A PROTOTYPE TOOL TO EVALUATE OIL WELL SAFETY DURING CONSTRUCTION DESIGN USING GRAPHS TECHNIQUE AND RELIABILITY ANALYSIS

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ABSTRACT

During construction operations, two barrier envelopes – consisting of several well barrier elements – are the main wells mechanisms to prevent accidents of usually catastrophic proportions. The primary barrier envelope is concerned with preventing the occurrence of a kick, while the secondary barrier envelope aims to avoid a scenario in which the kick evolves to a blowout. Therefore, evaluating the quality of these barrier elements and the relationship among them – and, consequently, of the envelopes formed – is fundamental to guarantee well safety during well construction. Before the well is built, an important prior step is well design; here, everything in terms of equipment and sequence of operations will be selected to achieve the desired goal and deliver the well to production. In this work, we present a methodology to evaluate the safety of a selected well design, considering the particularities of the well and the drilling rig. We focus only on drilling operations. The barrier envelopes are mapped using the graphs technique, while the barrier elements' quality is measured through their reliabilities obtained from expert judgment. The reliability of each barrier envelope is calculated considering the individual barrier element reliabilities and how they compose to form the envelopes. Then, an operational sequence is selected, and a score is given to each operation by considering which envelopes are present and if any barrier elements have been deactivated. This score is dubbed "barrier envelope integrity index". This methodology is implemented using commercial software, creating a prototype tool. An example using the prototype is then showcased.

Keywords: barrier elements, well design, well safety, well integrity, drilling safety, well construction safety, graphs technique, barrier envelope integrity index.

1. INTRODUCTION

Well safety has been a constant concern in the oil industry. Accidents in which well safety protocols have not been followed thoroughly often have disastrous consequences causing human life and equipment losses, environmental damage, economical losses, and deterioration of the public image of companies and of the industry itself. Accidents, such as Piper Alpha and Deepwater Horizon platforms, also shape the industry, changing what is acceptable in terms of preventing the causes and managing the consequences. Considering the great impact that accidents have on society, evaluations of well safety are a necessity to avoid these scenarios.

In this context of well safety, the concepts of barrier elements and barrier envelopes gained traction to ensure that wells could be built and produced safely. The major challenge is identifying all barrier elements present inside the well and their relationships culminating into the barrier envelopes. For example, elements may be redundant (i.e., at least one of the associated elements must be functioning) or mandatory (i.e., all elements must be functioning). Besides, operations during well construction are constantly either removing and/or deactivating existing barrier elements or adding and/or activating new ones. Intricate knowledge of how wells are built and how operations are performed is necessary to map these relationships properly.

Considering this ordeal, different views have been presented in the literature regarding what is considered a barrier element or a barrier envelope (API, 2013; NORSOK, 2013; Miura et al., 2006). Here, we will follow the Brazilian view, which is an extension of the Norwegian view to include elements in the interconnections between flow paths. More details are provided in section 2.

This work presents a methodology to evaluate well safety through the usage of graphs. Graphs are visual tools that illustrate the relationship between barrier elements and how they combine to form the primary and secondary barrier envelopes. Jaculli et al. (2019) is an early work that uses the same concept presented here, but since then the graphs have been reviewed, updated, and expanded. Fourteen graphs are presented, covering all drilling phases (from rig positioning to drill-in) and both barrier envelopes in a conventional hypothetical well in the Santos Basin pre-salt in Brazil: 4-phase vertical well with production casing. The graphs technique can also be used for quantitative evaluations; if reliability values are provided for all barrier elements, the barrier envelope's reliability is calculated through a combination of the barrier elements and Boolean logic gates ("AND" and "OR" gates, according to their interdependency). A sample calculation of the barrier envelope integrity index is provided.

2. THEORETICAL BACKGROUND

To develop fully the graphs technique for this problem, we present in this section the relevant theory. This is divided into two parts to explain and define the relevant concepts: one related to well safety (barrier elements, barrier envelopes, and flow paths) and one related to the graphs technique itself (elements, logic gates, and calculations).

2.1 Well Safety Concepts

First, we need some definitions (Miura et al., 2006). "Well safety" is defined as the quality and condition displayed by a well during intervention operations (construction and workover) to endure a potential top event (blowout), resulting in a probability of failure within acceptable levels, thus minimizing the consequences associated with human, economic and environmental losses. To verify this quality and condition, we need to ascertain the existing barrier elements, barrier envelopes, paths, and interconnections.

A "barrier element" is a physical or operational separation capable of preventing the unintended flow of fluids from a permeable interval (formation) along all existing paths and/or possible shortcuts; under certain criteria, the combination of barrier elements forms a barrier envelope. Meanwhile, a "barrier envelope" is a set of several barrier elements preventing fluids from flowing unintentionally from the formation into the wellbore, into another formation, or to the external environment (blowout), considering all possible flow paths. By definition, the primary envelope is the one closest to the formation, while the secondary envelope is the one right above it. Different barrier envelopes should not share barrier elements. Figure 1 illustrates the primary and secondary barrier envelopes (dubbed only as "well barriers") during a drilling operation, according to the NORSOK D-010 (2013).

Complementing these concepts, "paths" are possible passages in which hydrocarbons can flow through towards the environment, outside the well; four flow paths exist in a well – rock, annulus, well, and column – though, depending on the phase or operation, some of them may not exist or exist simultaneously. Then, the "interconnections" are shortcuts that can exist between paths, especially if there is a leakage from one path to another; they can occur between rock and annulus, rock and well, annulus and well, and well and column. Figure 2 illustrates the existing paths; the shortcuts can occur along with any point of contact between two paths.

Therefore, to ensure safety, we must guarantee that we have barrier elements placed in all possible paths and interconnections, forming at least two independent barrier envelopes. This is the basis for constructing the graphs in sections 3 and 4.

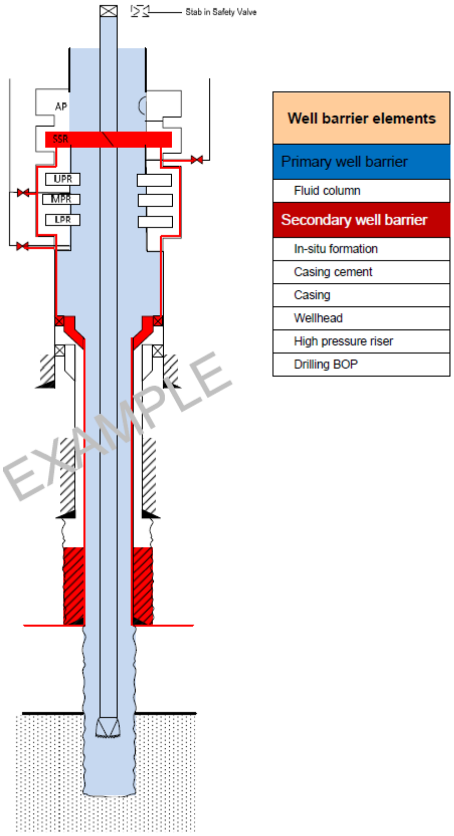

Figure 1: Example of primary and secondary barrier envelopes for a drilling operation (adapted from NORSOK D-010, 2013).

