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MODELING AND ANALYSIS

On the rapid discharge of subsea accumulators: remarks on the normed design method and proposal of improvement

Roberto Cipollone[1], Fabio Fatigati[1], Davide Di Battista[1], Paolo Allara[2] & Nicola Carini[2]

[1]University of L'Aquila, via Giovanni Gronchi18, L'Aquila 67100, Italy
[2]Saipem S.p.a., Via Martiri di Cefalonia 67, San Donato Milanese (Milan) 20097, Italy

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Correspondence
Fabio Fatigati, University of L'Aquila, via Giovanni Gronchi18, L'Aquila, 67100, Italy.
E-mail: fabio.fatigati@univaq.it

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Abstract

This study is focused on the design of the subsea accumulators currently used to deliver a pressurized fluid whose function is to actuate safety operations on a subsea well. API 16D, whose specifications regulate the design method of a bank of accumulators, was revised, discussed, and resumed in terms of a nomogram whose engineering value is useful for designers. An additional nomogram was derived allowing to perform the verification process which is suggested by the norm, in order to verify the fulfillment of the actuations requested to the accumulators. This verification phase caught the interest of the Authors: API 16D assumes for the design that the Functional Volume Requirement (FVR) – the sum of the quantities of pressurized fluid to be delivered for different sequenced-in-time functions – is delivered at the Minimum Operating Pressure (MOP) requested by the last actuation. This hypothesis simplifies the design, but the result cannot fulfill the previous functions because of the pressure lack (energy content in the pressurized propelling gas) which can happen. The use of the two nomograms proposed simplifies the application of the design procedure and allow to discuss main sensitivities of the variables involved (FVRs & MOPs), evidencing which variables deserve more attention and accuracy. In particular, the use of the second nomogram permits to verify that the right volumes of fluid during the actuations are delivered above a minimum pressure level, so guaranteeing the fulfillment of the function. It is based on a thermo-fluid-dynamic discharge modeling of the accumulators. The paper outlines a design direction which minimizes the number of accumulators and opens the way to a different design approach, based on a fully physical discharge process description.

Introduction

A system of accumulators is a set of pressure vessels charged with inert gas and used to store pressurized hydraulic fluid. Energy accumulation through pneumatic-hydraulic devices is widely used in renewable energy generation (in order to solve the discontinuity of the source) [1, 2] or in mobile applications (principally for energy recovery) [3, 4]. Moreover, they can be used to actuate specific functions, mainly related to safety reasons. In the oil and gas sector, for instance, these devices are commonly used to fulfill most part of the actuations which can be near or far away from the accumulators themselves. In the off-shore deep-water drilling, when the actuation times must be very short, discharge of the pressurized fluid must be almost instantaneously: in the severe environments represented by high water depths, these accumulators are sited close to the well. From this position, they assist a system of valves (Blowout Preventer, BOP) which definitively close the well in case of critical situations for human safety and environmental concerns. Main limitation of these devices is the low-energy storage density [5]. An additional concern is due to the dependence of the fluid pressure to the quantity of the fluid delivered: during discharge, the pressure inside the accumulators decreases and it can reach levels unsuitable for a correct actuation. So, the requirements of energy accumulated and power delivered push the design toward heavier and larger systems [6].

In the oil and gas sector, the use of pneumatic-hydraulic accumulators represents the only reliable technological option for valve management and safety ultimate actuations. In spite of this, the specific literature is limited and the sector demonstrates a certain degree of technological inertia. In most severe situations, BOP management produces an irreversible situation represented by the cut of the drill pipe and the sealing of the well.

Blowout is an uncontrolled jet of crude oil and/or natural gas which may be due to the high formation pressure, lower mud density, short borehole mud slurry column height, or other improper measures [7, 8]. The procedure of a blowout preventer is done through a shut in of the well, which, however, has some concerns related to over pressures and actuation times [9–11]. If the BOP system fails, the consequence could be devastating as happened in the Gulf of Mexico on 20 April 2010 during the Deepwater Horizon accident, the worst Environmental Disaster in history of the United States [12, 13]. This event increased the international scientific and technical interest toward the reliability issues of the BOP, even though main cause of the disaster was also referable to other circumstances [14].

In any case, in order to prevent definitively blow out when the evidence of a disaster is approaching, some emergency actions have been considered as last operations, most of them are irreversible. They are recognized by the international standards API Standard 16D [15], and by the API 53 [16] and are referred as Autoshear System (AS), Deadman (DM) and Deadman/Autoshear (DMAS). Autoshear System (AS) is defined as "safety system that is designed to automatically shut in the well-bore in the event of a disconnect of the LMRP. When the autoshear is armed, a disconnect of the LMRP closes the shear rams and this is considered a rapid discharge system." Furthermore, the Deadman (DM) is defined as "a system designed to automatically shut-in the well-bore in event of simultaneous absence of hydraulic supply and control of both subsea control pods," and it is considered also a rapid discharge system. The Deadman/Autoshear System (DMAS) is designed so that the function for the High Pressure Shear Rams is the same for the Autoshear and Deadman as reported in the API Specification 16D [15].

An additional and optional system is the Emergency Disconnect Sequenced System (EDS), which is defined in the study by Han and Zhang [10] as a system that "shall be provided for a deep-water floating drilling rig when there is a requirement to rapidly disconnect the riser in the event of inability to maintain rig position within a prescribed watch circle." EDS is classified as a rapid discharge system as well. AS, DMAS, and EDS need to be actuated by rapid discharge accumulators: a pressurized fluid delivered by them is used to accomplish the functions which require given quantities of fluid at a specified pressure level which insure the right energy content. Actuating time must be lower than 3 minutes as required by API 16D [15]. In order to be sure about the actuations, accumulators are mounted in a subsea position as backup power fluid supply source.

All the energy accumulators dedicated for these specific functions (AS, DM, EDS) must work properly, and in case of AS and DM also independently from any other high-pressure fluid supply from topside: they represent, therefore, the last chance to prevent blow out and avoid unpredictable consequences.

The severity and the enormous worldwide relevance of the blow out events invite to a design of the actuation system scientifically based, without ambiguities, reliable and consistent with experimental data [17–19]. This paper offers a contribution in this direction, considering the severity of the events which could happen if a failure occurs to one of the three actuations.

The correct design of the bank of accumulators which deliver a pressurized fluid to accomplish AS, DMAS, or EDS must comply the requirements reported by API 16D-Method C [15]; some additional references can be found in API Standard 53 [16]. The cited norm gives proper rules to size and define the pressure conditions inside the accumulators. Several operating parameters must be specified in order to manage the processes which influence the quantity of the pressurized fluid that can be delivered: AS, DM, and EDS actuations are considered as the most important safety sequence.

The effect of the surface and subsea temperatures and precharge pressure uncertainties are not to be neglected: these uncertainties, particularly relevant during typical off-shore severe operating conditions, should be included in the design sizing [20]. As the water depth increases, it is known that the delivery of a pressurized fluid become more difficult due to the effect of the hydrostatic head and pressure increase inside the accumulators: the development of the accumulator technology (to reduce the negative effect of the water depth on the volumetric efficiency) has also been analyzed [21]. In order to compensate the effect of the hydrostatic pressure on the usable fluid, the increase of the precharge pressure can be handled, but this is limited to the rated pressure of the accumulator. Moreover, the liquid volume (when the precharge pressure increases) could be too low, do not insuring the actuation requirements in terms of fluid delivered. An interesting technological alternative is offered by the so-called Constant Differential Accumulators [22] which ensure to satisfy the functional requirement (fluid delivered) without additional propelling gas pressurization.

