

ABSTRACT : Accidents are occasionally reported to occur due to violent ignition of oxygen pressure regulators on opening the gas cylinder valve.

These ignitions can be attributed either to oil contamination, to particle impact or to "adiabatic compression" i.e. rapid pressurization of oxygen when opening the cylinder valve.

Since oxygen regulators, like any oxygen equipment, are normally specially cleaned to remove traces of oil, greasy products and combustible materials, prevention of "oil contamination ignition" mainly consists in advising customers to avoid contamination in service. Particle impact ignitions can be avoided by using dust caps over the cylinder valve outlets during transport, in-line filters and by advising users to momentarily "crack" the cylinder valve before connecting the regulator.

In this paper we concentrate mainly on investigating the conditions which could lead to ignition by "adiabatic compression". Numerous tests have been carried out in L'AIR LIQUIDE's Laboratory to try to explain how such ignitions occur and how to avoid them. The influence of the materials used in the construction of regulators has been studied, i.e. non-metallic and metallic materials (including aluminum). This influence although very important, has been found to be closely related to and affected by the regulator internal design.

Examples of solutions to prevent such ignition are reported in this paper.

Another important aspect discussed is the influence of the testing equipment and procedure used to establish the ability of a regulator to resist adiabatic compression. There are already some national Standards in Europe (Germany, France, etc) or international Standard (ISO) which specify ignition test methods, however, it has recently been determined that they are not adequately precise or reliable. In fact, some tests carried out according to these Standards have produced different results (regulator acceptable or non-acceptable) depending on which laboratory performed the test. In this paper, we identify the important parameters which must be taken into account when performing the tests.

KEYWORDS : oxygen pressure regulators, ignition, adiabatic compression, oxygen compatibility, Standards, testing procedure, selection guide.

1 - L'AIR LIQUIDE Direction Technologie, Centre de Technologie et d'Expertises - Le Blanc Mesnil - FRANCE

1 - INTRODUCTION

Pressure regulators are a necessary and important part of equipment for industrial gas users when gases are delivered in high pressure gas cylinders. They can be directly fitted on the outlet of the cylinder valves or incorporated in the distribution manifold. Oxygen regulators are used in many fields including welding and medical applications. Accidents are sometimes reported on such oxygen regulators to be due to violent ignitions when opening the gas cylinder valve.

In the following we try :

- to analyse the different causes of regulator ignitions in oxygen service,
- to describe the testing requirements of the national and international Standards, the testing procedure we normally use, and its main differences from the Standards,
- to mention the important parameters concerning the constitutive materials and the design to take into account.

2 - POSSIBLE IGNITION CAUSES

An oxygen regulator already contains what is normally necessary to produce an ignition i.e., an oxidizing gas (the oxygen) and potentially flammable products (the material the regulator is made of, or some contamination) ; ignitions can thus occur in an oxygen regulator either if some materials are too easy to ignite (due to the energy normally supplied in service) or if too much energy is delivered to the system [1, 2].

The possible ignition causes are then :

- . oil contamination : oil, grease and common lubricants are normally very easy to ignite in oxygen service, and the ignition of these products can be easily propagated to the other materials ;
- . material incompatibility : materials such as elastomers, plastics or lubricants may be very easy to ignite in oxygen service ; metallic materials like aluminum, when ignited, may lead to catastrophic combustion ; a safe oxygen regulator shall then be manufactured from oxygen compatible materials ;
- . energy delivered to the system by friction, particle impact, static electricity or "adiabatic compression" i.e. high temperature increase following a rapid pressure increase *.

* The theoretical final temperature when oxygen is compressed assuming the process is adiabatic, is calculated from the following equation

$$T_f = T_i \frac{P_f}{P_i}^{(n-1)/n}$$

Normally no significant friction occurs in the regulator when the gas cylinder valve is opened ; particle impact or static electricity also are not the predominant causes as the gases are normally clean in terms of particle contents (if not, dust filters can be used) ; some Standards e.g. ISO 2503 specify that a dust filter shall be mounted upstream of the regulator.

On the other hand, "adiabatic compression" is probably the main source of energy delivery in an oxygen regulator, and, in this way, the main cause of ignition in oxygen service. Adiabatic compression will occur, for example, when opening the cylinder valve if the seat of the regulator is closed, because the quantity of oxygen located downstream of the cylinder valve and upstream of the regulator seat will suddenly be compressed to cylinder pressure.

