CENTRIFUGAL COMPRESSORS FOR OXYGEN SERVICE

AIGA 071/13

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Table of Contents

Figures

Tables

Amendments to AIGA 071/11

Section	Change
	Editorial to align style with IHC associations
2.2.2.3.1	Clarification of piping systems
3.3.2	Clarification of limitation of use
3.4.1.2.1	Addition of “Casings and volutes”
3.4.1.6	Clarification of agreements
3.5.3	Clarification of machining element
3.6.1.1	Change from “overhang” to “overhung”
4.1.2.5	Clarification of which openings
4.7.1	Addition of term “first out”
4.7.5	Change from “white metal” to “bearing pad”
5.2	Clarification of responsibilities
5.4.4	Change “broken” to “removed” for clarity

Note: Technical changes from the previous edition are underlined

1 Introduction

This document has made a significant contribution to the safe compression of oxygen primarily because the manufacturers and users have fully and openly shared their philosophies and experiences. It is recognised by the Working Group members that the feedback of operating experiences makes a powerful contribution to safe operation and design.

Oxygen compression represents a special risk in that the compressor can burn violently. This document defines design and operating parameters for centrifugal oxygen compressors. Compliance with this document can reduce the likelihood of, and the hazards arising from, a fire in a compressor to a level equal to or lower than those commonly accepted in the air separation industry

The document requires that all those who build and operate centrifugal oxygen compressors that have been specified to comply with the document should contribute towards it by fully reporting the circumstances surrounding oxygen fires. For the purpose of safe operation of the compressor and its auxiliaries the user and the manufacturer shall establish full agreement on the possible and expected modes of compressor operation (e.g. specified operating points, normal operating range, start-up and shutdown, etc.)

The industrial gases companies have engaged, through the International Harmonization Council (IHC), comprised of the Asia Industrial Gases Association (AIGA), Compressed Gas Association (CGA) and the European Industrial Gases Association (EIGA), Japan Industrial and Medical Gases Association (JIMGA) in a process of developing harmonized safety practices and this publication is one of them.

1.1 General

1.1.1 Objective

The objective of this document is to provide guidance on the design, manufacturer, installation and operation of centrifugal oxygen compressors, thereby safeguarding personnel and equipment. Fire in an oxygen compressor can be caused by a variety of reasons which include mechanical deterioration resulting in excessive vibration and/or loss of running clearances within the compressor; ingress of oil (e.g., through the seal system) or foreign bodies passing through the machine.

An oxygen compressor shall be provided with a safety support system that shall minimise the development of a potentially dangerous operating condition. In the event of an incident on the compressor, which results in combustion of the materials of construction, the safety systems shall be designed to minimise the effect of the fire.

The safe and reliable compression of oxygen using centrifugal compressors can only be achieved by the successful combination of many factors. The document identifies and addresses these factors:-

1.1.1.1 Design of the compressor system (Sections 3 & 4)

- Robust and well proven compressor design
- Stable rotor system
- Safe materials in critical areas
- Comprehensive instrumentation
- Safety shutdown system
- Auxiliary system

1.1.1.2 Cleaning, preservation and inspection (Section 5)

- Correct and properly enforced procedures carried out by well trained personnel.

1.1.1.3 **Erection, testing and commissioning** (Section 6)

- Skilled and well trained erection personnel
- Comprehensive testing programme to verify the design.

1.1.1.4 **Operation** (Section 7)

- Well trained and experienced personnel
- Correct procedures

1.1.1.5 **Planned Maintenance** (Section 8)

- Condition monitoring
- Planned preventive maintenance
- Well trained and experienced personnel

1.1.1.6 **Personnel Protection** (Section 2)

- Identification of the hazard
- Safety barriers
- Location of the compressor
- Emergency procedures

1.1.2 Other Specifications

Additional guidance on installation and operation can be found in Ref [10] (CGA G-4.6). The CGA and AIGA are aligned in their aims and values and the CGA document shall be regarded as complementary to this one. In this document, information as well as figures were taken from the actual CGA G-4.6 document.

In case of conflict between this document and the user's specification the information included in the order shall be the more stringent. The supply shall be in conformity with the rules of the country of the user and/or of the manufacturer.

See also 3.9.2 (References)

1.1.3 Terminology

<u>Although application of this document is voluntary a clear distinction is made between the definitions of shall and should.</u>

- Shall is used only when procedure is mandatory. Used wherever criterion for conformance to specific recommendation allows no deviation.
- Should is used only when a procedure is recommended.

1.2 Application of this document

1.2.1 Oxygen purity

This document is based on experience in manufacturing and operating centrifugal oxygen compressors and it is applicable to those machines operating on dry gases containing 90% oxygen and above and less than 10 ppm water (volume basis).

1.2.2 Oxygen enriched gases

Experience in compressing oxygen enriched gases containing less than 90% oxygen is very limited at this time. In the absence of such experience or established data, the working group members recommend that this document shall be considered for centrifugal compressors operating on oxygen enriched gases, and the degree of implementation shall be agreed between the manufacturer and user.

1.2.3 Moisture

Experience in compressing oxygen containing moisture is limited. Special precautions need to be taken particularly with reference to the materials of construction. Additional requirements shall be agreed between the manufacturer and user.

1.2.4 Axial turbo compressors

At the time of the revision of this document experience exists with pure axial compressors operated with enriched air less than 35% of oxygen which is not considered as oxygen service and not the purpose of this document. The working group members feel that the design of an axial compressor results in it representing a significantly greater hazard than a centrifugal compressor when used in oxygen service. The use of axial compressors in oxygen service is not covered by this document.

1.2.5 Discharge pressure

The recommendations in this document are based on the experience gained in the compression of oxygen up to 8.5 MPa in split line and barrel type casings, 4 MPa for integrally geared type compressors.

The requirements of the document have been shown to be adequate for these higher pressures. However, above 5 Mpa, it is recommended that attention should be paid to the use of compatible materials and a detailed rotor dynamics analysis conducted. The additional requirements shall be agreed between manufacturer and user.

1.2.6 Suction pressure

Traditional experience is with gas produced from Air Separation Units, i.e. a compressor suction pressure of less than 0.2 MPa g. This is the application that has been considered when putting forward the design of ancillary systems. If the compressor has an elevated suction pressure it is possible that some ancillary systems may need modification, e.g. the seal gas recovery system.

1.2.7 Driver

The majority of experience has been with the use of constant speed electric motor drivers. The document has been written giving the solution for this type of driver. However where another type of driver, e.g. steam turbine requires a different solution, this has also been identified by the document.

1.2.8 Maximum operating temperature

This is the highest temperature, which can be measured anywhere in the main gas stream, under the most severe operating conditions. Most experience exists for an operating temperature below 200°C which shall be considered as a maximum operating temperature. .

Note: Temperatures up to 60°C greater than the maximum main gas stream temperature can be found in certain parts of the compressor. These are normally areas where low gas velocities and high rotational speeds are found (e.g. behind the impellers). However, since, in production machines, it is not practicable to measure these temperatures they are not used as limiting parameters.

1.2.9 Speed

Speeds shall be according to ref [5] (API 617 Section 1.5 (7^{th} Edition 2002) e.g. Rated Speed, Normal Speed, Maximum Continuous Speed as well as Trip Speed.

2. Compressor installation

2.1 Hazard area

2.1.1 Description

The hazard area is defined as the area where an incident is most likely to occur and as a consequence is capable of causing danger and/or injury to personnel.

Note: The term hazard area should not be confused with Electrical Hazardous Area Classification.

It is necessary to consider a number of pertinent factors when determining whether or not an area should be classified as a hazard area. These include:

- Specific equipment service conditions of pressures, temperatures, gas velocities, purity, contaminants, etc;
- Compressor and other system equipment design factors such as type, size, materials of construction, operating speed, rotor dynamics, internal clearances, type of seal system, etc;
- History for equipment of similar design and operating conditions;
- Extent of safety monitoring and shutdown devices that provide early detection of problems before equipment failure;
- Proximity of oxygen equipment to personnel walkways, work areas and other equipment ; and
- Plant operators' standards, local government requirements, or other specific requirements.

The hazards that can result from a compressor fire include:

- jets of molten metal;
- projectiles;
- flash;
- blast and overpressure; and
- energy release in the gear case (if situated within the hazard area).

It is the responsibility of the user to specify the extent of the hazard area on a case by case basis.

2.1.2 Enclosure of the hazard area by a safety barrier

In most instances the hazard produced by a centrifugal oxygen compressor is such that the resultant hazard area would be so large as to be impracticable unless its extent is reduced by enclosing the compressor within a safety barrier. It is recognised that the extent of the hazard area is specific to the size and pressure of each application.

If the user proposes not to enclose the hazard area within a safety barrier then the user shall analyse the hazard, determine the extent of the hazard area, and demonstrate that the required safety criteria can be met without the use of a barrier.

Barriers shall be installed above 2.0 MPa gauge discharge pressure. However, in current practice, most users have adopted a 0.4 MPa gauge limit. National regulation may require a safety barrier for less than 0.4 MPa gauge.

2.1.3 Access to the hazard area

When the compressor is operating on oxygen, access to the hazard area is not permitted without specially written procedures. Warning notices to this effect shall be posted. Maintenance access panels shall be closed. Routine visual inspection shall be done remotely through approved safety windows or by using cameras, or other devices.

Before entering the hazard area, after the compressor has been shut down or changed over to dry air or nitrogen, the atmosphere within the enclosure shall be analysed to ensure that it is safe to enter. The oxygen concentration shall be between 19.5% and 23.5%. When personnel are within the area, the oxygen concentration shall be continuously monitored.

2.1.4 Equipment location

2.1.4.1 Equipment that shall be within the hazard area

- Compressor casings/volutes;
- Compressor gas coolers and inter stage piping;
- Suction filter;
- Throttling valves and downstream piping to the first elbow or tee – e.g. recycle valve;
- The first elbow in each pipe to and from the compressor; and
- Piping components subject to sonic velocities or high velocity impingement.

2.1.4.2 Equipment that shall be outside the hazard area

- All instrumentation except, primary sensing elements, vibration and position proximitors, and temperature measurement junction boxes; and
- All valves and controls that require manual adjustment while the unit is operating on oxygen service shall be capable of operation from outside the safety barrier.

2.1.4.3 Equipment that may be either inside or outside the hazard area

- Power operated isolation valves and discharge check valve

If located within the hazard area these valves shall be protected from the effect of the fire with their own shield;

- Gearbox and lube oil reservoir

The gearbox and lube oil reservoir location is determined by the compressor design and equipment layout;

a. Driver

  - If the driver is not an electric motor then it shall be outside the hazard area. In the case of an electric motor drive it is preferred that it should be located outside the hazard area.
  - If the motor is located within the hazard area, the safety barrier ventilation should be arranged in such a way that air from outside the enclosure is drawn across the motor to ensure that in the event of an oxygen leak an oxygen concentration build up around the motor is minimized; and.

- Lubricating oil system

If located within the hazard area, the number of connections shall be minimized to prevent oil leaks

2.1.5 Service pipes and electric cables within the hazard area

If it is not possible to avoid the routing of service pipes and cables through the hazard area then they should be protected against fire as far as practicable.

2.2 Safety barrier

2.2.1 Purpose

The primary purpose of a safety barrier is to prevent injury to personnel. It has a secondary function in that it lessens damage to adjacent equipment. A safety barrier achieves the above by preventing flames, jets of molten metal or projectiles that have caused burn through of any of the oxygen containing equipment within the hazard area from penetrating or collapsing the barrier in the event of an oxygen fire.

2.2.2 Responsibilities

It is the responsibility of the user to design and specify the safety barrier. The manufacturer shall supply any necessary information as required.

2.2.3 Nature of “Burn through”

2.2.3.1 Likely burn through positions

The majority of fires start in areas of high internal component or gas velocity. Therefore the areas around the impeller or recycle valve are likely sites. “Burn through” is most likely to occur at places close to the seat of the fire where the gas pressure and/or velocity are high and the thermal mass is low. Therefore the primary risk areas are:

a. compressor casing;

b. compressor shaft seals;

c. expansion bellows adjacent to the casing/volute;

d. first and second bends in the process pipework immediately upstream and downstream of the compressor flanges;

e. recycle valve and its associated outlet pipe and the first downstream bend

f. drain and vent connections; and

g. <u>safety valve piping systems</u>.

2.2.3.2 The Results of “Burn through”

2.2.3.2.1 Jet of flame and molten metal

This will burn through equipment on to which it impacts directly, unless this equipment is of large thermal mass or is protected by a fire-resistant heat shield. The barrier shall also be strong enough to withstand the impact of the jet.

2.2.3.2.2 Spray of molten metal

Accompanying the jet is a widening spray of molten metal which spatters equipment over a wide area.

2.2.3.2.3 Blast and overpressure effect

This is caused by the release of high pressure gas. This will cause the barrier to collapse unless it has been allowed for in the design. Normally the barrier is designed to withstand a certain overpressure and a sufficient vent area is provided to ensure that the design overpressure is not exceeded. This is a particularly difficult design problem in the case where the safety barrier is also an acoustic shield.

2.2.3.2.4 High velocity projectiles

The release of pressure and the rotational energy of the rotor accelerate projectiles which either pass through holes burnt in the casing or rip holes in the casing and go on to hit the safety barrier. The barrier shall be strong enough to withstand the impact.

