2 HYDRAULIC MOTOR DRIVE FOR FIRE WATER CENTRIFUGAL PUMP

TECHNICAL SUPPORT

2.6.2.1 DIESEL ENGINE / HYDRAULIC MOTOR FIRE WATER PUMP PACKAGE - DESCRIPTION

The package comprises a Diesel Engine driving a Vertical Multi-Stage Centrifugal Pump on Fire Water service, as per Section 2.6.1. However, instead of the right angled gearbox and long vertical drive shaft, a hydraulic pump and hydraulic motor are used to drive the pump. This gives the following advantages:

- The pump need not be vertically below the engine
- The pump drive train does not have to be dismantled in order to lift the pump
- One engine could drive more than one pump
- One pump could be driven by an engine and an electric motor
- Auxiliary drives e.g. cooling water pumps, ventilation fans, are very simple

Figure 2.6.2 – 1 Schematic Diagram – Diesel Engine/ Hydraulically driven Fire Pump
2.6.2.2 PACKAGE ENTITY

The package will be very similar to the equipment in Section 2.6.1.2 and performs the same function. The right angle gearbox and pump headgear are replaced by a hydraulic pump, driven by the diesel engine. The hydraulic oil is then fed through supply and return hydraulic pipes to the hydraulic motor, located on the bottom end of the pump shaft. The pump still has a vertical discharge pipe, this no longer contains a drive shaft, instead the hydraulic lines are clipped on externally. Since hydraulic lines can be run in any direction (but should be kept as short as possible), the conductor pipe can be displaced from being directly below the engine. This may be done to take advantage of a lifting well in the platform, or simply to avoid having to lift the pump up through the engine enclosure. Hydraulic pumps normally have a variable speed, variable torque facility for very smooth pump starting and priming.

2.6.2.3 PACKAGE ELEMENTS

2.6.2.3.1 Diesel Engine

See 2.6.1.3.1 This unit will be identical to a shaft-drive engine.

2.6.2.3.2 Submersible Centrifugal Pump – driven by Hydraulic Motor

See 2.6.1.3.2 The pump itself will be similar, but instead of being driven from above by a long shaft, the drive is from below by a close-coupled hydraulic motor.

The vertical discharge pipe thus does not contain drive shaft or guides, and is much easier to dismantle when lifting the pump.

The reason for driving from below is that a top mounted motor would block the discharge pipe direction. There is now a requirement for a thrust bearing within the pump, to provide axial shaft location and carry the residual axial loads. The majority of axial loads will be absorbed by the impeller hydraulic balancing arrangement.

The pump shaft will pass out of the bottom of the pump housing itself, at the level of the inlet ports, thus at suction pressure. The pump does not have a mechanical seal, but one will be required for the hydraulic motor, to exclude sea water. The shaft connection to the hydraulic pump will typically be a clamped muff (rigid) coupling.

With the pump disconnected from the discharge pipe at one end and the hydraulic motor at the other, the pump is then a reasonably compact unit for handling and shipping.

2.6.2.3.3 Hydraulic Pump

The hydraulic pump will be linked to the diesel engine flywheel, either close-coupled or via a flexible coupling. The pump will typically be of variable-displacement design, which can be set to zero displacement for engine starting. Hydraulic pumps are rotary positive displacement machines, producing high pressure oil to drive hydraulic motors or cylinders. There are many types of hydraulic pump, some are fixed displacement and some are variable displacement. Swash Plate pumps are typical of variable displacement pumps, and comprise a body containing a rotating set of cylinders set in a circle, as in the chambers of a revolver. Each cylinder contains a piston, whose end rides on a bearing pad on a disc fitted into the pump body. The disc is held at an angle, thus as the set of cylinders rotate, driven by the input shaft, the pistons move up and down in the cylinders, in a symmetrical pattern. The cylinder body runs
against a valve disc containing inlet and outlet ports, thus harnessing the pumped oil. As the disc or "Swash Plate" angle is changed, the pump displacement varies from maximum to zero and even to negative on appropriate designs.

Animated views of the operation of these and similar pump types can be found by searching on the Internet under "Swash Plate Pumps" and looking at related sites.

The zero angle design permits engine starting without load but is a control action only and cannot be treated as power isolation. The variable displacement can be used to manage driven equipment by speed (measured as speed or as oil flow) or torque (as hydraulic pressure).

The rotary piston pumps are used for high pressure applications, typically those with long hydraulic lines or where the pumps and motor sizes must be kept as small as possible. Low pressure applications can use the simpler screw or gear pumps.

Various other designs, particularly of the mechanically simpler fixed displacement pumps, use axial or radial cylinders, rotating cylinders or fixed cylinders. Fixed displacement pumps cannot alter the flow, have no control system or rocking discs, and are hence much simpler.

Generally, in order to lubricate the internal moving parts and avoid corrosion, pumps must use high quality clean mineral or synthetic oils. Where there is a significant risk of oil spillage (e.g. underwater portable tools) there have been moves to use bio-degradable water-based oil substitutes. These fluids are poor lubricants, suitable pumps are very sophisticated, containing ceramics and engineering plastics rather than carbon steel contact parts. It is assumed that a fire pump duty has a low spillage risk and that the simpler and cheaper hydraulic oil based equipment will be used. This may change in the future as environmental pressures increase.

![Figure 2,6,2 – 2 Typical Hydraulic Pumps](image)

### 2.6.2.3.4 Hydraulic Motor

The hydraulic motor is simply a fixed displacement hydraulic pump working in reverse. Variable speed is achieved by using variable displacement hydraulic pump. The hydraulic motor should not, in general, be of variable displacement design. This is because internal mechanical loads increase as displacement decreases, and available torque decreases. The result would be an unpredictable stall effect, and high internal wear.

The motor speed is proportional to the hydraulic oil flow, less some allowance for internal leakage. The available torque is proportional to the oil pressure across the pump, less an allowance for friction. Motors require supply and return hydraulic lines, these are frequently run
as armoured flexible hoses. The power lost as a result of friction in the hoses is significant, hence shorter lines, larger diameter, higher supply pressure all contribute to better efficiency. Motors are ideal for high torque low speed applications, typical running speeds of 500 – 1500 rev/min are preferred. The motor output speed will be matched to the pump, to avoid the need for a gearbox.

The motor will require a mechanical seal to avoid loss of oil into the sea water, or, worse, the ingress of salt water into the oil. Since the hydraulic oil makes a very good seal lubricant, it should be used as the seal support fluid, controlled to be at a higher pressure than the surrounding water (the return oil line should provide an appropriate pressure). It would be good design to include a second seal or at least a throttle bush, to control the rate of oil loss in the event of failure. Oil loss will show up if the hydraulic oil reservoir level is monitored.

Since the hydraulic motor is mounted below the pump, either the intake flow has to pass the pump body, or the intake grilles should be located opposite the pump suction. The hydraulic hoses need to pass up the outside of the pump body then be fastened at intervals to the delivery pipe. The hoses must be protected, where appropriate, from mechanical damage or fretting.

2.6.2.3.5 Hydraulic System

The hydraulic system will include all piping, valves, filters, instruments and oil storage tank. These will be standard industrial designs except that stainless steel will be preferred for tank and pipework. The system must be kept scrupulously clean internally, hence in-line filtration, top-up connection filtration. The tank level, operating pressures and flows, will have local instruments and appropriate repeats to the control room.

The hydraulic system should not be cross-connected to any other system. Provision for topping up should be under manual control, using clean dedicated containers or transfer hoses.

The hydraulic system will be protected from fire by being installed inside the drive engine enclosure, or by pipe runs inside the vertical conductor tube. It would be logical to spill excess water, used cooling water, down the conductor tube to aid protection. If the system design includes a pipe run from the enclosure to the conductor, this must be run inside an appropriately protected duct or pipe.

Provision should be made for blanking off open pipe ends when pipe is dismantled for maintenance activities.

2.6.2.3.6 Lubrication System

The Diesel Engine will have its own lubrication system. See Section 3.6

The Hydraulic Pump and Hydraulic Motor will be lubricated by the hydraulic oil.

No other lubrication is required.

2.6.2.3.7 Control System

See Section 2.6.1.3.6 for overall system control. The hydraulic system will require slight differences to control, it will probably be simpler, all that should be required is that the hydraulic pump be set to zero displacement until the engine reaches running speed, then ramped steadily to full displacement.
2.6.2.3.8 Diesel Engine Fuel and Air Systems

See Section 2.6.1.3.7

2.6.2.3.9 Engine Starting Systems and Energy Storage

See Section 2.6.1.3.8

2.6.2.4 INTEGRATION ASPECTS

See Section 2.6.1.4

Additionally, it would be possible to link two drivers e.g. Diesel Engine + Electric Motor, to one pump, or two pumps to one driver. The increased flexibility given by such arrangements would have to be weighed against the potential risk of a common mode failure.

The huge potential advantage of the hydraulic system is the mechanical decoupling of the driver from the pump. The module containing the engine need not be rigidly linked to the conductor carrying the pump.

2.6.2.5 HAZARD ASSESSMENT

See Section 2.6.1.5

Additionally :-

The hydraulic system introduces some additional hazards because of the handling of high pressure hydraulic oil. These risks are low because the system is infrequently operated, and the majority of the pipework is under fire protection thus isolated from people.

There is a significant safety benefit from the much simpler lifting practices associated with the hydraulic drive.

2.6.2.6 MAINTENANCE ISSUES ON HYDRAULIC SYSTEMS

Maintenance activity on hydraulic systems gives the potential for the release of hydraulic oil, and the reverse effect of contamination of the system. Hydraulic oil is of low flammability at ambient temperatures, and low toxicity. It does cause skin damage/dermatitis, the greatest safety issue is probably the slips/ falls risk on contaminated floors and particularly stairs. Hence the need for good design for containment, and good practices to prevent/ contain/ clean up spillage. Good design includes drain-off points, well-located isolation valves. Good practices include draining or purging lines, immediate blanking of open ends, local containments in place to catch spillage.

A separate issue relates to the pollution caused by spillage into sea water. This will be dealt with by hardware e.g. effluent cleaning system, and by practices e.g. avoiding spilling oil over the edge of platforms.

Since the engine, oil tank and oil pump are physically the highest point of the system, there is no convenient drain off point on the pump pipework. It is possible to install a third pipe, of a smaller bore, and displace the majority of oil from the system. Alternatively any joints to be broken should be lifted up to deck level and blown through with low pressure air, before breaking them.
Hydraulic systems are sensitive to the presence of grit and water. Filters can give some protection but the best answer is to apply good working practices at all times. Assume that any open ends or removed components will attract dirt and water, hence protect immediately by capping/covering. Never fit internal plugs which might be forgotten, unless these have handles or robust tails. External caps or flanged plugs are best.

2.6.2.7 APPLICABLE STANDARDS

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations (Transposed Harmonised Standards) can be found in Section 5.15 the specific standards relating to this package are:

- BS EN 809 1998 Pumps and pump units for liquids – Common safety requirements.

Selection of API Standards Relevant to Machinery in use in Refineries / Offshore:

- API 610 1995 Centrifugal Pumps for Petroleum, Heavy Duty Chemical and Gas Industry Service
- API 14G 1993 Fire Prevention & Control on Open Type Offshore Production Platforms

General Standards for machinery can be found in Section 5.15
SECTION 2.7 UTILITIES

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Utilities provide all the basic services for an installation. They must be reliable enough to be taken for granted.

Utilities include service supplies of air, water (fresh and salt), electric power, hot or chilled water (for process).

This description excludes utility supplies specifically provided for or within accommodation modules.

Utility supply must take account of the potential for an incident that destroys or damages a utility system. Some form of duplication or short-term emergency alternate supply will be required, if the utility is safety-critical.

Linked platforms offer the potential for shared utilities, provided that the risks of losing the supply via the linking bridge are assessed.

This document is split into the following sections :-

Section 2.7.1 Diesel Engine driven Alternator (Emergency Generator)
Section 2.7.2 Gas Turbine driven Alternator (Power Supply)
Section 2.7.3 Electric Motor driven Screw Compressor (Compressed Air)
Section 2.7.5 Electric Motor driven Submersible Centrifugal Pump (Sea Water Lift)

For machine (driver) information refer to :-

Sections 3.3, 3.4, 3.5 for A.C. Electric Motors (Generic, LV, HV)
Section 3.6 Diesel Engine

For Rotating (driven) Equipment information refer to :-

Section 4.2 Screw Compressor (Air Service)
Section 4.11 Submersible Pump
Section 4.14 Power Generating Set (Alternator)

Offshore, supply of a utility can not be taken for granted; the Safety Case sets out the provision for Utilities, including the essential supplies for safe shutting down and for fighting fires.

There are two separate requirements to be satisfied :-

1/ A reliable utility supply to cover normal production operations and accommodation requirements. This is likely to cover duplicate or multiple supplies, and strategic storage, to avoid nuisance trips. This requirement is not linked to hazards.

2/ A basic level of essential utility supply to ensure personnel and plant safety even if parts of the system are unavailable or have been compromised. This may involve equipment that is only run during emergencies.

The first requirement is typically met by having several similar base-load providers of the utility service, housed in at least two separate locations and distributed by duplicate or ring-main systems. It will be normal practice to switch between providers according to load and to suit maintenance requirements. These changes will be, in general, invisible to the users.

If there is a situation (for example a major electrical distribution failure and fire) which could threaten life, then it is the practice to install emergency service providers. Emergency units are
normally significantly smaller than normal utility drives, both because they are only required to provide safety-critical services, and because smaller drives are quicker to start. Emergency drives are not rated for continuous service. They tend to be provided as fully stand-alone packages provided by specialist manufacturers. Their design philosophy differs significantly from normal utilities.

2.7.0 TYPICAL UTILITIES

An offshore installation requires :-

- Electric Power
- Cooling Water
- Fire Water & other Fire Fighting support
- Fresh Water
- Heating / Cooling
- Compressed Air
- Ventilation Air
- Nitrogen and other service gases.

Electric Power generation will be provided by on-board High or Low Voltage A.C. 3 phase Alternators. The drivers will be Gas Turbines or Diesel Engines, with the fuel being Diesel Fuel and/ or produced gas. Since electricity cannot be stored in any realistic amounts, multiple machines will normally be required to provide security of supply. One or two Emergency Generators may be installed, to power equipment such as control systems, communications, cranes, accommodation, ventilation, lighting, fire pumps. Electric power will be distributed at appropriate lower voltages to suit the installed equipment. D.C. power loads will be met by rectified A.C., there will be relatively small battery storage for engine starting, emergency lighting, UPS systems.

Cooling water will normally be distributed as once-through pumped sea water. This is corrosive/ erosive thus will often be used as an indirect coolant. Cooling water pumps will be vertical submerged pumps, typically electrically driven. In the event of an incident, cooling water will still be required to cool Power Generation equipment.

Fire Water may well be derived from the cooling water pumps, if these are still running. Additional, emergency Fire Water pumps will be installed, these will have stand-alone diesel engine drives. The drives can be cooled by the Fire Water.

Other Fire Fighting support will take the form of Fire & Gas detection systems, Fire Water distribution, monitors and hose reels. Enclosures may be fitted with CO2 Gas or Dry Powder fire suppression systems.

Fresh Water is required for the accommodation, for washing down purposes, and for topping up closed circuit cooling systems. There may also be a process requirement for fresh water. Fresh water is generated from sea water in custom-built desalination packages. Fresh water can be stored thus loss of supply should not be considered a hazard.

Heating and Cooling is required for accommodation and working spaces, and may be required for process purposes. The accommodation will be self-contained with its own central heating and air conditioning systems. There may be heated or chilled water services provide around the installation. Loss of these services should not be considered a hazard. Note that High Pressure Hot Water, if used, poses a serious personnel hazard.

Compressed Air, in the form of Instrument Air and Service Air, will be generated centrally and distributed to users. Where strategic supplies are required, especially for emergency engine starting, it will be stored locally, inside a fire-resistant enclosure. Hence loss of service should not be considered a hazard.
Ventilation Air is required to provide fresh air, to remove heat, exhaust fumes and gases. Ventilation fans will be local to modules but require electric power. Intakes will be from "safe" areas, below the platform or upwind or potential releases. Ventilation air will be lost if the power fails, and must be shut down if it is going to draw in gas or smoke. Duplicate ventilation inlets must be considered, as even a small smoke ingress can make a "sealed" area uninhabitable, if the smoke cannot be purged out.

Nitrogen and other service gases are normally supplied in portable cylinders, although nitrogen can be generated locally from instrument air. Where loss of supply would cause a hazard, some form of local storage is required.

Figure 2.7 – 1 Utility Diesel Generator Unit
2.7.1 DIESEL ENGINE DRIVEN ALTERNATOR PACKAGE
(EMERGENCY GENERATOR)

TECHNICAL SUPPORT

2.7.1.1 DIESEL ENGINE DRIVEN ALTERNATOR - DESCRIPTION

The package comprises an Industrial Diesel Engine driving an Industrial High or Low Voltage
Alternator on Emergency Generator Duty, complete with Control System & Ancillary Equipment,
all mounted on a 3-point mounting skid baseplate. The complete package and ancillaries are
enclosed in a Fire-resistant Acoustic Enclosure with its own Fire-fighting System. Ancillary
Equipment & systems will include:

- Inlet Air System & Filter
- Fuel System
- Starting Systems(s)
- Exhaust Pipe and Silencer
- Lubricating Oil System
- Shaft Coupling
- Local Switchgear
- Cooling System
- Control System
- Batteries and Emergency Lighting

Figure 2.7 – 2 Commercial Emergency Generator Unit
The Schematic Diagram of such a system is shown below.

![Schematic Diagram](image)

**Figure 2.7 – 3 Schematic Diagram – Diesel driven Emergency Generator System**

### 2.7.1.2 PACKAGE ENTITY

Physically, the package is an enclosed diesel engine driving an alternator. All machine elements are contained in a fire-resistant acoustic enclosure mounted on a common baseframe that is sufficiently rigid to maintain machine alignment, despite movement of the supporting structure or vessel. The 3-point mounting system eliminates the transmission of twisting forces to/from the baseframe. In order to protect them from external fire/explosion, all of the ancillary systems e.g. fuel system, lubrication oil system, cooling system, switchgear, are inside the enclosure. The control panel will also be inside the enclosure. There will be energy storage e.g. diesel fuel, compressed air, batteries, to provide for starting and running the system for in excess of the guaranteed time without outside support or service.

The Fire-resistant Acoustic Enclosure will be large enough for personnel to work inside, and fitted out with lighting, ventilation and Fire Detection systems. The internal space will be tightly packed, making access to internal components quite difficult. There must be enough room to permit servicing and system testing in the minimum time without removing access panels from the enclosure. The interior of the enclosure will be very hot and noisy in operation, the insulation of the enclosure, while primarily for fire purposes, will limit noise transmission and heat loss. Noise levels within such enclosures can be very high, exposure to such noise may be allow only for very limited time, if at all.

The air inlet filter will be located inside the enclosure, the air intake will be from a low fire risk area, probably below the platform adjacent to the conductor tube.

### 2.7.1.3 PACKAGE ELEMENTS

#### 2.7.1.3.1 Diesel Engine

The Industrial Diesel Engine mounted within the Emergency Generator Package will be foot mounted from the baseframe, in order to carry the considerable weight of the machine. The main drive shaft, which is horizontal, will connect the engine flywheel to the alternator via a flexible coupling. Auxiliary Drives within the engine will typically be mounted on the front (opposite from flywheel) end and driven by chains or belts. Flexible connections will link to the inlet and exhaust ducts, and cooling water pipes.
Hot surfaces will be fitted with heat shields or thermal insulation. These must be in place for operator safety.

The engine is dependent on various ancillary systems for safe operation, operating procedures and control system must ensure that these are operational prior to engine start, and at all times during operation. Note that in an emergency duty the failure of a service will not trip the engine, but should instead raise an alarm. Hence the reason why test runs should be monitored by the operator. This emergency duty requirement is a major inversion of normal design philosophy, correctly designed systems may be intended to operate in or fail to a “danger” mode.

Test runs should be on no load, and on full alternator load. The engine governor must be able to cope with an instant change from full load to no load. This process is referred to as "Full Load Rejection".

Any mechanical failure of the engine, or an explosion within the enclosure, could disrupt fuel pipework, with the potential for a release. Missiles, in the form of bits of turbocharger or other components, may be thrown in a mainly radial direction, with the potential to damage people or critical systems within the enclosure. With the exception of the turbocharger, diesel engine parts are low speed and very unlikely to penetrate the enclosure. There are several energy storage systems in close proximity to the engine. During servicing, these systems are still “live” and have the potential to cause major injury.

Technical and safety aspects of the Diesel Engine system are described in more detail in Section 3.6 of the Guidance Notes.

### 2.7.1.3.2 Alternator (Emergency Generator)

The Industrial Alternator mounted within the Emergency Generator Package will be foot mounted from the baseframe, in order to carry the considerable weight of the machine, and to ensure alignment with the engine. Although referred to as a "Generator" from historical practice, since the machine is used to produce Alternating Current electricity, its correct and accurate title is "Alternator". In order to produce 60 Hz power, the alternator must run at a speed equal to 3600 rev/min or simple fraction of this. Hence in order to suit an appropriate diesel engine, a 4 pole (1800 rev/min.) or 6 pole (1200 rev/min.) machine would be appropriate. Note that although 60 Hz is the norm offshore, 50 Hz systems do exist especially in the Southern North Sea sector. See Section 3.3 Appendix 1 for electrical terminology.

Speed matching could be achieved by a speed increasing gearbox but this adds complexity, cost and more things to go wrong.

Alternators comprise a massive rotor running within a massive and robust stator. Mechanical failure can result in severe internal damage but this is extremely unlikely to pose a direct hazard to people, due to the robust construction. The mechanical risk during normal operation primarily relates to maintenance and inspection activities. There will always be a risk to personnel from electric shock, if they are working on or near live equipment. Live conductors should always be fully screened by robust earthed metal panels.

The real safety risk posed by the Emergency Generator is that it will not work when it is required in an emergency. Electrical circuit checks, alternator condition monitoring & slowroll testing may be possible but the only realistic check is a regular full power test run exercise, with the unit running on a realistic load.

Technical and safety aspects of the Alternator are described in more detail in Section 4.14 of the Guidance Notes.
2.7.1.3.3  Main Drive Coupling / Clutch

The use of flexible couplings within a machine package is essential to provide the necessary degrees of freedom to enable the elements of the machine to be aligned and compensate for thermal expansion and any flexibility inherent in the installation skid. This is particularly the case for a diesel engine with its large torsional fluctuations and general vibration level.

The most sophisticated emergency generator systems may include a flywheel/ clutch system as an energy store. The heavy flywheel is kept running at full speed, driven by the alternator which has been designed also to function as an electric motor for this purpose. Alternators are totally suitable for continuous running and take very little power in this mode. The diesel engine is kept warm and serviced, but is not kept running. In the event of loss of power, or potential loss of power, the clutch is engaged smoothly, bringing the engine up to speed. The heavy alternator rotor is now a positive asset as a rotating energy store. Once the engine is up to speed, it can be started in the normal manner. This permits emergency power to be available in seconds. Such systems are supplied as heavy duty UPS (Uninterruptible Power Supply) units for industrial use, but are not common.

Misalignment of the coupling, even within its tolerance limits, puts increased loads on adjacent shaft bearings. It also reduces the service life of the coupling, as flexible elements are subjected to greater strains. Coupling lubrication (where required) and inspections must be proactively maintained as the coupling has significant mass and has the potential to become a dangerous missile if it fails. Loss of drive is not normally a safety-related incident; special design requirements apply if drive continuity is critical. For emergency drives this continuity is critical, this is a feature to check for in the design, also a maintenance check that the coupling is not in the part-failed condition.

Technical and safety aspects of flexible shaft couplings are described in more detail in Section 5.6 of the Guidance Notes

2.7.1.3.4  Engine Lubrication System

The supply of oil for lubrication of bearings and couplings, support to sealing systems and hydraulic operation of actuators requires clean oil at appropriate pressures. For package units this can be delivered from a common system feeding all elements within the package. However for Diesel Engine drives the engine oil has different requirements from alternator bearing oil, and can also become contaminated with fuel. Thus the engine should have a self-contained oil system (manufacturer’s standard with, possibly, a battery driven pre-start/ standby pump which can be tested without starting the engine). The alternator can sensibly have its own oil system, which will be shared with the gearbox (if fitted) and any clutch lubrication/ oil cooling requirements.

Liquid fuel or the heavier fractions of hydrocarbon gases can dissolve in oil, reducing its viscosity and increasing its flammability. The diesel engine is inevitably going to suffer from fuel contamination of the crankcase oil, the large plain bearings used are reasonably tolerant of this and the carbon that also tends to accumulate in the oil. Gear drives, in particular, are not tolerant of these contaminant.

Shaft driven oil pumps may well be internally mounted and inaccessible, this should not be a problem for the limited running hours required. They can easily be tested in service by checking the oil pressure, and perhaps the flow if sight glasses or flow meters are fitted. Bearing temperature monitoring will confirm satisfactory lubrication. For reliability, the systems should be simple, accessible, robust, easily understood. Thus designs based on manifold blocks, welded/ flanged connections, are much preferred to lengths of small bore screwed pipe. Where flexible connections are required, they should use hydraulic type hose with appropriate fittings, and be laid out logically and with ample clearance for tool access and inspection. Drip trays should be
fitted to keep the floor clean and to monitor for any oil leaks. Labelling will be required to ensure that the correct oil and filters are used in each system.

The oil level, oil pressure, oil temperature, and the availability of main/standby pump, should be monitored by the alarm system, with fault alarms as appropriate. For simplicity, standby pumps will probably be set up on a “both running” basis with non-return valves to control back-flow.

The most serious issues for the supply of oil to a machine package arise from either failure of the supply that can lead to inoperability of the machines, or from oil spill or leakage resulting in a fuel source for potential fires. In either case this would be a major failing, the pump drive system must be operable at any time and cannot survive a fire inside the enclosure.

### 2.7.1.3.5 Alternator Lubrication System

In the simplest model, the alternator will have simple self-contained oil lubricated bearings. These can be fitted with temperature and oil level sensors. On a larger machine, or if a gearbox or sophisticated clutch is fitted, there may be a requirement for a pumped oil flow, for lubrication or cooling purposes. If this system is kept separate from the diesel engine system, a very simple pumping and cooling unit will provide the required oil supply.

Technical and safety aspects of lubrication systems are described in more detail in Section 5.2 of the Guidance Notes.

### 2.7.1.3.6 Control System

Machines within a package must be integrated to function as a complete system. Therefore control systems are designed to provide this essential control and protection for the machine elements.

The control system is required to monitor the system as closely as practicable when not in use, to confirm availability and starting mode(s). Once running, the control system provides alarm and monitoring only. There will be provision for manual or automatic start, according to operating requirements. Stopping should be a local manual operation only, to minimise the risk of the system stopping unintentionally. Similarly, damage to cabling outside the fire-resistant enclosure should not trip the engine, except in the event of a short circuit on the outgoing power cables.

