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Statistical and simulation tools for designing an optimal blanketing system of a multiple-tank facility

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ABSTRACT

The blanketing process consists of creating and maintaining an inert atmosphere inside a closed equipment to prevent the contained product from mixing with oxygen. This technique is widely used in chemical, pharmaceutical and food industries operations, to avoid the ignition, degradation or evaporation losses of their products. This work deals with the design process of an optimal blanketing system in terms of cost, safety and environmental issues, for a multiple-tank storage facility. With this objective, the feasibility of installing a manifold in the system as an alternative to the traditional approach of an individual component in each tank has been technically studied by means of statistical analysis and fluid flow simulation. Moreover, economical, environmental and safety analyses have been performed. The reported results shed light to a more economical solution, which entails a decrease in atmospheric emissions and offers an even higher reliability than traditional systems.

1. Introduction

The blanketing process consists of creating and maintaining an inert atmosphere inside a closed equipment to prevent the contained product from mixing with oxygen. This technique is widely used in chemical, pharmaceutical and food industries operations, in order to avoid the ignition, degradation or evaporation losses of their products. However, it has been scarcely dealt in the literature [3,7].

A common blanketing application consists of storage tank blanketing [2,8,14]. The most usual tank blanketing policy involves keeping the operating conditions between very tight pressure limits. Pressure regulation is needed since temperature changes and liquid transfer operations entail tank pressure variation. Therefore, if pressure decreases inside the tank, blanketing gas is introduced, whereas if pressure increases, vapors are vented outside the tank. Otherwise, vacuum or overpressure would damage the tanks [14].

Different devices such as autoregulating devices or control valves may be installed on top of the tank in order to control pressure. The blanketing and the venting devices, respectively, introduce inert gas and eliminate tank vapors from the gas space when necessary. The venting valve can discharge to a remote treating unit or directly to the atmosphere. In addition, vacuum and pressure reliefs are used to prevent vacuum and overpressure under normal conditions, whereas an emergency venting device is usually added to vent in case of fire. Finally, auxiliary measurement devices such as manometers may be necessary.

This work aims at providing tools and procedures for optimizing the design of a blanketing and venting system, in terms of cost minimization, enhanced operational safety, and emissions reduction, considering an additional objective of high flexibility and easy control of the facilities under any condition the plant may face.

2. Motivating case study

To illustrate the advantages of the proposed solution procedure, let us consider a motivating case study. An industrial group owns a plant which recycles industrial solvents and treats a total amount of about 26,000 Tm per year of degraded product (plant raw material), 9000 Tm of final product and over 18,600 Tm per year of waste. This plant has a multiple storage tank facility whose tanks are opened to the atmosphere. Most of organic solvents are highly flammable and volatile. Therefore, these substances are easily released to the atmosphere as organic volatile compounds and entail pollution and safety risks for the facilities and surrounding area. Hence, the company intends to protect its facilities from fire and reduce pollutant emissions by installing a blanketing and venting system.

The storage facilities contain 42 tanks (Table 1) with a total capacity of 1700 m^3, which are divided in three adjoining zones according to the kind of stored product: product to be treated (zone 200), final product (zone 300) and waste (zone 400).

An additional key feature of the facilities consists of the existence of a common manifold for each four or six tanks in order to perform

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Table 1
Volumes of the storage tanks.

Tank ID (T-)	Volume (m^3)
201 to 204	45
205 and 206	55
207	35
208	50
209	45
210	35
211 and 212	45
213 to 216	30
301 to 316	30
401 to 408	100
409 and 410	120

Table 2
Pump flows.

Pump (P-)	Maximum flow (m^3/h)
101 to 107	60
201 to 203	20
301 to 303	60
401 to 402	60
502, 505, 506	60
601 to 606	20

liquid transference. Hence, a sole pump (Table 2) can be used at a time for emptying a tank out of four, and a sole pump for filling (Table 3).

Typical stored organic solvents, such as toluene, hexane, methanol or acetone do not exhibit undesired reactions among them. In addition, for the sake of product quality, storage tanks with final product must be carefully cleaned before changing the stored product.

Moreover, the plant has a liquid nitrogen tank which is used in a cryogenic condensation to separate organic volatile compounds from the different gas flows of the plant processes. Since nitrogen is available in the plant and it is compatible with stored products, it can be gasified and used as inert gas for the blanketing of the multiple-tank storage. The aforementioned stored substances have a limiting oxygen concentration with nitrogen of about 10% volume concentration [6] and the maximum recommended oxygen concentration is about 6%.

The most wide-spread blanketing solution in this case consists of a pipeline to supply nitrogen to each of the tanks and a pipeline for venting tank vapors. In addition, each tank should have a venting and blanketing device as well as vacuum, overpressure and emergency relieves. As a result, a high number of devices must be installed and nitrogen cannot be reused from one tank to another. In conclusion, a deeper analysis of the blanketing system may lead to improved solutions.

3. Design constraints

An important requirement to improve the traditional approaches consists of posing objectively the problem. Hence, technical, legislative, safety and environmental constraints affecting the system as well as economical objectives must be thoroughly analyzed.

3.1. Legislation

On the one hand, local legislation must be taken into account. Typically, technical instructions (for example, APQ-1 [10], in the case of Spain), deal with the storage of flammable and combustible liquids, and impose a series of rules and states the main leads on the design of this kind of facilities:

- As for atmospheric storage tanks, their relative pressure must not exceed a certain value (for example, 15,000 Pa, 150 mbar, according to [10]).
- Stored substances are classified according to its flammable temperature. Vapors from substances belonging to incompatible groups cannot be mixed. To be more specific, ventings of products whose boiling point is lower than 38 ° C cannot be connected to those of substances with boiling point higher than 38 °C.
- Some rules about how to calculate the minimum normal and emergency venting requirements have to be considered. In any case, the minimum venting diameter for the blanketing system must be equal to the maximum diameter of the pipe that fills the tank with liquid.
- For those tanks whose volume is greater than a minimum value (for example, 5 m^3 according to [10]), if the stored substances have a boiling point lower than 38 °C, the venting should be closed with the exception of vacuum and normal venting to the atmosphere.
- Existing recommendations for blanketing and venting systems should be considered. For example, standard API 2000 [1], entitled “Venting Atmospheric And Low Pressure Storage Tanks”, defines the main reasons for overpressure and vacuum in tanks, establishes a model for calculating the required inert gas quantities for blanketing and venting, and describes the means, selection, installation and maintenance of venting devices. Therefore, API 2000 has been taken as a reference guideline in the blanketing and venting systems design.
- If a blanketing system is adopted, the service must be maintained along the time, and the following rules are recommended:
  - ○ The inert gas must be compatible in terms of chemical stability with the stored products.
  - ○ The vapors in the tanks must be continuously analyzed in order to check that oxygen concentration is lower than the maximum allowed.

