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Handling Gas-In-Riser – Part I: Fundamental Concepts and Calculations Underlying 2023 IADC Riser Gas Guidelines

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Abstract

IADC published in 2023 new Deepwater Riser Gas Handling (RGH) Guidelines as well as a Riser Gas Tolerance (RGT) worksheet intended to make related calculations available to the industry. Both the Guidelines and the worksheet utilize terms and principles new to, or insufficiently documented within the industry.

Aiming to fill the gaps in documentation, this paper provides definition of terms and specifically addresses two fundamental concepts that are either little known or inconsistently applied to field operations, Riser Equilibrium and Riser Unloading. These concepts underly both the Guidelines and the RGT worksheet. Furthermore, the significance of fluid compressibility is quantitatively illustrated to address common, significant calculation errors.

Terms related to these concepts will be clearly defined and physically explained. The logic of related calculations (and derivation of formulae) will be clarified in order to provide the industry with a consistent basis for evaluation or further development of practical riser gas handling procedural issues.

Introduction

The Riser Gas Handling (RGH) subcommittee of the IADC UBO/MPD committee was formed to address how gas behaves and the consequences of gas finding its way into the riser while the drilling rig was furnished in the riser with RGH or surface backpressure MPD equipment. On understanding how the gas behaves, the purpose was then to develop the appropriate guidelines to safely remove the gas from the riser in several scenarios where it may be present. It was however explicit that the placement of the gas into the riser was inadvertent and not deliberate.

Initially the boundaries or limits in which these guidelines were to be developed were defined and were (1) the water depth the rig was operating, (2) the pressure and collapse rating of the marine riser and ancillary riser equipment, and (3) the pressure rating of the RGH or MPD surface equipment. Unlike the development of the Influx Management Envelop (IME) concept, the strength of the open hole was not considered since all the analysis made of the gas behavior assumed the riser was sealed at the bottom with the subsea BOP being closed.

To conform with the physics applied with conventional well control and the development of the IME, all calculations were based on Boyle's Law on a "single-gas bubble" with different mud weights of water and oil-based drilling fluid. This was necessary to establish the gas behavior in terms of pressure regimes and volumes of the gas influx wherever it sat in the riser. Compressibility of the drilling fluid and gas in the drilling riser was also considered in the calculations because of the impact it had on pressures in the deepwater drilling environment. By not considering other parameters such as gas solubility in oil-based drilling fluids and dispersion of the influx when the well kicked meant that the final calculated results remained on the conservative side.

In parallel with the work done by the RGH committee, PhD candidates at Texas A&M University (Omer Kaldirim, 2018) and Louisiana State University (Mhendra R Kunju, 2023), who were also member of the RGH committee, conducted several experiments to characterize gas behavior while monitoring and measuring the gas response after its placement at the bottom of large-diameter annular spaces and it was allowed to migrate.

Propriety models and programs were also run in different gas-in-riser scenarios where the findings confirmed that the calculations, the experimental data and modelling results were all aligned and robust.

Having established the operational limits of the RGH or MPD systems and confirmed, by calculation, the physics of the behavior of gas in the riser it became incumbent upon the RGH committee to write the Riser Gas Handling guidelines.

The scope was to provide guidance on the development of procedures for safely managing and removing hydrocarbon gas that may or may not be present in the riser system with the well isolated from the riser at the SSBOP, and reestablishment of safe operational conditions prior to returning to planned operations on the rig.

The RGH Guidelines center around the new recommended process using the Fixed Choke Constant Outflow (FCCO) method where, with the SSBOP closed, circulation is established down the booster line at a rate within normal MGS limits then adjusting the choke to obtain an initial back pressure of 150-200psi on the riser. There may be some deviations in pressure while the gas is being circulated out the gas from the riser and the guidelines cover those deviations, but in principle the gas can be circulated out maintaining the backpressure and rate until the gas has passed the choke and into the MGS.

The Riser Gas Tolerance (RGT) worksheet has also been developed using the same principles and data.

Riser-Gas Behavior

The behavior of gas volumes nearing the top of a fluid column (as, for example, gas migrating or being circulated near the top of a marine riser) can be difficult to understand, since many factors simultaneously interact and may change quickly. Convoluted tools can be used to analyze the gas migration through a riser and even mitigate potentially dangerous scenarios (Zhaoguang Yuan, 2016), but by initially focusing only on the most dominant factors it should be possible to recognize the most significant trends and changes in behavior which may or may not be initially apparent. With that in mind, we will start this section by looking at some simplified examples of gas expansions in a riser, which is later followed by a more rigorous derivation of a riser-gas model. Finally, we use the derived relationships to establish a series of definitions and methodologies which can be used to understand and plan for actual gas-in-riser events.

Two major factors that obviously impact a system with gas nearing the top of a marine riser are the pressure acting down on the gas and the resulting volume changes caused by changes in such pressure. These pressure and temperature changes are related to each other following the Ideal Gas Law,

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

where P, V and T are the pressure, volume and temperature of a given amount of gas (i.e., a bubble) at two different conditions, which are represented by the indexes 1 and 2. Use of the starting assumption that the gas is a "single bubble", and that the temperature inside the riser is constant during the migration of the bubble helps simplify calculations while also providing a means to conservatively estimate "worst case" boundary conditions in the same way as is conventional done for more well control training. Under these assumptions, we are left with a simpler relationship known as Boyle's Law,

$$P_1 V_1 = P_2 V_2$$

Per Boyle's Law, there will be an increase in the volume of the bubble during migration as pressures are reduced. Therefore, the density of gas will reduce as the bubble moves higher in a riser. By the time gas nears surface, its density will generally have reduced to a point where it is possible to use the simplifying assumption that the gas gradient is negligible without losing reasonable accuracy. For the low-pressure examples shown below, pressure of the top of the bubble is considered equal to average pressure of the entire bubble.

It should be understood that the pressure within such a single bubble located deep in a riser is not independent of the pressure acting down on it, but is, in fact, caused by and is equal to such "confining pressure". Any bubble will either quickly expand or contract until an equilibrium exists between the bubble pressure and the confining pressure. This condition may only exist momentarily, but until something happens to change the confining pressure, its volume will remain constant. Again, this is under the simplifying assumptions that result from the use of Boyle's Law instead of the more precise Real Gas Law. In doing so, we are, for now, intentionally ignoring the effects of temperature and compressibility.

"Confining pressure" consists primarily of the combined effect of hydrostatic pressure caused by the density of fluid above the gas plus any surface pressure (including atmospheric pressure) acting on top of the gas. Since the system being considered is a marine riser with typically large diameter and slow rates of fluid flow and gas migration, friction within the system can also be initially ignored. Using these simplifying concepts, consider the example shown in Fig. 1. Please note that for simplicity, the drillpipe is not shown in the schematic drawing.

