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TECHNICAL PAPER

An integrity analysis approach for development wells

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Abstract Well integrity may be defined as the capability of the well to prevent leakage into the environment, which is a very important feature for oil and gas wells. A way to prevent leaks during operation is to perform maintenance interventions, seeking to keep redundancy in the well's safety barriers. Cost assessment regarding the wells maintenance interventions should be done during the initial phases of the production development project, when the construction campaign is both technically and economically evaluated. This paper presents an approach for development wells integrity analysis considering the existence of intermediate stages, when the integrity has not been lost but the well is considered to be in a degraded status. The method is based on the barriers integrated sets (BIS), proposed by Miura (A study on safety of construction and repair in offshore oil and gas wells (in Portuguese). PhD thesis, University of Campinas, Brazil, Campinas, 2004) and described by Miura et al. (J Pet Sci Eng 51:111–126, 2006), and on general reliability engineering techniques. The approach may be used for maintenance interventions resource assessment considering a well construction campaign. Furthermore, through the determination of the mean time to failure of each BIS identified in the completion configuration it is possible to estimate when the well is in a degraded status, relying on a single BIS, and when the well is expected to leak.

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Keywords Safety · Well integrity · Safety barriers · Reliability · Production development · Petroleum well design

List of symbols

$F(t)$	The cumulative distribution function
$R(t)$	The reliability function
λ	The failure rate

Abbreviations

AIV	Annulus intervention valve
AMV	Annulus master valve
ASV	Annulus swab valve
AWV	Annulus wing valve
BIS	Barriers integrated sets
BOP	Blowout preventer
BP	British petroleum
CFR	Constant failure rate
CIM	Chemical injection mandrel
CSG	Casing
EXL	External leakage
FTA	Fault tree analysis
FTC	Fail to close
GLM	Gas lift mandrel
GLV	Gas lift valve
ICV	Intelligent control valve
INL	Internal leakage
MTTF	Mean time to failure
NTS	Norwegian Technology Standards Institution
PDG	Permanent downhole gauge
PDGM	Permanent downhole gauge mandrel
PKR	Production packer
PMV	Production master valve
PSV	Production swab valve
PWV	Production wing valve

SCSSV	Surface-controlled subsurface safety valve
STA	Success tree analysis
TBG	Tubing
TH	Tubing hanger
WCT	Wet Christmas Tree
XOV	Crossover valve

1 Introduction

In Campos Basin, Brazil, the costs associated with well constructions are approximately one-third of the total value of the investment. However, in the pre-salt projects, the expected costs related to well construction is one-half of the total value of the investment [2]. Consequently, the predictability of material resources, such as equipment and vessels, gained more importance in the economic evaluation of oilfields' development projects.

Risks associated with the exploration and production have increased the efforts to ensure wells integrity. On the other hand, the decline of the British Petroleum Company (BP) market value after the Macondo blowout, demonstrates the extent to which an accident can reach during well construction activities.

One way to prevent oil spills is to perform maintenance operations to keep the wells in safe situations and with additional safety barriers. As subsea wells access great depths with higher pressures, such as the Macondo well, these wells have aggravating factors which make the prevention, control, and mitigation of oil spills more challenging. Thus, the attention given to safety in the design of such wells should be even higher.

Regarding safety, one of the first references for well design analysis is Takashina [10], which proposes the application of reliability theory fundamentals to take preventive actions related to quality assurance and to quantify the safety of the well design. Previous works considered only the need to quantify the barriers to the tubing and to the annulus between the tubing and the casing. Takashina is one of the pioneers to use safety barrier concepts for a whole oil well. Moreover, he proposes the use of failure rates and fault tree analysis (FTA) concepts to quantify the risks of leakage from an oil well. Finally, his paper introduces the need to find a "barriers integrated set able to keep the flow of an oil well under control", however, without deepening the theoretical foundation.

Over the decades of 1990 and 2000, the application of reliability theory concepts in the completion of oil wells gained attention from oil industry with publications focusing on the reliability of specific equipment such as the surface controlled subsurface safety valve (SCSSV) (Molnes and Iversen [7]), the permanent downhole gauges (PDG) (Van Gisbergen and Vandeweijer [11], Frota and Destro [4], and the Wet Christmas Trees (WCT) [8]. Frota [3] also applied concepts of the reliability theory in oil well projects, focusing on the treatment of real data to generate reliability parameters of the equipment used in the completion of subsea wells.

The idea of safety barriers as integrated sets was further developed by Miura [5] and Miura et al. [6], who proposes the concept of barriers integrated sets (BIS) as something that simultaneously sustains the pressure and the reservoir fluids along all possible leak paths to the environment.

