COMPUTATIONAL MODULE FOR RELIABILITY CALCULATION OF WELL DRILLING FLUIDS AND CASING TUBES

Adriano da Silva Rocha

João Paulo Lima Santos

adrianosrocha1@gmail.com

jpls@lccv.ufal.br

Universidade Federal de Alagoas

Av. Lourival Melo Mota, S/N - Tabuleiro do Martins, 57072-900, Maceió - AL, Brasil

Abstract. *In studies about oil well integrity, an important concept that must be addressed is the one of the well safety barriers, which represents complex systems of components present in all stages of an oil well lifetime. They act avoiding the occurrence of unwanted flows and pressure transmission from/to the surroundings of the well. Regular wells have their barriers arranged in two different systems (a primary and a secondary system), configuring in well integrity failure only when fault happen on both systems simultaneously. For its part, in order to occur a fault on a system, it is sufficient that only one of its components fails. Therefore, it is possible to estimate the chances of a well integrity failure based on the probability of failure of the equipment that compose the two well safety barrier systems. Failure probability analyses can also be performed on two specific barriers to know the existing chances of these two barriers fail, resulting in a well integrity failure. Within this scope, this paper has as objective to develop a computational module capable of calculate the failure probability of two drilling well barriers: the drilling fluid (representing the primary system) and the production casing (representing the secondary system).*

Keywords: *Oil well integrity, Failure probability, Well barriers*

INTRODUCTION

One of the most dangerous accidents that can happen at an oil well site is a blowout, which is characterized by uncontrolled flow of hydrocarbons to the surface or the ground/seabed (when the flux goes through the well to a permeable formation, also called underground blowout). Since hydrocarbons are highly flammable and explosive explosions and fires are common consequences of a blowout, which can lead to high volumes of oil spill, damages to the staff's health and to the environment, also economic losses caused by the fines and other costs. To avoid the occurrence of unwanted flux through the well and keep its integrity some equipment called well barriers are used. The renowned NORSOK D-010 (2004) technical standard about oil well integrity describes the necessary well barriers for each stage of an oil well lifecycle and for a well during the drilling phase the barriers are the drilling fluid, the casing string, the casing cement, the wellhead, the high-pressure riser and the drilling BOP. Therefore, if the casing string is not completely cemented and the formation is permeable, the failure of the drilling fluid column and the casing string may be enough to occur an underground blowout. To assist the design of these well barriers this paper presents the development of a computational module capable of calculating the simultaneous (drilling fluid and casing) failure probability.

1 THE WELL BARRIERS

When formation fluids penetrate the well at undesirable moments it is called a kick. When a kick happens, it can evolve to a blowout and flow to the external environment if the barriers are not able to withstand its pressure and maintain the well integrity. In order to occur a blowout, the first barriers the kick has to overcome are the ones installed in the deeper sections, those barriers compose the primary barrier system. If the primary well barrier system fails to contain the kick a secondary barrier system may prevent the formation fluid to reach the external environment, but if the secondary barrier system does not withstand either, the well integrity is lost and a blowout may occur.

Once a kick happens it will flow through the well following the possible flow-paths. There are four main flow-paths in ordinary wells: through the tubing string, through the annulus between the tubing and the casing strings, through the annulus between the casing strings and for last, through the rock formations around the well casing system. So, to be able to stop the kick the well barrier systems have components at every flow-path, in some cases one system can have more than one equipment at one path or have one same barrier acting simultaneously at different paths. When all the equipment of a well barrier system acting on a path fail that well barrier system fails and the kick is able to flow through the well until the next well barrier system. A typical oil well has two barrier systems available at all its lifetime, changing the components and configurations depending on its phase.