Riser capacity	0.33 bbl/ft
Initial gas volume	33 bbls
Riser fluid gradient	0.5 psi/ft
Surface pressure (atmospheric)	15 psia
Initial depth (bottom of gas)	1000 ft

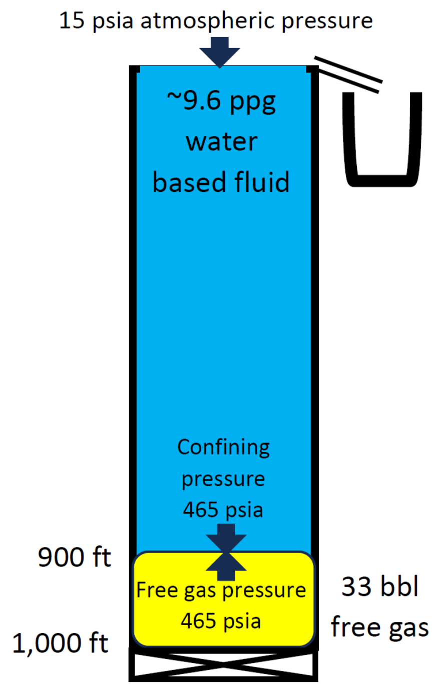

Figure. 1—Example of gas bubble in riser under confining pressure at its initial position.

Based on the information provided in Fig. 1, we can calculate the height of the gas bubble as 100 ft (initial gas volume divided by riser capacity), which implies that the column of liquid above the gas in the 1000 ft is 900 ft. Thus, the confining pressure on top of the gas bubble is

$$P_{confining} = \text{Height of mud column} \times \text{mud gradient} + P_{surface} = 900 \times 0.5 + 15 = 465\text{psia}$$

If the gas is now either moved upward in this open-to-atmosphere riser by circulation or migration, there will be a reduction in confining pressure, as there will be less fluid providing hydrostatic pressure above the gas.

Now, let's suppose that circulation or migration moves the bottom of the gas upward by 1 ft. As mentioned before, since the gas moved upwards, the pressure on top of the gas would have slightly decreased, leading to an increase in the bubble volume. Since we do not yet know what that increase in volume was, we will take an initial guess (similar to what is done when using iterative calculations) that the total height of the bubble inside the riser also increased by 1 ft. This means that the bubble volume increased by 0.33 bbl (due to the riser capacity). If such expansion did indeed occur, then it would result in a gas bubble of 33.33 bbls which (per Boyle's Law only) would have to have a pressure of

$$P_2 = \frac{P_1 V_1}{V_2} = \frac{465 \times 33}{33.33} = 460.4\text{psia}$$

Since the expansion can only occur upward (there is no energy available to force fluid below the bubble downward), the increase in gas volume must push overlying fluid upward by an equal volume amount. Therefore, the confining pressure of the gas must have changed because (a) 1 ft of the fluid column is now below, not above, the gas, and (b) expansion of the gas would have caused an equivalent volume of fluid to overflow at surface due to the fixed volume of the riser. Thus, if the gas expanded by 0.33 bbls, and the bottom of the gas is now at 999 ft, it follows that the top of the gas would have to be 101 ft (33.33 / 0.33) above that, i.e., at 898 ft. The calculated confining pressure at this depth would be

$$P_{confining} = 898 \times 0.5 + 15 = 464\text{psia}$$

Since this pressure exceeds the previously calculated 460.4 psia gas pressure, the guessed amount of gas expansion must be wrong: the actual expansion must have been less. This is illustrated in Fig. 2a, which is crossed out indicating the initial guess (i.e., the first calculation iteration) is not correct. Thus, by further iteration, we can calculate that the gas would only expand by about 1.5 inches (approximately 0.04 bbl) before its pressure reached "equilibrium" with the confining pressure at approximately 464.4 psia, as shown in Fig. 2b. Once that equilibrium pressure is reached, the gas simply stops expanding until additional circulation or migration moves it further upward.

Now, consider the same sequence but with the bottom of a different, but same-size bubble starting at a different depth. Suppose the bottom of such bubble is initially located at 160 ft with its pressure exactly equal to the confining pressure caused by 60 ft of fluid above it plus atmospheric pressure as shown in Fig. 3.

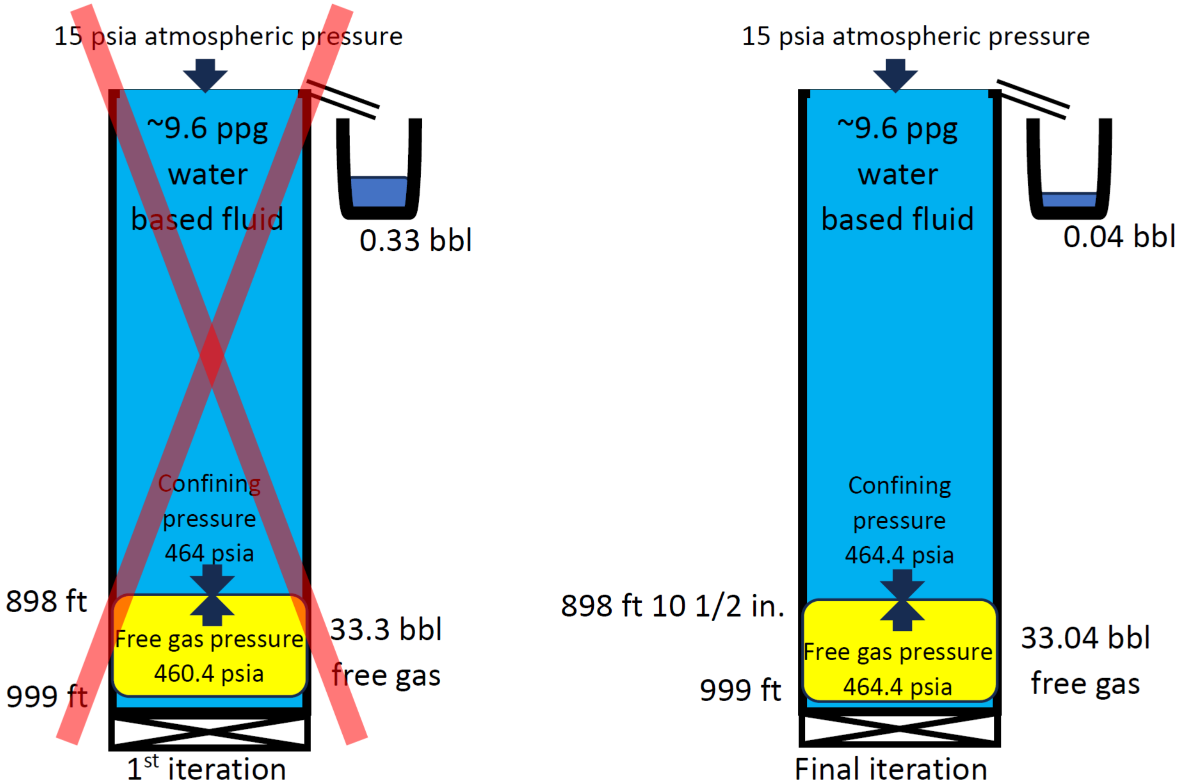

Figure. 2—Iterative process to calculate the gas expansion due to 1-ft upward migration inside a riser.