Norwegian Technology Standards Institution (NTS) also presents a formal concept of safety barriers such as containers that keep fluids and reservoir pressure under control during the various life stages of the oil well (NORSOK D-010 [9]). The presented concept of safety barriers demonstrates a trend in the industry to assess the well integrity more thoroughly, considering safety barriers as envelopes that hold the reservoir fluids under control.

Corneliussen [1] proposes an approach for risk analysis, during the wells production phase, based on the assessment of safety barriers as an envelope for the reservoir and using reliability theory concepts. This approach involves a detailed evaluation of the failure modes to which the equipment of a completion string is submitted to. However, the identification of these failure modes, represented by the identification of all possible paths and shortcuts from where leaks into the environment may occur, is extremely complex and there is great difficulty in ensuring that all paths were mapped, especially in completion strings for subsea wells.

This paper proposes an approach that enables integrity analysis of development oil wells, at the design stage, in the exploitation phase, considering situations where the well system may be at risk with loss of barriers, but without integrity loss; or leakage situations where the well integrity was lost. The methodology focuses on evaluating well designs, based on the concepts of BIS and general reliability engineering techniques.

This paper is organized as follows. In Sect. 2, the well integrity concept is presented. The safety barrier and BIS concepts are also presented. An integrity analysis for development wells is considered in Sect. 3. Section 4 presents a comparison with real data. The main conclusions are presented in Sect. 5.

2 Well integrity, safety barrier and barriers integrated set (BIS)

After the well completion, equipment installed on the well should prevent any unintentional leakage to the environment, ensuring the integrity of the well. However, obviously, there may be changes regarding the statuses of installed equipment: valves failure, corrosion and erosion, control lines leakage, and so on. Well integrity can

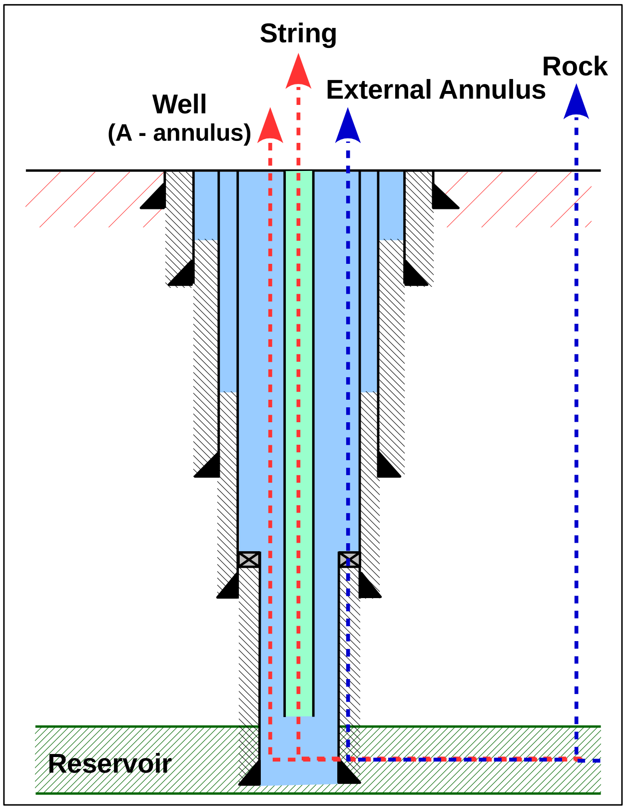


Fig. 1 Paths for integrity assessment in an oil well

be understood as the ability to keep the oil flow from the reservoir to the processing plant controlled, preventing spills of any kind to the environment. This capability or functionality is achieved by blocking all passageways or paths between the production flow and the environment by using equipment that guarantees an integral mechanical "fence" to the oil or its flow: the safety barriers. Miura [5] and Miura et al. [6] presented the concept of safety barriers in accordance to Brazilian oil industry tacit knowledge: physical separation able to prevent unintentional flow, from a permeable interval (formation) to the environment, along specific paths. In the present paper, four main paths between the reservoir and the environment will be adopted:

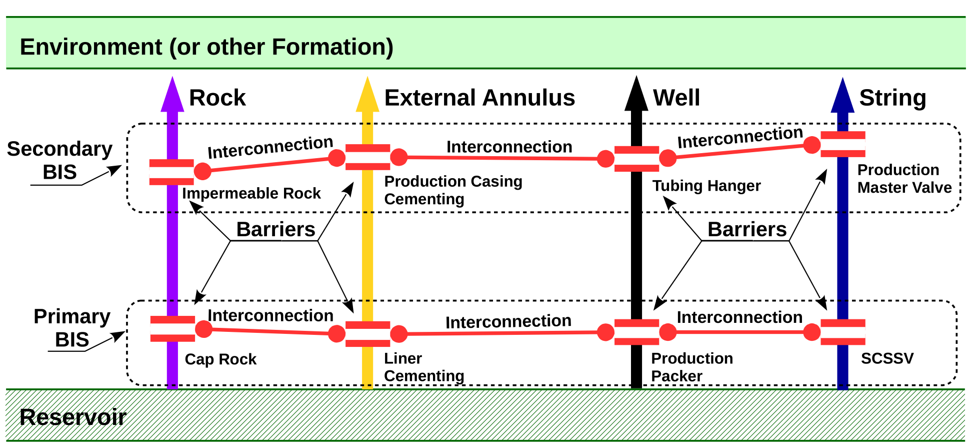
- String: a path that consists of any string inside the well, as drilling, testing, completion, production, injection, or workover;
- Well (or A-annulus): a path set as the inside of the last landed and cemented casing; if there is a string, it is the path of the annular gap between the string and its casing;
- External Annulus (or B, C, D-annulus): external annulus spaces to the last landed and cemented casing;
- Rock: a path between the reservoir and the environment through the lithological layers.

Figure 1 shows schematically these four paths.

The barrier definition presented by Miura encompasses the concept more accepted in the Brazilian oil industry, where equipment such as Packers (PKRs), safety valves, blowout preventer (BOP), Wet Christmas Tree (WCT), casings (CSGs), are classified as safety barriers instead of barrier elements. Additionally, a safety barrier can always be decomposed in its failure modes. Thus, one can say that a barrier is available if it remains intact for all failure modes mapped. The probability of success (reliability) associated with each of the identified failure modes for barrier components can be used to quantify the barrier's reliability.

The formal definition of BIS is presented by Miura [5] and Miura et al. [6] as an assembly composed of one or more barriers and components that interconnect those barriers, able to prevent unintentional flow of fluids from a permeable interval considering all possible paths. The components that tie in the barriers are specific kind of barrier, named interconnection barrier. In following on, the interconnection barrier can be defined as a physical separation able to prevent unintentional flow of fluid between two adjacent paths. Figure 2 shows a representative scheme of how the BISs (Primary and Secondary) and the barriers work in the four defined paths.

Fig. 2 Paths for integrity assessment in an oil well with safety barriers and two barriers integrated sets (BIS)



Primary BIS is a barrier envelope that is actually keeping control of both fluid and pressure from the formation. Secondary BIS is a barrier envelope that will keep control of both fluid and pressure from the formation in case of a primary BIS failure. The acceptance criteria for well integrity proposed in this paper is based on a concept of BIS: the assessment of risk of well integrity should be done by calculating the reliability of the BISs let in the last workover intervention on the well. Using the scheme of the subsea production well illustrated in Fig. 3, we can identify the safety barriers and two BISs (highlighted in Fig. 3b).

Even though the presence of two independent and verified BIS in the well is a sufficient criterion to determine a favorable condition regarding the integrity of the well, there are other devices that act as safety barriers, but they are not components of either BIS considered. For example, the production swab valve (PSV) and the production wing valve (PWV) are physical separations able to prevent unintentional flow to the environment along the string path and, although they are not a BIS part, they increase the integrity of the well. Such equipment may be considered alternative barriers or redundant backups to the BIS, with performances limited to determined paths.

The Barrier graph is used to explicit the relationships (logical model) between barrier components that lead to the availability of the barrier itself. Figure 4 shows a graph for the SCSSV as a barrier.