During maintenance work, automatic start will have to be disabled e.g. for servicing/filter changing, and the complete system disabled for more significant maintenance. This may, as appropriate, also require the isolation or draining of all stored energy systems which could result in injury to personnel. After maintenance or inspection, all systems must be restored and some form of system test (not necessarily a start) performed. Any Permits must be cleared to confirm that the unit is ready for instant operation.

Control software must be rigorously checked, subject to strict version and change recording and control. Pre-programmed cards can be fitted to the wrong machine; they may be physically identical (to Model and Serial Number) but carry different instructions.

Details of the requirements for these systems are noted in the Guidance notes for each element.

### 2.7.1.3.7 Diesel Engine Fuel and Air Systems

The diesel engine will be supplied with its own fuel tank, pumps and filters, in order to operate independently of the platform fuel supplies. The tank could be located inside the enclosure to benefit from the fire protection, mounted high up to provide a gravity feed to the fuel pumps. If
not mounted in the enclosure, the tank and its outlet pipework must be protected from fire and accidental damage. There will be provision to manually check the liquid level (e.g. a full height sight glass) and to check for and drain off any water in the fuel. The fuel level, in particular high and low levels, will be monitored by the control system, in such a way that any failure of the system cannot affect engine operability. Re-filling of the tank from the platform main supply will be under operator control to ensure clean fuel is supplied up to the correct level. The system should be designed to prevent over-filling, and should be isolated at the enclosure wall when not in use. Fuel leakage or spillage within the enclosure could lead to destruction of the fire pump driver.

All fuel pumps / heaters will be powered from the diesel engine and its batteries, to preserve complete isolation from main systems.

The intake air for the engine will be filtered locally to remove dust/dirt/salt. The combustion air must be drawn from a “safe” location which is at low risk of being subject to fire or significant amounts of flammable gas. Ingestion of flammable gas can cause diesel engines to overspeed and self-destruct.

The ventilation air for the enclosure can be drawn from the same location, although some silencing will be required to reduce the engine suction noise transmission to the enclosure. The exhaust air does not necessarily have to go to a “safe” location provided that fire cannot enter the duct. The ventilation system is intended to provide a working environment within the enclosure. It will pressurise the enclosure to prevent gas ingress, and will remove fumes e.g. from battery charging, and heat from exhaust pipes and hot surfaces. A large diesel engine will produce too much heat for air cooling to be viable.

2.7.1.3.8 Engine Starting Systems and Energy Storage

Emergency diesel engines require a self-contained starting system or systems. These may include battery start, compressed air start or even “pony motor” start. It must be assumed that no external energy supply is available, even for lighting, e.g. after a major power failure. This capability for a completely stand-alone start is referred to as a “Black Start” capability.

A battery start system requires a starter motor, large lead-acid storage batteries, a battery charging system and a control system to de-compress the engine cylinders until the engine is running fast enough to start. The batteries should be independent of those providing lighting. The battery charge condition should be monitored constantly and reported to the control room. The routine maintenance must include regular checks on the battery electrolyte level and strength. Note that lead-acid batteries contain sulphuric acid and generate hydrogen during and after charging.

Compressed air starting is used because it is effective and simple. Stored compressed air is fed to valve gear on the engine, where it is bled directly into the engine cylinders to rotate the engine. When the engine has reached its starting speed, fuel is introduced and normal valve gear restored. The compressed air storage cylinders must be located inside the enclosure, for fire protection, but the re-filling can be from the normal instrument air supply or from a dedicated compressor, this can be located outside the enclosure.

“Pony motor” is the term used for a small diesel engine which can be used to rotate the main engine at its starting speed. The pony motor is first started by batteries and run up to full speed, a clutch or hydraulic drive is then used to spin the main motor, decompressed. Finally the main motor is started. The pony motor drive must then disconnect or over-run safely, for the main motor to run up to full speed. If the drive does not disconnect, the drive or pony motor will be destroyed. Pony motor start is inevitably slower than direct starting.

For a large engine, a combination of air starting (for speed) and pony motor (as backup) might be used. The pony motor would be a convenient driver for a slowroll system, and for recharging compressed air storage tanks.
It is possible to use a motor-driven flywheel as an energy store for diesel engine starting. A flywheel starting system, if fitted, provides a very rapid start, but does not truly provide a "Black Start" capability, as the stored energy will be dissipated if there is significant delay in attempting a start.

Battery charging systems will be supplied from the platform main supply. A separate set of batteries should be used for lighting and other support functions, failure of this system should not affect system operation. Battery powered pumps etc., may be required during the starting sequence. Once the Generator Package is up to speed and on load, the alternator can drive the main pumps, and the battery pumps can be switched off.

The alternator will be brought up to the correct synchronous speed at nil load. If the main generation is still running, it would be normal to synchronise the emergency generator to the main supply. The alternator will then be put on load.

Manual start systems are used where the energy to start is stored by hydraulic pump up.

2.7.1.3.9 Local Switchgear

An emergency generator has its own local switchgear as it is, in effect, a small generating station. Each generator can be run up, tested, and connected to the appropriate part of the distribution network. The arrangement must work whether or not the network is already live. The switchgear must be set up so that switchgear and generators can be safely serviced while the rest of the system remains operable.

2.7.1.3.10 Cooling Systems

The diesel engine will typically have its own self-contained cooling system rejecting heat to air. The alternator, depending on size, will be air or water cooled. Air cooling loads require safe ventilation with significant air flows, this may not be practical within the fire resistant enclosure.

For general comments on cooling systems see Section 5.11.

2.7.1.4 INTEGRATION ASPECTS

2.7.1.4.1 Hardware Matching

The design of the package must ensure that the operating capability of each element of the package matches or exceeds the greatest potential demand placed on it by the system.

For an Emergency Generator System the major elements that must be considered are:

- Maximum emergency load
- Delay from start signal to full load
- Manual / automatic starting
- Size of fuel tank to provide the necessary emergency run period
- Source of ventilation air and cooling air/ water
- Location of equipment and fire protection
- Number of installed systems vs. number required to run for full protection

2.7.1.4.2 Operational Matching

The operation of a package unit requires that there are no conflicts within the system that would compromise effective operation of the system.
It is expected that the system will function with one or all main and emergency generators running, matching the load by alternator excitation and, if necessary, by shedding lower priority loads. The engine governor will maintain the supply frequency within acceptable limits when operating in a stand-alone mode.

In the event of abrupt tripping of the load, the engine/alternator must not overspeed, again by use of the engine governor.

The system must be able to start up and operate for an extended period with or without main generators running.

For more general Operation Guidance see Operation Support Guidance Section 6.

2.7.1.5 HAZARD ASSESSMENT

Fire and other emergency systems require a somewhat different approach to hazard assessment, as they pose little or no hazard when not in use, and must work reliably for a specified period on demand. The risks posed by energy storage systems, automatic starts and probably some unguarded hot surfaces, must be set against the paramount requirement for a fast and trustworthy start. The design and integration of the complete package by a specialist fire system supplier then makes complete sense, they can then buy in specialist items e.g. alternator, engine, specified for the rigours of fire service. A conventional packager of equipment will not normally have the experience or the right philosophy to get this right. See Section 7.2.4 for a structured set of Hazard Assessment Tables.

Hazards from the malfunction or non operation of utility equipment on the facility must be addressed as part of the overall design case and is outside the scope of this guidance.

2.7.1.5.1 Process Substance Containment Hazards

The acoustic enclosure should not contain any pipework or services which are not relevant to the Emergency Generator. There is the potential to spill Diesel Fuel (fire hazard), Lubricating Oil (less fire hazard) and cooling water (low hazard).

The enclosure is designed to protect the equipment from an external fire. It is not a safe refuge for people, and may not necessarily contain a breathable atmosphere. A fire inside the enclosure should be fully contained, people should readily be able to escape, but the equipment could be seriously damaged. The enclosure should have a Fire and Gas system to combat the risk. The Fire & Gas system must be disabled appropriately for personnel entry, according to PTW procedures.

See Section 3.6.3.1 for Ignition/Explosion hazards from the Diesel Engine.

See Section 4.14.3.1 for Ignition/Explosion hazards from the Alternator.

2.7.1.5.2 Equipment Hazards

In practice, mechanical hazards of packaged equipment are the same as the individual units. There is a risk of an incident on one component of the system adversely affecting the other, but this applies to any multiple machine installation.

The combination of a “pony motor” start (ref 2.7.1.3.8) with the diesel motor can cause catastrophic disintegration of the pony motor / coupling / gear box. Failures of automatic disengage couplings or errors in setting up remote operated systems can result in such events, high maintenance standards are needed on such systems as monitoring over over-speed of the pony motor may not react quickly enough to avoid damage.
All moving and hot parts should be guarded, the risks will relate to the stored energy/ automatic start systems and thus the potential for unexpected starting. The noise level in the enclosure during a start will be very high.

For information specific to the package elements see Sections 3.6.3.2 & 4.14.3.2

2.7.1.5.3 Operational / Consequential Hazards

Packaging should have no particular influence in this area; Mechanical, Process and Control interactions apply equally to Packaged and Non-packaged units. It can be argued that there is a reduction in risk, because the Package should have been designed as a whole to a consistent duty requirement.

For information specific to the package elements see Sections 3.6.3.3 & 4.14.3.3

2.7.1.5.4 Maintenance / Access Hazards

Maintenance on packaged units can be significantly more difficult because of very congested construction, this is not necessarily hazardous but can result in more sprains and similar injuries as people struggle to work in restricted spaces. Well-designed packaged units incorporate tailored lifting / slinging facilities. It is usually more appropriate to change out an assembly than to attempt to repair a failed component in situ. There is a potential issue of isolation of electrical and other energy sources where isolation of part of the package may not isolate a closely adjacent part. This must be covered by Maintenance / Permit to Work procedures.

The Emergency Generator package should have a little more access room than most, servicing must be done quickly and in particular without removing or disturbing other items. Energy sources must be disabled or drained prior to access, and restored thereafter. As this can be complex, risk assessments and sensible procedures are required to identify logical packages of servicing work. These packages must be followed through to completion, not altered in mid-stream.

In particular, major personnel hazards can be introduced during the lifting out of either the alternator rotor or major diesel engine parts. Here, heavy or awkward parts are being lifted from a confined space, often with people in close attendance at the bottom of the lift. The crane operator will not be able to see these people, but relies on instructions from a trained banksman. Lifting procedures must be good, e.g. no lifting without positive & continued instructions, dedicated radio channel, instructions by nominated and trained banksman only.

For information specific to the package elements see Sections 3.6.3.4 & 4.14.3.4

2.7.1.6 APPLICABLE STANDARDS

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations ( Transposed Harmonised Standards ) can be found in Section 5.15 the specific standards relating to this package are:

- BS EN 1037 1995 Safety of machinery – Prevention of unexpected start-up.

Selection of API Standards Relevant to Machinery in use in Refineries / Offshore:

- API 14F 1999 Design & Installation of Electrical Systems for Offshore Production Platforms
- API 14G 1993 Fire Prevention & Control on Open Type Offshore Production Platforms

General Standards for machinery can be found in Section 5.15

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2.7.2 GAS TURBINE DRIVEN ALTERNATOR (POWER SUPPLY)

TECHNICAL SUPPORT

2.7.2.1 GAS TURBINE DRIVEN ALTERNATOR (POWER SUPPLY) – DESCRIPTION

The package comprises an Aero-derivative Gas Turbine driving an Industrial High Voltage Alternator on Utility Generation service, complete with Control System & Ancillary Equipment, all mounted on a 3-point mounting skid baseplate. The Gas Turbine is enclosed in an Acoustic Enclosure with its own Fire & Gas System. Ancillary Equipment & systems will include:

- Inlet Air System & Filter
- Fuel System
- Starting System
- Exhaust System
- Lubricating Oil System
- Drive Gearbox
- Shaft Couplings
- Local Switchgear
- Cooling System
- Piping Systems
- Condition Monitoring

2.7.2.2 PACKAGE ENTITY

Physically, the package is an enclosed gas turbine with a drive gearbox, directly connected to an industrial alternator. All machine elements are mounted to a common baseframe, the control panel may be built on to the end of the baseframe (which is convenient for pre-wiring) or mounted separately (which permits control panels to be grouped together).

The Acoustic Enclosure for an Aero-derivative Gas Turbine will be close fitting, and fitted out with ventilation and Fire & Gas Detection Systems. The internal space will be tightly packed, making access to internal components quite difficult. Thus any problem on one component has the potential to affect adjacent components / systems, whether by release of material, vibration or over-heating. Similarly, it may be necessary to remove a component either to work on that component or to gain access to adjacent components.

The drive gearbox, being part of the gas turbine unit, and also noisy in its own right, will probably be inside the acoustic enclosure. Good design should permit ready access to bearings, seals, instruments and drive couplings. The alternator should not share the same air space as the gas turbine, in order to ensure that hot air or any release of fuel gas cannot reach the alternator or its switchgear. The alternator may well have its own enclosure, primarily for weatherproofing and also to permit control of the atmosphere around the alternator and switchgear. Such an enclosure will not be close fitting, as the weatherproofing is most valuable during maintenance activities.

The air inlet housing will be located separate from the gas turbine.
2.7.2.3 PACKAGE ELEMENTS

2.7.2.3.1 Gas Turbine

The Aero-derivative Gas Turbine mounted within an Offshore Package will be centre-line mounted from the baseframe, ensuring internal alignment while permitting thermal expansion of the machine. The main drive shaft, which will be at the “cold” or inlet end for an alternator package, will be fitted with a flexible coupling, as will any auxiliary drive shafts. Flexible connections will link to the inlet and exhaust ducts.

The turbine will be of the simpler “Single Shaft” arrangement as the unit will be started at nil load and will run at a fixed speed. The turbine, integral drive gearbox and alternator will be permanently coupled.

Technical and safety aspects of the Gas Turbine system are described in more detail in Section 3.1 of the Guidance Notes.
2.7.2.3.2 Alternator (Power Supply)

The Industrial Alternator mounted within the Utility Generation Package will be foot mounted from the baseframe, in order to carry the considerable weight of the machine, and to ensure alignment with the turbine system and gearbox. Although referred to as a “Generator” from historical practice, since the machine is used to produce Alternating Current electricity, its correct and accurate title is “Alternator”. In order to produce 60 Hz power, the alternator must run at a speed equal to 3600 rev/min or simple fraction of this. For a typical industrial alternator, rated between 5 and perhaps 20 MW, a 4 pole (1800 rev/min.) machine would be appropriate. Note that although 60 Hz is the norm offshore, 50 Hz systems do exist especially in the Southern North Sea sector. See Section 3.3 Appendix 1 for electrical terminology.

Since the turbine speed will be typically 8 to 10 times that of the alternator, a speed reducing gearbox, rated at the full alternator input power rating, will be required.

Alternators comprise a massive rotor running within a massive and robust stator. Mechanical failure can result in severe internal damage but this is extremely unlikely to pose a direct hazard to people, due to the robust construction. The mechanical risk during normal operation primarily relates to maintenance and inspection activities. There will always be a risk to personnel from electric shock, if they are working on or near live equipment. Live conductors should always be fully screened by robust earthed metal panels.

The real safety risk posed by a Utility Alternator is that it will abruptly cease generating. This will impact on the equipment being powered from the power system, potentially tripping drives, increasing load on other machines, requiring standby or emergency drives to be started. This sudden change in operating conditions could cause failures of other equipment, and will certainly give the operators problems to solve. In addition, the original cause of the failure will probably leave the Gas Turbine running at full power with no load. This could lead to an overspeed event if the control system does not react. The effect on the installation will largely depend on the quality of the equipment, maintenance procedures and operating personnel. If the likely effects have been thought out properly, protective devices set up and tested, and operators properly trained, then the effect will be minimal, with perhaps some processing equipment shut down for part of a shift while the fault is cleared.

Technical and safety aspects of the Alternator are described in more detail in Section 4.14 of the Guidance Notes.

2.7.2.3.3 Gearboxes

The inclusion of a drive gearbox within the machine package allows the manufacturer to match the necessarily high operating speed of the Gas Turbine driver and the lower speed of the Alternator. The gearbox will be large as it carries the full drive load. A single shaft Gas Turbine package will have a single main gearbox, integral to the “cold” end of the machine. Auxiliary shafts provide the necessary linkages for turbine starting, and mechanical drives where required for oil or fuel pumps. Technical and safety aspects of the gearbox are described in more detail in Section 5.5 of the Guidance Notes.

2.7.2.3.4 Main Drive Coupling

The use of flexible couplings within a machine package is essential to provide the necessary degrees of freedom to enable the elements of the machine to be aligned, to allow for thermal expansion, and to compensate for any flexibility inherent in the installation skid. Technical and safety aspects of flexible shaft couplings are described in more detail in Section 5.6 of the Guidance Notes.
2.7.2.3.5 **Lubrication System**

The supply of oil for lubrication of bearings and couplings, support to sealing systems and hydraulic operation of actuators requires clean oil at appropriate pressures. For package units this can be delivered from a common system feeding all elements within the package. Technical and safety aspects of lubrication systems are described in more detail in Section 5.2 of the Guidance Notes.

2.7.2.3.6 **Control System**

Machines within a package must be integrated to function as a complete system. Therefore control systems are designed to provide this essential control and protection for the machine elements. The package control will have two distinct functions, basically met by the Gas Turbine control system and the Alternator control system respectively.

The Gas Turbine control system, on a Single Shaft machine, has only one shaft speed to manage. It will ensure that all support services e.g. Lubrication Oil, are operating, and that the Alternator control system is giving the appropriate "Start Permit" signal. The gas turbine will then be started, the simplest way being via an electric motor powered from other Utility or Emergency generators on the installation. If a "Black Start" (See Section 3.3 Appendix 1) capability is required, a small diesel engine is the likely solution. Such a start would probably be manually controlled. The starting system will bring the turbine up to starting speed, bring on fuel and ignition, confirm ignition and bring the turbine up to normal running speed. When the various oil and gas pressures and temperatures have reached nominal values, and any pre-determined warm-up time has elapsed, the Gas Turbine control will indicate that the Alternator may now be synchronised and be put on load. Speed control, and hence overspeed control and trip, remains with the Gas Turbine.

For information on the Gas Turbine Control System see Section 3.1.6.5.
The Alternator control system will monitor the phase angle of the Alternator as compared to the electrical distribution system. It will interface with the Gas Turbine speed control system to adjust the speed very delicately until both systems are synchronised. The main switchgear can then be closed, automatically, locking the alternator to the rest of the system. The Alternator control system will then control the generated voltage (via the Exciter) and the shaft input power (via the Gas Turbine fuel control) to match the system need. Control of multiple generators is a complex subject and each system’s control philosophy is individually tailored.

In the event of a loss of electrical load, or an alternator fault requiring the load to be rejected, the alternator control system should trip the turbine, reducing the risk of an overspeed event.

For information on the Alternator Control System see Section 4.14.6.7. For more general comments on Control Systems see Section 5.13.

2.7.2.3.7 Air Intake Filter & System

Air feed to the gas turbine will be filtered through a series of filtration elements (Ref. Section 5.10)

2.7.2.3.8 Acoustic Enclosure

The gas turbine is enclosed in an acoustic enclosure – this reduces the risk from the noise hazard but introduces hazards of an enclosure possibly containing flammable gas. (Ref. Section 3.1)

2.7.2.3.9 Fuel System

The fuel system will take Gas Fuel and / or Liquid Fuel from the installation at the available pressure, filter the fuel(s) and raise pressure if necessary. The fuel system will control the rate of supply of fuel(s) and isolate the supply when necessary. See Section 5.1.1 & 5.1.2 for further details relevant to Gas Fuel and Liquid Fuel respectively.

2.7.2.3.10 Exhaust System

This system is specific to the Gas Turbine and is covered in Section 3.1.6.6

2.7.2.3.11 Local Switchgear

A utility generator has its own local switchgear to provide safe isolation from the rest of the system. The switchgear must be set up so that switchgear and generators can be safely serviced while the rest of the system remains operable. The switchgear may be designed for automatic starting, connection and disconnection or, more simply, for manual connection and automatic disconnection under fault conditions. The protective systems on the switchgear detect various fault conditions and trip the circuit breaker if the capacity of the system is exceeded.

2.7.2.3.12 Cooling System

The alternator will normally be water cooled. See Section 4.14.6.6. The lubrication oil system will require a cooler. Such coolers will usually be shell and tube heat exchangers built to a recognised code. ASME and BS 5500 are commonly used. Ideally, cooling will be against a closed fresh water cooling system, to minimise problems of corrosion, fouling and pollution. See Section 5.11 for further details.
2.7.2.3.13  Piping Systems

Piping systems are generally constructed to international standards, see Section 5.7 for details. Special standards are required for fuel gas where double skinned piping is installed. (See Section 5.1.1)

2.7.2.3.14  Condition Monitoring

Condition monitoring on larger Machine Packages will be provided as part of the package. Vendors will offer their own preferred system, or will agree to tailor a system to suit the client’s requirements. It is important to ensure that the system provided suits the proposed method of operating and maintaining the equipment. See Section 5.12 for more detail.

2.7.2.4  INTEGRATION ASPECTS

2.7.2.4.1  Hardware Matching

The design of the package must ensure that the operating capability of each element of the package matches or exceeds the greatest potential demand placed on it by the system.

For a Gas Turbine driven Alternator the major elements that must be considered are:

- Matching of Turbine to Alternator
- Power rating
- Rate of change of load (increase or decrease)
- System fault conditions
- Torsional critical speeds
- Lateral critical speeds

Details of the requirements for these systems are noted in the Guidance notes for the separate elements. Lateral & Torsional Critical Speed issues are covered in Section 5.6.1.

2.7.2.4.2  Operational Matching

The operation of a package unit requires that there are no conflicts within the system that would compromise safe operation of the system.

For a Gas Turbine driven Alternator the issues that must be considered are given in Operation Support Guidance Section 6.

2.7.2.5  HAZARD ASSESSMENT

The hazards posed by the package are a combination of the hazards posed by the individual machine and rotating equipment items, with possibly some additional hazard due to potential interactions. Assessment of the hazards from the package should, however, become easier at the design stage because one design team should be dealing with the complete package, and have all relevant information compiled together.

See Section 7.2.4 for a structured set of Hazard Assessment Tables.

2.7.2.5.1  Process Substance Containment Hazards

Hazards relating to the release/ignition of fuel within the Gas Turbine are covered in Section 3.1.3.1.

The potential for the turbine, alternator or ancillaries providing a source of ignition for releases from the fuel system, other equipment in the area, or from the lubrication system, should be covered by the area hazard assessment. The appropriate standards for the design and ventilation of the enclosure(s), and the requirements for segregation of turbine, alternator and switchgear can then be set.
2.7.2.5.2 Equipment Hazards

In practice, mechanical hazards of packaged equipment are the same as the individual units. There is a risk of an incident on one component of the system adversely affecting the other, but this applies to any multiple machine installation.

Hazards which are specific to gas turbine driven alternators are:

- Overspeed of the driven equipment; the gas turbine must be speed controlled with an appropriate speed monitoring, control and trip system to avoid overstressing the driven and transmission components. The alternator and transmission system must be designed to have the capability to run at trip speed plus 5% margin. Requirements for protection are given in Section 3.1.

The gas turbine is dependent on various ancillary systems for safe operation, operating procedures and control system must ensure that these are operational prior to turbine start, and at all times during operation. Induction of a flammable gas release to the Gas Turbine enclosure to be avoided by appropriate positioning of intakes and monitoring of atmospheric hydrocarbon releases.

The Mechanical Hazards associated with the elements are:

- Damage and loss of containment of machine elements due to high mechanical energy stored or transmitted within rotor shafts, gear box, couplings.

Description of the source of the hazards and the protection/ preventative measures necessary are given in Sections 4.14.3.2 and 3.1.3.2.

There is a risk of an incident on one component of the system adversely affecting the other, but this applies to any multiple machine installation.

2.7.2.5.3 Operational / Consequential Hazards

Packaging should have no particular influence in this area; Mechanical, Process and Control interactions apply equally to Packaged and Non-packaged units. It can be argued that there is a reduction in risk, because the Package should have been designed as a whole to a consistent duty requirement.

Relevant information for the machine elements is given in Sections 4.14.3.3 and 3.1.3.3.

2.7.2.5.4 Maintenance / Access Hazards

Maintenance on packaged units can be significantly more difficult because of very congested construction, this is not necessarily hazardous but can result in more sprains and similar injuries as people struggle to work in restricted spaces. Well-designed packaged units incorporate tailored lifting / slinging facilities. It is usually more appropriate to change out an assembly than to attempt to repair a failed component in situ. There is a potential issue of isolation of electrical and other energy sources where isolation of part of the package may not isolate a closely adjacent part. This must be covered by Maintenance / Permit to Work procedures.

Relevant information for the machine elements is given in Sections 4.14.3.4 and 3.1.3.4.
2.7.2.6  APPLICABLE STANDARDS

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations (Transposed Harmonised Standards) can be found in Section 5.15 the specific standards relating to this package are:-


BS EN 1037 1995  Safety of machinery – Prevention of unexpected start-up.

Selection of API Standards Relevant to Machinery in use in Refineries / Offshore:

API 11PGT 1992        Packaged Combustion Gas Turbines
API 616 1998         Gas Turbines for Refinery Services
API 14F 1999        Design & Installation of Electrical Systems for Offshore Production Platforms

General Standards for machinery can be found in Section 5.15
2.7.3 ELECTRIC MOTOR DRIVEN SCREW COMPRESSOR
(COMPRESSED AIR)

TECHNICAL SUPPORT

2.7.3.1 ELECTRIC MOTOR DRIVEN SCREW COMPRESSOR PACKAGE -

DESCRIPTION

The package comprises a High or Low Voltage Electric Motor driving a Two-stage Dry Screw Compressor on Instrument Air service, complete with Control System & Ancillary Equipment, all mounted on a 3-point mounting skid baseplate. The package includes a close-fitting Acoustic Enclosure. Ancillary Equipment & systems will include:

- Lubricating Oil System
- Integral Gearbox
- Shaft Coupling
- Intercooler, Aftercooler and Water Separators
- Relief Devices
- Cooling System
- Piping Systems
- Control System
- Condition Monitoring

Figure 2.7 – 6 Packaged Instrument Air Compressor (Ghost Cut-Away View)
The above unit is water-cooled.

Note that package screw compressors are only designed for compression of ambient atmospheric air. Vendors have on occasion modified machines for compression of nitrogen.

Oil-flooded screw compressors are simpler and cheaper than dry screw compressors. They can be fitted with sophisticated filters to remove virtually all of the oil from the delivered air. There is still some risk of oil carry over, particularly under part load conditions and if the filter maintenance has been neglected. Where instrument air is used for measuring instruments or positioning devices, or where oil might contaminate filter media or catalysts, it is good practice to insist on oil-free compression.