2.2.4 Strength and burn through criteria

The barrier shall withstand the force resulting from the impact of a jet of molten metal issuing from a hole burnt in the compressor or pipe work, hitting the safety barrier, plus the overpressure due to the release of the stored inventory of the oxygen. The above requires calculation on a case-by-case basis because it varies with the size and the discharge pressure of the compressor. The minimum force that the barrier shall be able to sustain is 2 KPa projected over the wall area. This value is based on the accumulated experience of members of this Working Group.

The barrier shall be designed to resist the effect of a jet of molten steel for 30 seconds without being breached. (see 2.2.5).

Therefore, the design shall consider the following load types:

- sustain temperature of molten metal
- blast and overpressure; and
- projectile impingement.

2.2.5 Materials of construction

Concrete safety barriers are a very effective way of meeting the strength and burn through criteria and have been used successfully (see 2.2.4). Experience has shown that the concrete can be badly damaged - but not breached by the direct impact of molten metal and flame.

Steel structures have been used successfully. The detail design shall ensure a structure which has no weak point that can be breached by the overpressure or the impact from jets of molten metal or projectiles. Structural steel members, carbon steel walls, doors and closure plates that are likely to be exposed to the impact of a jet of molten metal shall be protected by a fire resistant heat shield

The fire resistant heat shield may be a plaster like material which is “trowelled” on or it can be in the form of panels. Calcium silicate or shale board has been found to be effective. Not only shall the material form an effective heat shield but it shall also be mechanically strong enough to resist the scouring effect of the jet of molten steel. It is for this reason that the rockwool used in acoustic shields is not acceptable as a heat shield in this application. The fire resistant heat shield shall be supported so that it is prevented from being broken up by the force of the jet. Field trials by one of the working group members have shown that a layer of heat resistant material 20mm thick will satisfy the required burn through criteria.

Inspection ports, if provided, shall be covered with reinforced glass or equivalent and shall meet the required strength criteria.

2.2.6 Layout of the safety barrier

The barrier shall meet the following criteria:

- Vertical sides shall extend at least 0.6m (2 ft) and 15° degrees in the vertical elevation view above the height of any part of the compressor or piping that contains oxygen and no less than 2.4m (8 ft) above the walking area.

- The barrier shall block any line of sight to permanently installed platforms or buildings within 30m that have normal traffic or occupancy.

- There should be space inside the barrier to allow for normal maintenance.

- The design of the safety barrier shall be such that, when all the closure plates are in place and the doors shut and locked or latched, the wall shall provide a complete unbroken barrier with no weak spots. Consideration shall be made for emergency egress. Labyrinth entrances are also allowed as shown in Figure 1.

- If the barrier has a roof, ventilation ports shall be located at high level pointing in a safe direction.

- The safety barriers shall be designed to cope with the inventory of high pressure gas that is released when burn through occurs. If the barrier has an open top or a partial roof this does not represent a problem. If the compressor is fully enclosed, normally for acoustic reasons, then sufficient open area shall be provided to avoid over pressuring the enclosure. The following ways of achieving the required open area are recommended:

    - A permanently open area with acoustic splitters.

    - Acoustic louvers which are self-opening.

    - Acoustic doors, which are self-opening, hinged so as to have a small angular moment of inertia.

    - Concrete or steel caps, which are lifted by the gas pressure, provided that the caps are adequately restrained.

  Note: The open area shall be sited away from the compressor where the hazard is least. The open area shall be sited in a position so that the operation of the doors and the blast of hot gas shall not cause a hazard to personnel.

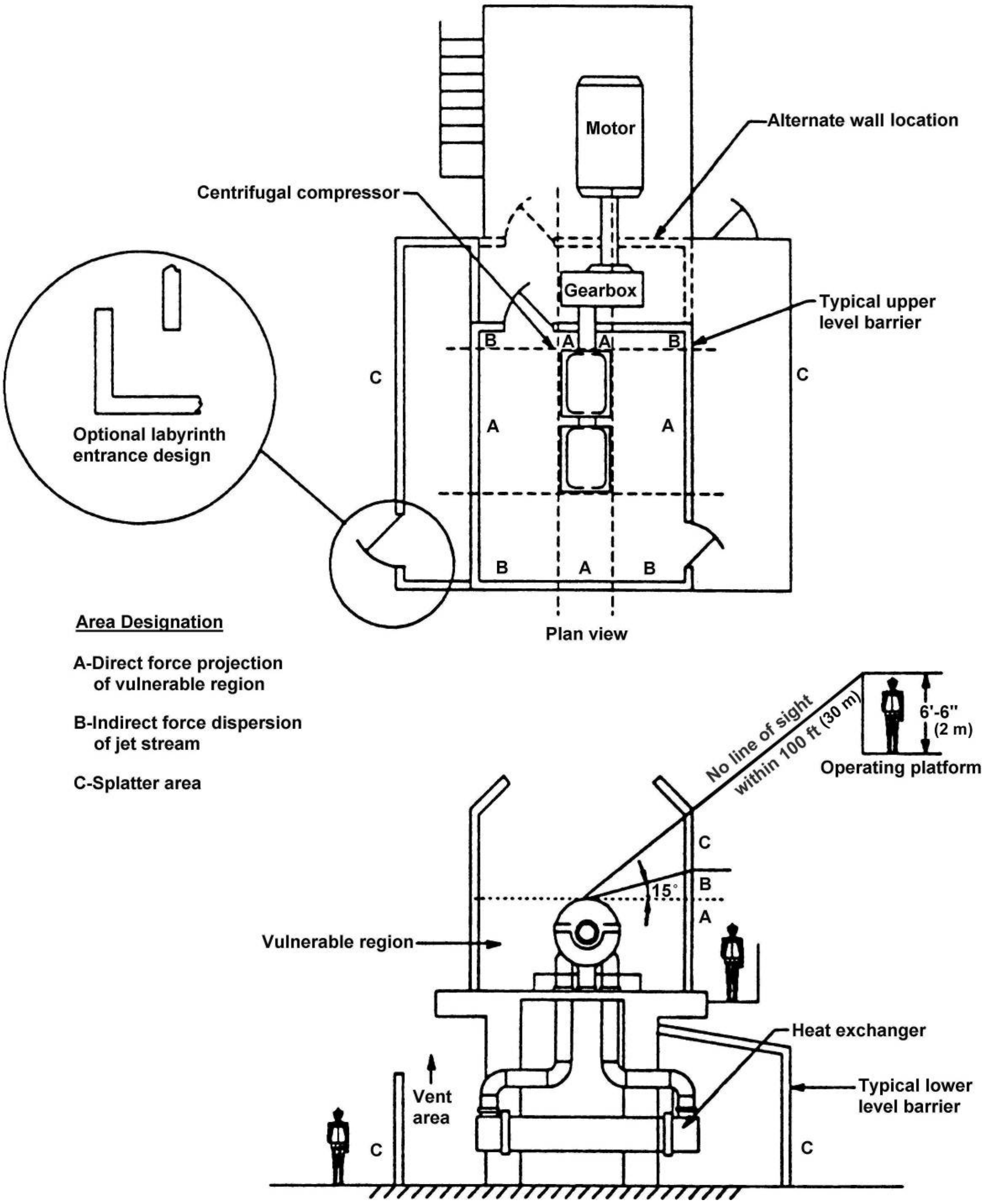

Figure 1 Centrifugal oxygen compressor impact force distribution on barrier

2.2.7 Safety barrier miscellaneous design features

2.2.7.1 Oxygen accumulation

Since oxygen is denser than air at the same temperature it tends to accumulate in depressions or enclosed spaces. It is preferred that trenches or pits are avoided. When trenches are used inside the hazard area for cable routing they should be filled with sand. The safety barrier shall be provided with sufficient ventilation to prevent a build-up of oxygen around the compressor. If the barrier is open topped this is normally adequate, however if it is enclosed then forced ventilation should be provided at the rate of not less than 6 air changes per hour.

2.2.7.2 Nitrogen asphyxiation hazard

If the compressor has the facility for being test run on nitrogen or nitrogen is being used for the seal gas then an asphyxiation hazard can exist. The barrier should be designed with at least two outward opening exit doors or labyrinth entrances at each level and sufficient walkways to allow quick exit.

2.3 Location

2.3.1 Compressor house

If the safety barrier is within a compressor house then the compressor house design shall take into account the overpressure from the release of high pressure gas that will occur in the event of a fire.

2.3.2 Safety of personnel and plant

Oxygen compressors should be located away from main walkways, normally occupied areas, (especially elevated ones) and other hazardous or critical equipment. It is important that there are good and clear evacuation routes from the vicinity of the oxygen compressor installation.

2.3.3 Erection and maintenance

The location shall be such that the equipment can be kept clean and dry during installation and maintenance. During the design phase attention should be paid to the crane set up and equipment lay down areas that will be required for erection and maintenance. Different styles of compressor have different requirements.

2.3.4 Overhead cranes

Precautions shall be taken to prevent oil or grease from, overhead or mobile cranes, entering the oxygen clean areas or contaminating the hazard area during erection, maintenance and operation. The layout should preclude the need for cranes to transit over operating oxygen compressors, if this is not possible the cranes should be pendant operated and their movement and load strictly controlled. When not in use the crane should be located away from the hazard area.

2.4 Fire protection and precautions

2.4.1 Introduction

Fires in oxygen compressors, once started, are nearly impossible to extinguish until all the contained oxygen gas is consumed in the fire or vented to atmosphere. While it is true that once the oxygen supply is cut off and the inventory reduced the actual oxygen fire will be over quickly, extensive damage is likely and sometimes other combustible material, such as oil, is ignited and continues to burn after the actual oxygen promoted fire is out. For these reasons, oxygen compressor systems shall be designed to minimize the initiation of any fires and to vent the oxygen inventory as quickly as possible in case of a fire or potential ignition. These are the most effective ways of reducing the chance of personal injury and minimizing equipment damage.

Fire protection should also include a strict housekeeping policy, developing an emergency plan with local fire officials and supplying the proper fire fighting equipment.

2.4.2 Isolation and quick venting systems

Isolation and quick venting of the oxygen inventory have been found to be the most effective methods of minimizing the extent of an oxygen fire. In case of a compressor trip due to an emergency, the primary consideration should be to isolate the compressor from the oxygen supply and immediately dump the oxygen inventory so that the pressure in the entire compressor system falls to 0.1 MPa gauge in less than 20 seconds. To achieve this, automatic and quick operation of isolation and vent valves are required. A vent valve at an intermediate stage may be required in addition to the discharge vent valve.

2.4.3 Flammable material

The presence of flammable materials in the hazard area constitutes a hazard and should be avoided wherever possible. Where this cannot be avoided, for example, during maintenance operations, then any flammable materials introduced into the hazard area should be removed before oxygen is introduced to the compressor

2.4.4 Protection of personnel

Entry into hazard area is to be discouraged and shall be carried out only by trained personnel with the appropriate personal protection equipment. When a person has been in contact with an oxygen enriched atmosphere their clothes may have become saturated with oxygen and even when they have returned to a safe area they shall be careful not to approach any source of ignition (e.g. matches or an electric fire) until they have changed their clothes.

3. Compressor design

3.1 Machine configuration

Long operating experience exists with single shaft compressors with closed wheels built in accordance with this document.

Integral gear compressors with open and closed wheels have become more commonly used. These have the following design differences:

- Greater number of seals letting down to atmospheric pressure and in close proximity to the gearbox;
- More complex assembly;
- In general the stable rotor dynamic design of integrally geared compressors is more difficult to achieve than in single shaft compressors. Therefore additional consideration in the rotor dynamic design must be taken to provide acceptable rotor stability in oxygen service; and
- Greater sensitivity to upset condition, such as surge or inter-stage pressure release

3.2 Design criteria

3.2.1 Possible causes of an oxygen compressor fire

It is normally very difficult to ascertain precisely the cause of a fire in an oxygen compressor because the material, at and around the ignition site, are completely burnt up. Therefore during the design and manufacture of centrifugal oxygen compressor both active and passive safety measures shall be taken to guard against all of the causes of ignition listed below.

Cause of ignition, source of friction, or foreign material:

- Mechanical rub:
  Improper design, clearances, vibration, operating pressure, assembly or maintenance errors, bearing failure, thrust, alignment, improper inter-cooling, start up/shutdown instability (can include shock, adiabatic compression and surge).
- Large debris impact:
  Screen/filter failure or improper mesh size, weld debris or slag, (friction/shock) maintenance debris, shot, sand;
- Debris:

  Rub in areas, screens, weld debris or slag, oxides such as rust, high gas velocity maintenance, debris, shot, sand.

- Contamination:
  Oil, improper design of bearings/seals and/or associated vents and drains.

- Resonance:
  Debris in dead areas.

3.3 Materials: General

3.3.1 Construction materials

Compressor components that come into contact with oxygen shall be selected for their oxygen compatibility. Materials that fulfil these criteria usually have the following properties:

- high ignition temperature;
- high thermal conductivity;
- high specific heat; and
- low heat of combustion.

3.3.2 Use of aluminium

Because of its high heat of combustion the use of aluminium or alloys containing aluminium shall be limited for oxygen wetted or potentially oxygen wetted parts. However, aluminium will not sustain combustion below certain pressures and purities. <u>The use of aluminium shall be limited to a pressure less than or equal to 0.2 MPa gauge for the oxygen purity range covered by this publication.</u>

In addition the maximum permitted aluminium content in a copper alloy is 2.5%.

3.3.3 Oxygen compatibility of non-metallic materials

Non-metallic materials (such as for gaskets, O-rings, lubricants) that have been approved by BAM. (Federal Institute for Material Testing, Berlin) Ref [7] or ASTM for the relevant oxygen duty are acceptable. This does not preclude other methods of determining compatibility by other independent bodies, laboratories and manufacturers.

