| | |
|---|---|
| Please fill in the name of the event you are preparing this manuscript for. | 2022 International Petroleum Technology Conference |
| Please fill in your 5-digit IPTC manuscript number. | IPTC-22152-MS |
| Please fill in your manuscript title. | Safest Available Technology to Reduce the Blowout Probability in High-H2S and High-Pressure Drilling and Completions Applications While Using a Surface BOP |

Please fill in your author name(s) and company affiliation.

| Given Name | Surname | Company |
|---|---|---|
| Altynbek | Kabdolov | North Caspian Operating Company (NCOC) |
| Davide | Feltracco | North Caspian Operating Company (NCOC) |
| Ken | Dupal | Kinetic Pressure Control |
| Reese | Jones | Kinetic Pressure Control |
| Fabrizio | Zausa | Eni |
| Gabriele | Gandini | Eni |
| Alessandro | Caia | Kwantis |

# ABSTRACT

With the goal to exhibit leadership in industry process safety, North Caspian Operating Company (NCOC), Eni, and Kinetic Pressure Control have collaborated to evaluate the feasibility and potential process safety benefits from use of the Kinetic Blowout Stopper (K-BOS®) technology in High-$H_2S$ and high-pressure drilling and completions and intervention applications from artificial islands in Kashagan field. The study focused on efforts to detect any showstoppers for the application of K-BOS, quantify the reduction in the blowout probability due to its application, and summarize the information currently available about the technology.

Using the Eni proprietary e-wise™ fault tree analysis approach, a quantitative risk assessment was performed to compare the probability of a blowout in Kashagan field using conventional BOP systems to the probability of a blowout with the K-BOS added to the stack. The study also reviewed OEM provided operating procedures, a risk assessment for running the equipment, as well as a feasibility study regarding any height restrictions in the BOP stack and the position of the K-BOS in the stack. The impact of alternative equipment for risk reduction such as additional redundancy was also assessed.

The application of the 13 5/8” 10M K-BOS system during reservoir drilling, completion and intervention operations significantly reduces the probability of a blowout by at least an order of magnitude. For drilling operations in the most challenging Rim portion of the reservoir, the blowout probability decreases by more than 90% and the residual value is below the blowout frequency for Producing Wells.

The improved shearing/sealing capacity and reduced closure time provided by the K-BOS enable a reduced likelihood of a blowout and enhance the risk profile for the oil and gas industry.

# Introduction

## Kashagan Field Background and Well Emergency Response Challenges

The Kashagan field (Figure 1) is the largest oilfield discovered in the North Caspian Sea Production Sharing Agreement (NCSPSA) contract area and developed by North Caspian Operating Company N.V. (NCOC). Kashagan field is located in the Kazakhstan sector of the Caspian Sea and extends over a surface area of approximately 75km by 45km. The reservoir lies 80km offshore from Atyrau at >4000m TVD below the shallow waters of the northern part of the Caspian Sea. Production and sour gas injection wells are drilled with land rigs from artificial islands offshore.

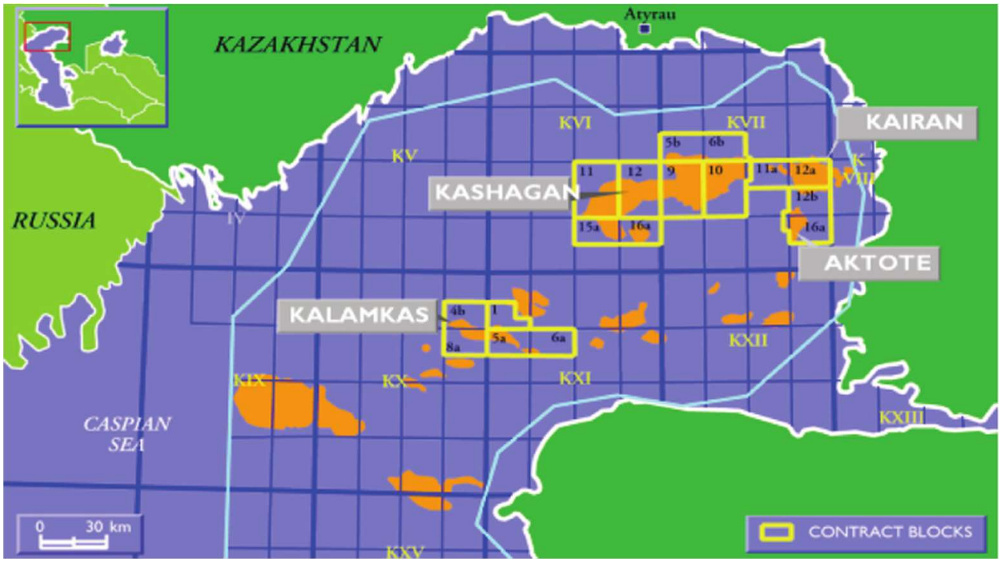


**Figure 1: Kashagan Field**

Two types of wells are identified with respect to the target location:

- Platform Interior wells, targeting the central body of the reservoir.
- Rim wells, targeting the boundary of the reservoir.

S-Shape directional Interior Platform wells are completed with 5½” tubing size. Rim wells are completed with 7” tubing (Figure 2). Rim wells pose the highest risk while drilling being that this reservoir area is prone to total losses and requires the application of the Closed-Hole Circulation-Drilling (CHCD) technique.

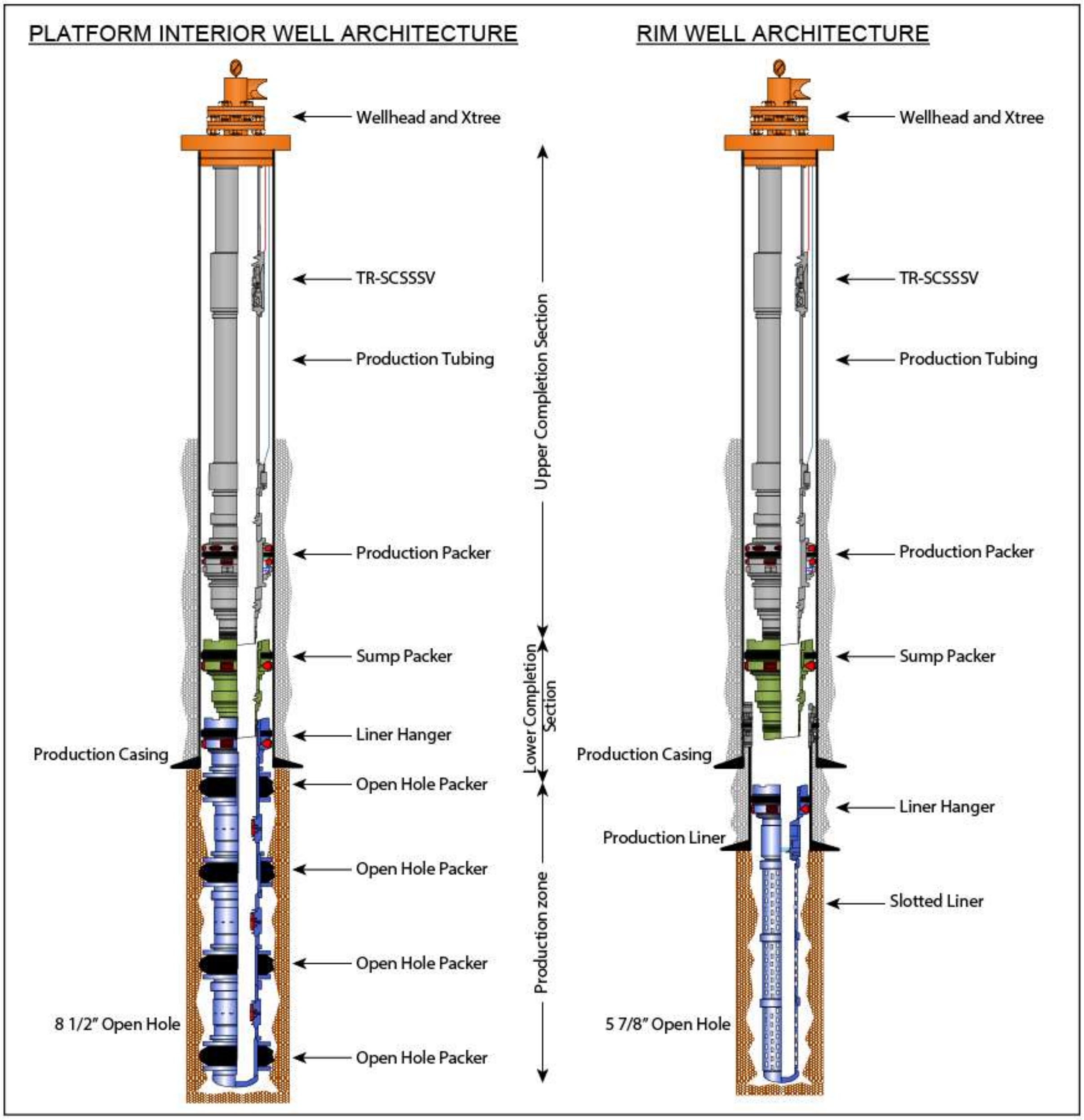


**Figure 2: Platform Interior (L) and Rim (R) Well Schematics**

The NCSPSA field development is complex due to the following challenges which would also affect Well Control and Well Emergency response activities:

- Highly pressurized wells and Deep reservoir (>4000m TVD) – high AOF potential.
- High $H_2S$ concentration in the reservoir fluid (sour) – $H_2S$ and $SO_2$ toxic hazards during the Emergency response interventions.
- Harsh offshore environment including shallow waters, wind surge and ice bound during the winter season – Complex logistics and delay in the response.
- Limited options to approach drilling and production islands due to their delimited configurations – Restricted working area and access to artificial islands.
- Decreasing trend of Caspian Sea level – Constrained logistics supply and operating timeframe.

## Well Emergency Dual Response Strategy

NCOC's current Well Emergency Response approach mandates a dual response strategy based on bringing a blowout under control by Surface Capping technique (surface intervention) and Relief Well drilling (sub-surface intervention). Both techniques would be pursued in parallel and in a converging mode.

NCOC's dual strategy was driven by studies which, by comparison with common practices in the industry and considering the Kashagan challenging conditions, concluded that surface capping alone could not be relied on and had to be complemented / supplemented with relief well intervention. Once the blowing well has been ignited to reduce pollution and mitigate $H_2S$ release, preparations for drilling a relief well as well as surface capping would commence simultaneously and proceed in tandem until the Capping intervention and/or the relief well effort succeeds.

## Consequences of Blowout in Kashagan and K-BOS Step Change

A blowout incident carries major potential consequences, including environmental damage, which can get further exacerbated if timelines of well emergency recovery measures is impacted by environmental conditions (e.g., ice bound, wind surge or toxic gas cloud).

A blowout event in Kashagan is a Major Incident Hazard regardless of the duration. Although a robust contingency plan is in place to assure the worst-case scenario release from a well can be resolved in timely fashion, attention shall be even higher on prevention measures at the left side of the bowtie (Figure 3). As a step change in management of Major Incident Hazard to ALARP, the applicability of the 5-1/8" 10M and 13-5/8" 10M K-BOS System for Well Intervention and D&C operations respectively was investigated. Specifications and details in this Paper are limited to the 13-5/8" 10M K-BOS.