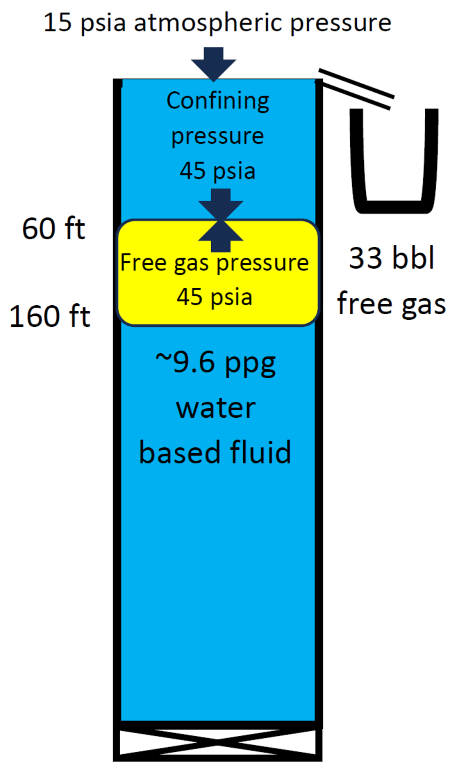

Figure. 3—Initial bubble example now placed at shallower depth inside the riser.

Once again, if the gas bubble is circulated or if it migrates 1 ft upward, we can say the bottom of the gas is now at 159 ft and our starting guess of 1 ft expansion puts the top of the gas at 58 ft, as shown in Fig. 4a. This would result in the gas volume increasing to 33.33 bbl with a pressure of

$$P_2 = \frac{P_1 V_1}{V_2} = \frac{45 \times 33}{33.33} = 44.55\text{psia}$$

On the other hand, the confining pressure is

$$P_{confining} = 58 \times 0.5 + 15 = 44 \text{ psia}$$

which is less than the pressure in the gas (calculated using Boyle's Law). This result indicates a trend opposite of what happened in the first example. Therefore, in this case, our first guess is again wrong, but instead of overestimating the volume change, it now underestimates gas expansion. So iteration in this case would require a new guess using more than one foot of expansion. However, if we try any larger guess, the calculated pressure difference will be even larger. This represents a lack of equilibrium. Fig. 4b shows the pressure imbalance if we redo the calculations by considering an additional 2-foot expansion of the. If that happened, it would mean that the confining pressure is now decreasing faster than the pressure in the bubble. The difference between gas pressure and confining pressure will continue to increase at an accelerating rate as we use larger and larger guesses. As a result, the system will never reach equilibrium, and gas pressure will not be equal to the confining pressure until the gas expands into the atmosphere after it leaves the riser.

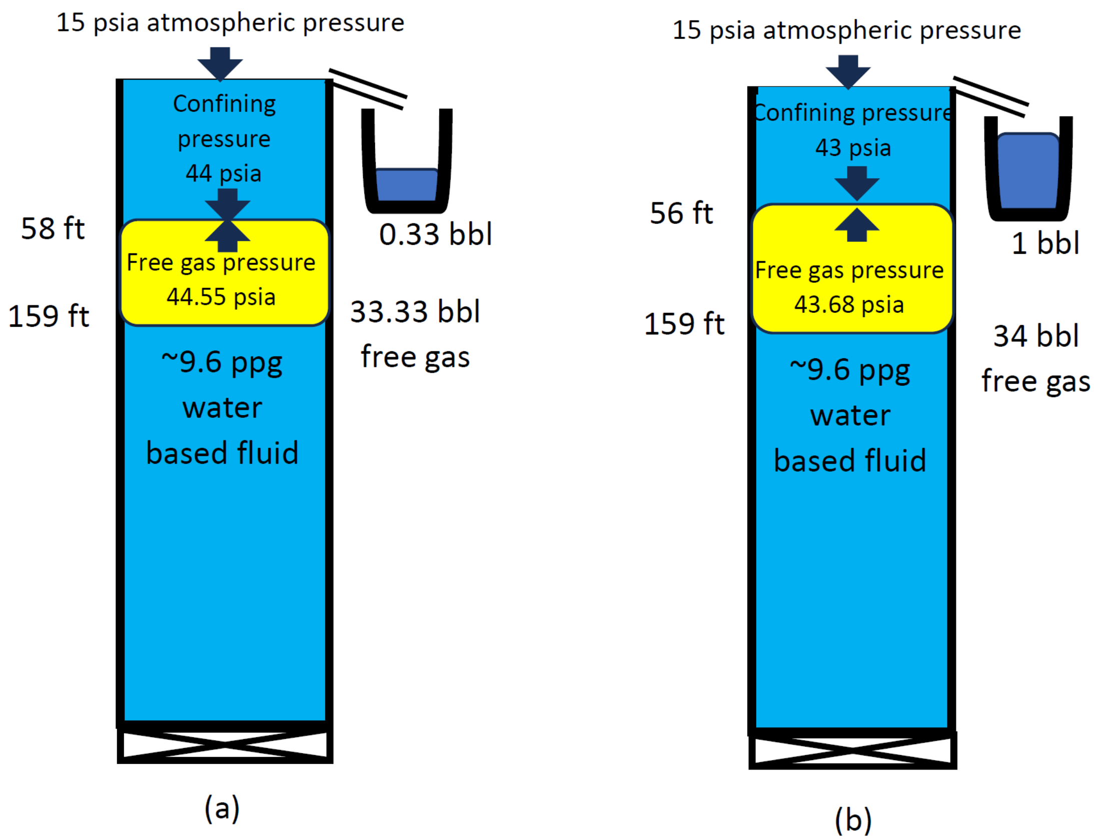

Figure. 4—Migration of 33 bbl bubble located near the surface after (a) 1 ft expansion and (b) 3 ft expansion.

Once started, this rapid, self-sustaining gas expansion can rapidly lift any remaining overlying fluids out of the riser. This is the process underlying what is referred to as "riser unloading". Note that no further movement of the bottom of the bubble is needed to sustain the unloading process. But if that happens, it will accelerate the process by further reducing the rate of gas pressure decline.