3.4 Casings, diaphragms, diffusers and inlet guide vanes

3.4.1 Casings

3.4.1.1 Casing allowable working pressure

Calculations shall be carried out to determine the maximum pressure that the casing can experience during operation. It shall be the highest pressure of the following options that can be reached in the casing (or subdivision of casings into chambers) multiplied by an agreed safety factor between the user and the manufacturer.

- The maximum operating pressure, at the surge limit resulting from the maximum specified suction pressure at the maximum continuous operating speed. Agreed deviations from gas properties and suction temperature are to be considered.

Note: In some instances a rotor stability test at greater than the maximum design operating pressure is specified. If this is the case it should be taken into account when specifying the casing allowable working pressure.

- The maximum pressure that results from the maximum specified suction pressure and the greatest pressure rise possible with the given maximum drive power at the maximum continuous operating speed. Agreed deviations from gas properties and suction temperature are to be considered.

- The maximum equilibrium pressure reached in the compressor system under certain running or shutdown conditions.

- If the casing pressure is limited by a safety device set to a pressure agreed between the user and manufacturer then this pressure can be used as the casing allowable working pressure. The casing may also be sub-divided into chambers for calculation and testing. In this case, the maximum possible pressure in these chambers is then to be used as a basis, taking into consideration the aforementioned aspects.

3.4.1.2 Pressure tests

3.4.1.2.1 Strength test

The compressor main casing or volutes shall be hydrostatically tested in the manufacturing facility with potable water at a minimum test pressure of 1.3 times the allowable working pressure of each portion of the casing. The casing allowable working pressure is defined in 3.4.1.1.

The test pressure shall be held for at least 30 minutes to permit complete examination of the casing under pressure. Casings and volutes that leak under hydrostatic test shall not be acceptable.

3.4.1.2.2 Porosity test

It is recommended that all compressor casings or volutes be subjected to an internal gas pressure not lower than the allowable working pressure and thoroughly examined for porosity by suitable methods as agreed between user and manufacturer in the order.

3.4.1.3 Casing material

The following materials have proved satisfactory with regard to the criteria listed in 3.3:

- grey cast iron;
- nodular cast iron;
- high alloy steel - cast or fabricated; and
- welding of cast-steel and fabricated steel casings is permitted if the execution and heat treatment are properly conducted.

3.4.1.4 Casing repairs

All internal spaces of the casing should be easily accessible for cleaning and inspection. Hard soldering or metal locking repairs to cast-iron casings are not permitted unless agreed between manufacturer and user. Minor defects in cast casings may be repaired with screwed plugs. The document requires that these plugs be positively prevented from falling into the compressor. The preferred way is to use positively locked, taper plugs from the outside only. Welding repairs to grey cast iron is forbidden, but, with the permission of the user, may be carried out on the other materials listed above. The use of non-metallic materials for repair work is forbidden.

3.4.1.5 Casing sealing material

If non-metallic materials are employed for sealing the casing, they shall be oxygen compatible and agreed by the manufacturer and user. Liquid sealant shall be applied to prevent it from creeping and projecting into the inside of the machine. If required, threads shall also be sealed by materials that are compatible with oxygen.

3.4.1.6 Anti-galling compound

If an anti-galling compound is to be applied to centreing fits, bolts, studs, etc. only compounds compatible with oxygen service shall be used. Molybdenum disulphides in powder form have proved their value for oxygen service. Compounds shall be mutually agreed between the manufacturer and the user.

3.4.1.7 External forces and moments

The compressor manufacturer shall specify the nozzle displacements due to thermal movements of the compressor. It is preferred that the permissible forces and moments on each flange/nozzle to which the user has to connect are 1.85 times the values calculated in accordance with standard ref [9]. If this is not possible then they shall be mutually agreed between manufacturer and user.

3.4.2 Diaphragms and diffusers

3.4.2.1 Materials of inter-stage diaphragms and diffusers associated with closed impellers

The diaphragms shall be designed to withstand the maximum possible differential pressures. : Grey cast iron and nodular cast iron have been widely used up to 5 MPa. High alloy steel; copper alloys; nickel alloys; copper nickel alloys are recommended above 5 MPa.

3.4.2.2 Materials of shrouds (diaphragms) and diffusers associated with open impellers

It is not permitted to use open impellers with shrouds made of materials less compatible than copper alloys or nickel alloys.

3.4.2.3 Diffuser - design features

3.4.2.3.1 Vane less diffuser with spiral collector

Pressure variation around the circumference of the diffuser can be powerful enough to excite the covers and back plates of the impellers. This phenomenon becomes more pronounced at “surge” and at “stonewall” conditions and more powerful at high pressures. If the diffuser is long enough the above danger is avoided. The diffuser diameter therefore shall be greater than 1.4 times the impeller diameter.

3.4.2.3.2 Fixed diffuser vanes

- The use of fixed diffuser vanes as integral part of the diffuser assembly in oxygen service has been proven over several years of operation. Fixed diffuser vanes can be used in oxygen service.

- The vanes are subject to strong excitation forces being close to the impeller and in an area of high velocity and changing density. The vanes shall therefore be subject to careful analysis to ensure that resonant modes are not excited. A fire is likely to be the result of diffuser vane failure.

- Diffuser vanes shall have no high energy excitation frequencies corresponding to multiples of the number of impeller blades and the rotating speed. The number of diffuser blades and the number of impeller blades shall have no common denominator and should preferably be prime numbers.

- The use of vaned diffusers is not permitted unless resonance calculations have been carried out. These calculations shall be based upon test data.

3.4.2.3.3 Variable diffuser vanes

Variable diffuser vanes involve very small angular movements, tight side clearances, blades with long unsupported lengths and complex operating mechanisms; when the above are combined with high excitation forces and their physical position in the compressor they represent a considerable additional risk. Because of the above and the relatively small operating experience, variable diffuser vanes shall not be used.

3.4.3 Variable inlet guide vanes

3.4.3.1 The use of inlet guide vanes is permitted. Experience exists with their use on the inlet of each casing of single shaft compressors and before each stage of integral gear compressors.

3.4.3.2 The design of the variable inlet guide vanes shall take into account

- Excitation due to the flow disturbances caused by the stage inlet piping;
- Excitation of the impeller;
- The design shall be such that either it is physically impossible for the vanes to go to the fully shut position or, if the vanes are permitted to go to the fully shut position, there shall be sufficient flow area to prevent the vanes being overloaded and to dissipate the heat caused by windage;
- They shall be of a non-lubricated design;
- The design shall avoid the risk of oxygen leakage to the atmosphere. The use of a seal gas system is recommended; and
- Suitable materials for oxygen service which shall be resistant to impingement and high velocity of gas

3.5 Rotating assembly

3.5.1 Impellers

3.5.1.1 Materials

High alloy steels (not austenitic) are the materials normally used for impellers.

3.5.1.2 Manufacture

Impellers may be cast, forged, spark-eroded, milled, brazed or welded. Riveted impellers shall not be used. The impellers shall be subjected to an over-speed test for 3 minutes at the speeds stated in 1.2.9. Following this test, the impellers shall be crack-tested and checked for dimensional changes. Two diameters, on the impeller, should be marked and the dimensional change for each diameter is to be found by comparing the length before and after the over-speed test. Impellers shall also be dye penetrant or magnetic particle tested. All dye and other penetrant shall be carefully removed after the test. Acceptance criteria shall be agreed between the manufacturer and the user.

3.5.1.3 Open impellers for geared compressors

- Open impellers have a smaller clearance between the rotating and stationary part of the stage, which leads to an increased risk of a high speed rub. This small clearance has to be set with the compressor cold. During transient operation, particularly during startup different parts of the compressor heat up at varying rates and there is a danger that this will cause the impeller to touch. The risk associated with this can be reduced by ensuring that the compressor is always started up using dry and clean air or nitrogen and brought close to operating temperature before changing over to oxygen.

- Open impellers are normally used in an overhung configuration. The seal system required for oxygen is quite long. The result is that the amplitude of vibration of the impeller can be large when a resonant mode of the rotor is excited. The smaller impeller to stator clearances used with open impellers results in a greater risk of a high speed rub.

- Impeller stress levels permit open impellers to be run at higher tip speeds with a resultant higher rubbing velocity.

- The blades on an open impeller are only supported at their base; therefore there is a greater likelihood of them being excited at a resonant frequency and failing in consequence. A frequency analysis of the individual impellers is of the utmost importance. The manufacturer shall demonstrate the location of the first three natural frequencies of the impeller and that these do not correspond to known existing frequencies due to, for example, diffuser vanes.

3.5.2 Shafts

The shafts of centrifugal compressors shall be forged from one piece and checked for defects using ultrasonic tests. The electrical and mechanical run-outs in the planes of the vibration probes shall be reduced to 6 micron peak to peak or less during the course of the manufacturing programme.

3.5.3 Rotor assembly

Shaft sleeves are permissible. Components shrunk onto or fitted to the shaft shall be carefully degreased before fitting.

For single shaft compressors, assembled rotors with shrunk on components shall be submitted to an over speed run prior to the final rotor balance in order to release all unequal settings of components on the shaft. Whenever a rotor is rebuilt, over speed shall be considered prior to balancing, see 3.9.1.

Thrust collars shall be machined <u>as part of the solid shaft</u> or positively retained using a locknut, shear ring or grip enhancement method. The use of a simple interference fit shall not be used.

3.6 Seals

3.6.1 Internal rotor seals

Depending on the type of compressor (single shaft or integrally geared), the internal rotor sealing has the function of keeping as low as possible the amount of gas leaking between impeller outlet and impeller inlet and between adjacent stages. Adequate clearances shall be provided between sealing tips and sealing faces, so that contact is limited to an amount agreed between manufacturer and user under all operating conditions. The internal seals of an oxygen compressor shall be only of the labyrinth type. The design and the choice of materials for the tips and sealing faces shall be such that in the event of contact the least possible amount of heat is developed and the resulting heat is readily dissipated.

3.6.1.1 Rotating tips

The following materials shall be used:

- Rotating tip - copper alloy or nickel alloy; and
- Stationary face – silver layer bonded to a copper alloy or nickel alloy backing

The thickness of the silver layer shall, as a minimum, take into account the shaft movement that will occur in the event of;

- a total bearing failure; and/or
- the rotor being excited in resonance

The silver shall be of such a thickness that the rotating tip will not cut through the silver layer and touch the copper alloy or nickel alloy backing.

The above criteria apply to both radial and axial labyrinths. It is important with this type of seal that the tips and the silver are designed in a way that ensures that the tips cut satisfactorily into the silver face.

Silver has shown itself to be a very safe material for use in seals. Experience has shown that it is safe to permit the rotating tips to cut into the stationary silver face during rotor excursions that occur during start-up and surge. The amount of cut in shall be agreed between manufacturer and user.

For <u>overhung</u> impellers, e.g., gear type compressor, the benefits of a silver counter face are well established in seal design. However, rotating labyrinth running against silver stationary counter face can lead to violent rotor excursions in the event of rub.

3.6.1.2 Stationary tips

The following materials shall be used:

- Stationary tip – silver mounted on copper alloy or nickel alloy base; and
- Rotating face – high alloy steel, copper alloy or nickel alloy

The stationary tip shall be of sufficient width to provide adequate strength and of sufficient height to prevent contact between the rotating shaft and the stationary copper or nickel alloy base in the event of a rotor excursion due either to a bearing failure or rotor instability. This criteria applies to both radial and axial labyrinths.

3.6.2 Atmospheric rotor seals

3.6.2.1 Function

The function of the atmospheric sealing is to preclude the possibility of any escape of oxygen out of the compressor as well as the possibility of the introduction of air or oil via the seal.

The seal must be effective during all operating conditions including standstill, start-up and run down, see 4.6.

3.6.2.2 Compressor atmospheric rotor seals - Labyrinth type

The atmospheric rotor seals shall be of the labyrinth type which is the only type of seal permitted by the document except under exceptional circumstances (see 3.6.2.3). With respect to design, materials and clearances this type of seal shall comply with 3.6.1.

At least 3 sealing chambers shall be provided. The inner chambers are connected to the suction in order to reduce the differential pressure across the seal to a minimum. The centre chamber is for venting or exhausting. The outer chamber is for the supply of seal gas.

It is an important safety feature and therefore a requirement of the document that the internal pressure of outer and centre seal chambers can be measured. The method of achieving this should be to provide separate measuring connections close to the seal chambers to ensure that the pressure measurement is affected as little as possible by the gas flow in the seal system. If the design of the compressor makes it impossible to fit separate measuring connections, when that it is agreed between the manufacturer and the user, it is acceptable to measure the pressure away from the seal chambers provided that the pressure drop due to flow between the seal chamber and the measuring point is insignificant compared to the pressure being measured. The manufacturer shall provide pressure drop calculations at seal clearances which are four times design. In the case of design clearances which are zero or negative the above calculation shall be based upon on clearances agreed between the manufacturer and the user.

3.6.2.3 Compressor atmospheric rotor seals - Alternative types

There are certain applications such as pipe line compressors where the use of labyrinth seals presents operating difficulties. Other types of seals may be considered as agreed between the manufacturer and the user.

3.6.3 Bearing housing seal

The function of this seal is to prevent oxygen from getting into the oil system and to prevent oil vapour escaping from the oil system. There are no special oxygen requirements. A labyrinth seal using normal seal materials has proved satisfactory.