Table 3
Description of relation among tanks, pumps and pipe diameter.

Tanks in manifold (T-)	Filling pump (P-)	D (in.)	Emptying pump (P-)	D (in.)
201, 202, 203, 204	106, 505	3	201	3
205, 206, 207, 208	105, 505	3	201p	3
209, 210, 211, 212	107, 506	3	202	3
213, 214, 215, 216	103, 506	3	203	3
301, 302, 303, 304	601	2	301	3
305, 306, 307, 308	601p	2	301p	3
309, 310, 311, 312	602	2	302	3
313, 314, 315, 316	603	2	303	3
401, 402, 403, 404, 405, 407	–	–	401	4
401, 403, 405	105, 502, 604	3	–	–
403, 404, 406	102, 502, 604	3	–	–
407, 408, 409, 410	101, 502, 605	3	402	4

- Control and regulating devices must be installed in order to guarantee permanent working operation. An alarm must also be available to inform about possible system failures.

3.2. Technical constraints

Technical factors are also crucial in the design of the system. As for pressure control, installed devices must allow a thorough control of pressure, that is, they must be able to deal with the maximum and minimum gas quantities for blanketing and venting. Hence, each case must be thoroughly analyzed in order to take into account the particular conditions of the facility to calculate the required quantities of inert gas. As a result, weather conditions, the plant working plan and liquid transfer quantities must be considered to perform the energy and mass balances, and so the inert gas requirements of the tanks.

In addition, the blanketing and venting devices can be installed one in each tank, as explained in the introduction, or in a manifold that joins the vapor head space of different tanks. Then, by controlling the pressure in the manifold, tank pressure is also controlled.

For the latter case, further considerations must be taken into account. In order to install a manifold, four conditions are necessary [14]:

- The mixing of vapors from different tanks must be always acceptable.
- All tanks must be able to work at the same pressure.
- Installed blanketing and venting devices must be able to manage the complete range of possible flows.
- The fact that all tanks joined by the manifold could go out of service simultaneously should not interfere with the satisfactory operations of the tank facility. Otherwise, each tank must have individual gate valves as well as its own vacuum-pressure devices installed.

The advantages of the manifold installation are obvious: the total number of installed devices and the piping length is reduced. Moreover, inert gas consumption can be decreased since there is a higher total gas volume that can buffer pressure changes. Moreover, blanketing system flexibility increases: the more the pressure range allowed in the tanks, the more flexible system operation is.

3.3. Environmental analysis

It is necessary to analyze the system approaches from an environmental point of view. Reported emissions can be classified as liquid and atmospheric.

As for liquid emissions, they consist of condensed vapors from the manifold, which are formed in case of temperature decrease. These must be collected and lead together with those flows condensed in the cryogenic condenser to tanks for waste or products to be treated.

The most important emissions of this system are atmospheric emissions, since organic solvents are an important source of organic volatile compounds. Emissions can be either controlled, which are those coming from the venting of the tanks and further treated in the cryogenic condenser unit, or not controlled, which include leakage flows from all the system, such as those from gaskets and seals. Uncontrolled emissions can not be cleaned from organic volatile compounds. The volume of leakage is a direct function of the equivalent leakage diameter and the existing overpressure inside the tanks.

3.4. Safety and risk analysis

From the safety point of view, qualitative and quantitative risk analysis of the system must be carried out in order to discuss which alternative best fits the safety requirements.

On the one hand, the keywords and Hazop analysis allow to identify the origins and consequences of the process parameters deviations. These analysis have been applied following the methodology presented and data reported in the literature [6]. The most important failures detected are vacuum failure, overpressure failure and fire failure. Anyway, unforeseen events may happen and the plant must be prepared to face them. The scope of this work is to assess and deal with the risk of the most probable failures.

Equipment or process failures occur as a result of a complex interaction of failures of individual components. The total failure probability of a process depends on the kind of relationship between events, namely alternative or simultaneous. The reliability of a system can be modeled by associating a statistic parameter called mean time to failure or mean time to repair to each of its components. The probability that a component does not fail in a specific time period t is usually described by an exponential distribution law. The associated complementary value to this probability is known as failure probability [6]. A quantitative analysis, such as failure tree analysis, yields the probability of occurrence of the previously identified failures.

3.5. Economic optimality

The blanketing system is related to keeping plant operation under safety conditions, so there is no direct income related to its adoption. Hence, the investment in blanketing is justified by safe operation, and not by direct economical benefit. Therefore, a key decision criterion is the total estimated investment and operating costs, which is used to adopt the best solution of compromise with the system features.

4. Proposed design methodology

According to the previous conditions and limiting factors, different alternatives for an improved final blanketing system can be posed (Fig. 1). On the one hand, a manifold can be installed. Its geometry can be either lineal, squared or mixed, that is, a main pipe that joins all tanks and splits at each pair of tanks (Fig. 2(a)), splits at each four tanks (Fig. 2(b)), or even a mixed approach (Fig. 2(c)). Alternatively, a structure with one device per tank can be adopted. Moreover, the final devices can be either control valves or autoregulated devices. Control valves are more expensive and more reliable, but they allow to control the system online, whereas autoregulated devices are adjusted manually, more economical and do not require auxiliary resources, such as compressed air.

Given the reported advantages of installing a manifold for blanketing and venting, a study about the manifold operation is carried out with a double objective: on the one hand, to analyze the upper and lower pressure levels existing in the tanks under normal liquid transfer and temperature changes conditions, and on the other hand, to select the best layout of the manifold. The study comprises

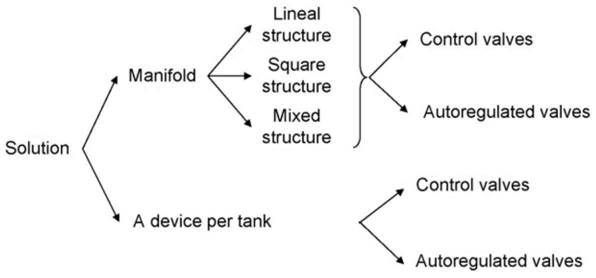


Fig. 1. Schematic representation for the solution alternatives.

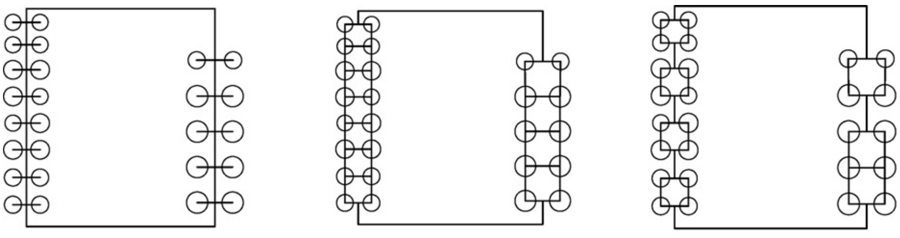

(a) Lineal layout. (b) Squared layout. (c) Mixed layout.

