RELIABILITY ANALYSIS OF VALVES USED IN URANIUM HEXAFLUORIDE PROCESSING PLANT

Paulo Eduardo Vicente Dias
Centro Tecnológico da Marinha em São Paulo – CTMSP
Rod. Sorocaba-Iperó, km 12,5 – Iperó – São Paulo - SP
paulo.dias@ctmsp.mar.mil.br

Gilberto Francisco Martha de Souza
Escola Politécnica da Universidade de São Paulo
Av. Prof. Mello Moraes, 2231 – Cidade Universitária – São Paulo - SP
gfmsouza@usp.br

Abstract. *The CTMSP is finishing the electromechanical assembly of a uranium hexafluoride production plant, where the use of imported valves for some stages of the process is foreseen with high potential of operational risks. The option of using imported valves reduces the uncertainties of the operational risk evaluation of the plant, since these suppliers are internationally recognized as manufacturers of excellence for the desired application. However, due to the native countries import restrictions, there is no guarantee of supplies suitable to the project in the desired amount and delivery dates; even the continuity of maintenance spare parts supply may be compromised*
In this context, this work presents a plan of reliability experiments, including the development of an infrastructure to support them and the preliminary results obtained, aiming the qualification of national manufacturers of blockage valves, for use in the reference plant. The reliability experiments are divided in two groups. The first one involves the execution of accelerated tests based on the increment of opening and closing cycles of the valves. The number of cycles that the valve is submitted is higher than the number of cycles predicted for the plant operational life. The second reliability experiment is related to the valve exposure to the most aggressive operational conditions faced during the uranium hexafluoride processing (in terms of pressure and temperature), for a period of time than the plant expected operational time at this condition .The verification of valve operational condition during the tests is based on the execution of pressure tests, at specific intervals of time, aiming at detection of non-expected leakages.
As for example, a reliability analysis of some valves is presented aiming at verifying the tests feasibility.
In such a way, at the end of the reliability test program execution it is expected the establishment of a solid base of national suppliers of valves, in order to guarantee the safe operation of the plant throughout its useful life.

Keywords*: Industrial valves, Reliability, Reliability Testing*

1. INTRODUCTION

The "*Centro Tecnológico da Marinha em São Paulo*" - CTMSP is finishing the electromechanical assembly of an uranium hexafluoride production (UF_6) plant, where the use of imported valves for some stages of the process is foreseen with high potential of operational risks. The option of using imported valves reduces the uncertainties of the operational risk evaluation of the plant, since these suppliers are internationally recognized as highly capable manufacturers for the desired application. However, due to the native countries import restrictions, there is no guarantee of supplies suitable to the project in the desired amount and delivery dates; even the continuity of maintenance spare parts supply may be compromised.

In this context, this work presents a plan of reliability experiments, including the development of an infrastructure to support them and the preliminary results obtained, aiming the qualification of national manufacturers of blockage valves, which will be used in the reference plant.

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The second reliability experiment is related to the valve exposure to the most aggressive operational conditions faced during the uranium hexafluoride processing (in terms of pressure and temperature), for a period of time smaller than the plant expected operational time at this condition.

The verification of valve operational condition during the tests is based on the execution of pressure tests, at specific intervals of time, aiming at detection of non-expected leakages.

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In such a way, at the end of the reliability test program execution it is expected the establishment of a solid base of national suppliers of valves, in order to guarantee the safe operation of the plant throughout its useful life.

2. PHYSICO-CHEMICAL AND MANUFACTURING PROCESS OF UF_6

Due to the large variations of density, vapor pressure and physical state with temperature, associated with their chemical characteristics, safe handling of UF_6 demand special procedures and sealed process systems, with high reliability. This is because in the case of a leak to atmosphere UF_6 reacts with moisture in the air and the reaction products are: the uranyl fluoride powder (UO_2F_2) and hydrofluoric acid (HF), both with high toxicity.

To illustrate the hazard of UF_6 leakage, if a person weighing seventy kilograms inhale 114 mg of UO_2F_2 she would have only 50% chance of surviving, according to data from NUREG 1391 (1991). This value is much lower than the mass required to cause radiation damage, which is approximately 1300 mg for the same person.