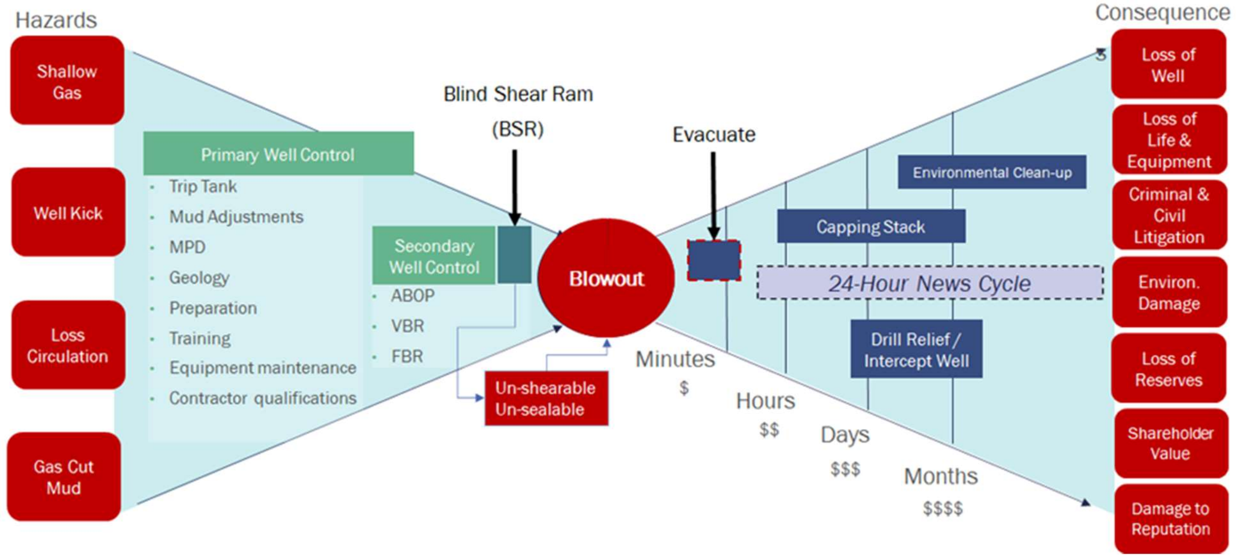


**Figure 3: Conceptual Bowtie for Well Blowout Event**

# K-BOS Overview

## Description and Function

The K-BOS model KB13A401 is a 13-5/8” bore electrically initiated, pyro-mechanical shear ram which performs the critical function of shearing and sealing during drilling, completions or intervention well control operations. The unique and patented design, utilizing the power of kinetic energy, greatly limits the potential existential threat posed by blowouts by being able to shear and seal under any conditions. This includes shearing and sealing under unmitigated blowout flow and pressure conditions as well as shearing through heavy well bore elements including tool joints, BHAs (except the drill bit) and heavy casing up to 13” OD.

The K-BOS working components are housed within a pressure vessel referred to as a K-BOS Bonnet. An insert is placed within the main body block and hermetically seals (full well bore pressure and temperature) the working components from the well bore fluids prior to activation. The upper limit of the design of the K-BOS in general is capable of withstanding and constraining well bore pressures of up to 20,000psi at temperatures up to 400F in extreme sour service conditions (5,000psi $H_2S$ partial pressure).

The K-BOS has a number of distinct phases during its operations. These include:

- Continuous Monitoring mode – The K-BOS is designed throughout its life in service to provide continuous functional availability, monitoring and testing of its critical systems.
- Initiation – The K-BOS may be initiated through the independent control system push buttons, automatically based on temperature and $H_2S$ sensors, remotely through external system interface and/or locally on the K-BOS through an independent manual activation circuit.
- Shearing Action – A gas generator consisting of an electric/pyrotechnic initiator and propellant is used to provide the working power to rapidly actuate the working components.
- Arresting – After the leading edge of the hammer assembly passes through the well bore, completing the shearing action and moving into the far side of the K-BOS main body, the residual energy of the hammer assembly is absorbed by the arresting block.
- Sealing – Prior to activation, the sealing components are isolated from exposure to well bore fluids and during the shearing action they are protected from any damage. Following the shearing action, the sealing components are engaged against the hammer assembly by a mechanically timed mechanism that is activated by the position of the hammer assembly.
- Locking – A locking mechanism is automatically timed and actuated by residual gas pressure from the gas generator once the gate has reached the seal position preventing the hammer assembly from re-opening.
- Re-Opening – Once well control has been re-established, the locking mechanism is unlocked via hydraulic intervention. The hammer assembly then retracts also via hydraulic intervention.

## Technical Specification

The main characteristics of the 13-5/8” 10M K-BOS system are indicated in Table 1 below. The K-BOS is suitable for operations in the Kashagan environment. The design can sustain a maximum of 5,000psi partial pressure $H_2S$ and is suitable for qualification for arctic service in -30F environments.

**Table 1 – 13-5/8” 10M K-BOS Summary of Design Capability**

| **K-BOS Model Number:** | KB13A401 |
|---|---|
| **Operator Type:** | Pyrotechnic Gate Valve |
| **Bore Size:** | 13-5/8” |
| **Pressure Rating:** | 10,000psi |
| **Shut-in Time:** | <<1 second |
| **Shearing Capability:** | Qualified to DNVGL-OS-E101 with reference to API 16A PR2<br>Tubulars incl Drill Pipe and Joints, BHAs & Casing:<br>• Up to 13” Outer Diameter<br>• Up to 158 lbs. per foot<br>• Up to MYS 165ksi Material Grade<br>• All typical Wireline |
| **API 16A 4th Edition Design Temperature Range:** | Metallic 0F/350F, Elastomer 30F/300F/350F – Normal Trim<br>Metallic -30F/350F, Elastomer -30F/210F/240F – Arctic Trim |
| **Fatigue Test:** | 1000, 0-10000psi pressure cycles |
| **API 16A Sour Service Limits:** | Partial Pressure $H_2S$ (max): 500psi $H_2S$ – NACE Trim<br>Partial Pressure $H_2S$ (max): 5,000psi $H_2S$ – Extreme $H_2S$ Trim |
| | Partial Pressure $H_2S$ (max) + $CO_2$ (max): 530psi (500psi $H_2S$, 30psi $CO_2$) – NACE Trim<br>Partial Pressure $H_2S$ (max) + $CO_2$ (max): 5000psi – Extreme $H_2S$ Trim |
| | Chloride Concertation (max): 180,000mg/L – NACE Trim<br>Chloride Concertation (max): No specific Limit – Extreme $H_2S$ Trim |
| | pH (min): No limit specified, any in situ production environment pH is acceptable providing the $H_2S$ + $CO_2$ Limits are not exceeded. |
| | Elemental Sulphur Resistant: No |

## Control System

The heart of the K-BOS pyrotechnic system is the NASA Space Standard Initiator (Figure 4). The initiator has a demonstrated reliability of 0.999956 with a 95% confidence interval. Kinetic’s chosen manufacturer has made over 1,000,000 of these initiators since the 1970’s without a single failure to function. The plausible failure modes identified for the initiator relate to lack of continuity through the bridge wire (most likely from broken connection or wire). In order to ensure that such failure modes are detectible, a minority current (below the safe non-fire level) is continually run through the bridge wire to ensure the continuity. Any break in this circuit will alarm and interlock the K-BOS system.

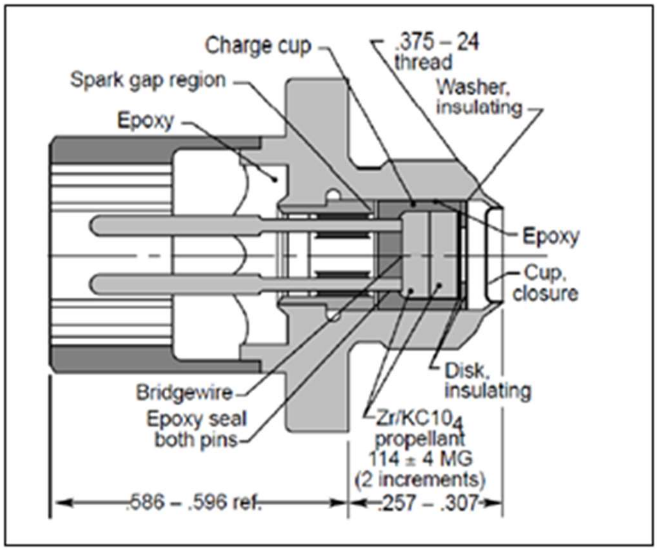
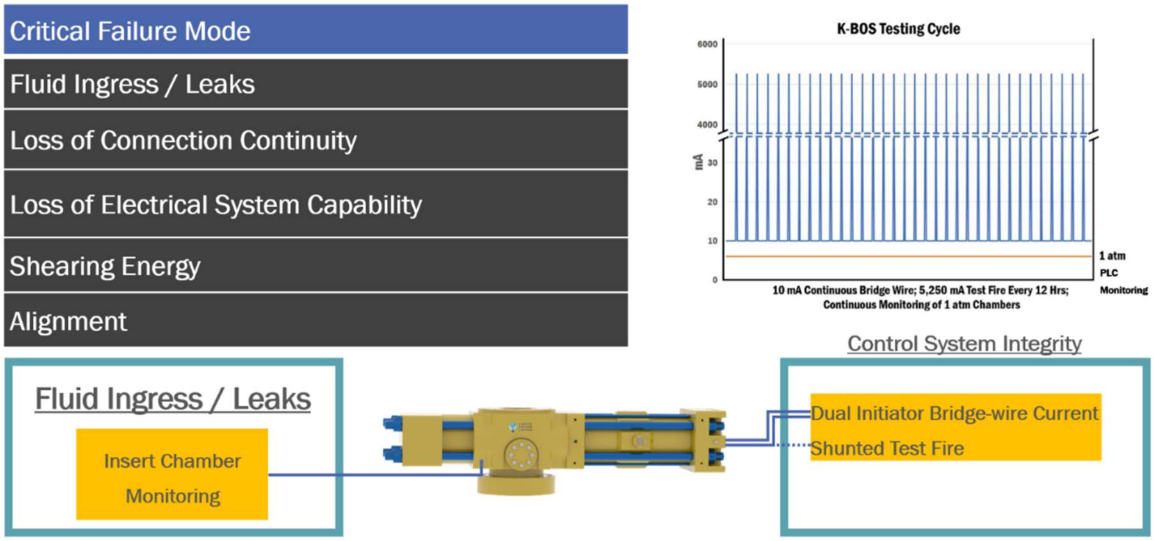


**Figure 4: NASA Space Standard Initiator Diagram**

## Pressure Chamber Online Monitoring

It is important to the reliable functioning of the K-BOS that its internal chambers are maintained at one atmosphere and free of fluids before activation. To ensure the condition of these chambers is known at all times, an online monitoring system is in place (Figure 5). In the event of an abnormal situation an alarm and interlock are generated in the control system to notify operators to perform remedial action.



| Critical Failure Mode |
|---|
| Fluid Ingress / Leaks |
| Loss of Connection Continuity |
| Loss of Electrical System Capability |
| Shearing Energy |
| Alignment |

**Figure 5– K-BOS Online Monitoring Diagram for Surface Applications**

## Qualification

The qualification program for the K-BOS is per DNVGL-RP-A203. The validation program and test activities to qualify the 13-5/8” 10M (13-10M) K-BOS were defined in accordance with the intent of API 16A, Specification for Drill Through Equipment 4th Edition as well as Kinetic’s Functional Design Specification. A gap analysis between API 16A and the test requirements for the K-BOS was completed together with a FMECA workshop led by DNV which included industry participation from regulators, operators and drilling contractors. The fully qualified product meets DNVGL-OS-E101.

Table 2 outlines the temperature, fatigue and shear testing activities for the 13-10M K-BOS qualification program successfully completed in October 2021.

**Table 2: Summary of Qualification Testing**

| Test # | Test Description | Test Purpose | Category | Location | Number of test serials |
|---|---|---|---|---|---|
| KT-01 | K-BOS Pressure components hydrotest | Validates Pressure integrity of device assemblies. | Qualification Testing | Kinetic Facility | 1 |
| KT-02 | API 16A Low Temperature, High Temperature, Continuous Operating Temperature (Pre-fire) | Simulate both hot and cold environmental conditions and stress device to Validate life cycle temperature fatigue.<br>NOTE: testing is based on 16A but modified to fit new technology. | Qualification Testing | Kinetic Facility | Per API 16A-PR2 |
| KT-03 | API 16A Low Temperature, High Temperature, Continuous Operating Temperature (Sealed & Locked) | Simulate both hot and cold environmental conditions and stress device to Validate life cycle temperature fatigue.<br>NOTE: testing is based on 16A but modified to fit new technology. | Qualification Testing | Kinetic Facility | Per API 16A-PR2 |
| KT-04 | Fatigue / Accelerated life cycle testing, internal well-bore pressure (Pre-fire) | Stress the device to show reliability and life cycle fatigue for internal well-bore pressure pre-fire.<br>NOTE: testing is based on 16A but modified to fit new technology. | Qualification Testing | Kinetic Facility | 1, (1000 cycles) |
| KT-05 | Fatigue / Accelerated life cycle testing (Sealed) | Stress the device to show reliability and life cycle fatigue for internal well-bore pressure post-fire.<br>NOTE: testing is based on 16A but modified to fit new technology. | Qualification Testing | Kinetic Facility | 1, (10 cycles) |
| KT-06 | Sealing Characterization | Fatigue Testing of post fire sealing arrangement. | Qualification Testing | Kinetic Facility | 10, open and close,<br>100 Pressure Cycles |

**API 16A PR-2 Blind Shear Ram Shear & Seal Test Requirements**

| Test # | 13-10M K-BOS Test Description | Location | Shear Target | Side Load | Test Condition Per API 16TR1 |
|---|---|---|---|---|---|
| ST-01 | API 16A-PR2 Shear & Seal Test (Diametrical Off-Center & Smallest OD)<br>API 16A-PR2 Shear & Seal Test (Largest WT) | Kinetic Facility | HWDP landing string: 6-5/8” 50.46# S135 | Yes | Condition B |
| ST-02 | API 16A-PR2 Shear & Seal Test | Kinetic Facility | 9-5/8” Casing 47# P110 | No | Condition B |
| ST-03 | API 16A-PR2 Shear & Seal Test (Largest OD) | Kinetic Facility | 10-3/4” Casing 45.5# P110 | No | Condition B |

Figure 6 shows a 13-10M K-BOS set up for an API 16A PR2 shear and seal test on a 10-3/4” OD 0.4” WT casing. The test was successful and included accelerated lifecycle testing of the redundant wellbore seals which actuate instantly following the shearing action.