Other technologies have been presented in order to sustain the fluid pressure inside the accumulators when the water depth increases, replacing the pressurized gas inside the accumulators with springs and heavy weight [23]. Subsea operations can be enhanced providing greater shearing pressure and delivering greater fluid volumes when high strength casing with thicker walls must be cut as it happens in deep-water wells [24]. Also different fluids and materials have been investigated for this purpose [25].

This paper analyzes some relevant aspects of the procedure standard reported by API 16D-Method C, and it reorganizes the design phase in one original nomogram in which the role of all the operating conditions is easily represented: this will give confidence about the importance of the different terms requested by API Specification 16D [15], outlining most relevant parameters and operating variables which are more sensible to the number of accumulators needed for the actuation sequence. Considering that the nomogram puts in evidence the role of all the variables involved in a design (according to the standard), it has an interesting engineering value and adds to the literature a further knowledge about the sensitivity played by different variables.

It is the aim of this paper, also, to highlight the "weakness" of the standard procedure which proposes a design simplification which does not inherently insure the success of the actuations for which the accumulators were designed. The design nomogram presented allows to have a graphical outlook of the design and to put in evidence the role of different variables referred to the environmental conditions as well as the overall quantity of actuating fluid to be delivered and the pressure at which the last actuation is requested. More recently, computational methods have been presented [26] to support the design and the Authors are also developing a fully physically consistent mathematical model. Nevertheless, a graphical approach allows to observe tendencies and most important parameters concerning the design. The graphical treatment allows to understand why the norm sometime fails (lack of pressure, i.e., of energy) understanding the "design distance" to a failure. In fact, the most important aspect when using the norm is that, for sake of simplicity, it simplifies the design phase considering the full delivery of the fluid (the sum of all the fluid quantities requested by the various actuations) at the Minimum Operating Pressure (MOP) which characterizes the last actuation (the one at the lowest operative pressure). So, the normed procedure does not consider in any case the pressure levels which characterize the previous actuations. Due to this, the norm requires a verification process which will put in evidence that all the actuations cannot be fulfilled. Following the first graphical approach, a second original nomogram has been derived in the paper through a thermodynamic model of the accumulators discharging process when they are sited close to subsea floor. The nomogram allows easily the verification process requested by the normed method and explains why, eventually, the design fails in terms of unsufficient pressure when specific quantity of fluid (FVRi) is extracted. Being the verification a very important process, the thermodynamic properties of the fluids involved (propelling gas and actuating fluid) were evaluated through NIST™ database without any simplification concerning the nature of the propelling gas.

Finally, the paper discusses how to manage the situation in which the verification process is not fulfilled. Indeed, API 16D Method C leaves to the designer the choice to overcome this occurrence, that is, increasing the number of accumulators or changing the precharge pressure with respect to the optimum value. In order to understand and to choose the best way to deal when the verification process is not fulfilled, an analysis using the second nomogram is proposed.

Materials and Methods

API 16D Method C [15] gives the guidelines to design rapid discharge accumulators used to actuate different functions mainly related to safety operations. Indeed, these are the last resorts in case of a blowout occurrence and, as prescribed by the regulation, all the function must be actuated in <3 min in order to prevent blow out and fire occurrence. Once the precharge pressure was set at surface, the regulation design procedure allows to predict the number of accumulators which ensures that the propelling gas is at its minimum pressure after the discharge of the entire volume of control fluid required by all the actuations. Therefore, the regulation requires to fix the pressure for the last actuation: it can be fixed by the requirements of the device or by the hydrostatic pressure if this is higher than the previous value. So, the norm provides the optimal value of the precharge pressure in order to deliver the whole volume required (Functional Volume Required, FVR_{tot}, as sum of the all actuations), minimizing the number of accumulators needed. In general, this approach cannot insure the requirements of the intermediate actuations: because of this, the API 16D Method C [15] advises to accomplish a further verification step to check about the success of all the actuations. In the following, in order to clarify the use the regulation and analyze the effects of the operational and environmental quantities on the design, the normed procedure was reorganized and implemented in an algorithm which produced a design nomogram (Fig. 4) particularly easy to be used. A further innovative nomogram (Fig. 5) has been presented suitable to easily proceed with a verification phase: it is based on a thermodynamic model of the accumulators discharge when they are sited close to wellhead.

An algorithm for the bank of accumulators design

The calculation method described in API Specification 16D [15] has been implemented in a MS Excel™ script, coupled to NIST™ fluid database, to evaluate all relevant properties of the propellant gas during the charging and discharging phases with the control fluid. The initial phase is the precharge of the accumulator: this precharge pressure is related to the initial charge of inert gas in the accumulators when the accumulators are at a certain surface temperature T_{surf} (off-shore platform level). After the precharge phase has been concluded (Fig. 1) and the accumulators have been moved down to the wellhead, the control fluid is pumped in the bottles from the rig.

Therefore, the inert gas inside the accumulators is compressed ensuring to store potential energy. The regulation suggests an optimum value of precharge pressure P_{opt} and explains how to calculate it. The optimum precharge pressure allows to maximize the Volumetric Efficiency of the accumulator VE, which depends on the precharge density D_0 value already calculated; this will minimize the number of accumulators to be submerged. VE, in fact, is the ratio between the usable volume fluid for the function i and the total amount of gas inside the accumulators:

$$\mathrm{VE}_i = \frac{(V_i - V_1)}{V_0 \cdot F_i}. \tag{1}$$

Being the gas volume equal to the ratio between the mass of gas and the density at the condition considered as:

$$\mathrm{V}_i = \frac{m}{D_i}. \tag{2}$$

Equation (1) gives VE_i as follows:

$$\mathrm{VE}_i = \frac{\left(\frac{m}{D_i} - \frac{m}{D_1}\right)}{\frac{m}{D_0} \cdot F_i} = \frac{\left(\frac{D_0}{D_i} - \frac{D_0}{D_1}\right)}{F_i}. \tag{3}$$

Equation (3) shows the volumetric efficiency at i-discharging condition; it depends also on two other thermodynamic quantities: D_1 and D_i. It applies that: D_1 is the density of the inert gas when the accumulators have been moved down at wellhead and have been charged with the control fluid (Fig. 2). According to API 16D in charged conditions, the thermodynamic state of the inert gas is at T_{sub} being the charging process enough long to assume the gas temperature equal ambient temperature. The pressure P_1 is given by the sum of the pressure of the Hydraulic Power Unit P_{HPU} (used to pump the fluid inside) and the hydrostatic pressure of column of control

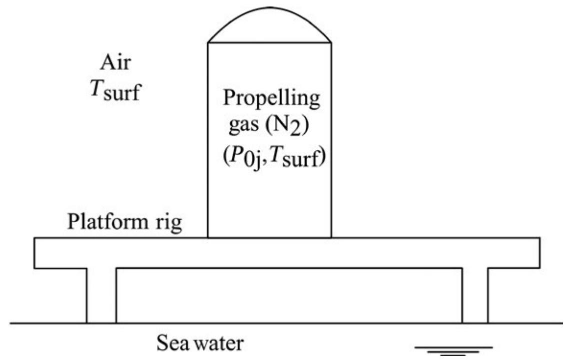

Figure 1. Conclusion of the precharge phase.

