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A maintenance strategy for a multi-valve cryogenic distribution system

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Abstract. Big scientific facilities that use cryogenic technologies usually need to transfer and distribute cooling power from a cryogenic plant to cryogenic users. This requires a cryogenic distribution system which includes a number of valve boxes at the interfaces to the cryomodules and magnet cryostats. Such systems consist of a number of components which can malfunction or get damaged in many ways leading to unwanted shut downs of the entire facility. In order to avoid these problems or mitigate their consequences the cryogenic distribution system should be properly operated and maintained. This requires planning of maintenance works, storing spare parts and ordering some service works. The paper presents a maintenance strategy for a multi-valve cryogenic distribution system.

1. Introduction

Big scientific facilities that use cryogenic technologies usually need to transfer cooling power from one or several cryogenic plants to cryogenic users. Typical cryogenic users are cryomodules with superconducting radiofrequency cavities and cryostats with superconducting magnets. The superconducting devices are usually immersed in liquid helium or cooled down by supercritical helium flowing in pipes, which are thermally lined to the superconducting components. Due to the complex architecture of the cryogenic systems, the cold helium usually needs to be not only transferred in long distances, but also precisely distributed among the different users. Such architecture requires a sophisticated cryogenic distribution system that includes a number of valve boxes at the interfaces to cryomodules and magnets' cryostats.

A typical cryodistribution system usually consists of a tremendous number of components that can malfunction or get damaged in many ways leading to unwanted shut downs of the entire facility. These components are control and on-off valves, check valves, heat exchangers, electrical heaters, temperature and pressure sensors, electrical feedthroughs, bellows, flexible hoses, injectors and safety devices. In order to avoid failures or at least mitigate their consequences the systems should be properly operated

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and maintained on regular basis. This requires planning all required maintenance works, storing spare parts and ordering some service works.

The majority of the mentioned cryodistribution system components are passive. Since they do not include any moving parts, they are less likely to fail. The only active devices are control and on-off valves. They are usually driven by pneumatic actuators, which are controlled by positioners including electronics and solenoid valves regulating the pressure of compressed air in the actuators. In order to avoid leakages of cryogenic fluids through the valve seat and through the valve stem to the atmosphere, the valves require very sophisticated sealing. Since valves consist of a number of elements that can age and wear out easily, they need to be inspected on regular bases and the sensitive elements have to be replaced. These activities require warming up and depressurizing the cryogenic circuits, so they have to be well planned ahead and aligned with the operation schedule of the entire scientific facility.

The paper presents a maintenance strategy for a multi-valve cryogenic distribution system. Possible failures of the system components are identified and required maintenance and reparation works are described. The presented maintenance algorithm is intended to support decision-making on spare part and service cost minimizations.

2. Multi-valve cryogenic distribution systems

A multi-valve cryogenic distribution system (CDS) is a system intended for distributing cryogenic fluids to a number of users and regulating the cryogen flows to and from the users. It can also allow for disconnecting a single user while keeping the others at cold conditions. A good example of such systems is the LHC cryogenic distribution, which is composed of eight 3.3 km long cryolines. Each cryoline include around 25 valve boxes, each containing 6 cryogenic valves [1].

Another example is the ESS linac cryogenic distribution system, currently under construction at European Spallation Source ERIC in Lund, Sweden. Its distribution line is only 310 m long, however, it comprises 43 valve boxes and one end box. In each valve box for the elliptical and spoke cavity cryomodules there are 6 and 8 cryogenic control valves, respectively, and 2 warm control valves [2]. Thus, there are 373 control valves in total. Figure 1 shows a schematic flow scheme of the ESS linac cryogenic distribution system.