One more calculation can illustrate the magnitude of this self-propelled gas expansion phenomenon. Consider what happens if the gas expansion is not impeded and continues to force fluid out until only 3 ft (approximately 1 bbl) of fluid remains above it in the riser (Fig. 5). Assuming the bottom of the gas bubble remains at 159 ft, the gas volume at that instant is

$$V_2 = (159\text{ft-}3\text{ft}) \times 0.33\text{bbl/ft}=51.48\,\text{bbl}$$

which results in a gas pressure of

$$P_2 = \frac{P_1 P_1}{V_2} = \frac{45 \times 33}{51.48} = 28.85\text{psia}$$

Meanwhile, the confining pressure at this same instant is

$$P_{\text{confining}} = 3 \times 0.5 + 15 = 16.5\,\text{psia}$$

That means the gas would be pushing the remaining 1 bbl of fluid out of the riser with a pressure differential of

$$\Delta P = 28.85 - 16.5 = 12.35\,\text{psia}$$

This pressure, acting on the riser cross sectional area, which is approximately 340 in^2 would create a force on the remaining 1 bbl of fluid of nearly 4,200 lbf. Given that the mud density is 9.6 ppg, the mass of the remaining 1 bbl of mud above the gas bubble is approximately 404 lbm (or 12.6 slug). Using Newton's Second Law of Motion, we can calculate the acceleration of the fluid as

$$a = \frac{F}{m} = \frac{4200}{12.6} = 333.3\text{ft/sec}^2$$

where a is the acceleration of the mud, F is the force acting on the mud, and m is the mass of the mud.

It is important to note that such an acceleration is 10.4 times the acceleration of gravity. This means that at this moment the mud would be accelerating upwards at 10 Gs. Lacking restraining force or significant friction, the rapidly increasing acceleration of an unloading gas bubble may be expected to reach surface moving at near sonic velocity.

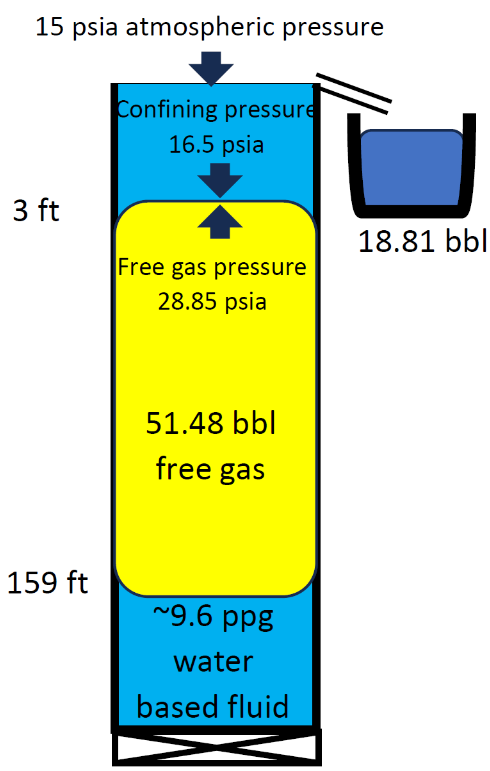

Figure. 5—Example of unrestricted gas expansion.

This example should also make clear the fact that at the moment the gas approaches the top of the riser, its pressure will not be simply atmospheric pressure. In fact, the 159-foot-long bubble has a volume of 52.47

bbl and an internal pressure of 28.3 psia. The example also suggests that if it were possible to close off and stop the outflow exactly when the gas is at the position shown in Fig. 5, the "trapped" pressure at the top of the riser must be the same 12.35 psig. Later in this work, we will look at how changing the confining pressure by adding surface backpressure on top of the riser will impact the initiation of riser unloading.

The dramatic difference between the speed and violence of an unloading event and the generally quite low pressures responsible for this violent behavior is probably one reason for the wide-spread lack of understanding that inhibits acceptance of mitigation strategies that utilize currently available riser closure devices (i.e., RCDs or annular closure devices).

Note that in this example we considered a relatively small near-surface gas bubble compared to potentially higher volumes that could result from even moderate volumes of gas located near the bottom of a long riser filled with heavier fluids.

Pressure Balance on a Gas Bubble Inside a Riser

We will now revisit the physical phenomenon explored in the previous paragraphs and give it a more rigorous analysis. In this new, first-principle based analysis, we will describe the pressure acting upon a gas bubble that moves from its known initial condition at the bottom of the riser to any other location inside that riser, as shown in Fig. 6.

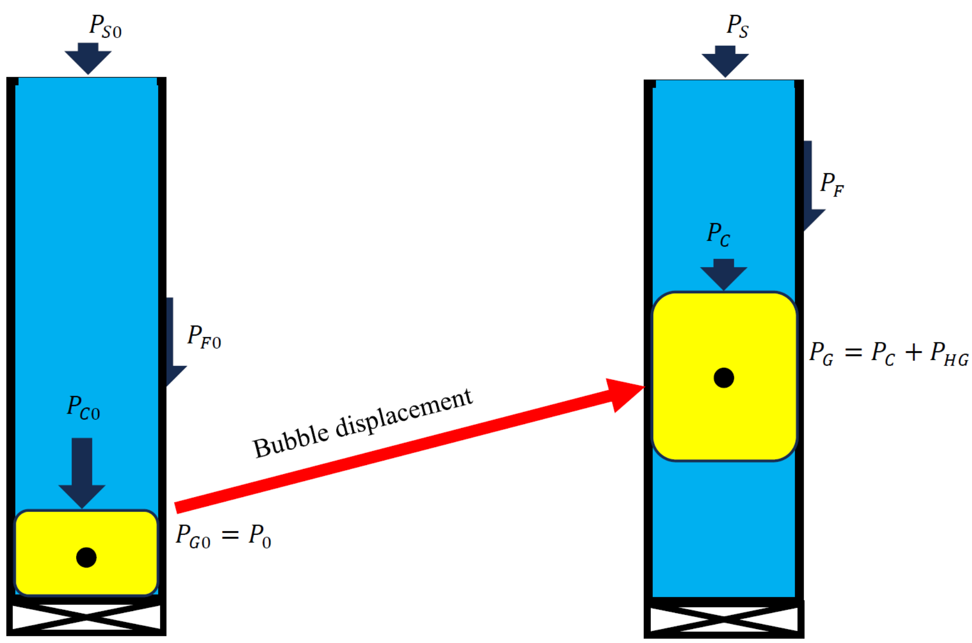

Figure. 6—Migration of a gas bubble inside a riser and the respective pressure components acting upon it as the bubble moves upwards.

As the Fig. 6 indicates, the average pressure of the gas is P_G is a result of the confining pressure acting on top of the bubble (P_C) and the average hydrostatic of the gas bubble (P_{HG}). The confining pressure can be calculated as

$$P_c = P_s + P_{HL} + P_F$$

where P_S is the surface pressure, P_{HL} is the hydrostatic pressure of the liquid (mud), and P_F is the frictional pressure due to liquid moving upwards. At initial conditions, the pressure of the gas (P_{G0}) is simply P_0 and the variables P_{C0}, P_{S0}, and P_{F0} refer to the initial values of the confining, surface and frictional pressures, respectively.