It appears that, to prevent ignition of oxygen regulators, compatible materials must be used, and the design of the regulator has to be such that a sudden increase of pressure in the equipment will not lead to an excessive energy delivery.

3 - STANDARDS - REQUIREMENTS CONCERNING OXYGEN COMPATIBILITY FOR REGULATORS

Some specific requirements concerning oxygen regulators are mentioned in some national Standards (DIN 8545 and 8546 for West Germany, AFNOR A 84.430 for France) and some international Standards (ISO 2503).

These requirements mainly concern :

- . recommendations for materials to be used with a special warning about lubricants and oil contamination,

where

T_f = final temperature, abs

T_i = initial temperature, abs

P_f = final pressure, abs

P_i = initial pressure, abs

and $n = \frac{C_p}{C_v} = 1.40$ for oxygen

where C_p and C_v are heat capacities for oxygen at constant pressure and constant volume respectively.

For examples :

if $T_i = 15^\circ\text{C}$, $P_f = 20$ MPa and $P_i = \text{atm. pressure}$, then $T_f = 1032^\circ\text{C}$

if $T_i = 60^\circ\text{C}$, $P_f = 24$ MPa and $P_i = \text{atm. pressure}$, then $T_f = 1316^\circ\text{C}$.

These theoretical temperatures are not achieved in practice because of heat losses to the surroundings.

. a specific test (i.e. an ignition test) to check if the regulator is compatible with oxygen service.

The ignition test conditions, as described in ISO standard n° 2503-1983 / Add 1.1984, are given below (see Fig. 1, extracted from this Standard, giving the schematic of the test conditions).

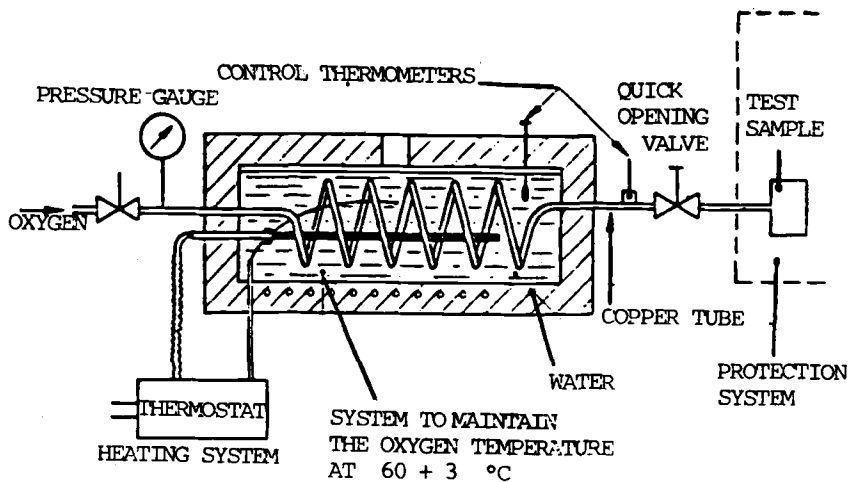


Fig. 1 - Description of the oxygen ignition test as given in ISO Standard 2503-1983/Add 1 - 1984 (E)

"The regulator with its valve completely closed (pressure adjusting screw completely unscrewed) is exposed through the inlet to pressure shocks from industrial oxygen (minimum 99.5 % purity without hydrogen). The test system shall be provided with equipment for preheating of the oxygen to $(60 \pm 3) ^\circ\text{C}$ at a minimum pressure of 200 bar (20 MPa). It shall be equipped with a quick-opening valve, with a bore of not less than 3 mm. The time for pressure increasing from atmospheric pressure up to the test pressure of 200 bar (20 MPa) shall be 20 ms. The connection between the quick-opening valve and the regulator under test shall be as short as possible.

Each test series consists of 20 pressure shocks at intervals of 30 s. Each pressure shock is applied for 10 s.

After each pressure shock the test regulator is brought back to atmospheric pressure. This is done not by the regulator but by an upstream tap.

During one test series, the inlet pressure shall not decrease by more than 3 %.

The regulator shall not burn out during this test and shall suffer no internal damage such as scorching.

For all tests, the equipment shall be provided with the filter described in 6.2.2. in ISO 2503.

Note : In case of multistage regulators, it is also necessary to test the first stage valve".