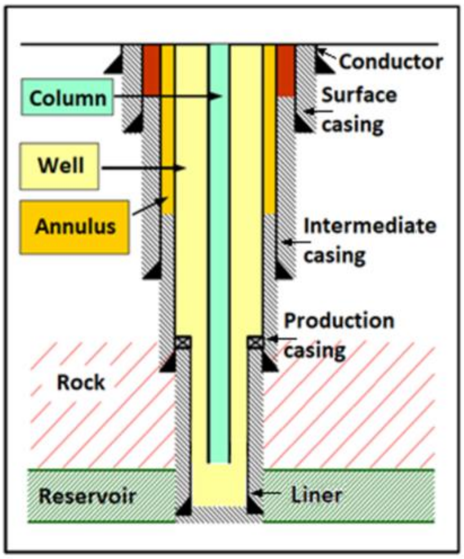

Figure 2: Four identified possible flow paths: “rock”, “annulus” (the annulus between rock and casing), “well” (the annulus between casing and tubing), and “column” (inside the string).

2.2 Graphs Technique Concepts

The graphs technique is a visual tool very similar to the fault tree analysis, consisting of elements that are linked through gates. However, instead of focusing on events, the focus is rather on components and their reliability and/or availability (Jaculli et al, 2019).

To build a graph, we firstly define some codification. Figure 3 illustrates the symbols used. Labels are used to identify if the graph is related to the primary (blue) or secondary (red) barrier envelope. Then, labels are also used to identify the flow paths (green) and interconnections (light orange). Four possible paths are available: rock, annulus, well, and column. Also, four interconnections are available: I1 (rock x annulus), I2 (rock x well), I3 (annulus x well), and I4 (well x column). There are two logic gates: the AND gate, represented by a bullet sign (·), and the OR gate, represented by a plus sign (+). Finally, icons represent barrier elements (yellow) and their components (dark orange).

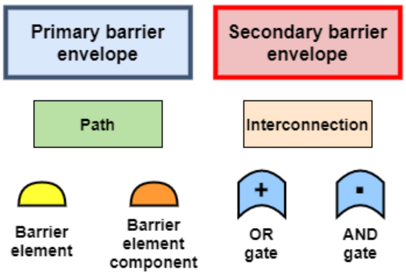

Figure 3: Codification used to build the graphs.

When reliability values are inserted into the barrier elements and their components, the logic gates can perform system reliability operations, depending on whether they are series or parallel systems. The AND gate represents a series system, in which all components must be functioning; otherwise, the system fails; the resulting reliability of a series system with N components is given by:

$$R_{AND} = \prod_{i=1}^{N} R_i \tag{1}$$

Meanwhile, the OR gate represents a parallel system, in which at least one component must be functioning, with additional components providing redundancy; the resulting reliability of a parallel system with N components is given by:

$$R_{OR} = 1 - \prod_{i=1}^{N} (1 - R_i) \tag{2}$$

Now, the next steps are to identify all the existing barrier elements and their components and build their relationships using logic gates. This is explained in the next section.

3. METHODOLOGY

Since wells can be built for several different purposes and trajectories, it was necessary to define a set of premises before constructing the graphs. The graphs that will be presented here apply to wells that fall under these premises; this methodology can be extended to include other types of wells.

The graphs are based on how most pre-salt wells are built in the Santos basin, Brazil, meaning that they are 4-phase vertical wells (conductor, surface, production, and drill-in), located in offshore fields with ultra-deepwater depths (2000+ m) and below the ocean salt deposits. This also implies the use of a floating rig (with a dynamic positioning system – DP) and a subsea wellhead. The conductor casing is cemented, but this cementing does not serve as a barrier element (it is performed strictly for structural reasons). A riser safety margin is present and used. An operational window for the fluid density (range between minimum and maximum permitted mud weight) is always available and wide enough. The fracture gradient increases with depth. The reservoir is characterized by a single fluid-bearing formation. Considering this scenario, the next step is to identify all the available barrier elements, considering each drilling phase. Table 1 summarizes all the barrier elements that were identified. These barrier elements can be combined to generate barrier envelopes.

Table 1: Available barrier elements.

Fluids	Seawater
	Drilling fluid
	Replenish lost drilling fluid
	Riser safety margin
Rock formations	Shallow natural barrier element
	Deep natural barrier element
	Formation above the impermeable rock
	Impermeable rock
	Rock at the surface casing shoe
	Formation above the cap rock
	Cap rock
Cementing operations	Surface casing cementing
	Production casing cementing
	Liner cementing and seal
	Cement plug
Strings	Riser
	Work string
	Surface casing
	Production casing
	Liner
Operational barriers	Operational barrier against shallow hazards
	Operational barrier: mud logging
	Operational barrier: trip tank
	Operational barrier: ability to control the well
Others	Wellhead
	BOP
	Inside BOP
	BHA float valve
	Stabbing safety valve
	Diverter
	Top drive

To illustrate reliability calculations using the graphs, values of reliability have been assigned to each barrier element. These are shown in Table 2. They only serve as a case study example; values are attributed using expert judgment. Further refinements are necessary by evaluating each barrier element reliability separately – the evaluation may vary due to drilling location and other variables.

Table 2: Barrier elements' reliabilities – case study.

Barrier element	**Reliability**
Seawater	0.95
Drilling fluid	0.95
Replenish lost drilling fluid	1.00
Riser safety margin	0.95
Shallow natural barrier element	1.00
Deep natural barrier element	1.00
Formation above the impermeable rock	1.00
Impermeable rock	1.00
Rock at the surface casing shoe	1.00
Formation above the cap rock	1.00
Cap rock	1.00
Surface casing cementing	0.95
Production casing cementing	0.95
Liner cementing and seal	0.90
Cement plug	0.95
Riser	1.00
Work string	1.00
Surface casing	1.00
Production casing	1.00
Liner	1.00
Operational barrier against shallow hazards	0.95
Operational barrier: mud logging	1.00
Operational barrier: trip tank	1.00
Operational barrier: ability to control the well	1.00
Wellhead	0.95
BOP	0.95
Inside BOP	0.95
BHA float valve	1.00
Stabbing safety valve	1.00
Diverter	1.00
Top drive	1.00

Now, according to the well safety concepts that were developed in the previous section, we may identify the existing barrier envelopes in each drilling phase. Each barrier envelope will result in a graph. Table 3 summarizes the existing barrier envelopes for each phase.