Fig. 2. Representation of different layouts of the manifold joining the vapor spaces of the tanks in zones 200 and 400. (a) Lineal layout. (b) Squared layout. (c) Mixed layout.

the modeling, simulation and results analysis. The files used along these stages are public in [5].

4.1. Manifold modeling

The operation of a manifold for blanketing and venting is based on the principles of gas flow through a complex net of pipings.

As for internal gas flow, gases are usually considered as compressible fluids, which entails a more difficult study. However, if Mach number is lower than 0.3 [4], and pressure variation is low, gas can be analyzed as incompressible. Moreover, if working pressure is near atmospheric values, gases show a near ideal behaviour. Therefore, gas phase is considered an ideal mixture of gases saturated with solvent, and Antoine equation is used to calculate the partial pressure of each solvent.

Regarding flow through a net of pipes, problems are usually complex, and different assumptions must be done: constant fluid density, subsonic permanent flow and the fact that pressure loss along a branch is higher than singular losses.

Using the aforementioned hypothesis, flow through the net of pipes can be found applying mass and energy balances. The following conditions must be accomplished:

- Mass conservation principle: the sum of flows Q arriving at each node n through pipelines p is equal to the sum of flows leaving it.

$$\sum_{p=1}^{P} Q_{pn} = 0 \qquad \forall n \tag{1}$$

- Energy conservation principle (Eq. (2)): pressure loss between any two nodes n of the net must be the same, whichever is the path (pipelines p) used for calculations.

$$P_n + \tfrac{1}{2}u_n^2\rho + \rho g z_n = P_{n'} + \tfrac{1}{2}u_{n'}^2\rho + \rho g z_{n'} + h_f + h_s \tag{2}$$

  where P is the static pressure, u the flow velocity, ρ, fluid density, h_f the frictional pressure loss and h_s are the singular pressure loss.
- Darcy–Weisbach pressure loss formula (Eq. (3)) must be valid for all the pipes under any working conditions.

$$h_f = \frac{L}{2D} f \rho u^2 \tag{3}$$

  where h is the pressure loss, L the pipe length, ρ the fluid density, D the hydraulic diameter, f the friction factor and u is the flow velocity.

In practice, complex nets can not be easily solved analytically. Hence, successive approximation methods are used. In this case, the most widely used is Hardy Cross method [4].

Since the previous assumptions may be applied satisfactorily to blanketing manifolds working at pressures near to atmospheric, the proposed analysis can be developed. However, given the high number of pipes to be modeled, the high difficulty in the solving methods, and the necessary flexibility in geometry for the blanketing manifold, a freeware program of the Environmental Protection Agency has been used, namely Epanet ™ [9]. This program is aimed at water distribution nets calculations; however, the program options and the programmer tools allow to adapt the calculations to gas flow. Hence, a macro has been programmed for a spreadsheet in order to establish communication between both softwares [5].

The objective consists of obtaining a model that describes the behaviour of the manifold, which is represented by means of the tank pressure temporal profile. On the one hand, Epanet ™ holds gas properties, the manifold structure, and the successive approximation method. On the other hand, in worksheets of the spreadsheet, pressures in the tanks are calculated from the liquid inflows and outflows of the tanks, and the behaviour of the blanketing and venting devices is simulated. As a result, tank pressures obtained in the latter are sent to the former, which calculates the flows through each manifold pipeline and sends them back so that new tank pressures are calculated for the next time period. This procedure is repeated iteratively over the whole simulation time horizon (Fig. 3).

This calculation procedure has been validated with several examples. Hence, a simple case study consisting of a net with four connected tanks (Fig. 4) is presented next. In this example, one of the four tanks is being emptied. The pressure profile in the four

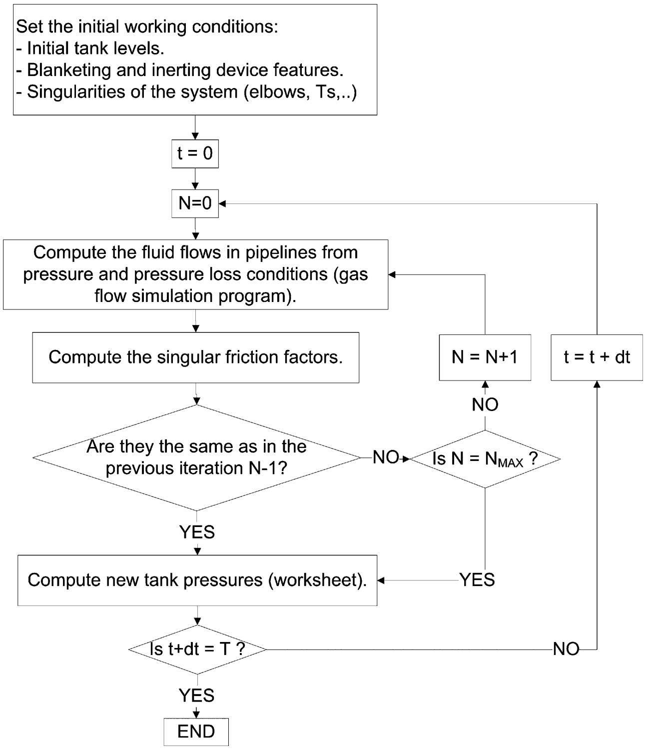


Fig. 3. General representation of the procedure to evaluate the manifold working conditions.