3.6.4 Separation of rotor process gas seal and oil seals

As contamination of the process gas seals by oil and/or oil mist as well as oxygen into the lubricated parts can lead to major safety hazards, precautions shall be taken to avoid such situations.

3.6.4.1 Single shaft oxygen compressors

An air gap open to the atmosphere between the compressor casing and bearing housing shall be provided. This shall have an arc width at least equal to the shaft diameter and large enough to guarantee atmospheric pressure in the gap and enable the shaft to be clearly viewed. Weather protection may be necessary in outdoor installations. No restriction or pipe will be fitted to this opening. A continuously falling drain should be led from the bottom of the chamber in order to remove oil and detect leaks. The size of the drain shall be as large as possible to avoid the risk of blockage.

3.6.4.2 Integrally geared oxygen compressors with an air gap

Some integral gear compressor designs have an air gap open to the atmosphere. If they have an air gap open to the atmosphere, they shall be in accordance with 3.6.4.1.

3.6.4.3 Integrally geared oxygen compressors without an air gap

If there is no air gap, additional instrumentation shall be installed according to 4.6. The inter-space between gas seal and gearbox seal shall be vented and drained through drillings in the gearbox and/or volute. Vent sizing shall limit the velocity to 30 m/sec (100 ft/sec).

3.7 Bearings and bearing housings

3.7.1 Bearing type

Radial and thrust bearings shall be of the hydrodynamic type, designed to damp out self-excited or externally excited vibration and designed to accept backward rotation. Radial bearings for high speed shafts shall be of the tilting pad design.

3.7.2 Thrust bearing size

The thrust bearings shall be sized for continuous operation under the most adverse specified operating conditions. Calculation of the thrust force shall include but not be limited to the following factors

- Seal minimum design internal clearances and twice the maximum design internal clearances;
- Pressurised rotor diameter step changes;
- Stage maximum differential pressures;
- Specified extreme variations in inlet, inter-stage, and discharge pressures;
- External thrust forces transmitted through the couplings;
- The maximum thrust force from the sleeve-bearing-type drive motor if the motor is directly connected;
- Thrust forces for diaphragm-type couplings shall be calculated on the basis of the maximum allowable deflection permitted by the coupling manufacturer; and
- If two or more rotor thrust forces are to be carried by one thrust bearing (such as in a gear box), the resultant of the forces shall be used provided the directions of the forces make them numerically additive; otherwise, the largest of the forces shall be used.

3.7.3 Provision for vibration probes

Bearing housings shall be designed to incorporate the following vibration measuring instruments:

- two non-contacting shaft vibration probes at right angles to one another on or near each high speed bearing and

- one keyphaser probe per high speed shaft.

3.7.4 Bearing failure - Resultant rubs

During normal operational procedures an agreed amount of limited contact is permitted in the seal, see 3.6. The manufacturer shall carry out an analysis to determine what parts of the compressor will rub in the event of a catastrophic rotor excursion which can be caused by an axial or radial bearing failure. The manufacturer shall make every effort to ensure that the resulting rubs that occur during the compressor run down shall meet the following criteria:

- The partners in the rub shall be any combination of silver, copper alloy, nickel alloy, high alloy steel, e.g., a cast iron to low alloy steel rub is not permitted, and

- At the rub site there is high heat capacity and good heat transfer.

At the design stage the manufacturer shall supply a table of clearances and materials that demonstrates that the above requirements have been complied with.

3.8 Rotor dynamic analysis, verification tests and data to be provided

3.8.1 Summary

An important contributor to the safe compression of oxygen is a well-designed compressor and an important aspect of the compressor design is a stable and well damped rotor system. An unstable rotor results in high vibrations and large rotor deflections, which in turn cause high speeds rubs which are a prime cause of oxygen fires. It is for this reason that the document emphasises the need for detailed mathematical modelling of the rotor system over the whole range of expected operating parameters followed by tests in the workshop or field to verify that the rotor system is satisfactory.

3.8.2 References

This document basically follows internationally recognised standards and practices API 617 (7th Edition 2002) Ref [5] item 2.6 shall be used as the basis including testing and acceptance criteria, with the exceptions and clarifications given as follows.

- For compressors with rigid coupling, train analysis shall always be performed (API 617 Item 2.6.2.6) Ref [5].

- An internal rub on an oxygen compressor is of much greater importance than on, for example, an air compressor since it represents a possible source of ignition. For this reason the maximum amplitude of any component within the oxygen envelope shall not exceed 75% of the internal clearance when the displacement at the probe location is at the trip level according to 3.9.2 (API 617 Item 2.6.2.12).Ref [5]

- Additional testing is proposed when either safety margins or clearance requirements have not been met. Since stable rotor-dynamics are essential for an oxygen compressor any failure to meet the design requirements must be rectified to meet the requirements of 3.8.

- Verification tests shall be performed using dry air or nitrogen.

Due to their physical nature any responding shaft vibrations that occur can always be related to forced, to self-excited or to parameter excited vibrations. The sources of these vibrations and their effects on the rotor system shall be analysed by calculations, if they are expected to occur in the actual design.

3.9 Balancing and vibration

3.9.1 Balancing

High speed balancing shall be considered on all rotors of single shaft compressors running above their first bending critical. The first bending critical is the mode in the real rotor system corresponding to the first critical of the same rotor in rigid bearings. The assembled rotors shall be balanced at their maximum operating speed. Balance corrections shall be done according to the mode shapes without any unallowable influence of the low speed balanced quality according to Ref [6] (ISO 1940]

The acceptance criteria to be met for the high speed balancing shall be as follows:

The bearing pedestal vibrations shall be in accordance with Ref [8] (ISO 10816) and shall not exceed the following limits:

- At critical speeds = 4.5 mm/s (RMS)
- within the operating speed range (from minimum operating speed to maximum continuous speed) v rms = 1.8 mm/s
- up to and including trip speed = 4.5 mm/s (RMS)
- The relative shaft vibrations in normal operating conditions shall be in accordance with API 617 item 2.6.8.8

3.9.2 Vibration alarms and trips

There is no recognized rule for setting alarm and trip levels. Many operators base the setting upon the actual running levels achieved in operation. Unless otherwise specified by the manufacturer of the compressor, the values set out below are based on API 617 [5] and should be regarded as maximum levels provided that these levels are below 75% of the nominal clearance.

- Maximum permissible alarm setting

  $A = 2.0 \times (25.4 \times (12{,}000/N_{max})^{½})$

- Maximum permissible trip setting

  $A = 3.0 \times [25.4 \times (12{,}000/N_{max})^{½}$

Where:

N_{max} = max continuous speed (rpm)

A=Amplitude of unfiltered vibration in micron peak-to-peak

3.10 Insulation and earthing

Great care shall be taken to insulate and earth the electric drive motor correctly to prevent currents circulating through the compressor which, experience has shown, can damage the bearings, couplings, and gear teeth. This phenomenon can occur in all types of compressor but special care is required in the case of oxygen compressors because the consequence of bearing damage could be a fire. Earthing of the compressor shafts is an optional requirement of the document.

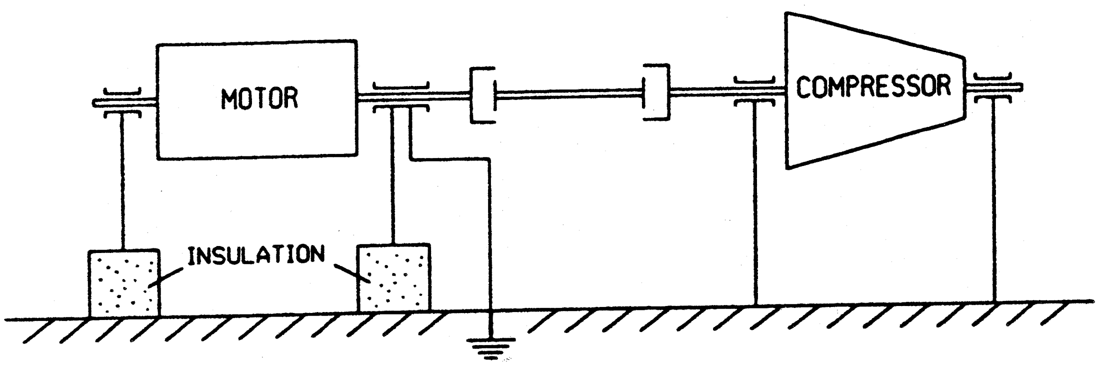

Figure 2 Earthing of compressor shafts

4. Auxiliaries design

4.1 Coolers

4.1.1 Scope of supply

It is recommended that the coolers be supplied by the compressor manufacturer as it is their ultimate responsibility to ensure that the complete machine be constructed under clean conditions. The user is responsible for ensuring that the manufacturer has been given sufficient information about the water quality to enable the correct materials to be selected.

4.1.2 Types of cooler

Any type of cooler can be accepted, provided that materials are oxygen compatible and that adequate cleaning can be achieved (see also 5.3).

4.1.2.1 Design features - Specific to coolers with gas in the shell

This type of cooler has “cooler heads” containing the water channels to tube bundle. To assure a positive inspection for oxygen cleanliness, they should have removable tube bundles.

4.1.2.2 Design features - Specific to coolers with gas in the tubes

This type of cooler should be U type or have a single gas pass

4.1.2.3 Design features common to both types of cooler

Care shall be taken that components, e.g., bolts, are positively secured to avoid the danger of them coming loose and being carried into the oxygen stream.

The design shall minimize the risk of leaks between the oxygen and the water sides.

Care shall be taken to ensure that the cooler tubes are properly supported and are not susceptible to machine or fluid induced vibration. The tube supports and baffles shall be of a suitable design and materials to ensure that they do not damage to the tubes. Experience has shown that to achieve this it is advisable that the support material that is in contact with the tube should be softer than the tube material.

When the tubes are expanded into the tube-sheets the lubricant used shall be oxygen compatible.

4.1.2.4 Material selections that are common to both types of cooler – Oxygen side only

The materials of the tubes and fins (if any) in contact with the oxygen shall be copper or copper alloy.

Commonly used materials are Muntz metal or naval brass for the tube-sheets and admiralty brass or 90/10 copper/nickel for the tubes. The fins are normally made of copper.

Tube-sheets made from carbon steel can also be used provided that cooling water quality avoids corrosion problems (for example with closed circuits or appropriate water treatment).

Gasket material in contact with the oxygen stream shall be compatible with oxygen and agreed between the supplier and the user. Gaskets shall not protrude into the gas stream.

4.1.2.5 Establishment and maintenance of oxygen cleanliness - Gas in Shell Type

One of the concerns with this type of cooler is the oxygen cleanliness of the cooler bundle because:

- It requires specific equipment to clean it after assembly or re-clean it if it becomes contaminated; and

- There is no simple way of checking its cleanliness in the field.

The following procedure has been found to work well and is recommended:

- clean for oxygen service, assemble the cooler completely and seal all openings with heavy blanks in dedicated workshop; and

- ensure that the blanks are only removed under the supervision of the “designated” person, (see 6.1).

If the cooler shell is made of carbon steel or cast iron the parts which are in contact with oxygen shall be preserved and protected against corrosion. Furthermore:

- paint is not permitted.

- zinc coating, in this application is permitted by the document, with the provision that good adherence is assured by compliance with the following conditions:

  - hot dipping is the only acceptable process

  - the cooler design shall be suitable for hot dipping

  - if zinc coating is used, the preferred thickness of the zinc is between 200-600 micron but a greater thickness is acceptable if good adherence has been verified.

- surface passivation by the use of phosphoric acid is permitted.

4.1.2.6 Establishment and maintenance of oxygen cleanliness - Gas in tube type

It is possible to establish oxygen cleanliness in this type of cooler, because the gas header can be detached for cleaning and inspection.

Appropriate cleaning equipment shall be used for this type of cooler in the field.

In order to ensure that the cooler remains oxygen clean during shipping and erection it is recommended that the unit is sealed with heavy blanks which are only removed under the supervision of the “designated engineer”, (see 6.1).

Precautions shall be taken for cleanliness preservation and re-cleaning shall be done when necessary.

4.1.3 Vents and drains

Suitable means shall be provided to vent all high points and to drain all low points on the water side. It shall be possible to check for cooling water leaks to the process side with water circulating prior to starting the compressor.

The oxygen side drains shall be directed to a ventilated area. The minimum pipe diameter of the vent and drain connections should be 20mm and equipped with a full bore valve. Vent and drain connection can run in critical flow conditions; therefore care shall be taken of high velocities and associated risks and appropriate exemption materials selected according to Ref [2] for personnel protection where necessary.

4.2 Process pipework

AIGA 021, Ref [2], states that it does not apply to compressor units. However, compressor piping specifications, fabrication, cleaning and inspection shall follow the criteria shown in Section 5 to 7 of the reference document.

4.2.1 Extent

The recommendations contained in this section shall be limited to the piping directly associated with the oxygen compressor and included within the oxygen compressor unit. In general terms this is the oxygen compressor envelope which is limited to the piping downstream of the suction isolating valve and will include the inlet filter system, all piping between the compressor and non-integral coolers, bypass valves and associated piping and discharge piping from the compressor through to the outlet shut-off valve.

4.2.2 Connections

All connections 40mm nominal bore or larger shall be flanged or welded.

4.2.3 Welding

The use of backing rings is forbidden. The root runs of all butt welds shall be made by a method that will minimise slag formation, a suitable method would be gas shielded arc welding. The welds shall be smooth and of regular form. Any slag or weld droplets shall be removed.