Oil-flooded compressors carry a known risk of internal oil mist explosions under certain fault conditions. This risk is minimised by using correct parts and maintenance practices, and by regular testing of protective devices.

2.7.3.2 PACKAGE ENTITY

Physically, the package comprises two twin-screw compressor elements mounted on an integral gearbox and driven by an electric motor. The gearbox and motor are mounted to a rigid common baseplate, which is itself on flexible mountings. The flexible mountings are bolted to the floor structure of the close-fitting acoustic enclosure. The complete compressor package is mounted on the appropriate 3-point mounting baseframe, along with other equipment in the same module. The 3-point mounting system eliminates the transmission of twisting forces to/from the compressor installation. All of the components of the compressor system are contained within the acoustic enclosure. Access is by bolted on, or hinged, acoustic panels.

The available space inside the enclosure is tightly packed, making access to internal components quite difficult. Thus any problem on one component has the potential to affect adjacent components/systems, whether by release of material, vibration or over-heating. Similarly, it may be necessary to remove a component either to work on that component or to gain access to adjacent components. Special tools, e.g. slide frames, may be required. Access is improved by removing all access panels.
Figure 2.7 – 7 Packaged Instrument Air Compressor (Ghost Cut-Away View)
The above unit is air-cooled.

Other components of the air system, e.g. pipework, air receivers, dryers, may be mounted close to the compressor. If they prevent removal of any access panels, maintenance potentially becomes more difficult.

All alignment within an air compressor package is by use of spigots and special tools.
2.7.3.3 PACKAGE ELEMENTS

2.7.3.3.1 Drive Motor

Air compressors may be driven by High or Low Voltage motors, depending on power rating and local preferences. This example shows a High Voltage motor.

The High Voltage Motor described is typical of 3.3 kV motors, rated around 250 to 500 kW. It will be of cast construction, flange mounted to the integral gearbox and possibly foot mounted on the baseplate. The motor is very similar to LV asynchronous motors. The motor shaft will be fitted with a flexible coupling, linking it to the bull wheel in the gearbox. The motor will have grease lubricated bearings, and require an available supply of cooling air to integral cooling fins. Mechanically, the motor is otherwise self-contained.

Three-phase power supply cables will link the motor terminal box to the starter cabinet (fixed speed motors) or inverter (variable speed motors). Some special electric motors have resistor boxes and similar large items of control equipment mounted locally.

Technical and safety aspects of the High Voltage Electric Motor are described in more detail in Section 3.5 of the Guidance Notes.
Screw compressor elements are precision-built modular assemblies comprising a matched pair of helical screws, with bearings and seals, fitted into a cast and machined housing. The housing has passages and drillings for lubrication and cooling purposes. Dry screw compressors require two elements working in series to achieve the pressure of 6 – 12 barg typically required for instrument air service.

The low pressure (LP) element takes air from the inlet filter, through the throttle/ unloading valve and into the inlet port. The screw element is fitted with a pinion, which meshes with the bullgear. The LP element compresses the air and delivers it through the discharge port. The air then passes to the intercooler, which removes the heat of compression, and the water separator, which removes condensed moisture. It then goes to the HP stage.

The HP element, which is physically smaller than the LP element, completes the compression process and delivers the air to the aftercooler.

For details of the compression and cooling process and components, see Section 4.2.6

**2.7.3.3.3 Integral Gearbox**

- The inclusion of a drive gearbox within the machine package allows the manufacturer to optimise operating speeds of the Electric Motor and Screw Elements separately. The compressor elements run at high speed to minimise the effect of internal leakage.
2.7.3.3.4 Main Drive Coupling

The main drive coupling connects the bullgear (which has its own bearings) with the electric motor shaft. The coupling is normally a rubber element type, selected by the package vendor. The coupling is fully enclosed within the gearbox housing, alignment should be determined by spigots. Vibration suggesting misalignment should be investigated, although it is difficult to install alignment tools. Misalignment could be caused by e.g. loose motor flange mounting bolts.

2.7.3.3.5 Lubrication System

The supply of oil for lubrication of bearings and gearbox, support to sealing systems and hydraulic operation of actuators requires clean oil at appropriate pressures. The motor does not require oil. Normally, the gearbox base serves as a sump, a small electric or shaft-driven pump provides lubrication oil to the gear meshes and compression element bearings. The bullgear bearings are splash lubricated. The oil is filtered and cooled.

Oil quality and condition are important, as bearings and gear mesh are highly loaded and will suffer from poor oil.

For more details see Section 4.2.8

Technical and safety aspects of lubrication systems are described in more detail in Section 5.2 of the Guidance Notes.

2.7.3.3.6 Cooling System

A package dry screw compressor will include a proprietary cooling system, with an internal water circuit cooling compressor screw element jackets, intercooler and aftercooler. The water may be cooling tower water, closed circuit plant cooling water (e.g. cooled against fresh water) or cooled against air by a package-mounted exchanger. For information on intercooler & aftercooler design and operation, see Section 4.2.6.4. For general information on cooling systems see Section 5.11.
2.7.3.7 Piping Systems

Piping systems within air compressor packages will be proprietary, often using special couplings to save weight or space. External connections will be to appropriate national standards. Hydraulic pressure tests should not be applied to packages as part of general system strength testing. Any tests should be to vendor's design limits, with internal components blanked off or removed as necessary. For general comments on Piping Systems see Section 5.7.

2.7.3.8 Control System

The control system will be a vendor-standard (and often vendor-specific) PLC based system. It will carry out all control and trip functions within the package. It will have limited facilities to interface with site DCS and other compressor control systems. The PLC will often include fault and event logging, this may only be accessible locally by the vendor's service engineer, or remotely via a modem. The vendor-specific PLC will have limited functionality, and may not be compatible with operator standards and equipment preferences. It should, however, be familiar to the vendor's service engineer. It is often possible, at extra cost, to install an industrial PLC control unit to the customer's preference. This does mean that a service engineer is unlikely to be familiar with the PLC or its software.

2.7.3.4 INTEGRATION ASPECTS

2.7.3.4.1 Hardware Matching

Instrument air screw compressors have been developed as packages over many years, the only item which is commonly a customer option is the type and specification of the drive motor. It may be possible to change the supplier of items like solenoid valves, to suit operator preference. If the compressor is to be maintained through a service contract, it is preferable to stay with vendor standard parts, and more important to ensure that the contract is set up and operated properly.

2.7.3.4.2 Operational Matching

All parts within the package are rated together for the design duty, and should not pose any problems. There is little or no overload margin.

It is important from a reliability and energy cost point of view to have a workable match between the capacities and pressures of the installed compressor(s) and the system demand. This could pose an indirect safety risk, by reducing the reliability of the instrument air supply.

2.7.3.5 HAZARD ASSESSMENT

See Section 7.2.4 for a structured set of Hazard Assessment Tables.

2.7.3.5.1 Process Substance Containment Hazards

Containment hazards relating to the Screw Compressor are covered in Section 4.2.3.1

See Section 3.5.3.1 for Ignition/ Explosion hazards within the H.V. electric motor.

Compressed air systems pose certain very specific hazards, these are quite manageable provided that an effective modification procedure and Permit to Work system are in place. The hazards are low compared to handling e.g. LPG, but are not negligible.

Increased air pressure significantly increases the flammability of hydrocarbons. Hence a gas/ air mixture which is below the L.E.L. (Lower Explosive Limit) at atmospheric pressure could become explosive within the compressor. A dry screw compressor would not normally be able
to ignite such a mixture, but could do so under fault conditions. Similarly, lubricating oil mist becomes flammable under the conditions normally found in the discharge of the HP compressor element. Dry screw compressors avoid the risk by ensuring that there is no oil present at this point.

There is a known problem if connecting together dry (non-lubricated) and oil-injected or oil-flooded compressors. If the systems are connected together too close to the compressors, and are badly operated and maintained, hot air from a dry machine can mix with oily air from an oil injected machine, resulting in spontaneous combustion and an explosion. Air systems should only connect after all oil filters, after-coolers, temperature alarms and trips. The air receiver is the correct place for any necessary cross connections. It is not normally good practice to interconnect "wet" (oil lubricated) and "dry" (oil free) systems as it introduces some risk of oil contamination, even if pressure reducers and non-return valves are used.

Compressed air is often used to pressurise liquid storage or purge liquids out of pipework. This must be done with extreme care, under a safe system of working, preferably from a reservoir which operates at a lower pressure than the main supply, and which is only used for this purpose. There are known cases where hazardous materials have been introduced into, and distributed by, the instrument air system. The risk is greatest if purging is done with temporary connections (via flexible hoses) connected directly to instrument air points.

2.7.3.5.2 Equipment Hazards

In practice, mechanical hazards of packaged equipment are the same as the individual units.

The Mechanical Hazards associated with the elements are:
- Damage and loss of containment of machine elements due to high mechanical energy stored or transmitted within rotor shafts, gear box, couplings.

For guidance specific to the Air Compressor see Section 4.2.3.2

Electrical Hazards:

Description of the source of the hazards and the protection / preventative measures necessary are given in Electric Motor Sections 3.3 (Generic A.C.) and 3.5 (High Voltage > 500 kW) of the Guidance Notes.

There is a risk of an incident on one component of the system adversely affecting the other, but this applies to any multiple machine installation.

2.7.3.5.3 Operational / Consequential Hazards

Packaging should have no particular influence in this area; Mechanical, Process and Control interactions apply equally to Packaged and Non-packaged units.

The Operational Hazards associated with the elements are:
- Contamination of air by corrosive gases/ salts (leading to problems with downstream equipment)
- Contamination of air by toxic materials (injury to technicians or operators close to instrument air vents)
- Contamination of air by lubricating oil (leading to erratic operation of pneumatically operated devices)
- Low instrument air pressure (leading to sluggish or erratic operation or faulty signal)
- Wet air (failure of water traps or air drier) – freezing of air lines, solenoid valves.

For guidance specific to the Air Compressor see Section 4.2.3.3

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2.7.3.5.4 Maintenance / Access Hazards

Maintenance on packaged air compressors is difficult because of very congested construction, this is not necessarily hazardous but can result in more sprains and similar injuries as people struggle to work in restricted spaces. Well-designed packaged units incorporate tailored lifting / slinging facilities. It is usually more appropriate to change out an assembly than to attempt to attempt a failed component in situ. There is a potential issue of isolation of electrical and other energy sources where isolation of part of the package may not isolate a closely adjacent part. This must be covered by Maintenance / Permit to Work procedures. In general it is best to specialist maintenance contractors (vendor nominated & trained).

2.7.3.6 APPLICABLE STANDARDS

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations ( Transposed Harmonised Standards ) can be found in Section 5.15 the specific standards relating to this package are :-

BS EN 1012-1 1996 Compressors and vacuum pumps – Safety requirements – Part 1: Compressors.


Selection of API Standards Relevant to Machinery in use in Refineries / Offshore :-

API 672 1996 Packaged, Integ rally Geared Air Compressors for Petroleum, Chemical & Gas Industry Services

API 541 1995 Form-Wound Squirrel Cage Induction Motors – 250 HP and larger

API 546 1997 Form-Wound Brushless Synchronous Motors – 500 HP and larger

General Standards for machinery can be found in Section 5.15
2.7.5 ELECTRIC MOTOR DRIVEN SUBMERSIBLE CENTRIFUGAL PUMP (SEA WATER LIFT)

TECHNICAL SUPPORT

2.7.5.1 ELECTRIC MOTOR DRIVEN SUBMERSIBLE CENTRIFUGAL PUMP PACKAGE - DESCRIPTION

The package comprises a High or Low Voltage Electric Motor driving a Vertical Multi-Stage Centrifugal Pump on Sea Water Lift service. The water could be used for dedicated or general cooling use, or for Fire Water.

2.7.5.2 PACKAGE ENTITY

The package consists of a small diameter multistage water pump, close coupled to a specialised submersible electric motor. The pump and motor unit will be at the bottom of a vertical conductor tube leading from the lower deck of the platform. Access to the pump is only possible by removing access covers from above the top of the conductor, then lifting the complete pump assembly out onto the deck. The pump has a vertical discharge pipe, with the motor power cable clipped on externally.

2.7.5.3 PACKAGE ELEMENTS

2.7.5.3.1 Submersible Electric Motor

See Sections 3.3, 3.4, 3.5 for the general design and working principles of AC electric motors.

The electric motor used will basically be the same as that designed to work down boreholes. While working on exactly the same principles as a standard industrial motor, downhole type submersible electric motors have a very special construction to permit their unique operating location. This must take account of :-

- Operation continuously submerged in sea water at depths of up to 30 m
- Narrow diameter to suit driven pump
- External water cooling only
- Inaccessible location

The resultant motor is long and slim, and may be clad in stainless steel to minimise corrosion. Cooling is entirely by water contact to the outer skin. The housing will be sealed by "O"rings to prevent water entry. The motor shaft will typically pass through an oil-filled double mechanical seal to prevent water entry. Note that the shaft is exposed to the water at this point, which matches the inlet of the pump. The electrical cable, which is very long and with no external joints, will be fed straight into the motor through a pressure tight glanding system. The terminal housing will probably also be completely filled with waterproof epoxy resin.

Figure 2,7 – 11 Outline of Electric Motor driven Submersible Pump
The motor will have some sensors to check for winding temperature, moisture penetration and perhaps bearing temperature. These sensors should be wired out through additional cores in the main cable, to avoid the need for a second cable gland.

Movement of cooling water over the housing is aided by its location in the pump suction stream. The inlet grilles in the conductor tube should therefore be located lower than the motor. There is no additional impeller for water circulation. Hence the motor cannot be run in air for more than a few seconds, as it would overheat. The motor may only be able to run when in the correct vertical orientation, to prevent damage to the seal.

2.7.5.3.2 Submersible Centrifugal Pump

See Section 4.11.6

The pump itself will be similar, but instead of being driven from above by a long shaft, the drive is from below by a close-coupled electric motor.

The vertical discharge pipe thus does not contain drive shaft or guides, and is much easier to dismantle when lifting the pump.

The reason for driving from below is that a top mounted motor would block the discharge pipe direction. There is now a requirement for a thrust bearing within the pump, to provide axial shaft location and carry the residual axial loads. The majority of axial loads will be absorbed by the impeller hydraulic balancing arrangement.

The pump shaft will pass out of the bottom of the pump housing itself, at the level of the inlet ports, thus at suction pressure. The pump does not have a mechanical seal, but one will be required for the electric motor, to exclude sea water. The shaft connection to the electric motor will typically be a clamped muff (rigid) coupling.

Figure 2.7 – 12 Electric Motor driven Submersible Pump (separated)

With the pump disconnected from the discharge pipe at one end and the electric motor at the other, the pump is then a reasonably compact unit for handling and shipping.
2.7.5.3 Electric Cable

The electric cable to the motor needs to pass up the outside of the pump body then be fastened at intervals to the delivery pipe. The cable must be protected, where appropriate, from mechanical damage or fretting.

2.7.5.4 Lubrication Systems

The Electric Motor will have self contained grease or oil lubricated bearings, possibly using the same oil as the mechanical seal.

The pump will have simple water lubricated bearings.

No other lubrication is required.

2.7.5.5 Control System

The pump may simply have on/off control, but a soft start unit could be used to reduce heavy starting currents, allowing smooth acceleration and discharge pipe filling. This reduces mechanical loads and may have the benefit of permitting a lighter supply cable to be used. The soft start unit will also contain monitoring facilities to check on the electrical health of the motor, which is totally inaccessible in service.

Restart of the pump will be inhibited for a short period to allow any reverse rotation, caused by water draining down from the vacuum breaker, to stop.

2.7.5.4 INTEGRATION ASPECTS

The pump assembly is supplied as a single unit. Integration consists of ensuring that it fits correctly into the conductor tube and stops at the correct depth. The cable must be routed and supported without strain. The delivery pipe will be supported from a mounting at the top of the conductor, and connected to vent and isolation valves.

The venting (and, probably, vacuum breaking) arrangements should be automatic, to minimise the risk of water hammer or gas locking effects.

2.7.5.5 HAZARD ASSESSMENT

The hazards posed by the package are a combination of the hazards posed by the individual machine and rotating equipment items, with possibly some additional hazard due to potential interactions. Assessment of the hazards from the package should, however, be made easier at the design stage because one design team should be dealing with the complete package, and have all relevant information compiled together.

See Section 7.2.4 for a structured set of Hazard Assessment Tables.

2.7.5.5.1 Process Substance Containment Hazards

See Section 3.5.3.1 for Ignition/Explosion hazards within the H.V. electric motor.

As the complete pump is submerged, and the duty is normally sea water (although this type of pump could be used for lifting oil from deep storages) there is no direct hazard from a pump
failure. Failure of pipework on the platform could cause a hazard, as with any other pipework failure.

Pump intakes should be located as far as possible from outfall caissons to avoid drawing in effluents e.g. sewage, produced water.

As divers working close to the pump suction could be at risk of being sucked in (depending on screening / shielding arrangements) it is normal to suspend pumping when diving is in progress local to the pump. This suspension has to be managed within the Permit To Work system as may constrain other operations.

2.7.5.5.2 Equipment Hazards

All of the moving parts are contained within the pump and motor casings which are contained within the conductor.

The greatest mechanical hazard is probably a mechanical collapse or dropping of pump assembly during a crane lift or other similar maintenance. People working in the area, and vessels below, would be at risk.

An electrical fault on the motor could cause overheating or damage to switchgear. This could cause injury if personnel were present e.g. during a pump test start.

For details of Bearings, Seals, Shaft Couplings and related hazards see Section 5 – Auxiliary Systems & Equipment.

2.7.5.5.3 Operational / Consequential Hazards

See Section 4.11.3.3 for issues relating to the pump.

The greatest problem is probably unexpected loss of supply. An electrical fault on the motor or switchgear could trip associated circuits.

For this reason, important utility service pumps should be separated, and powered from different sources or supply links.

2.7.5.5.4 Maintenance / Access Hazards

The complete assembly must be lifted out for maintenance. Dismantling has to be done in the vertical plane as the unit may collapse if slung horizontally. Pump and motor modules can be handled, after separation, and taken for further dismantling under workshop conditions. Due to the requirement for water cooling and lubrication, little or no run testing can be done before the complete assembly is returned to its berth in the conductor.
2.7.5.6 APPLICABLE STANDARDS

Selection of British Standards Relevant to Machinery in use in Petrochemicals Installations (Transposed Harmonised Standards) can be found in Section 5.15 the specific standards relating to this package are:

BS EN 809 1998 Pumps and pump units for liquids – Common safety requirements.

Selection of API Standards Relevant to Machinery in use in Refineries / Offshore:

API 610 1995 Centrifugal Pumps for Petroleum, Heavy Duty Chemical and Gas Industry Service
API 541 1995 Form-Wound Squirrel Cage Induction Motors – 250 HP and larger
API 546 1997 Form-Wound Brushless Synchronous Motors – 500 HP and larger

General Standards for machinery can be found in Section 5.15
Machines are items of equipment, which power a continuously rotating output shaft. This
description includes machines deriving their energy from fuel, electricity, air and hydraulic power
sources. There is a general bias (certainly compared with the on-shore process industry) for
lightweight, compact, sophisticated equipment to be bought in preference to heavier/simpler/
cheaper equipment. The main types of machine considered in this section of the guidance notes
are:- gas turbines, electric motors and diesel engines. For an air-powered application see
Section 2.5.1, and for a hydraulic powered application see Section 2.6.2.

The guidance in this section covers the following machines found on Offshore installations:

- Gas Turbine (Aero-derivative)
- Gas Turbine (Industrial).
- Electric Motor - LV
- Electric Motor - HV > 500 kW.
- Diesel Engine

Gas turbines are compact, low vibration, high power-to-weight, and are available either as
Aero-derivative or Industrial designs. The Aero-derivative design is lightweight and compact,
thus more suitable for Offshore installations. The light weight is achieved by the use of
sophisticated materials; radial split casings, and special designs of rolling element bearings. The
engines require relatively frequent service, but can quickly be dismantled into their key modules
using special jigs and tools. Overhaul outages are thus kept short and access space
requirements are minimal. The manufacturer or agent then overhauls modules on a service
exchange basis. The heavier and more robust Industrial machine is available in a wider range
of power ratings, and is often used for Onshore Power Generation. Construction is based on
steam turbine / industrial compressor design with heavy cast casings and white metal bearings.
The operating interval between overhauls is much longer than for Aero-derivatives, but overhaul
times are also longer. In this case the unit is overhauled in situ, requiring large clean dry
working areas. Industrial gas turbines are available in low emission designs and can be adapted
for combined cycle and heat recovery duties.

Electric motors are the standard driver for smaller rotating machines. Onshore, where reliable
grid power is available, electrical drives are used up to about 20 MW rating. Offshore, electric
motor drives are likely to be used up to about 2 MW rating. Electric motors are compact, robust
and simple. They are available for use in Hazardous Areas and can run for years with little or no
maintenance. Standard electric motors are nominally fixed speed machines, but can be made
variable speed with the addition of inverter drives.

Diesel engines are heavy and fairly bulky, and are generally only used as "stand-alone" drivers
for emergency or stand-by service. They are readily available as tailored packages rated from
perhaps 25 kW to 1 MW or so. The major disadvantage of diesel engines is that they require
frequent maintenance and thus are not suitable for extended continuous running.

Machines like steam turbines require heavy supporting plant and are not covered for Offshore
use.
This section of the guidance covers an Aero-derivative Gas Turbine, as used for driving gas compressor(s), a large pump, or an alternator, on an off-shore installation.

- **Gas Turbines are designed to operate on hydrocarbon gas and / or liquid fuels, the major hazard relates to release of fuel at high pressure and consequent explosion risk. Gas Turbines are virtually always mounted inside acoustic enclosures, these tend to compound the hazard by limiting access and confining any fuel release.**

- **The high energy density and high tip speed give some risk of injury / damage from ejected blades, this risk is increased if the turbine is subject to mal-operation, poor maintenance or over-speed trip events.**

- **Each Gas Turbine has a number of support systems, these use conventional machine components e.g. Pumps, Fans, Mechanical Seals. Gas Turbines are normally provided in a Package format tailored to the requirements of the driven machine.**
3.1.1 INTRODUCTION

- Although Aero-derivative Gas Turbines are used extensively in industrial applications, their aircraft background should be recognised. The design of the machine has an enormous influence on the potential hazards relating to its operation and maintenance. The gas turbine design must address the effective integration into an offshore installation, permitting safe operation and maintenance.

Figure 3.1 – 1  Cut-away View of Aero-derivative Gas Turbine

Aero-derivative gas turbines can be recognised by their radial symmetry, achieved by the use of deeply machined cylindrical casing sections. Rolled or pressed sheet metal is also used where possible, with a minimal use of castings. They are normally installed in close-fitting acoustic housings, access is gained by opening panels. There is certainly no room to walk around the machine inside the housing.
### BACKGROUNDB & HISTORY

- **Gas Turbines** were developed for use as aero engines. They are much simpler than reciprocating engines hence inherently more reliable. The huge market and drive for high efficiency and reliability ensure that most technical developments happen first on aero engines.

- Aero engine designs modified for industrial use are referred to as "Aero-derivatives". They are technically advanced and light in weight.

- "Industrial" gas turbines use process equipment engineering to produce heavier and more rugged designs. These are easier to modify for exhaust emission control or heat recovery purposes.

Gas turbines were first developed in the 1940's as aero engines. There is currently no other practical power plant for fast high-altitude aircraft. Since that time there has been tremendous and continuous development of engines for this huge market, the emphasis being on high power / weight ratio and fuel economy. The inherent simplicity compared with reciprocating engines gives a very high potential reliability, which the aero industry has to some degree been prepared to sacrifice for higher power, by accepting relatively short maintenance intervals. This has led to the development of sophisticated condition monitoring & inspection processes. Since an aircraft wing is a very poor location for carrying out maintenance on complex equipment, the design has evolved to permit removal of the entire power plant to a workshop where it can be inspected, overhauled and tested.

More recently, environmental considerations have been taken more seriously, with combustion system improvements reducing smoke and NOX, and significant reductions in noise.

Industrial versions of gas turbines have also been developed, in most cases by different manufacturers than aero-derivative engines. The preference here is for high reliability, low emissions and low first cost. As weight is not an issue onshore, high power electrical generation gas turbines are of the industrial design.

Most gas turbines are of "simple cycle" design with no heat recovery or compressor efficiency enhancement. Significant output power increase (or improved fuel economy) can be gained by fitting such heat exchange devices, but they are very bulky and add dramatically to the first cost. They are rarely used offshore.

Aero-derivative gas turbines are basically aero engine designs converted for industrial use. They are normally de-rated for continuous sea level operation and longer service intervals. Modern engines are derived from high-bypass turbofans, by removing the fan and attaching a drive shaft. Ancillary components (e.g. lubrication systems) can be removed from the engine and placed on a skid. The engine core is thus very small & light, designed for off-site maintenance. The rotor bearings are rolling element thus suffer from statistically predictable fatigue-related failures. Inspection and maintenance are carried out using special tools; a suitably skilled crew can do this very rapidly. The engine is normally mounted in a close-fitting acoustic enclosure, as there is no access required with the engine running.

They may be particularly suitable for offshore installations because of their compact size, low weight and low vibration. Provision is required to mount special tools to remove / replace engine assemblies. Maximum shaft power currently available is about 50 MW.
3.1.3  HAZARD ASSESSMENT

- The potential hazards must be assessed for a complete installation over its full-anticipated operating cycle.

- Fuel release poses the greatest hazard, the complex fuel piping harness around the combustor the most likely location. Stringent procedures are required for assembly and leak testing of fuel pipework.

- Injury from contact with moving parts / hot surfaces is possible but exposure to hazard is low. Mechanical failure tends to be contained by the casing & acoustic enclosure, even if the machine is badly damaged. The main exception is a failed compressor blade, or drive coupling, which could result in ejection of parts from the machine. The hazard assessment must cover the consequential effect of a turbine trip - can the rest of the plant cope safely?

- There are a separate set of hazards relating to the maintenance of a turbine, these cover effective isolation risks & mechanical handling risks.

The hazards associated with a gas turbine have to be considered over its complete operating/maintenance cycle, not just full steady load operations. Mal-operation / excursions / driven system failures and emergencies must all be covered. The hazards must be seen in context with the installation as a whole, and be compared with alternate drive strategies.

See HSE Guidance Note PM 84 "Control of safety risks at gas turbines used for power generation" and Draft Guidance Note "Control of safety risks at gas turbine driven CCGT & CHP plant".

3.1.3.1  Fuels

Gas turbines can operate on a range of liquid or gas hydrocarbon fuels, cleanliness is important in terms of both solids and corrosives content. Fuel is always controlled to give a fuel-lean mixture, otherwise the combustor and turbine would rapidly overheat and burn out. The air passing through the machine is primarily the working fluid and only incidentally the oxidiser. Combustion and turbine temperatures are constantly monitored, so the likelihood of a fuel explosion inside a working gas turbine is very low.