The surface pressure can be written as

$$P_s = P_{atm} + SBP$$

where P_{atm} is the atmospheric pressure and SBP is the surface backpressure applied on top of the riser. The hydrostatic pressure of the liquid is

$$P_{HL} = \rho_L g H_L$$

where ∂_L is the density of the liquid (mud weight), g is the gravity acceleration, and H_L is the height of the liquid column above the top of the bubble. Given the large diameters of risers and the low velocities of fluid moving upwards before a riser unloading event, we will consider the frictional pressure P_F negligible, that is, $P_F = 0$. However, it is important to notice that once riser unloading starts, the liquid velocity may be significantly high and, thus, the frictional losses are no longer negligible. The added frictional loss, however, will actually help balancing the gas expansion, which makes the $P_F = 0$ assumption a conservative one.

For the purpose of this work, we will assume that the gas bubble occupies the entire cross section of the riser. Thus, the average hydrostatic pressure of the gas bubble will depend only on the density of the gas itself, such that,

$$P_{HG} = \rho_G g \frac{H_G}{2}$$

where H_G is the height of the gas column, which can be rewritten as a function of the volume of the gas bubble itself, and the riser capacity (C) as

$$H_G = \frac{V_G}{C}$$

Therefore, the pressure at the center of the gas bubble can be calculated as

$$P_G = P_C + P_{HG} = P_C + \rho_G g \frac{V_G}{2C}$$

As stated previously, the initial conditions of the bubble are known. Namely, the volume, pressure, and density of the gas when it is located at the bottom of riser are P_0, V_0, and ∂_0. From the Real-Gas law, we know that (assuming temperature does not change),

$$\frac{P_G V_G}{Z_G} = \frac{P_0 V_0}{Z_0}$$

where z_G and z_0 are the z-factors at the moment of interest and at initial conditions, respectively. Now, given the mass of gas is conserved in the system, then

$$\rho_G V_G = \rho_0 V_0$$

Thus, we rewrite the pressure of the gas bubble at any location in the riser as

$$\rho_G = \frac{P_0 V_0}{V_G} \frac{z_G}{Z_0} = P_C + \frac{\rho_0 V_0}{V_G} g \frac{V_G}{2C}$$

If we derive this equation in respect to the position of the top of the bubble, i.e., H_L, we obtain

$$\left[P_0 V_0 \frac{z_G}{z_0}\right] \frac{\partial}{\partial H_L}\left(\frac{1}{V_G}\right) + \left[\frac{P_0 V_0}{V_G} \frac{1}{z_0}\right] \frac{\partial}{\partial H_L}\left(z_G\right) = \frac{\partial}{\partial H_L}\left(P_C\right) + 0$$

from where

$$-\left[P_0 V_0 \frac{z_G}{z_0}\right] \frac{1}{V_G^2} \frac{\partial}{\partial H_L}\left(V_G\right) + \left[\frac{P_G}{z_G}\right] \frac{\partial}{\partial H_L}\left(z_G\right) = \frac{\partial}{\partial H_L}\left(P_C\right)$$

With

$$\frac{\partial P_c}{\partial H_L} = \frac{\partial P_s}{\partial H_L} + \frac{\partial}{\partial H_L}\left(\rho_L g H_L\right) + \frac{\partial P_F}{\partial H_L} = 0 + \rho_L g + \frac{\partial P_F}{\partial H_L} = \rho_L g + \frac{\partial P_F}{\partial H_L}$$

As noted previously, the frictional pressure is negligible during most of the gas migration, up to the point where riser unloading occurs, and so is its derivative (i.e., $\partial P_F / \partial H_L = 0$).

The relationship above suggests that the changes in the volume of the gas are proportional to the changes in the pressure on top of the bubble, but the two are not linearly related due to the V_G^2 term. With that in mind, we manipulate further the relationship by dividing both sides by the confining pressure. We then obtain,

$$\left[\frac{1}{P_C}\frac{P_0 V_0}{V_G}\frac{z_G}{z_0}\right]\left(-\frac{1}{V_G}\frac{\partial V_G}{\partial H_L}\right)+\left[\frac{P_G}{P_C z_G}\right]\frac{\partial z_G}{\partial H_L}=\frac{1}{P_c}\frac{\partial P_c}{\partial H_L}$$

and simplify it as

$$\left[\frac{P_G}{P_C}\right]\left(-\frac{1}{V_G}\frac{\partial V_G}{\partial H_L}\right)+\left[\frac{P_G}{P_C}\right]\left(-\frac{1}{z_G}\frac{\partial z_G}{\partial H_L}\right)=\frac{1}{P_C}\frac{\partial P_C}{\partial H_L}$$

This can be rearranged as Eq. 1

$$\frac{\frac{1}{P_C}\frac{\partial P_c}{\partial H_L}}{-\frac{1}{V_G}\frac{\partial V_G}{\partial H_L}+\frac{1}{z_G}\frac{\partial z_G}{\partial H_L}}=\frac{P_G}{P_C} \tag{1}$$

Please note that throughout our derivation, we were not concerned in describing how the bubble moved upwards. The pressure equilibrium between gas and liquid interface must be satisfied independently of bubble migration or pump rate.

The equation derived above cannot be easily computed manually and would likely require the use of numerical tools to properly solve for it. Furthermore, while it is not obvious at first glance, the use of such a model implies the use of gas equations of state, which can make the entire process overwhelming.

To simplify the model, we will reintroduce two assumptions used in the first examples in this work. First, Boyle's Law can be used to describe gas behavior inside a riser where temperature is constant. This means that $z_G = z_0 = 1$, and the derivative of the z-factor is zero ($\partial z_G / \partial H_L = 0$). The second assumption is that the hydrostatic pressure of the gas is negligible, which implies $P_G = P_C$. While this is not true, it is a conservative approach as it decreases the pressure of the gas bubble, which in turn leads to a larger gas expansion.

With these assumptions and based on the last equation of the previous section, here we rewrite Eq. 1 as Eq. 2

$$\frac{\frac{1}{P_C}\frac{\partial P_c}{\partial H_L}}{-\frac{1}{V_G}\frac{\partial V_G}{\partial H_L}}=\frac{P_G}{P_C}\approx 1 \tag{2}$$

Riser Equilibrium

The confining pressure derivative in the simplified relationship above is relatively easy to calculate numerically. In fact, we have already shown that since the frictional pressure is negligible, then

$$\frac{\partial P_c}{\partial H_L}=\rho_L g$$

Therefore, the numerator on the left-hand side of Eq. 2 becomes Eq. 3

$$\frac{1}{P_C}\frac{\partial P_c}{\partial H_L}=\frac{\rho_L g}{P_S+\rho_L g H_L} \tag{3}$$

From this, we introduce a new definition, the percentage change in confining pressure due to the upward displacement of the bubble as Eq. 4

$$\%\Delta P_C=\frac{\rho_L g}{P_S+\rho_L g H_L}\times 100 \tag{4}$$

Now, the derivative of the bubble volume in relation to position of the top of the bubble is not as straightforward. If we consider that the top of the bubble moves from a reference position H_r by an amount h, this does not mean that the bubble expanded by the proportional volume magnitude hC. During this displacement, the bottom of the bubble also travels upwards although at a lower rate. With that in mind, we pose the following inequality (Eq. 5)

$$\frac{\partial V_G}{\partial H_L} \approx \frac{V_G(H_L = H_r) - V_G(H_L = H_r - h)}{h} \leq \frac{V_G(V_G = hc)}{h} = -C \tag{5}$$

This inequality means that the change in volume of a gas bubble as a function of its position is smaller than the relative expansion of such bubble if it remained static. This will hold true while the gas expansion is controlled, and riser unloading does not occur.