Welding checks shall be carried out. The methods and extent shall be agreed between the manufacturer and the user.

4.2.4 Prefabrication

To reduce the possibility of contamination on site due to ingress of moisture and dirt, oxygen piping should preferably be prefabricated except for the closing ends. All ends shall be suitably capped prior to dispatch to site.

4.2.5 Vents to atmosphere

Vent outlets shall be directed away from personnel and shall be located so that a concentration of oxygen is avoided. In the case of continuous vents, it is recommended that a dispersion calculation is carried out. The vent line is continuously exposed to the atmosphere and shall therefore be constructed of corrosion resistant material. The design of the pipework shall preclude the accumulation of water, Ref [11].

4.2.6 Special piping

Piping downstream of a recycle or dump valve shall be considered as a pressure letdown station and shall meet the requirement according to 4.2. The material selection for the recycle valve and the dump valve as well as the downstream piping shall be agreed between the manufacturer and the user.

A type of pressure reducing system which has proved satisfactory is the use of a matched combination of a valve plus a static pressure reducing device. This is typically either a multi hole radial diffuser or a multi plate axial diffuser. In this system the pressure let down is shared between the valve and device and it is normally designed so the velocity in the pipework downstream of the device is sufficiently low to permit the pipework to be made of carbon steel.

Note: The velocity in the individual diffuser holes will be sonic and the materials used shall take this into account. It is recommended that the valve and pressure-reducing device be purchased as a matched pair from the same supplier.

Whatever solution is chosen shall result in a low noise and low vibration pressure reducing system.

The recycle system shall be designed to pass 120% of the surge flow or 100% of the rated flow, whichever is the greater, at all operating conditions up to the maximum continuous speed. The recycle system, except for the special pressure reducing section described above may be made of carbon steel provided that the velocities comply with the limits specified in AIGA 021 [2]. This includes the point of entry to the main suction line and the main suction line itself.

The entry of the recycle stream into the suction line shall be upstream of the suction filter. In order to prevent damage to the suction filter the distance between the entry point and the suction filter shall be not less than twice the diameter of the suction piping.

4.2.7 Bellows

Bellows shall be entirely of metallic construction and made from corrosion resistant materials. They shall have a smooth inner sleeve to reduce turbulence and dust accumulation. Before assembly of the sleeve the inside of the corrugations shall be inspected for cleanliness.

4.2.8 Gaskets

Refer to 3.3.3

4.2.9 Acoustic and thermal insulation

Pipe external acoustic and thermal insulation material shall be compatible with oxygen at atmospheric pressure. Care shall be taken to ensure that the pipe insulation is sealed against the ingress of oil vapour. The material used shall be agreed by the manufacturer and the user. Pipe internal insulation is not permitted by the document.

4.2.10 Silencers

Silencers are forbidden in the recycle or interstage pipework. It is preferred that silencing of the suction is achieved by insulating the suction pipe but if this is not practical then the use of suction silencers is permitted. Suction silencers, if fitted, shall be located upstream of the suction filter. The silencer shall be manufactured using oxygen compatible materials and the design shall be so that the possibility of the internals breaking up is prevented.

4.2.11 Vaned elbows

Vaned elbows are permitted by the document. They shall be treated as impingement sites and therefore if fabricated in carbon steel shall comply with the impingement site velocity criteria according to 4.2. The formation of internal slag shall be precluded by the use of a welding procedure that uses inert gas shielding. The design of the vaned section shall facilitate post fabrication oxygen cleaning and inspection.

4.3 Manual valves

4.3.1 Manually operated main isolation valves

The manually operated main isolation valves are not covered by this document. Refer to 4.2

4.3.2 Manual valves which form part of the oxygen compressor envelope

Manual valves which form part of the oxygen compressor envelope, but which cannot be operated while on oxygen and not in oxygen flow path, which therefore will not experience high velocity oxygen may be made of carbon or low alloy steel. Valves which can be operated on oxygen shall be made of copper alloy, nickel alloy or stainless steel, e.g., low point drains and instrument root valves.

4.4 Main suction filter

A filter shall be provided in the main suction line as close as practicable to the machine inlet flange. It shall be installed before startup and remain throughout the lifetime of the machine.

4.4.1 Rating

The filter rating shall be capable of capturing all particle sizes larger than 150 micron maximum.

4.4.2 Materials and design strength

Refer to 4.2

4.4.3 Flow direction

The filter unit shall be designed so all attachments are upstream of the filter elements to be contained within the elements should failure occur.

4.4.4 Free area

The filter element shall provide a mesh open area of at least the area of the main suction pipe.

4.4.5 Precaution against installation errors

The filter unit shall be designed to prevent incorrect installation. An external indicator, such as an arrow, shall be provided to indicate the direction of flow.

4.4.6 Inspection

The filter element shall be easy to remove for inspection and cleaning. During removal it should fully retain all foreign particles.

4.5 Lubricating oil system

4.5.1 General

Parts requiring operator attention or on-line maintenance should be outside the enclosure. Lubricating oil pipes within the hazard area shall be kept as short as possible and be routed clear of oxygen pipework where possible. The number of joints shall be kept to a minimum and, where their use is unavoidable; they shall be easily accessible and located to avoid the possibility of lubricating oil dripping onto pipework or other equipment.

4.5.2 Oil pumps

A mechanically driven main oil pump which provides adequate lubrication during run down, caused by total loss of power, is the method preferred for motor driven units. All other methods are more complex and require careful consideration. However, if in a particular design the mechanically driven oil pump is not able to provide sufficient lubrication during the run down period, accumulators or an emergency oil pump should be provided to supply the required oil. Care shall be taken to keep the amount of stored oil to the minimum required so that, in the event of a seal gas failure, the likelihood of oil contamination is still negligible. Severe damage, which may result in a fire, will be caused if a compressor runs down without lube oil. It is therefore considered unsafe to continue to run the compressor on the auxiliary lube oil pump if the main mechanically driven pump has failed.

4.5.2.1 Steam turbine driven units

Experience with steam turbine driven oxygen compressors is limited and the solution is more complex due to the requirement of the turbine bearings to be fed with oil during the cool down period. In the case where the compressor is shut down and the seal supply has failed a method of automatically isolating the compressor from the lube system shall be provided (see 4.6).

4.5.3 Filter

Dual oil filters should be provided. Switch-over during normal operation of the compressor without interrupting the oil flow to the bearings shall be possible. The filters shall be of a 10 micron rating and shall be installed downstream of the cooler. All the lube oil supply pipework downstream of the filter shall be stainless steel.

4.5.4 Oil heater

The surface area of the oil heater, if provided, shall be so no local over heating or cracking of the oil can occur.

4.5.5 Oil vapour extractor system

The lube oil tank shall be fitted with an oil vapour extractor complete with oil demister system. The design shall be such that it shall not be possible to exceed a predetermined negative pressure in the lube oil tank. Gas eductor/ejector system is preferred. Alternatively, precautions shall be taken if electrical equipment is used with regards to risk of ignition of oil vapour in oxygen enriched atmosphere. Electrical grounding of the system shall be ensured. The exhaust piping exiting the oil vapour extractor shall be directed to safe location. Non-metallic material shall not be used for the piping of this system.

The compressor startup should be interlocked in case of oil vapour extractor system is not working. If the oil vapour extractor falls during operation an alarm shall be given.

4.5.6 Oil tank

The lube oil tank shall be installed so that oil spillages during filling are limited to a specific area from which the oil can easily be removed.

In order to protect the oil tank from over pressure, resulting from hot gases generated by a compressor fire, an overpressure protective device vented away from personnel areas should be fitted in the top of the lube oil tank. It should be the same size as the lube oil return line and should have a relief pressure commensurate with the allowable pressure in the lube oil tank.

4.5.7 Control

The temperature and pressure of the oil supply shall be controlled automatically.

4.6 Seal gas system

4.6.1 Compressor seal gas system

The seal gas shall be dry oil free air or nitrogen. The compressor seal system shall maintain proper pressure differentials between sealing chambers under all possible operating conditions. This ensures proper gas flow direction within the seal. Special attention in this regard shall be paid to the transient pressures during startup and shutdown periods where adverse pressure differentials can occur.

High grade differential pressure measurement devices shall be installed at each shaft end seal location to signal adverse pressure distributions, and to shut down the compressor automatically in case of an unsafe seal chamber pressure distribution. See Figure 3 and 4 and 3.6.2.

In order to protect the compressor from the possibility of oil contamination when the seal gas supply has failed the seal gas and lube oil systems shall be suitably interlocked. See 4.6.3 Note 2 - and 3.6.2.

The pipework downstream of the compressor seal gas filter shall be made of non-rusting material, normally copper or stainless steel.

The seal gas filter shall have a rating of 10 micron or less.

4.6.2 Bearing seal gas system

This system has the simple function of preventing atmospheric air, which can be enriched with oxygen from getting into the oil system. It is not required to have the same high integrity as the compressor seal gas system, nor is it subject to process variations; it is therefore a much simpler system.

4.6.3 Schematic diagrams

Figures 3 and 4 and accompanying notes show the compressor seal gas systems in detail for both single shaft and integral gear compressors.

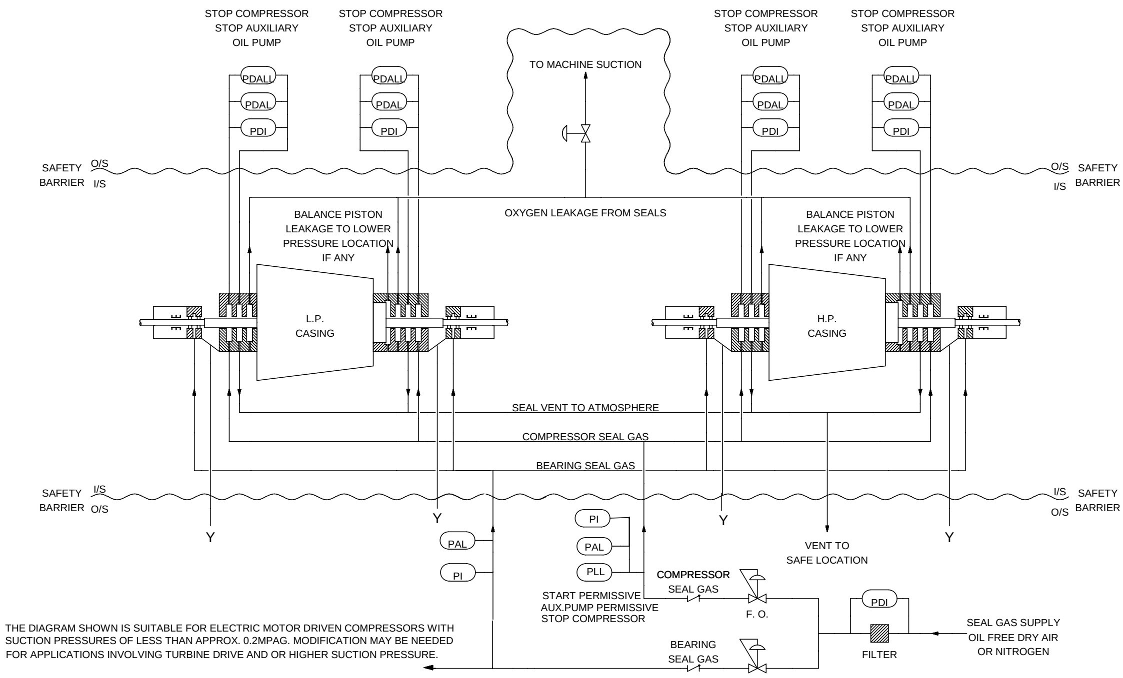

Figure 3 Single shaft gas supply schematic diagram

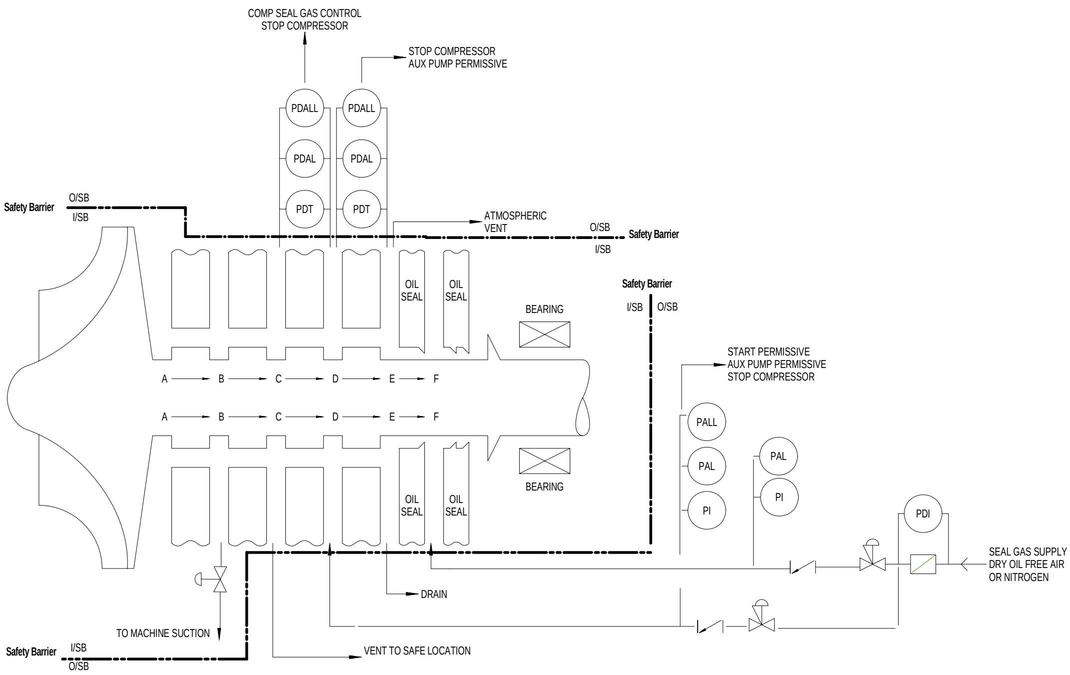

Figure 4 Geared compressor seal gas supply schematic diagram

Note 1 Sources of seal gas

a) The figures show both the compressor seals and the bearing seals being fed from the same supply. In order to ensure that there is no possibility of oil vapour back flowing along the bearing seal gas line and then being pushed in to the compressor seal gas line, the bearing seal system shall be supplied with a separate non-return valve and pressure regulator. The pipe run from the branch off the compressor seal gas system to the nearest bearing shall be at least 5 metres to minimize the risk of contamination by migration of oil. The compressor seal gas supply shall also be supplied with a non-return valve to ensure that there is no possibility of oxygen getting into the seal gas supply header.

b) An equally acceptable option is for the bearing seal gas and the compressor seal gas to be supplied from separate sources, e.g. nitrogen for the compressor seal gas and instrument air for the bearing seal gas. In this case the bearing seal gas does not have to be oxygen clean, or is a minimum length of line between the supply point and the nearest bearing required.