During a turbine start, there is the potential for unburned fuel to accumulate and then be ignited by a spark. This is avoided by a programmed purge and start sequence. The pipework, and purge sequence, must be designed to avoid trapped air or hydrocarbons e.g. by opening all vents / drains. It is important that the fuel valves open, and in particular close tightly, when required. Double isolation of fuel by twin trip valves is preferred.

On dual-fuelled machines, there is the potential to feed both fuels, or none, during a changeover. This is avoided by a correctly programmed sequence, which is functionally tested without fuel after any maintenance work that could have affected it. Fuel changeover requiring manual intervention within the acoustic enclosure is of particular concern.
The greatest risk is probably posed by a failure of the external fuel piping. This is complex, extensive and subject to heat and vibration. It is difficult to fully inspect, and the parts between the fuel isolation valve and the combustor cannot in practice be pressure tested. Gas fuel leaks cannot be seen, the gas is mobile and easily ignited by hot surfaces. The risk of a gas fuel explosion is greatly reduced by an effective enclosure ventilation system. This dilutes any release below the flammable limit, minimises dead spots where gas may accumulate, and draws air away from hot parts. Liquid fuel leaks at low pressure tend to form puddles and are relatively difficult to ignite. High-pressure liquid fuel (after the fuel injector pump) may form a spray or atomised mist. This is much easier to ignite than a liquid stream or pool, particularly if projected onto a hot surface.

Figure 3.1 – 2  External Fuel Pipework

Dual wall piping may be used where vibration induced fatigue failure of pipework is thought to be likely. Note that the ventilation system will have less effect on a liquid fuel release, good pipe routing and minimisation of fittings are the best protection.

It is crucial that the pipework is carefully assembled and rigorously tested after maintenance work, and a foolproof tagging system used to check the integrity of every joint. It may be necessary to inspect / test joints in groups, before access is blocked by further components. Absolute commitment from the whole team is vital, no compromise is possible.

Gas leakage detection (fuel cell) devices are normally installed around the turbine, but because of the dilution effects of ventilation air, small releases may go undetected. On new installations it may be appropriate to use smoke bomb testing to check that the gas detectors are correctly located. A pair inside each ventilation exhaust would be a good start.

3.1.3.2  Mechanical

During normal operation the main risk of injury is to people working close to the machine - noise and burns. The few accessible moving parts (mainly on ancillaries) should have fixed guards. Very high metal temperatures can lead to severe burns, the normal procedure is to fit perforated metal guards that prevent contact while permitting ventilation & cooling.

Blade ejection is in theory possible at any time while the machine is running, but the risk is higher during an over-speed event or the first few hours run after any work on the blading. Aero-derivative machines, with their lighter construction, offer a higher risk. Over-speed events cannot be planned for, but their frequency and potential severity are avoided by keeping the monitoring and protection systems in good order, and by prohibiting operations known to have a risk of load tripping.

Work on the blading should only be carried out by skilled people, and the first few runs up to speed should be monitored closely. It would also be sensible to minimise unnecessary access to the area radial to the machine, and take precautions like leaving process gas systems depressurised until the turbine is fully re-commissioned.
Over-speed can occur during normal running if the control system fails. Because of the inertia and load of the driven machine, the acceleration will be moderate and the trip system should be able to cut the fuel long before a dangerous speed is reached. A process trip unloading the driven machine will cause faster acceleration, imposing a more stringent demand on the trip system. The most dramatic event is the failure of the load gearbox or shaft coupling; this will cause the turbine to accelerate very quickly. It is possible to simulate such a fault during commissioning, but there is no way of carrying out a practical test. Provided that the gearbox / coupling are of suitable design and properly maintained, the risk of such an event can be kept low. During such an event, the driven machine will stop, or even try to run backwards. If this would pose a hazard, then appropriate trips based on driven machine, not turbine shaft, are required.

Gas turbines do not like ingesting things, and the intake filter system is there to prevent this. Badly fitted or blocked filter pads can be drawn into the compressor section, causing severe damage. In the extreme the inlet filter house or duct can be sucked flat. To minimise the risk, a robust debris grid (able to stop a broken filter pad) and a "blow-in door" should be in place. A visual internal check of the inlet duct by a senior person, wearing overalls with no pockets, is a good idea after any work in the filter. He/ she should then supervise the sealing of the access door.

High vibration or high exhaust temperatures are a sign of distress that may indicate irreversible deterioration in the machine. Careful attention should be paid to blade creep temperatures, a 10 C exhaust temperature rise can significantly reduce creep life – the operating life of hot components will be determined by estimation of remaining creep life, higher temperature operation will lead to shorter operational life, and can result in premature failure of the component, and major damage to the machine ahead of the predicted preventative replacement routine.

Thermocouples are arranged around the turbine exhaust. In theory all temperatures measured at one section should be equal. In practice they are not, due to thermocouple errors as well as imperfect gas combustion and distribution. The greater the inequality, the greater the risk of creep damage, particularly if it does not change with time.

Lubricating oil can pose a slipping hazard, particularly on metal plates & where lighting is poor. Oil fires are possible if a cracked oil line sprays onto hot exhaust ducting - look at the hot end bearing arrangement. Damaged / crushed / twisted oil supply pipes can restrict oil flow, causing a bearing failure. Blocked oil return pipes or excessive oil levels can cause bearing overheating or leakage from shaft seals. On older equipment, oil seepage under bearings can collect in dead spaces.

### 3.1.3.3 Operational / Consequential

In normal operation a gas turbine should pose little threat to the safe operation of the installation. Heat from badly insulated or leaking exhaust ducting can damage cabling or other services. A significant, uncontrolled, fuel emission poses an obvious risk. If this occurs inside the enclosure then it will be diluted and vented from the enclosure vent fans. A small fire or explosion inside the enclosure is likely to be fairly well contained, and damage may well be restricted to the local area. An ejected blade or larger rotor part, due to its high velocity, can penetrate the enclosure and cause injury and damage many metres away from the turbine. The Safety Case for the installation should consider the location of vulnerable equipment, particularly radial to and above Gas Turbines. Additional protection in the form of blast / impact walls may be required.
No Gas Turbine system is totally reliable. A well selected, operated and maintained unit should be able to achieve > 95 % reliability. Proper operation of the condition monitoring system and attention to outputs should permit problems to be anticipated, resulting in a controlled elective shutdown, less damage, and thus a quicker, cheaper repair. Unplanned, unpredicted shutdowns can have undesirable consequential effects by throwing rapid load changes to other equipment, and by preventing controlled venting or purging of gas lines. These risks must be taken into account in the Safety Case as no installation relying on the continued operation of a single machine for its safety, can be considered to be satisfactory.

3.1.3.4 Maintenance / Access

![Figure 3,1 – 3 Gas Turbine Opened up for Maintenance](image)

Access during operation. This may be required for simple monitoring & servicing purposes, or to repair faulty components while running on the spare. The major risk is personnel injury from hot surfaces & while working in cramped conditions, and working in a zoned hazardous area. Work on or near the fuel system should be undertaken only after careful planning. It has to be accepted that there is a risk of an unplanned trip of the turbine- and should be addressed by the safe system of working in practice. Operators must be aware of switches or interlocks, which can cause, or require, a machine shut down on opening enclosure doors.

Though most systems are designed for remote operation, access to start up and shut down the machine should be considered and designed to permit free movement. Access to the enclosure should be restricted once the fuel system is live, with the provision of interlocks, monitored in the control room.
Access for maintenance once the machine is fully shut down and cool, may require removal of access panels and the erection of scaffolding. The fuel and power supplies should be isolated outside the working area. Lifting, particularly over people or vulnerable pipework & equipment, should be subject to prior assessment and protection installed where required. Permits to Work will specify what electrical work may be carried out and what gas tests may be required to maintain the Permit.

### 3.1.4 OPERATING REQUIREMENTS

- **Gas Turbines are selected and set up for a particular operating pattern. The selection of power rating, ancillaries, control & monitoring will be affected by the intended operation. A change to the operating pattern could lead to greatly reduced operating life and frequent unplanned outages.**

The most benign operating pattern is continuous steady operation with slow load adjustments. Under these circumstances the turbine will operate entirely on automatic control, with operator supervision only. The unit will be expected to run for extended periods between scheduled outages, although a standby unit will normally be present, with operators performing a planned changeover at regular intervals. Provided that the load and speed demands on the machine are within its intended design envelope, reliability will be high and can be managed by condition monitoring.

A more onerous duty is when the load demand pattern has large and frequent swings, for example when the driven compressor or pump is only required periodically to deal with a build-up of gas or liquid. The machine can be made to cope with this, by good initial design and by operating within defined load-change rates. Thermal expansion and creep problems are more likely on such a duty.

Where duties are shared between several machines, it is better to share the load change evenly, rather than start and stop one machine frequently.

Where the installation is subject to significant motion, for example when under tow or during a storm, the motion may exceed the capabilities of the turbine. The unit may have to be shut down as a precautionary measure; otherwise mechanical damage may be caused. The most sensitive system is likely to be the lubrication oil system; movement or roll angles may interfere with oil distribution & return, or cause spurious level trips.
3.1.5 MAINTENANCE REQUIREMENTS

- Machine, reliability and safety depend on effective maintenance, and protection devices, in particular speed control and temperature trip systems.

![Process Schematic Diagram – Gas Turbine Core Engine](image)

Aero-derivatives turbines benefit from the aero engine market, with a collection of sophisticated maintenance tools aimed at minimising downtime. These tools, sufficient space, and highly skilled technicians are required to maintain the engines to the desired levels. The tools have to be kept in a dry store close to the machines, while engine sub-assemblies could be kept on board (in specially designed containers), or more likely shipped out on demand. The components are very compact but not tolerant to rough handling. The plant area must have access room and lifting facilities, maintenance will normally be carried out with the rest of the installation in full operation.
3.1.6 GAS TURBINE – MAIN COMPONENTS

- Gas Turbines are protected from dirt by air intake filters and fuel filters. Even so, periodic compressor washing may be required.

- Mechanical integrity can be monitored on-line, and inspected during production outages. On-line monitoring includes continuous temperature & vibration readings, and trending of process parameters. Recorded monitoring includes spot checks on temperature / vibration, and sampling of e.g. lubricating oil.

- Protective systems need to be designed to an appropriate integrity level, and tested regularly.

- Gas Turbine bearings are no different from those on other machines, and monitoring and maintenance as appropriate can greatly extend bearing reliability.

- Compressor and turbine problems should be minimised by good air and fuel filtration, and steady operation within the design envelope.

- Liquid fuel system will contain high-pressure fuel. Leakage may be as a mist, which is readily ignited.

- Gas Turbine enclosure cooling is straightforward, however, dirty water or air can foul the cooling surfaces and limit cooling. Cooling air can dilute gas leakages but can also transport large gas clouds into other locations where they could introduce a hazard. Internal cooling systems for the machine if not appropriately maintained may lead to reliability problems.

- Gas and oil sealing uses conventional seal technology. Due to the small clearances and high speeds, seals are easily damaged and should be monitored or inspected at appropriate occasions.
3.1.6.1 Gas Generator

The key component of a gas turbine is the "Gas Generator", often referred to as the "Core Engine". This is often treated as a pre-assembled component and is transferred onshore for overhaul after a specified number of running hours. It comprises 3 main sections:

Combustion Air Compressor

The air compressor comprises the front part of a gas turbine. This is a high-speed multi-stage axial compressor. Filtered atmospheric air is compressed to 10 barg or higher. Compressors are very simple in concept, using aerodynamic effects to increase the pressure (also density & temperature) of the air. Inherent in the design is the effect of inputting energy to air, firstly accelerating the air and then diffusing the speed to increase its pressure.

This is the exact equivalent of an aircraft wing creating lift, and similarly there will be problems if the airflow is disturbed or unstable. Disturbance can be caused by dirt, obstructions (ingested or displaced items), damaged blades or intake blockages. Because of the very high energy input, disturbed airflow can cause large radial and axial forces (usually pulsating or rotating) on the compressor. These will show up as vibrations, if these are severe the machine will normally be tripped immediately. Effective intake filtration and load control should prevent most of these problems, cleanliness & tidiness during maintenance the rest.

A damaged compressor blade, particularly in the initial (larger size) stages, can form a lethal missile and penetrate the casing. If it cuts a fuel line or lubricant line, a fire is probable for which the trip systems and remote isolations are designed.

See also information on Axial Compressors included in Section 4.2.

Combustion System

The combustion system receives the uncooled air from the compressor, mixes it evenly with the fuel and burns it in combustion chambers manufactured from special high temperature alloys.

Fuel is burned in excess air to create the hot gas, which drives the turbine. The combustion system always runs fuel-weak so there should never be a risk of explosion in normal operation. (Control systems are also used to ensure that this hazard is also avoided during transient operations – Start up, shut down, etc.) The combustion temperature is so hot that even the special alloys used would melt, if the inlet air did
not cool them.

The fuel is lit off by a high-voltage ignitor / pilot light arrangement. Once lit, the pilot light is no longer required and the assembly is usually withdrawn from the hot zone. The flame is then monitored by (usually two) flame eyes; flame failure trips the turbine.

Sulphur oxides (toxic and corrosive) are generated if the fuel contains sulphur. These can be reduced by the use of low-sulphur fuel. Nitrous / nitric oxides (NOX) are generated from atmospheric nitrogen by the high combustion temperatures. These are also toxic and corrosive. However, the amount of NOX generated can be greatly reduced by sophisticated combustor design and control.

Land-based turbines are now required by legislation to achieve tight emissions limits, particularly for NOX. The requirements for marine (ship or platform) turbines are currently less stringent but are likely to get tighter.

Gas sensors in the exhaust monitor the emissions levels. It is the responsibility of the operator to monitor and record emission levels, calibrate and test sensors. Exhaust emissions can be remotely analysed by infrared monitors.

Aero-derivative turbines have annular combustors, these snug in close to the body of the turbine to minimise the front cross-section (as required in the flight engine). There is less scope (currently) to minimise NOX generation on this arrangement.

Industrial turbines have one or more can-type combustors; these are larger and can be designed for staged combustion, with greatly reduced NOX levels.

**Power Turbine**

The hot gas is ducted to the power turbine. This is a multi-stage axial turbine, which extracts energy from the hot gas. The power turbine is on a common shaft with the compressor, running at the same speed and providing the energy for air compression. Excess energy is available to drive the output shaft from the turbine, to power the driven equipment. Turbines are effectively compressors in reverse, however because the airflow is expanding they do not suffer from the same stability problems as compressors, and any dirt in the air should have been caught in the compressor. Turbine problems will occur because of dirty fuel, poor combustion or excessive combustion gas temperatures. In modern gas turbines the combustion gas temperature is so high that the blades would fail rapidly unless they were cooled. This is normally done by bleeding air from the outlet of the compressor section through complex holes in the blade. The air cools the metal, then forms a film over the surface of the blade, providing a partial barrier to the heat from the combustion gas.
Loss or restriction of this cooling air will result in high temperatures in the section of blading so affected. Rotor blades (buckets) will stretch radially through creep effects until they start to bind or rub. Uneven creep will cause unbalance. Creep of stator blades (nozzles) will be through bending until they start to rub on stator blades. Damaged blades even if they have not caused catastrophic failure must be replaced with new sets (despite expense), so the monitoring of temperatures throughout the turbine has real value.

Turbine failures are less likely to have serious safety implications. A turbine failure can result in a surge of very hot gas into the exhaust duct, which must be designed to survive a temperature excursion.

For power generation purposes a "Single Shaft" design is used. Here the air compressor, power turbine and output shaft are common and run at the same speed. This arrangement is suitable for alternators, which can be run up to full speed at no load. This system is also fixed speed, giving simplicity in design and operation. A drive gearbox is required to match the lower alternator speed.

For machine drives the "Twin Shaft" variant is used. Here there are two shafts mounted end-to-end, and the power turbine is split into 2 sections. The high-pressure section drives the air compressor; the low-pressure section drives the output shaft. The separate shafts are “coupled” aerodynamically but not mechanically. The starter system does not have to deal with the drag and inertia of the driven load. The main advantage is that the output shaft may operate at a different speed from the gas generator, giving higher efficiency for variable speed loads. Control of two variable speed systems is much more complex than the single shaft system. High-speed process compressor can be matched to the turbine, eliminating the drive gearbox.

### 3.1.6.2  Fuel & Ignition System

The fuel system distributes the selected fuel to the appropriate fuel nozzles, at the correct pressure and flow. It also provides isolations and pressure relief.

Gas fuel is normally provided to the skid at high pressure and is let down through valves and nozzles to give control and correct mixing.

Liquid fuel (diesel – unrefined crude oil is generally not suitable for use due to contaminants such as tar, and sulphides) is normally provided to the package at low pressure, local pumps generate the necessary nozzle pressures.

The ignition system ensures correct purging, lighting of pilots or energising of igniters before main fuel valves are opened. It constantly monitors for correct combustion and will trip on flame failure.
3.1.6.3 Gearboxes

Single shaft machines use a gearbox to transmit power to the alternator / generator. This gearbox is mounted on the main shaft and also provides auxiliary drives for the starting system and oil pumps. On early designs this would operate the governor and mechanical overspeed trip systems. Twin shaft machines use an auxiliary gearbox mounted on the gas generator shaft to provide the necessary auxiliary drives. There may be a drive gearbox where this is required to match the speed of the driven machine to that of the output shaft. For details of Gearboxes and related hazards see Section 5.5.1.

Figure 3.1 – 6 Drive Gearbox

3.1.6.4 Support Systems

The baseframe is a fundamental part of the turbine, providing a rigid mechanical support for the heavy components, and a location for the lubrication package. The rigidity of the baseframe becomes a significant issue if the frame it is mounted on is subject to bending or twisting loads.

A self-contained lubrication system is built into the baseframe; this lubricates the gas generator and may provide oil to the low stage power turbine & driven machine. A mixture of motor and shaft driven oil pumps will be used to provide oil prior to start-up, during operation, and for a limited period after stopping. Mineral oil is normally used; oil cooling will be against air or cooling water. For details of Lubrication Systems and related hazards see Section 5.2.

Where the turbine can operate on liquid fuel (offshore, this will be diesel), a local pump is normally used to boost the fuel to the pressure required for injection to the combustion chamber.

For starting, the gas generator shaft must be brought up to a minimum speed before fuel can be introduced and lit. This is normally done from an auxiliary gearbox drive. An example of an effective modern starting system is a hydraulic motor driven by an electric motor/ pump unit. This gives a very compact variable speed drive. “Black start” turbines (e.g. for power generation) are likely to use a diesel engine starter.
3.1.6.5 Control & Management Systems

The operation of the turbine is normally controlled by a dedicated PLC. This is provided by the package vendor, to a standard design. It will have various options for controlling ancillary systems and communicating with the process control systems on the installation.

Turbine starting. The control logic checks interlocks, starts oil and fuel pumps, operates the starter motor and establishes combustion.

Load control is done by adjusting compressor settings and fuel flow to achieve required speeds for 1st and 2nd shafts. An input from the process control system will be required to define the targets. Variable speed, variable power is the most complex requirement. External systems’ Emergency Shutdown (ESD) systems may be interfaced to shut down the gas turbine and its associated rotating equipment.

The speed control over-rides the load control to keep the shafts within their permissible speed ranges. The turbine will trip on overspeed, modern systems using multiple electronic speed sensors with a voting system.

Temperature and Vibration Monitoring. Gas turbines operate at very high gas temperatures and high shaft speeds. Monitoring, recording, alarm and trip functions are required to limit excursions.

Pressure, temperature and flow of lubricating oil are controlled by simple mechanical systems. In the event of loss of electric power (and thus normally the PLC operation) the lubrication system must continue to work until the rotors have stopped and the bearings cooled sufficiently.

Fuel isolation and vent valves are interlocked with the ignition and flame detection system, to ensure safe operation. Systems that are able to control two fuels at once and change over while in operation, become quite complex.

3.1.6.6 Intake & Exhaust

Air Intake System

This may be physically remote from the turbine and linked by shortest possible large bore ducting – to minimise pressure drop. It will include filtration, de-icing (for UK and North Sea locations), and silencing. The location will be chosen to minimise ingestion of salt spray, and the possible ingestion of hydrocarbon gas. The location on a fixed installation is thus likely to be low down or underneath, with a vertical rising rising section. On a vessel which always operates head-to-wind, the intake will be forward facing and reasonably high up. For details of Air Filtration Systems and related hazards see Section 5.10.

Exhaust System

The hot exhaust gases from the turbine must be ducted to a safe place; this is done through large bore insulated ducting fitted with a silencer. Heat may be recovered from a heat exchanger mounted in the duct. The siting of this exhaust must bear in mind operations, which may take place in or down-wind of the plume. Examples are “monkey board” operator in the derrick, helicopter approach and crane operator. Items hung in or lifted through the plume may actually be damaged by the heat.

The exhaust duct will have high temperature lagging, and it is in general not safe to operate with any of this lagging removed. A leak in the ducting could cause a hot spot at some distance away, as the gas finds a weak spot in the lagging. Any bellows should be subject to periodic inspection.
3.1.7 INTEGRATION ASPECTS

Gas turbines are supplied as standard units tailored to customer requirements. The customer does not have significant influence over the detail design or testing of the internal components. The customer’s main input is to ensure that the interconnections and services are correctly designed. Safety information provided by the operator will have been sourced from the manufacturer. Hence there are a number of very similar units in place with different operators. Common knowledge is held by the manufacturer, also “user groups” of operators have been set up to share experience and pressure the manufacturer to solve known problems, usually of component reliability.

3.1.7.1 Filtration / Cleanliness

Gas Turbines consume colossal quantities of air and act as very effective centrifugal and impingement air filters. Ingested solids will build up inside the compressor, reducing efficiency and causing eventual failure. An efficient inlet filter takes out virtually all dirt and salt spray, provided it is maintained. It is normal practice is to shut down the turbine periodically and wash the compressor with a mix of de-mineralised water and special detergent. It is vital that the dirty wash water is drained away and does not re-deposit the dirt in cooling air passages. This could have the effect of throwing the turbine out of balance, or burning out parts of the machine. Some machines can do an on-line compressor wash, which defers (but does not avoid) the shut down wash.

Dirty fuel is likely to damage combustor nozzles, causing uneven combustion, combustor damage and hot spots. In the worst event fuel trip valves may jam, causing control problems and possibly an overspeed event. If the fuel is known to be dirty, improved filtration and trip valve testing may be called for, although the best solution is improved fuel quality. Tars in suspension may pass through a filter and then deposit in hot or stagnant areas.

Due to the small clearances and tiny cooling passages, any debris getting into the turbine during maintenance is a serious matter, casings and covers should never be left open and loose materials like lagging, cleaning cloths, carefully controlled. It is a mark of a good operating / maintenance culture that an operator or fitter would admit to possibly dropping something, and offer to search for it.

Good inspection procedures, including formatted reports and photographs, can indicate the trend of cleanliness (and other machine conditions) with time, and should be encouraged.

3.1.7.2 Mechanical Integrity

The rotor sections of gas turbines spin at very high speeds and are of relatively light construction. Different assembly techniques are used, according to the manufacturer, and special tools and inspection techniques are required. Use of wrong tools (e.g. impact rather than torque) can crack or dent fasteners. Fretting or damage to assembly bolting can be serious, and damaged components should be replaced as a complete set. The rotor balance must be checked after any work, which potentially could affect the balance. Changes in balance with time suggest either changes in geometry (e.g. thermal "ratcheting" of joints) or deposit of solids, and should be investigated. Spare rotors should be stored in manufacturer's original packaging (or agreed storage system) under their recommended conditions. Storage locations subject to vibration are likely to cause problems.

Stator sections are subject to high temperatures and internal pressure, so the fastening systems must be in good order and tightened according to the approved method. It is not practical to do hydraulic strength testing of stator sections in the field, so good inspection processes will be the main check of component condition. Components in the combustor and its ducts are subject to cracking and corrosion, especially on units subject to frequent starts / major load changes.
3.1.7.3 Condition Monitoring

The condition of the machine may be checked by inspection during shutdowns, access ports are normally provided for endoscope (optical fibre telescope) examination, special design eddy current probes can be used to check blade condition. Photographs & consistent records will help with trending. Cleanliness / effectiveness of cleaning can be monitored in the same way.

Oil condition can be monitored on-line, good oil analysis can identify bearing and gear problems, cooling problems as well as gross problems like water ingress. Water, in particular, can cause serious bearing damage by promoting lubrication breakdown.

Vibration monitoring, in particular by trending, can identify a range of machine problems. For details of Condition Monitoring Systems and related hazards see Section 5.12.

3.1.7.4 Protective Systems

Systems providing alarm only action should be subject to periodic testing. However delays to such tests, or known calibration errors, do not cause a direct safety risk and can be managed. Trending of the data prior to an alarm coming in can give valuable pre-warning; intelligent use of combined trends can indicate developing fault conditions. (E.g. drop in active thrust bearing pad temperature and rise in inactive pad temperature indicates a reversal of normal thrust loads - may be a blockage or leak in thrust balance gas passages).

Temperature, flow, pressure, vibration trips. These are all safety protective systems requiring tests and, vitally, validated return to operation after test. Trip test procedures must be validated and adhered to. Trips may be disabled during machine start - ideally the measured values are recorded at high sample rates during a start, for examination should there be a problem. Also the enabling process must be validated - particularly on a new machine or after software / instrument modifications. Failure of a single trip is not likely to lead to an unsafe condition - a problem is likely to be detected in several different ways, and the machine tripped before a dangerous condition is reached. There may be some internal damage e.g. to a bearing.

Over-speed Trips. These are different in nature, as the signal they measure is normally very stable (particularly for electrical generator service), yet dangerous overspeed can be reached within seconds of a load trip. Hence the use of voting systems with sophisticated self-test systems. No compromise can be accepted in the operability of these systems, although it is usually possible to continue to operate with one failed speed sensor due to the available redundancy of the system for a limited time. The decision to permit this should be recorded in the operating instructions. The trip action must be rapid and complete (closing of fuel valves). Two independent trip valves in series should be the norm, to minimise common mode failures. Testing procedures should permit testing of parts of the system independently, full blown overspeed trip trials should be restricted to the absolute minimum number of proving tests because of the stress they put on the equipment.

Use of software trip systems. While it is recognised that the reliability, cost-effectiveness and sophistication of modern digital control systems mandates their use for the management control of complex plant equipment, the risk of common-mode failure must be assessed. Key trips (e.g. overspeed) should therefore be based in separate modules, with fail-safe operation and stringent controls on software changes. The design must be based on the principle of: - Loss-of-signal or power trips the fuel. Software systems may offer advantages because of their ability to monitor the health of key sensors, and report problems prior to a failure.
3.1.7.5  **Bearings**

The bearings in gas turbines are dependent on a continuous supply of oil for lubrication and, more importantly, cooling. Generally, oil must be pressure-fed prior to machine start, and continue to flow for a cooling period after shutdown. Hence a selection of oil pumps, driven by AC power, machine shaft, DC battery, or UPS supply. Post-shutdown flow requirements are lower and can be met by a smaller pump. Oil quality in terms of grade, cleanliness, low moisture content, temperature and adequate flow, are vital. Oil grades, even "equivalents", should not be mixed without draining the complete system.