For an oil well during the drilling stage the NORSOK D-010 (2004) standard states that the primary well barrier system is composed by the drilling fluid column and the secondary well barrier system by the casing string, the casing cement, the wellhead, the high-pressure riser and the drilling BOP, like shown in the figure 1 below, where the primary barrier system is shown in the blue color and the secondary barrier system in the red color:

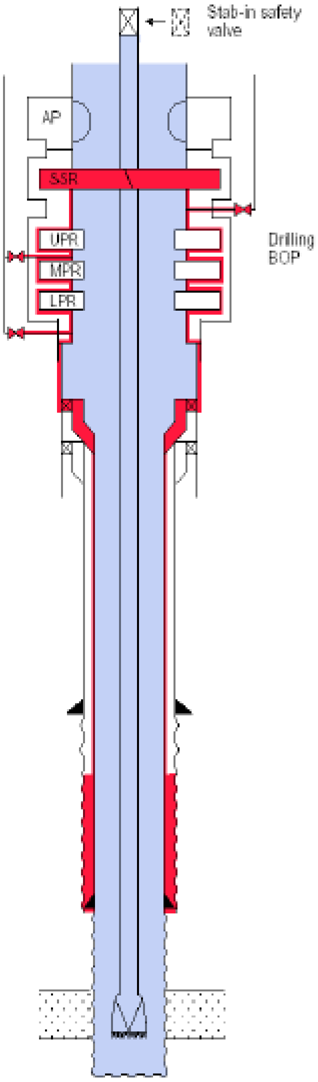

Figure 1: Well barrier systems for a well during the drilling phase.

When a kick happens during the drilling phase, the first barrier the intruder fluid encounter is the drilling fluid. If the drilling fluid column has not enough pressure to prevent the flow in the inside direction the primary well barrier system fails and several elements of the secondary barrier system are put on demand. In the case of a well which its last casing string installed was not completely cemented, the failure of the casing string will expose the formation to the intruder fluid. If the formation is permeable or can not withstand the pressure of the kick, an underground blowout will happen.

Considering that the kick happens in a non-circulating well, the resistance of the fluid column can be estimated by the hydrostatic pressure as shown in Eq. (1) below:

$$R = g\,\rho\,D \tag{1}$$

Where R is the resistance of the column fluid, in Pa, g is the gravity acceleration in m/s^2, ρ is the fluid density in kg/m^3 and D is the depth in m.

Since the casing string has to resist the internal pressure the resistance is given by its internal strength, which can be calculated as in Eq. (2) (API 5C3,1994) shown below:

$$R = 0.875 \,.\left(\frac{2\,Y_p\,t}{d_e}\right) \tag{2}$$

Where R is the resistance to the internal pressure of the casing string in Pa, Y_p is the minimum yield stress in Pa, t is the thickness of the casing wall in m, d_e is the external diameter in m and the coefficient 0.875 is a safety coefficient to adjust to the minimal wall thickness.

2 STRUCTURAL RELIABILITY THEORY

The structural reliability theory focusses on the likelihood of a structure to perform its functions as perfect as it was intended in project, which means, the likelihood of the structure does not fail within a given period and assuming that circumstances of usage are the specified in the project (Beck, 2011). For being a complementary event of the reliability, the failure probability can be used as a reliability indicator of a structure. The structural reliability theory is based on a limit state function, G(U), which has positive values for safe conditions and zero or negative values for failure conditions. The limit state function G(U) is shown in Eq. (3) below:

$$G(U) = R(U_1) - L(U_2) \tag{3}$$

Where U is a vector with all the random variables, $R()$ is the resistance function, U_1 is a sub-vector of U with all the random variables related to the resistance, L() is the load function and U_2 is the sub-vector of U with all the random variables related to the load.

The failure probability to the limit state function G(U) can then be calculated by solving the Eq. (4) below:

$$P_f = \int_{\Omega_f} f_U(\,u)du \tag{4}$$

Where Ω_f is the failure domain (where $G(U) \leq 0$) and $f_U(u)$ is the joint probability density function of the random variables. However, the Eq. (4) can become complex to solve with the increase of random variables quantities or even because of the non-linearity of the limit state function, so some alternatives developed to that are numeric simulations and analytical approaches.