Table 3: Existing barrier envelopes for each drilling phase.

Phase 0 (rig movement)	Primary Envelope: Shallow Hazards
Phase 1 (conductor casing)	Primary Envelope: Shallow Hazards
	Primary Envelope: Hydrostatics
Phase 2 (surface casing)	Primary Envelope: Shallow Hazards
	Primary Envelope: Hydrostatics
	Primary Envelope: Cemented Casing
Phase 3 (production casing)	Primary Envelope: Hydrostatics
	Primary Envelope: Cemented Casing
	Secondary Envelope: Well Control Safety Equipment (with column)
	Secondary Envelope: Well Control Safety Equipment (without column)
Phase 4 (drill-in)	Primary Envelope: Hydrostatics
	Primary Envelope: Cemented Liner
	Secondary Envelope: Well Control Safety Equipment (with column)
	Secondary Envelope: Well Control Safety Equipment (without column)
Total	**14 barrier envelopes (14 graphs)**

From Table 3, we identify 14 barrier envelopes in the 5 phases (4 construction phases plus one rig movement and positioning phase):

- **Phase 0**: the floating rig is moving to the well site and preparing to start the well drilling. At this point, we have only the Primary Envelope: Shallow Hazards, which consists of knowledge acquired through seismic, ROV, pilot wells, and previous field knowledge (offset wells).
- **Phase 1**: we are drilling the conductor casing phase. We are still counting on our shallow hazards knowledge, but now we also have the seawater acting as a barrier element (even though we do not have full control over its density since we cannot circulate it similarly to the drilling fluid), configuring the Primary Envelope: Hydrostatics.
- **Phase 2**: we are drilling the surface casing phase. We are still counting on our shallow hazards knowledge and the seawater, but now we are also cementing the surface casing at the end of this phase, creating the Primary Envelope: Cemented Casing.
- **Phase 3**: we are drilling the production casing phase. We have just installed the BOP and riser, which changes our barrier envelopes. Now, we can use a drilling fluid instead of seawater, which changes the Primary Envelope: Hydrostatics. We are also cementing the casing at the end of this phase, thus keeping the Primary Envelope: Cemented Casing. We also added the Secondary Envelope: Well Control Safety Equipment due to the installation of a BOP. Two secondary envelopes are defined to account for two possible scenarios: Secondary Envelope: Well Control Safety Equipment (with column) – for when a work string is into the well – and Secondary Envelope: Well Control Safety Equipment (without column) – for when a work string is not into the well. These two secondary envelopes are not concomitant.
- **Phase 4**: we are performing the drill-in into the reservoir. The same envelopes from phase 3 apply, only updated with a few different barriers.

Finally, Table 4 presents a sample operational sequence for drilling a 4-phase well.

Table 4: Operational sequence to drill a 4-phase well.

ID	Phase	Operation name
#01	Phase 0	Navigating with rig
#02	Phase 0	Tuning dynamic positioning
#03	Phase 0	Making up and running bit
#04	Phase 1	Drilling and simultaneous hole opening
#05	Phase 1	Tripping for well conditioning
#06	Phase 1	Pull out BHA with bit
#07	Phase 1	Base and casing running
#08	Phase 1	Cementing
#09	Phase 1	Pilot well
#10	Phase 1	Making up and running bit
#11	Phase 1	Cement and rat hole drilling
#12	Phase 2	Drilling
#13	Phase 2	Tripping for well conditioning
#14	Phase 2	Pull out BHA with bit
#15	Phase 2	Housing and casing running
#16	Phase 2	Cementing
#17	Phase 2	Pressure testing
#18	Phase 2	Pull out work string
#19	Phase 2	Nippling up and installing BOP
#20	Phase 2	Setting wear bushing
#21	Phase 2	Making up and running bit
#22	Phase 2	Kick control drive
#23	Phase 2	Negative pressure test
#24	Phase 2	Changing well fluid
#25	Phase 2	Cement and rat hole drilling
#26	Phase 3	Drilling
#27	Phase 3	Leakoff test
#28	Phase 3	Pull out BHA with bit
#29	Phase 3	Making up and running bit
#30	Phase 3	Drilling
#31	Phase 3	Tripping for well conditioning
#32	Phase 3	Pull out BHA with bit
#33	Phase 3	Casing hanger and casing running
#34	Phase 3	Cementing
#35	Phase 3	Pressure testing
#36	Phase 3	Packoff installation
#37	Phase 3	Negative pressure test
#38	Phase 3	BOP testing
#39	Phase 3	Pull out work string
#40	Phase 3	Cement quality and correlation logging
#41	Phase 3	Making up and running bit
#42	Phase 3	Kick control drive
#43	Phase 3	Cement and rat hole drilling
#44	Phase 4	Drilling
#45	Phase 4	Leakoff test
#46	Phase 4	Pull out BHA with bit
#47	Phase 4	Making up and running bit
#48	Phase 4	Drilling
#49	Phase 4	Tripping for well conditioning
#50	Phase 4	Pull out BHA with bit

#51	Phase 4	Well logging
#52	Phase 4	Casing hanger and casing running (liner)
#53	Phase 4	Cementing
#54	Phase 4	Pressure testing
#55	Phase 4	Negative pressure test
#56	Phase 4	Pull out work string
#57	Phase 4	Cement quality and correlation logging

4. RESULTS AND DISCUSSION

In this section, the 14 graphs are properly presented, and then an example calculation is performed.

4.1 Phase 0 – Rig movement

This phase is composed of moving and positioning the rig in the location. To protect the rig, we only have at our disposal the Primary Envelope: Shallow Hazards.

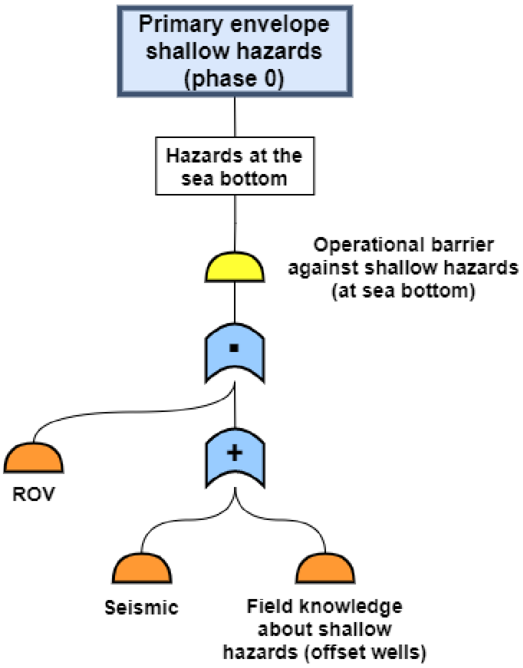

Figure 4: Primary Envelope: Shallow Hazards – phase 0.