**Figure 6: Example of API 16A PR2 shear and seal test set-up for the 13-10M K-BOS**

Figure 7 shows the top and bottom fish from the API 16A PR2 shear and seal test set up presented in Figure 6. These results where predicted by Kinetic's proprietary shear modeling which provided a very high level of confidence in the K-BOS performance for any given tubular specification.

**Figure 7: 13-10M K-BOS shear and seal on a 10-3/4" OD Casing, 0.4" WT, P110**

**6-5/8" OD HWDP Landing String, 0.813" WT, S135 – Modeled Shear Result vs. Test Result:**

On the plane of blade entry, the upstream material of the tubular is rapidly displaced towards the center. This ripping is more pronounced in the test result but is observed in the model as well. The profiles of the model and the test result show similarities in global deformation, seen in the peak formed on the downstream side of the tubular.

Figure 8: 6-5/8" OD HWDP Landing String, 0.813" WT S135 - Model (L) vs. Test Result (R)

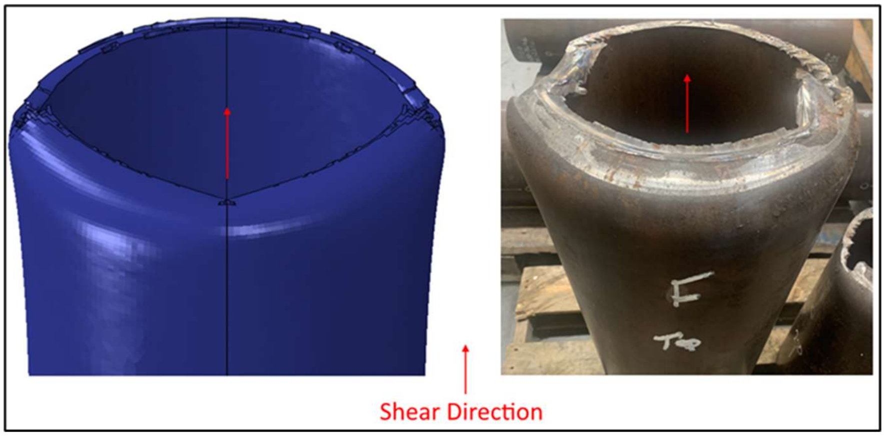
### 9-5/8" OD Casing, 0.472" WT, P110 – Modeled Shear Result vs. Test Result:

In Figure 9, the failure observed on the upstream side of the tubular suggests the material at the plane of blade entry deformed and folded inward in a ductile manner prior to significant blade penetration. As the blade travels through the tubular, the casing reaches a point where the remaining material can no longer withstand the tensile forces induced, leading to a region of clean, brittle failure. These global deformation behaviors were observed also in the model result.

**Figure 9: 9-5/8" OD Casing, 0.472" WT, P110 - Model (L) vs. Test Result (R)**

**10-3/4” OD Casing, 0.4” WT, P110 – Modeled Shear Result vs. Test Result:**

In Figure 10, the 10-3/4” Casing experienced failures similar to the 9-5/8” Casing. A region of folded, ductile failure is observed at the plane of blade entry. As the blade moves through the wellbore and shears more material, the downstream side of the tubular breaks in a clean, brittle manner. These failure modes were also well predicted by the model before conducting the physical shear test.



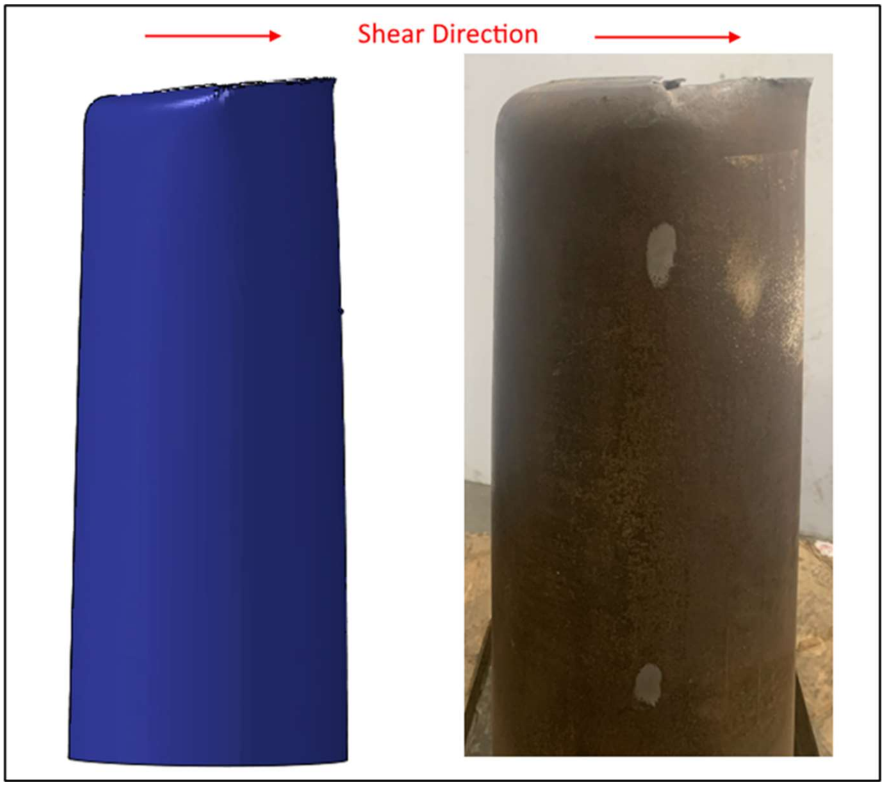


Figure 10: 10-3/4" OD Casing, 0.4" WT, P110 - Model (L) vs. Result (R)

### Kinetic Energy Margin of Safety

The Kinetic Energy Margin of Safety (KEMS) is defined as the ratio of the energy input to the energy required for shearing. The KEMS for the 13-10M K-BOS among each shear test configuration was calculated and plotted for future reference (Figure 11).

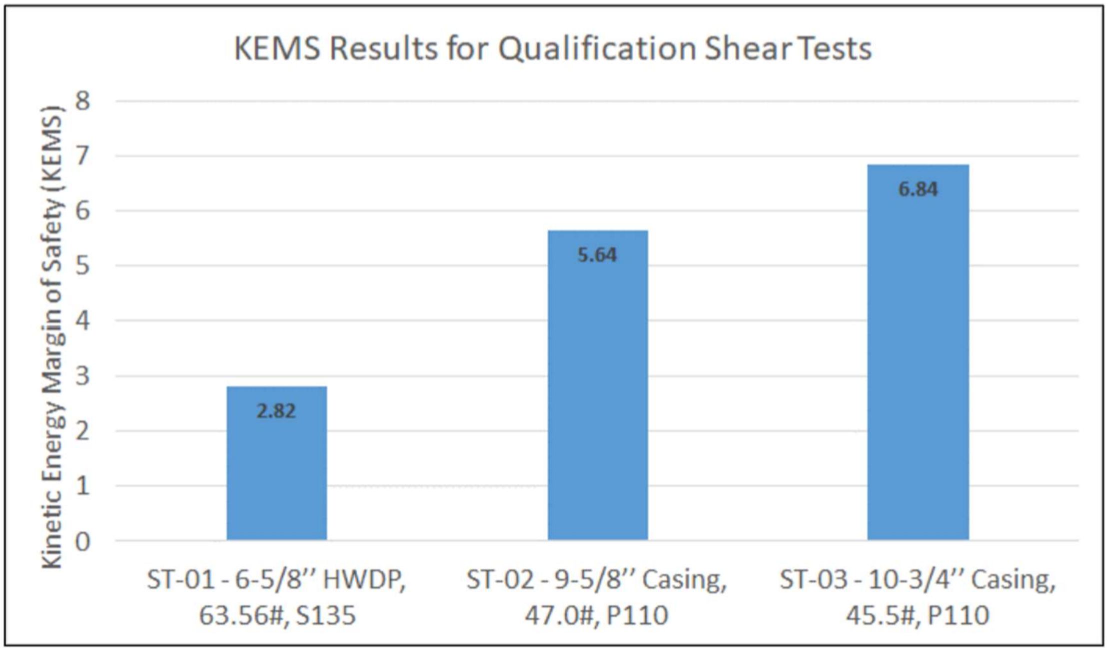


**Figure 11: Kinetic Energy Margin of Safety values for the 13-10M K-BOS**

## 13-10M K-BOS – Scope of Supply and Stack-up Configurations for NCOC Operations

### System Components

The K-BOS may be mounted directly on the tree or wellhead or mounted in the BOP stack, replacing the drilling spool for example. The K-BOS uses an independent control system. The device complies with existing categories for regulation/deregulation of pyrotechnically actuated special tools and has no special handling requirements procedures, or operating permits once deregulated in each country. No electrical connection is required during storage or transit. The equipment consists of the following components (Figure 12):

- K-BOS skid
    - 1x 13-10M K-BOS with mounted control box
    - Forklift/crane portable skid base
    - 13-10M test stump flange
- Control skid including armoured cables and a control panel
- Secondary remote-control panel
- Spare parts and re-opening tools (batteries, etc.)

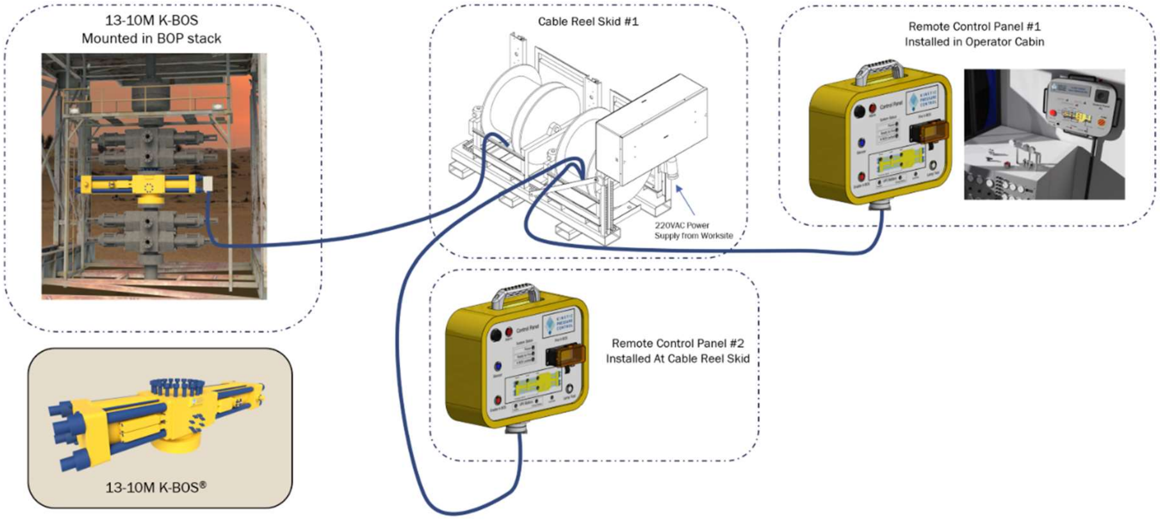


**Figure 12 – 13⅝" 10M K-BOS Typical Worksite Deployment**

In the case where a SIL 3 control system is specified, the K-BOS scope of supply will include hazardous area Ex Zone 2 rated CCU cabinets and HMI control panels as shown in Figure 13.