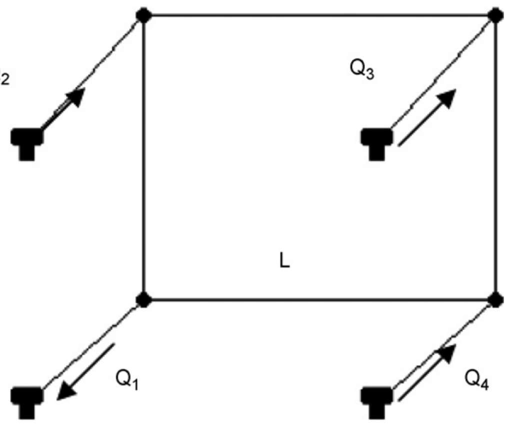


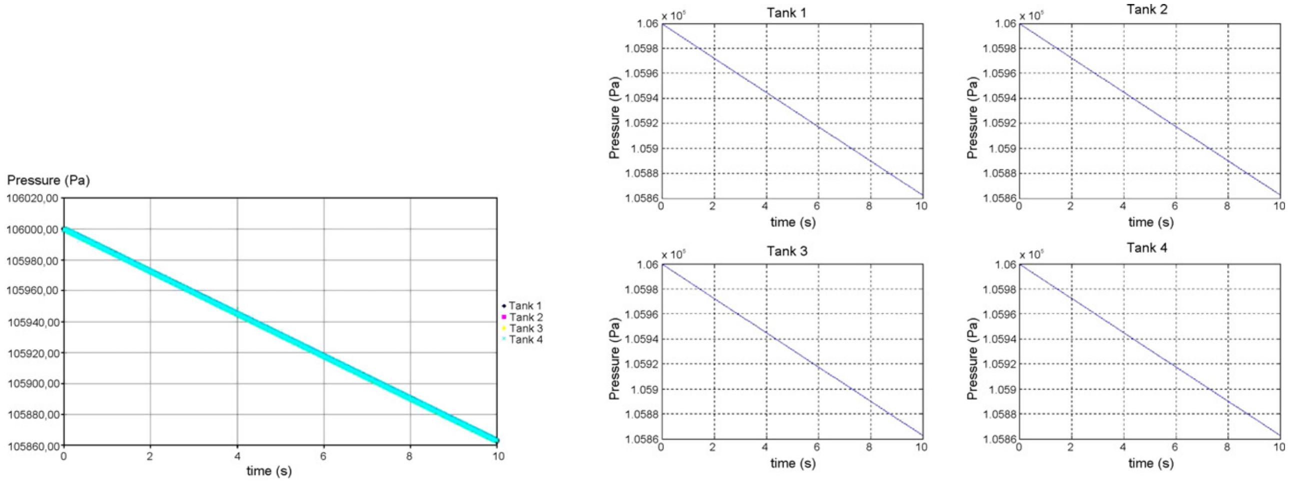
Fig. 4. Layout of the four tanks to test manifold simulation.

tanks, obtained with the proposed calculation procedure, is compared to that obtained by solving the mass balances for the tanks and both the energy and mass balances for the pipelines (Eqs. (1) and (2)) along time. The latter set of equations is non-linear, so the Newton-Raphson numerical method [15] is used to solve them and Matlab$^{(MT)}$[12] is chosen as a high level computing language to implement this method [5]. Results are presented in Fig. 5(a) and (b), sharing quite similar pressure profiles for both methods. Fig. 5(c) shows the absolute error over time, whose maximum value is about 5 Pa, that is, around five orders of magnitude less than the pressure inside the tanks.

Finally, the venting and blanketing devices are also modeled, although this is not the aim of the manifold analysis. Hence, they are considered pressure control valves, and adjusted as a proportional and integral control by means of Ziegler-Nichols method in open loop [16].

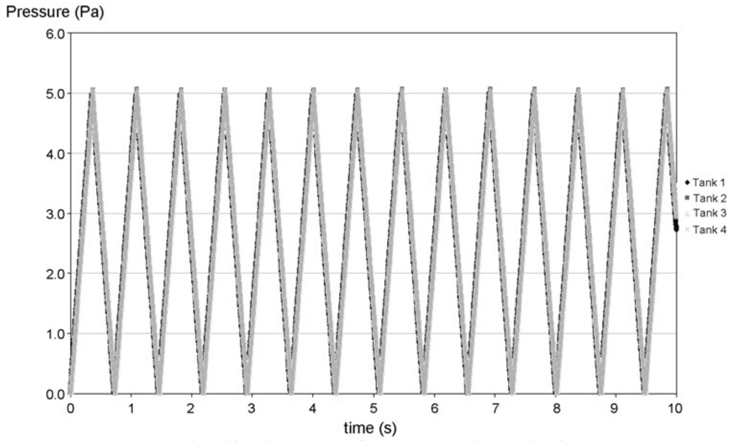
4.2. *Manifold simulation*

The study of the effect of the weather conditions and general production plan of the facilities in the tank pressures has been carried out using Monte Carlo simulation [13,5]. This technique is applicable to those systems where the random component is very important. It consists on generating a big enough number of scenarios, assigning random values to the input variables according to their probability distribution. The results are stored and analyzed to describe the behaviour of the system. However, a list of worst-case scenarios was generated, and the results were examined. Results show that pressure does not differ more than 10% around the working pressure in the worst scenarios; so the manifold layout decision is not conditioned by the worst-case scenarios analysis. In any case, safety operation rules can be introduced for the multiple-tank storage facilities in order to avoid extreme working conditions. Specifically, the establishment of a limit on the number of tanks that can be simultaneously filled or emptied; or the condition of the operation of tank filling or



(a) Results with Epanet (TM).

(b) Results with analytical method.



(c) Absolute error between both methods.

Fig. 5. Results for the tank pressure profile for a simple case study. (a) Results with Epanet$^{(TM)}$. (b) Results with analytical method. (c) Absolute error between both methods.

emptying subject to a maximum flow rate of the demanded nitrogen.

5. Results

The case study adjusts to the previous conditions for considering the alternative of manifold installation. In addition, the contamination that could be produced by vapor evaporation and condensation of the stored product is negligible, and the effects in final product are irrelevant. Therefore, the proposed methodology is systematically applied in order to shed light to its efficiency in improving traditional blanketing systems.

5.1. Case study assumptions

In order to perform the simulation, it is necessary to pose some hypothesis about the working conditions, which are detailed next.

- Nitrogen is considered as an ideal gas. Its viscosity and density are constant and do not depend upon temperature.
- Design temperature and pressure are 20 ° C and 106,000 Pa, respectively.
- The flow is permanent, and the transient conditions are approximated as a succession of steady states.
- Flow through piping is unidimensional. Fluid properties correspond to the average conditions in the cross-section.
- Flow is considered subsonic, and Mach number does not exceed 0.3; so, incompressible flow constraints are valid.
- Simulation is performed for a manifold that joins tanks containing products to be treated and waste. The results are also valid for the final product tanks zone.
- Blanketing and venting devices can supply the nitrogen calculated by the controller.
- Pipelines diameters for the manifolds are those imposed by the applicable rules: 7.62 cm (3 in.) for zone 200 and 10.16 cm (4 in.) for zone 400. Since both zones are joined, an unique manifold of 4 in. diameter is installed.
- The different manifold layouts are studied under the same initial conditions in the simulations.
- There is no interaction between blanketing and venting valves during system operation. They are able to supply maximum and minimum flows required by the whole storage facility.
- Simulation for the first twenty seconds of operation is enough to establish the tank pressures at which the system reaches stationary conditions.
- A piping friction factor of 0.5 mm is adopted, which is the maximum value for a welded lightly rusty steel pipe [4]. This assumption considers pipe aging, and more conservative results are obtained.
- Manifold pipelines are connected on top of the tanks, with a straight pipe of a minimum 0.5 m length, in order to avoid high singular pressure losses.
- Two blanketing and two venting devices are each installed in opposite sides of the manifold. Their performance is lead by the proportional and integral control actions, but not the derivative given the fast process response [16]. In addition, the parameters of the control loop for the valves are tuned through the Ziegler-Nichols method for an indicial pressure input of 100 Pa. The controller computes the error between the set-point and measured pressure, and adjusts the valve flow accordingly, and closes the control loop. The valve design is done after the simulation, taking into account the needs of the process system and the valve manufacturer catalog.
- The objective of the controller is to maintain the pressure in the manifold to 6 kPa relative Pa (0.06 bar), which is an intermediate value between the maximum allowable (15 kPa relative Pa, 0.15 bar) and atmospheric pressure.