4.2 Phase 1 – Conductor casing

For well and rig protection in Phase 1, we have two envelopes: Primary Envelope: Shallow Hazards and Primary Envelope: Hydrostatics.

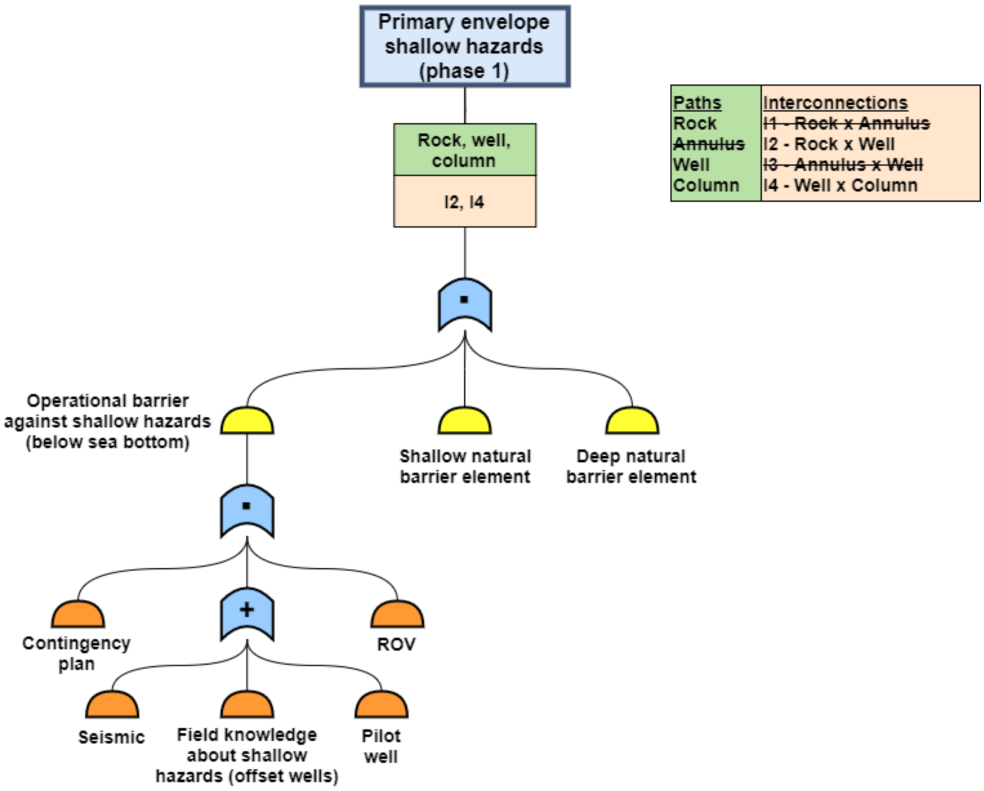

Figure 5: Primary Envelope: Shallow Hazards – phase 1.

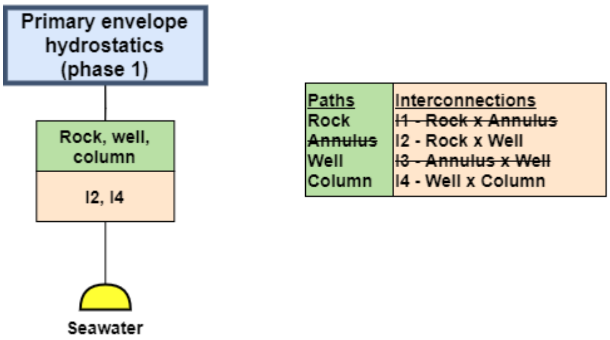

Figure 6: Primary Envelope: Hydrostatics – phase 1.

4.3 Phase 2 – Surface casing

To construct this phase, we highlight three envelopes: Primary Envelope: Shallow Hazards, Primary Envelope: Hydrostatics, and Primary Envelope: Cemented Casing.

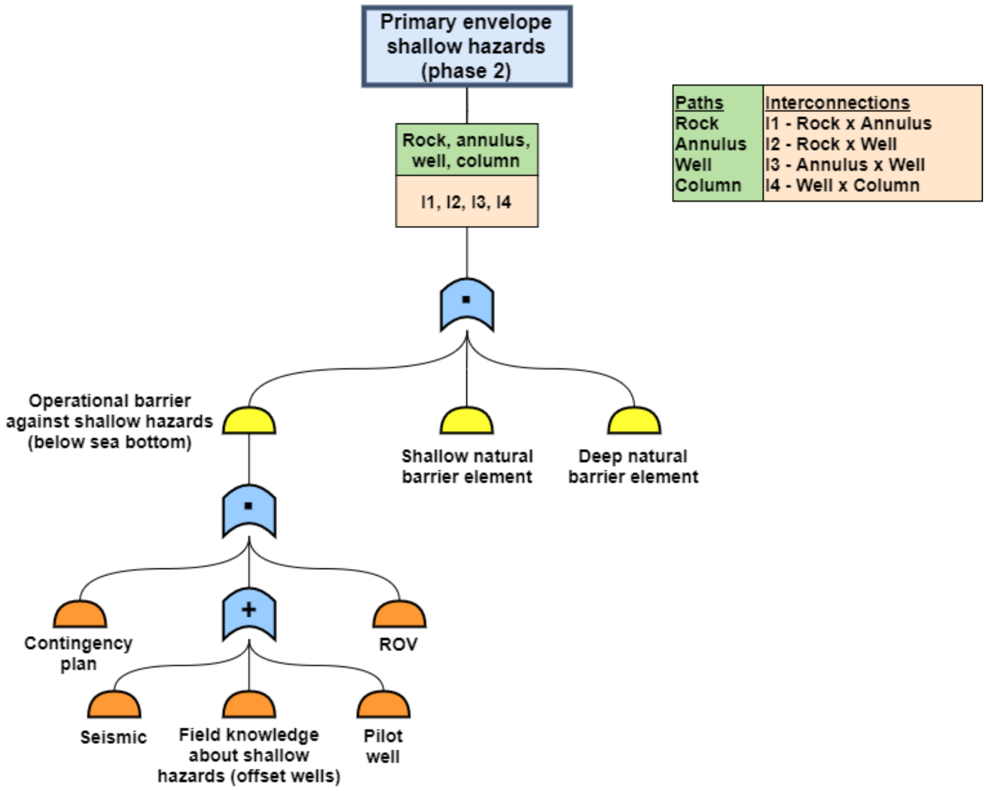

Figure 7: Primary Envelope: Shallow Hazards – phase 2.