The right-hand side of the inequality in Eq. 5 is much easier to calculate than the derivative itself; thus, we use that to define the estimated percentage change of gas volume as Eq. 6

$$\%\Delta V_G = \left| \frac{\frac{V_G - (V_G + hC)}{h}}{V_G} \right| \times 100 = \frac{C}{V_G} \times 100 \tag{6}$$

In practical terms, Eqs. 4 and 6 mean that the derivatives in Eq. 2 can be calculated by numerical approximation. Furthermore, we chose to represent the normalized derivatives as percentages as that allows for an easier interpretation of the results.

From these definitions, we now introduce a new concept called the Riser Equilibrium Ratio (RER), which is expressed mathematically as Eq. 7

$$RER = \frac{\%\Delta P_C}{\%\Delta V_G} \tag{7}$$

As discussed earlier, we know from Eqs. 3 and 4 that

$$\%\Delta P_C = \frac{1}{P_C} \frac{\partial P_C}{\partial H_L} \times 100$$

and, from Eqs. 5 and 6 we can infer Eq. 8

$$\%\Delta V_G \geq \left| -\frac{1}{V_G} \frac{\partial V_G}{\partial H_L} \right| \times 100 \tag{8}$$

Thus, at closer examination, we can see that RER is an approximation of Eq. 2. Furthermore, we can say that, while riser unloading does not occur, RER value must not exceed 1 (Eq. 9),

$$RER = \frac{\%\Delta P_C}{\%\Delta V_G} \leq \left| \frac{\frac{1}{P_C} \frac{\partial P_G}{\partial H_L}}{-\frac{1}{V_G} \frac{\partial V_G}{\partial H_L}} \right| = 1 \tag{9}$$

However, once riser unloading starts taking place, the gas pressure becomes unbalanced in relation to the confining pressure, and uncontrolled expansion of the gas happens. This process was illustrated by the examples shown earlier in this Section. As mentioned in those examples, after riser unloading begins, the estimated gas expansion (which we redefined as $\%\Delta V_G$) will always be smaller than the real rate of (normalized) gas volume expansion, effectively inverting the inequality in Eq. 8 to

$$\%\Delta V_G < \left| -\frac{1}{V_G} \frac{\partial V_G}{\partial H_L} \right| \times 100$$

Thus, during riser unloading the ratio between $\%\Delta P_C$ and $\%\Delta V_G$ is such that

$$RER > 1$$

Of particular interest is the relationship derived from Eq. 9 when RER = 1. At this moment we reach the threshold of equilibrium, which we define here as the Riser Equilibrium Point (REP). The REP can be calculated in terms of volume, pressure and depth. Since RER = 1, it follows that

$$RER = \frac{\%\Delta P_C}{\%\Delta V_G} = \frac{\frac{\rho_L g}{P_S + \rho_L g H_{REP}} \times 100}{\frac{C}{V_{REP}} \times 100} = \frac{\rho_L g}{P_S + \rho_L g H_{REP}} \frac{V_{REP}}{C} = 1$$

where V_{REP} and H_{REP} are the volume and the depth of the top of the gas bubble when REP, respectively. If the confining pressure at REP is

$$P_{REP} = P_S + \rho_L g H_{REP}$$

we can rewrite it as a gas pressure (our assumption is that $P_G = P_C$), thus, from Boyle's Law,

$$P_{REP} = \frac{P_0 V_0}{V_{REP}}$$

Therefore, we can calculate the volume at REP as Eq. 10

$$\frac{\rho_L g}{P_{REP}} \frac{V_{REP}}{C} = \frac{\rho_L g}{P_0 V_0} V_{REP} \frac{V_{REP}}{C} = \frac{\rho_L g}{C P_0 V_0} V_{REP}^2 = 1 \Rightarrow V_{REP} = \sqrt{\frac{C P_0 V_0}{\rho_L g}} \quad (10)$$

From that, it follows that the gas pressure at REP is given by Eq. 11

$$P_{REP} = \sqrt{\frac{\rho_L g P_0 V_0}{C}} \quad (11)$$

and the height of the column of liquid (i.e., the depth of the top of the bubble) is calculated with Eq. 12

$$H_{REP} = \sqrt{\frac{P_0 V_0}{C \rho_L g}} - \frac{P_S}{\rho_L g} \quad (12)$$

As an example, we use the initial scenario discussed in this work, when the top of the gas was at 900 ft. The relative estimated gas volume change for a one-foot expansion, $\%\Delta V_G$, can be calculated as

$$\%\Delta V_G = \frac{C}{V_G} \times 100 = \frac{0.33}{33} \times 100 = \frac{1\%}{\text{ft}}$$

In that same situation, the $\%\Delta P_C$ is

$$\%\Delta P_C = \frac{\rho_L g}{P_S + \rho_L g H_L} \times 100 = \frac{0.5}{465} \times 100 = \frac{0.11\%}{\text{ft}}.$$

Thus, at this instant, RER is

$$REP = \frac{\%\Delta P_C}{\%\Delta V_G} = \frac{0.11}{1} = 0.11 \le 1$$

As mentioned before, the RER will be less than 1 in any situation in which the gas bubble is still below the REP. But when the top of gas is above that depth, the RER will be greater than 1, and it will not be possible to re-establish an equilibrium between gas pressure and confining pressure after any further gas expansion occurs (assuming no additional back pressure is applied).

Let us now use the example from Fig. 4 to draw a comparison with the previously calculated RER value (RER = 0.11). From Fig. 4, we calculate

$$\%\Delta V_G = \frac{0.33}{33} \times 100 = \frac{1\%}{\text{ft}},$$

and

$$\%\Delta P_C = \frac{0.5}{44} \times 100 = \frac{1.1\%}{\text{ft}},$$

which results in

$$RER = \frac{1.1}{1} = 1.1 > 1$$

The change of confining pressure, expressed as a percentage, is now greater than the corresponding percentage change in gas volume. This means that, at this point, any gas expansion at this depth causes a greater percentage reduction in confining pressure than is occurring in the gas pressure itself. The unloading process after this point remains not only self-sustaining, but rapidly accelerating.

Consider now the example from Fig. 5 where the gas reaches 3 ft below the surface. At this instant, the RER is

$$RER = \frac{0.5/16.5}{0.33/51.48} = \frac{3.03}{0.64} = 4.7$$

This RER value is 4.3 times greater than the RER of when the gas top was at 58 ft and unloading had just begun, confirming that the imbalance or dis-equilibrium condition has worsened as the unloading has progressed.