The hydrogen fluoride have the same potential of hazard because its concentration in the air immediately dangerous to life and health (IDLH) is 137 mg/m^3 for an exposure time of 60 seconds in according to the Niosh (2007).

Regarding physical characteristics of UF_6 there are several factors that can accelerate the failure of the valves or increase the consequences of an accident. The first is the possibility of changing the physical state of UF_6 as a function of pressure and / or temperature, which can cause the crystallization of UF6 in cold regions and these crystals, may scratch the seat or even jam the stem for opening / closing operation, causing the failure of the valves. Another important physical characteristic of UF_6 is its volumetric expansion of approximately 33% when liquefied. This creates the possibility of catastrophic ruptures due to excessive hydraulic pressure at points blocked, for example, valves or tubes, when heated.

Other factors that influence the performance of the valves are the operating conditions as for the manufacturing of UF_6, that are presented in Fig. 1.

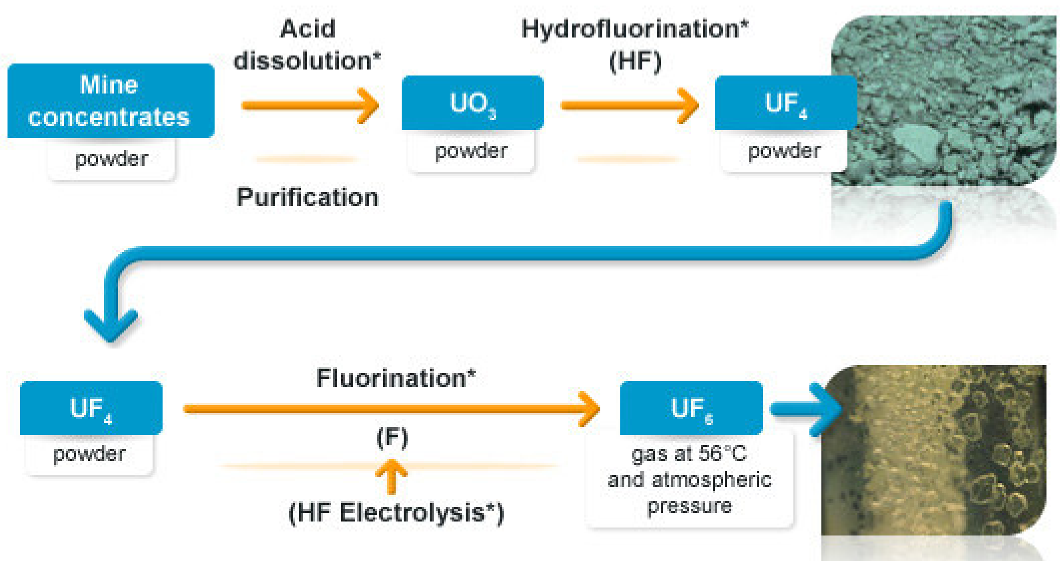


Figure 1. Manufacturing process of UF_6 (Adapted AREVA)

The steps between the dissolution and hidrofluorination are intermediate steps responsible for the purification of concentrate uranium and adequacy of the physicochemical properties of uranium and don't have influence on the performance of the valves.

The next step is fluorination, where the fluorine reacts with the powder of UF_4 in the reactor flame, producing the UF_6 (g). The UF_6 (g) goes through porous metal filters to retain the solids (powders UF_4 and non-volatile fluoride) and is solidified in crystallizers at -20 °C.

When it reaches its maximum storage capacity, it is closed and the gas stream is diverted to a second crystallizer, by valves maneuvers, ensuring the continuity of the manufacturing process. So UF_6 stored in the first crystallizer is liquefied at about 80 °C and it is transferred through valves maneuvers to cylinders for storage.

The details of the manufacturing process of UF_6 above presented shows stress conditions which the valves are subjected. The valves are exposed to UF_6, with solids (powders UF_4 and fluoride non-volatile) and corrosive (HF and fluorine) contaminants and to process temperatures ranging from -20 to 80 º C. In this context of hazardous and extreme conditions inherent to manufacture of UF_6, it is necessary the use of special valves with high reliability and reduced leakage probability in order to reduce the risk of accidents.