fluid $P_{Hydro,CF}$ (eq. 4.1) for not regulated circuit or the hydrostatic pressure of the sea water P_{Hydro} for regulated circuit (eq. 4.2), as specified in [16].

$$\mathrm{P}_1 = P_{HPU} + P_{Hydro,CF} \tag{4.1}$$

$$\mathrm{P}_1 = P_{HPU} + P_{Hydro} \tag{4.2}$$

In API Specification 16D [15], it was stated that the value of P_{HPU} is the at "pump stop pressure" if the accumulators are isolated with a check valve or at "pump start pressure" if the accumulator pressure fluctuates with pump pressures as the main accumulators normally do. From this knowledge, the entropy S_1 of the gas when the accumulator is placed on the subsea floor and when it is ready for operation can be evaluated. This quantity is fundamental to evaluate the thermodynamic state during the discharge phase because this process is modeled as an adiabatic (isentropic) transformation;

According to API Specification 16D [15], D_i is the density of the inert gas at withdrawal condition of interest (Fig. 3), such as minimum operating pressure (D_2) or total discharge condition (D_3). Concerning the real gas state at minimum operating pressure, this condition is defined by the MOP (the lowest delivery pressure of the sequence corresponding to the last function) or by the sea water hydrostatic pressure P_{Hydro} if it is higher than MOP, and the S_1 being the discharge phase modeled as an adiabatic isentropic transformation. Otherwise, in the total discharge case which represents the situation of a full discharge of the fluid, if the gas pressure in the accumulators P_3 is higher than Hydrostatic Pressure P_{Hydro}, the fluid in the accumulators will be discharged entirely and the thermodynamic state of the inert gas is defined by P_3 and S_1. Nevertheless, if P_3 is lower than P_{Hydro}, a part of the control fluid will remain in the accumulator after discharge and P_3 will be called sea-head limited: the thermodynamic state of the gas is defined by P_{Hydro} and S_1. The regulation disposes that the Volumetric Efficiency is equal to the minimum between Volumetric Efficiency for

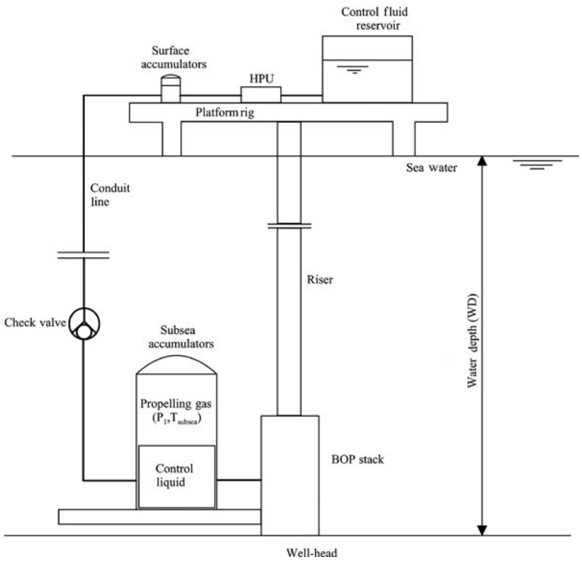

Figure 2. Accumulators at charge condition.

pressure-limited case VE_p (eq. 5), corresponding to the MOP condition (the lowest among the MOP_i of the functions in the sequence or P_{Hydro} if this value is higher than MOP) and Volumetric efficiency for Volume limited case VE_v (eq. 6) corresponding to the total discharge condition only if P_3 is greater than P_{Hydro}, otherwise P_3 is sea-head limited.

$$VE_P = \frac{\left(\frac{D_0}{D_2} - \frac{D_0}{D_1}\right)}{F_P} \tag{5}$$

$$VE_V = \frac{\left(\frac{D_0}{D_3} - \frac{D_0}{D_1}\right)}{F_V} \tag{6}$$

In equation (5), D_0 must be lower than D_2. Moreover, as reported in API Specification 16D [15], if the minimum MOP is lower than P_{Hydro}, D_2 is the density of the gas at the thermodynamic state defined by P_{Hydro} and S_1.

According to the regulation, there is an optimum value of precharge pressure: this happens when VE_v is equal to VE_p. Therefore, this optimum precharge pressure could be obtained as in the following:

$$\frac{\left(\frac{D_0}{D_2} - \frac{D_0}{D_1}\right)}{F_P} = \frac{\left(\frac{D_0}{D_3} - \frac{D_0}{D_1}\right)}{F_V} \tag{7}$$

API 16D introduces F_P and F_V in order to provide a more conservative design of accumulators. These coefficients are assumed equal when the API 16D Method C is used; the effect is a reduction of the Volumetric Efficiency (VE_p, VE_v) by 10%. Thus, equation (7) can be rearranged as follows:

$$\frac{D_0}{D_2} = \frac{D_0}{D_3} \tag{7.1}$$

Equation (7) implies that $D_2 = D_3$. The optimum value for the precharge density is given by the condition $D_2 = D_0$ which insures that the accumulators will be empty in terms of actuating fluid at the end of the last discharge. Considering that the temperature at the surface is known (during the precharge phase), the optimum precharge pressure is univocally defined.

Being the Functional Volume Requirement given by the sum of all the specific volumes required by the single actions defined as

$$\mathrm{FVR} = \sum_{i=1}^{\mathrm{nf}} \mathrm{FVR}_i \tag{8}$$

the Volumetric Capacity (VC) required for the accumulator system is:

$$\mathrm{VC} = \frac{\mathrm{FVR}}{\mathrm{VE}} \tag{9}$$

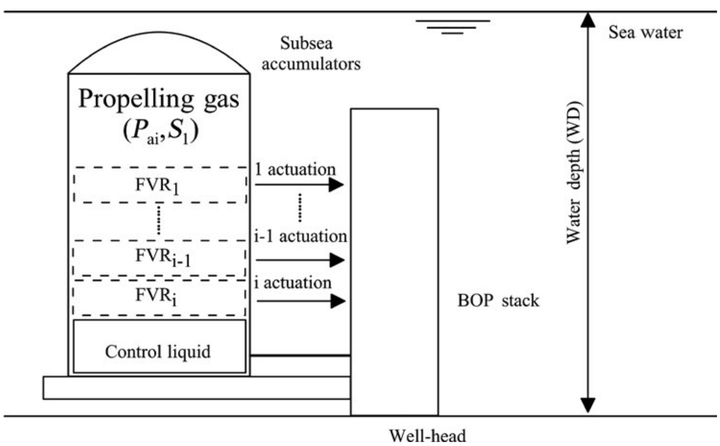

Figure 3. Accumulator state at withdrawal condition of interest (after the actuation of *i*-th function).