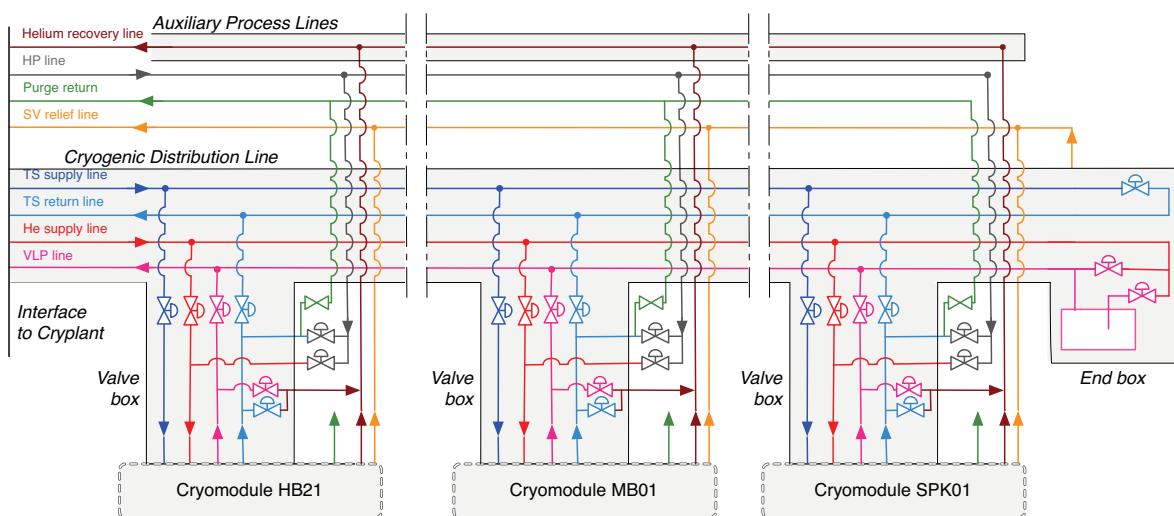


Figure 1. General flow scheme of the CDS for the ESS Linac

3. Design of a cryogenic valve

A typical cryogenic valve for application in cold helium installations is presented in figure 2. The valve body in its bottom has an inlet and outlet, which are welded to a process lines, whilst at its top there is a flange that is welded to the vacuum jacket of a valve box. So, the fluid room is separated from the

vacuum by a continuous metallic barrier. It is also separated from the external environment by a complex sealing system, allowing the valve to operate. The valve body is often connected through a heat interception to the valve box thermal shield. No replacement of the body is thus possible, unless the valve box is being dismantled.

The cryogenic valve needs to contain moving parts to control the opening, which is an actual flow passage, between the flow plug and the seat. The movements of the plug is driven by a pneumatic actuator and transmitted by a stem located inside the insert. These parts are responsible for the function of the valve; however, they are more or less subjected to a certain wear during the time.

In order to perform all operations of maintenance, the valve is built in such a way, that the internal parts, down to the seal and the plug, can be extracted from the upper side, without breaking the vacuum, nor needing any intervention on the valve body. Figure 3 shows dismantling of a valve for cold helium installations. After unscrewing and removing the actuator the valve insert with the bellows and flow plug can be pulled up out of the valve body.