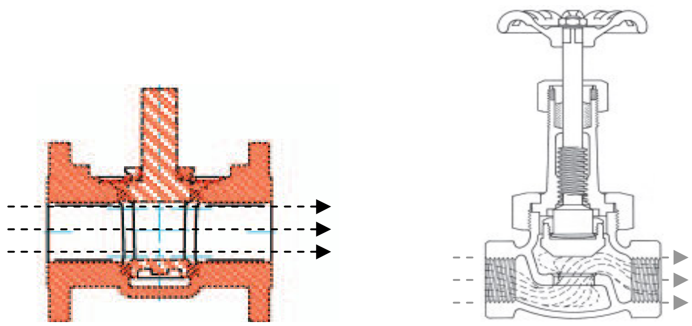
2.1. Valves types used in the manufacture of UF_6

As mentioned before, this work is limited to describe the qualification of blockage valves, since it is the most numerous type of valve used in UF_6 manufacturing plants. Among the possible types of blockage valves were the globe and plug valves were selected for the following reasons: constructive characteristics of the set obturator / seat that allow high sealing capacity, indicated for frequent drives, recommended for liquid and gaseous fluids.

Figures 2a and b show schematic draws cuts of the plug and globe valves, respectively, showing the main differences in valves design, which are the mechanism for closing the obturator (1/4 turn back for plug valve and rising stem globe valve) and flow pattern inside the valves. Because of those differences the plug valve has lower load loss and a shorter time for closure that the globe valve.

Other differences between these types of valves are the small space for mounting the plug valve and the possibility of building the system obturator /seat in metal/metal for globe valves, which are not allowed to plug valves, at least to operate with UF_6.

As for maintainability, both types have advantages and disadvantages in relation to one another, e.g. globe valves offer the facility of exchange of body sealing and shutter without having to remove it from the line. The valve type plug doesn't offer this facility, but admits to a certain extent, adjustments of the sealing tightness in service, which could reflect the higher mean time between failure (MTBF).



(a) (b)

Figure 2. Direction of the fluid flow: (a) plug valve; (b) globe valve

3. RELIABILITY TESTS

The metric of reliability is the probability of the item to fulfill the mission which was designed for through a given operational time. Therefore, if this value is known the decisions on issues relating to operational safety and costs are more effective. For example, what is the right time to use the item to keep the operation safe? What is the best maintenance strategy to be applied? What is the spare parts stock level to be maintained? Also, as suggested by O'Connor (1985), the reliability demonstrates the product quality in the time domain, unlike the actions of quality control, which aren't time-dependent.

According Colmenero (1999) the measurement of reliability is made by tests to determine or control the component performance decrease. The tests to determine the reliability aims at establishing correspondence between the measured values and the requirements of technical conditions imposed by design, as well as determining the mathematical function that best represents the distribution of failures. The product reliability is achieved if the prototype meets pre-set values of acceptance. According to the same author, these tests may be applied in one or more of the following experimental phases:

- Product design
- Product development
- Prototypes
- Pre-production series
- Production normal
- In real state the use of the product

The reliability tests should be made preferably, in the "field", because the value of the reliability also depends on the operating environment, to which the item is inserted, since real operational conditions are easily simulated in laboratory tests. However, this is not always possible for various reasons, such as catastrophic consequences of failure, cost of operational time available for testing, necessary instrumentation to monitor performance, loss of quality or production. In these cases the reliability tests are made on test benches, which may simulate operating conditions or in conditions more severe test, called the accelerated life tests.

In accelerated life testing the applied test conditions are more severe than those of normal use precipitating the occurrence of failure. The values obtained in this condition are extrapolated to normal usage conditions, through models of acceleration. The advantage of these tests is that reliability is determined more quickly and economically. The acceleration methods typically used, according Colmenero (1990), is based on the increase of the usage rate or loading rate.

The increase in usage rate is applied to items that do not work continuously. The remaining operating conditions are kept within the design values of the item under test. In this particular it is not necessary the extrapolation of data for models of acceleration in order to predict life under normal use.

The increase in the loading rate is a type of test, where the operational conditions that interfere with the mechanism of failure are exceeded, such as vibration, pressure, temperature, voltage, among others. The time until failure obtained under these conditions is then extrapolated to the usage conditions. However, according to Vassiliou and Goals apud Sassero and Abackerli (2003) the test design should be carefully executed aiming at not introducing failure modes that would not occur under normal use. So, for this type of test is recommended to keep the stress values within the design limits of the item to be tested but higher than those expected in the usage condition.