4 - L'AIR LIQUIDE APPROVAL PROCEDURE FOR OXYGEN REGULATORS

Our specific approval procedure for oxygen regulators is based on :

4.1. General requirements

- use of a dust filter upstream of the pressure regulating valve to prevent ignition due to particle impact or static electricity,
- use of clean materials free of oil and grease (maximum accepted content 100 mg/m²),
- use of plastic and elastomeric materials compatible with oxygen. This selection is made by using the auto-ignition test ("bomb test") as described in reference [3].

4.2. Testing requirements

The test procedure that we use is reported in Appendix. Our testing procedure sometimes differs from that of the Standards mentioned previously ; in the following we will try to explain why and to indicate what are the important testing parameters that it is necessary to specify clearly in the testing procedure :

- . to make sure that the regulator approved will really be safe in oxygen service,
- . to avoid conflicting results from different laboratories (e.g. a regulator found acceptable by one laboratory and unacceptable by another one)

4.2.1. Position of the regulator valve

In the relevant standards (see paragraph 3) it is normally specified that a regulator has to be tested with its valve completely closed (pressure adjusting screw completely unscrewed). As we also experienced some ignitions with the valve in the open condition, we believe that regulators have to be tested both in the completely closed and completely open conditions. Furthermore, for certain applications regulator design is such that the valve seat is normally open before pressure application.

4.2.2. Oxygen pressure

Service pressure for gas cylinders is normally defined at a reference temperature (15°C in Europe, 21°C in North America, etc). However, cylinders in use may be warmed by ambient conditions to a temperature of 50°C to 65°C. Such an increase of temperature corresponds to a pressure increase approaching 20%.

Consequently we recommend performing the test at 1.2 times the service pressure of the gas cylinders.

4.2.3. Pressure cycle

The time for the pressure increase up to maximum pressure is of course very important because it will determine the severity of the "adiabatic compression" and the maximum temperature reached at the dead end. In the Standard specifications this time is normally 20 ± 5 ms. This time of course depends on the design of the regulator tested and on the dimensions of the connections used between the quick-opening valve and the regulator.

To avoid any erratic results from one laboratory to another, a calibration procedure similar to the one included in the ISO Standard draft "Gas Cylinder Valves - Specifications and Testing" [4] is proposed i.e. the maximum pressure at the dead end of a copper pipe (1 m in length, 5 mm inner diameter "ID") has to be reached within

20 ± 5 ms.

Another important aspect is that the same rate of pressure increase shall be guaranteed for all the pressure shock cycles, i.e. the test pressure shall remain as constant as possible (a maximum pressure decrease of 3 % is normally specified in the relevant Standards) and the pressure drop upstream of the quick-opening valve shall be compatible with the frequency of the pressure cycles, e.g. large storage vessels in which the oxygen temperature is adjusted to 60°C are recommended (see Fig. 2) instead of serpentine tubes as normally represented in the Standards.

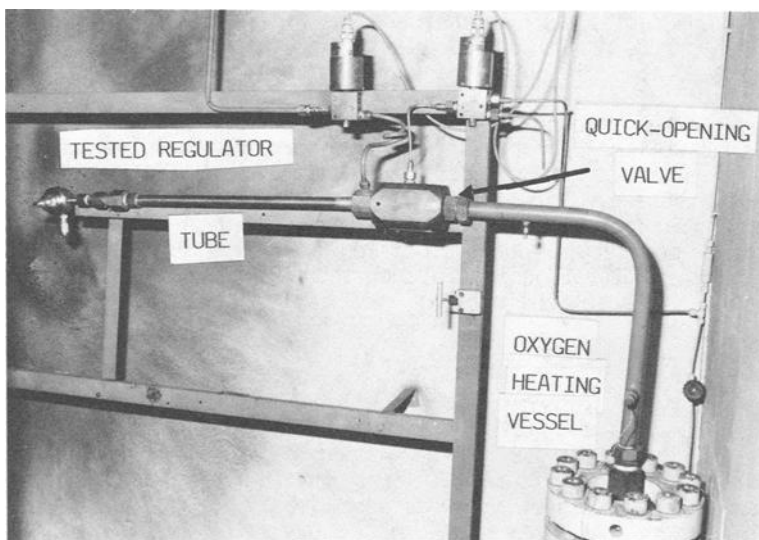


Fig. 2 - Adiabatic compression test : equipment used for oxygen regulator testing

4.2.4. Number of pressure cycles and frequency

It is necessary to perform a minimum number of pressure shocks to be sure of the reliability and safety of the regulator, because very often the ignition occurs after a given number of cycles ; 20 cycles, as normally specified in the Standards, seem to be an appropriate figure.