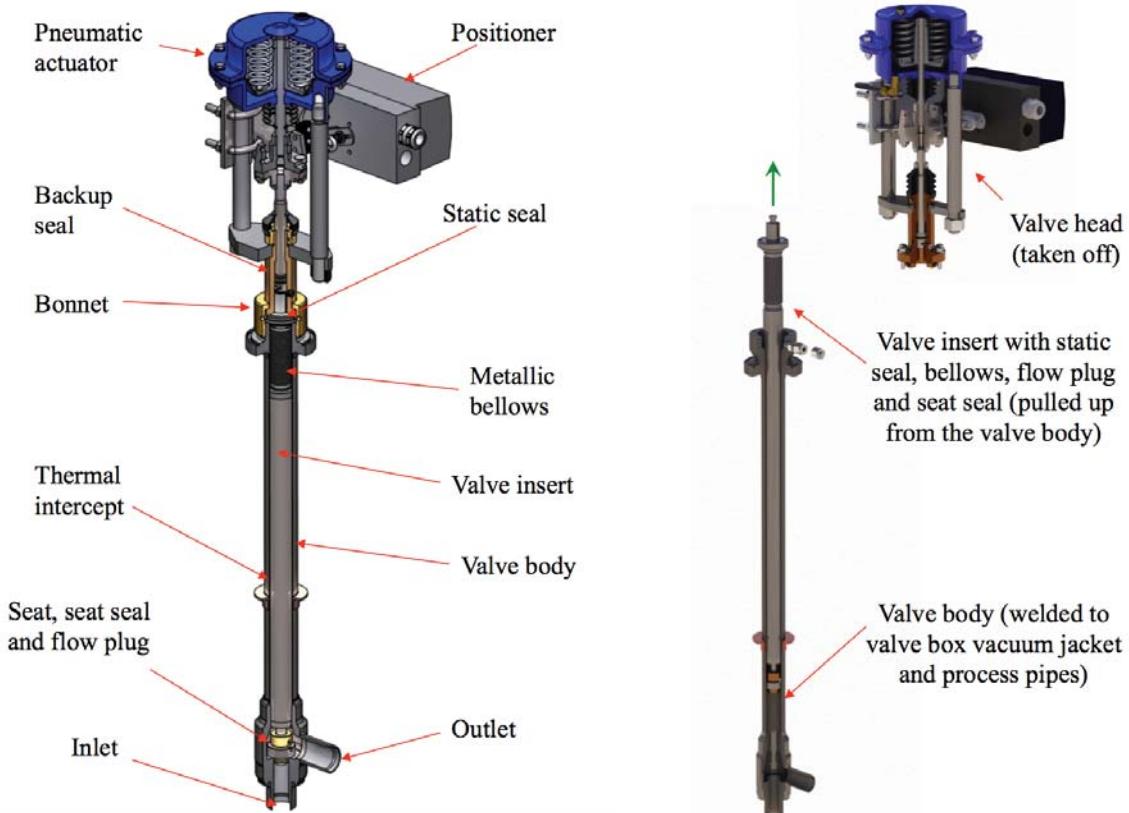


Figure 2. Main components of a cryogenic valve for cold helium installations

Figure 3. Dismantling of a cryogenic valve

Figure 4 illustrates some details of the sealing system from the atmosphere. The main component is metallic bellows which connect the moving part of the stem with a ring. The ring is fixed to the body of the valve and sealed by two o-rings. The bellows create a continuous barrier between the internal room of the valve, where the process fluid (helium) is located, and an intermediate room. If the o-rings are not perfectly tight or the bellows break, the process fluid can leak to the intermediate room. And when the process fluid is at sub-atmospheric pressure, this intermediate room shall be filled with guarding warm helium in order to avoid leaks of the air to the internal room and further to the process line.

4. Cryogenic valve failures

The failures of cryogenic valves are generally due to fatigue, accumulation of impurities and aging of materials. In the following the origin and frequency of the failures on the valves is being analysed.

4.1. Metallic Bellows

Fatigue is the main origin of a rupture of the metallic bellows of the valve. This very important component is being extended and compressed during the operation of the valve. The design criterion foresees to choose bellows for 10^4 full strokes at the design pressure. This value cannot be anyway easily interpolated to a fatigue limit in the case of reduced amplitude. The manufacturers of bellows show that their products that are not subjected to excessive solicitations are able to perform 10^7 cycles without breaking. This may be the case of a control valve, used in quasi-static regime.

4.2. Seat Seal

The experience shows that the seat seal reflects the cleanliness of the process fluid circuits as well as the operating conditions like fluid pressure and velocity. The most failures of the seat seal occur in the first start-up of the cryogenic system, when the pipelines can still contain some unwanted solid impurities (usually metal debris, MLI cuttings, etc.) remaining after manufacturing and assembly processes. These impurities can flow with the cryogenic fluid stream and be shot at high velocity against the surface of the seal. In general the fastest flow of particles takes place at the start-up of the installation after its commissioning or maintenance break. Thereafter the probability of some debris getting to the valve seat seals is reduced.

Valves with seals made of softer materials, like PTFE or high-density polyethylene, are less sensitive to these particles, whereas valves with seals of hard and radiation resistant materials are more influenced.

Hence, the seat seal failures result from a progressive reduction of the seal tightness and appear at the moment when the maximum acceptable leakage level is exceeded.

4.3. Static Seal

All the seals and gaskets that are located at the warm end of the valve and are not movable are commonly referred to as static seals. They are usually made of elastomeric materials, but in very special cases some metal alloys are applied. Leakages caused by a failure of these components are very rare, even if a valve is being revised after a long time, mainly because these parts are not subjected to direct mechanical solicitations.