Calculations such as these support the initial statement that whenever the RER is less than 1, the gas bubble will not continue to expand unless the confining pressure is further reduced either by circulation, migration, or by bleeding pressure at surface if the riser is aligned to a choke at the top. It is important to notice that by reducing the surface pressure (that is, the confining pressure on top of the gas), the Riser Equilibrium Point depth will shift to a deeper point in the riser, which means that riser unloading will take place sooner. When the gas is at the Riser Equilibrium Point, the RER will be equal to 1. Pressure in the gas at this location is equal to confining pressure and the amount of this pressure is defined as the REP pressure. Whenever the RER is greater than 1, gas will quickly self- expand until all fluids above it are expelled unless friction – or flow path blockage – compensates for the loss of hydrostatic pressure that triggered this escalating process.

The logic presented above can be represented graphically, where the Riser Equilibrium Point depth (H_{REP}) and Riser Equilibrium Point pressure (P_{REP}) can be readily determined. The graphical method, as well as the equations presented previously, form the basis of the Riser-Gas Tolerance worksheet, a resource publicly available on the IADC UBO/MPD Committee web page (IADC).

Fig. 7 shows an example of the graphical representation of the percentage changes per foot of confining pressure and gas bubble volume, as well as the corresponding "theoretical" RER. (Remember that the "actual" RER will always be approximately 1 while gas is below REP, as indicated in Eq. 2). The calculations are based on an 8,000 ft riser filled with 12 ppg mud and a 100 bbl gas bubble at the bottom. The riser ID is 19.25 in. and the drillpipe OD is 6.625 in. The atmospheric pressure is 14.7 psia and an additional surface backpressure (SBP) of 200 psig is applied at the top of the riser.

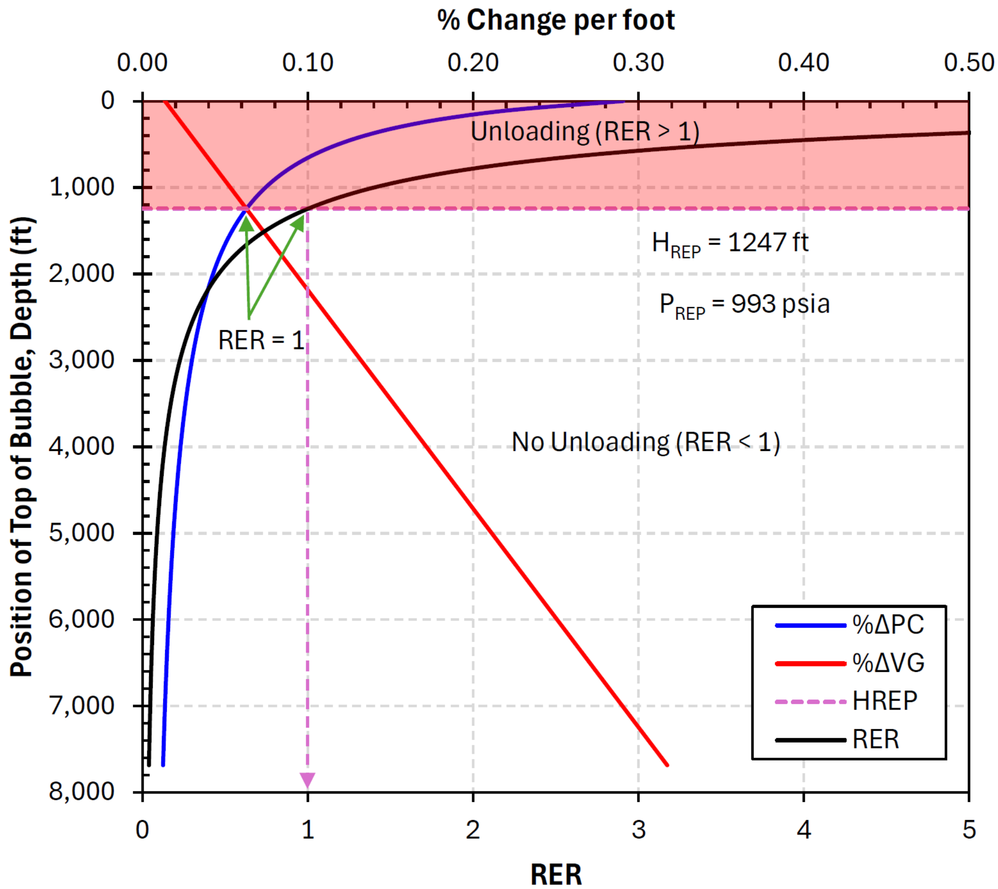

Figure. 7—Graphical representation of RER and REP.

Using the equations derived in this work, we can trace the lines plotted on the graph and determine REP. For example, the REP depth (Eq. 12) is

$$H_{REP} = \sqrt{\frac{P_0 V_0}{C\rho_L g}} - \frac{P_S}{\rho_L g} = \sqrt{\frac{(14.7 + 200 + 0.052 \times 12 \times 7685)100}{0.317(0.052 \times 12)}} - \frac{14.7 + 200}{0.052 \times 12} = 1,254\text{ft}.$$

Discussions

An understanding of the physical relationships underlying these riser equilibrium concepts leads to a conclusion that an unloading event can be precluded or stopped by preventing the unobstructed expulsion of fluid above the gas bubble. Notably, field procedures often selected for use in managing gas-induced riser flow are designed to achieve exactly the opposite condition; diverter systems are typically designed to minimize backpressure caused by returning fluid flow and strictly prevent the possibility of creating a blockage in such fluid flow paths, essentially diverging and attempting to relieve any extra pressure to overboard.

That means that conventional use of a diverter to direct fluid away from the rig without creating backpressure can be expected to maximize the flow rate during a gas-in-riser unloading event. But perhaps even worse is the fact that in doing this, the possibility of a pressure increase below the diverter still exists and, in a large volume event, could cause high liquid and gas flow rates while concurrent pressure still remains significantly above atmospheric pressure.

By contrast, the understanding of the underlying cause of riser unloading (caused by the gas being above the Riser Equilibrium depth as described above) makes it relatively easy to quantify the maximum pressure that can be created in a riser system if flow is either stopped when unloading begins or could exist if continued flow is permitted. Since the pressure in the gas at that moment must be no greater than the REP Pressure (PREP), it can be conservatively concluded that surface pressures resulting from fully stopping outflow from the riser at, or after unloading begins, cannot exceed that pressure (PREP). This is the logic underlying the definition of a system's "Riser Gas Tolerance" (RGT). The RGT is the maximum gas volume at the bottom of the riser which will not cause the surface pressure to exceed the maximum allowable surface pressure when that gas bubble is at REP. For example, if we use the same parameters as before (8,000 ft riser, 19.25 in. riser ID, 6.625 in. drillpipe OD, 12 ppg mud, 3.0×10^{-6} psi^{-1} mud compressibility, 14.7 psia atmospheric pressure, 200 psig SBP) and set the maximum allowable surface pressure to 1,250 psia, we can estimate RGT graphically to be approximately 180 bbl, as shown in Fig. 8. This Figure is a direct output from the Riser-Gas Tolerance worksheet publicly available at the IADC UBO/MPD Committee web page.