Table 4
Summary of the simulation results.

Net structure	Average pressure (Pa)	Maximum pressure (Pa)	Minimum pressure (Pa)
Lineal	105998	106029	105949
Squared	106001	106009	105991
Mixed	106001	106016	105981

On the other hand, parameters for modeling conditions must be identified. Input random variables are the liquid level of the tanks, liquid transfer operations (time and flows) and temperature changes, which have an associated probability of occurrence. Over the time horizon of the plant, the different tanks are filled and emptied, so pressures inside the tanks vary at these time points. With the Monte Carlo simulation, time points with specific tank level and tank operation are randomly selected and the pressure profile for all the tanks is obtained by solving the model under the given conditions. In this case, one hundred time points have been selected, taken randomly from a ten years operating period. The selected sample has proven to be representative of the manifold operation conditions, by comparing the results with those obtained for a different sample with two hundred scenarios.

5.2. Manifold simulation analysis

Simulation results have been treated statistically and analyzed in order to draw conclusions from the manifold behaviour and its feasibility. The studied output variable is tank pressure. Therefore, the maximum and minimum working pressure values for each simulation have been collected and analyzed by computing the average maximum and minimum pressure values as well as the standard deviation for each manifold layout.

Fig. 6 shows the result for a single simulation. In this case, a tank is being filled, so its pressure increases up to a limit when the maximum working pressure for those conditions is reached since the equilibrium between increase in pressure and the venting flow is established. Those tanks located in the same zone as the operated one also suffer an increase in pressure. In this case, pressure increases a 0.15% regarding tank relative pressure for the tank that is being filled, whereas the surrounding tanks suffer an increase in pressure of about 0.07%. This pressure change is even lower in those tanks that are far from the tank being operated. Tank pressure profiles vary qualitatively according to the manifold structure.

Figs. 7–9 present the probability density for lineal, squared and mixed manifold layouts, resulting from simulations. Table 4 summarizes the values obtained. In most cases, manifold behaviour is characterized by taking a pressure value near the objective pressure. However, linear manifold has a higher deviation, and squared structured manifold shows the lower deviation from objective pressure.

Although manifolds have a significant different behaviour according to their layout, the differences are only in the order of the tenth of mbar. As a result, the manifold layout selection criteria can be different from the operational issues, so the lineal structure is selected because of its lower total length and easiness in implementation. Since any manifold can be technically installed, the solution analysis is further taken from other perspectives.

5.3. Safety and risk analysis

Table 5 shows typical mean failure rates and the failure probabilities of the components of the inerting and venting systems, which

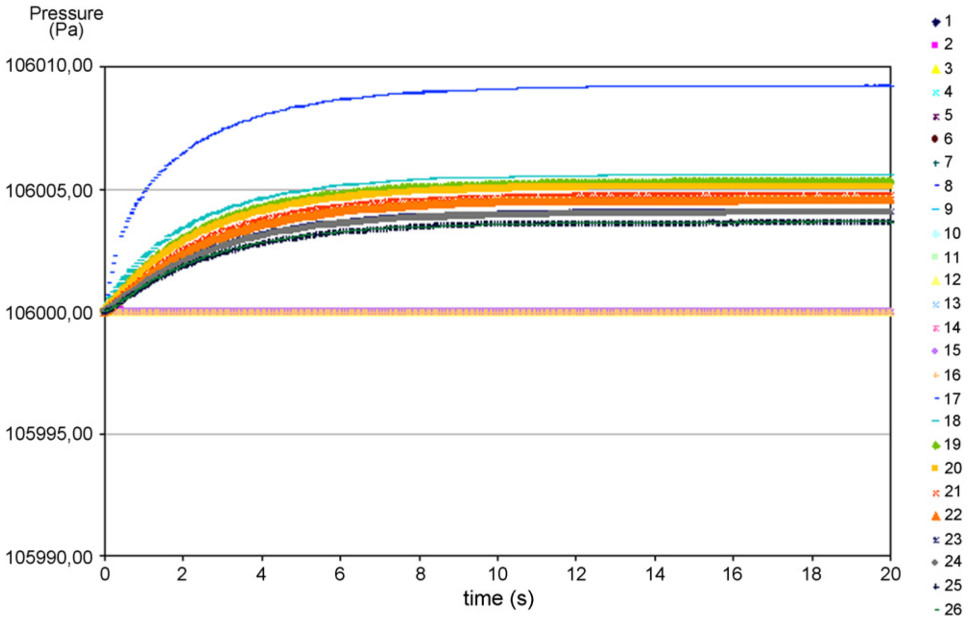


Fig. 6. Pressure profile results for zones 200 and 400 while filling tank T-401.

Table 5
Failure rate and probability for the identified failures [6,11,17].

Failure	Failure rate (error/h)	Failure prob. (yearly)
Vacuum device	3.00×10^{-5}	0.2311
Nitrogen regulating valve	1.10×10^{-6}	0.0096
Control valve	0.60	0.4512
Regulating pressure device	0.022	0.0218
Oxygen measurement	5.65	0.9965
Pressure measurement	1.41	0.7559
Pressure reductor	1.10×10^{-6}	0.0096
Electricity supply	1.10×10^{-4}	0.6185
Compressor	2.00×10^{-5}	0.1607
Lack of nitrogen	1.00×10^{-6}	0.0087
Pipeline break	2.00×10^{-7}	0.0018
Instrument not alerts about failure	3.10×10^{-4}	0.9338
Instrumentation not work	3.00×10^{-4}	0.9278
Operator not realize control valve		0.01
Operator not react		0.6
Alarm does not work	0.35	0.2953

are taken from literature [6,11,17]. These data refer to failures that constitute basic and intermediate events in the failure tree analysis, and they are necessary to calculate the system failure probability. Further details can be found in [5].

Table 6 summarizes the main results, related to the time between failure of gas venting (t_{out}) and nitrogen blanketing (t_{in}). In case control valves were installed, the frequency of failure is much lower than that corresponding to autoregulated valves since the former allow to monitor continuously tank and manifold pressure, whereas autoregulated valves failure can only be detected in maintenance operations and when failure consequences are already evident. In case of a device per tank, the frequency is higher, but it must be noted that the consequences of failure are less important since damage would only affect a single tank.