3.1. Basic standards used for establishing reliability testing of valves

The procedure for qualification of suppliers of valves, through tests of reliability is supported by two standards. The first standard is NBR-9320 (1986) which deals with the formalism of developing a test plan for reliability analysis. The second standard is the NBR 15827, ABNT (2007), which establishes requirements for design and test prototypes of valves for the oil industry installations. The standards adopted are summarized in the sequence of this text

<u>NBR-9320 (1986) - Reliability of equipment: procedure</u>

This standard lists the conditions and makes specific recommendations on the development of procedures, verification or determination of reliability in equipment or systems. The major guidelines are presented briefly in Tab. 1. Additionally, this standard emphasizes that the final test of reliability has not only the function of indicating the acceptance or rejection of the item, but also of investigating the causes and consequences of each failure observed during the test. Thus, it is expected more effective corrective actions or improvements in design, aiming at increasing the reliability of the item.

It is also worth mentioning the requirement 6.6, which details the general conditions for the choice of test conditions, "items considered critical, such as for safety, the test conditions should be the more severe, without omitting any of the conditions use, listed in the design". However, these conditions (severity levels) may not exceed the limits specified for them.

Table 1- Guidelines for testing the reliability - NBR-9320 (1986)

Necessary information		Item
Items under test and test types	• Type of equipment tested. • Type of test to be performed (bench or field). • Population from which the sample will be withdrawn.	5.1.3 6.1
Characteristics of reliability and statistical procedures	• Indication of the characteristic of reliability as well as apply the value of acceptable reliability. • Compliance Testing or determining the reliability. • Statistical tests for checking the validity of the hypothesis of statistical distribution considered when applicable.	6 6.2.4
Conditions and test cycles	• Environmental conditions and operation. Including operating system, loading, handling and actual conditions. • Preventive maintenance can be performed during the test. • Test cycle.	6.7 6.13 6.8 6.6
Performance of the items under test and criteria for identification of damage	• Functional parameters to be followed and criteria for identification of damage. • Types of failure for immediate rejection. •Types of failures not relevant. • Period of testing time to be considered as relevant. • Time of testing or minimum number of operations and / or maximum, for each item under test.	6.10.1 6.10.2 6.10.4 6.10.3 6.10.5
Pre-conditioning and corrective maintenance	• Testing, adjustment, calibration and debugging of the items under test. • Corrective maintenance procedures for use and display of items or parts that can be replaced before the end of the test.	6.1 6.11.2

<u>NBR15827 (2007) - Valves for industrial installations of exploration, refining and transportation of petroleum products: Project requirements and prototype testing</u>.

This standard establishes requirements for design and test prototypes of valves for the oil industry installations. Its adoption was not completely possible, due to the type of valves selected for the present study. However, it was adopted in the preparation of tests for the reliability aiming at defining design documents that must accompany the prototype which are listed below:

- ✓ Dimensional drawings of the valve with a list of all components and material specifications
- ✓ List of manufacturing drawings of all components in its latest revision and assembly procedures, including torque of screws;
- ✓ Degree of completion of the seats, valves and sealing area of the stems as well as hardness and toughness differentials where applicable;
- ✓ Presentation of the curve of pressure drop and flow capability;
- ✓ Presentation of the torque requirements in the valve shaft under nominal conditions of operation (TNO), maximum torque of operation (TMO) and the maximum allowable torque (TMA).

This standard also suggests the incorporation in reliability testing of valves the analysis of performance when submitted to thermal cycling and systematic measurements of signature of the valves.

The signature of the valve records the torque imposed on the valve stem along its course during opening and closing, for a given pressure and temperature test system (bench). However, the determination of the signature of the valve was adapted in this study. In this case, as indicative of the signature of the valves, was used the measurement the linear displacement of the stem (globe valves) or the angular displacement of the stem (plug valves) as a function of air pressure in the actuator and temperature of the test system. The signatures of the new valves will be used as standards for manufacturing, as suggested by the standard and the signatures made during the tests will be used as possible parameters for predicting failure of the valve.