Rolling element bearings - Aero-derivative Gas Turbines.

Aero gas turbines use rolling element bearings for the main shafts, aero-derivatives follow the same practice. Rolling element bearings are lighter and require less lubricant. They do, however, have a fatigue life and are vulnerable to impact loading & contaminated oil. For details of Bearings and related hazards see **Section 5.9**.

3.1.7.6  **Cooling (External)**

The main obvious external cooling requirement on a gas turbine is the lubricating oil; this can be cooled against air or water. Loss of cooling effect normally results in a controlled trip with no safety implications. A cooler tube failure can be more subtle - air cooled tube failure can spray oil mist causing a fire risk, water tube failure can contaminate oil causing rapid bearing failure. The cooler design should permit tube inspection / testing, corrosion resistant materials must be used, and gasketed water to oil joints avoided.

A less obvious cooling need is the acoustic enclosure ventilation. This serves to limit temperature rise within the enclosure. Should the flow be blocked or channelled, some areas of the enclosure may overheat. If unsuitable materials have been used, or lagging becomes soaked with oil, equipment damage or fire may result. Acoustic enclosures are not convenient weatherproof stores for toxic or flammable chemicals. Operating instructions must cover the issues relating to access to the enclosure, and as to whether the access doors may / must be left open when someone is inside, or at any other time.

The acoustic enclosure ventilation air must be drawn from a safe location i.e. with a low risk of drawing in hydrocarbon, toxic or corrosive gases. Exhaust air should be vented to an unoccupied location as it could contain leakage gases and in extreme events a flammable mixture. For details of Cooling Systems and related hazards see **Section 5.11**.

3.1.7.7  **Sealing**

**Gas sealing**

This is fairly simple, and the use of labyrinth seals throughout is normal. Clearances will be checked and recorded at overhauls. To permit thermal expansion, static seals may use metal bellows. These will require to be inspected. Failure of seals may lead to unexpected temperatures / pressures in parts of the unit, not designed for it. For details of Gas Seals and related hazards see **Section 5.3.2**.

**Oil seals**

These will be primarily labyrinth seals, with lip seals on ancillary equipment. The seals only work effectively if oil levels & flows, and ventilation air pressures, are satisfactory. Hence the lubrication system ventilation is important. Oil return pipes will often have 2-phase flow, any modification should be of appropriate design to ensure ventilation and avoid the creation of traps or lutes which can promote slugging and collect sludge.
Where an oil seal failure could lead to oil being thrown on to a hot surface, some form of secondary containment, to deflect or collect the oil, should be in place. For details of Oil Seals and related hazards see Section 5.3.5.

3.1.8 CONTROL

- **The control system for the turbine should be self-contained and not dependent on external signals or supplies for safe operation.**
- **The trip and alarm facilities should be subject to a formal change control process.**
- **The operators require a clear understanding of start up procedures including which alarms/trips are over-ridden during start, and why.**
- **The control system will initially be configured to suit the intended duty of the machine; this should be subject to review should the duty pattern change.**

The control system for the turbine should be self-contained and not dependent on external signals or supplies for safe operation. All trip functions / valves should go to safe condition on loss of power or signal. Battery or UPS systems may be in use to provide ride-through of a power failure, if these should fail the turbine must trip. If this means loss of post-cooling or post-lubrication, the turbine may be damaged but no safety issues raised. For failure analysis purposes, it is advantageous for some form of battery-backed data & event recording system to be fitted. After any failure, obtaining a secure copy of this data is a high priority. If an investigation is instigated several days after an incident, the data will probably have been overwritten.

The trip and alarm facilities should be subject to a formal change control process, with clear definition of which (if any) changes may be made without manufacturer approval. Similarly the manufacturer's (or other) service engineer should not be permitted to change settings or software without formal record. Access to settings is often by key or password, however the segregation of which items may be changed without formal approval, and those which may not, is often missing.

The operators require a clear understanding of start up procedures, for example which alarms/trips are over-ridden during start, and why. Test procedures are required to validate that the important trips are re-enabled at the correct time. Formal testing and recording of alarm / trip tests, at intervals defined by or agreed with the manufacturer, are required. If tests are done with the machine on line, it must be recognised that the trip is disabled during the test, and that a partial test only is possible.

The control system will initially be configured to suit the intended duty of the machine. Should the duty pattern change significantly, the control system may have to be re-configured to achieve effective results. Frequent spurious trips or difficulties during start / stop might indicate a problem in this area. Abrupt trips during warm-up are particularly stressful, particularly as there will be strong interest in a rapid re-start, without waiting for the unit to cool.

The control system in most cases will be "standard", supplied by the gas turbine manufacturer. There may be a number of "tailored" standard options and add-ons. These will normally be readily compatible with the standard kit & understood by service staff. It is unwise to specify non-standard control equipment except for a very good reason - it will be necessary to carry spares and train personnel to service and maintain the panel through out its lifetime, as vendor's
service engineers will have difficulty in supplying these to the facility. The vendor may offer a choice of control system options, particularly if a technology upgrade is in hand. The dilemma will be whether to stay with the "proven" system and perhaps be forced to convert in a few years' time, or accept the risk of teething problems with a new system, which will in time become the standard. The key requirement is to obtain contractual commitment to maintenance support of the selected system for a realistic number of years.

3.1.9 ACOUSTIC ENCLOSURES

- The primary purpose of the acoustic enclosure is to protect personnel from high noise levels.
- The design of the enclosure should permit necessary safe access to the turbine, while preventing casual access.
- The enclosure should contain its own fire & gas system, with provision for testing, and inhibition of the system during personnel access.

3.1.9.1 Acoustic Requirements

The primary requirement is to reduce noise levels to an acceptable level outside the enclosure, such that hearing protection is not required and normal conversation is possible. Even a small opening can compromise that, so panels must fit properly & doors be kept closed. Excessive noise (except so far as it prevents people from communicating & hearing alarms) does not pose an immediate threat to safety, but will result in progressive hearing loss & subsequent compensation claims. The silencers built into the enclosure vents must be kept clear and working, the mineral wool type fill material is ineffective if soaked in liquid, or blinded with salt crystals. Oil contamination of acoustic material can pose a serious fire risk.

Figure 3.1 – 7 Acoustic Enclosure

3.1.9.2 Safe Access

Ideally, access should be prohibited with the turbine running. This may be impractical in reality. Access should always be controlled to ensure that only competent persons go in, and that they can be evacuated in an emergency. Typical operator access will require permission and a key from the control room; one operator enters while a second remains outside. Any work beyond normal operating will require a Permit to Work. Internal lighting levels should be enough to permit safe movement, and the reading of instruments.
Access with the ventilation system inactive is particularly risky due to the potential for being overcome by heat or released fuel gas. In such cases the use of breathing apparatus would be appropriate, with a lifeline and rescue plan. While it is probably desirable that the access doors be lockable or otherwise capable of being fastened, could a person be trapped inside? Good door locks include an internal handle, which cannot be locked. For details of Acoustic Enclosures and related hazards see **Section 5.4**.

### 3.1.9.3 Fire & Gas Systems

The enclosure should contain its own fire & gas system, signalling to an external panel & to the control room. Operating procedures must cover the actions to be taken on alarm - should the machine be tripped? Sending someone inside the enclosure to inspect could be risky. Similarly a fire suppression system (e.g. CO2) must not be activated if personnel are inside the enclosure. The fire & gas sensors and system should be subject to regular inspection & testing. On new or modified installations, smoke bomb tests may be appropriate to demonstrate that the sensors are sensibly located (and accessible).

### 3.1.10 ANCILLARIES

- **The range of ancillary equipment should not pose any great direct hazard, provided normal design, maintenance & inspection procedures are followed.**

- **It may be possible to service twinned ancillaries with the turbine on line. This may pose safety and reliability risks.**

- **The baseframe is an integral part of the package; the stiffness of the baseframe ensures the alignment of the machine shafts. The baseframe must be designed to suit the stiffness (or lack of it) of the supports.**

- **The lubrication system will often be built into the baseframe. Oil quality / cleanliness is vital for reliable operation. Oil leakage can pose fire and slipping hazards. Air or nitrogen purging will be required.**

- **The liquid fuel system (if fitted) may require purging, preferably by nitrogen.**

- **Main drive couplings on modern equipment should be of membrane type, which do not require lubrication or maintenance. A failed coupling can be thrown a considerable distance.**

- **Smaller ancillary drive couplings pose fewer hazards, but should still be of non-lubricated design where possible.**

- **Hydraulic variable speed gearboxes may be used as drive gearboxes.**

The range of ancillary equipment should not pose any great direct hazard, provided normal design, maintenance & inspection procedures are followed. Guarding of shafts & hot surfaces is still required, even if inside the enclosure. Additional / new guards must be designed with care, preferably after consulting the manufacturer. A guard may block a cooling airflow or provide a collection point for fuel. Particularly during system start / stop, ancillaries may start without warning. Where valve actuators and spindles are readily accessible, it may not be common practice or indeed practical to fully guard them. Consideration needs to be given to the relevant
risk of a hand or arm trap while working in such a confined space. Some form of shielding may be more appropriate than a full guard.

Where certain ancillaries e.g. filters, oil pumps, are twinned, it is possible to service or remove one unit while the turbine is on line. The operating instructions must cover the attendant risks of operating with one such unit unavailable, and the potential consequences of an incorrect changeover. One example is putting an oil filter on line without priming it, lubricating or control oil supply may be interrupted. Instructions and, if necessary, labels, may be required if changeover valves must be operated in a particular sequence, or can readily be mal-operated.

The lubrication system for the turbine will normally be built into the baseframe. Oil quality / cleanliness is vital for reliable operation although this does not directly affect safety. Oil samples should be taken for condition monitoring purposes. Access is required for filter changing, good flooring & lighting to minimise trips / slips risk. A small amount of oil on a smooth floor can pose a serious personnel hazard. The lubrication system will be purged to remove moisture and any hydrocarbon gases. The purge could be by dry air, with some attendant fire risk. A safer system uses nitrogen, with flow / pressure monitoring to confirm safe operation. The purge vents should open to safe area.

The liquid fuel system (if fitted) may be built into the baseframe, or mounted locally. There may be a requirement for a gas purge system; this should preferably use nitrogen for safety. Purge vents should open to safe area.

Main drive couplings transmit power to the driven rotating machine. Modern designs normally use flexible element membrane couplings; these transmit high power without maintenance. In certain cases (where torsional damping is required) rubber block couplings may be required. Older designs still in service may use oil lubricated gear couplings. These rely on a continuous supply of clean oil for safe operation. Gear couplings in particular may lock up and be thrown radially for a significant distance. If the coupling is within a drive housing or the acoustic enclosure, it may be contained. Coupling failure normally results in a loss of drive, this is not normally an unsafe condition.

Small e.g. ancillary drive couplings may be of appropriate proprietary design. "Dry" type e.g. flexible membrane or rubber block, are much preferred, as they do not require maintenance. Lubricated couplings will fail if maintenance is ignored. Certain drives e.g. shaft driven oil pump, should be selected to continue to drive even if the flexible coupling element fails.

It is possible to run a fixed speed e.g. single shaft turbine driving a variable speed pump or compressor. This is achieved using a variable speed gearbox, typically the variable fill hydraulic Fluid couplings. This will give a cheaper installation than using a variable speed multi-shaft turbine, but will be less efficient, due to the slip properties of the coupling.

For details of Ancillaries and related hazards see Section 5 – Ancillary Systems & Equipment.
SECTION 3.1.11 EXPANDER DRIVEN CENTRIFUGAL GAS COMPRESSOR

(TURBOEXPANDER – COMPRESSOR)

The machine duty is covered in Section 2.1.4. Mechanically the unit consists of :-

a) A central bearing housing with bearings, lubrication system, labyrinth gas seals and service pipe connections (blue in diagram below).

b) Expander housing (orange in diagram below) with radial inlet, inlet guide vanes, impeller back plate and neck ring, smoothly tapered axial exhaust.

c) Compressor housing with axial inlet, impeller back plate and neck ring, discharge volute (green in diagram below).

d) Rotor comprising shaft and two off 3-dimensional impellers

Hazards associated with Turbo expanders are in general similar to those for the barrel compressor (see Section 4.1.3). Of particular note are :-

Pressure capability of the machine, which should be the same over the turbine, bearing arrangement, and the compressor given that in event of a failure there could be pressure equalisation across the machine.

Overspeed of the turbo-expander is possible, though this is unlikely to result in loss of containment as the rotor would be expected to be retained within the machine casing. However, it is appropriate to fit emergency shut off valves to both suction and delivery to react to trip conditions from the process, overspeed monitoring, process seal condition, lubrication and bearing condition, and vibration monitoring.

The materials of construction must be able to take the mechanical loads; in addition those parts in contact with the process gas must be chemically compatible. Note that operating conditions are often well below 0 C, requiring the use of low temperature tolerant materials. Operating procedures should avoid thermal shocks and maintenance activities should avoid the creation of cracks, notches and other stress raisers which could lead to crack initiation.

There is no physical access to rotating parts, and since there is no mechanical means of controlling the shaft speed, the shaft speed monitoring system and control/trip valves are vital to the safe operation of the unit.
The expander gas inlet will have a trip valve and control valve, or one valve combining both functions. The control at the duty may be achieved using inlet guide vanes to control the flow through the expander and the speed of the rotor. In addition there may be a bypass valve to let down excess gas to the discharge. Gas Expanders are very sensitive to liquid or solid particles in the gas, some combination of separator, pre–heater and gas filter are likely to be fitted. The outlet gas will be chilled, thus there may be an after–heater.

The gas compressor will have an inlet isolation valve, possibly a suction throttle valve, certainly a recycle/ surge valve. Centrifugal compressors are also sensitive to liquid or solid particles, a separator and possibly a filter should be included in the system.
SECTION 3.2   GAS TURBINE – ( INDUSTRIAL )

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Figure 3.2 – 1   Industrial Gas Turbine ( cut-away )

3.2.1  INTRODUCTION

Compared to Aero-derivatives, Industrial Gas Turbines look more like conventional gas compressors, with horizontal split cast casings and pedestal bearings. They are thus heavier and take up more room than aero-derivatives, but can be maintained on site with less dependence on specialist tools and labour. The use of tilting pad plain bearings, duplicated oil pumps, etc., can mean very long continuous operating periods, with maintenance dictated more by condition monitoring and blade life, than fixed schedules and parts wear. This makes them particularly suitable for power generation. Due to the longer development cycles and greater emphasis on emissions control, industrial turbines tend to have a higher specific fuel consumption because of lower pressure ratios and lower turbine inlet temperatures.

Industrial turbines tend to be installed in "walk-in" acoustic enclosure "houses" which double as weather protection for the machines. This increases the physical size of the installation and also poses the issue of people working inside the enclosure.

Industrial Gas Turbines are not normally used offshore, their greater size, weight, and maintenance space requirement are all factors which favour the aero-derivative.
3.2.2 HAZARD ASSESSMENT

Hazards are similar to those for an Aero-derivative gas turbine, see Section 3.1.3. The more robust design should reduce the risk of ejected parts, but the large acoustic enclosure gives the potential that people will be at risk working inside the enclosure, and the large volume gives a potential for a larger explosion, should there be a gas release. The noise levels within the enclosure will be very high.

![Industrial Gas Turbine with Top Cover Removed (Note Axial Split Design)](image)

3.2.3 INTEGRATION

3.2.3.1 Base Load

When selecting equipment for base load operation, the buyer is looking for steady, efficient and reliable operation. This will often require machines to be de-rated to achieve long MTBF intervals. Smooth, relatively slow start-ups and shut-downs will be the norm, ancillaries will normally be spared and can be overhauled with the turbine running. Sophisticated monitoring will give the best information to permit maintenance intervention to be well-planned and of the shortest possible duration. On-line cleaning equipment may be fitted to maintain peak efficiencies.
3.2.3.2 Peaking Duty

Industrial turbine sets can be designed to meet short term power generation peaks and therefore run regularly but for short periods. Most planned maintenance can be done between demand periods, otherwise additional capacity may be leased or load peaks managed out. Start-up will be quite fast and will be automated to give consistent time-to-load. Ancillaries do not need to be spared except to provide for run-down lubrication. Running a peaking set continuously is likely to lead to frequent failures and a reputation for unreliability.

3.2.4 MAINTENANCE

Industrial turbines are designed for on-site maintenance, requiring less sophisticated tools and skills than those required for Aero-derivative Gas Turbines. Much more space is required to remove and lay down awkward shaped components; and weather protection is required for parts when exposed to prevent corrosion. The design of the installation must consider maintenance factors relating to protecting the opened equipment from debris, and disturbance by curious onlookers. A coin or displaced nut dropped into the machine can cause serious damage. Rotors will be changed as units, transported in heavy crates requiring heavy lifts. Most other spares will be in relatively small packages.
This section covers A.C. electric motors of all voltages. It describes the general features of single phase and 3 phase motors of standard construction, but not special motors that may be built into special purpose equipment.

See Appendix 1 for Electrical Terminology.
The information is referred to from other electric motor sections, to avoid duplication.  
**Section 3.4** covers Low Voltage A.C. Motors (up to 1000 V)  
**Section 3.5** covers High Voltage A.C. Motors (1000 V and above) of > 500 kW rating.

![Asynchronous L.V. Electric Motor (Cut-away)](image)

**3.3.1 INTRODUCTION**

Electric motors are very widely used as rotating equipment drivers. As they do not require either a fuel source or an energy storage system, they are simple, compact, cheap and reliable.

Alternating Current (A.C.) motors are generally used because of their simplicity, reliability and low cost. Small (domestic) electric motors up to about 2 kW are "single phase", having only 2 power wires. These generally have brushes supplying power to the rotor, and are variable (but not usually controllable) speed. Speed varies greatly with load. For high reliability duties e.g. central heating pumps, a "brushless" design is used, which requires a large capacitor as part of the system. These motors typically have a form of selectable speed control.

Direct Current (D.C.) battery powered drives are used in certain applications, mainly for emergency services and for "Black Start" purposes. ("Black Start" assumes that all power distribution systems are shut down). D.C. drives are used for certain variable speed purposes e.g. drilling, in these cases the D.C. supply is usually rectified from the A.C. power supply.

Low Voltage industrial A.C. motors above 0.5 kW are normally "three phase" having 3 power wires. These use a "brushless" design and are referred to as "asynchronous" motors, as they run close to, but not quite at, the speed determined by the supply frequency. These are covered in more detail in **Section 3.4**.
High Voltage A.C. motors (1000 V and above) are all "three phase". Smaller units are simply a development of Low Voltage asynchronous motors, but larger units tend to be of the more efficient "synchronous" design. High Voltage motors > 500 kW are covered in more detail in Section 3.5.

Industrial variable speed motors may use any of the above motor technologies combined with matching control gear. The modern approach is to use 3-phase inverter systems with near-standard industrial asynchronous and synchronous motors.

Special electronically controlled A.C. and D.C. motors are used in high technology consumer applications, in machine tools and industrial servo drives.

3.3.2 BACKGROUND & HISTORY

- Early electricity generation and motors were D.C. (Direct Current).
- These were gradually overtaken by A.C. (Alternating Current) although D.C. drives were common until late 1970’s
- Early refineries had a proportion of steam turbine drives, large drives were mostly steam turbine.
- Offshore installations use Gas Turbines for large unit drives and Generation, Diesel Engines for Emergency purposes, and electric motors for everything else.

Early electrical generation was D.C. (Direct Current) as it was easy to create local networks of generators and users. D.C. Generators and motors use high current brush gear which is maintenance intensive. D.C. motors are inherently variable speed and can be difficult to control. A.C. systems were gradually introduced because A.C. electricity can be stepped up to high voltages for efficient long distance transmission, and stepped down again for use at multiple voltages, according to requirements. Conversion between D.C. voltages has been (until recently) expensive and inefficient. It is still effectively impossible to convert to / from high D.C. voltages at useful power ratings.

Early chemical plants and refineries used steam turbines (higher power) and D.C. (lower power) for rotating equipment drives. These could be fixed or variable speed, in both cases requiring governor control. As plants increased in complexity, the simplicity and low cost of A.C. motors encouraged their selection for virtually all drives, even up to Megawatt ratings.

Modern variable speed inverter drives use basically standard A.C. motors, so the use of special variable speed motors is reducing. D.C. variable speed drives are still used for drilling applications. Many new drilling rigs, especially those designed or built in Norway, have A.C. variable speed drive drilling systems.

The question of whether A.C. or D.C. drive is the correct choice for any particular user is entirely dependent on the requirements of the individual application involved e.g. high starting torque requirement, continuous operation at low speed.

Offshore installations cannot afford the weight and size of steam raising equipment to operate steam turbines, so power generation and large rotating equipment drives (> perhaps 5 MW) will be by Gas Turbines. Emergency / Standby drives which must work during a power outage are
usually Diesel Engines although small Gas Turbines are possible. All other drives will be electric motors.

A very small number of D.C. motors, for example emergency lubrication and ventilation drives, will be powered by U.P.S. (Uninterruptible Power Supply) systems. U.P.S. and battery systems require a high level of care and maintenance to guarantee reliability.

### 3.3.3 HAZARD ASSESSMENT

- **Electric Motors are generally Low Hazard items as they do not contain Flammable Materials, also live and moving parts are well guarded.**
- **High Voltage motors are known for internal spark generation, particularly under fault or starting conditions.**
- **External surfaces should not be capable of becoming hot enough to ignite flammable materials.**
- **Mechanical damage or poor maintenance can result in mechanical rubs, exposed live or moving parts.**
- **It must be possible to stop the drive on demand, to remove the energy supply from driven equipment.**

See Section 7.2.4 for a structured set of Hazard Assessment Tables.

### 3.3.3.1 Ignition / Explosion Hazards

"Brushgear" motors (primarily D.C. and single phase A.C.) can generate intense sparks continuously when running. These motors can only be used in hazardous areas if specially designed to isolate the internal air space effectively from the surrounding atmosphere, e.g. by continuous, monitored, purge of hydrocarbon-free air. Open ventilated motors would be very hazardous, also the brushgear is un-insulated and can be shorted out by salt water.

Asynchronous A.C. electric motors, as normally installed on oil & gas installations, should have no exposed electrical conductors, and since there is no brush gear, there should be no spark generation in normal operation.

High Voltage (> 1000 V) motors can generate internal "brush discharges" from the rotor during starts. In addition, damaged or incorrectly built rotors can spark in normal service as internal currents jump across damaged insulation.

This is not normally a problem because the air space inside the motor is quite well sealed from the environment, and inaccessible to people. In the event of a flammable atmosphere being present external to the motor, flammable gas will diffuse through the shaft seals into the motor core, creating a flammable mixture inside. An internal spark or rub could then ignite the gas. Low voltage motors are so robustly built that the motor itself is very unlikely to come apart, although items like the terminal box cover could fail.

High Voltage motors normally have a "closed" internal air circuit, but faulty construction or maintenance can result in drawing in outside air, and any flammable gas.
Various philosophies are adopted to prevent a small internal fault from creating a major external explosion, these are codified under "Ex" motor ratings.

Motors may be purged with clean air to prevent ingress of flammable vapour.

Motors may be designed and built to minimise the risk of internal sparking.

Motors may be built to survive an internal explosion without sufficient emission of hot gas to cause an external explosion. The motor may suffer severe internal damage and cease to function.

Motors are designed such that external surfaces do not exceed specified temperatures in service. Thermistors will be fitted to larger motors. These trip the drive if temperatures rise, e.g. due to poor ventilation.

Variable speed motors may require additional consideration, for example as motors slow down, cooling fans move less air and surface temperatures can rise to unacceptable levels. Inverter drives can also increase the electrical losses and thus heat generation in the motor.

In all cases the motors have to be selected, built, installed and maintained in accordance with Electrical Safety Guidelines and local Area Classification. The ATEX Directive now covers this process.

Electric motors can also cause ignition through external rubs e.g. pulleys on steel guards. This is not covered by "Ex" classifications, but by good engineering practice & maintenance.

Portable tools and appliances are often unsuitable for use in hazardous areas. Operators normally control the use of all portable equipment, whether by their own personnel or by contractors. Tools suitable for hazardous area use are certified and tested for this purpose. Contractors normally require specific permission to use portable tools, after they have been checked for compliance.

3.3.3.2 Equipment Hazards

Electric motors are fully contained and well guarded, the risk of personal injury is very low in normal operation. Poor guarding of a drive is a possible risk.

Motors with brushgear, particularly series-wound D.C. motors, can reach dangerously high speeds if running unloaded. Other types of D.C. motors are prone to overspeed if the stator field is lost. This is particularly true if the brush and control gear is also faulty. The motor itself is likely to contain parts even after catastrophic failure, but items like couplings, pulleys, broken drive shafts, will probably be ejected at high speed. Conventional overload protection or fuses will not prevent the failure, as little power is being drawn. Only a tachometer based trip, correctly designed and fitted, can achieve this. Effective protection might be based on a trip on high or low driven equipment shaft speed. (Low speed trip is the only way to detect a drive shaft failure). This should protect against both loss of service and overspeed. A tachometer on the motor shaft can protect against overspeed only.

Poor maintenance, e.g. failure to replace guards, covers or fasteners, can give access to moving or live parts. There are legal controls over work on Explosion Proof motors. Guidance on acceptable best practice is available from BEAMA (British Association of Electrotechnical & Allied Manufacturers Association) and AEMT (Association of Electrical & Mechanical Trades). For example the AEMT/ BEAMA Code of Practice for the Repair and Overhaul of Electrical Equipment for use in Potentially Explosive Atmospheres.

Standard electric motors are not fitted with brakes and have very low friction. An uncoupled motor can take a long time to stop.
3.3.3.3 Operational / Consequential Hazards

In normal operation an electric motor should pose little threat to the safe operation of the installation.

Electric motors do require cooling, losing around 10% of their rating as heat. Low Voltage motors are normally air cooled, if this heat is not effectively removed, the environment will become uninhabitable and equipment may be damaged or shut itself down. Heat removal is normally by simple ventilation (which can draw flammable gas into the enclosure) although air conditioning may be used.

High Voltage motors may be water cooled, making them suitable for operation in ambient temperatures between 0 and 50 C. Sub-zero operation requires anti-freeze.

It is vitally important that a motor can be stopped on demand, whether as a normal operation or by a trip system. This requires that the key electrical components be of adequate quality, and correctly installed, to give reliable operation. Emergency stop and trip systems should be subject to periodic inspection and test, and modifications only permitted according to company change control procedures. High voltage motor stop systems can be more complex than low voltage, having separate "start" and "stop" circuits.