The most important conclusion driven from the safety analysis is that not only does manifold installation not affect negatively tank safety, but it improves the whole system safety. In addition, it is

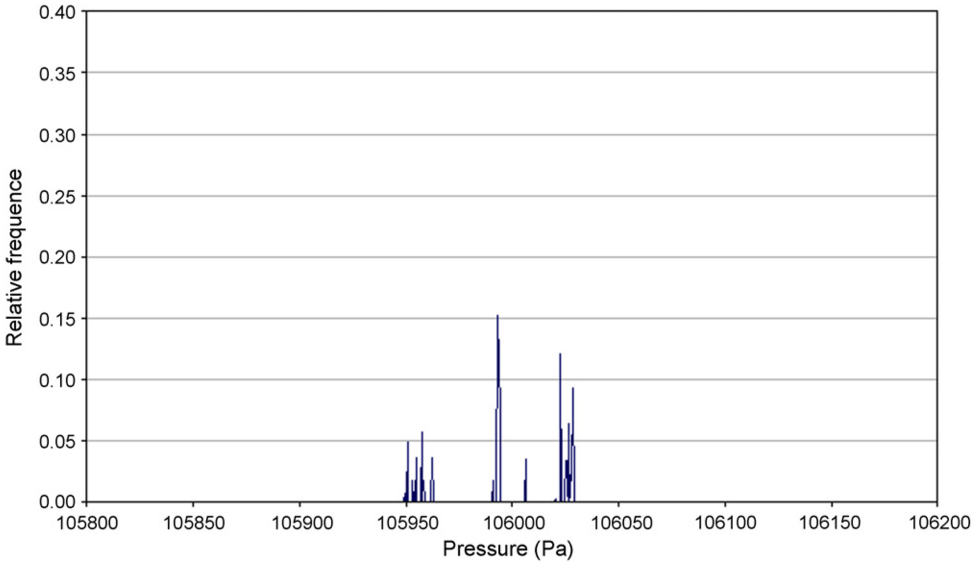


Fig. 7. Results for the lineal manifold structure operation.

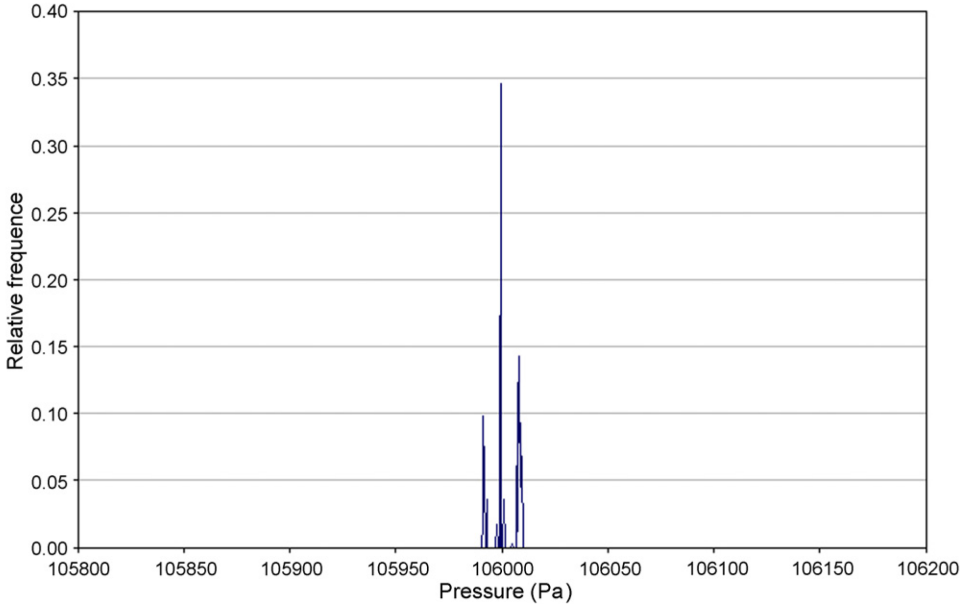


Fig. 8. Results for the squared manifold structure operation.

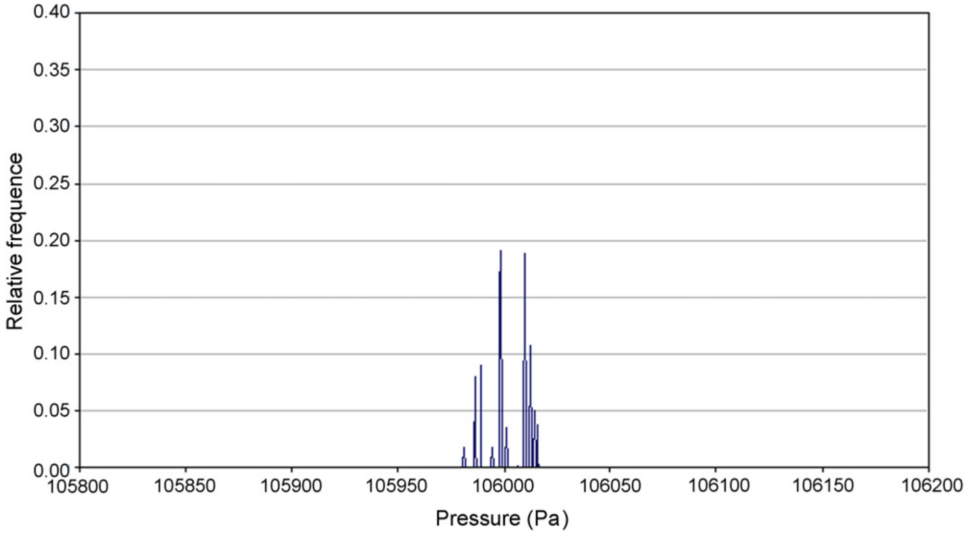


Fig. 9. Results for the mixed manifold structure operation.

proven that control valves increase the system reliability, since they allow an immediate detection of failures through the control loop. In any case, vacuum and overpressure reliefs are necessary in order to protect the facility from vacuum and overpressure. Moreover, if manifold is used for blanketing, the number of installed devices can be decreased without compromising the system safety, unless tank isolation is essential. Finally, it is also highly recommended to install a pressure alarm in order to have a good control of the tank blanketing system performance.

5.4. *Atmospheric emissions*

Fig. 10 represents the nitrogen emissions volume as a function of the equivalent leakage diameter [6]. Increasing the leakage

Table 6
Consequences of failure and frequency in the remote venting and blanketing systems.