The Monte Carlo's method is a numeric solution where a large amount of events are simulated randomly and the number of failure events (when $G(U) \leq 0$) are counted, then the failure probability can be simply calculated by the division of the number of failure events by the number of total simulations (Beck, 2011). For each random scenario simulated, an aleatory value is attributed for each random variable, so, in spite of the simplicity of the method and of its good results, it is also time and computational expansive, used generally to validate other ways to calculate the failure probability. Another characteristic that should be highlighted is that the accuracy of the results depends on the number of iterations and, since it lies on choosing random values, the higher the number of iterations the higher the accuracy. The number of iterations can be estimated by performing the method more than once to compare the results and see if they converge.

Another option to calculate the failure probability is to use analytical methods such as the First Order Reliability Method (FORM). This method uses a linear approximation to represent

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the limit state function in a standardized normal space to where the random variables should be transformed. In this standardized normal space the transformed variables have mean equals to zero and standardized deviation equals to one. After transforming the variables into this space, a non-linear optimization problem is solved to determine which point in the failure domain is the closest one to the origin, also called project point. There are many ways to solve this optimization problem, like the HLRF algorithm (Hassofer e Lind, 1974; Rackwitz e Fiessler, 1978), used in this paper. Once it is solved the distance from the origin to the project point, also called reliability indicator (β), is calculated and used to estimate the failure probability as shown in Eq. (5) below:

$$P_f = \Phi(\beta) \tag{5}$$

Where Φ() is the joint probability density function of the normal distribution. The FORM algorithm also provides another important information, the project point (y*) is the most probable point in the failure domain to occur, which means that when y* is transformed back to the original space the corresponding values are the most probable values of the random variables that can lead to a failure (Sagrilo, 2003). Some important characteristic should be emphasized about this method and the HLRF algorithm, the variables transformed from the original space to the standardized normal space should have gaussian distribution, when it does not happen it is necessary first to take the equivalent normal parameters of those variables, after that, the variables can be transformed and it follows the algorithm as explained before. The FORM method provides an approximated result of failure probability, but usually close enough to the result of the integral of Eq. (5).

3 THE COMPUTATIONAL RELIABILITY MODULE

The Fluid-Casing Reliability Module (FCRM) was created using Python 3.6 version. The libraries "Numpy" and "Scipy" were extremely important to the development of the program because they allow a simple use of arrays and statistical functions. The graphic interface was done using Python's self-library "Tkinter", so it can be ran at any computer with Python installed and can be supported on most of the operational systems (Windows, Linux, Mac OS).

As explained before, the FCRM evaluates the simultaneous failure probability of two well barriers, the fluid column and the casing string. Hence, the FCRM uses two different limit state functions, one for each barrier. As mentioned in chapter one, the resistance of the fluid column is its own hydrostatic pressure as shown in Eq. (1), and to prevent a kick it must be higher than the pore-pressure load, that is treated as a random variable itself in the FCRM. So, the limit state function for the fluid column barrier (G_F) can be written as in Eq. (6) below:

$$G_F(\bar{\rho}, \bar{L}) = \bar{\rho} \text{ g D - } \bar{L} \tag{6}$$

Where $\bar{\rho}$ is the random variable density in kg/m³, g is the gravity acceleration in m/s², D is the depth in m and $\bar{L}$ is the random variable pore-pressure load in Pa.

For the casing string barrier, the limit state function is composed by two terms as well, one that represents the resistance to internal pressure as assumed in API 5C3 (1994), shown in Eq. (2), but without the deterministic safety coefficient (0.875) applied to the wall thickness, and the other term represents the load, that here is treated as a deterministic variable. The limit state function to the casing string (G_C) can be written as in Eq. (7) below:

$$G_C(\overline{Y_p}, \overline{d_e}, \bar{t}) = \frac{2\,\overline{Y_p}\,\bar{t}}{\overline{d_e}} - L \qquad (7)$$

Where $\overline{Y_p}$ is the random variable minimum yield stress in Pa, $\bar{t}$ is the casing wall thickness in m, $\overline{d_e}$ is the external diameter in m and L is the deterministic variable load in Pa.