The number of accumulators na comes by dividing the entire VC by the volume of a single accumulator SVA:

$$\mathrm{na} = \frac{\mathrm{VC}}{\mathrm{SVA}} \tag{10}$$

Being VC known as well as the precharge density of the gas, the volume of the propelling gas and that of the actuating fluid can be obtained according to equations (11) and (12), respectively:

$$\mathrm{V}_1 = \left(\frac{D_0}{D_1}\right) V_0 \tag{11}$$

$$\mathrm{V}_{\mathrm{L1}} = \mathrm{VC} - \left(\frac{D_0}{D_1}\right) V_0 = V_0 \left(1 - \left(\frac{D_0}{D_1}\right)\right). \tag{12}$$

The design specified by the norm has been synthesized in the nomogram reported in Figure 4.

It has been conceived following a sequence of steps, having chosen specific values for the horizontal and vertical axes and suitable parameters which specify the different curves.

The steps reported in Figure 4 have been referred to the data reported in Tables 1 and 2 which makes reference to a typical sequence of actuations and operating conditions.

To apply the nomogram, the following data must be specified:

1. water depth;
2. HPU pressure;
3. density of the seawater;
4. density of the fluid;
5. subsea temperature at the well.

Once the surface temperature is known on the rig (*x*-value in Fig. 4A), for a specified precharge pressure selected for the gas inside the accumulator, the precharge density D_0 could be obtained (*y*-value in Fig. 4A), according to a real gas state equation. Indeed, in Figure 4(A), each line represents a specific precharge pressure. As shown by the graph, when the pressure is kept constant, the gas density decreases if the temperature increases. All the curves require an equation of state for real properties of the gas (Nitrogen). The choice of precharge pressure radically influences the accumulator performance in terms of number of accumulators and fluid deliverable.

Then, introducing the precharge density D_0 in Figure 4(B) as *y*-value, it is possible to define the Volumetric Efficiency VE (*x*-value of Fig. 4B) for the MOP considered. So, inserting in Figure 4(C) the VE as *x*-value fixing the whole FVR, the Volumetric Capacity (VC) needed to fulfill all the actuations can be defined (*y*-value of Fig. 4C). Finally, the Volume of working fluid VL_1 stored in accumulators is outlined in Figure 4(D) as *x*-value, by knowing the VC (*y*-value of Fig. 4C) and the density of the propelling gas at precharge (*y*-value of Fig. 4A).

The analysis of the nomogram in Figure 4 allows to understand the criticity of some operations, in particular for very influencing parameters, like the volumetric efficiency. Some interesting observation on the operating quantities can be summarized:

1. The density of the propelling gas D_0 inside the accumulator (*y*-value of Fig. 4A) once the precharge phase has been concluded should be selected in order to obtain the maximum Volumetric Efficiency (VE) (*x*-value of Fig. 4B) when the MOP of the last actuation has been fixed. Therefore, the optimal gas precharge density $D_{0_{\mathrm{opt}}}$ for a certain final MOP is that value which corresponds to the maximum of the respective VE curve in the (B) part of Figure 4. As can be observed, the maximum of VE shifts upward as the MOP of the last function increases, thus the $D_{0_{\mathrm{opt}}}$ becomes higher.
2. The precharge pressure P_0 which ensure to obtain a given density of the propelling gas D_0 increases as the Surface Temperature grows, as can be observed from the Figure 4(A). Therefore, the precharge phase should be performed when the surface temperature is lower because the same density of the gas can be obtained at lower pressure compared with the case when this temperature is higher. Nevertheless, in this case, the accumulators should be submerged as soon as possible because if the surface temperature grows, the pressure in the accumulators increases and may become higher than its maximum pressure rating.
3. The MOP of the last function should be the lowest possible value in accordance with the functional requirement, in fact the trend of the VE curves (Fig. 4B) corresponding to higher values of the last MOP tends to be quite vertical. Thus, considering that the slope of the Functional Volume Requirement (FVR) curves strongly increases as the VE decreases the Volume Capacity (VC) (*y*-value of Fig. 4C) needed to perform the considered actuation becomes larger.
4. For a given precharge pressure P_0, gas density D_0 at precharge is slightly linear with respect to surface temperature; the linearity remains more or less constant regardless to P_0. Similar linearity characterizes gas density D_0 at precharge with respect to volumetric efficiency; in this case, the linearity (slope) depends on minimum operating pressure (MOP_3). As much as MOP_3 increases, the slope increases (as absolute values): this means that volumetric efficiency changes as much as MOP_3 decreases, requiring in this case more precision in the original surface temperature. At higher MOP_3, the volumetric

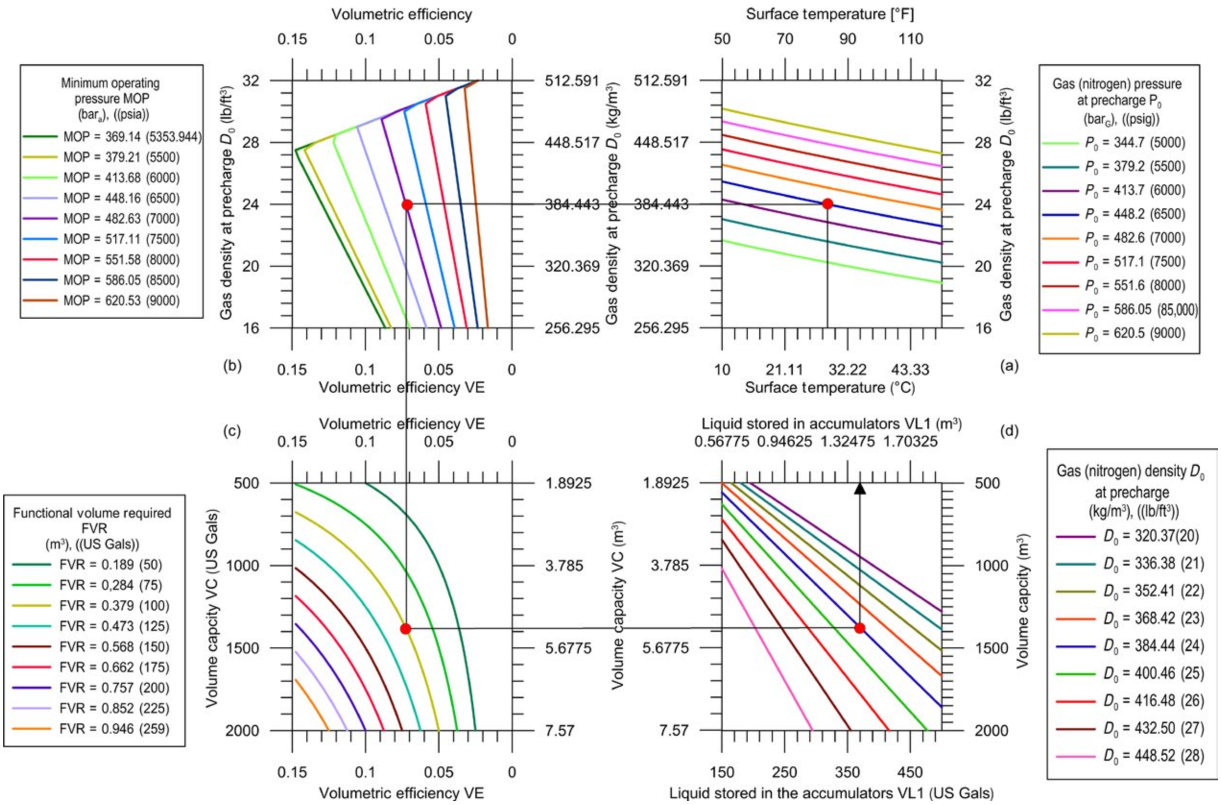

Figure 4. Design chart in a nomogram form (water depth = 3657.6 [m] (12,000 [ft]); HPU = 345.77 [bar$_a$] (5015 [psia]); subsea temperature = 1.67[°C], ([35°F]); Seawater density = 1025.088 [kg/m^3], 8.556 [lb/US gal], Control Fluid Density = 997.934 [kg/m^3], (8.33 [lb/US gal])). P_{Hydro} is equal to: 369.14 [bar$_a$], 5353.944 [psia]).