	Out N_2 Freq. (years)	In N_2 Freq. (years)
Control valves, manifold	132	1106
Autoregulated, manifold	1	21
1 device per tank	1	7
Consequences	Overpressure in the manifold Venting pressure device open Vapors to the atmosphere	Underpressure in the manifold Vacuum-pressure device open Enters air in the system

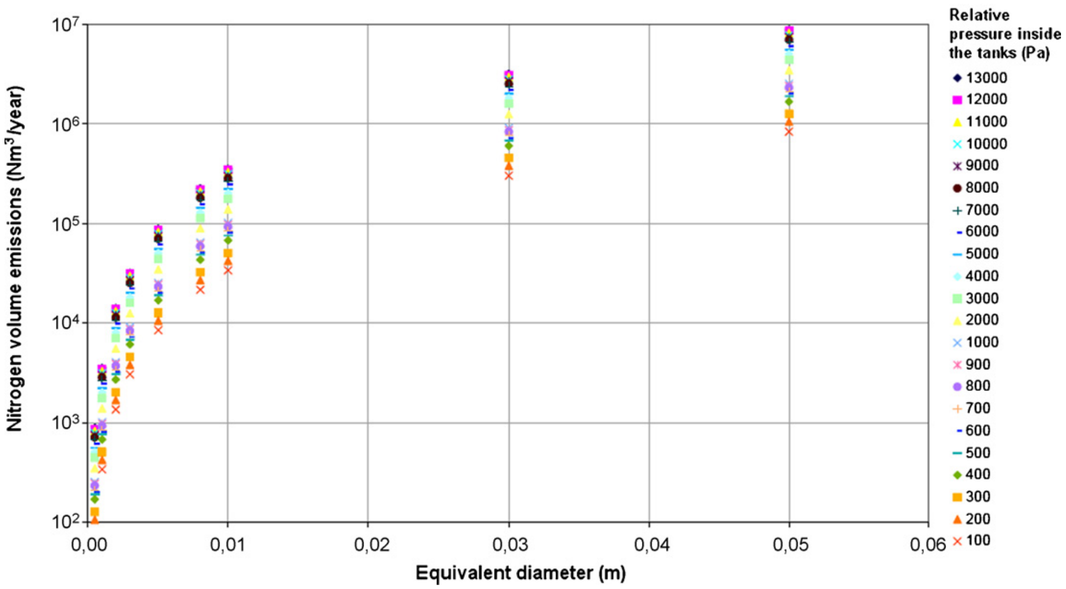


Fig. 10. Leakage volume for as a function of equivalent leakage diameter and internal pressure.

equivalent diameter, increases exponentially the leakage volume. Likewise, increasing the relative pressure inside the tanks, the leakage volume also increases.

Therefore, it is concluded that the lower pressure inside the tanks, the lower leakage, and more nitrogen savings. However, overpressure in the tanks also entails savings in nitrogen, since the higher the difference between blanketing and venting pressure is, the more nitrogen can be reused in the manifold itself. Fig. 11 shows the consumed nitrogen volume as a function of the maximum relative pressure allowed inside the tanks, for different lower blanketing pressures, with an estimated equivalent leakage diameter of 2 mm, which is a reasonable value for a welded system with few points for fugitive emissions. Therefore, increasing the maximum tank overpressure, the consumed nitrogen increases in turn, mainly because of leakage. However, if the whole vapor volume of the tanks is used as a buffer and a range between blanketing and venting pressures set-points is allowed, then significant savings in nitrogen can be obtained. In any case, overpressure can not be increased without limit, because from a given pressure, nitrogen savings do not make up for the leakage volume regarding overpressure. For higher equivalent leakage diameters, the same reasoning is valid.

Further conclusions derived from the environmental study are summarized as follows:

- Pressure set-points of the blanketing and venting devices must be different enough in order to avoid interaction among the different valves, and so useless nitrogen consumption. In addition, a range between both set-points can be established in order to save inert gas, taking into account that leakage volume also increases with overpressure.
- Nitrogen can be saved up to a 50% in liquid transfer operations if a manifold is installed. The layout of a single device per tank does not allow nitrogen reutilization. Therefore, the latter option entails a higher nitrogen consume, higher power consume to pump inert gas, and higher volume of condensed products in the cryogenic condenser.
- Control valves allow to monitor the profile of leaking gas. As a result, venting pressure can be adjusted as a function of the equivalent diameter of leakage. Therefore, organic volatile com-

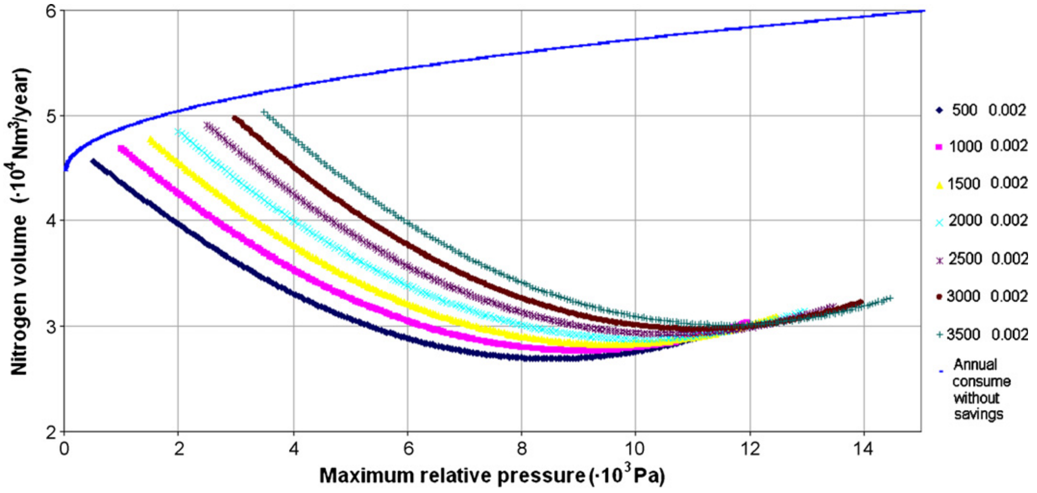


Fig. 11. Nitrogen consume for a leakage diameter of 2 mm and different blanketing pressures.

Table 7
Equipment and devices for the three alternatives of the blanketing and venting system.

	Alternative A	Alternative B	Alternative C
Piping system			
Piping (m)	240	240	530
Elbows (90°)	52	52	94
Ts	50	50	92
Complements to weld	52	52	94
Mechanical purger	2	2	2
Shut valves	54	54	168
Oxygen measurer	2	2	3
Manometer	9	9	22
Interting and venting system			
Vacuum-pressure valves	42	42	42
Blanketing valves	3	3	42
Venting valves	4	4	42
Vacuum pump	1	1	1
Vacuum pump return pipe	100	100	180
Blanketing system complements			
Pressure sensor	3	3	3
Compressor	1	–	–

Table 8
Capital investment cost for each alternative (×10^3 euro).