3.2. Procedure for qualification blockage valves, by means of reliability test

The qualification of blockage valves is executed in three tests benches. In the first bench the prototype is submitted to accelerated life testing and in the other two benches a valve is exposed to UF_6 in two critical conditions, simulating its manufacturing process.

The construction details of the benches and procedures of reliability testing for each phase are itemized below. However, before it is defined as functional failure of the valve the occurrence of any leakage of fluid by one of their sealing systems (seat; castle / stern and body / bonnet). The measurement of leakage is done by pneumatic leak test, as recommended by ORO-651 (1987) and also for the simplicity of implementation that enables its application in the "field" without requiring the use of special equipment or procedures. It is also worth mentioning that this method is given in several standards of manufacturing valves, such as API-598 (1990), ANSI / FCI 70-2-2006 (2006) and ISO-5208 (1993), once those requirements are easy to be understood by the manufacturers participating in the qualification program.

The pneumatic leak test is performed with the valve opens to measure the leakage of sealing systems of body / bonnet and castle / stem. To measure the leakage of the seat, the pneumatic test is conducted with the valve closed. Both tests are performed, as specified below:

- Fluid pressure: compressed air at 6 ± 1 bar.
- Test temperature: room temperature and 120 ºC.
- Leak measurement time: five minutes.
- Criteria for identification of failure (leakage): the system can’t present pressure drop during the test time, indicated by a pressure transmitter capacitive cell, i.e., no leakage is allowed during the measurement period.

3.2.1. Accelerated life testing

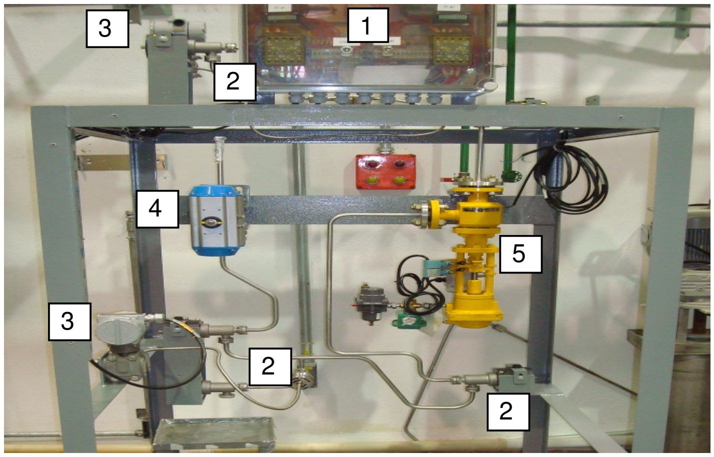
The purpose of accelerated life testing is to precipitate a failure in the shortest possible time and to show the deficiencies in the design, assembly and / or materials quality of the valve. In this step it is considered as not relevant failures the adjustments gaskets of the globe valves and the settings of the plug on plug valves.

The test procedure is as follows:

a) Installation of valves and electrical trace heating system (piping and valves).
b) Check initial leakage of the valve and system.
c) Record the signature of the valve as received at room temperature.
d) Start cycling valve and after 500 cycles measure the valve leakage.
e) Heating the system at 120 ° C and start cycling the valve for 10 times.
f) Measurement of leak after hot cycling.
g) Removing the heat source and restart the valve cycling at room temperature.
h) Repeat the steeps d-f twice more.
i) After 1500 cycles, record the signature valve at room temperature and at hot environment.
j) Completion of testing and removal of valves in the system

The valves that don't fail at the end of the suggested number of cycles are considered approved and move on to the remaining tests. The number of cycles proposed represents 3 times the expected use of these valves in the campaign to produce UF_6.

Figure 3 shows the general arrangement of test bench.



Legend: 1-Control Panel; 2 – On/off valve; 3 - Pressure Transmitter; 4 - Plug valve under test and 5 - Globe valve under test

Figure 3. General set of bench accelerated lifetime testing

3.2.2. Tests of valve with real fluid

These tests aim at studying the behavior of the valve seals when exposed to real fluid in two critical situations found in the UF_6 manufacturing process. The first critical condition is the exposure of internal part of valve to the gas stream output of UF_6reactor, which contains many impurities, among them, HF (g), F_2 (g), UF_4 powder and other non-volatile fluorides. These impurities can degrade the seals and cause valve failure due to physical and chemical phenomena such as corrosion and abrasion. The total exposure time for prototype is 80 hours, and measures of leaks held every five hours. The remaining operating conditions are: temperature of the valve is 120 °C and internal pressure system 5 mbar. The schematic drawing of this bench is shown in Fig. 4.