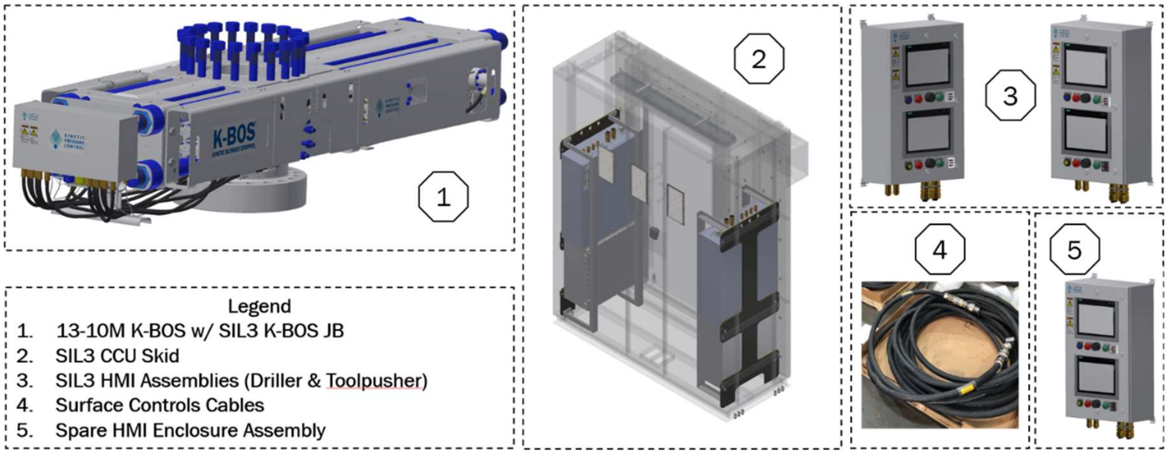


**Figure 13 – 13⅝" 10M K-BOS System Components with SIL 3 Controls**

## 13-10M K-BOS – External Dimensions

The K-BOS can be positioned right above the wellhead or in the BOP stack at the discretion of the Operator. If cellar height is restricted, the K-BOS fits into the same height as a typical drilling cross flow spool and is rated for continuous service in this configuration.

The K-BOS is configured with two side outlets rated for continuous service and are suitable for mounting of existing choke and kill flanges, valves, actuators, and hoses.

The 13⅝" 10M K-BOS with Flange bottom x Studded top measures 30.5" in height (Figure 15). The studs up x studs down version measures 20" in height (not shown).

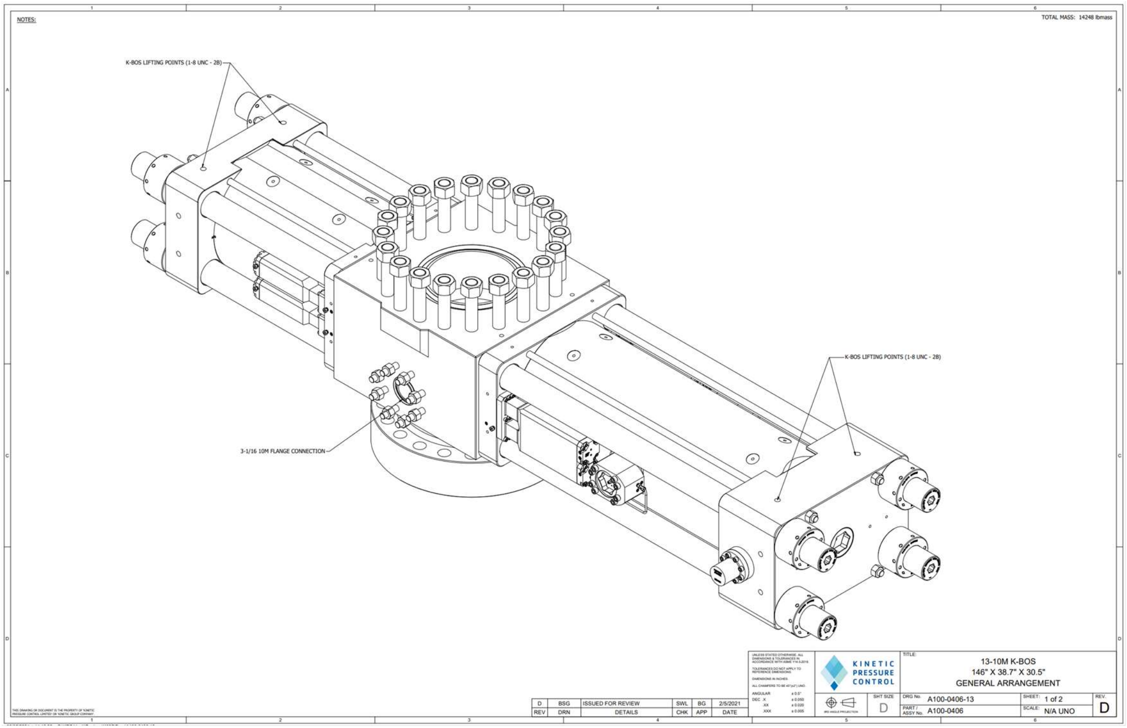


Figure 14 – View of 13⅝" 10M K-BOS with Flange bottom x Studded top

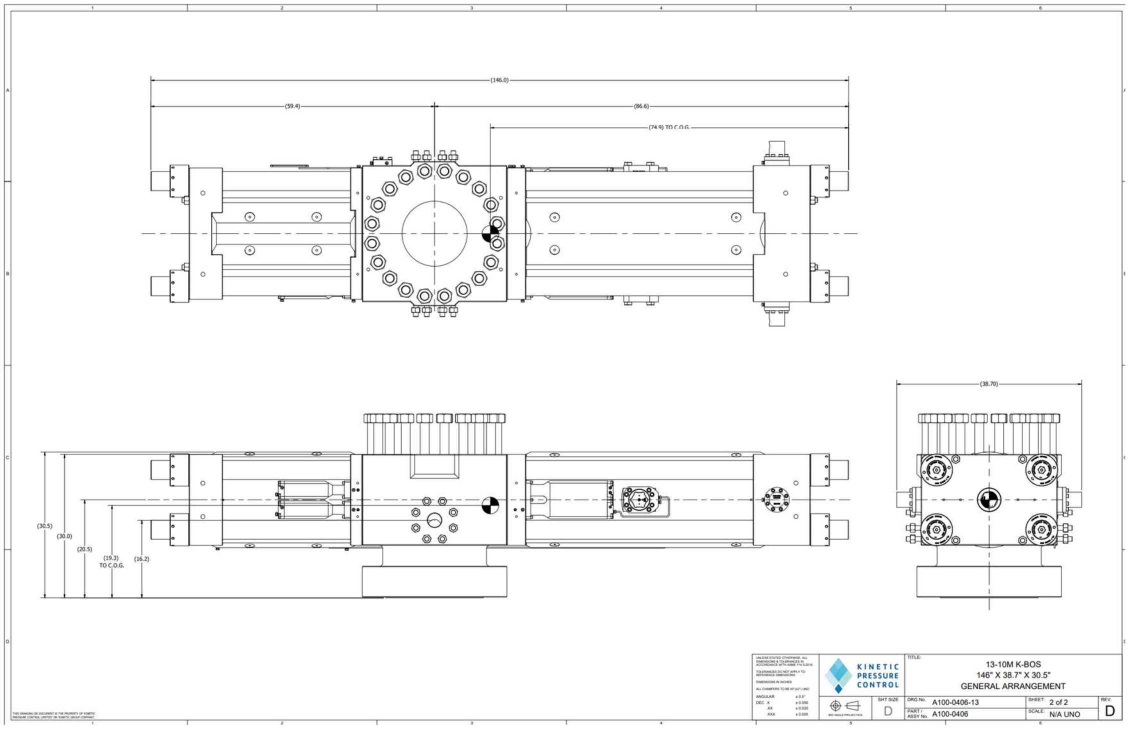


Figure 15 – Dimensions of the 13⅝" 10M K-BOS with Flange bottom x Studded top

## K-BOS Stack-Up Configurations for NCOC Drilling and Completion Operations

The BOP stack on the left in Figure 16 shows the typical 13⅝” 10M BOP configuration used during the previous drilling and completion campaign in Kashagan. Total height of the BOP stack including the RCD was ~7.2m.

The K-BOS can be installed just above the wellhead connector (if enough clearance with nearby wells/facilities allows that), above the BOP riser, or in between the BOP stack rams. Two possible combinations are represented in Figure 16.

The main benefits of placing the K-BOS in between the BOP stack rams are the following:

- The K-BOS would replace the drilling spool.
- The stack is more compact and easier to handle if the BOP crane has enough capacity and the rig air gap allows to move it as a single piece. The total height of the stack-up is ~7.4m therefore little to no change is required in the new wells cellar design.
- In this position, the K-BOS would provide a full back up to the shear rams with the drilling string hung off. The consistent fish shape after shearing allows for circulation and would therefore ease the subsequent well killing and re-entry operations. Moreover, since K-BOS can shear also the DP tool joint, space-out is not required prior to activation.
- Rig choke/kill lines can be maintained in their standard position (e.g. connected on the Double BOPs) and a third set of choke/kill lines to be connected otherwise to the K-BOS body are not be required.

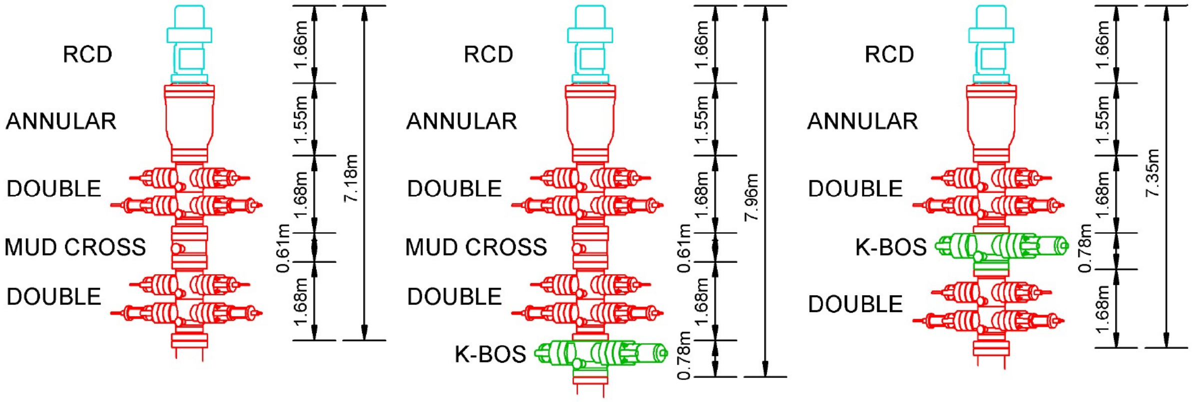


**Figure 16 – Examples of K-BOS Position in the BOP Stack**

Since the impact in the stack-up total height is minimized, no modifications are required to the designed workover rig substructure (Figure 17). The space above the BOP foldable deck is sufficient to accommodate the complete K-BOS+BOP+RCD stack and to allow workover interventions with no interference with the protection frames and Xmas Trees in the various artificial islands. The worst-case scenario is on D Island where due to the ‘Shallow’ well cellars the top of the bulky protection covers and top of Xmas Trees is at 6.2m and 4.6m respectively. Even in this scenario, if precautions are taken despite the presence of the K-BOS during the N/U and N/D operations, the drill floor elevation from ground level does not need to be increased with structural fillers.