Note 2 Interlock with auxiliary lube oil pump

The interlock shown (low differential pressure between the seal centre chamber and seal outer chamber causes the compressor to trip and prevents the auxiliary lube oil pump from starting) is the best system for motor driven compressors with mechanically driven oil pumps.

Note 3 Control of the pressure in the seal inner chambers of the compressor shaft seal system

a) If the inner chambers of the seal system are connected to the suction pipework up stream of the suction throttle device (if fitted) then pressure in them will remain constant.

b) If the seal inner chambers are connected downstream of the throttle device then the pressure in them will vary according to the amount of suction throttling. In extreme cases this could cause the pressure in some of the seal inner chambers to become subatmospheric.

c) When starting up on total recycle with the suction and discharge isolation valves shut, the suction pressure will often drop well below atmospheric pressure for a period of several minutes and there is consequently a risk of dirt and damp air being sucked into the compressor via the vent and the seal centre chambers.

If this ingress of dirt and air is considered to be a hazard or represent a product purity problem then it is recommended that a back pressure valve is fitted in the line between the seal inner chambers and the suction thus ensuring that the seal inner chamber pressures are always kept positive and constant. Experience has shown that a self-acting control valve is not accurate enough for this application.

If the problem only occurs during start up then a power operated valve, which is shut during start-up and trip, but open during normal operation, is an effective solution. This system has the advantage over the back pressure valve in that it maintains the seal inner chambers at the lowest possible pressure and therefore minimises the leakage of oxygen to atmosphere via the seal centre chambers.

The mandatory protection of low differential pressure between seal outer chamber and seal centre chamber at each seal location protects against failure of the seal gas supply and dangerous failure of any of the seal components. This has been proven to be effective. However, failure of the inner section of the labyrinth seal will only be detected when it causes the seal centre chamber pressure to rise; by this time there will be a large flow back to suction. It may be of advantage to detect this leakage early. There are two methods:

- monitor the differential pressure between the seal inner chamber and seal centre chambers; and

- monitor the flow in the return line to suction.

Note 4 Seal pressure sensing points

The actual position at which the seal chamber pressures are sensed is very important and is discussed fully in 3.6.2.

Note 5 Gears for single shaft compressors

If the gears are situated within the hazard area then the bearing seal gas system shall be connected to the gear case and the gas used shall be nitrogen. Consideration should also be given to the fitting of a differential pressure indication, alarm and trip between the gear case pressure and the bearing gas supply pressure.

Note 6 Geared compressor seal gas supply schematic diagram

Geared compressor designed with a seal gas system with an open air gap shall have at least a pressure differential measurement between C and D with the associated alarms and trips.

Otherwise, additional pressure differential measurements between ports D and E shall be used with alarms and trips.

4.7 Controls and instrumentation

4.7.1 General

Protective controls and instrumentation shall be provided for every oxygen compressor in accordance with but not limited to those described in the following paragraphs. The minimum alarm and trip requirements are shown in paragraph Table 1. All measurements taken inside the hazard areas whilst the machine is on oxygen service shall be remotely read in a safe environment.

The trip system may be executed by computer software provided that the reliability, integrity and security are not less than the equivalent hardwired system.

The speed of the tripping system should be as fast as possible therefore the slowing down of the system to avoid trips due to transient voltage dips, etc. should be kept to an absolute minimum commensurate with the engineering of a reliable system.

If a fluid is used in a pressure transducer then it shall be oxygen compatible.

A “first up” or “first out” alarm system is recommended.

4.7.2 Control system

The control may be pneumatic, electrical or hybrid.

Table 1 Minimum instrumentation of oxygen compressors

Function		Indicator	Alarm	Trip	Interlock
1.0	**Oxygen**				
1.1	Compressor Suction pressure (after filter)	Σ	Lo	-	
1.2	Compressor Final discharge pressure	Σ	(Hi)	-	
1.3	Suction filter diff. pressure	Σ	(Hi)	-	
1.4	Compressor suction temperature	Σ	(Lo)	-	
1.5	Temperature of main gas stream at each process	Σ	Hi	Hi	
1.6	Temperature after each cooler	Σ	-	-	
1.7	Compressor flow	Σ	-	-	
2.0	**Seal Gas System**				
2.1	Compressor seal gas supply pressure	Σ	Lo		
2.2	Diff. Pressure between seal chambers (refer to Figures 3 and 4 and 4.6)	Σ	Lo	Lo[1]	
2.3	Bearing Seal gas supply pressure	Σ	(Lo)	-	
3.0	**Cooling Water System**				
3.1	Main supply flow	(Σ)	(Lo)	-	(Lo[2])
4.0.	**Bearings and Lube Oil System**				
4.1	Oil Filter diff. pressure	Σ	(Hi)	-	
4.2	Pressure after filter and cooler	Σ	Lo	Lo[3]	
4.3	Temperature in supply manifold after the oil cooler	Σ	Lo	-	Lo[2]
4.4	Temperature of each journal bearing	Σ	Hi	(Hi)[4]	
4.5	Temperature of each thrust bearing	Σ	Hi	(Hi)	
4.6	Main tank level	Σ	Lo	(Lo)	(Lo)
5.0	**Shaft Position and Vibration**				
5.1	Axial position (see 4.7.6.1 2)	Σ	Hi	Hi	
5.2	Radial vibration of high speed shaft at each bearing location (see 4.7.6.1 .1)	Σ	Hi	Hi	
6.0	**Miscellaneous**				
6.1	Speed (in case of variable speed drive)	Σ	-	Hi	
6.2	Surge detection	-	-	Σ	

NOTES

- \- = not required
- Σ Hi, Lo = mandatory
- (Σ), (Hi), (Lo) = recommended

1. interlock with auxiliary oil pump (see 4.6)
2. interlock to prevent start-up
3. starts auxiliary pump (see 4.5)
4. Trip on bearing temperature is mandatory for geared compressor

4.7.3 Anti-surge system

4.7.3.1 Introduction

A compressor in surge is subject to flow reversal, thrust reversal, rotor vibration and heating. Compressors are built to withstand a certain amount of surging without damage; however, if the compressor is allowed to surge continuously then severe damage can result. The consequences of an internal rub can be much more severe in oxygen service than other gases therefore specific considerations shall be taken in the design of the anti-surge system.

Protection against damage due to surge takes two forms:

- A modulating anti-surge system to keep the compressor out of surge; and
- A surge detector to shut down the compressor in the event of surge.

4.7.3.2 Modulating anti-surge control

The compressor is prevented from going into surge by the action of an automatically controlled recycle valve which allows gas to flow from the discharge (via a cooler) to the suction.

The system shall be designed to prevent the operator from overriding the automatic anti-surge controller.

The anti-surge control shall be designed to prevent the compressor from going into surge under all foreseen operating conditions and upset conditions. It is recognised that if there is a sudden failure in the system the compressor may surge and then be shutdown by the surge detector system. (see 4.7.3.3).

When the compressor anti-surge system is being designed the following points should be considered:

- Operation of quick acting valves downstream of the compressor may be a potential cause of surge and for this reason the entire anti-surge control system shall have a fast response time;
- The recycle valve and its associated downstream pipework shall be designed for continuous operation;
- If operation close to surge is required the effects of changes of pressure and temperature (gas and cooling water) on the surge characteristic should be considered;
- The position of the suction throttling device relative to the recycle line (see diagram 4.7.11). If the device is positioned downstream of the recycle line then it shall be equipped with a mechanical minimum opening stop so that there is still sufficient flow area to allow the anti-surge system to be effective;
- There is no simple algorithm which describes the position of the surge line of a multistage, inter cooled centrifugal compressor under varying conditions of capacity control, suction and cooling water temperature. The complexity of the modulating anti-surge system depends upon how close to surge it is intended to operate, how wide the variation in operating conditions are; and how severe the potential system upsets are;
- The anti-surge control line shall be set at least 8% by flow (at the design operating pressure) from the surge line and the following verifications shall be done:
    - The manufacturer shall calculate the surge points depending on site conditions (i.e. varying inlet and cooling water temperatures). These predicted surge points shall be checked on site over as wide a range as possible.
    - When the surge map has been produced an anti-surge controller shall be designed to fit the surge map.

- Consideration should be given to fitting a device which senses the rate at which the compressor is approaching surge and, if this is greater than a predetermined value then the recycle valve is opened a preset amount. The subsequent action depends upon the design of the system.

- The anti-surge control system shall meet the following requirement:

  - The anti-surge controller shall either be analogue or digital. If digital, the calculation is made a maximum of every 100 milliseconds. The shorter the calculation interval the quicker the possible system speed of response. .

Note: It is considered acceptable to use the main plant control computer (DCS) to carry out the anti-surge control functions provided that it can meet the above speed requirements and that it is as secure as a separate stand-alone controller. No delays, other than those required to combat transient electrical disturbances, shall be permitted.

4.7.3.3 Surge detection shut-down device

A surge detection and shutdown device shall be fitted. This shall trip the compressor after a maximum of 4 surges, thus safeguarding it from damage in the event of failure of the anti-surge control.

This device and the modulating anti surge control system shall be designed so that the risk of common mode failure is minimized.

Axial position or reverse flow detection (dp) shall be used for surge detection.

4.7.4 High oxygen temperature protection

Fast response sensors shall be installed in the oxygen path at each process stage outlet. They shall be positioned as close as practicable to the discharge nozzle and they shall be located before the first elbow. The temperature sensors can also detect a fire and trip and isolate the compressor.

The alarm and trip set points shall be agreed between the manufacturer and the user.

If production reliability is a concern, 2 out of 3 voting should be utilized.

4.7.5 High bearing temperature protection

The temperature of all high speed bearings shall be monitored with suitable sensing devices located in or close to the bearing pad. The measurement of the oil temperature leaving the bearing is not acceptable.

Note: In the case of tilting pad bearings it is important to:

- measure the temperature of the loaded pad(s); and
- ensure that the sensing device does not restrict the movement of the pad(s).

4.7.6 Vibration and shaft position

4.7.6.1 Compressor

4.7.6.1.1 Radial vibration

For single shaft type compressor, two vibration probes shall be fitted at 90° degrees from each other at each high speed bearing location. For geared type compressor, these probes shall be fitted on each bearing adjacent to the impeller.

4.7.6.1.2 Axial position

Non-contacting probes to monitor the axial position of high speed shafts shall be used for shafts with high speed thrust bearings and should be used for shafts with thrust collars. If axial probes are not fitted to high speed shafts with thrust collars then the axial position of the relevant slow speed shaft shall be monitored with a non-contacting probe.

The measurement point should form an integral part of the shaft.

4.7.6.1.3 Keyphaser

Provision shall be made to fit a keyphaser probe on each high speed shaft.

4.7.6.2 Gearbox

High speed parallel shaft of separate gear boxes shall have probes as the compressor (see 4.7.6.1.1).

Epicyclic gearboxes shall be fitted with an accelerometer based alarm and trip system.

4.7.6.3 Vibration probe monitoring system

The unfiltered output of at least one radial probe per location and the output of all axial probes shall be monitored continuously.

The time delays built into the alarm and trip system shall be reduced to a practicable minimum.

Failure of the system shall give an alarm.

Provision shall be made for the connection of vibration frequency analysis and phase displacement measurement equipment.

If starting on inert gas then a manual or time delay startup override is acceptable. If starting on oxygen then the trip system shall remain live and starting can be achieved using a ‘trip multiplier’ during the run up period.

4.7.7 Safety shutdown system valves

4.7.7.1 Purpose

The purpose of the safety shutdown system is to isolate the oxygen compressor and dump the oxygen inventory and minimize the consequences of a possible fire.

The system shall consist of the following valves:

- automatic suction isolation valve;
- discharge non return valve;
- automatic discharge isolation valve;
- high pressure and low pressure (if required) dump vent; and
- recycle valve.

The failure modes and operating speeds should be as shown in Table 2 and their position in the system according to the Figure 5

If the low pressure coolers are gas in shell then a Low Pressure dump vent is sometimes required to meet the requirement of reducing the discharge pressure to 0.1 MPa in 20 seconds, (see 2.4.2).