The FCRM allows the user to select the random variables distributions between 5 options: normal (gaussian), log-normal, Rayleigh, type one to maximum values and type one to minimum values. After selecting the distributions, the normal equivalent parameters are taken for the non-gaussian distributed variables. The FORM algorithm is then used to calculate the failure probability of the fluid column and after that, the failure probability of the casing string. The failure probabilities are then multiplied and the probability of a simultaneous failure in both barriers is acquired.

The main window of the FCRM, where the data can be introduced to the program (all in S.I. units), is shown in figure 2 below:

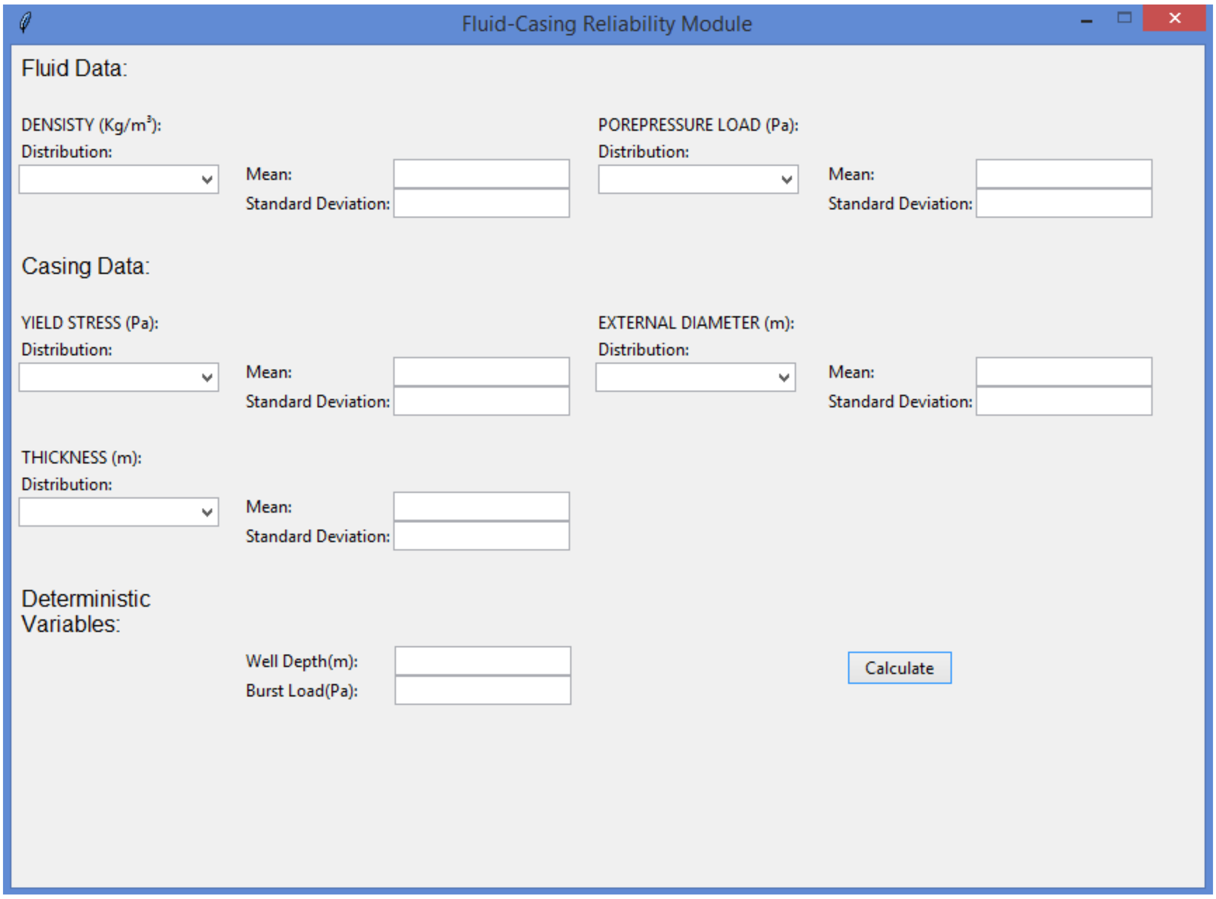

Figure 2. FCRM's main window.