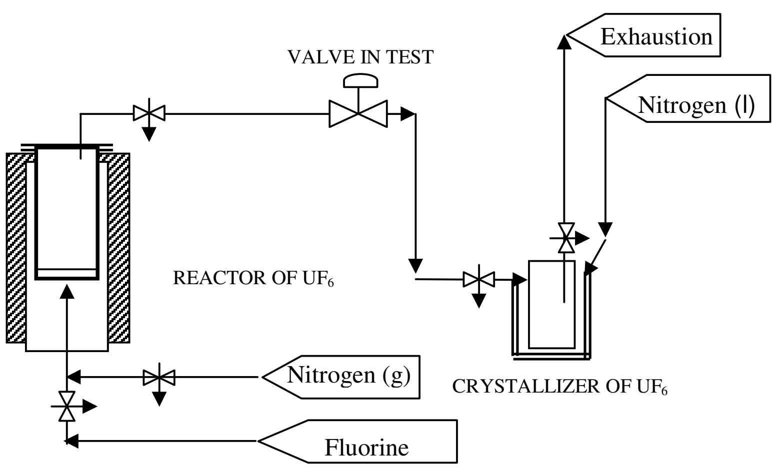
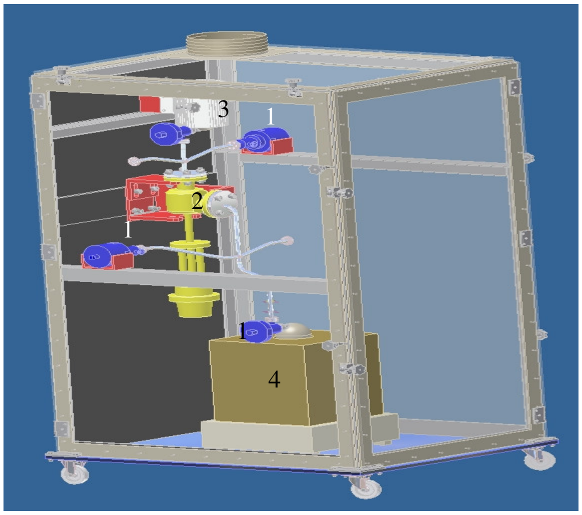


Figure 4. Schematic drawing of the testing bench for internal exposure of the valve to the flow of gas from UF_6 manufacturing reactor

The valves that do not fail the first test should be exposed to a second bench that simulates the liquid transfer of UF_6 crystallizers to the storage cylinders. This moment is considered critical due to the abrupt drop pressure and fast acceleration of fluid through the valve, which can cause premature wear of seals. The test is conducted between the pneumatic tests. Figure 5 shows the schematic drawing of the bench.

Finally, the valves submitted to these tests will be dismantled, as recommended by the NBR 15827, ABNT (2007), aiming:

- ✓ Photographic record of all seal areas and their elements.
- ✓ Final metrology of components subject to wear.
- ✓ Non-destructive testing for defects considered unacceptable, such as loss of coating, extrusion, corrosion and cracks.



Legend: 1 - stop valves, 2 - valve test, 3 - Ampoule with UF_6 liquefied and 4 - Ampoule receiving UF_6

Figure 5. Test bench for exposing the valve to liquefied UF_6

4. VALVE MANUFACTURERS PARTICIPATING IN THE QUALIFICATION PROCESS

In the qualification process five manufacturers of valves had participated, with two models imported from traditional manufacturers of valves for UF_6. They were included in the study because they represents the standard to be achieved or improved.

Table 2 presents the identification and the main construction characteristics of all valves. It should be emphasized that details of construction of the valves were omitted because they are properties of manufacturers participating in the qualification program.