The frequency shall not be too high because it is of paramount importance to bring the regulator back to atmospheric pressure. It is also necessary to apply the maximum oxygen pressure during a given period of time because it appears that combustion ignition takes time. However, from experience, we know that in practice, if the combustion is just initiated when the oxygen is released, at the next cycle the complete ignition will occur within a very short time. A cycle period of 30 s with stabilization time of 10 s at maximum pressure and 3 s at atmospheric pressure is recommended.

4.2.5. Dust filter

When a regulator is equipped with a dust filter, the pressure drop created by this filter will decrease the pressure increase rate downstream when oxygen shocks are applied. We recommend to test the regulator with and without this filter. If the regulator is not ignited with the filter present but ignited without it, we recommend a procedure as mentioned in Appendix.

4.2.6. Tubes located between the quick-opening valve and the regulator

For the "adiabatic compression test", the volume or quantity of oxygen located between the seat of the quick-opening valve and the dead end of the regulator is of paramount importance. This is because this quantity of oxygen will be suddenly compressed when opening the quick-opening valve ; this compression will lead to a temperature increase of this quantity of oxygen ; by thermal exchange the material in contact with this will be heated and ignited if the temperature reached is higher than the auto-ignition temperature of the material.

It follows that, for a given pressurization rate, a regulator could be ignited or not, depending on the quantity of oxygen located between the quick-opening valve and the regulator.

Some Standards (ISO 2503, DIN 8546, NF 84.430) specify that for a regulator fitted directly on a gas cylinder no tube shall be used and that the connection between the quick-opening valve and the regulator shall be as short as possible.

Other standards (DIN 8546) specify that for a manifold regulator a tube 750 mm in length, 14 mm in ID shall be used.

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We carried out extensive investigations to evaluate the influence of this oxygen quantity on the ignition conditions. The principle of these tests was to determine the minimum pressure necessary to ignite (by "adiabatic compression") a disk of plastic material located at the dead end of a tube installed on the outlet of the quick-opening valve.

Tubes of different lengths (from 0.5 m to 1.75 m), different I.D. (5 mm, 12 mm and 14 mm) and, thus, different internal volume (from 9.8 to 269.5 cm³) were investigated. Various plastic materials (PTFE, polyamides, etc) were tested ; the test specimens (disk shape) were from 5 to 14 mm in diameter, from 1.5 to 4.5 mm in thickness and from 0.1 to 1.5 g in weight. Examples of some typical results are given in Fig. 3.

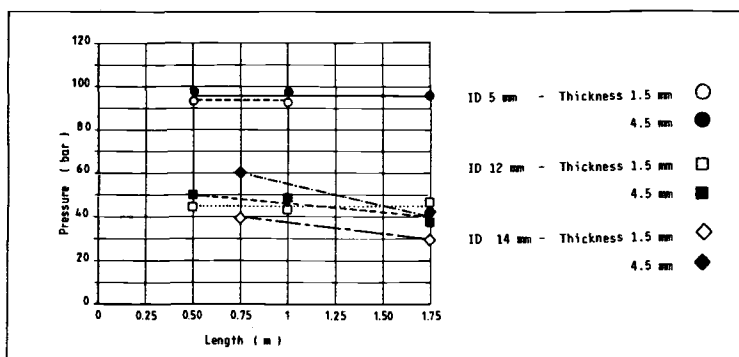


Fig. 3 - Influence of the length of the tubes (ID 5, 12 and 14 mm) located between the quick-opening valve and the regulator. Minimum ignition pressure during the adiabatic compression test for PTFE disk specimens of different thicknesses (1.5 and 4.5 mm)

Our main conclusions were that :

- . for the same diameter, the length of the tube between 0.5 to 1.75 m is not the predominant factor, minimum pressure for ignition being roughly constant,

- . when the diameter is increased from 5 to 12 mm, the minimum pressure for ignition is decreased significantly, but no significant change is noticed between 12 and 14 mm,

- . the minimum pressure for ignition depends on the diameter of the tube but not directly on the internal volume of the tube (see Fig. 4).