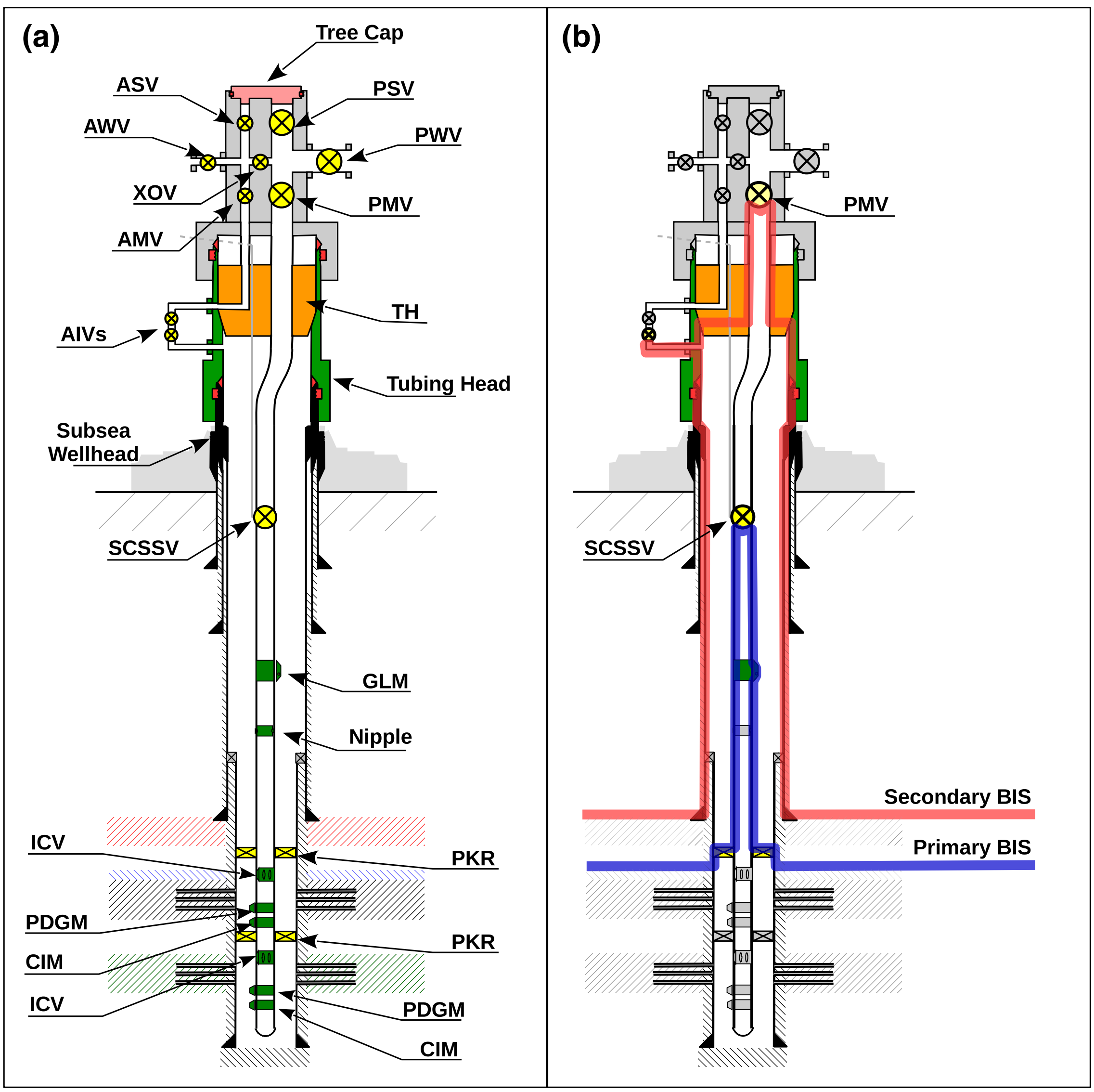
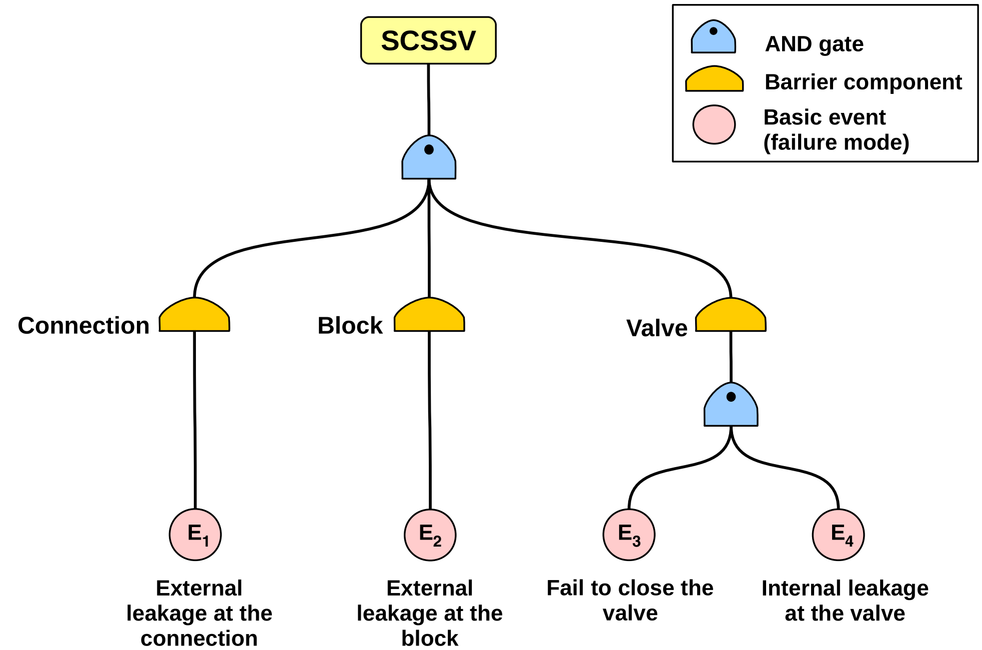