Anyway, it is important to notice, that elastomers can decay over time, in particular when exposed to ionizing radiation. Once the components lose their elastic properties, their tightness can be no longer guaranteed. In this case a static seal can fail and lead to a progressively increasing leak.

4.4. Actuators

Failures of actuators are also very rare and are almost always due to failures of the diaphragm and compressed air gaskets, since the other components (springs and bolts) practically never get worn out and damaged due to fatigue.

The diaphragm and gaskets that has to be made of elastomers are subjected to aging within time and to the influence of ionizing radiation. Moreover, these components are usually designed for a maximum air pressure of 6bar(g), above which the tightness is no longer guaranteed. In case of a failure of the diaphragm, the air pressure is no longer capable to actuate the valve. Then the valve should get to the failsafe position given by the springs.

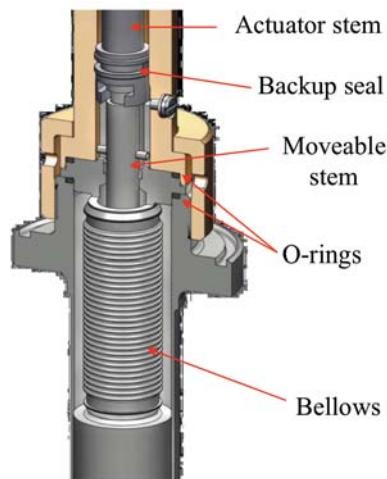


Figure 4. Sealing system from the atmosphere

4.5. Solenoid valves, positioners and air regulation units

Components needed for controlling the air pressure to the actuators are normally not subject to direct wear. They are conceived for a very broad application field in the industry, where they should undergo severe tests. Failures are mostly due to human error, like an overload in the current/voltage supply or a mechanical shock. Only rarely, the tightness of the seals can be affected.

4.6. Tentative values for elaborating a maintenance algorithm

The analysis of about 5000 valves performed by WEKA AG over 4 years gives some assessments of the probability of valve component failures [3]. Table 1 presents estimated failure rates for chosen components.

Table 1. Estimated failure rates for cryogenic valve subcomponents

Valve component	Failure rate
Metallic Bellows	from 10^{-4} to 10^{-5} fails per valve per year
Seat Seal	10^{-3} fails per valve per year (first year)
	from 10^{-4} to 10^{-5} fails per valve per year (following years)
Static Seal	from 10^{-5} to 10^{-6} fails per valve per year
Pneumatic Actuator	from 10^{-6} to 10^{-7} fails per valve per year

5. Cryogenic valve maintenance

Typical maintenance operations are replacements of used o-rings, seat seals and metallic bellows. They can also include the exchange of some components of the control units, such as the diaphragm and compressed air gasket of the actuator as well as the compressed air solenoid valves of the positioner.

Since a number of parts that need to be exchanged are located in the internal and intermediate rooms, the maintenance work can require warming up and depressurisation of the process line. Depending on the size of the circuit, quantity of cryogenic fluid, size of the cold mass, the preparation for a maintenance operation can last up to a dozen of days or more. A lot of maintenance works require preserving the cleanliness of the valve components, as well as a very low humidity.

5.1. Seat seal

As the seat seal decreases its performance with the accumulation of particles on its surface, the preventive maintenance should be adapted to the cleanliness condition of the plant (cleanliness of the supply gas, frequency of maintenance of the plant in general). A good recommendation is to change the seals after 5-7 years.

5.2. Bellows

The valve inserts with bellows should be extracted each time when the seals need to be changed. On this occasion, it is worth to inspect the bellows in order to detect possible damages. In particular, not straight bellows can lead to an abnormal wear of the sliding elements, which are for centring the stem, and can even damage the surface of the flow plug. Moreover, stems sticking or moving not smoothly can break more frequently under fatigue than straight and well guided stems.

5.3. Static Seal

Like the seat seal, the static seal is being repaired by extraction of the valve stem, an operation which is recommended to be executed at the occasion of the seat seal exchange, i.e. after 5-7 years. It takes into consideration the decrease of elasticity due to aging of elastomeric material of the static seal.