Table 2 Failure modes and operating speeds of system valves

Valve duty	Valve action					
	On Compressor Shutdown	**On Loss of Control Signal**		**On Loss of Electrical Signal or Motive power**		**Speed of action**
Automatic Suction isolation valve [1]	Shut	Not Applicable		Shut		10 sec [2]
Automatic Discharge isolation valve	Shut	Not Applicable		Shut [3]		10 sec[2]
Final Dump Vent	Open	Not Applicable		Open		2 sec.max [4]
Intermediate dump vent (if fitted)	Open	Not Applicable		Shut		2 sec.max[4]
Recycle valve	Open	Open		Open		2 sec Max.

1. For normal shutdown, the automatic suction valve can remain open if the suction pressure is < 0.1 MPa
2. The (maximum) time given above for closing the isolation valves shall be adjusted so that the dump vent valves and recycle valve have opened first.
3. If the valve loses supply it will fail into the correct position for isolating the compressor and may lead the compressor toward surge. However, the compressor is protected against surge according to 4.7.3
4. Auto reclose after 1 minute or when system is depressurized (See 2.4.2)

4.7.8 Oxygen humidity

4.7.9

If a dew point indicator is provided to detect water leaks, it should be able to be installed downstream of individual coolers.

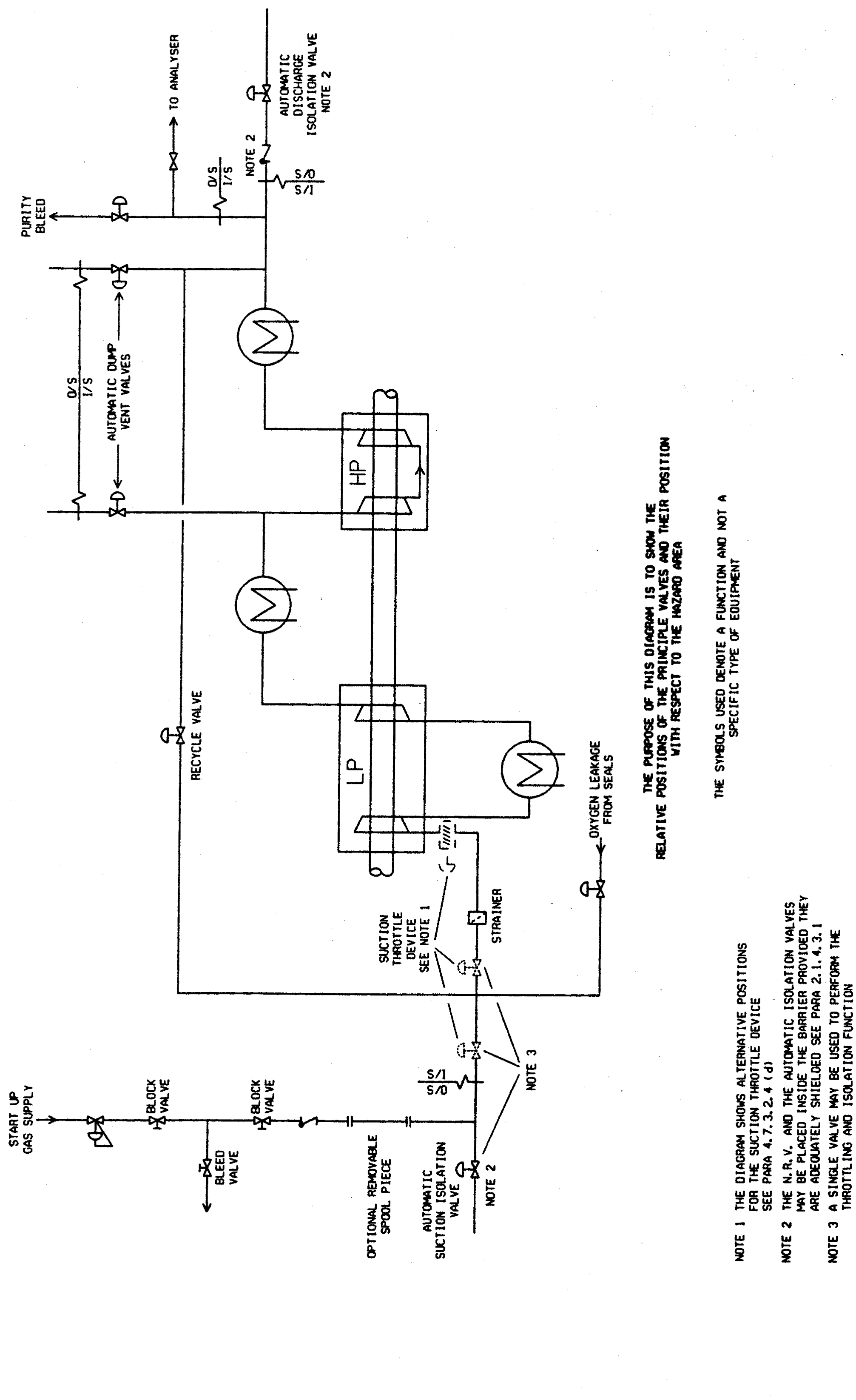

Figure 5 Centrifugal oxygen compressor system flow diagram

5. Inspection and shipping

5.1 Introduction

Compressors can be shipped from supplier's works either as fully assembled, and tested, oxygen clean units or as separate components to be erected on site. This can include site fabricated piping.

Any combination between the two above extremes is also possible.

5.2 Responsibility

Whatever the extent of prefabrication, there shall be a "designated" person responsible for ensuring that the compressor is correctly built. On request, the manufacturer or their representative shall provide from his staff an experienced oxygen compressor erector, who will be in charge of the unit until it is handed over to the user. It can be seen however that, if units or subassemblies are brought to site cleaned, tested and sealed, then the "designated" person's responsibilities extend back to the manufacturer's and major sub supplier's works.

5.3 Inspection and cleanliness standards

Cleaning methods and acceptance criteria to be followed shall be those shown in AIGA 012 "Cleaning of equipment for oxygen service" Ref. [3].

The criteria "clean for oxygen service" shall apply to:

- All parts that come in contact with oxygen; and
- Systems that supply gas to the oxygen compressor (e.g. startup gas) to the extent that the gas supplied is free of particles and hydrocarbons.

5.4 Preservation of oxygen cleanliness during shipping and storage

5.4.1 Equipment

All equipment sent to site "clean for oxygen service" shall be protected against contamination and corrosion. A label stating, "cleaned for oxygen service" shall be visible from outside the package. The size and complexity of the equipment being shipped dictates the appropriate method of preservation.

5.4.2 Individual components

Individual items such as valves, regulators, filters etc which are being shipped separately shall be protected, either by sealing within a strong clean plastic bag or for smaller components by vacuum wrapping.

Note: If the component requires protection against rusting then the plastic bag shall contain bags of desiccant with a colour change additive to detect moisture.

5.4.3 Subassemblies, which can be made pressure tight

5.4.3.1 Rust protection not required

Subassemblies that do not require protection against rusting for example a gas in shell cooler with a stainless steel shell shall have their openings sealed with full-face gaskets of oxygen compatible material and substantial covers of wood or metal. Plastic plugs or gaskets secured with tape are not permitted.

5.4.3.2 Rust protection required

Subassemblies that require protection against rusting shall have their openings sealed with gaskets and metallic covers. Their integrity shall be demonstrated before leaving the suppliers' works by leak checking against a low internal pressure. All spaces shall be blown out with dry oil free air or nitrogen before the subassembly is sealed.

Rust protection can be provided by one of the following means:

- Bags of desiccant, which contain colour change additive to detect moisture, shall be attached to the inside of appropriate opening covers and elsewhere within the subassembly as required. The number and position of the desiccant bags shall be painted on the subassembly exterior; or

- Pressurising the subassembly with dry oil free nitrogen. The subassembly shall be fitted with a pressure gauge and have a notice painted on it warning that it is pressurised.

Colour change type moisture detectors shall be fixed to the inside of selected opening covers to give confirmation that the preservation measures have been effective.

5.4.4 Arrival on site

When oxygen clean components and subassemblies arrive on site the preservation arrangements shall only be altered or removed with the approval of the “designated” person.

If the preservation is found not to be intact and if the moisture detectors, if fitted, have changed colour then the subassembly shall be opened for inspection and recleaned until the “designated” person is satisfied that the equipment is “clean for oxygen service”.

6. Erection and commissioning

6.1 Erection

6.1.1 Responsibility

(See Section 5)

The increased emphasis on packaged compressors means that the responsibility for the correct erection and the maintenance of cleanliness of the compressor system may well extend back to the manufacturer’s and major sub-suppliers’ works. Section 5.3, applies to the cleanliness standards throughout the erection of the compressor unit. The “designated” person shall keep a chronological record showing who carried out the main assembly work and who took the “as built” measurements and carried out the testing. This applies even if the person concerned came from another firm. It is also recommended that he keeps an “Oxygen Cleanliness Log” which records the time, person and place that each part of the oxygen circuit, including the gas feeds to the compressor were approved as “clean for oxygen service”. It should also record the inspection method used, e.g. ultra violet light, solvent analysis, etc.

The compressor should remain under the direction of the manufacturer until the provisional handing over has occurred. This normally takes place after a successful initial oxygen run.

6.1.2 Clearances

All axial and radial clearances between stationary and rotating parts of the compressor shall be measured and the results recorded during preparation in workshop or during erection at site.

6.1.3 Prevention of undue forces

To prevent undue forces being imposed on the compressor all joints shall be assembled without undue stress. Flanges shall be parallel and correctly aligned. This requirement applies to each flange of the compressor and the pipework.

6.1.4 Tools

The tools, appliances and measuring devices used during installation and assembly of the compressor and auxiliary equipment which come into contact with oxygen shall be cleaned with a suitable cleaning agent. Tools for the lubricating oil system or other parts of the machine shall not be used for oxygen carrying components. Only lint free cleaning cloths shall be used. When using lifting tackle, any contamination by oil from the ropes, gears or other sources of lubrication shall be prevented.

6.1.5 Hazard area

At an appropriate stage of erection the hazard area shall be declared a clean area and access restricted to authorised personnel only. All personnel entering the clean area should wear clean shoes or overshoes and clean overalls without pockets. Personnel shall be instructed in the need for cleanliness.

6.1.6 Oil flushing

Flushing of the lube oil system shall not be carried out unless the seal gas system and its associated interlocks with the lube oil system are fully functional. It is recommended that the lube oil system be checked for leaks during flushing by raising the temperature of the oil slightly above its normal operating point.

6.1.7 Foundation sealing

In order to prevent oil impregnation, the foundation of the compressor and associated equipment should be properly sealed prior to the commissioning of the lube oil system.

6.1.8 Purging after assembly

Once the compressor has been closed up, an oil-free, dry, non-flammable gas purge shall be maintained in the compressor via the labyrinth seals and at other points (e.g., coolers, piping, gaseous drain points) as necessary to ensure that a non-corrosive atmosphere is maintained in the machine.

6.2 Testing and commissioning

6.2.1 Introduction

High energy costs ,high site costs and the ability of manufacturers to test at full power in their works complete compressor assemblies in their contract configuration has meant that in some instances the best option is to ship from the manufacturer's works as a complete fully tested, oxygen clean compressor system. However, in other instances the best option is to site erect and site fabricate the compressor system.

It can be seen from the above that the section on testing must be flexible enough to cope with widely different circumstances. It is for this reason that the document now stipulates what objectives the testing shall achieve, and the type of test and readings that shall be taken to meet the objective. It does not stipulate where and in what order the testing shall be done.

6.2.2 General

Any instrumentation required for testing the machine, e.g., pressure gauges, flow meters should only be used for this duty. When they are used on site they shall be specifically cleaned and marked "FOR OXYGEN USE ONLY". All parts which are normally under pressure including the instrumentation, gas and oil pipework shall be subjected to a pressure test, unless specified elsewhere in the document. The type of test and test pressure shall be agreed between the manufacturer and the user.

6.2.3 Testing objectives

It is not permitted to put the compressor into oxygen service unless the testing has achieved the following objectives:

- Demonstration of the mechanical integrity of the complete compressor system over the predicted operating range;
- Verification of the rotor dynamic prediction and the stability of the rotor;
- Verification of the predicted thermodynamic performance;
- Functional demonstration of the instruments and controls; and

- Verification that the compression system is “clean for oxygen service”.

6.2.4 Demonstration of mechanical integrity

6.2.4.1 Acceptable test conditions

For the test to be valid it shall meet the following criteria:-

Gas	-	Mol Wt. 28-32
Flow	-	Design mass flow
Suction Pressure	-	Design
Speed	-	Nominal design speed
Discharge pressure	-	As close to design as the test gas permits
Duration of the test	-	Total of 12 hours not necessarily in one continuous test

6.2.4.2 Tests to be carried out

- Logs every 30 minutes;
- Surge test;
- Soapy water leak check of the flanged joints of all compressor casings, coolers, piping systems, etc.; and
- Visual leak check of lube oil system.

6.2.4.3 Post test inspection

After the surge test, the compressor shall be opened and the seals and impellers inspected for rubs. Touching is not acceptable except in the seal area where by design it is permitted to happen (see 3.6).