Fig. 3 Barriers integrated sets (BIS) for a subsea production well. **a** Well completion scheme with main equipment. **b** Primary and Secondary BISs

Fig. 4 Barrier graph to SCSSV



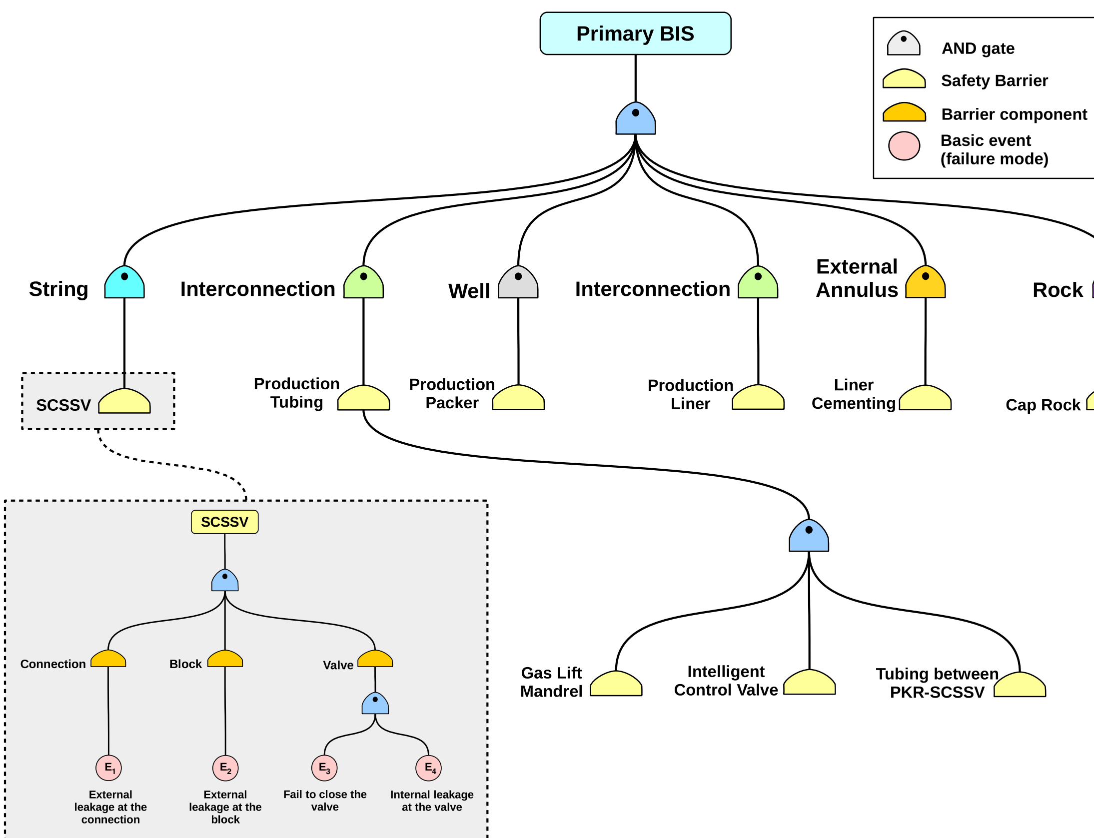


Fig. 5 Graph of the Primary BIS for the subsea production well

Similarly, the graph of the BIS represents the relationship between barriers and components comprising the system, assessing the availability of the BIS. Figure 5 shows the graph of the Primary BIS described in Fig. 3.

Those graphs are a kind of success tree and consequently a success tree analysis (STA) can be a useful tool in identifying the availability of a safety barrier or a BIS. An STA is the logic complement of a FTA. In the next section, the suitability of such methods is illustrated in an application.

3 Application: well design integrity based on BIS

The approach proposed in this paper comprises two major phases. The first phase consists of collecting reliability data for each of the barriers (equipment) used in well design. The second phase is to quantify the reliability of the well design based on both STA and reliability data collected. These two phases are subdivided into the following steps:

- Analyzing well completion design;
- Identifying safety barriers and BISs (Primary and Secondary);
- Identifying expected failure rate for well equipment comprising the BISs;
- Elaborating barriers and BIS graphs;
- Quantifying well system reliability.

Each of these steps is detailed using a typical Santos Basin oil well as a case example. This case example is based on a subsea production well illustrated in Fig. 3a. The well completion design considers the production of two zones with selectivity controlled remotely by intelligent control valves (ICVs), chemical injection mandrels (CIMs), SCSSV, and gas lift mandrel (GLM) foreseeing an artificial lift.