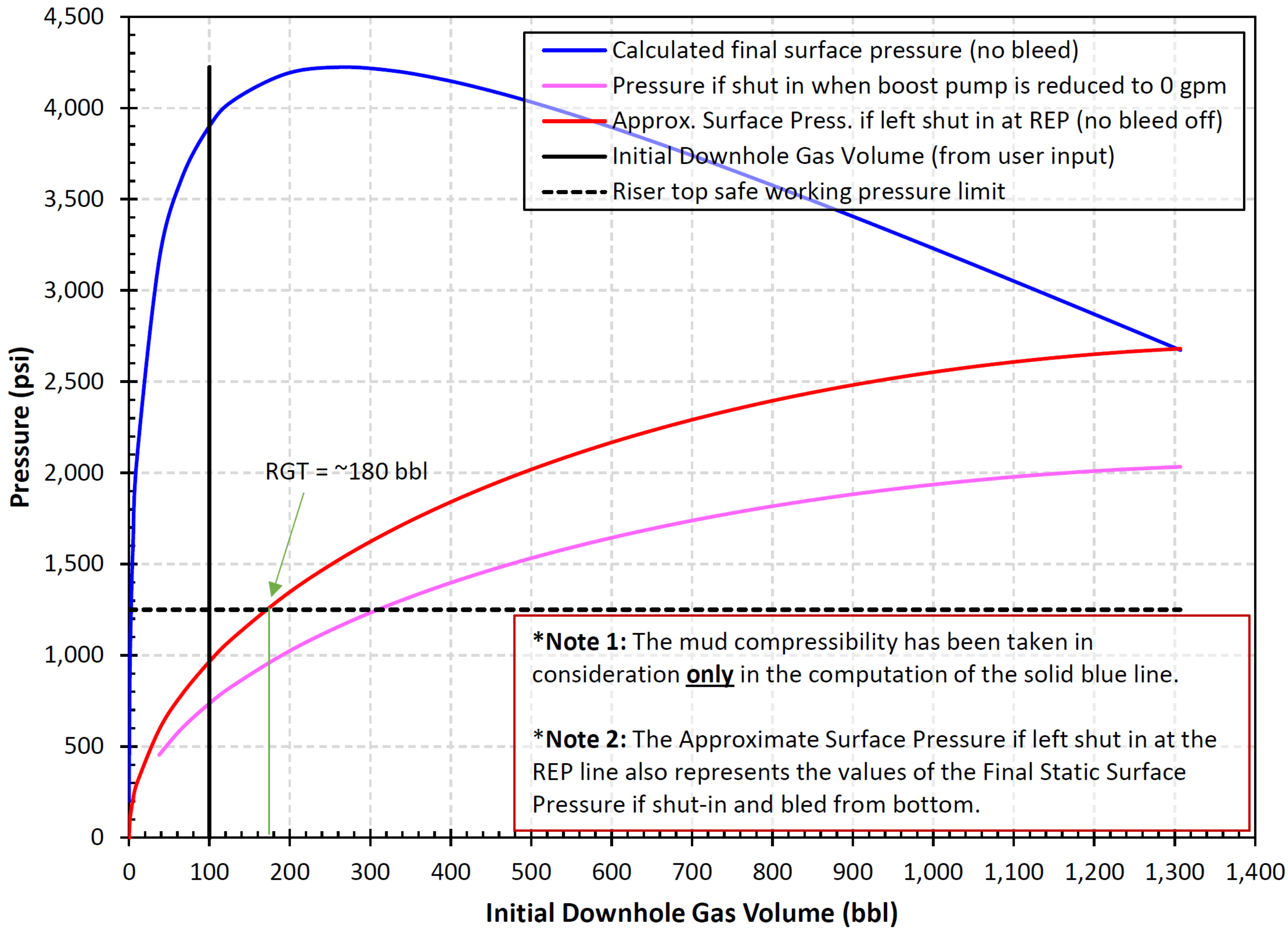

Figure. 8—Graphical representation of Riser Gas Tolerance.

Such calculations could support design and development of diverter systems sufficient to safely manage worst-case gas-in-riser events (which design process does not exist for diverters today). But such calculations also quantify the ability of existing flow control devices (notably systems utilizing RCDs or annular flow controllers at the top of a marine riser) to provide simple and safe methods for control and controlled release of riser gas without the need to bypass existing mud/gas separation devices, thus reducing pollution while enhancing safety.

The consequences of providing a safe, simple and reliable way of managing even large riser gas events may be numerous and profound. To promote understanding and implementation of procedures using the

Riser Equilibrium concept, the IADC Gas In Riser Subcommittee of the IADC UBO/MPD Committee has developed and published explicit, new, Riser Gas Handling Guidelines to replace previous guidelines provided in the IADC Deepwater Drilling Guide.

These guidelines may be applicable to both conventional and MPD operations requiring only that specific control equipment be available. The guidelines include guidance regarding prioritization of riser circulation only when conditions require it, thus potentially improving well kill operations and improving overall efficiency while improving rig and environmental safety.

Conclusions

Through a simplified approach, this works sheds light on the otherwise convoluted process of gas upward displacement inside a riser. The definitions, mathematical derivations, and observations in this paper can be summarized by the following points:

- Defined riser unloading, riser equilibrium ratio (RER), and riser equilibrium point (REP);
- Presented a method to calculate RER and determine REP graphically;
- Derived equations to calculate REP depth, pressure, and bubble volume;
- Introduced the concept of riser-gas tolerance (RGT);
- Discussed the importance of proper riser-gas handling.

References

IADC Underbalanced Operations & Managed Pressure Drilling Committee [Online].- https://iadc.org/wp-content/uploads/2023/10/Riser-Gas-Tolerance-Worksheet-v1.0.xlsx.

Mhendra R Kunju Mauricio A Almeida Analysis of Riser Gas Pressure from Full-Scale Gas-in-Riser Experiments with Instrumentation [Journal] // *SPE Drill & Compl.* - 2023. - Vol. **38**. - pp. 170–186.

Omer Kaldirim Jerome J Schubert Experimental Study on Riser Gas Expansion and Unloading [Conference] // SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition. - New Orleans, USA: [s.n.], 2018.

Zhaoguang Yuan Dan Morrell, Paul Sonnemann, Colin Leach Mitigating Gas in Riser Rapid Unloading for Deepwater Dual Gradient Well Control [Conference] // Paper presented at the Offshore Technology Conference. - Houston, TX, USA: [s.n.], 2016.