6.2.5 Verification of the rotor dynamics prediction and the stability of the rotor

6.2.5.1 Acceptable test conditions

For the test to be valid it shall meet the following criteria:

Gas	-	Mol Wt. 28-32
Flow	-	Min. to Max.
Suction pressure	-	Design
Discharge pressure	-	as close to design on the test gas permits*
Speed	-	Min. to max.
Oil temp	-	Max. to min.
Duration	-	As required

*Note: To test the stability of the rotor it might be required to run on a safe gas just below the relief valve set pressure or at a higher molecular weight to give an equivalent density.

6.2.5.2 Test to be carried out

Refer to 3.8.2

6.2.5.3 Post test inspection

None planned as a normal part of the test.

6.2.6 Verification of the predicted thermodynamic performance

6.2.6.1 Acceptable test conditions

- Site test using plant instruments. In this instance the acceptable conditions shall be whatever can be achieved during plant startup.
- Thermodynamic performance test to an internationally recognised standard. This could be in the works or on site but the acceptable conditions shall be set by the test protocol.

6.2.6.2 Tests to be carried out

At several suction throttle valve/guide vane settings run the compressor from surge to stonewall and log flow, power and stage temperatures and pressure so that the surge line and performance of the compressor can be compared with that predicted for the test gas being used.

<u>The purpose of this test is to confirm that the compressor is operating satisfactorily. Plant instrumentation can be used for this test.</u>

If the guaranteed thermodynamic performance of the compressor has to be checked then special test accuracy instruments are required and an internationally recognised test procedure followed.

The tests can be carried out using dry oil free air or nitrogen.

6.2.6.3 Post test inspection

None planned as a normal part of this test.

6.2.7 Functional demonstration of the instruments

6.2.7.1 Acceptable test conditions

No special test conditions are required to demonstrate the instrument controls so this can be done when the compressor is being run to achieve other test objectives.

6.2.7.2 Tests to be carried out with compressor stopped

Put the breaker into the test position and start the compressor. This means that although the compressor is stopped as far as the protection and trip system is concerned it appears to be running.

Carry out functional checks of the following:

- alarm and trips;
- all interlocks; and
- dump vent and power operated isolation valves.

It is assumed that all the instruments have already been calibrated and loop checked.

6.2.7.3 Test to be carried out with the compressor running

- Check the function of the control and anti-surge system; and

- Check the operation of the dump vent and isolation system and check that the discharge pressure falls to 0.1 MPa g in 20 seconds.

6.2.7.4 Post test inspection

None planned as a normal part of this test.

6.2.8 Verification that the compression system is clean for oxygen Service

6.2.8.1 Acceptable test conditions

The compressor shall be oxygen clean and fully completed in the final configuration.

6.2.8.2 Tests to be carried out

The dump system to be operated - this creates high flows in the system and will ensure that any debris lying in areas of low velocity will be dislodged before the compressor is put on oxygen.

6.2.8.3 Post test inspection

Examine the suction filter and the recycle valve for particulate contamination.

6.2.9 Test programme

The document does not require any specific test programme provided that all the test objectives are achieved as defined in 6.2 and the test program shall be agreed on a case by case basis between the manufacturer and the user.

6.2.10 Commissioning on oxygen

6.2.10.1 Preparation for the initial run on oxygen

Before running the compressor on oxygen the designated person shall ensure that:

- All the test objectives have been met.
- The entire compressor system has been certified “clean for oxygen service”.
- There is satisfactory proof that the pipeline upstream of the compressor has been cleaned for oxygen service. This can be demonstrated by blowing through with dry air upstream of the filter at a velocity not less than normal operating velocity for a period of several hours. This blow through shall be vented upstream of the suction filter and as close to it as possible.
- The hazard area is clean and free from all combustible materials and that the safety barrier that surrounds the hazard area is complete and fully functional.

6.2.10.2 Initial run on oxygen

When the compressor is running to the satisfaction of the designated person, the hazard area shall be cleared of all personnel and the access secured. Oxygen should first be introduced to the running machine slowly over a period of at least two hours. During the startup and until establishment of constant operation all indicating instruments should be constantly watched, with special attention devoted to the gas pressures and temperatures and the vibration levels. The values indicated should be logged at short intervals (approximately every 15 minutes). After approximately four hours of operation readings may be taken and logged at hourly intervals.

7. Operation

7.1 General

Factors requiring specific attention in the operation of an oxygen compressor are as follows:

7.1.1 Combustible matter

Dust, oil, grease and other forms of combustible matter readily ignite in oxygen.

7.1.2 Machine rubs

Rubs in a machine can cause ignition, due to localised high temperatures being generated.

7.1.3 Rotor/bearing instability

Rotor or bearing instability can cause large shaft deflection leading to dangerous rubs.

7.1.4 Machine vibrations

Machine vibrations due to misalignment, rotor unbalance, gearing defects, etc can cause bearing failures, subsequently leading to rotor rubs.

7.1.5 Leaking cooler tubes

Leaking cooler tubes result in rusting in the casing, forming a dust nucleus for ignition.

7.1.6 Gas leakage hazard

Leakage and accumulations of gases can occur without operators being aware. Any source of open flame or ignition can cause a fire in operator's clothes which may be saturated with oxygen. Oxygen deficiency can cause asphyxiation.

7.1.7 Compressor surge

Surge is a cause of strong vibrations and excitation of the shaft and impellers that can lead to rubs and mechanical failure which in turn can cause a fire.

7.2 Safety certificates

When the responsibility for the machine changes hands, from the manufacturer to the user, operator to maintenance personnel, etc., a certificate is required confirming that the machine is in a suitable condition.

7.3 Qualifications and training for operating personnel

The operating personnel should have special training in machine operation and should be fully aware of the special significance to be attached to variation in instrumentation readings.

Certain knowledge of the machine construction is necessary to fully understand the importance of oxygen safety. Every opportunity should be given for operating personnel to maintain close liaison with the machine manufacturer's engineers during erection and maintenance.

7.4 Hazard area

If it is considered necessary to enter the hazard area for the analysis of defects when the machine is operating it must first be changed over to dry clean air or inert gas. It should be noted that, in the vicinity of the hazard area, both an oxygen enrichment and an oxygen deficiency can occur, due to, for example leaking flanges or defective seal systems. The oxygen concentration shall be between 19.5% and 23.5%.

7.5 Fire drills

All personnel whose work is associated with an oxygen compressor installation should be instructed in the special hazards involved. The difference between fire in an oxygen enriched atmosphere (more than 23.5% oxygen) in contrast to fire in ordinary air, should be emphasised. The person in charge in the event of an incident should be known. Instructions should be augmented by frequent drills so action can be taken immediately on the occurrence of a hazard condition. The local fire fighting authority should also be aware of these considerations (See 2.4).

7.6 Emergency purge and vent systems

If an emergency inert purge system that may be operated from pressurised storage systems is installed it should be regularly checked to ensure that adequate gas supplies are available.

7.7 Record of machine operation

The manufacturer's commissioning engineer shall prepare a log of normal operating conditions, derived from commissioning and design data, and this shall form the basis of the log sheet for use by operating personnel.

Log sheets should be regularly compiled for the machine. If automatic logging is used it is still essential that the log sheet be regularly scrutinised at least once per shift by the supervisor.

A record of the number of machine starts and hours run shall be kept.

7.8 Tripping devices

7.8.1 Operating checks

The operation of tripping devices, control valves and check valves, should be checked on routine shutdowns, by actuating such trips, valves, etc. where this can be done without affecting the safety of the machine and/or installation.

7.8.2 Trip override

Permanent trip overrides shall not be used. Temporary override is allowed during startup sequences and other exceptional circumstances provided that such situation is supervised and agreed. Where a machine is shutdown by one of its protective trip functions it shall not be restarted until the reasons have been fully investigated.

7.9 Interlock systems

Operators shall be familiar with the principles and operations of any interlock system installed.

7.10 Oil strainers

Regular attention shall be paid to routine examination of oil strainers and magnetic filters if installed. All oil spillage occurring from filter examination should be thoroughly cleaned up immediately and prevented from spreading.

7.11 Startup procedures

Routine operation of an oxygen compressor can require shutdown and subsequent startup as a normal procedure. The decision as to whether to start up directly on oxygen or on dry, clean air or inert gas shall be taken by the user.

Caution: *There shall be no startup of a machine after a trip without a pre-established procedure*

Dry clean air or inert gas shall be used for start-up on the following occasions:

- start-up of a new machine after erection;
- start-up of a machine after maintenance of the following type:
    - maintenance that has necessitated the purging of the machine with dry clean air or inert gas;
    - replacement of bearings;
    - resetting of the anti-surge control system; and
    - startup of a machine after prolonged standstill.

Dry clean air or inert gas or oxygen is permissible for start-up on the following occasions:

- startup as a normal procedure after a planned shut-down;
- startup of an operational stand-by machine previously on oxygen service; and
- startup of a machine after maintenance, except the types of maintenance under 7.11.1.

8. Maintenance

8.1 General

8.1.1 Method

Because of the possible consequence of a breakdown while a centrifugal compressor is in oxygen service, its maintenance should be to the highest possible standards. To achieve these standards maintenance personnel should be properly trained and careful records should be kept of all maintenance work undertaken.

The frequency and content of maintenance work should be agreed between the manufacturer and the user. In the event of adverse trends being observed in machine operation the machine should be shutdown for examination and remedial action taken. Regular and detailed analysis of the running data is of the utmost importance in ensuring the safe operation of the compressor. This data can be used as a guide in establishing the period between major overhauls.

It is not possible to state a precise period between major overhauls which covers all circumstances. The period will depend upon the following:

- manufacturer’s recommendations;
- number of hours run;
- number of starts, since the last overhaul; and
- previous operating behaviour and history.

It is recommended that the manufacturer be involved in major maintenance or repair work. The requirements and standards covered in Section 6 shall be complied with.

Note: It has been noted that a number of fires have occurred immediately after overhauls. It is therefore recognised that internal inspections could also be the cause of an increased risk.

8.1.2 Functional test

The correct operation of the compressor trip system and the dump and isolation valves is an important contributor to the safe operation of oxygen compressors. In order to ensure correct operation, all the components should be recalibrated and the system subjected to a full functional test every 3 years at least.

8.2 Cleanliness during maintenance

During maintenance of the compressor the standards of cleanliness specified in 5.3 should be observed.

8.3 Rotor checks

8.3.1 Compressor open for overhaul

When the compressor is open for overhaul or inspection, it is recommended that the impellers be inspected for cracks provided that cleaning and cleanliness is performed and controlled.

8.3.2 Check balance of spare rotors

It is recommended that spare rotors be subjected to a check balance before installation. This precaution is important for rotors that have been in storage for more than 1 year and particularly for rotors with shrunk on components.

8.4 Spare parts

8.4.1 Manufacturer replacements

It is recommended that replacements for all parts originally manufactured by the machine manufacturer should be purchased from the manufacturer. All other replacement parts should be in accordance with the manufacturer's specification.

8.4.2 Oxygen components

All components that come into contact with oxygen gas should be preserved as specified in 5.4. Balancing certificates, etc., included with spare rotors should be transferred to the operator's maintenance records, when a change of rotors takes place.

9. Instruction manual

9.1 General

The instruction manual shall highlight the specific safety aspects in operating and maintaining oxygen compressors and the need for a high standard of cleanliness. The instruction manual shall cite this document as a reference.

9.1.1 Manufacturer / user input

Within the framework of the preparations made by the user for a major overhaul it is recommended that the user invites the manufacturer to discuss the following objectives.

- Exchange of information between the manufacturer and user with the objective of ensuring that the highest safety standards are maintained.

- Review the operating manual taking into consideration operating experience gained by the user and the latest standards of the manufacturer.

The minutes of the meeting should then form part of the instruction manual.

9.2 List of minimum information

9.2.1 Instruction manual

The instruction manual shall contain the following information as a minimum:

- compressor design data and performance characteristics including the surge line
- description of the following items, placing emphasis on the details which are special for oxygen service:
  - compressor
  - lube oil system and frequency of oil check
  - seal system
  - controls and instrumentation with set points of alarms and trip
  - associated equipment
  - installation;
- operation with starting, shut-down and restarting procedures to safeguard the compressor;

- maintenance with disassembly and assembly procedure and spare parts stocking conditions;
- protection of the compressor unit during prolonged standstill;
- list of materials of construction;
- overall drawing with seal and bearing clearances and tolerances; and
- trouble shooting guide.

9.2.2 Additional Information

Information that shall be supplied but which may be separate from the instruction manual:

- detailed list of the spare parts with sectional view, subject and reference numbers;
- records of balancing and over speed tests;
- records of crack tests of the impellers; and
- records of all the tests carried out by the manufacturers.

10. References

[1] AIGA 005 'Fire hazards of oxygen and oxygen enriched atmosphere'.

[2] AIGA 021 'Code of Practice - Oxygen Pipeline and Piping Systems'

[3] AIGA 012 'Cleaning of Equipment for Oxygen Service'.

[4] CGA G-4.1 Cleaning of Equipment for Oxygen Service

[5] API 617 (7th edition, 2002) Axial and Centrifugal Compressors

[6] ISO 1940 (2003) Mechanical Vibration – Balance Quality Requirements

[7] BAM Liste der Nichtmetallischen Materialien BG M041-1

[8] ISO 10816 (1997) Evaluation of Machine Vibration by Measurement on Non-rotating Parts

[9] NEMA SM23 (2002) Steam Turbines for Mechanical Drive Service

[10] Compressed Gas Association publication G-4.6 (2008 3rd Edition) Oxygen Compressor Installation and Operation Guide.

[11] AIGA 067 'Safe Location of Oxygen & Inert Gas Vents'