Table 1. Sequence of three functions test case.

Function	MOP_i [bar$_a$], ([psia])	FVR_i [m^3], ([US gal])	FVR^*_{ci} [m^3], ([US gal])	FVR_{ci} [m^3], ([US gal])
1	551.6 (8000)	0.189 (50)	0.189 (50)	0.208 (55)
2	510.2 (7400)	0.114 (30)	0.303 (80)	0.333 (88)
3	482.6 (7000)	0.076 (20)	0.379 (100)	0.417 (110)

Table 2. Environmental and operating conditions.

Pump start pressure (absolute)	713.87 (10353.9)	Bar$_a$ (psia)
Gas volume per bottle	0.052 (13.8)	m^3 (US gals)
Water depth	3657.6 (12,000)	m (ft)
Surface temperature at precharge	28.7 (83.7)	°C (°F)
Subsea (mudline) water temperature	1.7 (35)	°C (°F)
Sea water density	1025.2 (8.556)	m^3/kg (lb/US gal)
Sea water head pressure	369.1 (5353.9)	bar$_a$ (psia)

efficiency remains almost constant and as a function of surface temperature and gas density at precharge condition P_0.

5. Volumetric efficiency versus volume capacity is not linear, for a specific overall functional volume required: when volumetric efficiency increases, volume capacity decreases as more as the functional volume requirement decreases: this produces a significant variation in the volume capacity at higher volumetric efficiencies: small surface temperature variations can produce higher volume capacity changes, as much as the functional volume requirement decreases. Volume capacity and liquid stored in the accumulators change almost linearly: variation for the liquid stored is greater when gas density at precharge pressure P_0 decreases.

Improvement on the normed design to verify all the actuations

After the design procedure, the regulation disposes to check if the design of the accumulators allows to fulfill all the functions in terms of volume and pressure requirements. This verification is mandatory because in the design procedure according to equations (5) and (6), VE is evaluated according to the final MOP condition corresponding to the last function. For this reason, the regulation does not consider the volumes of control fluid required by the other functions at their respective MOP_i.

The verification can be done according to a mathematical model of the discharging process based on the mass conservation of the propellant gas from the charged condition to the pressure inside the accumulators when the *i*-specific is done (P_{ai}).

When the charging process of the accumulators is completed, the volume of the propellant gas in the accumulators is given by equation (11). If a generic function is correctly actuated, starting form charged condition and being the control fluid incompressible, the amount of control fluid delivered, is equal to FVR_{ci} (eq. 13).

$$V_i = V_1 + FVR_{ci} \quad i = 1,2 \ldots \text{nf} \tag{13}$$

as the difference between the V_i (the volume occupied by the propellant gas in the accumulators at the actuation of the generic *i*-th function) and the volume V_1.

The density of the propellant gas after the delivery of a specific quantity of actuating fluid FVR_{ci} can be calculated as follows:

$$D_{ai} = \frac{D_0}{\left(r_V + \frac{D_0}{D_1}\right)} \tag{14}$$

The volumetric ratio r_V is defined as follows:

$$r_V = \frac{FVR_{ci} \cdot F_V}{VC} \tag{15}$$

Being FVR_{ci} given by

$$FVR_{ci} = \sum_{k=1}^{i} FVR_i \cdot F_V. \tag{16}$$

The already defined P_{ai} value (pressure of the propellant gas P_{ai} at the thermodynamic state defined by D_{ai}) can be immediately evaluated considering that the entropy of the propelling gas remains constant during expansions.

If Pressure P_{ai} is higher than the maximum value between the Minimum Operating Pressure MOP_i and the Hydrostatic Pressure P_{Hydro}, the accumulators allow to deliver a quantity of control fluid equal to FVR_{ci}. Otherwise, the accumulators are unable to deliver the right quantity of actuating fluid. Therefore, the design meets the functional request if:

$$P_{ai} > \max\left(PMOP_i, P_{Hydro}\right), \quad \text{for } i = 1,2 \ldots \text{nf}. \tag{17}$$

This verification phase has been implemented in a new nomogram conceiving a sequence of steps represented in Figure 5. Specific values for the horizontal and vertical axes and suitable parameters which characterize the curves have been suitably chosen: they correspond to main variables of the discharge phases.

Figure 5 has been produced considering the same design data reported in Tables 1 and 2. Verification is insured if the actual pressure P_{ai} of the propelling gas, after the *i*-discharge, is greater than the maximum value between its respective Minimum Operating Pressure (MOP_i) or Hydrostatic Pressure P_{Hydro} (eq. 17).

The use of the nomogram in Figure 5 can be specified as follows.

In Figure 5A, the input (*x*-value) is the Volumetric Capacity (VC) of the accumulators (see *y*-values of Fig. 4C). For a curve referred to a specific cumulated Functional Volume Required FVR^*_{ci}:

$$FVR^*_{ci} = \sum_{k=1}^{i} FVR_i \quad \text{for } i = 1,2 \ldots \text{nf} \tag{18}$$

evaluated without multiplying each FVR_i by the F_v, r_V can be calculated: it has been reported in the *y*-axis of Figure 5A.

Moving to Figure 5B and for a given D_0 (*y*-value of Fig. 4A), P_{ai} is evaluated and reported in the *x*-axis. On the same *x*-axis, Figure 5B reports the MOP_i as reference values. If, for every discharge, the P_{ai} fulfills the condition expressed by the equation (17), the accumulators allow to meet the functional requests.

As it can be observed in Figure 5, all the pressure levels respect the condition expressed by the equation (17) as reported in equation (19):

$$\begin{aligned} P_{a1} &> \max\left(MOP_1, P_{hydro}\right) \\ P_{a2} &> \max\left(MOP_2, P_{hydro}\right) \\ P_{a3} &> \max\left(MOP_3, P_{hydro}\right) \end{aligned} \tag{19}$$

Therefore, the accumulators allow to deliver the volume of control fluid required. If at least one of the condition expressed in the equation (19) is not satisfied, the design process must be repeated.

The complete fulfillment of the actuations is further demonstrated in Figure 6A, where each P_{ai} is reported as a function of the precharge pressure. N_2 is considered as propelling gas.