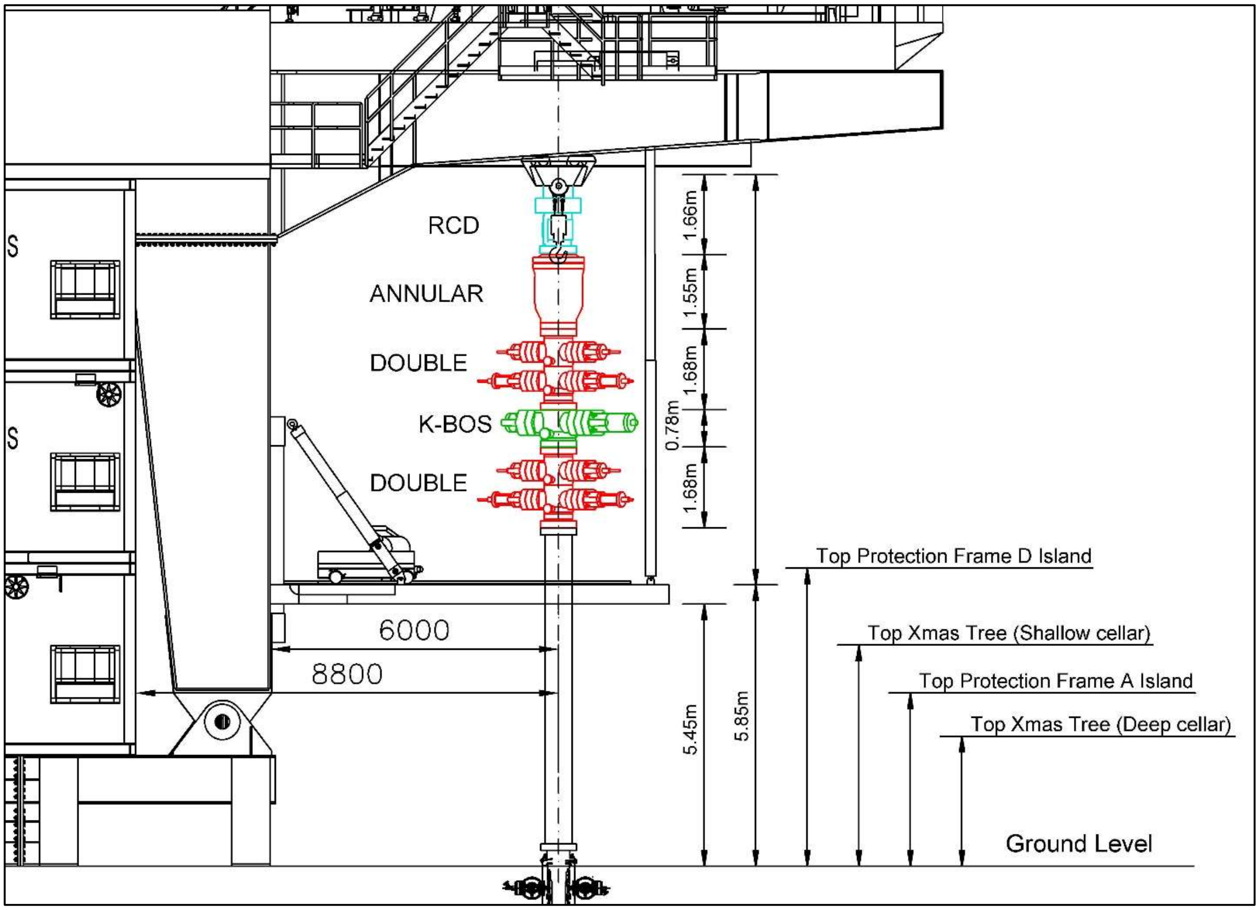


**Figure 17 – Workover Rig with example of 13⅝" 10M RCD+BOP+K-BOS stack configuration**

## Blowout Probability Modeling Approach

### e-wise™ Methodology

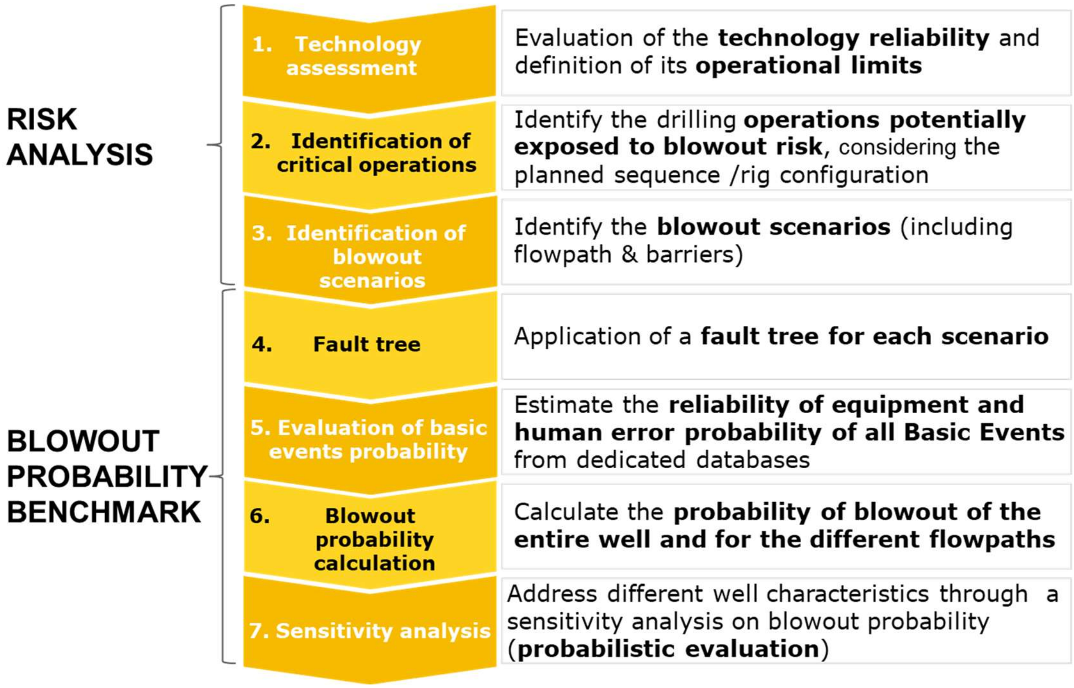
Blowout probability modelling is based on a standard methodology developed by Eni for assessing blowout probability during well operations. The methodology is adopted inside the e-wise™ system (Eni - Well Incident Systematic Evaluation), and technically validated by DNV GL.

e-wise™ is a comprehensive, well-specific methodology grounded on the evaluation of three root causes affecting the well blowout:

1. Geological uncertainties,
2. Equipment reliability,
3. Human errors.

These three elements are automatically combined in a Fault Tree model by using the dedicated e-wise™ tool, giving a quantification of the well blowout probability.

The methodology of blowout probability calculation is performed through a seven-step process (Figure 18).



Evaluation of the **technology reliability** and definition of its **operational limits**

Identify the drilling **operations potentially exposed to blowout risk**, considering the planned sequence /rig configuration

Identify the **blowout scenarios** (including flowpath & barriers)

Application of a **fault tree for each scenario**

Estimate the **reliability of equipment and human error probability of all Basic Events** from dedicated databases

Calculate the **probability of blowout of the entire well and for the different flowpaths**

Address different well characteristics through a sensitivity analysis on blowout probability (**probabilistic evaluation**)

**Figure 18. e-wise™ methodology to estimate blowout probability**

The e-wise™ methodology does not cover the following events:

- Operations not compliant with the drilling program or with Eni (or equivalent industry best practice) procedures,
- Insufficient engineering studies,
- SIMOPS (e.g., interference due to civil construction works, collision during helicopter movements),
- Lack of personnel or equipment,
- Intentional acts (terrorism, sabotage, vandalism),
- Natural disaster (e.g. earthquake, storm, weather conditions not adequate to the operations).

As a consequence, this blowout probability assessment does not take into account any of the aforementioned events/conditions.

## e-wise™ Fault Tree Analysis (FTA) Approach

In order to have a blowout, a kick and a failure on the second barrier safety equipment must occur simultaneously as presented in Figure 19 (Gate AND among “Kick” and “Failure second barrier” events). A kick can occur when the wellbore pressure drops below the pore pressure, this might be caused by several factors such as human errors during operations or a wrong pore pressure prognosis. The second barrier, which is the BOP stack in most of the drilling and completion operations, may not be effective due to several factors, such as human errors (e.g., bad evaluation of the situation or lack of intervention) or equipment failure. The Fault Tree can be further developed following the same principles to describe each second-level contributors until the desired level of detail.

Figure 19 shows an example of a fault tree for drilling, completion and heavy workovers operations where the hydrostatic barrier of drilling mud is usually considered as the primary barrier for a blowout event. The fault tree slightly differs for rigless Well Intervention operations that most of the time are performed in "live"/producing wells and rely on pressure control equipment as primary and secondary barriers, generally a stuffing box/stripper and a CT/SL BOP.

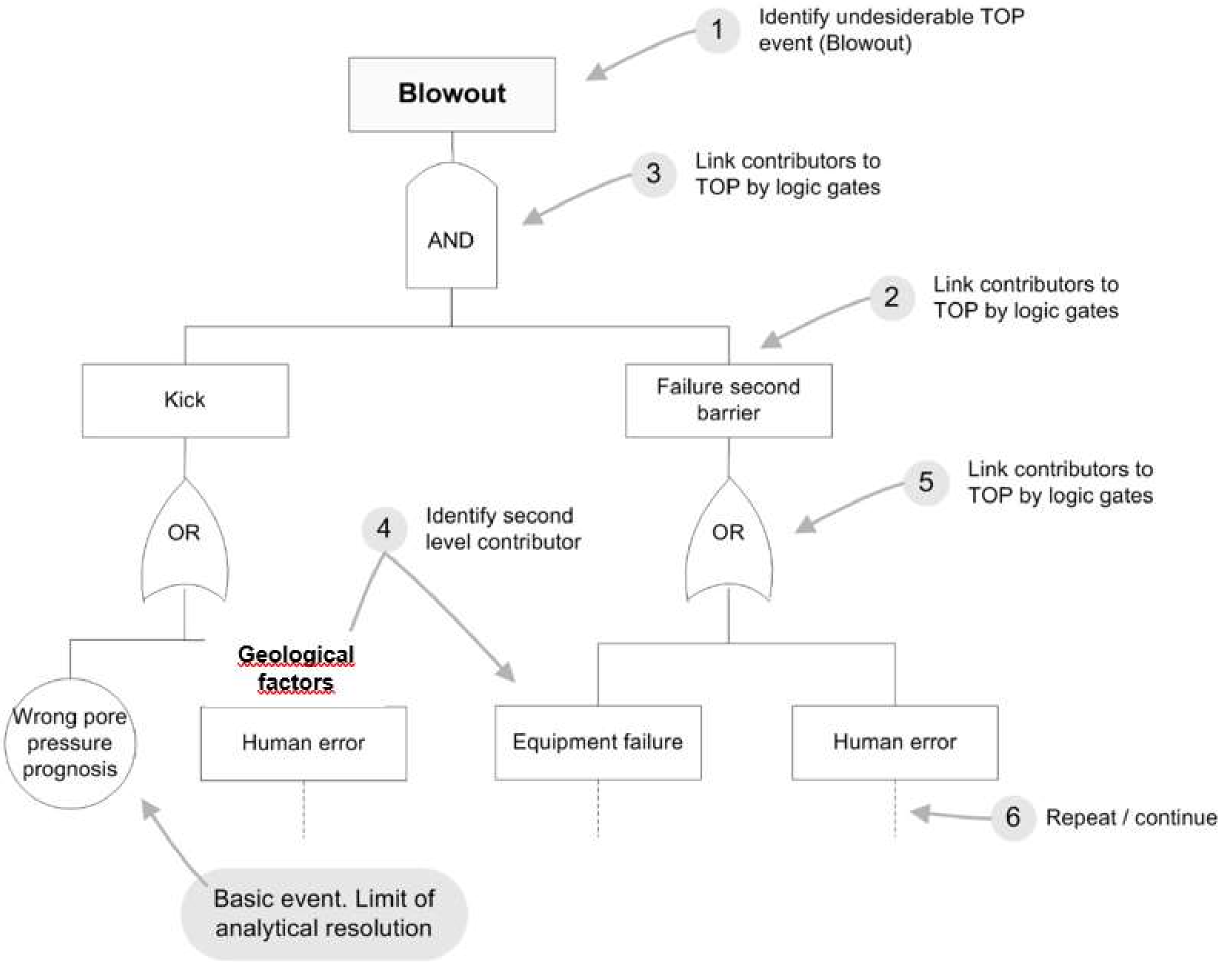


**Figure 19. Example of e-wise™ Fault Tree for blowout probability calculation**

e-wise™ provides engineers with a quantitative value of blowout probability for a specific well, characterized by its particular well architecture, sequence of activities, safety equipment and exposure time to the blowout risk as a result of the specific well design and planned operations schedule. e-wise™ methodology complies with Eni technical specification that aims at reducing human errors and at steering equipment and procedural choices during the planning phase. This tool provides also a bow-tie representation of results.