4 RESULTS

In order to validate the algorithm of FCRM comparing the failure probability results acquired by the FCRM with results taken from Monte Carlo method, the program was ran for the values shown in the table 1 below:

Table 1: Random variables used to feed the program.

Random Variable	Mean	Standard Deviation
Fluid density (kg/m^3)	1220.36	43.933
Pore-pressure load ($x10^6$ Pa)	33.365	0.867
Minimum yield stress ($x10^6$ Pa)	276.502	27.487
External diameter ($x10^{-2}$ m)	26.096	0.063
Thickness ($x10^{-2}$ m)	1.936	0.049

All the random variables were considered to have a gaussian (normal) distribution. The program also receives values for two deterministic variables, which are: well depth (3000 m for this hypothetical scenario) and the casing internal pressure load (35,867 x 10^6 Pa). The main window with the input data and the window containing the results are shown in figure 3 and 4 respectively:

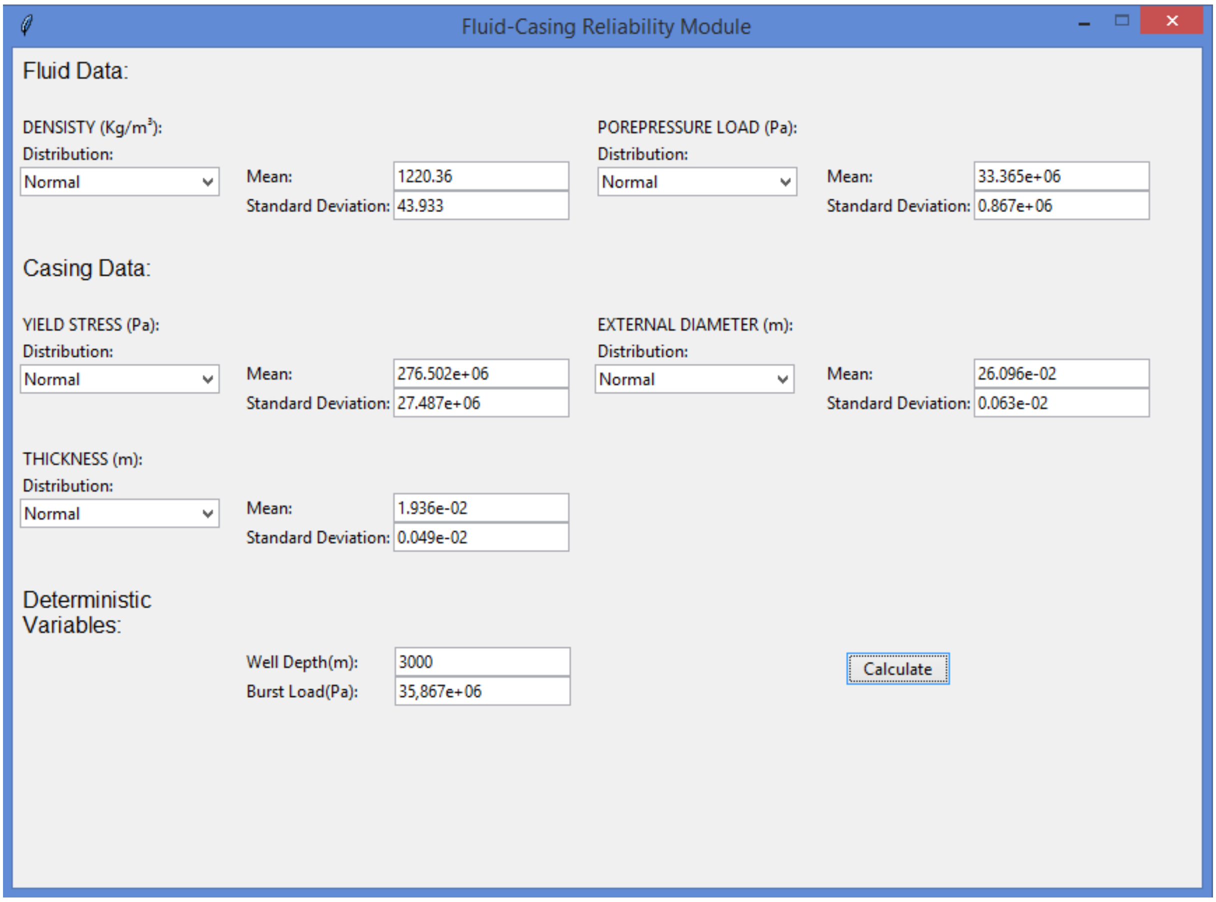

Figure 3. FCRM's main window with input data.

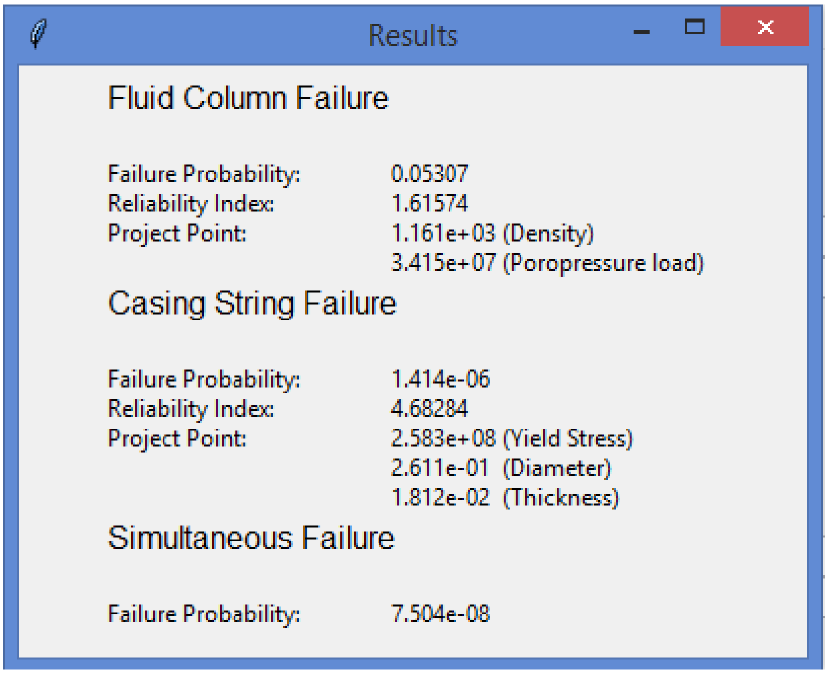

Figure 4. FCRM's results window.

The figure 4 shows the failure probabilities for each barrier and also the probability of both barriers fails to contain the kick simultaneously. In addition to that, the project point, the most probable point of failure, is shown in the original space, providing information about the most critical values for the random variables.

In the table 2 below, the failure probabilities found by the program and by the Monte Carlo's method (using 5 x 10^7 iterations) are compared:

Table 2. Failure probabilities calculated by the FCRM and Monte Carlo's method.

Barrier Element	FCRM	Monte Carlo
Fluid column	0.05307	0.05297 – 0.05308
Casing string	1.41e-06	1.28e-06 – 1.56e-06
Both barriers	7.504e-08	6.78e-08 – 8.28e-08

5 CONCLUSION

The results acquired by the FORM approach used in the FCRM algorithm is near to the values found by the Monte Carlo's method, it is inside the interval of the lowest and the highest failure probabilities for all cases. Thus, it is possible to affirm that the Fluid-Casing Reliability Module is validated and is so a useful tool that can assist on the casing design and on decision-making processes involving the drilling fluid and the casing string.

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