Table 2 - Identification and the main characteristics of valves in the qualification process

Manufacture	Origin	Type	Stem sealing	Set seat / obturator
A	Imported	Angular globe	Bellows	Metal/resilient
B	Imported	Plug	Metal + PTFE	Metal/resilient
C	National	Straight globe	Bellows	Metal/metal
D	National	Plug	Metal + PTFE	Metal/resilient
E	National	Straight globe	Bellows	Metal/metal

The standard globe valve (imported), has the angular construction and specification of the type metal-resilient seal seat / obturator, different from other two manufacturers of globe valves. This fact could be explained by the impossibility of importing a straight line globe valve and the unavailability of resilient material in the same specification, as used in the globe valve imported.

Therefore, globe valves use the type metal-metal seal of the seat / obturator, which require greater force of pneumatic actuators to achieve the same tightness. Consequently, National globe valves are heavier and occupy more space for assembly, due to the construction of more robust pneumatic actuators as shown in Fig. 6.

Figure 6. Difference between size of the globe valve actuator of manufacturers A and C

5. PRELIMINARY RESULTS OF RELIABILITY TESTS

This item presents the preliminary results of accelerated life testing of valves, as well as the difficulties and deviations found in their application. Other tests using UF_6 are still not finished and shall be presented in future work.

5.1. The A manufacturer - imported angle globe valve

The valve was tested according to the test plan and approved, but there was a need for adjustment of the gasket at the beginning of the tests and after 500 cycles of opening and closing the valve. Those failures, not considered relevant have been resolved, according to procedure of the manufacturer. Figure 7 shows the graph of signature of this valve, according to the actuator supply pressure, temperature and amount of cycles.

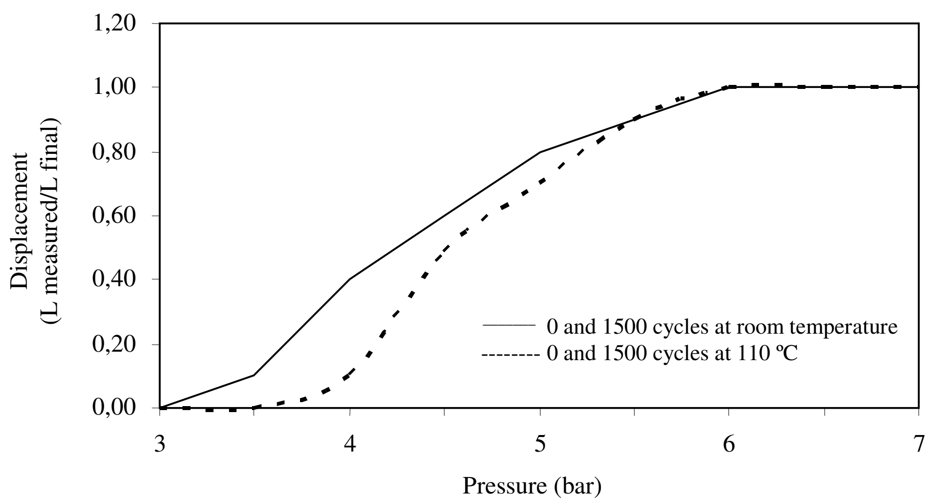


Figure 7. Displacement the stem according to the actuator pressure, temperature and numbers of cycles of the valve A

The analysis of the graphic, considering the limitation of the measuring system of the signing of the valves, concludes that for supply pressure of actuator to 5.5 bar, the displacement the stem is higher at room temperature than at elevated temperature. This effect can be explained by the expansion the stem when the valve is heated, which increases the contact force between the stem and gasket. Also, there was no correlation between the number of cycles and displacement the stem. Perhaps this fact has been caused by the low accuracy of the measurement system of displacement of the stem, which masked the results, or the number of cycles was not sufficient to cause differences in behavior of the system in question.

5.2. The C manufactures – national globe valve

It was tested two versions of the manufacturer's design and both failed. It was identified as the cause of failure, the following deficiencies of design and manufacturing: seals between the valve body and bonnet of inadequate material, lack of cleanliness of the internal valves parts and poor finishing of seat and obturator.

5.3. The E manufactures – national globe valve

This valve has been approved in accelerated life tests. The behavior of the stem displacement according to air pressure could not be determined in this case because the actuator used is the air / air type. This fact represents a deviation from the valves specification and was only accepted for this phase of learning and project development project.

5.4. The D manufactures – national plug valve

The first version of the design was reproved by a poor design and deficiency in the selection of materials of the fixture system of the plug in the valve bonnet.