## e-wise™ Bow-tie Diagram for Blowout Risk

The bow-tie analysis is a commonly used risk assessment technique which aims to describe in a simple and immediate way the pathways of a Top Event, from the causes (Threats) to its Consequences (Figure

20, ISO.IEC 31010:2009). The left part of the bow-tie displays the potential causes leading to the undesired event and all prevention controls (or Barriers) which decrease its probability of occurrence. The right-hand side identifies the potential outcomes of the undesired event including mitigation and recovery controls to reduce their impact. The effectiveness of prevention and mitigation controls can be weakened by Escalation factors often counteracted by the Escalation controls.

e-wise™ system includes an automatic generation of a bow-tie diagram as integral part of the final blowout risk report. Through a bow-tie representation, the Company can clearly identify and display to third parties the main threats for a blowout event, the barriers in place, the flow paths and other relevant input data used to calculate the blowout probability for the specific well under evaluation. Each element of the bow-tie is presented with the associated probabilities of occurrence (or failure) allowing to build a robust risk assessment, to facilitate a workshop environment or to comfortably communicate to Senior Management or Authorities the effectiveness of the control measures.

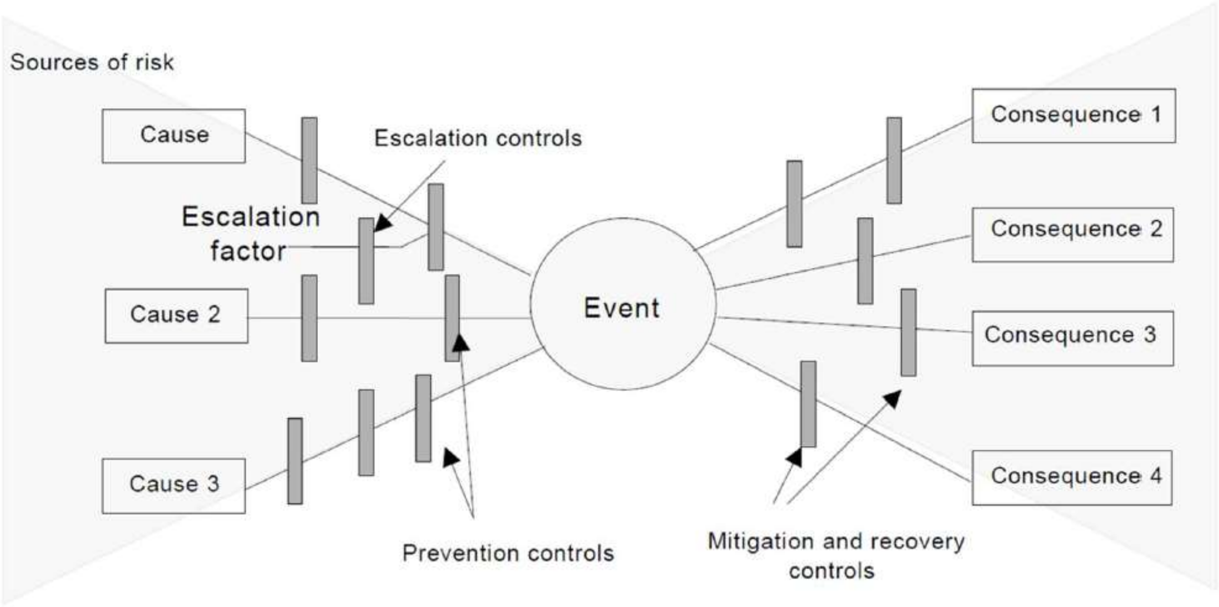


**Figure 20. Schematic representation of bow-tie diagram (ISO.IEC 31010:2009)**

## Application of e-wise™ Methodology and Blowout Probability Modeling Results

### K-BOS Reliability Assessment

As first step to determine the impact of the K-BOS system in the reduction of the blowout probability during drilling and completion and rigless Well Intervention operations, a thorough analysis of K-BOS equipment has been carried out to identify all the components involved in the closure of the ram during a blowout emergency event and to quantify the reliability of the overall K-BOS system regarding its activation function and its capability to cut the tubular elements inside the wellbore and to seal the well from potential uncontrolled flows.

The Closing Function sequence of the K-BOS ram involves various subsystems (Figure 21) and consists in the following steps:

1. Closing Function of the K-BOS ram is launched from one of the control panels,

2. Signal goes through the control lines up to the control modules, from where it is dispatched to the dedicated firing circuit,
3. Firing circuit activates the bridge-wires initiators, thus igniting the propellant in the gas generator module,
4. A pressure build-up in the pressure chamber rapidly actuate the K-BOS ram to shear and seal the wellbore,
5. The ram kinetic energy is dispersed in the arresting chamber thus the K-BOS ram comes to a halt.

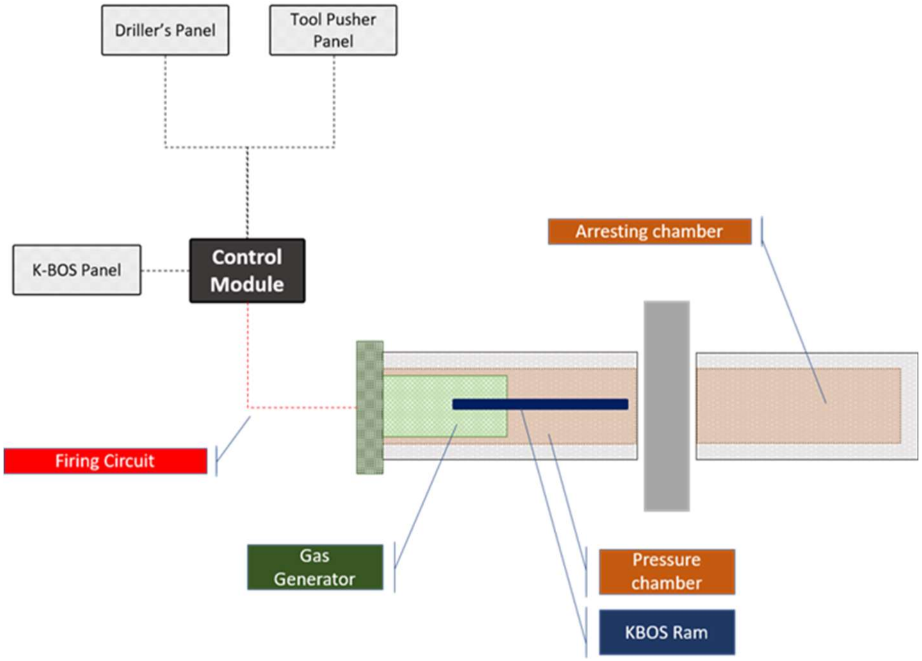


**Figure 21. Subsystems schematic of the closing function of the K-BOS ram**

The reliability of the Closing Function of the K-BOS system was studied through the following:

1. Identification of failure modes of the K-BOS components via a Failure Mode, Effects, Criticalities and Detection Analysis (FMECDA),
2. Identification of fault modes which can cause the failure of a subsystem and definition of relevant numerical parameters for reliability calculation (e.g., failure rates, test interval times, mean time to repair),
3. Evaluation of overall K-BOS system reliability through the e-wise™ Fault Tree Analysis (FTA) approach.

Kinetic Pressure Control performed several tests of the K-BOS system in different configurations to identify faults modes and to assess the reliability of the system, covering the firing circuit, gas generator system, pressure and arresting chambers, and K-BOS ram.

A series of fault modes were identified, and failure rates and test intervals were calculated accordingly. Fault modes were classified into 4 categories:

- Safe, detectable modes (SD): results in loss of production or service, but not a loss of safety, revealed by online diagnostics,

- Safe, undetectable modes (SU): results in loss of production or service, but not a loss of safety, revealed by functional tests or upon a real demand for activation,
- Dangerous, detectable modes (DD): may result in loss of safety, revealed by online diagnostics,
- Dangerous, undetectable modes (DU): may result in loss of safety, revealed by functional tests or upon and a real demand activation.

Detectable fault modes are monitored at 10hz frequency by the K-BOS continuous health monitoring circuit, with the exception of the Firing Circuit which is tested every 12 hours although test intervals can be customized and reduced.

Each fault mode was analysed with different reliability equations to determine the following:

- **Overall K-BOS Availability**: it is a measure of the availability of the system during normal operations. Availability is calculated for all fault modes by applying the following equation:

$$A_{KBOS} = \frac{MTTF_{K-BOS}}{MTTF_{K-BO} \; + MTTR_{K-BOS}}$$

$A_{K\text{-}BOS}$: K-BOS Availability
$MTTF_{K\text{-}BOS}$: K-BOS Mean Time to Failure [hours]
$MTTR_{K\text{-}BOS}$: K-BOS Mean Time to Repair [hours]

- **Overall K-BOS Probability of Failure on Demand (PFD)**: it is a measure of the probability of failure of the system when its closing function is activated by the drilling crew. PFD is calculated only for DD and DU fault modes by applying the following equation:

$$PFD_{KBOS} = \sum\nolimits_i PFD_{DD\ and\ DU\ FM,i} = \frac{1}{2}\, \lambda_i\, T_{test,i} + \lambda_i\, MTTR_{K-BOS}$$

$PFD_{K\text{-}BOS}$: Probability of Failure on Demand of overall K-BOS
$PFD_{DD\ AND\ DU\ FAULT\ MODES}$: Probability of Failure on Demand of DD and DU fault modes
$\lambda_i$: failure rate of DD and DU fault modes [# failures/hour]
$T_{test,i}$: test interval time of DD and DU fault modes [hours]
$MTTR_{K\text{-}BOS}$: K-BOS Mean Time to Repair [hours]

In addition to the reliability of the K-BOS ram, the reliability of the control system and the human error factor in failing to activate the K-BOS were also examined and quantified. The reliability of the K-BOS Surface Control System, including the K-BOS Remote Control Panels #1 and #2, is comparable to a standard surface BOP control system. Figure 22 shows the conceptual fault tree branches for the calculation of the reliability of the K-BOS system that includes all the aforementioned factors:

- K-BOS ram failure (mechanical) accounting for K-BOS Availability and PFD,
- K-BOS control system failure,
- Human error (Failed activation of K-BOS ram closing function).

After quantifying the overall reliability of the K-BOS system, the result was applied inside the desired well operation FTA to determine the specific reduction in blowout probability.

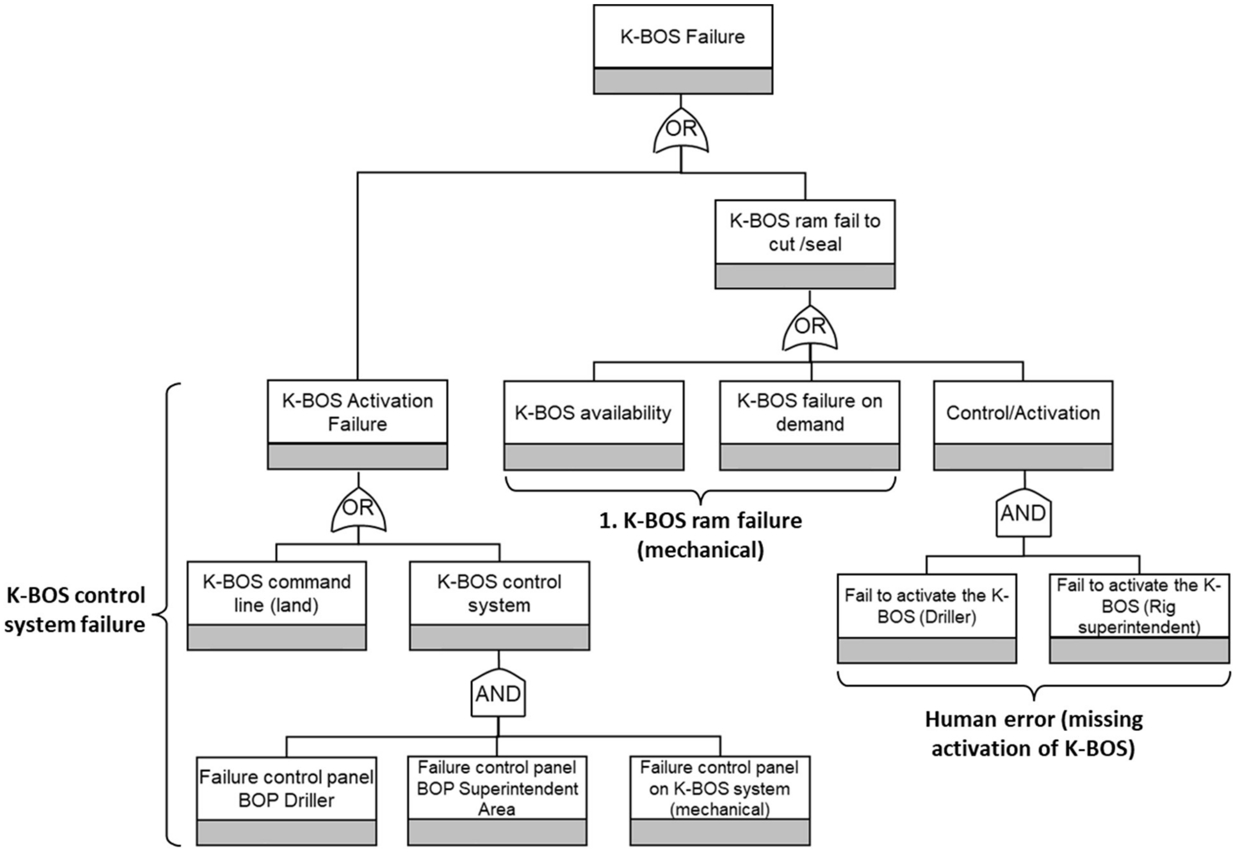


**Figure 22. Conceptual FTA of overall K-BOS system failure for K-BOS ram closing function**

## Effect of an Additional Standard BSR on the Blowout Probability

Before considering the K-BOS System, it was assessed the reduction of blowout probability for including an additional standard Blind Shear Ram to the conventional BOP stack in use during drilling and completion operations in Kashagan field. Figure 23 shows the configurations of the PCE for the “Base case” (conventional Kashagan BOP) and “With additional BSR” scenarios for D&C case studies. For this assessment, it was assumed that the additional Blind Shear Ram is placed below the Lower Pipe ram and that it is activated with the same control system and hydraulic accumulators used for the other preventers in the BOP stack.