After mapping all well equipment, the next step is to identify the well safety barriers for each major path and to integrate those barriers as barrier envelopes of the well (a.k.a., BIS). Having both Primary and Secondary BIS and a list of the well equipment that compose each BIS, the subsequent step is to survey both failure modes and failure rates for that equipment.

Usually, the data collected for reliability analysis purposes are confidential and are not in the public domain. We had access to sample data that are representative of reality. However, to be released, the data was grouped into blocks. Table 1 shows the identified barriers, failure modes, and failure rates of well equipment that compose the Primary BIS. The fourth column is an example of how to organize the failure modes. Also note that failure modes for the rock path barriers were not considered. Because of the lack of reliability data, it was assumed that there is no risk of formations fracture during the production phase.

Before quantifying the BIS reliability, we to need the define relationships between the barrier components and between BIS components. The reliability of BIS is determined by the logical model of barriers that composes it, as well as, the reliability of the well system is given by a logical model between BISs. This logical model is described using graphs. As an example, Fig. 5 shows the barrier graph model for the Primary BIS.

Once the data regarding the reliability of all equipment that composes every BIS were collected and the relationships between the barriers and BISs on graphs were mapped, the next step is to quantify the reliability of the well design. The reliability of each component is found considering the constant failure rate (CFR) model for each component. Then, from each equipment failure rate (λ) and the mission time (t), the reliability function $R(t)$ is expressed as:

$$R(t) = e^{-\lambda t} \tag{1}$$

By using the STA, the reliabilities of each BIS are found. The reliability for the Primary BIS, with the mission time of 27 years, is given by:

$$R_{(\text{Primary BIS})} = \prod_{i=1}^{n} R_i(t) = 0.03704 \approx 3.7\ \% \tag{2}$$

The reliability of the Primary BIS is low, which was expected because the failure rate of the equipment in the tubing (TBG) is high. The gas lift valve (GLV) has a failure rate of 11.9×10^{-6} failure per operating well·hour, with a mean time to failure (MTTF) of 9.6 well·year. As the mission time is almost three times greater than the MTTF of this equipment, its probability of failure during this mission is pretty high and its reliability is therefore low.In a similar way, the reliability for the Secondary BIS is given by:

$$R_{(\text{Secondary BIS})} = \prod_{i=1}^{n} R_i(t) = 0.65129 \approx 65.1\ \% \tag{3}$$

Considering that the well system will be safe if any of the defined BISs are active, the reliability of the well system can be evaluated by (OR gate):

$$\begin{aligned} R_{\text{system}} &= 1 - [1 - R_{(\text{Primary BIS})}] \cdot [1 - R_{(\text{Secondary BIS})}] \\ &= 0.6642 \approx 66.4\ \% \end{aligned} \tag{4}$$

To calculate the equivalent failure rate (failure per operating well·hour) for the well system, we use:

$$\lambda_{\text{system}} = \frac{-\ln[R_{\text{system}}]}{t} \approx 1.729 \times 10^{-6} \tag{5}$$

Table 1 Safety barriers and reliability data with the mission time of 27 years

Primary BIS						
Path	**Barrier**	**Component**	**Failure Mode**	**Failure Rate (per 10^6 well·hour)**	**MTTF (well·year)**	**Reliability R(t)**
Rock	Cap Rock	--	E_{22}: INL	0	--	1.00000
External Annulus	Liner Cementing	--	E_{21}: INL	0.05800	1966.8	0.98637
Interconnection	Production Liner	Block	E_{20}: EXL			
		Connection	E_{19}: EXL			
Well	Production Packer (PKR)	Block	E_{18}: INL	0.12100	942.8	0.97177
		Connection	E_{17}: INL			
Interconnection	Tubing between PKR and SCSSV	Block	E_{16}: EXL	0.25000	456.3	0.94255
		Connection	E_{15}: EXL			
	Intelligent Control Valve (ICV)	Valve	E_{14}: INL			
			E_{13}: FTC			
		Block	E_{12}: EXL			
		Connection	E_{11}: EXL			
	Gas Lift Valve (GLV)	Valve	E_{10}: INL	11.90000	9.6	0.05981
			E_9: FTC			
		Block	E_8: EXL			
		Connection	E_7: EXL			
	Gas Lift Mandrel (GLM)	Block	E_6: EXL			
		Connection	E_5: EXL			
String	Surface Controlled Subsurface Safety Valve (SCSSV)	Valve	E_4: INL	0.72000	158.4	0.84332
			E_3: FTC	0.56000	203.7	0.87587
		Block	E_2: EXL	0.31608	360.9	0.92792
		Connection	E_1: EXL			