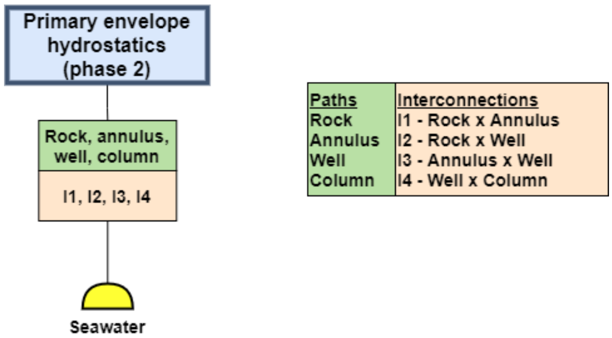

Figure 8: Primary Envelope: Hydrostatics – phase 2.

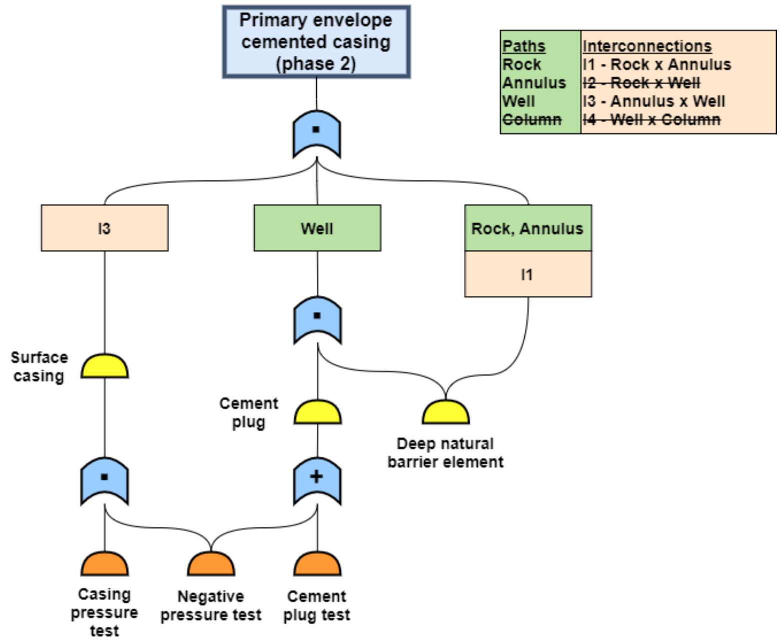

Figure 9: Primary Envelope: Cemented Casing – phase 2.

4.4 Phase 3 – Production casing

In this phase, we have four paths and four shortcuts to protect. We select four envelopes – two primary and two secondary; the two secondary envelopes are active at different operations during this phase. The primary envelopes considered are Hydrostatics and Cemented Casing, and the secondary envelopes are Secondary Envelope: Well Control Safety Equipment (WCSE), with a column in the well, and WCSE but without a column in the well.

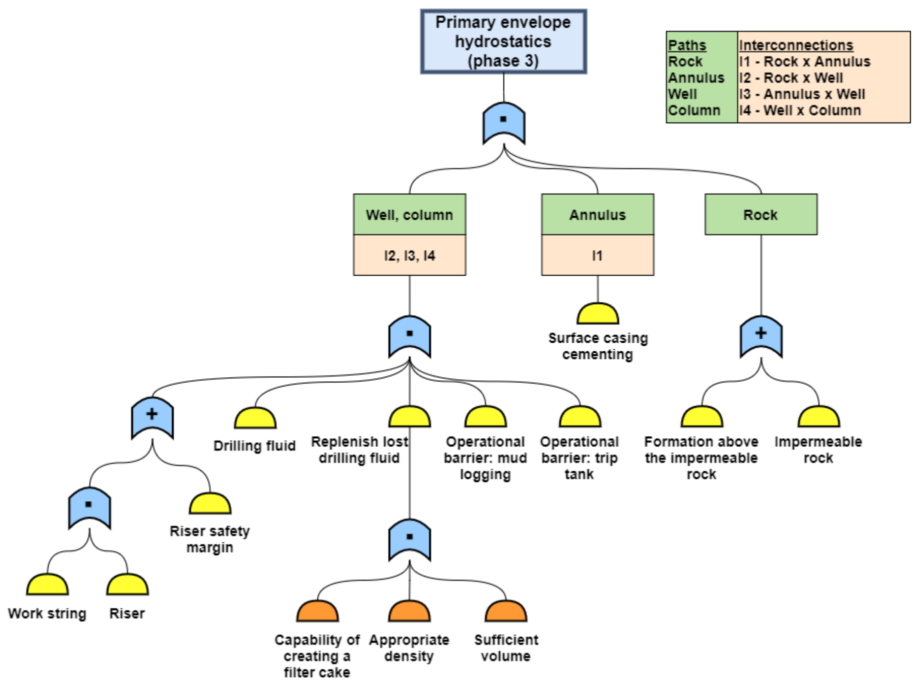

Figure 10: Primary Envelope: Hydrostatics – phase 3.

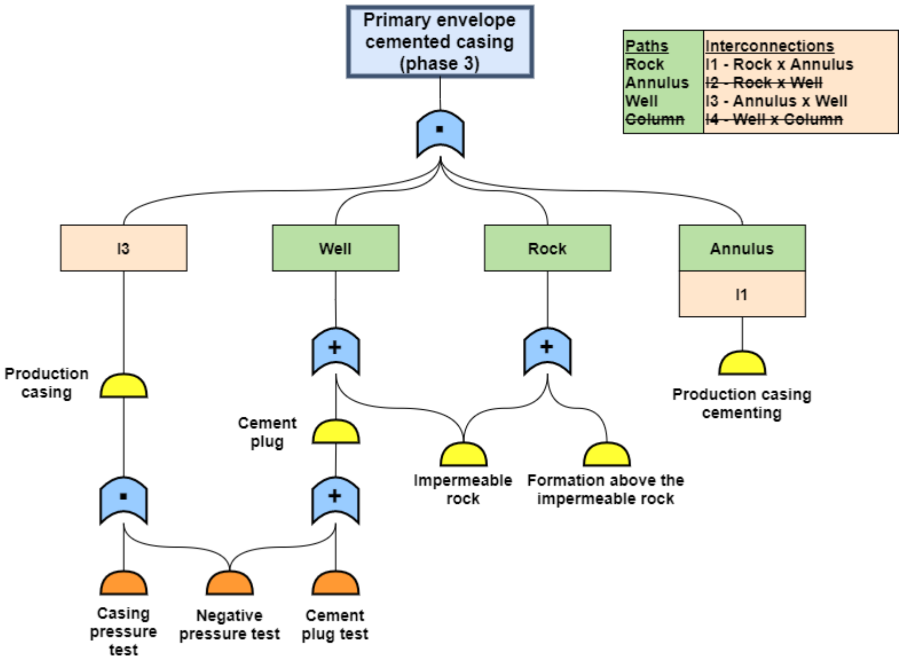

Figure 11: Primary Envelope: Cemented Casing – phase 3.