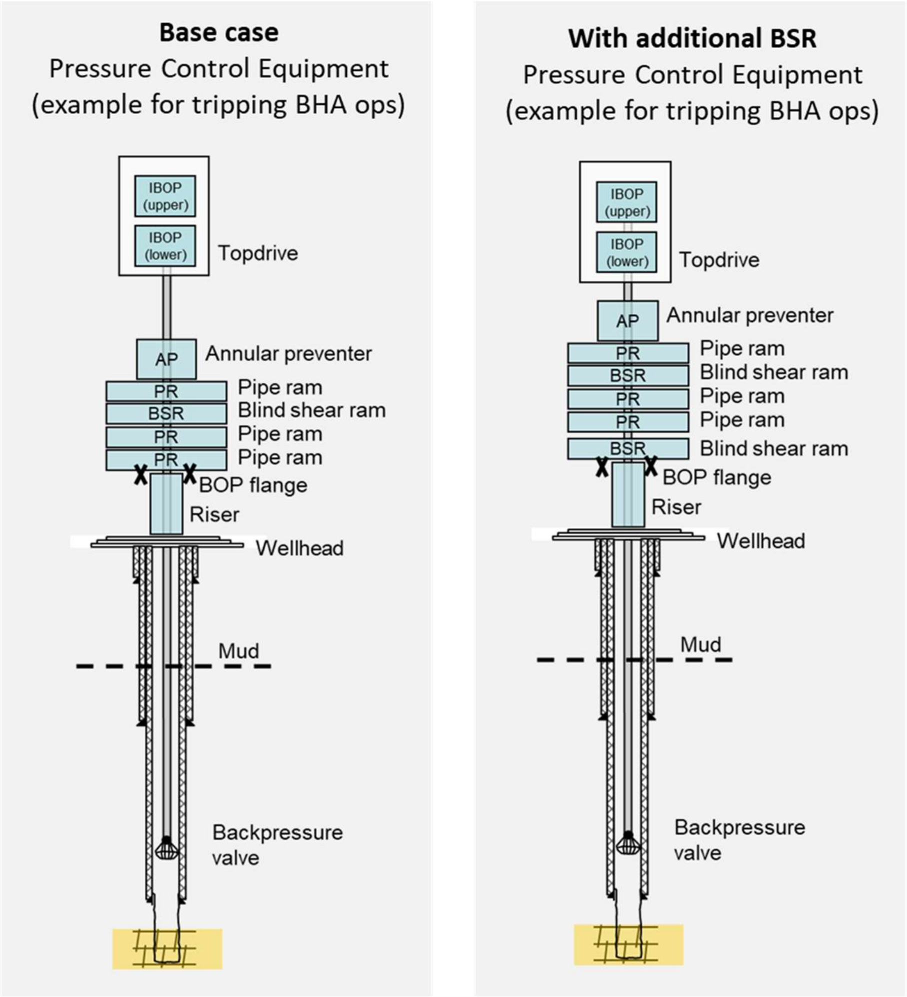


**Figure 23. "Base case" and "With additional BSR" PCE configurations for tripping BHA during D&C operations**

The blowout probability for both scenarios was calculated for Drilling and Completion operations applying e-wise™ fault tree analysis approach. The absolute values of blowout probability ($P_{BO}$) are not reported in this Paper but instead normalized values of blowout probability ($P_{BO,normalized}$) were calculated as follows and are displayed in the following graphs:

$$P_{BO,normalized,Base\ Case} = 1, (100\%)$$

$$P_{BO,normalized,With\ additional\ BSR} = \frac{P_{BO,With\ additional\ BSR}\ [\#events/operation]}{P_{BO,Base\ Case}\ [\#events/operation]}$$

The results of this assessment are plotted in Figure 24. For both drilling and completion operations the additional standard Blind Shear Ram does not decrease the blowout risk as the reduction is by less than 1%. This negligible reduction is justified by looking at the conceptual FTA represented in Figure 25: the additional standard BSR improves the redundancy of rams able to seal the wellbore (-85.9% probability of failing to cut/seal the well with BOP rams) but the probability of failure of the Control System remains unchanged leading to an unaffected probability of failure of the overall BOP stack. As a consequence, probability of secondary barrier loss does not change.

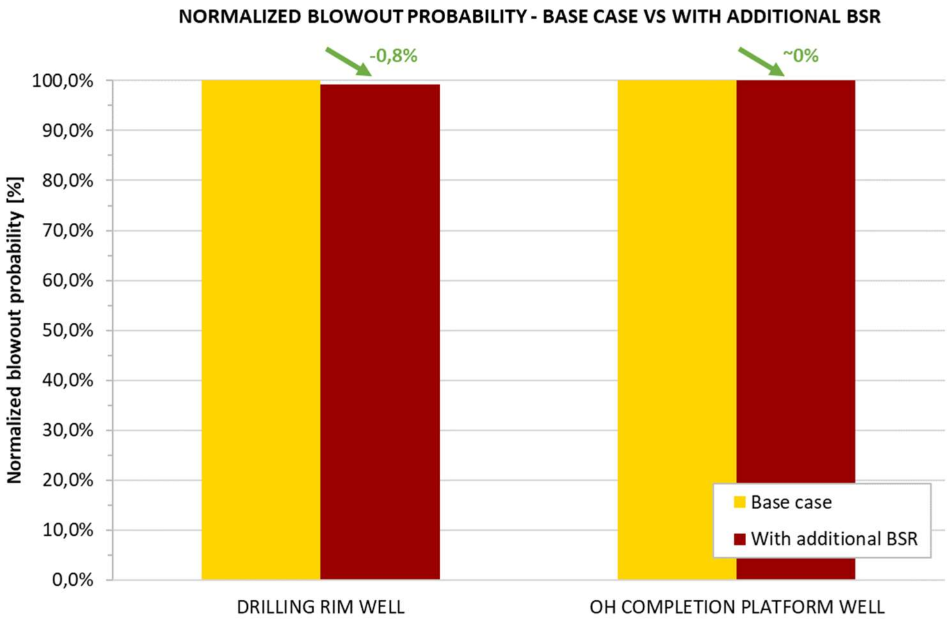


Figure 24. Comparison of Normalized Blowout Probability for “Base case” and “With additional BSR” PCE configurations

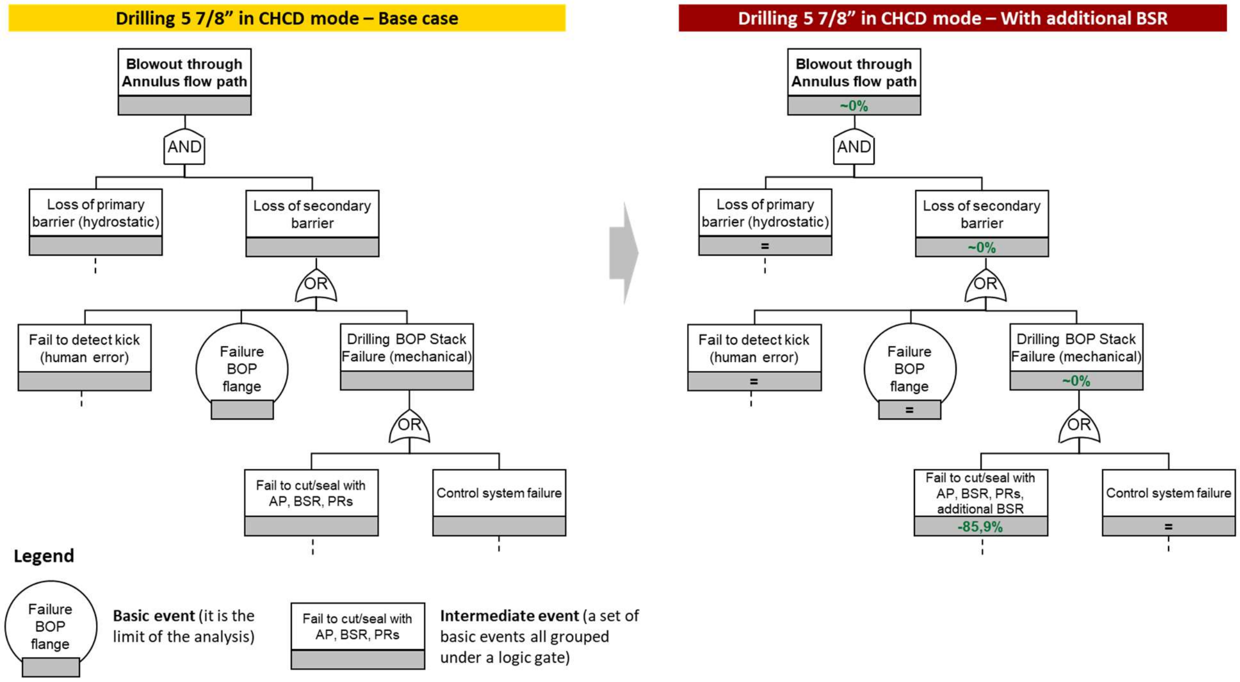


Figure 25. Comparison of conceptual FTA for “Base case” and “With additional BSR” PCE configurations for a blowout scenario through Annulus during drilling 5-7/8” section in CHCD mode