When the precharge pressure increases, P_{ai} remains constant till an optimum value (for the precharge pressure) to which it corresponds a fully voided accumulator. It is evident that to this precharge value, a minimum number of accumulators corresponds (Figure 6B). After this precharge pressure, a further precharge pressure

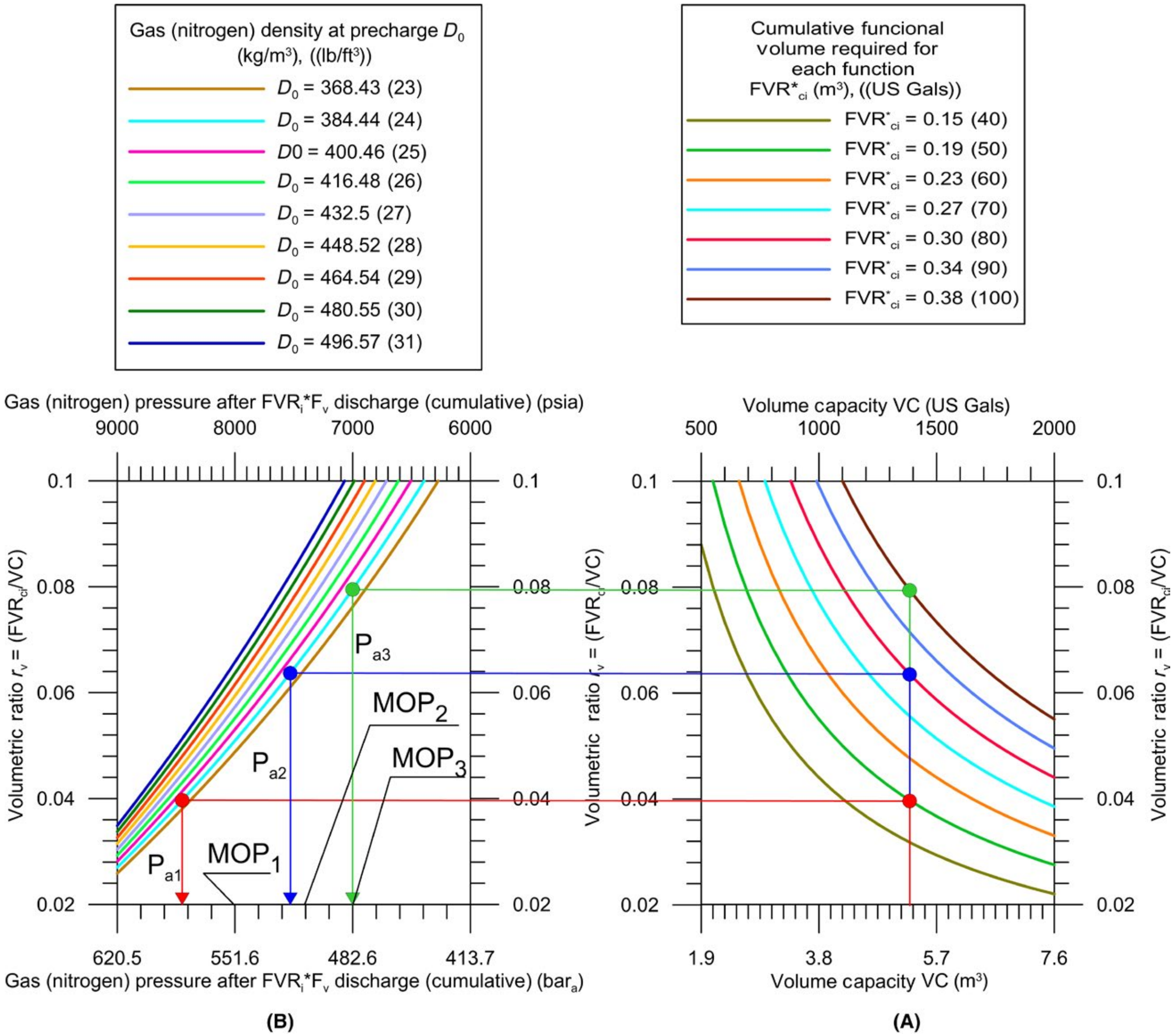

Figure 5. Design verification process in a nomogram form (Water depth = 3657.6 [m] (12,000 [ft]); HPU = 345.77 [bar_a] (5015 [psig]); subsea temperature = 1.67[°C], ([35 °F]); seawater density = 1025.088 [kg/m^3], 8.556 [lb/US gal], Control Fluid Density = 997.934 (8.33 [lb/US gal]). P_{Hydro} = 369.14 [bar_a], (5353.944 [psia]).

increase produces a reduction in the volumetric efficiency, realizing an increase in the number of the accumulators and a residual pressure after each discharge higher than the minimum requested. Figure 6A shows the success of the design.

Remarks on the Design of the Bank of Accumulators

If the fulfillment of all the actuations is not reached, the regulation leaves to the designer the following choices:

- initial precharge pressure variation of the propelling gas;
- increase of the number of the accumulators

till to the fulfillment of the function(s) previously failed, without indicating a specific choice. In any case, the final design is far from being optimized in terms of number of accumulators which was the first goal of the norm.

The failure happens because the energy stored in the propelling gas is unable to deliver the requested quantity of the actuating fluid above a specific minimum operating pressure. When the lowest pressure of the last

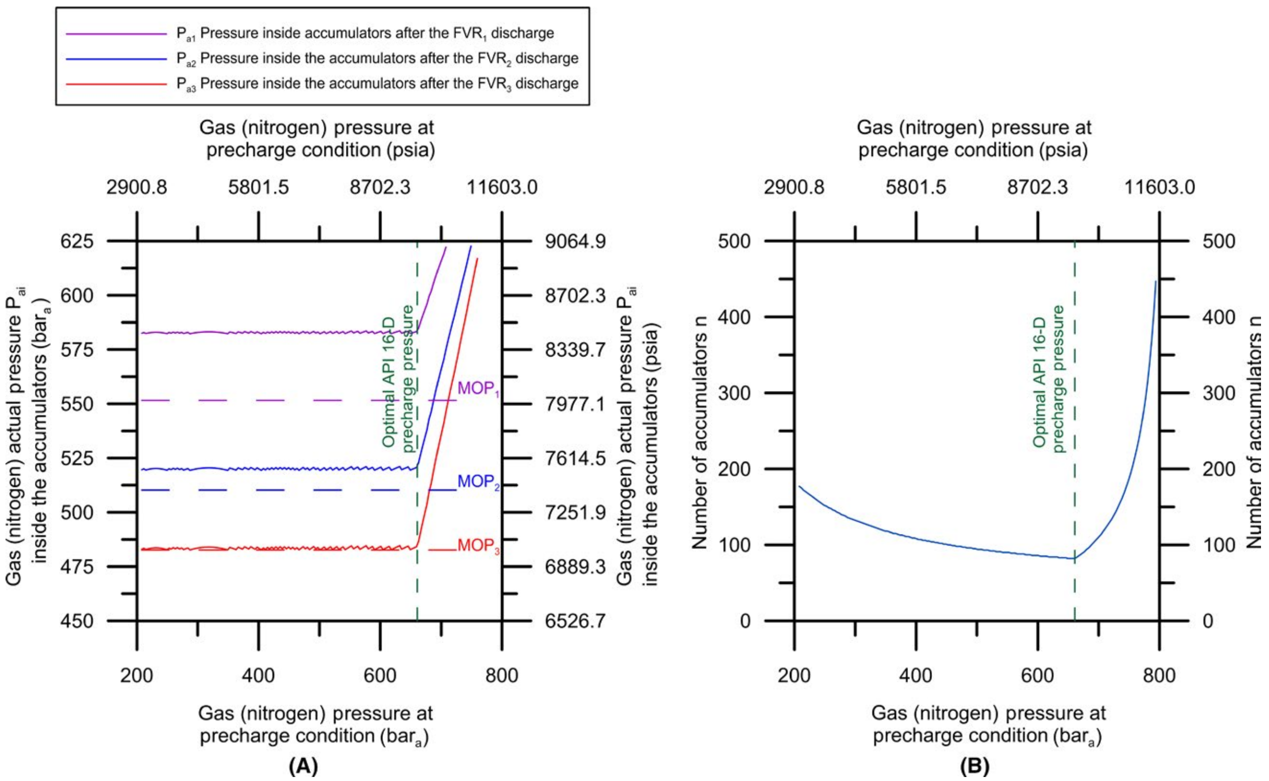

Figure 6. (A) Pressure inside the accumulators when FVR_i are extracted as a function of the precharge pressure. (B) Number of minimum accumulators required varying the gas precharge pressure value. The design has been done according to the norm.