5.4. Pneumatic Actuators

Pneumatic actuators can be repaired by changing the diaphragm and air gaskets connecting the air chamber with the stem. The lifetime of their diaphragms made of EPDM can be estimated even for 20-25 years of continuous operation [4]. However, since such failures can lead to loss of the control on the valve, it is recommended to preventively maintain actuators every 15-20 years. In case of valves exposed to ionising radiation this period may be reduced even to 5-7 years.

5.5. Solenoid valves, positioners and air regulation units

Malfunctions of the components controlling the air pressure circuit are difficult to be predicted for preventive maintenance. The components are anyway out of the valve box and can be easily replaced, unless the valve box itself is working on a radiation area with restricted access. The tightness of the internal and external connections can be detected by detection spray and repaired by replacing the components.

6. CDS maintenance strategy

6.1. Assumptions, goals and algorithms of reparation and maintenance works

CDSs are one of key subsystems, the functioning of which can have a significant impact on the performance of the entire facility. Its equivalent availability, defined here as the capability of being in operable and properly functioning conditions in specified time periods of the machine operation, can be specified at the level of 99% to even 99.9%.

For the purpose of the present study it is assumed that the CDS availability can be affected only by failures of valve components, whilst all the maintenance works can be done during planned shutdowns of the entire scientific facility. These shutdowns may be scheduled for at least once a year and has a duration of 8 weeks. Thus, the main goal of the maintenance strategy is to evaluate the required resources for all the typical maintenance activities related to the control valves. The other goal is to assess and minimize the costs of all reparations of malfunctioning or damaged components of the CDS control valves, which do not allow meeting the requirement of a given equivalent availability.

Repair and maintenance work procedures need to include several activities such as detection of failure source, work preparation, purchase and delivery of spare parts and materials, contracting service works and finally replacing or reparation of broken or malfunctioning components. For some parts, it may be required to warm up and depressurise the CDS, and later to pump and purge the affected circuits, followed by cooling down the entire installation. Figure 5 shows two example algorithms for reparation of such a part. It is assumed here that the warm-up and cool-down may take 10 days each. If staff members can do the work and all needed spare parts are stored at the site the shutdown of the machine lasts 22 days. However, if there is a need for purchasing reparation parts and ordering external workforce the shutdown may last longer, depending on how long it takes to purchase and deliver the parts and contract the service. Here it is anticipated that material purchasing and service ordering may take up to 2 working days, whilst the material delivery can take two weeks. So, the total shut down lasts 27 days. For reparations that do not require any warm up the shutdowns last 2 and 17 days, respectively.

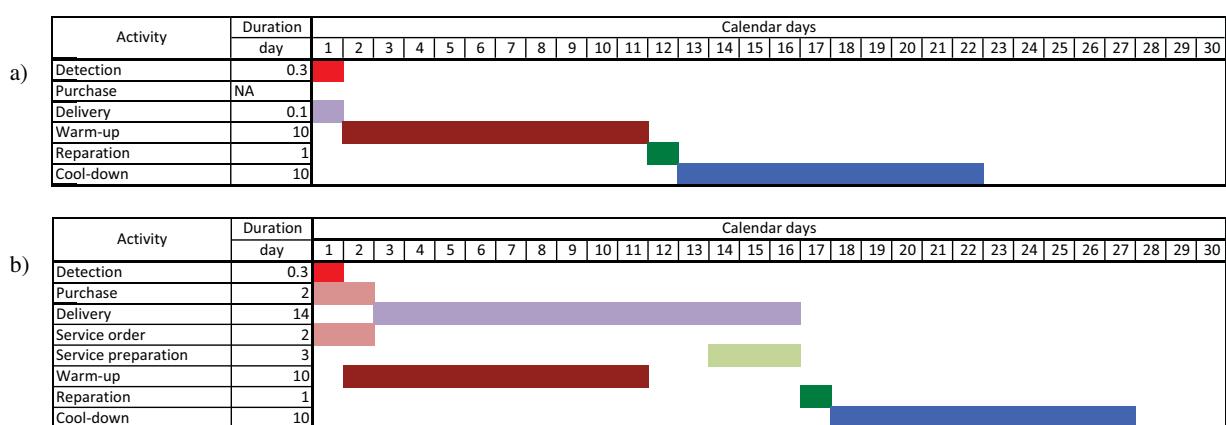


Figure 5. Example procedures for reparation of damaged insert with a) internal workforce and stored repair parts and b) purchased service and repair parts

In case of maintenance works there is usually a need for contracting service works and purchasing a certain quantity of spare parts. Figure 6 shows an example procedure for relatively extensive maintenance works to be done with external workforce. It shows that the preparation works should start even 4 months before the planned shutdown.