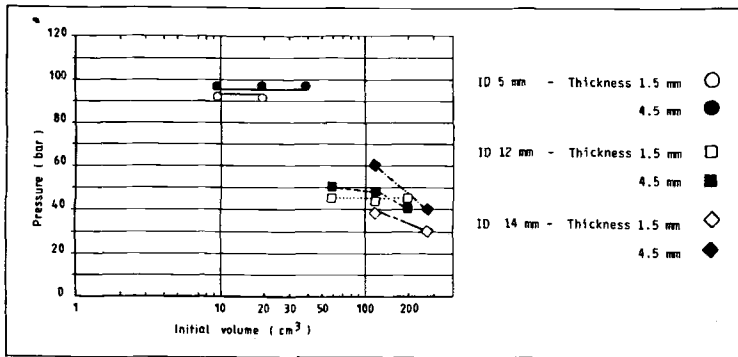


Fig. 4 - Influence of the volume of the tubes (ID 5, 12 and 14 mm) located between the quick-opening valve and the regulator. Minimum ignition pressure during the adiabatic compression test for PTFE disk specimens of different thicknesses (1.5 and 4.5 mm)

This can be explained as follows : if internal volume plays an important role (proportional to the quantity of oxygen compressed and heated which will increase the temperature of the regulator materials by thermal exchange), the efficiency of the compression also depends on the diameter of the tube, i.e. for the same internal volume a tube with small diameter (5 mm) and long length certainly leads to a lower "efficiency" than a tube with large diameter and short length (see Fig. 4).

Our testing philosophy is based on these results.

1 - REGULATORS DIRECTLY FITTED ON THE OUTLET OF THE CYLINDER VALVE

The current Standards normally specify that the connection between the quick-opening valve and the regulator shall be as short as possible ; this requirement is easy to understand : the aim is to reproduce service conditions.

However in practice the volume upstream of the dead end (e.g. the valve regulator seat) can vary considerably due to :

- manufacturing tolerances of the regulators ; for instance if the bore of the inlet fitting (typically 10 cm in length) varies from 3 mm to 4 mm the internal volume will vary from 0.7 cm³ to 1.26 cm³ (the internal volume about doubles),
- the type of cylinder valve on which the regulator is fitted on (the internal volume downstream of the seat may vary greatly from one type of valve to another).

So it is important that under the testing conditions, the internal volume upstream of the regulator dead end is greater than or equal to the most severe condition in service. The other point is that conflicting results from one laboratory to another (i.e. some regulators found either acceptable or not acceptable) are to be avoided. The solution that we propose is to use a tube between the quick-opening valve and the regulator.

The aim of this tube is at the same time to introduce a safety factor and to involve an additional volume great enough to make the volumes in the valve and in the regulator negligible.

To achieve this a volume of at least 10 cm³ which corresponds to a tube of 5 mm in ID and 0.5 m in length is necessary. As our results showed that there is no difference between 0.5 m and 1 m length for a tube of such diameter (see Fig. 9) we recommend to use a tube with a length of 1 m (ID = 5 mm) because this already corresponds to the specification of the ISO Standard draft for gas cylinder valve testing [4].

2 - MANIFOLD REGULATORS

Our tests with tube of different lengths and diameters, showed that the ID of the tube or piping is the predominating factor and that the influence of the length (> 0.5 m) is negligible. Base on these results, we recommend, as the industrial gas manifolds are normally manufactured with pipes and fittings with a bore between 4 and 12 mm to test them in adiabatic compression with an intermediary tube of 12 mm in ID and 1 m in length.

5 - OXYGEN COMPATIBILITY : INFLUENCE OF THE MAIN PARAMETERS

We have performed many tests on different types of oxygen regulators according to the testing procedure described previously. From these test results, we have tried to analyse the influence of the main parameters on the risk of ignition. In the following these parameters are considered into different groups :

- . the first group deals with the influence of the materials used,
- . the second with the influence of the regulator design,
- . the third one with the "surrounding conditions" (e.g. the equipment used upstream of the regulator).

5.1. INFLUENCE OF THE MATERIALS USED

Three types of materials are considered, plastic and elastomeric materials, lubricants, and metallic materials.

5.1.1. Plastic and elastomeric materials

As previously mentioned, plastic and elastomeric materials are checked and/or selected by using the auto-ignition test. This test allows one to select material presenting high enough auto-ignition temperature in high pressure oxygen. If the ignition of a regulator during the "adiabatic compression test" initiates on a plastic material, the replacement of this material with one having a higher auto-ignition temperature may avoid ignition during subsequent tests.