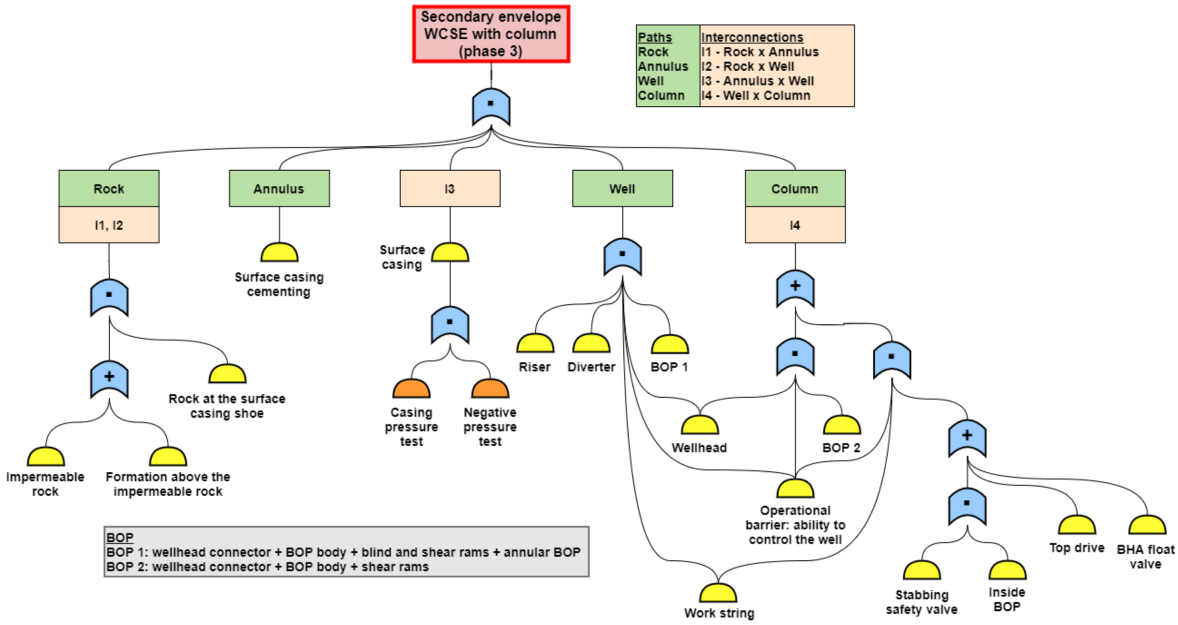

Figure 12: Secondary Envelope: Well Control Safety Equipment (with column) – phase 3.

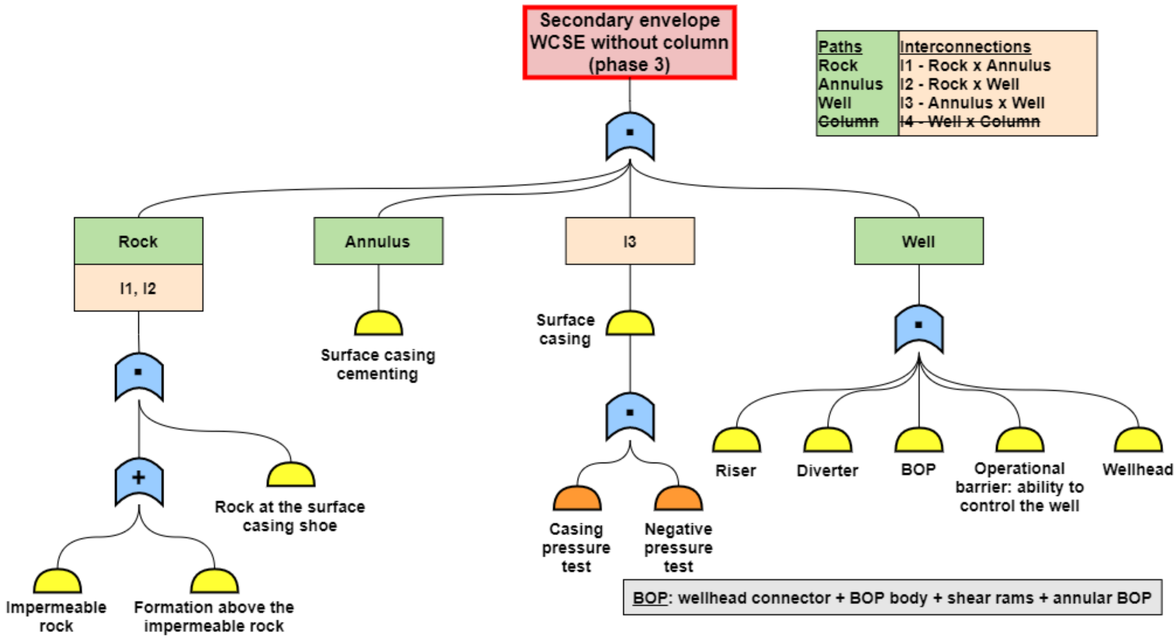

Figure 13: Secondary Envelope: Well Control Safety Equipment (without column) – phase 3.

4.5 Phase 4 – Drill-in

In this phase, as in the previous one, we have four paths and four shortcuts to be protected. Likewise, we selected four envelopes – two primary and two secondary, active at different times during this phase. The primary envelopes considered are also Hydrostatics and Cemented Casing, and the secondary envelopes are also WCSE with column and WCSE without column.