Electrical sequence controls and running/ stopped indication are normally based on the control circuit and detect if the contactor is open (stopped) or closed (running). This does not actually indicate that the motor has power or not, still less whether the motor and driven equipment are both rotating or stopped. Intelligent use of the ammeter (where fitted) can be very informative, but the only true check is the use of a tachometer on the rotating equipment shaft. With PLC and DCS controls it is very simple to set up a simple tachometer that confirms that the shaft is running above a specified speed. For pump or compressor operation, that speed might be 90% of nominal speed. If a true stop check is required, e.g. for switching off oil or coolant pumps, a speed of 1 rev/min can be set. Note that analogue equipment is not trustworthy for such speed checking duties, particularly if fitted with a manual potentiometer.

Electric motors deliver as much power (basically as shaft torque) as the driven equipment demands, even if this causes damage. Overload systems are generally basic and provide nominal protection to the motor only. More sophisticated equipment is required if the driven equipment must be protected.

Pumps and compressors are generally tolerant to speed variations caused by power system voltage or frequency changes. If a particular drive requires very accurate speed control, inverter driven variable speed drive can give this accuracy over a range of speeds.

If a variable speed drive is installed, over (or under)-speed is possible under fault conditions or due to human error. If this is important for safety or operational reasons, additional protection or control measures may be required.

No electric motor (and in particular its control and switch gear) can be 100% reliable. If 100% reliability of a service is required, some form of redundancy and monitoring will be required. The ideal being some form of totally independent supply. There is, however, virtually nothing more reliable than a Direct on Line A.C. electric motor drive.

3.3.3.4 Maintenance / Access Hazards

Electric Motors may be located inside acoustic enclosures, or in locations with no safe fixed access. They are quite heavy (see Nameplate for weight). Rigging points will be provided. Motors should be lifted with care, using approved procedures and lifting equipment. The driven equipment or package vendor's instructions should be checked for arrangements to release couplings.
It is vitally important that the electrical isolation of the equipment is assured prior to the removal of any covers. Normally the isolators will be locked off and the fuses removed, under the control of the installation Permit to Work system. Preferably a responsible member of the group who are to work on the motor will see the fuses removed, or be told in person by the electrician who removed the fuses. Similarly, replacement of fuses, and any associated tests / checks, will be under the PTW and, preferably, by personal contact.

Care must be taken to ensure that the correct item of equipment has been identified on the PTW and then isolated. Identification labels on equipment and switchgear should be double-checked, personal communication is valuable as a cross-check, and it is imperative to carry out voltage and earthing checks on exposed conductors before handling them. Conductors should be assumed to be live until proven to be dead. On smaller drives it should be standard practice to carry out a test start, where practicable, both before and after isolation. Obviously, a successful start after “isolation” is a serious safety incident and requires investigation.

If the entire package has not been shut down, adjacent equipment may not have been isolated or may even be running.

3.3.4 OPERATING REQUIREMENTS

- Electric motors are very tolerant of variable operating loads, but must not be started too frequently.

Standard electric motors cannot tolerate too frequent starts, in particular they must be allowed to stop before re-start. Small motors are typically rated 10 starts per hour, very large motors may be limited to 2 starts per hour. Special motors for e.g. Cranes, can tolerate frequent starting, and may be fitted with brakes.

Standard Low Voltage motors can work in any orientation and while being moved, within limits particularly on acceleration and impact. Standard motors can be run in either direction, but some high efficiency motors must rotate in one direction only, or they will overheat. The most benign operating pattern is continuous operation, motors are very tolerant of load and even speed changes, within the design range. Motors can operate for long periods without maintenance, subject to routine lubrication, cleaning, condition monitoring as required.

H.V. motors work in fixed berths and have operating limits on tilt and acceleration. These limits will be defined by the manufacturer.

Motors can tolerate long periods out of service (e.g. on stand-by) but ideally should be run periodically, protected from salt spray, and in particular protected from high-frequency vibration. This vibration can cause bearing damage (“brinelling”). Electric heaters are fitted to prevent internal condensation.
3.3.5 MAINTENANCE REQUIREMENTS

- Asynchronous motors require very little maintenance. Specialists must be employed for major work.

- “Brushgear” motors do require periodic inspection and maintenance of commutator and brushgear.

- Large motors, especially H.V., require periodic lubrication, internal inspection and cleaning.

The only routine maintenance is cleaning, inspection and lubrication. Otherwise motors or major component parts must be removed to workshop conditions. Smaller motors can be lifted complete but for larger units it is more practical to remove components.

Most motors have grease lubricated bearings. Small motors have greased-for-life bearings. This “life”, as defined by the manufacturer, may be as low as 25 000 hours. For these motors, periodic specialist overhaul and bearing replacement based on hours run, is a practical policy. For larger motors, grease nipples and relief devices should be provided, as routine re-lubrication will be required; this can be done in service. Only the correct amount of grease should be charged. Unless grease relief devices are fitted, over-lubrication is a significant problem. Larger H.V. motors will have oil lubricated bearings, typically roller bearing cartridges with an oil feed from the driven equipment oil console.

Note that, although the direction of rotation is determined by the wiring connections in the terminal box, after overhaul or maintenance work these connections may have been altered. Hence every electric motor going back into service must have a direction of rotation check carried out before coupling to the rotating equipment.

It is a good policy to paint shop overhauled motors a different colour from new build. Maintenance records must be updated.
3.3.6 ELECTRIC MOTOR – MAIN COMPONENTS

- The stator carries electrical windings to drive the motor.
- The rotor is driven by the magnetic fields generated within the stator.
- Most motors have rolling element bearings. Large motors may have plain bearings.
- Cooling air is moved by very simple fans.
- Motors with brushgear are electrically more complex.

Figure 3.3 – 3 Asynchronous Motor (dismantled)

The standard construction of Low Voltage Industrial Motors is Totally Enclosed Fan Cooled (TEFC). The internal air does not exchange with outside air except via narrow air gaps along the shaft. Internal and external cooling air circulation is by simple shaft mounted fans. "Open" motors have a through flow of air and are not suitable for most industrial applications.

See Section 3.3 for more specific coverage of industrial asynchronous motors.
Larger High Voltage motors may be of a different, “frame”, construction. The principle is the same. See Section 3.5 for H.V. Motors > 500 kW.

3.3.6.1 Stator

The main body of a low voltage electric motor comprises the stator and 2 end caps. The stator has the mechanical purpose of supporting the windings, and locates the end caps. It consists of a pack of thin metal laminations inside a tubular casing made of Cast Iron, Aluminium or Mild Steel. The metal laminations are made of a special steel alloy called “soft iron”. Insulated copper wires are wound into shaped coils and bonded into slots in the laminations. The coils are connected to the terminal box, forming the electrical circuit of the motor. A set of thermistors (normally 3) is buried inside the coils to detect over-temperature. These are connected (via the terminal box) to an external trip amplifier.

Most of the heat generated in the stator is conducted to the outside casing of the motor, which has axial cooling fins.

The stator carries the mounting feet (normally a cast block) and the terminal box(es). Terminal box(es) are typically of cast metal and provide sufficient space to gland off and terminate supply power and signal cables. “Ex” rated motors for hazardous areas have special heavy duty terminal boxes.

“Brushgear” motors (mainly on D.C. service) have an extended rear stator cap to provide room for the brushgear. Access is provided via cover plates over holes in the sides of the cap. These covers must be secure and well fitting, as they access live and moving parts.

3.3.6.2 Rotor

In asynchronous motors, the rotor consists of a carbon steel shaft running in two rolling element bearings, fitted with a “squirrel cage” element made of soldered copper bars fitted through “soft iron” laminations. When the power supply is switched on, magnetic fields in the stator “rotate”, creating “rotating” fields in the rotor. These create eddy currents in the squirrel cage, applying torque to the rotor. Torque is proportional to the slip speed between the stator magnetic field, and the rotor, up to the overload limit. Heat is generated in the rotor. This has crude fans built into the ends of the squirrel cage, circulating heated air against the cooler surfaces of the end caps and stator. The Drive End of the rotor extends beyond the casing, and is shaped and keyed to carry a coupling, pulley, etc., Special shaft ends are available for direct-coupled pumps. The Non-Drive End of the rotor is fitted with the External Cooling Fan.

In D.C. or A.C. motors fitted with brush gear, the rotor has a set of wound coils instead of the “squirrel cage”. The coils are powered via carbon brushes, spring loaded into contact with a rotating slotted copper ring on the rotor. The ring, the “commutator” is connected to the coils. By controlling the current to rotor and stator, variable speed in forward or reverse can be achieved. The speed of these motors is very sensitive to load torque, unless some form of speed governor is fitted. This normally requires the use of control circuits within the power converter equipment to maintain the speed/load characteristic.

Because of mechanical wear and electrical arcing, brush gear requires frequent maintenance to achieve a reasonable reliability.

High Voltage “Synchronous” motors are covered in Section 3.5
3.3.6.3 End Caps

The End Caps are cast metal dishes, usually of the same material as the tubular casing part of the stator, and carry the shaft bearings. The End Caps are bolted to the stator. In Flange Mounted motors the Drive End cap carries a spigoted mounting flange.

3.3.6.4 Bearings

Rolling element bearings are pressed into the end caps. Simple labyrinth seals exclude dirt and water. Normally the NDE bearing is axially located, the DE bearing has some axial float.

Small motors, e.g. tools and electrical appliances, have simple self-aligning bush bearings. They may be sintered or have felt pads, to retain some lubricating oil. Excess oil will normally find its way into the adjacent brush gear. This can cause excess sparking, smoke, and occasionally a small fire.

3.3.6.5 External Cooling Fan

A simple fan is fitted to the NDE of the motor shaft. This draws air in through a perforated grille, and blows it out along the cooling fins on the stator.

Small tools and appliances have a single fan drawing air through the body. As they also usually have brush-gear, they are not generally suitable for use in hazardous areas.

See Section 3.5.6.5 for the more sophisticated cooling system on large H.V. motors.

3.3.6.6 Starter, Inverter & Control Systems

All motors require switchgear to start and stop them. Generally there is a mechanically operated switch (the "isolator"), an electrically operated switch (the "contactor"), a set of fuses and an overload trip device. Most industrial motors are simply switched on (referred to as "Direct on Line" starting) although a range of reduced load starting devices exist.

Motor fault detection devices e.g. thermistors, phase fault relays, will be linked to a trip relay which will release the motor contactor.
Inverters are modern electronic devices that generate synthetic A.C. at a controlled frequency. This A.C. can then be used to make a standard or near-standard motor behave as a variable speed drive. Motor and inverter unit must be compatible. The inverter units cannot normally be installed in hazardous areas and are usually located in switch houses. Inverters generate heat and require cooling. A.C. motors with integral inverters are now available, in a limited range of sizes.

### 3.3.7 INTEGRATION ASPECTS

Most A.C. motors are supplied off the shelf as standard units. Generally the supplier will select the appropriate motor, given the range of duties, but it is much better if the client or contractor's rotating equipment and electrical engineers are consulted. Hazardous area requirements are fundamental, as these safety features cannot be added afterwards.

Certain types of drive have particular characteristics, which must be recognised. Large centrifugal compressors and fans take a long time to start, this may exceed standard overload design limits. Reciprocating compressors can have a rapidly fluctuating torque characteristic that may cause problems with other machines on the same power net.

Any inverter drive can produce harmonic signals that can impact on control systems or damage electrical equipment. The larger the drive, the bigger the potential problem. Use of inverter drives requires the active input of a competent electrical engineer.

A "Soft Start" is a form of inverter drive that is only used for a short period to start the motor. The soft start can be set up to turn the shaft very gently for a few seconds, before accelerating to full speed. This is of particular benefit if there is any possibility of the motor or rotating equipment being partially or completely stalled or seized, as it checks for free rotation before applying full torque.

#### 3.3.7.1 Cleanliness

TEFC motors can cope with a moderate amount of dirt. If the fan intake grille is obstructed, or the cooling fins covered with lagging debris or similar, the motor will overheat. Provided that thermistors are fitted and working, the motor will be tripped and no damage will be done.

In particularly dirty locations, it is possible to duct a supply of clean air to the motor, which is then enclosed in a shroud. The motor starter should be interlocked to the supply fan, or an air flow switch.

#### 3.3.7.2 Mechanical Integrity

Electric motor rotors turn at relatively low speeds and are contained within massive housings. Ejection of parts is very unlikely. It has been known for an electric motor to become completely detached and fall on the floor, while still running.

#### 3.3.7.3 Condition Monitoring

Vibration monitoring, in particular by trending, can identify a range of machine problems. For details of Condition Monitoring Systems and related hazards see Section 5.12.

Specialist electrical test equipment can be connected to running motors, and can be used to detect a range of electrical and mechanical problems. A high level of interpretative skill is required. Routine use of this equipment cannot normally be justified, symptoms like overheating or strange noises will prompt further study.
3.3.7.4 **Protective Systems**

Motors are protected against, typically, short circuit, overload and overheating by devices fitted in the starter cabinet.

Inverter drives carry this protection plus a number of more sophisticated checks on the electrical supply.

3.3.7.5 **Bearings**

The bearings in Low Voltage motors are fully self-contained.

Certain rare motors of larger size are not fitted with thrust bearings, but rely on the thrust bearing in the rotating equipment. This is not a problem provided that it is properly understood. Uncoupled rotation checks may be prohibited. Shaft axial position must be checked against a marker when fitting the coupling.

3.3.7.6 **Cooling (External)**

Certain special motors do not have a shaft driven external fan, and are cooled by an external motor driven fan, or by a ducted air supply. The motor must be interlocked to prevent operation without the cooling supply.

3.3.7.7 **Sealing**

TEFC motors have simple labyrinth shaft seals, they should be reasonably dust tight and hose proof (IP55) but are not gas tight. It is good practice to set up terminal boxes and cable glanding to avoid water ingress down the cable. Terminal boxes are not isolated from the motor internal air space.

3.3.8 **CONTROL**

- *The motor will be controlled as part of the package.*

Electric motors are controlled as part of the package in which they are installed. In very simple installations the control will be a manual push button station.

3.3.9 **MOTOR RUNNING SPEEDS**

The section briefly describes how to determine the normal running speed of an electric motor. In all cases the nameplate should carry this information. A motor running well off this speed is probably faulty.

*“Brushgear” motors.*

The brushgear acts as a supply switch, energising the rotor coils at the correct time to make the motor drive. Hence this type of motor does not rely on the supply frequency to determine its speed. The motor will be designed with a particular supply in mind, connection to the wrong supply, particularly the wrong voltage, can give unpredictable or dangerous effects. The working speed range will be limited by the electrical and mechanical design, typically such motors
deliver a nominal power, and are matched to a driven item requiring that power. Speed control may be simple, by switching resistors into part of the circuit. A car heater fan is a good example of simple speed control of a D.C. motor. More complex speed control uses a tachometer and electronic switching, as used in modern washing machines, power tools.

Brushgear motors give full torque at zero speed, making them suitable for lifting systems e.g. cranes. Such duties are prone to over-heating.

Special industrial machines may use multiple brushgear assemblies, switching in and out of windings, or load resistors, to achieve speed control. This type of equipment is now being replaced by inverter drives, which are simpler and much more reliable.

**Asynchronous motors.**

These motors contain 3 sets of coils, energised progressively and sequentially by being connected to a 3-phase mains A.C. supply. The progression of the field energisation rotates around the stator, this generates progressively rotating magnetic fields. These fields interact with magnetic fields in the stator, applying drive torque. Since the drive torque is related to the slippage between the field rotation and the rotor rotation, the rotor runs more slowly than the field. This “slip” increases with torque until a limit is reached, the motor stalls and the rotor stops. This causes no mechanical damage but the motor will overheat unless it is tripped by the overload device.

The stator carries pairs of “poles”, these are the blocks around which the coils are wound. The nominal running speed of a motor is the supply frequency in Hz, multiplied by 120, divided by the number of poles (always an even number! ). Hence a 2 pole motor on 60 Hz supply has a nominal speed of 3600 rev/min. A 6 pole motor on 50 Hz supply will have a nominal speed of 1000 rev/min. The light running speed will be very close to the nominal speed. The full load speed, as given on the nameplate, will typically be 2 – 3 % slower. Asynchronous motors cannot be driven faster than the nominal speed.

Drives with power recovery capability, e.g. fitted with power recovery turbines, can sometimes run faster than the nominal speed if the power recovery exceeds the power demand. In this case the motor will act as a brake. Switching off the motor will permit the shaft to run faster, with potential overspeed. Switching the motor back on, particularly with a large drive, will probably blow the fuses. Such drives require an overspeed protection device on the power recovery turbine shaft, linked to the trip valve.

Single phase “brushless” motors, e.g. domestic central heating pumps, are 3 phase asynchronous motor designs fitted with, typically, a resistor-capacitor network to generate a pseudo-3-phase supply. Switching of resistors alters the set speed. These drives are only used at small powers as the network generates out-of-phase currents that can affect other consumers.

**Synchronous motors**

Large H.V. motors generate a great deal of heat in the rotor, this is wasted energy and is difficult to remove. An improved design of rotor is used which is more efficient than the asynchronous rotor, and generates less heat. It is more expensive and complex than a standard rotor, hence used in high power machines where the energy saving is worth while.

The effect of the synchronous design is that the motor runs at exactly the nominal speed, with no slip. The only effect of torque changes, up to the torque limit, is that the rotor angle changes slightly relative to the supply frequency. One important feature of these motors is that fluctuations of the supply frequency will be reflected immediately in the drive.

For mechanical design see **Section 3.5**.
## 3.3 APPENDIX 1

### Electrical Terminology

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternating Current (A.C.)</td>
<td>Electrical supply whose voltage varies sinusoidally about a zero mean voltage. Most distributed power systems are A.C.</td>
</tr>
<tr>
<td>Alternator</td>
<td>Rotating Equipment used to generate A.C. power.</td>
</tr>
<tr>
<td>Asynchronous</td>
<td>The motor is not locked to the supply frequency, but will run approx. 0 to 5 % slower than appropriate sub-multiple. A motor running uncoupled will be very close to the supply speed.</td>
</tr>
<tr>
<td>Battery</td>
<td>Electrochemical device for storing electrical energy. Batteries are a very expensive storage medium.</td>
</tr>
<tr>
<td>Black Start</td>
<td>The term used when an electrical generating unit must be able to start without any external energy sources. Always applies to Emergency Generators.</td>
</tr>
<tr>
<td>Brush Gear</td>
<td>Means of providing electrical connection to moving rotor. Low power brush gear is used for control purposes and is reliable. High power brush gear is used to power the rotor, this brush gear generates sparks, wears and requires maintenance.</td>
</tr>
<tr>
<td>Brushless</td>
<td>Motor type with no electrical connection to the rotor</td>
</tr>
<tr>
<td>CACA</td>
<td>Cooling Air internal, Cooling Air external</td>
</tr>
<tr>
<td>CACW</td>
<td>Cooling Air internal, Cooling Water external</td>
</tr>
<tr>
<td>Direct Current (D.C.)</td>
<td>Electrical supply whose nominal voltage is fixed and does not vary with time.</td>
</tr>
<tr>
<td>Direct on Line (DOL starting)</td>
<td>In this arrangement, electric motors are started by directly connecting to the power supply.</td>
</tr>
<tr>
<td>Frequency</td>
<td>The variation rate of A.C. current. Cycles per second = Hertz (Hz). European supply is 50 Hz ; American is 60 Hz. Offshore is usually 60 Hz (based on American practice ) but 50 Hz is used.</td>
</tr>
<tr>
<td>Generator</td>
<td>Rotating Equipment used to generate electricity. Loosely used for A.C. &amp; D.C., but strictly applies to D.C. generation only.</td>
</tr>
<tr>
<td>Inverter</td>
<td>Device, with no moving parts, for converting D.C. power to A.C. These are complex electronic devices.</td>
</tr>
<tr>
<td>IP Rating</td>
<td>Ingress Protection. A code for protection against dust and water. IP 22 (drip proof) is suitable for domestic applications. IP 55 (hose proof) is suitable for most industrial/ offshore platform applications. Increased protection is more expensive.</td>
</tr>
<tr>
<td>Low Voltage</td>
<td>Circuits and equipment operating at less than 1000 V</td>
</tr>
<tr>
<td>High Voltage</td>
<td>Circuits and equipment operating at 1000 V or more</td>
</tr>
<tr>
<td>Motor</td>
<td>Device (normally rotary) for converting electrical energy to motion.</td>
</tr>
<tr>
<td>Multi-Phase</td>
<td>The same principle as 3 Phase but split more ways. Always an odd number. Used for special high torque drives e.g. Ship propulsion.</td>
</tr>
<tr>
<td>Part-wind Starting</td>
<td>Some special motors have two sets of coils. Power is initially supplied to one set of coils to start the motor, then to all coils for normal running.</td>
</tr>
<tr>
<td>Rectifier</td>
<td>Device, with no moving parts, for converting A.C. power to D.C.</td>
</tr>
<tr>
<td>Single Phase</td>
<td>Two-wire A.C. power supply. The third (earth) wire, if connected, is a safety feature. Strictly, 1 phase + neutral + earth.</td>
</tr>
<tr>
<td>Soft iron</td>
<td>A special carbon steel alloy used in electrical devices. It is normally in thin sheets or &quot;laminations&quot;. &quot;Soft&quot; relates to magnetic properties, mechanically the material is hard and brittle.</td>
</tr>
<tr>
<td><strong>Squirrel cage</strong></td>
<td>An electrically conducting cage used to harness eddy currents to drive a motor. So called because of its shape.</td>
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<tr>
<td>------------------</td>
<td>-----------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Star-Delta Starting</strong></td>
<td>In this arrangement, the motor coils are first connected in &quot;Star&quot; high resistance mode, to start the drive moving. After a few seconds, the connection switches to &quot;Delta&quot; low resistance mode, for normal running.</td>
</tr>
<tr>
<td><strong>Synchronous</strong></td>
<td>The motor is locked to a sub-multiple of the supply frequency.</td>
</tr>
<tr>
<td><strong>TEFC (TEFV)</strong></td>
<td>Totally Enclosed Fan Cooled (Ventilated). The term for the basic design of most industrial motors.</td>
</tr>
<tr>
<td><strong>Three Phase</strong></td>
<td>Three-wire A.C. power supply. Each wire carries a varying voltage, the algebraic sum of the 3 voltages is zero. There will be a neutral wire (not always used) and an earth (safety) wire. Strictly, 3 phase + neutral + earth.</td>
</tr>
<tr>
<td><strong>Transformer</strong></td>
<td>Device, with no moving parts, for converting A.C. power to a different voltage. Not 100% efficient.</td>
</tr>
</tbody>
</table>

### 3.3 APPENDIX 2

**Explosion Protection and ATEX**

Electric Motors and other electrical equipment for use on process plants are marked with a set of code letters/numbers, compliant with Cenelec/IEC standards. This system has been in place for a number of years. The term "Ex" indicates that the equipment has some capability for operating in Hazardous Areas, the following characters indicate the type of protection and the limitations. The tables below provide the interpretation. More recently, the ATEX (ATmospheres EXplosives) regulations have introduced additional codings, which now apply to mechanical equipment as well. The ATEX codes are also covered below. There are, as yet, no standards for the construction and testing of mechanical equipment, to establish compliance with ATEX.
EXPLOSION SAFETY HIERARCHY (European Standard EN 1127-1)

Avoid the hazard
- Use non-flammable materials, or
- Contain the flammable materials in order to avoid the formation of an explosive atmosphere

Control the risk
If an explosive atmosphere cannot be avoided, even under abnormal conditions:
- Prevent ignition of the explosive atmosphere, or
- Control the effects of explosions to avoid damage to people and property

METHODS OF PROTECTION: STANDARDS

<table>
<thead>
<tr>
<th>Electrical equipment for gases, vapours and mists (G)</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>CENELEC EN</td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>General requirements</td>
<td>50014</td>
</tr>
<tr>
<td>Oil immersion</td>
<td>o</td>
</tr>
<tr>
<td>Pressurized</td>
<td>p</td>
</tr>
<tr>
<td>Powder filled</td>
<td>q</td>
</tr>
<tr>
<td>Flameproof enclosure</td>
<td>d</td>
</tr>
<tr>
<td>Increased safety</td>
<td>e</td>
</tr>
<tr>
<td>Intrinsic safety</td>
<td>ia</td>
</tr>
<tr>
<td>Intrinsic safety</td>
<td>ib</td>
</tr>
<tr>
<td>Encapsulated</td>
<td>m</td>
</tr>
<tr>
<td>Type of protection 'n'</td>
<td>n</td>
</tr>
<tr>
<td>Category IG</td>
<td>50284</td>
</tr>
<tr>
<td>Category MI</td>
<td>50303*</td>
</tr>
</tbody>
</table>

Electrical equipment for flammable dusts (D)

| Construction and testing | 50281-1-1 | + | + | + |

Non-electrical equipment

<table>
<thead>
<tr>
<th>Code</th>
<th>CEN EN</th>
</tr>
</thead>
<tbody>
<tr>
<td>General requirements</td>
<td>13463 - 1*</td>
</tr>
<tr>
<td>Restrictive breathing enclosure</td>
<td>r</td>
</tr>
<tr>
<td>Flameproof enclosure</td>
<td>d</td>
</tr>
<tr>
<td>Inherent safety</td>
<td>13463 - 4*</td>
</tr>
<tr>
<td>Constructional safety</td>
<td>c</td>
</tr>
<tr>
<td>Control of ignition sources</td>
<td>b</td>
</tr>
<tr>
<td>Pressurised</td>
<td>p</td>
</tr>
<tr>
<td>Liquid filled</td>
<td>k</td>
</tr>
</tbody>
</table>

*Standards in preparation - contact EECS for updates
PROTECT IGNITION SOURCES

Category of protection
(EU Directive 94/9/EC - ATEX)

Mining equipment - Group I
Category M1
Very high level of protection.
Equipment can be operated in presence of explosive atmosphere
Category M2
High level of protection.
Equipment to be de-energised in presence of explosive atmosphere

Non-mining equipment - Group II
Category 1
Very high level of protection.
Used where explosive atmosphere is present continuously or for long periods of time (Zone 0, 20)*
Category 2
High level of protection.
Used where explosive atmosphere is likely to occur in normal service (Zone 1, 21)*
Category 3
Normal level of protection.
Used where explosive atmosphere is unlikely to occur and would be infrequent and for short time (Zone 2, 22)*

Equipment Marking

CENELEC/IEC

E Ex d IIB T6 Tamb = -40°C to +50°C

Conformity with European Standard.
IEC marking omits this character.