It is difficult to determine an absolute minimum auto-ignition temperature above which a plastic material will never be ignited in oxygen service. This minimum temperature depends on the function of the plastic or elastomeric material : for instance an O-ring normally very well protected will be less sensitive to ignition than a diaphragm or a seat directly exposed to the flow-stream ; this temperature also depends on the regulator design. However from experience, it is possible to specify minimum auto-ignition temperatures at the design stage, and to thus select appropriate materials.

For this selection of course the other properties of the materials (pressure resistance, tightness, etc ...) have also to be taken into account.

5.1.2. Lubricants

If lubricants have to be used in direct contact with oxygen, they shall be compatible with oxygen. Lubricants with the highest auto-ignition temperature shall be selected. We recommend to use only lubricants possessing auto-ignition temperatures greater than 400°C.

Contamination by lubricants, greases, oils and other hydrocarbons shall be avoided ; a maximum figure of 100 mg/m² is very often recommended by the industrial gas associations [5]. However some tests performed showed that some well designed regulators could not be ignited during adiabatic compression tests, even when some parts were severely contaminated.

5.1.3. Metallic materials

A limited number of metallic materials are normally used in the manufacture of high pressure regulators. Brass is the most common material used for the body of such equipment, but aluminum alloys are also very often used. Other materials such as low alloyed steel or stainless steel are used, especially for the springs.

Extensive work has been carried out during the last few years to investigate the flammability of metallic materials in oxygen atmospheres [6, 7]. A very large part of this work was covered by ASTM Committee G-4 Metals Flammability Test Program [8, 9]. The aim of such investigations was to rank metals according to their suitability for use in oxygen systems ; aluminum alloys are sometimes reported to be ranked the lowest [8] ; however according to other papers [7] the ranking of aluminum is very erratic and strongly depends on the testing procedure used. Based on these results and/or on former results there is a trend in the industrial gas business not to use aluminum regulators for oxygen service ; thus, some company specifications do not authorize the use of aluminum regulators.

To check this assumption many adiabatic compression tests have been carried out on aluminum and brass regulators. It clearly appears that when they were ignited, due to voluntary contamination or bad design (e.g. ignition initiated on plastics materials), the results of the ignition might be of the same order of magnitude in both cases (Fig. 5 and 6 show results for the same testing conditions of ignited aluminum and brass regulators).



Fig. 5 - Example of a regulator ignited by adiabatic compression test - Aluminum body



Fig. 6 - Ignition with a brass body regulator

Our conclusion is that aluminum pressure regulators can be safely used in oxygen service equally well as brass regulators.

The necessary conditions for such safe use being both for aluminum and brass regulators, no hydrocarbon contamination and appropriate design, the quality of which has to be checked according to a reliable test procedure.

However, for dust filters, in which by principle the surface area of metal in contact with oxygen is very large, and/or where particles impingement is likely to occur, we do not recommend to use aluminum or stainless steels materials but to use bronze which proves to present an excellent safety record in practice.

5.2. INFLUENCE OF REGULATOR DESIGN

The weakest points of a regulator are the plastic or elastomeric materials that it is necessary to use for external tightness, for the valve seat of first/second stage, and for the elastomeric diaphragms.

One possibility, is of course to use plastic or elastomeric materials presenting the highest auto-ignition temperature (see paragraph 5.1.1.) ; however, especially when a dead end does exist e.g. at the valve seat of a regulator, the use of plastic material of the highest grade in terms of oxygen compatibility like PTFE or PCTFE, might be not enough to avoid oxygen ignition by adiabatic compression ; in such cases, the design of the regulator shall be such that the susceptible materials are well protected.

In this respect, from the experience we obtained from numerous test we performed, we found that :

- 1) for external tightness it is better to use O-ring seals rather than annular flat rings ;
- 2) plastic parts of the valve seat in direct contact with the oxygen stream need to be protected (Fig. 7 gives examples of good and bad design for the valve seat of some regulators) ;

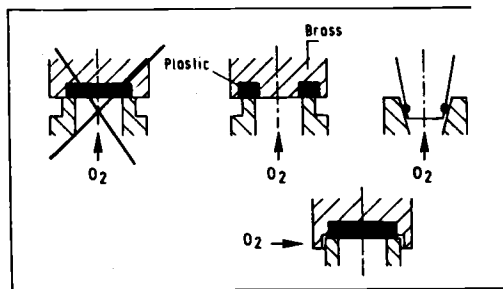


Fig. 7 - Oxygen regulator - Good and bad design for the valve seat

3) in some cases, other dead ends that the closed valve seats may exist in a regulator ; see an example given in Fig. 8, which shows material to be avoided and to be used ;