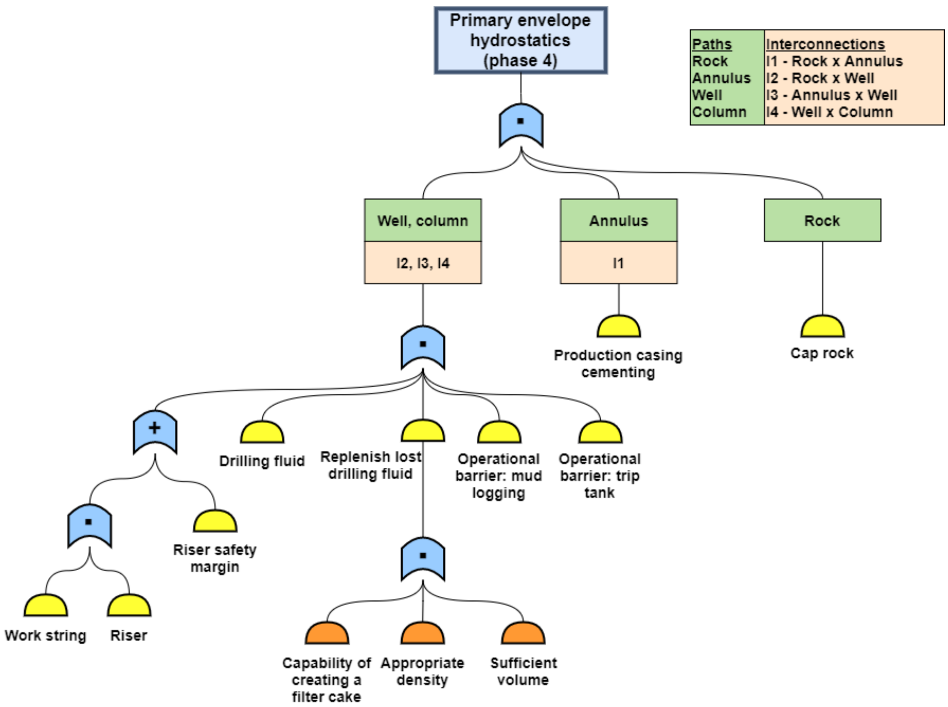

Figure 14: Primary Envelope: Hydrostatics – phase 4.

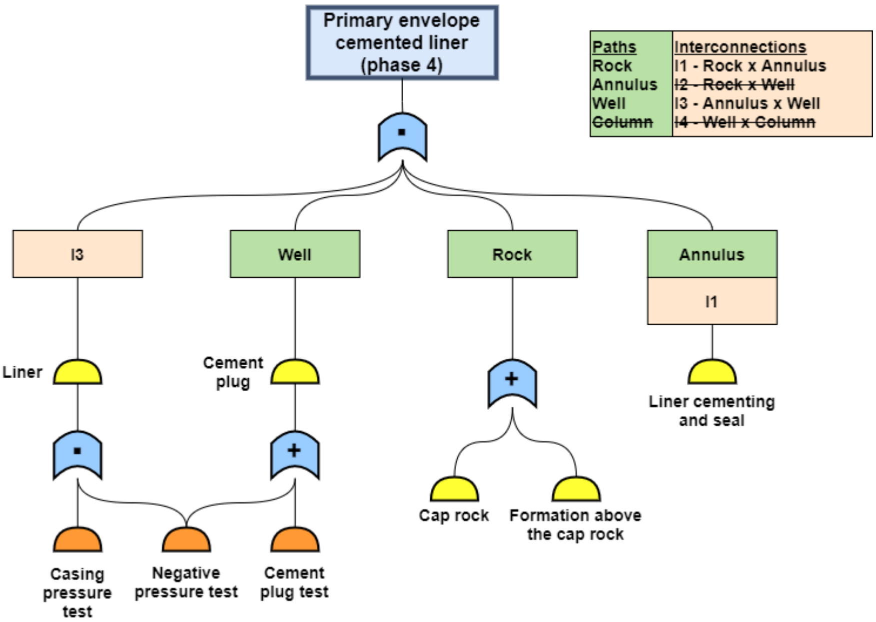

Figure 15: Primary Envelope: Cemented Liner – phase 4.

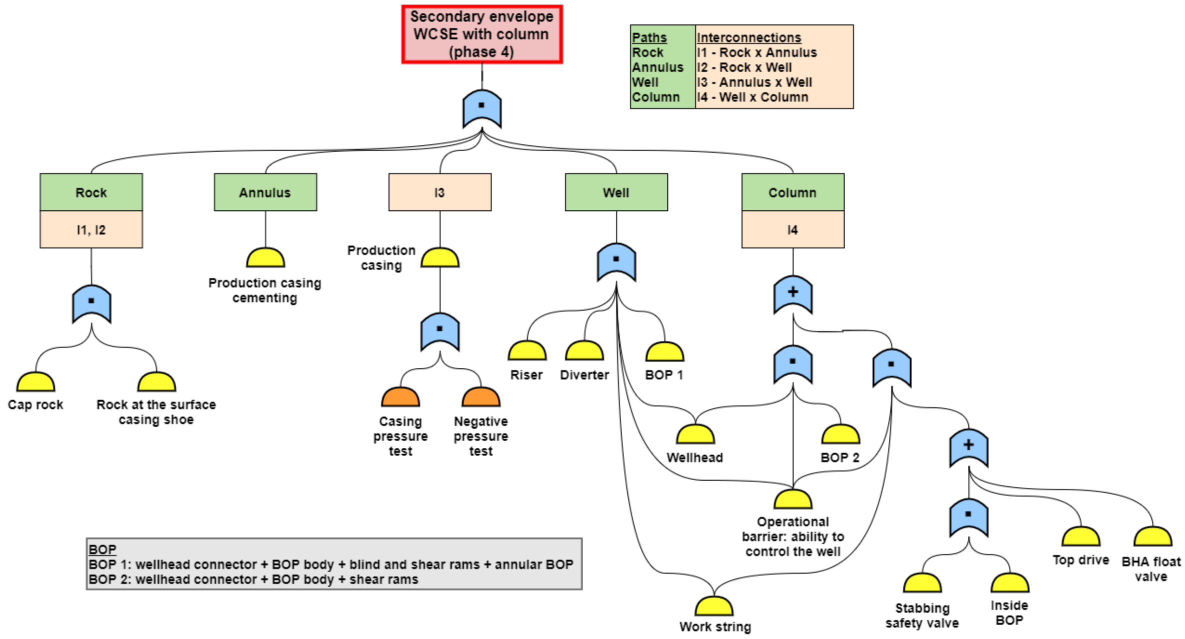

Figure 16: Secondary Envelope: Well Control Safety Equipment (with column) – phase 4.