INL internal leakage, *EXL* external leakage, *FTC* fail to close

Table 2 Results obtained through the proposed methodology for 27 years mission

Parameter	Primary BIS	Secondary BIS	Well system
Reliability, $R(t)$	3.7 %	65.1 %	66.4 %
Equivalent failure rate (per 10^6 well·hour)	13.925	1.812	1.729
MTTF (well·year)	8.2	63.0	66.0
Failure probability	96.3 %	34.9 %	33.6 %

Table 3 Results obtained through the proposed methodology, considering alternatives barriers (backups) and 27 years mission

Parameter	Primary BIS	Secondary BIS	Well system
Reliability, $R(t)$	3.7 %	88.1 %	88.6 %
Equivalent failure rate (per 10^6 well·hour)	13.925	0.533	0.512
MTTF (well·year)	8.2	214	222.8
Failure probability	96.3 %	11.9 %	11.4 %

It is also possible to determine the equivalent failure rate, mean time to failure, and the failure probability for each of the BISs. These results are summarized in Table 2.

Through the proposed approach it is possible to include alternative barriers (backups) in the probability of failure of the BIS and the well system assessment. For comparison purposes, the alternative barriers to the Secondary BIS were considered, and the calculated parameters are described in Table 3.

We observed a significant difference in the risks associated with the completion design when the alternative barriers are considered in the integrity analysis. The Secondary BIS has a reliability of more than 88 %, about 35 % above the value obtained when disregarding alternative barriers (approximately 65 %). The reliability of the well system was increased by one-third, from 66 % to approximately 88 %. It is important to emphasize that the parameters described in Table 3 are related to the risk of loss of integrity of the well system, representing the risk of leakage to

Table 4 Completion of subsea wells in the production development campaign

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Production wells	2	6	−1	7	5	1	7	14	9	19	12	5	1	1	0	1	1
Injection wells	0	0	0	3	9	−1	0	7	9	7	7	1	1	0	0	2	0
Total production wells	2	8	7	14	19	20	27	41	50	69	81	86	87	88	88	89	90
Total injection wells	0	0	0	3	12	11	11	18	27	34	41	42	43	43	43	45	45
Well·year	2	6	−1	10	14	0	7	21	18	26	19	6	2	1	0	3	1
Total	2	8	7	17	31	31	38	59	77	103	122	128	130	131	131	134	135

the environment during the production phase without any workover intervention for barriers replacement during its lifetime.

4 Comparison of proposed approach with real subsea field data

We compared the results obtained from this approach with data from a real subsea field development, containing information about its first 17 years, when 135 wells were built, completed and operated. The distribution of the inputs of the wells along the field development campaign is shown in Table 4.

From the temporal data displayed in Table 4, it is possible to reach the number of well·year number of this campaign by multiplying the number of wells per year by its production time. In this campaign we considered 1284 well·years.

To evaluate the results obtained, all maintenance workovers motivated by safety barrier's failures were identified, such as, failure in the action mechanisms of the WCT valves, leaks in tubing strings, SCSSV failures, among others. 36 cases were identified. Considering 1284 well·years, for which the 36 recorded failures were distributed, we have, approximately, a failure rate of 3.198×10^{-6} failure per operating well·hour, with a mean time to failure (MTTF) of 35.7 well·years.

Only cases motivated by equipment failures from both the Primary BIS and the Secondary BIS that caused loss of integrity of one of these BISs were accounted for. Other failures such as the ones that cause loss of production but no loss of BIS integrity, were not accounted for. GLV leaks do not appear among the reasons for workovers despite GLV low reliability. This is because, in practice, a workover is rarely programmed to correct this kind of failure, since the continuous gas injection ensures that there is no leakage from the string to the annulus. The total of the maintenance workovers during campaign was of 144. Considering the 1284 well·year, we have a mean time between workovers of 8.9 well·years, lower than the expected MTTF for GLV. In practice, in all these maintenance workovers, performed every 9 years on average, the GLV is always replaced and its erosion is usually observed. So, to compare the results of the proposed approach with the data from this field development campaign, we disregarded the GLVs (low reliability) from the system reliability calculations.