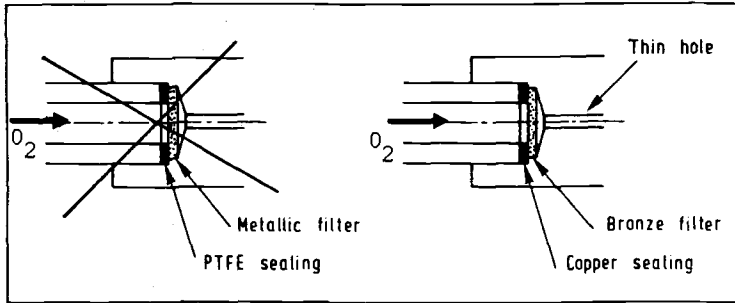


Fig. 8 - Oxygen regulator - Materials to use in a dead end.

4) some devices, such a filters, located in the regulator upstream of the dead end (e.g. the valve seat), may be used to decrease the pressure increase rate at the dead end and to avoid ignition due to adiabatic compression (see Fig. 9) ; in such cases it should be insured that :

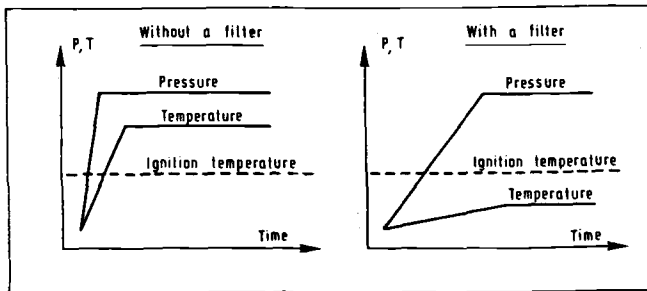


Fig. 9 - Schematic representation of the influence of a dust filter during adiabatic compression.

- this device will stay in the regulator during all its life (in an efficient state),
- if such devices, e.g. filters, are produced in large quantities, the minimum pressure drop created will surely protects the regulator from ignition by adiabatic compression, and that the maximum pressure drop created is compatible with the intended use.

5.3. INFLUENCE OF THE "SURROUNDING CONDITIONS"

. Sudden increase of pressure being the most frequent cause of regulator ignitions in oxygen service (see paragraph 2), it shall be checked if equipment like cylinder valves, shut off valves, etc ... located upstream of the regulator are not susceptible to lead to pressure increase rates (inside the regulator) higher than the one for which the regulator has been designed or tested for oxygen resistance.

. It shall be checked that the equipment located upstream are also compatible with oxygen service ; we recently found by testing that a regulator presenting a good behavior when tested according to our procedure (see paragraph 4), was ignited, if the plastic components (PTFE, PCTFE) of any complementary pipe equipment located upstream is ignited by adiabatic compression according to paragraph 4. The very severe ignition of the regulator (Fig. 10) was in this case due to the formation of hot products (mainly gases) resulting from the combustion of the plastic component of a complementary equipment which passed through the inlet filter of the regulator and led to the ignition of the plastic or elastomeric materials of the regulator.

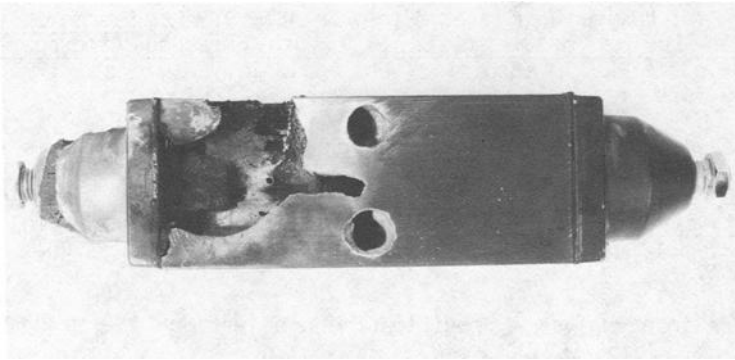


Fig. 10 - Example of regulator ignition due to formation of hot gases resulting from PCTFE combustion upstream of the regulator aluminum body

6 - CONCLUSION

"Adiabatic compression" or sudden increase in pressure is the predominant cause of regulator ignition in oxygen service.

Testing conditions (adiabatic compression test) were extensively discussed. A testing procedure has been proposed which will allow to select safe regulators and avoid conflicting results from one laboratory to another. It is proposed to use our results when reviewing the existing Standards.