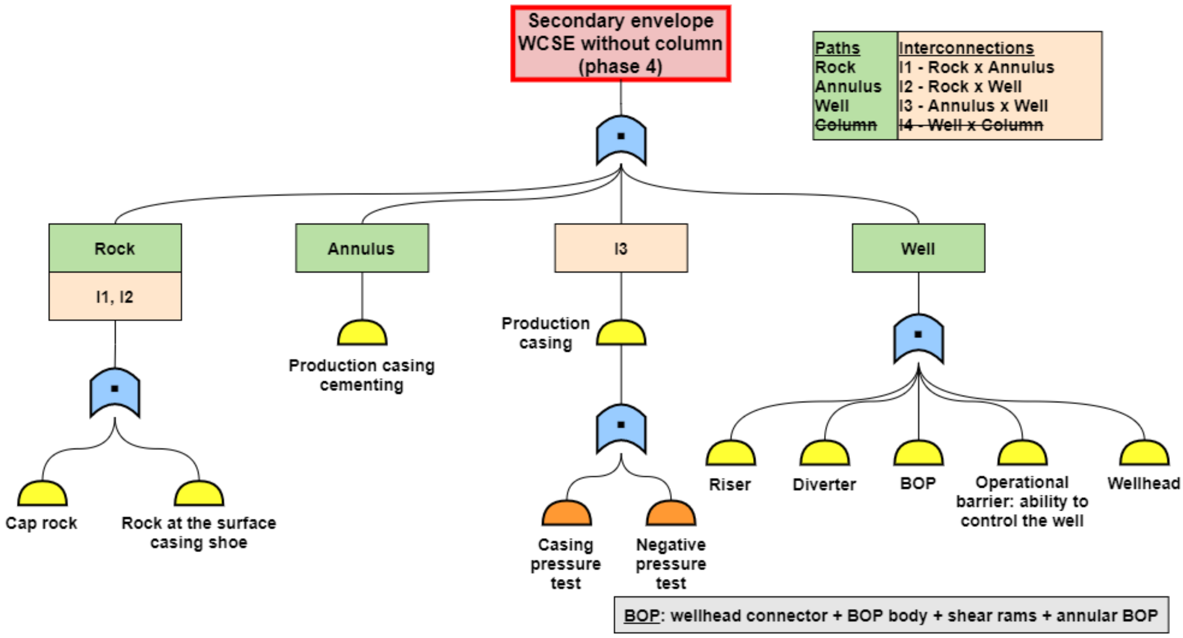

Figure 17: Secondary Envelope: Well Control Safety Equipment (without column) – phase 4.

4.6 Barrier envelope integrity index – example calculation

Using the graphs presented in Figures 4 to 17, the reliability values from Table 2, the system reliability equations, seen in equations 1 and 2, and the operational sequence from Table 4, we can calculate the barrier envelope integrity index for each operation. The results are presented in Table 5. The column "envelopes" presents the number of available envelopes in a given operation – as if they had 100% reliability – while the "integrity index" column is the calculation of the barrier envelope integrity index, which is the aggregated reliabilities of all barrier envelopes available in that particular operation.

Table 5: Barrier envelope integrity index for an operational sequence.

ID	Phase	Operation name	Envelopes	Integrity Index
#01	Phase 0	Navigating with rig	1	0.95
#02	Phase 0	Tuning dynamic positioning	1	0.95
#03	Phase 0	Making up and running bit	1	0.95
#04	Phase 1	Drilling and simultaneous hole opening	2	1.90
#05	Phase 1	Tripping for well conditioning	2	1.90
#06	Phase 1	Pull out BHA with bit	2	1.90
#07	Phase 1	Base and casing running	2	1.90
#08	Phase 1	Cementing	2	1.90
#09	Phase 1	Pilot well	2	1.90
#10	Phase 1	Making up and running bit	2	1.90
#11	Phase 1	Cement and rat hole drilling	2	1.90
#12	Phase 2	Drilling	2	1.90
#13	Phase 2	Tripping for well conditioning	2	1.90
#14	Phase 2	Pull out BHA with bit	2	1.90
#15	Phase 2	Housing and casing running	2	1.90

#16	Phase 2	Cementing	2	1.90
#17	Phase 2	Pressure testing	2	1.90
#18	Phase 2	Pull out work string	2	1.90
#19	Phase 2	Nippling up and installing BOP	3	2.76
#20	Phase 2	Setting wear bushing	3	2.76
#21	Phase 2	Making up and running bit	3	2.76
#22	Phase 2	Kick control drive	3	2.76
#23	Phase 2	Negative pressure test	4	3.71
#24	Phase 2	Changing well fluid	4	3.71
#25	Phase 2	Cement and rat hole drilling	3	2.76
#26	Phase 3	Drilling	3	2.71
#27	Phase 3	Leakoff test	2	1.76
#28	Phase 3	Pull out BHA with bit	1	0.86
#29	Phase 3	Making up and running bit	2	1.76
#30	Phase 3	Drilling	2	1.76
#31	Phase 3	Tripping for well conditioning	2	1.76
#32	Phase 3	Pull out BHA with bit	1	0.86
#33	Phase 3	Casing hanger and casing running	2	1.76
#34	Phase 3	Cementing	2	1.76
#35	Phase 3	Pressure testing	2	1.76
#36	Phase 3	Packoff installation	2	1.76
#37	Phase 3	Negative pressure test	3	2.71
#38	Phase 3	BOP testing	3	2.71
#39	Phase 3	Pull out work string	2	1.81
#40	Phase 3	Cement quality and correlation logging	3	2.71
#41	Phase 3	Making up and running bit	3	2.71
#42	Phase 3	Kick control drive	3	2.71
#43	Phase 3	Cement and rat hole drilling	2	1.76
#44	Phase 4	Drilling	2	1.76
#45	Phase 4	Leakoff test	2	1.76
#46	Phase 4	Pull out BHA with bit	1	0.86
#47	Phase 4	Making up and running bit	2	1.76
#48	Phase 4	Drilling	2	1.76
#49	Phase 4	Tripping for well conditioning	2	1.76
#50	Phase 4	Pull out BHA with bit	1	0.86
#51	Phase 4	Well logging	2	1.76
#52	Phase 4	Casing hanger and casing running (liner)	2	1.76
#53	Phase 4	Cementing	2	1.76
#54	Phase 4	Pressure testing	2	1.76
#55	Phase 4	Negative pressure test	3	2.61
#56	Phase 4	Pull out work string	2	1.71
#57	Phase 4	Cement quality and correlation logging	3	2.61

5. CONCLUSIONS

A methodology to evaluate the integrity of barrier envelopes has been presented, using reliability calculations and the graphs technique. Combining individual values of reliability for the barrier elements and their relationships identified in the graphs, a barrier envelope integrity index has been proposed, which evaluates the reliability of the envelopes for all operations in an operational sequence. This required mapping the existing barrier elements to compose barrier envelopes in each drilling phase and each particular operation.

The method presented seems to be an excellent tool to anticipate problems or deficiencies in barrier envelopes already during the design phase of well construction. This will allow the designer to make the changes deemed necessary to achieve the desired minimum reliability. It can also be used for operational monitoring during actual construction, being able to detect any barrier envelopes failures introduced, for example, by the total or partial failure of some barrier element, or the introduction of some operation not foreseen in the design phase.

The example calculation illustrates the usefulness of the technique, whose goal is to provide a more robust well integrity analysis. Further studies are necessary to replace the barrier elements' reliabilities with data from the literature instead of relying on expert judgment. This development is planned for the next publications.

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