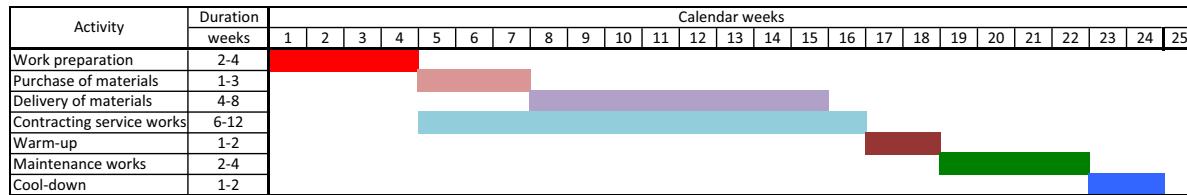


Figure 6. Example procedure for maintenance with outsourced service and purchased repair parts

6.2. Example case study

The present case study is done for a CDS consisting of 400 control valves designed for a 43-year operation period. Table 2 presents assessments of the costs of the required spare parts and workforce (1 man-hour = 60 EUR). It shows that the cost of personnel varies from 10% (actuator) to 65% (insert bellows) of the total maintenance cost. It is assumed that during maintenance works all parts are inspected but only a certain given fraction is exchanged, except gaskets at warm end. Based on the estimated usage times, review periods and costs two contrasting plans for maintenance works were elaborated. In the first plan, depicted in figure 7a, all the required maintenance works are done in one turn literally when the recommended usage time or review period is over. It results in very uneven distribution of required personnel and financial resources. In contrary to this, in the other plan, the works are done in 7 campaigns, each lasting 5 consecutive years. This approach results total costs of 1012 kEUR, which is lower by 176 kEUR in respect to the first one. In both cases the total cost of workforce is at the level of 36 %.

Table 2. Estimations of the required workforce and costs for the maintenance of CDS control valves

Control valve components	Usage time / review period [year]	Quantity per system [-]	Maintenance work time per component [hour]	Minimum required number of workmen [-]	Required personnel resources [man-hour]	Total cost of personnel resources [EUR]	Fraction for replace [%]	Unit cost of spare parts [EUR]	Total cost of spare parts [EUR]	Total cost of maintenance [EUR]
Gaskets	5-7	800	1/8	1	100	6000	100%	50	40000	46000
Seat seal	5-7	400	1/4	1	100	6000	50%	100	20000	26000
Bellows	20-25	400	1/2	1	200	12000	20%	1300	104000	116000
Actuator	5-7	400	3/4	2	600	36000	10%	500	20000	56000
Air valve	15-25	800	1/4	1	200	12000	10%	300	24000	36000
Air gauge	15-25	400	1/4	1	100	6000	10%	300	12000	18000

Table 3. Estimations of statistical downtimes caused by failures of control valve components for internal (I) and outsourced (O) workforce, and for purchased (P) and stored (S) repair parts

Control valve components	Failure rate [1/year]	Quantity per system [-]	Cumulative failure rate [1/year]	Downtime for incident [day]				Statistical downtime per year [day]			
				I/P	I/S	O/P	O/S	I/P	I/S	O/P	O/S
Gaskets at warm end	5.0E-06	800	4.0E-03	27	22	27	22	0.108	0.088	0.108	0.088
Seat seal	5.0E-05	400	2.0E-02	27	22	27	22	0.54	0.44	0.54	0.44
Insert bellows	5.0E-05	400	2.0E-02	27	22	27	22	0.54	0.44	0.54	0.44
Actuator	5.0E-07	400	4.0E-04	17	2	17	6	0.0034	0.0004	0.0034	0.0012
Air solenoid valve	5.0E-05	800	4.0E-02	17	2	17	6	0.68	0.08	0.68	0.24
Air gauge	5.0E-06	400	2.0E-02	17	2	17	6	0.34	0.04	0.34	0.12
				Total:				2.21	1.09	2.21	1.33