	Alternative A	Alternative B	Alternative C
Fixed capital expenses			
Direct costs			
Equipment and installation			
Equipment purchase cost	393	396	530
Installation costs	106	110	189
Electrical and control installation	47	24	32
Auxiliary facilities			
Compressed air installation	50		
Site development	16	16	21
Indirect costs			
Engineering and supervision	61	55	77
Construction fees	61	55	77
Contingency	39	35	49
Total expenses for fixed capital	773	690	976
Working capital			
Total expenses for working capital	39	35	49
Total cost of the investment	812	725	1024

pounds emissions related to nitrogen venting and leakage also decrease.

- The manifold allows to decrease the volume of leakage since there are less installed devices in the tanks as a whole.

5.5. *Cost analysis*

From the results of previous sections, three alternatives have been posed in order to discuss their economical cost. Alternatives A and B consist of installing a lineal manifold with control valves and autoregulated devices for tank blanketing and venting, respectively. Alternative C refers to the case for which individual blanketing and venting device per tank are adopted.

Firstly, it is necessary to select the appropriate equipment for each alternative (Table 7). Next, the total capital investment can be estimated from the equipment and installation costs, using a rough approximation as a percentage for the other items. Table 8 shows the main results of total capital investment cost for the three alternatives. The investment cost of the manifold with control valves is 11% higher than the manifold with autoregulated devices because the former needs an additional control system and a compressed-air facility. In both cases, their cost is between a 21% and a 29% lower than when a unique device per tank is installed.

Moreover, it is necessary to consider manufacturing expenses so that manifold performance is also taken into account in the cost analysis. Therefore, nitrogen (Table 9) and general services consumption must be estimated. As a result, the cash-flow has been estimated for the three alternatives for a ten years time period (Table 10). Table 11 shows the net present value for each design, considering a discount rate of 12%.

These results show that the manifold system with control valves (1.03 Meuro) entails savings of a 22% and the alternative with autoregulated devices (0.93 Meuro), savings of 29% compared to the design without manifold (1.32 Meuro), which is the traditional approach.

5.6. *Proposed design*

The main features of the proposed blanketing and venting system are decided according to the aforementioned discussions on feasibility, safety, environmental issues and cost.

The best solution consists of a lineal structured manifold that joins the zones of product to be treated and waste, whereas a second lineal manifold joins the tanks containing final product. The piping of zones 200 and 400 has a total length of 180 m of 10.16 cm (4 in.), whereas zone 300 has a total length of 60 m and 7.62 cm (3 in.) of diameter. The piping to the nitrogen source and cryogenic condenser is 250 m long and 10.16 cm (4 in.) diameter.

Control valves are selected as blanketing and venting devices. They are not as economical as autoregulated devices, but they allow a more thorough control over pressure and tank emissions. In addition, it is also necessary to install vacuum and normal pressure venting devices. In case that it was not possible to interrupt the whole blanketing system and so, storage operation, for tank maintenance, a shutting valve should be installed before each tank and so that it must be provided with a vacuum-pressure device and the corresponding fire-emergency valves. Otherwise, vacuum-pressure devices can be reduced to twenty vacuum, and twelve normal pressure devices out of twenty-six, for zones 200 and 400, whereas five for vacuum and twelve for overpressure, out of sixteen, for zone 300.

The relieves and regulating devices of the final approach and their set-points are shown in Table 12. The set-points are chosen different enough in order to prevent device interaction, and to have a wide enough range of pressures for nitrogen reusage.

Moreover, manometers and oxygen measures must be installed in order to control the correct operation of the blanketing and venting system. In addition, devices for purging the condensates produced in the manifold are installed in the lowest points of the piping system. Finally, a liquid nitrogen gasifier is needed for supplying gas at a minimum pressure of 400 kPa (4 bar), and the

Table 9
Estimates on nitrogen consumption of the inerting and venting system.

	Q_{transf} (m^3/yr)	Q_{saved} (m^3/yr)	Q_{leak} (m^3/yr)	Q_{on} (m^3)	Q_{cond} (m^3/yr)	Q_{tot} (m^3/yr)	Tot. consumption liq. N_2 (m^3/yr)
Alternative A	63990	−38617	201320	8661	136939	372292	447
Alternative B	63990	−25745	201320	3909	136939	380413	457
Alternative C	63990	0	261528	9964	136939	472420	567

Table 10
Cash-flow for each alternative for a period of five years (×10^3 euro).

		Year										
		0	1	2	3	4	5	6	7	8	9	10
Alternative A	Annual investments	773	39	0	0	0	0	0	0	0	0	−39
	Annual income		−37	−38	−39	−40	−41	−43	−44	−45	−46	−48
	Cash-flow	−773	−75	−38	−39	−40	−41	−43	−44	−45	−46	−9
Alternative B	Annual investments	690	35	0	0	0	0	0	0	0	0	−35
	Annual income		−35	−36	−38	−39	−40	−41	−42	−44	−45	−46
	Cash-flow	−690	−70	−36	−38	−39	−40	−41	−42	−44	−45	−12
Alternative C	Annual investments	976	49	0	0	0	0	0	0	0	0	−49
	Annual income		−49	−51	−52	−54	−56	−57	−59	−61	−63	−65
	Cash-flow	−976	−98	−51	−52	−54	−56	−57	−59	−61	−63	−16

Table 11
Net present value for each alternative.

	NPV (Meuro)
Control valves design	−1.03
Autoregulated devices design	−0.93
1 device per tank	−1.32

Table 12
Set-points for the tank devices.

	Set-point (mbar)	P_{open} (mbar)	P_{close} (mbar)
Vacuum relief	−2 to −0.2		
Blanketing control valve	25	22.6	27.7
Venting pressure N_2 recovery	42	45.7	39.3
Pressure relief	70 to 100		
Emergency relief	100 to 130		

cryogenic condenser must be dimensioned to suction the venting flows from the storage tanks.

6. Conclusions

The main goal of designing an improved optimal blanketing system in terms of economical, safety and environmental issues has been achieved. An structured methodology which considers the possibility of manifold installation is proposed, developed and checked through a motivating case study. The solution adopted in that case consists of a lineal structured manifold installation, with control valves as blanketing and venting devices. In addition, normal vacuum-pressure devices, emergency venting devices, sensors and propelling equipments are also included in the design. The cost of the proposed solution is much lower than for traditional systems, namely a 22% lower for the case study, emissions to the atmosphere are also greatly reduced, arriving at a 50% savings in nitrogen consumption, and finally, its flexibility and controllability is higher than traditional systems since tank pressure can be continuously monitored.

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