Explosion Protection symbol
Type of Protection
Code see table above

ATEX
(EU Directive 94/9/EC)

CE Marking

EU Explosive Atmosphere Symbol

Temperature Class (Group II)
Refer to ambient of -20°C to +40°C unless indicated as above

Class T

T1 450°C
T2 300°C
T3 200°C
T4 135°C
T5 100°C
T6 85°C

Gas Group
1 Methane (firedamp) Mining only
IIA Propane Typical gases classified
IIB Ethylene according to ignitability
IIC Hydrogen of gas/air mixture
II No ignitability classification

Equipment Category
I mining
M1 - energised*
M2 - de-energised*
* In presence of explosive atmosphere

II non-mining
1 - very high protection
2 - high protection
3 - normal protection

Type of explosive atmosphere (Group II)

G Gas vapour mist
D Dust

Zone
Zone

0 20
1 21
2 22
SECTION 3.4 - LOW VOLTAGE ELECTRIC MOTORS

CONTENTS

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3.4.6 Electric Motor – Main Components......................................................................Page 3.4 – 5
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3.4.8 Control..................................................................................................................Page 3.4 – 6

This section covers asynchronous A.C. electric motors on voltages below 1000 volts. It covers single phase and 3 phase brushless motors of standard construction, but not special motors that may be built into special purpose equipment.

To avoid unnecessary duplication, generic remarks in Section 3.3 will not be repeated, but are referenced. See Section 3.3 Appendix 1 for Electrical Terminology

3.4.1 INTRODUCTION

Low Voltage A.C. electric motors are the most widely used industrial rotating equipment drivers. They are chosen because they are simple, compact, cheap and reliable. They do require a distributed power system, this is available on virtually all except the most remote installations.

Most Industrial Low Voltage motors are "three phase" having 3 power wires. They are referred to as "asynchronous" motors, as they run close to, but not quite at, the speed determined by the supply frequency. "Brushless" single phase motors are available, these are physically the same as three phase motors but have a special electrical arrangement to permit operation from a single phase supply.

Figure 3.4 – 1 Vertical Flameproof Motor on Pumping Duty
3.4.2 BACKGROUND & HISTORY

- **A.C. motors have been the standard industrial drive since the 1960’s.**
- **Higher power and higher voltage drivers have been progressively developed.**
- **Recently there have been significant improvements in efficiency and reduced noise.**
- **The basic design principle has not changed.**
- **Very recently, integral inverter drives have been developed in a limited range of sizes.**

Led by refineries, chemical plants and other industrial users, A.C. motors have been the standard industrial drive since the 1960’s. They steadily replaced steam turbines and D.C. motors despite not having a built-in variable speed capability. Low cost (capital and running), simplicity and high reliability were all factors in the change.

Progressively higher power motors have become available, this led to the development of High Voltage motors for more efficient operation of higher power units.

Increases in energy costs since the late 1970’s, and concern about noise-related hearing loss, has led to the development of quieter and more energy-efficient motors. The two improvements are related, as more efficient motors require less cooling, and the cooling fan is a major noise source. Motors have also become more reliable as manufacturing quality processes improve.

The basic design principle has remained unchanged, although materials and manufacturing methods have changed.

More recently, inverter drives have become available to cover the whole range of low voltage A.C. motor duties. Small sizes are “off the shelf”, larger sizes are made to order from catalogues. There are still a few traps for the unwary when selecting inverters, intelligent dialogue with a competent supplier is required. Combined with CE marking issues, packaging of driver, inverter, control system and rotating equipment by one supplier, is a sound policy.

3.4.3 HAZARD ASSESSMENT

Hazards associated with electric motors are covered in general in **Section 3.3.3.**

The material below is specific to Low Voltage industrial A.C. motors.

3.4.3.1 Ignition / Explosion Hazards

Low voltage electric motors should have no exposed electrical conductors, and since there is no brush gear, there should be no spark generation in normal operation.

In the event of a flammable atmosphere being present external to the motor, flammable gas will diffuse through the shaft seals into the motor core, creating a flammable mixture inside. An internal spark could then ignite the gas.
If this happened in a standard motor, the explosion could propagate outside the motor, causing a major explosion. Low voltage motors are so robustly built that the motor itself is very unlikely to come apart, although items like the terminal box cover could fail.

In areas assessed as Hazardous, only appropriately rated Hazardous Area motors should be used. Any work on these motors must be by competent persons, to maintain the protection.

There are a number of special categories, the common ones are :-

Ex N – (Type N non sparking). These motors are suitable for use in Zone 2 (low risk) areas.

EEx d – Flameproof. These motors are suitable for use in Zone 1 (high risk) areas subject to the appropriate surface temperature limits for the potential hydrocarbon gas involved. The motors work on the principle of containing an internal explosion.

EEx e – Increased Safety. These motors are suitable for use in Zone 1 (high risk) areas subject to the appropriate surface temperature limits for the potential hydrocarbon gas involved. The motors work on the principle of preventing an internal explosion. They have a more limited application range than EEx d.

EEx p – Purged. These motors work on the principle of a monitored purge of Nitrogen or clean air.

Note that the term “intrinsically safe” applies to the use of very low voltages and currents and cannot apply to industrial electric motors. “Intrinsically safe” instrumentation might be used on a drive motor.

3.4.3.2 Equipment Hazards

Due to the fully enclosed construction of industrial motors, there is very little risk except for overspeed potential relating to variable speed drives, power recovery turbines or reverse runaway of pumps or compressors. In all cases the rotating equipment and drive coupling will pose a greater hazard than the motor.

Some commercial electric motors of American manufacture permit hand contact with the rotor via open cooling slots (IP 22 design). These motors are not suitable for industrial applications except perhaps inside weatherproof acoustic enclosures. Even so, additional guarding is required.

3.4.3.3 Operational / Consequential Hazards

Low Voltage Electric motors do require cooling, losing around 10% of their rating as heat. Such motors are air cooled, if this heat is not effectively removed, the environment will become uninhabitable and equipment may be damaged or shut itself down. Heat removal is normally by simple ventilation (which can draw flammable gas into the enclosure) although air conditioning may be used.

If it is important that the drive continues to run, because it supports an important or safety-related service, then monitoring (of the continued provision of the service) is required. It may be appropriate to have one or more standby systems, powered by different energy sources, and switched in automatically or manually, according to criticality. In the ultimate, several sources in parallel, all running. The most crucial attribute is the avoidance of common mode failures e.g. all controls go via a single manual switch.
3.4.3.4  Maintenance / Access Hazards

Low Voltage electric motors are very compact, cooling relies on a fan to blow air over a finned casing. Other than external cleaning (most industrial motors can be washed down in service), the only in-situ maintenance is lubrication, and checking of electrical connections. Obviously, for safety, the motor must be electrically isolated before accessing the connections. Surfaces may be hot to the touch but should not actually burn.

Motors may be located inside acoustic enclosures, under or among other equipment, or in locations with no safe fixed access. They are also heavy for their size (see Nameplate for the weight). The eyebolt, if fitted, may have suffered corrosion or damage to its screw thread. Motors should be lifted with care, using approved procedures and lifting equipment. The driven equipment or package vendor’s instructions should be checked for arrangements to release couplings or drive belt tension prior to attempting to move the motor.

If the entire package has not been shut down, adjacent equipment may not have been isolated or may even be running.

Figure 3.4 – 2  Typical Access Constraints
3.4.4 OPERATING REQUIREMENTS

See Section 3.3.4

Additionally, the direction of rotation of low voltage motors is determined by the order of connection of the 3 phase wires to the windings. Installation electrical practice should be to maintain rigorous use of the correct wire colour (Red, Yellow, Blue) for each phase throughout the distribution system.

Similarly, the motor manufacturer should adhere to the industry standard for the order of connection of the motor tails to the terminal box. Thus, in theory, the direction of rotation must be right every time.

It is known that overhauled motors often have incorrect wiring rotation, due to lack of care by assembler. Equipment packages often do not have a clear direction of rotation arrow affixed at the time when the motor is wired up. While it may be obvious to a mechanical engineer which is the correct direction of rotation (with the notable exception of some pumps and reciprocating compressors), electricians may not know this.

For all the above reasons, there is no certainty that a motor will spin in the correct direction following an overhaul, electrical disconnection or any work on the power supply wiring. The normal practice to be adopted is to carry out a motor “flick” by running it for a few seconds. It should be standard practice to remove the coupling element for this test, unless it is certain that the rotating equipment can tolerate dry reverse running.

Certain electric motors (without thrust bearings) cannot be “flick” tested without due care, and no canned motor or mag-drive pump should be so tested. The operating instructions for each package should clearly identify what form of direction checking is required, and the level of authority (linked to the risk) required to approve the test.

If all else fails, special works testing of the motor, and site phase rotation checks, can avoid the need for a site test.

3.4.5 MAINTENANCE REQUIREMENTS

See Section 3.3.5

3.4.6 LOW VOLTAGE ELECTRIC MOTOR – MAIN COMPONENTS

See Section 3.3.6

Low voltage asynchronous motors do not have brushgear, references in Section 3.3.6 may be ignored.
These motors are standard units, thus any motor suitable for the application may be substituted for any other. It is important that Hazardous Area ratings are meticulously checked to assure compliance. For this reason, unless it is intended to carry no spares at all, or to carry dedicated spares for every drive, it is good practice to specify a limited number of Hazardous Area ratings, to minimise the risk of a dangerous motor substitution. Because of the linkage between mechanical size and power rating, a motor of significantly greater or lesser power simply will not fit. The only other consideration is shaft speed, a pump intended to be driven at 1450 rev/min by a 75 kW motor could have a 2900 rev/min 55 kW motor fitted by mistake, as the physical size is the same.

The installation procedures should ensure that a “new” motor fully matches the specification of the one that has just been taken out of service, and is cross checked with the equipment file. Some operators issue unique motor numbers, and create substitution charts.

3.4.7 INTEGRATION ASPECTS

See Section 3.3.7

3.4.8 CONTROL

See Section 3.3.8
SECTION 3.5
HIGH VOLTAGE ELECTRIC MOTORS (> 500 KW RATING)

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3.5.8 Control ......................................................................................... Page 3,5 – 12

This section covers A.C. electric motors on voltages above 1000 volts. It covers asynchronous and synchronous motors of standard construction, but not special motors that may be built into special purpose equipment. It covers motors of the design that is typical above 500 kW rating. Note that H.V. motors < 500 kW are typically of TEFC design, and very similar to the L.V. motors described in Section 3.4

To avoid unnecessary duplication, generic remarks in Section 3.3 will not be repeated, but are referenced. See Section 3.3 Appendix 1 for Electrical Terminology.

- **A.C. Electric motors are available from a few watts to > 20 MW.**
- **A.C. motors run at speeds determined by the supply frequency, this is 50 Hz for European sites, and 60 Hz for North America and many offshore installations.**
- **Many H.V. motors can be driven by inverters at variable speeds**
- **H.V. motors with brush gear are also variable speed but are not covered within this guide.**
3.5.1 INTRODUCTION

- **High Voltage (defined as 1000 V or more) motors are used for higher power drives.**
- **For offshore installations the choice for high power driver will be between Gas Turbine and H.V. electric motor.**

For electric motors above about 250 kW, it is more cost-effective to use voltages of 1000 V or more. This is because motors, cables and switchgear can be lighter and thus cheaper than the equivalent low voltage equipment. Efficiencies can be higher, saving energy. Medium power motors are of asynchronous design, similar to three phase L.V. motors.

Special high power motors (typically above about 5 MW) are of "synchronous" design. They are more efficient and more complicated than asynchronous motors, having coils on the rotor as well as the stator. They operate exactly on the speed determined by the mains frequency.

![Figure 3,5 – 1 Typical High Voltage Motor. Note Oil Pipes.](image-url)
3.5.2 BACKGROUND & HISTORY

- *High Voltage drives are A.C. only and have only been available since about the 1960's*
- *Inverter drives are now available to suit many H.V. motors.*

High voltages cannot be handled readily by brush gear, thus High Voltage drives were not developed until A.C. motors were commonplace, and modern polymer insulation materials were available. Operating voltages have increased (typically 3 300 V and 10 000 V) as have power ratings. Until recently, variable speed was difficult to achieve, requiring special motors and switchgear. High power inverter drives (up to about 12 MW) are now available.
3.5.3 HAZARD ASSESSMENT

- Electric Motors are generally Low Hazard items as they do not contain Flammable Materials, also live and moving parts are well guarded.

- High Voltage motors are known for internal spark generation, particularly under fault or starting conditions.

- External surfaces should not be capable of becoming hot enough to ignite flammable materials.

- Mechanical damage or poor maintenance can result in mechanical rubs, exposed live or moving parts.

- It must be possible to stop the drive on demand, to remove the energy supply from driven equipment.

Hazards associated with electric motors are covered in general in Section 3.3.3.

The material below is specific to High Voltage industrial A.C. motors.

3.5.3.1 Ignition / Explosion Hazards

High voltage (> 1000 V) asynchronous electric motors should have no exposed electrical conductors, and since there is no brush gear, there should be no spark generation in normal operation. Contact with High Voltage conductors is likely to be fatal.

Synchronous motors may have brush gear and slip rings to power the rotor coils. This gear will have exposed conductors and may generate sparks in service, particularly if the interior of the motor is dirty.

High Voltage motors can generate internal "brush discharges" from the rotor during starts. In addition, damaged or incorrectly built rotors can spark in normal service as internal currents jump across damaged insulation.

This is not normally a problem because the air space inside the motor is quite well sealed from the environment, and inaccessible to people. In the event of a flammable atmosphere being present external to the motor, flammable gas will diffuse through the shaft seals into the motor core, creating a flammable mixture inside. An internal spark could then ignite the gas.

Industrial High Voltage motors normally have a "closed" internal air circuit, but faulty construction or maintenance can result in drawing in outside air, and any flammable gas.

Various philosophies are adopted to prevent the resultant major explosion, these are codified under "Ex" motor codings. See Section 3.4.3.1

Motors may be purged with clean air to prevent ingress of flammable vapour.

Motors may be designed and built to minimise the risk of internal sparking.
Motors may be built to survive an internal explosion without sufficient emission of hot gas to cause an external explosion. The motor may suffer severe internal damage and cease to function.

Motors are designed such that external surfaces do not exceed specified temperatures in service. Thermistors will be fitted to trip the drive if temperatures rise, e.g. due to poor ventilation.

In all cases the motors have to be selected, built, installed and maintained in accordance with Electrical Safety Guidelines and local Area Classification. The ATEX Directive now covers this process.

Electric motors can also cause ignition through external rubs e.g. pulleys on steel guards. This is not covered by "Ex" classifications, but by good engineering practice & maintenance.

High voltage motors normally have pressure oil fed bearings. Leakage of oil into the motor is possible, particularly on vertical shaft motors and on those motors where oil pipework is run inside the casing. This oil may catch fire, e.g. by “hot work” during maintenance, when flammable gas is not present.

### 3.5.3.2 Equipment Hazards

High Voltage motors are simply bigger and heavier versions of smaller motors, with consequently greater shaft inertia.

### 3.5.3.3 Operational / Consequential Hazards

In normal operation an electric motor should pose little threat to the safe operation of the installation.

High Voltage electric motors lose around 5% of their rating as heat. They have an internal air cooling circuit, heat is then passed to either an external air circuit, or to cooling water. As 5% of even a 2 MW load is 100 kW, air cooled motors must be installed in a well ventilated area. If ventilation is lost, the area will overheat very rapidly and the motor must be shut down.

“Start” and “Stop” circuits (normally referred to as “Closing” and “Tripping” circuits) on H.V. motors may be more complex than on L.V. systems. Typically, a heavier duty version of the “contactor”, called a “circuit breaker” is used. This is designed to open the circuit very quickly, to minimise sparking and internal damage. This opening action is driven by a solenoid device, powered from a separate circuit, often battery powered. The health of this circuit should be monitored continuously, as its failure will make the motor difficult to stop.

### 3.5.3.4 Maintenance / Access Hazards

High Voltage electric motors can be physically quite large, normally in the form of a rectangular box. Access is by bolted panels and terminal box covers.

H.V. Motors may be located inside acoustic enclosures, or in locations with no safe fixed access. There is usually no fixed access to the top (often where the heat exchanger is fitted). They are also very heavy (see Nameplate for weight). Rigging points will be provided. Motors should be lifted with care, using approved procedures and lifting equipment. The driven equipment or package vendor’s instructions should be checked for arrangements to release couplings.
If the entire package has not been shut down, adjacent equipment may not have been isolated or may even be running.

3.5.4 OPERATING REQUIREMENTS

- *Electric motors are very tolerant of variable operating loads, but must not be started too frequently.*

The most benign operating pattern is continuous operation, motors are very tolerant of load and even speed changes, within the design range. Motors can operate for long periods without maintenance, subject to routine lubrication, cleaning, condition monitoring as required.

High Voltage motors cannot tolerate too frequent starts, in particular they must be allowed to stop before re-start. The typical limit is 2 or 3 starts per hour. Starting a High Voltage motor puts a huge strain on the local power distribution network. Operators must ensure that sufficient generation capacity is on-line, and avoid errors like starting two large drives at once.

Motors can tolerate long periods out of service (e.g. on stand-by) but ideally should be run periodically, protected from salt spray, and in particular protected from high-frequency vibration. This vibration can cause bearing damage ("brinelling"). Electric heaters are fitted to prevent internal condensation.

H.V. motors work in fixed berths and have operating limits on tilt and acceleration. These limits will be defined by the manufacturer.
3.5.5 MAINTENANCE REQUIREMENTS

- **Motors require very little maintenance. Specialists must be employed for major work.**

The only routine maintenance is cleaning, inspection and lubrication. Otherwise motors or major component parts must be removed to workshop conditions. Smaller motors can be lifted complete but for larger units it is more practical to remove components.

Bearings, fans and heat exchangers may be serviced or repaired in situ. The rotor must be removed to a specialist repairer for any work, the removal process is very tricky as the rotor is "threaded" through the stator with very narrow clearances. Minor electrical repairs to the stator can be done in situ, otherwise the stator must be removed. Major work can take many weeks.

Smaller motors may have grease lubricated bearings. Grease nipples and relief devices should be provided, as routine re-lubrication will be required, this can be done in service. Larger motors will have oil lubricated bearings, typically roller bearing cartridges with an oil feed from the driven equipment oil console.

Note that, although the direction of rotation is determined by the wiring connections in the terminal box, after overhaul or maintenance work these connections may have been altered. Hence every electric motor going back into service must have a direction of rotation check carried out before coupling to the rotating equipment.

See Section 3.4.4 for further comments in this area, although H.V. drives should be built and wired with sufficient care to assure correct rotation.

Maintenance records must be updated after any overhaul work.

3.5.6 HIGH VOLTAGE ELECTRIC MOTOR – MAIN COMPONENTS

- **The stator carries electrical windings to drive the motor.**
- **The rotor is driven by the magnetic fields generated within the stator.**
- **Rolling element or white metal bearings are fitted.**
- **Cooling air is moved by fans.**
3.5.6.1 Frame

The frame is normally of fabricated carbon steel, typically a box section chassis supporting the stator and bearings, with a lighter sheet steel box forming the air circuit and supporting terminal boxes, heat exchanger. Bolted panels give access to the interior.

3.5.6.2 Stator

The stator has the mechanical purpose of supporting the windings, and is mounted on the frame. It consists of a pack of thin metal laminations made of a special steel alloy called "soft iron". Insulated copper wires or bars are wound into shaped coils and bonded into slots in the laminations. The coils are connected to the main terminal box, forming the electrical circuit of the motor. A set of thermistors (normally 3) is buried inside the coils to detect over-temperature. These are connected (via the auxiliary terminal box) to an external trip amplifier.

Most of the heat generated in the stator is removed by cooling air passing through slots. Some motors have cooling water pipes embedded in the stator.
Terminal boxes are typically of sheet steel and provide sufficient space to gland off and terminate supply power and signal cables. "Ex" rated motors for hazardous areas have special heavy duty terminal boxes.

3.5.6.3 Rotor

In asynchronous motors, the rotor consists of a carbon steel shaft running in two bearings, fitted with a "squirrel cage" element made of soldered copper bars fitted through "soft iron" laminations. When the power supply is switched on, magnetic fields in the stator "rotate", creating "rotating" fields in the rotor. These create eddy currents in the squirrel cage, applying torque to the rotor. Torque is proportional to the slip speed between the stator magnetic field, and the rotor, up to the overload limit. Heat is generated in the rotor and stator. The rotor has fans at both ends of the squirrel cage, forcing air around the internal air circuit. The Drive End of the rotor extends beyond the Drive End bearing, and is shaped and keyed to carry a coupling. Special shaft ends are available for direct-coupled rotating equipment. The Non-Drive End of the rotor carries the External Cooling Fan, if fitted.

In "synchronous" motors, the rotor carries a set of low power coils that are powered via an "exciter" system. This power may be transferred by a rotating slip ring system, or by the newer "brushless" induction system. Slip rings look similar to D.C. motor brush gear, but are not subject to the same wear and unreliability issues. The "brushless" system looks like a very short, large diameter electric motor fitted to end of the main rotor, in effect it is a rotating transformer. Since these coils are permanently energised when the motor is running, the magnetic fields from the rotor “lock” to the rotating magnetic fields in the stator. The rotor is thus forced to rotate at the same speed as the applied fields. A synchronous motor thus does not change speed with changing load, although the phase angle between the rotor and the applied field will increase with load. If the applied torque exceeds the motor limit, the magnetic fields will “unlock” and the motor and drive will stall.

If this happens the drive must be automatically tripped to prevent motor and drive train damage. Once the drive has stopped, and the cause of the excess torque remedied, the drive may be re-started normally.

3.5.6.4 Bearings & Lubrication

The shaft bearings are typically in cartridge format, supported by the end cross-members of the frame. Simple labyrinth seals exclude dirt and water. Normally the NDE bearing is axially located, the DE bearing has some axial float.

Smaller motors have rolling element bearings, larger units typically have plain white metal bearings. On these larger motors, there may be simple axial "bump rings", but no thrust bearing as such.

There is a magnetic effect that tends to pull the rotor towards the "magnetic centre" of the stator. This effect is exploited to permit operation without a thrust bearing, but the effect is lost on switch-off, and the rotor can float axially between the bump stops.

Where oil lubrication is used, the bearings may be self-contained or be oil fed. Even oil fed bearings often have a small oil reservoir to cover run-down in the event of oil supply failure.

For further information on Ancillaries, see Section 5.2 for Lubrication Oil Systems, and Section 5.9 for Bearings.
3.5.6.5 Cooling System

On CACA motors, a fan is fitted to the NDE of the motor shaft. This draws air in through a perforated grille, and blows it through the tubes of a heat exchanger. Exhaust air returns to atmosphere. The warm air in the internal circuit passes across the exchanger tubes. The heat exchanger is normally mounted on top of the frame.

On CACW motors, the internal fans circulate air against water cooled coils, mounted either internally or on top of the frame. Cooling water is supplied by the main plant system. There should be a system to collect and detect any condensation or leakage from the cooling water coils.

3.5.6.6 Starter, Inverter & Control Systems

All motors require switchgear to start and stop them. Generally there is a mechanically operated switch (the "isolator"), an electrically operated switch (the "contactor"), a set of fuses and an overload trip device. Most industrial motors are simply switched on (referred to as "Direct on Line" starting) although a range of reduced load starting devices exist.

Motor fault detection devices e.g. thermistors, phase fault relays, will be linked to a trip relay which will release the motor contactor.

Inverters are modern electronic devices that generate synthetic A.C. at a controlled frequency. This A.C. can then be used to make a standard or near-standard motor behave as a variable speed drive. Motor and inverter unit must be compatible. The inverter units cannot normally be installed in hazardous areas and are usually located in switch houses. Inverters generate heat and require cooling.

High voltage electrical conductors are potentially fatal, so access to high voltage equipment is normally restricted to specially trained personnel. The outside areas of H.V. motors are safe, but only authorised personnel should remove access covers.
3.5.7 INTEGRATION ASPECTS

High Voltage A.C. motors are built to order. Generally the supplier will select the appropriate motor, given the range of duties, but it is much better if the client or contractor's rotating equipment and electrical engineers are consulted. Hazardous area requirements are fundamental, as these safety features cannot be added afterwards.

Certain types of drive have particular characteristics, which must be recognised. Large centrifugal compressors and fans take a long time to start, this may exceed standard overload design limits. Reciprocating compressors can have a rapidly fluctuating torque characteristic that may cause problems with other machines on the same power net.

Any inverter drive can produce harmonic signals that can impact on control systems or damage electrical equipment. The larger the drive, the bigger the potential problem. Use of high voltage inverter drives requires the active input of a competent electrical engineer.

High Voltage drives also impose huge loads on the power distribution network, especially during starting. Equally, unplanned tripping can result in over-voltage and large generator load changes. The proposed drive must be assessed for its suitability to fit into the power grid, starting and power factor characteristics can be tailored to give the best practical match.

A "Soft Start" is a form of inverter drive that is only used for a short period to start the motor. It has a particular benefit if there is any possibility of the drive being seized prior to start, or seizing during start. The soft start can be set up to turn the shaft very gently for a few seconds, before accelerating to full speed.

3.5.7.1 Cleanliness

CACA motors can cope with a significant amount of dirt, provided that the fan intake grille is kept clear. CACW motors are insensitive to dirt, unless it actually gets into the bearings or inside the casing. Internal cleanliness is important, otherwise dirt will foul heat exchanger surfaces. Oil contamination inside the machine poses a fire risk.

3.5.7.2 Mechanical Integrity

Electric motor rotors turn at relatively low speeds and are contained within massive housings. Ejection of parts is very unlikely. H.V. motors require a rigid mounting structure, poor mounting can distort the frame, causing vibration and potential damage.

3.5.7.3 Condition Monitoring

Vibration monitoring, in particular by trending, can identify a range of machine problems. For details of Condition Monitoring Systems and related hazards see Section 5.12.

Specialist electrical test equipment can be connected to running motors, and can be used to detect a range of electrical and mechanical problems. A high level of interpretative skill is required. Routine use of this equipment cannot be justified; symptoms like overheating or strange noises will prompt further study.

3.5.7.4 Protective Systems

High Voltage motors normally have temperature sensing devices in the bearings, coils and internal cooling air circuit. These may display locally or in the control room, or simply operate protective devices. It is normal to have pre-alarm and trip on each temperature.
Protection relays are fitted to trip the drive based on:­

- Short circuit (overcurrent for a short time period)
- Overload (overcurrent for a longer time period, more sensitive but slower than short circuit protection)
- Earth Fault (often achieved by measuring each phase current and checking that the resultant is zero)

Inverter drives add a number of more sophisticated checks on the electrical supply.

3.5.7.5 Bearings

Where the bearings are oil fed, the oil supply is derived from the driven equipment. The motor must be interlocked to the supply oil pressure, and tripped if the pressure falls.

Many motors of larger size are not fitted with thrust bearings, but rely on the thrust bearing in the rotating equipment. This is not a problem provided that it is properly understood. Uncoupled rotation checks may be prohibited. Shaft axial position must be checked against a marker when fitting the coupling.