function MOP_3 is assumed to be inside the accumulators after the full discharge of the actuating fluid (as the norm assumes), this hypothesis could not insure the fulfillment of the intermediate actuations. To overcome this situations, if this pressure is assumed equal to the MOP_1 (first actuation), all the actuations are fulfilled but a severe overdesign is produced (increase of the number of accumulators).

In order to put in evidence this situation, a new set of data concerning the accumulator design is reported in Table 3. The sequence of BOP actuations of this second test case has the same functions requirements of the first sequence reported in Table 1, except for the second actuation which has an higher MOP, while the operating conditions are the same (Table 2).

In this new situation, the overall cumulative FVR is equal to 0.379 [m^3] (100 [US gals]) and MOP (third action) is 482.6 bar$_a$ (7000 psia); so, according to the API 16D design procedure, the optimal precharge pressure, the minimum MOP_i, and the FVR for the entire sequence of the functions do not change with respect to the previous case (Table 1). Thus, the number of accumulator prescribed by the regulation is the same.

Figure 7A shows the P_{ai} values after each discharge: it is evident that the second actuation is not fulfilled being the MOP_2 greater that the P_{a2}. This happens also beyond the optimum precharge pressure value, as defined by the norm (660.76 [bar$_a$]-9583.6 [psia]). Only if the precharge pressure is greater than 676.7 [bar$_g$] (9815 [psia]), the second actuation is fulfilled but with a number of accumulators (91) greater than the minimum one (82).

For sake of completeness, if MOP_1 is assumed after the full fluid discharge, the optimal gas precharge pressure would be 712.4 [bar$_a$] (10,332.5 [psia]) and the number

Table 3. Functions requirements.

Function	MOP_i [bar$_a$], ([psia])	FVR_i [m^3], ([US gal])	FVR^*_{ci} [m^3], ([US gal])	FVR_{ci} [m^3], ([US gal])
1	551.6 (8000)	0.189 (50)	0.189 (50)	0.208 (55)
2	537.8 (7800)	0.114 (30)	0.303 (80)	0.333 (88)
3	482.6 (7000)	0.076 (20)	0.379 (100)	0.417 (110)

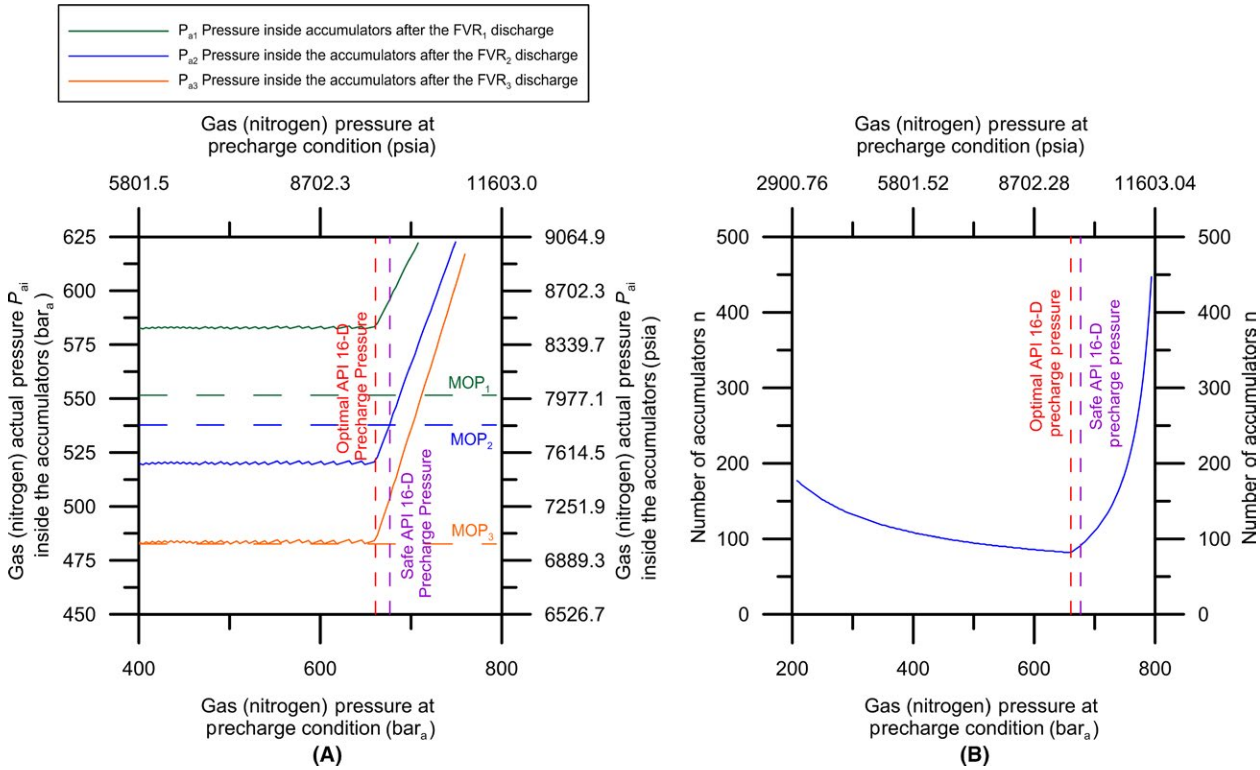

Figure 7. (A) Pressure inside the accumulators when FVR_i are extracted as a function of the precharge pressure; (B) number of minimum accumulators required varying the gas precharge pressure value.

of the accumulators would be 123. In Figure 8, this design is represented in terms of pressure levels inside the accumulators after each discharge: it is evident the overdesign produced by the norm.

Conclusions

In this paper, the API 16D Method C design procedure for rapid discharge subsea accumulators was implemented in a software platform. A result was to provide an original nomogram which allows the sizing of the accumulators in a graphical form immediately evidencing the role of all the operating parameters involved and the sensitivity of these variables in the final design. Due to this, the procedure developed makes the design easier (within the respect for the API 16D), transforming the normed procedure into the application of a nomogram.

Moreover, in order to verify if the design obtained ensures the fulfillment of the requirements of all the actuations, a verification nomogram has been developed. A result was to provide a second innovative nomogram whose theoretical base has been a thermodynamic model of the discharge of the accumulators.

The verification nomogram allows to understand the reason of an eventual failure which can happen if the API 16D Method C is used. The procedure developed shows that failure happens due to the insufficient pressure (energy) inside the propelling gas. In reality, for sake of completeness, after the design, the norm invites to verify the fulfillment of all the actuations, but it does not assist the designer on how to modify the design if an actuation in not insured.