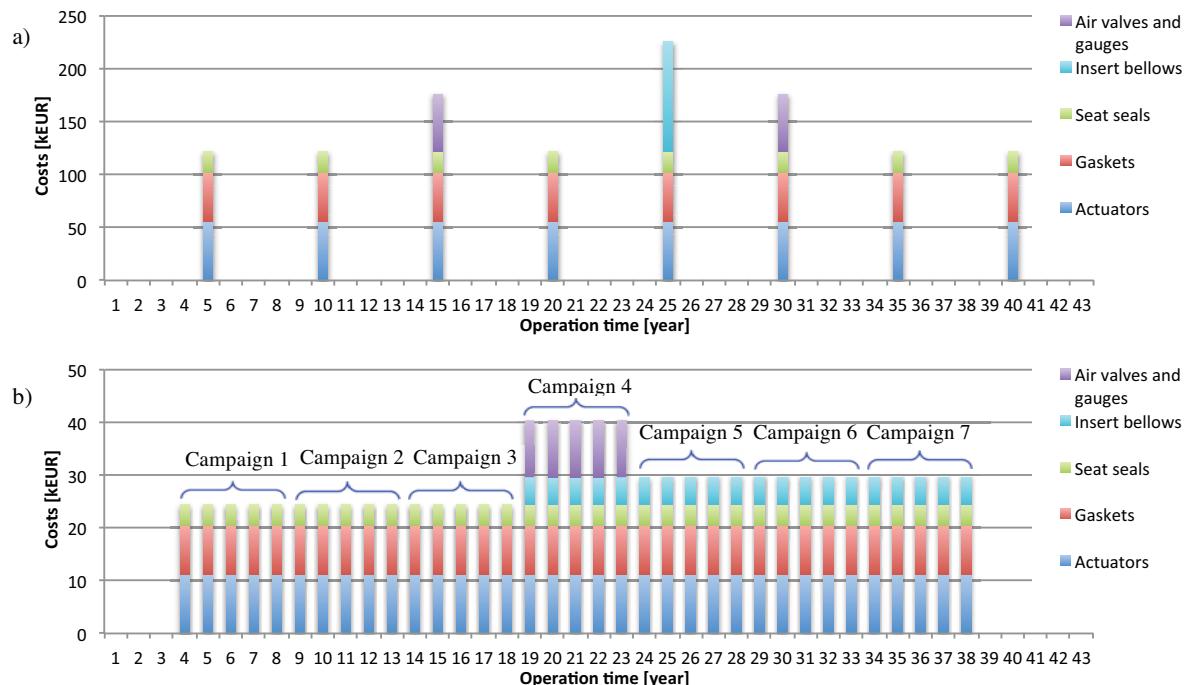


Figure 7. General plans for maintenance works a) each scheduled for one shut down and b) distributed for several consecutive shut downs

Even if all the valves are maintained properly there is still a certain risk of some failures due to fatigue or unexpected worn-outs. Table 3 presents the estimations of downtimes due to failures of the analysed CDS valve components. The results show that the lowest statistical downtime is equal to 1.09 days per year, for the case of using internal workforce and storing repair parts at the facility. Then, the availability of the analysed CDS is at the level of 99.6%.

7. Conclusions and discussion

The presented maintenance strategy for a multi-valve cryogenic distribution system shows that in a long run (43 years) the cost of spare parts may exceed 1.6 kEUR per valve. To perform appropriate and thorough maintenance works there is a need for 15 man-hours per valve. Proper planning and scheduling maintenance activities may help to lower to a certain extent the total cost of the maintenance works. If all the works are planned to be done in one turn for all the valves at the end of recommended review periods it results in severe irregularities in needs for financial and personnel recourses. Planning the maintenance activities in long-term campaigns (of several years) may help to definitely allocate required resources. Figure 7b shows that the yearly cost of maintenance work can vary from 60 to 100 EUR per valve.

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