By applying the proposed approach for the case well, disregarding GLV failure data from the analysis, the reliability of the Primary BIS, for a 17 years mission, is given by:

$$R_{(\text{Primary BIS})} = 0.71905 \approx 71.9\ \% \tag{6}$$

And, the reliability of the Secondary BIS for the case well is:

$$R_{(\text{Secondary BIS})} = 0.74699 \approx 74.7\ \% \tag{7}$$

To evaluate all workovers motivated by safety barriers failures, it is necessary to consider both the Primary and the Secondary BIS together (AND gate), resulting in:

$$R_{\text{system}} = R_{(\text{Primary BIS})} \cdot R_{(\text{Secondary BIS})} = 0.53712 \approx 53.7\ \% \tag{8}$$

The equivalent failure rate (failure per operating well·hour) is given by:

$$\lambda_{\text{system}} = \frac{-\ln[R_{\text{system}}]}{t} \approx 4.1707 \times 10^{-6} \tag{9}$$

The expected MTTF for the well is given by:

$$\text{MTTF} = 1/\lambda = 27.4 \text{ well} \cdot \text{years} \tag{10}$$

The result is similar to that observed in the case example and its response is more conservative regarding the mean time to failure (MTTF).

From MTTF it is possible to estimate the expected number of workovers for the case example. In other words, from the expectation of the wells entry along the campaign stipulated in the design, it is possible to find the total of well·year. Dividing this amount by the calculated MTTF, an estimated number of workovers motivated by safety barriers failures is obtained. In the case example, we obtained about 46 interventions.

For the distribution from the proposed approach, we assume that every time the accumulation of well·years reaches the MTTF, a workover motivated by safety barriers failures should be performed. The cumulative distribution is

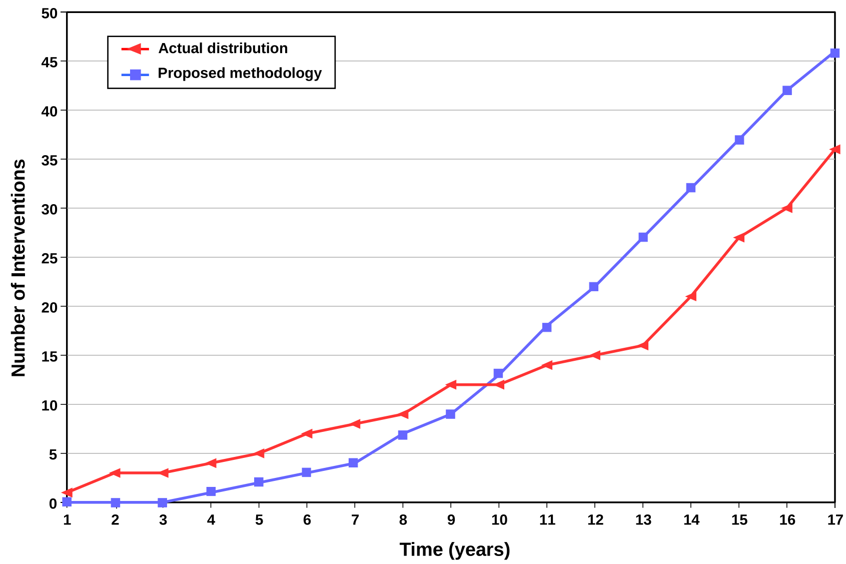


Fig. 6 Actual distribution and calculated by the methodology of the interventions motivated by safety barriers failures

shown in Fig. 6. In this case, although maintenance workover has been initiated in the first year of the project, the approach can represent the trend line of the actual data. The total amount of interventions estimated by the approach, 46, was about 28 % greater than the actual amount, 36 interventions.

5 Conclusions

The proposed approach focuses on the integrity analysis of development wells during their production phase. By considering the barriers that compose the BIS, the approach has a well-defined scope and presents conservative results. The calculation of BIS reliability data allows an estimate of the occurrences of the degraded state, when one of BIS is lost but leakage to the environment is not expected. The approach is more conservative than other methodologies, because it considers only the minimum barriers that compose the Primary and Secondary BIS. The approach disregards alternative or backup barriers. However, one can include these alternative barriers for further assessment of the well integrity.

The generated results can be analyzed for both the entire well system and each of the existing BISs. The MTTF of each BIS provides an estimate of the occurrence of the degraded state, when a set of well barriers has been lost. With this information, it is possible to foresee necessary resources, such as rigs and completion equipment for a maintenance workover campaign. This assessment can be done in the early stages of a field development campaign, contributing to a more accurate assessment of the economic viability of the project. The comparison of the proposed approach and the actual field development campaign demonstrates its potential in predicting the need for maintenance workovers.

Methodologies based on reliability allow us to detect critical points in the system. The identification of these “weak” components in the well design, enables optimized investments to reduce the risk of the well integrity loss during its productive life. In the case example, alternatives to increase the reliability of the well can range from the development of a new GLV with higher reliabilities to an economic analysis considering the installation of blinded valves, instead of a GLV, even the need for gas lift becomes essential for the economic viability, presupposing then a workover to exchange blinded valves for a GLV. Finally, the approach allows comparative reliability analysis for different well designs, providing an important parameter to select equipment and configurations.

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