This aspect represents a critical issue of the norm which should be defined in a unique way and in all parts in order to avoid uncertainties, difficulties when a comparison is made among different choices, introducing a degree of freedom which should not be allowed when a standard is applied. In case of failure of one actuation, the norm invites the designer to: (a) produce a new design modifying the precharge pressure and repeating the normed method; (b) increase directly the number of accumulators keeping the same optimal precharge pressure. In any case, the number of accumulators is anymore optimized.

It is opinion of the authors that a novel design procedure of the accumulators scientifically based is needed, so definitively improving the design and removing the hypotheses usually assumed. The procedure should allow a physical representation of the discharge process relating fluid deliveries and pressure levels.

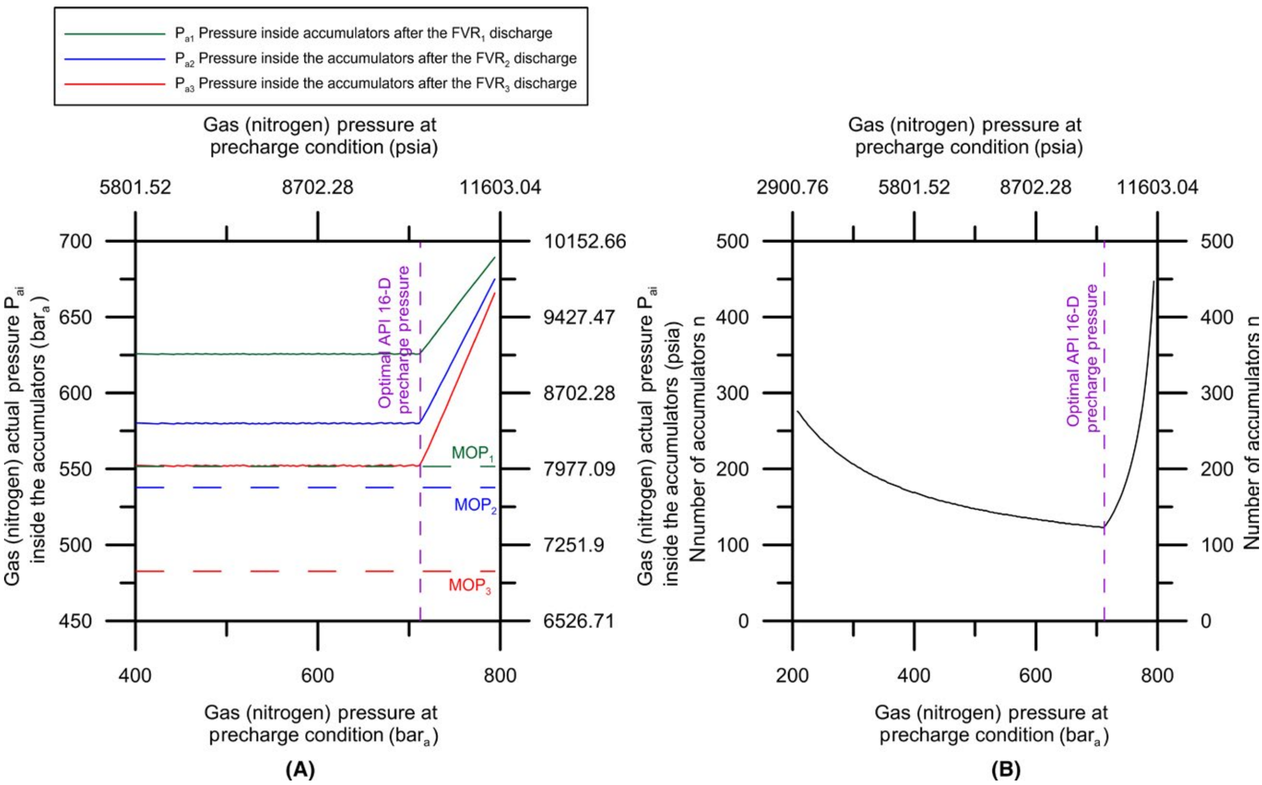

Figure 8. (A) Pressure inside the accumulators when FVR_i are extracted as a function of the precharge pressure: the MOP1 is assumed after the full discharge; (B) number of accumulators required varying the gas precharge pressure value.

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Conflict of Interest

None declared.

Nomenclature

AG air gap [m], [ft]

D_0 gas density at precharge condition [kg/m^3], [lb/ft^3]

D_1 gas density at charged condition [kg/m^3], [lb/ft^3]

D_2 gas density at MOP condition [kg/m^3], [lb/ft^3]

D_{i} gas density at intermediate MOP_i condition [kg/m^3], [lb/ft^3]

D_3 gas density at total discharge condition [kg/m^3], [lb/ft^3]

D_{opt} gas density at optimum discharge condition and surface temperature [kg/m^3], [lb/ft^3]

EDS emergency disconnection sequenced system

F_p design factor at pressure limited condition

F_v design factor at volume limited condition

FVR_i functional volume required for i-function [m^3], [US gals]

FVR functional volume required for the entire sequence of the functions [m^3], [US gals]

FVR_{ci} cumulated functional volume required with volume factor F_v

FVR^*_{ci} cumulated functional volume required at i-th function actuation without volume factor F_v

LMRP lower marine raiser package

MOP_i minimum operating pressure for an intermediate function, [bar_a], [psia]

MOP lowest minimum operating pressure of the last function [bar_a], [psia]

m mass of inert gas stored in bottle after the precharge phase [kg], [lb]
nf number of function
na number of accumulators
P_0 gas precharge pressure (gauge) [bar_g], [psig]
P_1 gas pressure at charged condition [bar_a], [psia]
P_3 pressure at total discharge condition [bar_a], [psia]
P_{HPU} hydraulic power unit delivery pressure [bar_g], [psig]
P_{Hydro} hydrostatic pressure [bar_a], [psia]
$P_{hydro,CF}$ hydrostatic pressure of column of control fluid [bar_a], [psia]
P_{Opt} optimum precharge pressure [bar_a], [psia]
P_{ai} actual pressure of propellant gas in the accumulator after discharge FVR_{ci} [bar_a], [psia]
r_v volume ratio
S_1 entropy of the gas at charged condition [kJ/kgK], [BTU/lb°F]
SAV single accumulator volume [m^3], [US gals]
T_{sub} subsea temperature at wellhead [°C], [°F]
T_{surf} Air temperature on the rig [°C], [°F]
VC accumulators volumetric capacity [m^3], [US gals]
V_0 gas volume at precharge condition [m^3], [US gals]
V_1 gas volume at charged condition [m^3], [US gals]
V_i gas volume at MOP_i condition [m^3], [US gals]
V_2 gas volume at MOP condition [m^3], [US gals]
V_3 gas volume at total discharge condition [m^3], [US gals]
V_{L1} liquid volume at charged condition [m^3], [US gals]
V_{Li} liquid volume at MOP_i condition [m^3], [US gals]
VE volumetric efficiency
VEp volumetric efficiency at pressure limited condition
VEv volumetric efficiency at volume limited condition
VEi volumetric efficiency at generic *i*-condition
VF volume factor
WD water depth [m], [ft]

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