Materials of construction and more specifically plastic and elastomeric materials have to be properly selected. Brass or aluminum bodies can both be used safely as long as the regulator design, which has a paramount influence, is appropriate and well checked. Guidelines for safe oxygen regulators are given.

REFERENCES

- [1] Slusser J.W., Miller K.A., "Selection of Metals for Gaseous Oxygen Service" in ASTM STP 812 Flammability and Sensitivity of Materials in Oxygen Enriched Atmospheres, Ed. BL. Werley, Philadelphia, PA, July 1983, pp 167 - 191.
- [2] Gusky F.J. "Oxygen Regulator Myths" in ASTM STP 986 Flammability and Sensitivity of Materials in Oxygen Enriched Atmospheres Third Volume, Ed. D. Schroll - Philadelphia, PA, Sept. 1988 - pp 359-367.
- [3] Barthélémy H., and Vagnard G., "Ignition of PTFE Lined Hoses in High Pressure Oxygen Systems : Tests Results and Considerations for Safe Design and Use" in ASTM STP 986 Flammability and Sensitivity of Materials in Oxygen Enriched Atmospheres Third Volume, Ed. D. Schroll, Philadelphia, PA, Sept. 1988, pp 289-304.
- [4] "Gas Cylinder Valves - Specification and Testing" ISO Standard draft- ISO/TC 58/SC2 Doc. N 232
- [5] Cleaning of Equipment for Oxygen Service - Guideline - IGC Doc. 33/86/E Ed. Soudure Autogène, 32 Bld de la chapelle 75880 PARIS.
- [6] Flammability and Sensitivity of Materials in Oxygen Enriched Atmospheres 2nd Volume ASTM STP 910, Ed. M. Benning Philadelphia, PA, May 1986.

- [7] Flammability and Sensitivity of Materials in Oxygen Enriched Atmospheres 3rd Volume ASTM SPT 986, Philadelphia, PA, Sept. 1988.
- [8] J.O. Cronk "ASTM Committee G-4 Metals Flammability Test Program : Rationale and Goals" in ASTM STP 986, Flammability and Sensitivity of Materials in Oxygen Enriched Atmospheres, Third Volume, Ed. D. Schroll, Philadelphia, PA, Sept. 1988 pp 21-27.
- [9] J.M. Stotzfus et al "ASTM Committee G-4 Metals Flammability Test Program : Data and discussion" ASTM STP 986, Flammability and Sensitivity of Materials in Oxygen Enriched Atmospheres, Third Volume, Ed. D. Schroll, Philadelphia, PA, Sept. 1988 pp 28-53.

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A P P E N D I X

ADIABATIC COMPRESSION TEST ACCORDING TO L'AIR LIQUIDE PROCEDURE

The regulator has to be tested to make sure that it will resist adiabatic compression. Tests similar to the one described in the Standards are performed (Fig. 2) ; our testing conditions are as follows :

- . Number of regulators to be tested per type : 5
- . Position of its valve : completely closed - then completely open
- . Purity of oxygen : 99.5 % - traces of hydrocarbons < 10 ppmV
- . Test temperature : 60°C (\pm 3°C)
- . Test pressure : 120 % of the service pressure of the gas cylinder
- . Time * for pressure increase from atmospheric pressure up to test pressure : $20 \pm \begin{smallmatrix} 0 \\ 5 \end{smallmatrix}$ ms
- . Number of pressure shocks per test : 20
- . Pressure cycles : period 30 s - stabilization time 10 s at maximum pressure and 3 s at minimum pressure
- . Dust filter : tests are carried with and without the dust filter.

If the regulator is ignited without dust filter and not ignited with the dust filter, the regulator can be used for oxygen service only if following requirements are fulfilled :

- the dismantling of the filter shall be impossible for the user or it should be clearly marked on the regulator that the dismantling is not allowed,
- a minimum porosity for the filter (leading to the maximum flow rate) has to be defined ; the tests shall be carried out on regulators equipped with filters presenting this porosity,

This time has to be checked regularly ; it shall correspond to the time necessary to reach (from the atmospheric pressure) the maximum maximum pressure at the dead end of a copper tube (1 m in length - 5 mm in internal diameter).

- . Tube located between the quick-opening valve and the test regulator :
 - if the regulator is intended to be used directly fitted on a gas cylinder : length = 1 m - ID = 5 mm
 - if the regulator is intended to be used on a manifold : length = 1 m - ID = 12 mm