3.5.7.6 Sealing

H.V. motors have simple labyrinth shaft seals on the air circuit, they should be reasonably dust tight and hose proof (IP55) but are not gas tight. It is good practice to set up terminal boxes and cable glanding to avoid water ingress down the cable. Terminal boxes are not isolated from the motor internal air space.

After maintenance, the dust and water tightness will be lost if the panel seals are damaged or ill-fitting.

3.5.8 CONTROL

- The motor will be controlled as part of the package.

Electric motors are controlled as part of the package in which they are installed. In very simple installations the control will be a manual push button station.
This section covers a Diesel Engine used as a fixed berth driver for offshore equipment. It covers the range of sizes commonly used, with emphasis on Emergency Service Duty. It does not cover ship propulsion or vehicle applications.
### 3.6.1 INTRODUCTION

Diesel engines are used as rotating equipment drivers, where electric drive is not possible or appropriate. Diesel engines are complex and noisy machines, requiring relatively frequent maintenance. Hence they should not lightly be chosen as drivers in preference to electric motors.

Diesel engines are multi-cylinder reciprocating machines requiring fuel, combustion air and cooling. Smaller engines are derived from vehicle technology, larger engines from marine propulsion. Vehicle engines focus on light weight, high shaft speed, high power to weight ratio. This makes them suitable for portable or semi-portable equipment, and for engine starting "pony motors" for larger engines. Marine engines focus on reliability, fuel economy, and practical in-situ maintenance. This makes them more suitable as offshore rotating equipment drivers.

Diesel engines normally operate on a light liquid distillate fuel, although they can be adapted to run on various gas mixtures. The fuel must be physically clean, to reduce engine wear; sulphur and other contaminants can be tolerated but increase corrosion, exhaust pollution and visible smoke.

Industrial diesel engines have shaft speeds of 1000 – 2000 rev/min, and are variable speed within a limited effective range. They produce significant vibrations through their mountings, and torsional vibrations through the output shaft. Vibrations are reduced by the use of a large heavy flywheel, flexible mountings and/ or rubber element shaft couplings. They are not suitable for extended running at nil load at any speed.

Diesel engines require an energy source for starting; storage batteries, compressed air or even a smaller "pony motor" engine crank the engine over before it can be started on its own fuel. With batteries to power the control gear, this gives the "black start" capability required for emergency drives and some utilities.

### 3.6.2 BACKGROUND & HISTORY

- **The first diesel engines were derived from petrol engines for cars**
- **Large marine diesels became common in the 1950’s**
- **On land, diesel engines are mainly used for heavy vehicle propulsion**
- **Static diesel engines are currently used for emergency drives**
- **Recent developments include smaller fuel-efficient engines and Diesel-based CHP schemes**

Early diesel engines were derived from petrol engines built for cars. They did not require the (then) unreliable spark ignition system, and ran on cheaper, less refined, fuel. Their greater weight, lower responsiveness and better fuel economy led to them being developed as the preferred power plant for heavy goods vehicles and locomotives.

Even larger engines were developed for marine propulsion as oil replaced coal. Diesel engines were preferred to steam engines, being much smaller, simpler and cleaner. Hence a smaller engine room and a smaller crew. Marine diesel engines were built into the ship, all maintenance had to be done in situ.
On land, energy production stayed with steam plant, developing high efficiency, high power units with long service intervals. Diesel engine generation was (and still is) used only where small unit generation, perhaps less than 10 MW, is required. Diesel engines are used for fixed and portable emergency generators, where their compact size and relatively low capital cost scores highly.

This practice has been adopted offshore, but since steam plant is impractical, its place has been taken by Gas Turbines.

The most recent developments include smaller fuel-efficient engines for car and van engines; and static diesel engines as part of Combined Heat & Power schemes, which recover waste heat for building heating.

3.6.3 HAZARD ASSESSMENT

- **Diesel Engines are generally Medium Hazard items as they use Diesel Fuel, which is Flammable but not highly volatile.**

- **The mechanical containment of the engine system, and the amount of fuel stored local to the engine, are significant factors in hazard assessment.**

- **Diesel engines can draw in, and ignite, flammable gases released elsewhere.**

- **Emergency drives pose a special form of hazard – failure to operate.**

- **The starting system requires an energy store, itself posing a level of hazard.**

- **The segregation of engines from other hazards is an important issue.**

3.6.3.1 Ignition / Explosion Hazards

Diesel engines normally run on diesel fuel, which is a light distillate fuel, less volatile than petrol/pentane/hexane thus significantly less flammable. Fuel onto a sufficiently hot surface will ignite, but to create an explosion a vapour cloud or aerosol is required. The fuel storage and handling system is not likely to generate such results, but the final fuel injection stage works at very high pressures, and fuel leakage onto the hot exhaust can generate vapour clouds. Hence the highest hazards are probably on the engine itself, rather than its ancillaries and support systems. Prevention is by ensuring containment of high pressure fuel, as it is unlikely that a vapour cloud or aerosol would be easy to detect. Metal surfaces might well not be hot enough to initiate an explosion, but an exhaust gas leak, e.g. from a split bellows, certainly can. It must be assumed that a source of ignition will be present, although the risk is reduced by good equipment layout.

Engines, particularly on emergency duties, will be located inside robust and probably fire-resistant acoustic enclosures. A small fire or explosion inside such an enclosure will probably be contained, although it could do major damage to people or equipment inside. A large fire or explosion will not be contained.

A diesel engine can ingest, and ignite, flammable gases present in the intake air. The air intake should be located in a "safe" area and fitted with gas detection.
The crankcase can contain a flammable mixture, particularly if one cylinder is faulty and some unburned fuel is passing the piston rings. This mixture can be ignited by a mechanical rub e.g. inside a damaged bearing. This risk can be removed by nitrogen purging, but this then poses an asphyxiation risk during major maintenance, when crankcase covers are removed.

The incoming fuel supply line should have a fire-safe isolation valve at the enclosure wall, being a normally closed manual valve, or a trip valve linked to the fire & gas system, as appropriate to the system function. Any local fuel storage, as would be required for an emergency unit, should have a sealed vent, fitted with a flame arrestor, routed to a safe place. This is to avoid the risk of a vent fire inside the enclosure.

Only the appropriate fuel may be used, dilution with or substitution of more volatile fuels could cause major engine damage and increase the risk of fires and explosions.

### 3.6.3.2 Equipment Hazards

Engines are fully enclosed and all moving parts should be guarded. Some gaps may have to be left to permit flexible connections to work, and to allow thermal expansion. Hand/ arm trapping could occur. Diesel engines have large areas of very hot metal on the exhaust system, it is impractical to lag these as the metal could then overheat and fail. Good practice is to fit robust mesh shields to prevent contact while permitting cooling. Hot surfaces which are out of reach need not be guarded, but maintenance access may be required to a running engine.

Most diesel engine parts are relatively slow-moving, thus do not pose much of a missile risk, and certainly not outside the enclosure. An internal explosion, or normal combustion pressures, could eject a badly fitted cover at high speed. All covers should be fully bolted and secure before the engine is turned over. The one high speed component of large diesel engines is the turbo-charger, this is a small exhaust gas turbine/ air compressor powered by the exhaust gas. The turbocharger runs at several thousand revs/min, not directly linked to engine speed. The unit can burst, ejecting parts of the rotor. This is a rare event, the risk is managed by periodic inspections and by preventing engine overspeed events.

Mechanical hazards are mainly confined to the interior of the enclosure, and only with the engine running. The risk is probably greatest when starting after overhaul, or when the engine is being investigated for a reported problem. The minimum number of people should be present at these times.

### 3.6.3.3 Operational / Consequential Hazards

Diesel engine enclosures are hot and noisy with the engine running. Even with appropriate PPE, conditions are uncomfortable and stressful, alarms & radio messages cannot be heard. All possible operator duties should be done from outside the enclosure, or from an acoustic booth.

No essential services should run through the engine enclosure, except for dedicated connections to the engine itself. In particular, no hydrocarbon lines or ventilation ducts should route through the enclosure.

Diesel engines are variable speed machines, normally controlled by an internal governor to a set speed appropriate to the duty. It is a known risk that ingestion of flammable liquid or gas, at a rate greater than the fuel requirement, will cause a speed increase which the governor cannot control. Similarly, a governor failure could cause overspeed. Unlike petrol engines, diesel engines do not have a suction throttle valve and thus cannot be stopped by closing such a valve. The appropriate action is to isolate the fuel or, where possible, operate cylinder decompression valves. Decoupling the load is not preferred as that will cause the engine to overspeed dramatically.
Engines may be fitted with proprietary systems that inject suppression chemicals into the intake. This will only work if the volume and duration of injection are great enough to make the engine stop. Any engine which has over-speed, or which has been stopped by the use of a suppression system, will require a major overhaul and inspection.

The consequence of an overspeed event will be to increase the pressure/flow/frequency of the delivered service. For a utility driver, the normal practice would be to alert the operator and trip the drive to prevent damage to downstream equipment. For an emergency driver, continuity of supply is paramount. Ideally the system will be very tolerant of the overspeed condition and will have an overloading power curve, which will inherently tend to limit the degree of overspeed.

A governor fault, fuel starvation or fuel contamination is likely to lead to an underspeed condition. Again, for a utility, this will lead to an operator alarm and a drive trip. Again, for an emergency service, it would be preferred to advise the operator and keep the service on line to provide as much benefit as possible.

For an emergency driver, the most serious consequence is if the driver does not start on demand. Since the emergency start will be automatic and there will not be time to make adjustments or open valves, the unit must actually be ready to start. This can only be assured by good procedures, proved by regular test runs under realistic starting conditions.

The control system must monitor the availability of the engine and the state of charge of energy storages e.g. batteries and compressed air receivers.

### 3.6.3.4 Maintenance / Access Hazards

Minor servicing may be done with the engine running, but anything more major will be with the unit stopped. Since the engine will normally be in its own enclosure, working conditions should then be reasonable. If the enclosure is shared then consideration must be given to the noise, heat and risk of contact with the running engine.

Due to the presence of fuel, batteries, compressed air storage, inside the enclosure, a fire on the engine has to be a possibility. The enclosure fire detection system should provide local and control room indication in the event of a fire, to permit prompt action and prevent dangerous entries. Any Halon or CO2 fire suppression system must be deactivated before entry, and reactivated on departure, according to the PTW.

The necessary lifting facilities should be built into the enclosure, scaffolding or additional platforms may be required for personnel access. Any fuel, nitrogen, supplies must be fully isolated. Stored fuel, compressed air, batteries, should be isolated, drained or removed as appropriate to the work being done.

The main hazards are falls from height, dropped objects or tools, and manhandling awkward and fairly heavy components. Much of the work is via access covers with attendant risk of trapping injuries or sprains.
3.6.4 OPERATING REQUIREMENTS

- **Diesel engines work best on steady speed and load, at design speed and close to design load.**
- **They are tolerant of load changes but are not suitable for rapid speed changes.**
- **Frequent service intervals prevent long continuous operating runs.**

Although diesel engines are inherently variable speed, each engine has a fairly narrow band of speed and load where it performs best. The large machine inertia and the way the fuel system operates prevent rapid speed changes. Engines generate significant vibrations, so operating over a variable speed range is likely to excite resonant frequencies somewhere. Changes in load without great speed changes are tolerated well.

Diesel engines require frequent servicing, so long continuous operating runs are not possible. Diesel driven utilities are thus normally specified in groups, for example 3 installed units, 2 running, or 4 installed, 2 or 3 running. For emergency operation the selection would perhaps be 2 off 100 % installed units, servicing and test runs controlled to always keep 1 system in operation.

Diesel engines require combustion air, fuel and cooling support. These are sourced externally but may be set up in such a way as to permit an emergency set to operate alone for a limited period.

3.6.5 MAINTENANCE REQUIREMENTS

- **Diesel engines are complex and thus require frequent servicing**
- **Servicing is often carried out by specialists**
- **Components may be removed to workshop conditions**
- **Even major overhaul work must be done in situ**

Diesel engines require relatively frequent servicing compared to most process plant equipment. This is a consequence of the complex reciprocating mechanism, vibration, and the contamination of lubricating oil by water, carbon and fuel. The work is often done by specialist engineers as diesel engines are quite different from other process plant equipment.

All maintenance will be done in situ, although components and sub-assemblies may be removed to workshop conditions. Much of the maintenance is based on cleaning, inspection, adjustment, replacement of small parts.

There must be sufficient laydown space within or local to the enclosure. A relatively large area is required for effective maintenance. For major overhaul work, parts of the enclosure may have to be dismantled.
3.6.6 DIESEL ENGINE – MAIN COMPONENTS

- The main visible components are the crankcase, cylinder heads, manifolds
- All major components are large and heavy
- No moving parts are visible in normal operation
- Engines are normally vertical in-line or Vee configuration, with valve gear and manifolds above.
- Ancillary components are mounted on the engine or very close nearby
- Flexible connections are required on cooling water, inlet and exhaust ducts

The engines described are a vertical in-line 4-stroke diesel engine as used for on and off-shore utility generation, and the Vee format used for smaller, emergency, drives. 2-stroke engines and other cylinder formats are used for special applications especially rail traction where high power must be combined with low weight.

Figure 3.6 – 2 Diesel Engine with Alternator and Switchgear
3.6.6.1 Crankcase

The main body of an industrial diesel engine is the crankcase. This is typically of cast construction for low cost and very high stiffness. Typical design has 6, 8 or 12 vertical cylinders in line, requiring a long narrow, but simply shaped crankcase. This design gives good inherent dynamic balance, suits ship propulsion and is perfectly workable for offshore drive purposes. A "V" format may be used, resulting in a shorter, wider engine. The stiff construction is required to ensure alignment of the multiple crankshaft bearings and cylinders. Cast along the centre-line of the crankcase are a set of bearing housings, for the crankshaft main bearings. The lower side of the crankcase is closed by a bolted on sump, which collects and contains the engine lubricating oil. The crankcase is normally bolted solidly to the baseframe or deck, but rubber block type anti-vibration mounts may be used to minimise vibration transmission.

3.6.6.2 Crankshaft and Flywheel

The crankshaft will be a single piece forging, with a heavy flywheel flanged to one end, and one or more drive gears/ pulleys on the other end. The shape and arrangement are akin to a car engine. The crankshaft runs in a number of plain bearings bolted into housings set in the crankcase. These bearings are line bored in a single operation to ensure correct shaft alignment. Each crankshaft "throw" carries a "big end" bearing to drive one piston (in-line design) or two pistons (Vee design). The crankshaft "throws" are arranged at angles chosen to give the best possible mechanical balance and to even out the firing strokes. Some engine designs require additional rotating balance shafts, these run alongside the crankshaft and are driven by it. The number of cylinders, and the cylinder arrangement, determine this requirement.

The flywheel is a massive disc, with its mass concentrated at the rim, used to smooth out the firing impulses. It is rigidly bolted to the end of the crankshaft, although some additional flexibly mounted weight may be used to reduce vibration at certain frequencies.

3.6.6.3 Pistons

The pistons are directly connected to the crankshaft via individual connecting rods. A separate cross-head bearing is not required. The arrangement is thus similar to a car engine. Each piston runs inside, and bears on, the engine cylinder. The piston is fitted with a set of piston rings to control gas leakage, and to minimise lubricating oil loss. As the piston bears hardest on the cylinder wall during the power stroke, the piston is designed to fit one way round only, with the best bearing surface in place during the power stroke. The piston crown may also be shaped to suit the valve arrangement.

3.6.6.4 Bearings

The crankshaft and piston pin bearings are of plain design, either of cast block or shell type. The crankshaft bearings (main and big end) must be split to fit round the crankpins, and are bolted in place. The piston to connecting rod bearing (little end) will typically be pressed into the connecting rod and machined to suit the pin. The bearings are lubricated by a pressurised oil feed via drillings in the crankshaft. There should be no net end thrust on the crankshaft, which is located axially by a simple plain thrust bearing.

3.6.6.5 Cylinders and Cylinder Head

Each piston runs in its own cylinder, one end of the cylinder is thus open to the crankcase, the other is closed by a cylinder head, fitted with inlet and exhaust valves, injectors and possibly decompression gear. The cylinders may be cast in a block (smaller engines) or individually fitted (large marine designs) to permit maintenance. It is common practice to fit cylinder liners, these
can be replaced when they wear. The cylinder (or liner) is accurately aligned with the crankshaft throw, and honed to a suitable finish to act as a bearing for the piston.

The cylinder head provides the containment for each cylinder, heads may be individual or cast in blocks, depending on the engine design. In all cases the function of the cylinder head is to contain the high combustion pressure and provide a mounting block for the valves and injectors. The shape enclosed between piston, cylinder and cylinder head is referred to as the combustion chamber.

Cylinders and cylinder heads normally have integral water cooling jackets and passages.

### 3.6.6.6 Camshafts and Valve Gear

As with a car engine, the combustion air must be let into the cylinder at the right time, and the exhaust vented. This is done with poppet type valves, 1 or 2 inlet valves and 1 or 2 exhaust valves per cylinder. As the valve operates once per two crankcase revolutions, the valves are operated by camshafts rotating at one half of crankshaft speed. As the camshafts rotate, the cam profile operates a lever, rocker or push-rod to open each valve. When the valve is released, it is closed by a coil spring. The cylinder pressure helps to keep the poppet design valve closed. Camshafts are mechanically driven from the crankshaft.

Some engines, specifically marine diesels, can be started and run in reverse after altering the camshaft drives.

### 3.6.6.7 Inlet and Exhaust Systems

The inlet and exhaust systems are nominally very simple, fresh air is drawn in through an intake filter and silencer, the exhaust is vented through a silencer. Diesel engines do not have a throttle valve, although they may have inlet heating and air flow measurement. To reduce vibration transmission and allow for thermal expansion, bellows are typically used in inlet and exhaust ducts. The inlet bellows can be simple rubber or fabric type, but exhaust bellows will typically be convoluted metal type, which will be at some risk of corrosion and cracking.

However, in order to improve power to weight ratio and fuel economy, most industrial engines are now fitted with turbochargers. These are a miniature power recovery turbine driving an inlet air booster compressor. The increased inlet air pressure gives more mass flow per crankshaft revolution, thus more power. Since the mechanical losses will be much the same, this also improves the fuel economy.

Turbochargers take the hot exhaust gases and expand them through radial expander, extracting energy and, conveniently, cooling the gases somewhat. This expander is mounted on a common shaft driving a single stage centrifugal compressor, compressing the inlet air. The compressed, and thus heated, air goes to an intercooler to achieve maximum density thus maximum engine power. There is no mechanical linkage between the engine and the turbocharger shaft, which runs at high speeds governed purely by the gas velocities. Since the turbocharger only works efficiently at high loads, turbocharged engines only deliver full power and economy at close to their rated load and speed.

In the event of an engine overspeed, the turbocharger will also overspeed (driven by the increased gas load) and could burst. High speed parts can be ejected through the relatively light casings, posing a serious risk to personnel. A robust acoustic enclosure, particularly with fire proofing, should contain such parts. Turbochargers should be subject to routine inspection for corrosion, cracking and rotor damage, and should be fully inspected after any overspeed event. If in any doubt, the rotor should be changed.
3.6.6.8 Fuel and Injection Systems

Typically, a small storage tank inside the enclosure will hold filtered fuel for each engine. This permits the engine to run for a period even if the supply system is shut down, or while supply filters are cleaned or changed. This is particularly appropriate for emergency service diesels which must run independently for a specified period. The fuel is being handled at low pressure and at ambient temperature, so should pose little risk. The fuel is then passed to the injection pump, which raises it to the high pressure required to overcome cylinder compression and inject fuel directly into the combustion chamber. In traditional designs this pump is mechanically driven from the crankshaft or camshaft, and mechanically controls the timing, rate and quantity of fuel injected to each piston for each firing stroke.

Diesel engines are very sensitive to air locks in the injection pump, these may prevent engine starting after maintenance. Particularly for emergency units, tolerance of air locks is a major good feature on an engine.

Diesel engines ingest a nominally constant volume of intake air per revolution, and add only the required amount of fuel for combustion. To increase speed or load, more fuel is added. Thus they always operate fuel-lean, unlike petrol engines which should always operate just below stoichiometric (ideal) mixture.

With the advent of modern digital electronic controls, it is now possible for the metering to be managed electronically.

The fuel is fed into the actual cylinder by an "injector" which is a form of pressure-operated poppet valve with an atomising nozzle built into the tip.

3.6.6.9 Speed Control System

Industrial diesel engines are supplied with an integral governor to achieve a controlled set speed and prevent overspeed if the drive load is reduced. The unit will be proprietary to the engine manufacturer and will be integrated into the injection control system. An operator-set speed will be compared to the actual measured speed, and the result used to control the fuel injection rate. There will normally be some speed variation with load, which is quite acceptable for pump and compressor drives. Where the engine is being used to drive a utility alternator, and the output frequency must be controlled within fine limits, a more sophisticated control system may be required.

The control units are normally housed in switchboard cubicles in engine/ control rooms and take the form of electronic control units linked to engine actuators and sensors.

Diesel engines are controlled purely by the management of the fuel injection, the engine is stopped by stopping the fuel injection process.

3.6.6.10 Starting System

Diesel engines must be run up to a minimum speed before fuel is injected and a start attempted. Smaller engines use electric starter motors, larger engines may use compressed air starting or a smaller engine or "pony motor" driving the crankshaft up to starting speed. For emergency duties, two independent starting systems should be specified.

Mechanical starting systems use an electric starter motor, or a mechanical drive, to crank the engine at starting speed. Engines may be fitted with Cylinder Decompression devices, which vent cylinder pressure and thus reduce torque. With the engine up to starting speed, decompression devices are released and fuel injected. To aid initial combustion, engines are often fitted with "glow plugs" which provide a hot surface to ignite the fuel during the starting
sequence. Once the engine has started, but before acceleration to running speed, the starting drives must disengage. Otherwise they could be destroyed, with a consequent risk of ejected parts.

Compressed air starting uses additional valves to feed air into cylinders during the power stroke, until the starting speed is reached. Fuel injection then proceeds as above. The compressed air storage may be replenished from the instrument air supply, or from a local compressor.

3.6.6.11 Engine Ancillaries

Diesel engines normally carry their own oil and water pumps, and an alternator to power electrical systems and top up storage batteries.

The engine lubrication system will be self-contained, using the engine sump as the oil reservoir. Oil will be pumped, filtered and cooled before being fed to the crankshaft, connecting rod and camshaft bearings. Unlike process gas compressors, the lubricating oil in diesel engines has a very finite life, due to incremental contamination by combustion products and fuel leaking past piston rings. Effective filtration can remove some of the carbon and, extending the effective life of the oil somewhat.

Engine cooling should be by a closed circuit water system, circulated by integral pump(s). This permits the circuit to be treated, and to operate at a constant high temperature. The high temperature gives important efficiency benefits, and minimises condensation and associated condensation. The closed circuit water can be cooled against sea water or (for smaller units) air.

The engine-mounted alternator is only intended to power the local controls and to charge up the starting batteries. On a utility duty, driving a power alternator, it may be practical to dispense with the engine-mounted alternator.

On utility duties, there may be some duplication e.g. of filters to permit servicing. On emergency duties, twin parallel units e.g. pumps driven from different supplies, may be used to increase reliability.

3.6.7 INTEGRATION ASPECTS

Diesel engines are normally supplied complete with ancillaries, as a standard provision by the vendor. The packager must identify which services are already provided, and how to link them to the package and plant controls.

For emergency service the design philosophy is somewhat different than for a utility duty, specialist manufacturers of, for example, fire pumps have a track record in tailoring engines for the duty.

Engines must fit into the relevant enclosure and provide reasonable access. This is more important on emergency duties, where servicing activities compromise safety cover thus must be completed quickly. The vibration from the engine must be attenuated to a tolerable level where it will not damage other equipment or compromise working conditions. This is less of an issue on emergency drives, with their low running hours.

The drive must be matched to the engine, if necessary by fitting a drive gearbox. Belt drives are unreliable and not preferred. It must be possible to start the engine, by disconnecting or unloading the rotating equipment until the engine is running properly. The rotating equipment must then be brought up to speed and load, how this is done is primarily determined by the type of equipment being driven.
3.6.7.1 Cleanliness

Diesel engines have air intake filters so are protected from airborne dirt and debris. Diesel fuel leakage tends to make surfaces slippery, leakage should be avoided by good maintenance practices. In particular, drip trays and prompt mopping up during maintenance keeps any spillage from spreading. The combustion process produces quantities of fine carbon dust/sludge, which can be released during maintenance. Again, good maintenance practices are required, contaminated items or materials should be cleaned locally or bagged for handling.

3.6.7.2 Mechanical Integrity

Diesel engine parts move at relatively low speeds and are contained within massive housings. Ejection of parts is very unlikely. Rarely, connecting rods fail and punch a hole in the crankcase.

A fault in the disengagement of a starter motor or pony motor can result in the destruction of the drive.

Turbochargers pose the risk of high speed parts ejection, related to overspeed incidents or damaged impellers.

3.6.7.3 Condition Monitoring

Vibration monitoring, in particular by trending, can identify a range of machine problems. For details of Condition Monitoring Systems and related hazards see Section 5.12.

Temperature measurements can be valuable on diesel engines, as they can be used to locate a fault more easily than by Vibration Monitoring. Infra-red measurements are instant and do not require fixed sensors or close access to hot parts.

Oil sampling and trending is probably the most effective condition monitoring tool, it confirms that the oil is still capable of lubricating, and identifies bearing and piston wear by the presence of metals in the oil. Fuel, water and carbon content all give valuable information which can be used to pre-empt problems.

3.6.7.4 Protective Systems

Engines are protected against overheating, low oil pressure, overspeed by their own control systems.

As appropriate, links to external start permit, cooling water supply, interlocks with the rotating equipment, fire and gas systems, are required.

3.6.7.5 Bearings

The bearings in diesel engines are oil lubricated from the integral lubrication system. Ancillary components will typically have greased-for-life bearings.

3.6.7.6 Cooling (External)

Some form of external cooling is required, for all except small engines this will be by sea water. This water should not directly cool the engine, but should be indirect via a heat exchanger. For emergency systems the cooling water should be derived from a very secure source.
3.6.7.7 Sealing

The crankshaft and other drive shafts will have simple lip seals or labyrinths to retain lubricating oil. These are reasonably effective provided that the crankcase ventilation system is working. If not, oil will tend to be blown out.

Fuel and other pumps will have mechanical seals.

Static sealing will be by a wide variety of proprietary seal materials. For fuel and combustion system seals, it is unwise to use substitute materials.

3.6.8 CONTROL

- **The engine will be controlled as part of the package.**
- **It is important that it be clear how the engine speed is to be managed and in particular how the engine is to be stopped in an emergency.**

Diesel engines are controlled as part of the package in which they are installed. The control has to manage engine speed and engine power in response to load changes. Where the control is split between the package and the engine, it must be clear how the system is split.

It is important that it be clear how the engine is to be stopped in an emergency, for example if the normal control device has failed.