After correction of these deficiencies a second version of the valve was tested, where it was observed that after cooling of the valve (item 3.2.1 step F), it began to leak, requiring adjustment of the plug to stop the leakage. Even though such failure is not considered relevant and therefore does not reprove valve. The manufacturer withdrew the test valve in order to improve its design.

To determine the cause of that failure exploratory tests were conducted and concluded that the plug dilatation caused plastic strain in the sleeve sealing seat. Consequently, when the valve is cooled there is loss of contact between the plug and the sleeve causing the leakage through valve seat.

Figure 8 shows the displacement of the stem as a function of the actuator pressure, where it is observed the signature of the valve performed at room temperature, hot (120 ºC) and after cooling the system, highlighting the phenomenon of plastic deformation of the seat sleeve sealing after cooling valve.

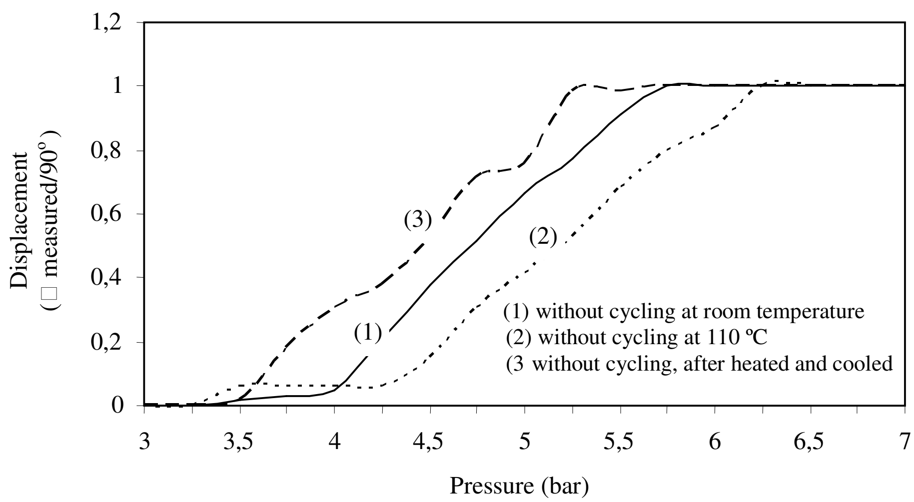


Figure 8. Displacement of the stem depending on the valve actuator pressure and temperature

5.5. The B manufactures – imported plug valve

The tests of this valve showed the same behavior pattern of national plug valve, ie, after every cycle of heating and cooling it was necessary to adjust the plug of valve.

6. CONCLUSIONS

This work has been motivated by the difficulty of importing valves to be used in a plant of uranium hexafluoride (UF_6). To ensure their safe and proper operation, a formal plan of reliability experiments was presented, including the building of three tests benches to support them. For preparing the test plan it was considered the standards NBR9320, ABNT (1986), and NBR15827, ABNT (2007), as well as the conditions and particularities of the plant under analysis.

Despite all the three types of reliability experiments have not been executed, the results of accelerated life tests were sufficient to precipitate the failure of valves, either due to poor design, materials or manufacturing, and lack of safety for operators.

In particular, the results of accelerated life tests of plug valves showed their limited use in systems and processes that have steep thermal cycles. This phenomenon was unknown even by the manufacturers of plug valves and not mentioned in the literature.

Another interesting conclusion was the change in registers of the signatures of the valves, as function of the number of cycles and temperature. However, due to the low sensitivity of the system used and the absence of continuous monitoring during all the test sequence it was not possible to extract relevant data for globe valves, such as the need for adjustment of gaskets and seat seals wear. Meanwhile, the system used was able to indicate the failure of the seal seat for plug valves.

Despite the deviations found, such as the absence of system for continuous recording of torque and the temporally impossibility to execute tests with UF_6, the results obtained in this initial phase demonstrated the importance of using tests of reliability as a tool in product development and / or qualifying suppliers.

Finally, it is believed that finished the reliability test plan as designed, besides the final objective that is the qualification of national manufacturers of valves, the test results may support the decision-making on operation and maintenance of plant reference contributing for reduce the risk inherent in the process of manufacturing UF_6.

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