## Beneficial Effect of K-BOS Application on Well Blowout Probability

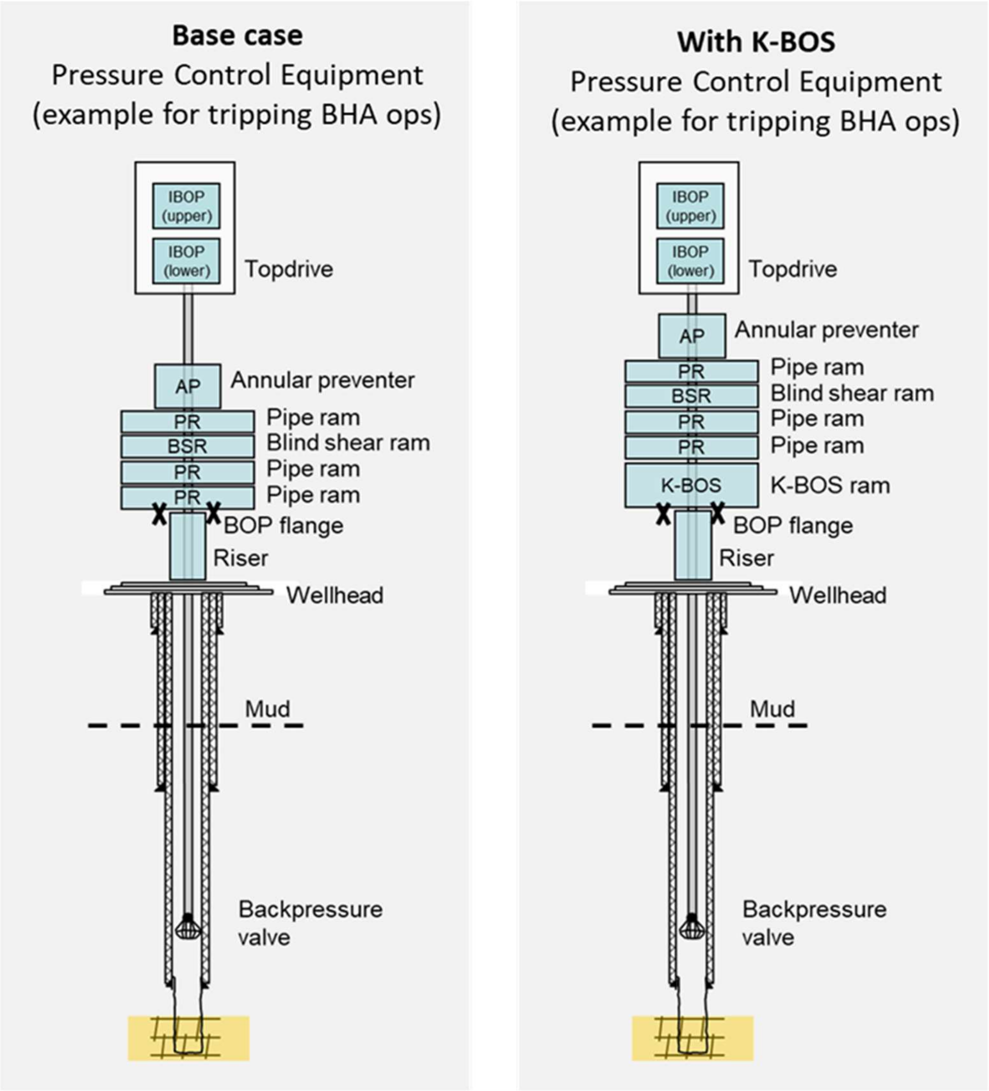
As the benefit of the additional standard Blind Shear Ram proved to be negligible leaving the overall blowout probability at the same level as the “Base case” (reduction by less than 1%), the attention moved on measuring the beneficial effect of including a single K-BOS ram in the conventional BOP stack in use in Kashagan field.

Utilizing the K-BOS reliability results and applying the e-wise™ methodology, a quantitative risk assessment was performed for the following Kashagan well operations case studies:

- Drilling of a Rim well,
- Open Hole Completion of a Platform Interior well,
- Coiled tubing acid clean-out,
- Slickline production logging.

A comparison is presented between the “Base Case” (conventional BOP in Kashagan field) and the “With K-BOS” scenario which entails the addition of a single K-BOS ram to the standard Kashagan BOP. Figure 26 and Figure 27 show the well barriers schematics for the various case studies:

- Drilling and Completion operations (Figure 26) – The K-BOS is installed below the Lower Pipe ram of the “Base Case” BOP.
- CT operations (Figure 27.A) – The K-BOS is installed in substitution of the Lower Quad CT BOPs typically applied in Sour Kashagan field.
- SL operations (Figure 27.B) – The K-BOS is installed below the standard SL BOPs, in substitution of the Cable Cutter Valve typically applied in Sour Kashagan field.



**Base case**
Pressure Control Equipment
(example for tripping BHA ops)

**With K-BOS**
Pressure Control Equipment
(example for tripping BHA ops)

**Figure 26. “Base case” and “With K-BOS” PCE configurations for tripping BHA during D&C operations**

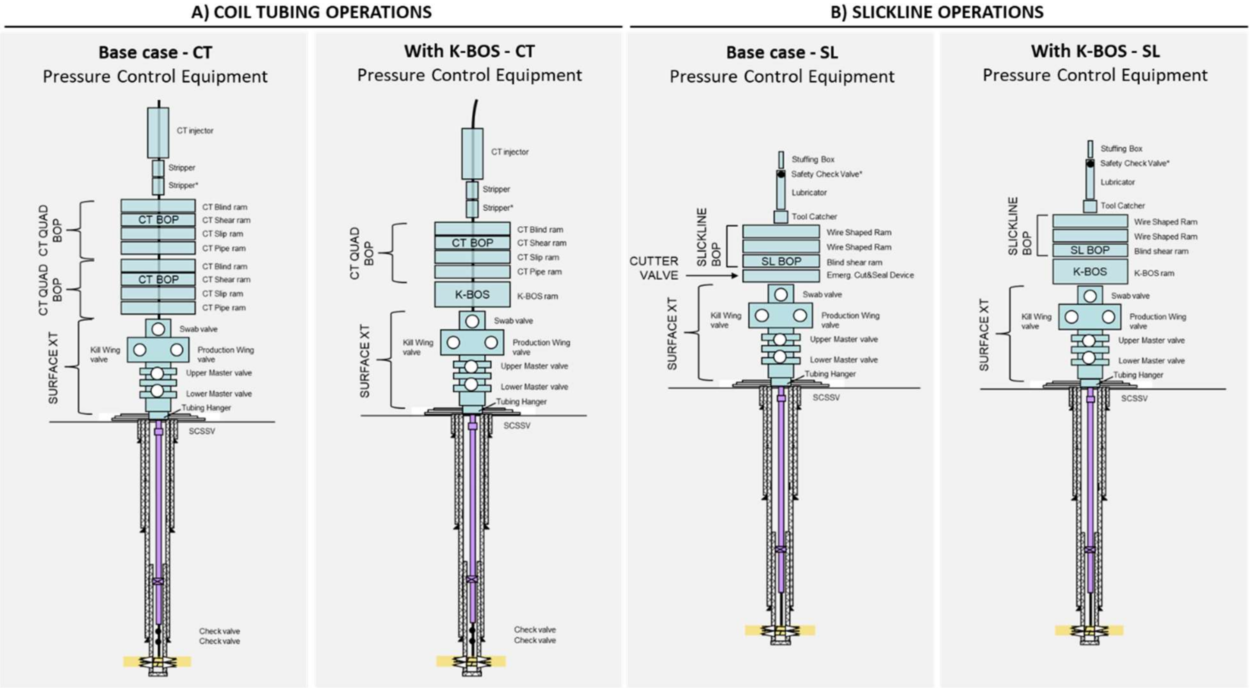


**Figure 27. "Base case" and "With K-BOS" PCE configurations during CT (A) and SL (B) operations**

The blowout probability was calculated for the aforementioned Drilling, Completion and rigless Well Intervention operations applying e-wise™ fault tree analysis approach. The normalized values blowout probability ($P_{BO,normalized}$) were calculated as follows and are displayed in the following graphs:

$$P_{BO,normalized,Base\ Case} = 1, (100\%)$$

$$P_{BO,normalized,With\ K-BOS} = \frac{P_{BO,With\ K-BOS}\ [\#events/operation]}{P_{BO,Base\ Case}\ [\#events/operation]}$$

The Figure 28 shows a comparison of the e-wise™ fault trees for the "Base case" and "With K-BOS" PCE configurations for a blowout scenario through the Annulus flow path during drilling the 5-7/8" hole in CHCD mode. The effect of having the K-BOS ram in the conventional surface BOP stack corresponds in adding redundancy of pressure control equipment (including the control system) as it is visualized in the conceptual fault tree in Figure 28:

- <u>"Base case" – Blowout through Annulus flow path</u>: this scenario is modeled with a fault tree addressing the failures of primary barrier (equivalent hydrostatic) and secondary barrier (failure of drilling BOP). Loss of secondary barrier can occur if at least one of the following intermediate events occur:
    - Failure to detect kick (caused by human error),
    - Failure of BOP flanges,
    - Mechanical failure of drilling BOP Stack which in turn can be caused by a BOP Control System failure, or a Mechanical failure of the annular and pipe rams preventers.
- <u>"With K-BOS" – Blowout through Annulus flow path</u>: the K-BOS System is applied as an additional safety equipment well barrier. Its position inside the fault tree is below a new intermediate event

which groups together the mechanical failure of the Drilling BOP and the K-BOS ram. Other intermediate events of the fault tree remain unchanged since the application of K-BOS has no effect on primary barrier control or on kick detection. BOP flanges failure rating also remains the same, regardless of the position of the K-BOS in the Stack. The application of K-BOS allows to reduce by 92.3% the probability of losing the secondary barrier which reflects in the same reduction of blowout probability through the Annulus flow path.

Although the fault trees in Figure 28 are specific for a blowout scenario through Annulus while drilling the 5-7/8" section in a Rim well, similar considerations on the general effect of the K-BOS in the FTA apply for all other scenarios in Kashagan field analysed with e-wise™ (e.g., tripping BHA, running slotted, etc.). However, to different operations and blowout flow paths correspond different percentage of reduction of blowout probability resulting in the specific values reported in Figure 29 for the overall drilling, completion and rigless operations.

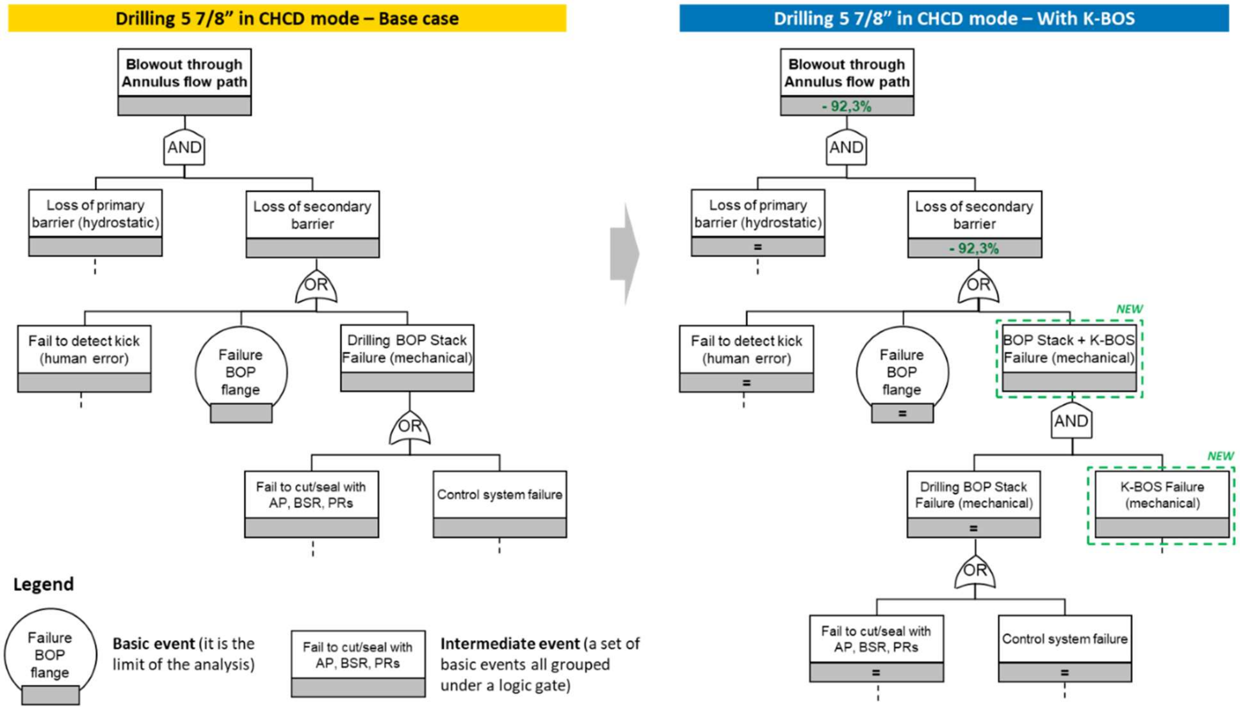


**Figure 28. Comparison of conceptual FTA for "Base case" and "With K-BOS" PCE configurations for a blowout scenario through Annulus during drilling 5-7/8" section in CHCD mode**

The normalized blowout probability values for the "Base case" and "With K-BOS" scenarios are reported in Figure 29. Figure 29 shows also the percentage of reduction of blowout probability achieved by including the K-BOS ram in the conventional BOP stack:

- For Drilling and Completion operations in Kashagan, the presence of the K-BOS in the surface BOP allows for a significant reduction in blowout probability by over 92% equivalent to about one order of magnitude.
- For CT operations, the replacement of the 2nd Quad CT BOP with a single K-BOS ram allows a marked reduction in the probability of blowout by over -40%.

- In SL operations in Kashagan, replacing the Flanged cable cutter valve with the K-BOS System entails a strong reduction of blowout probability by more than 98% (almost two orders of magnitude).

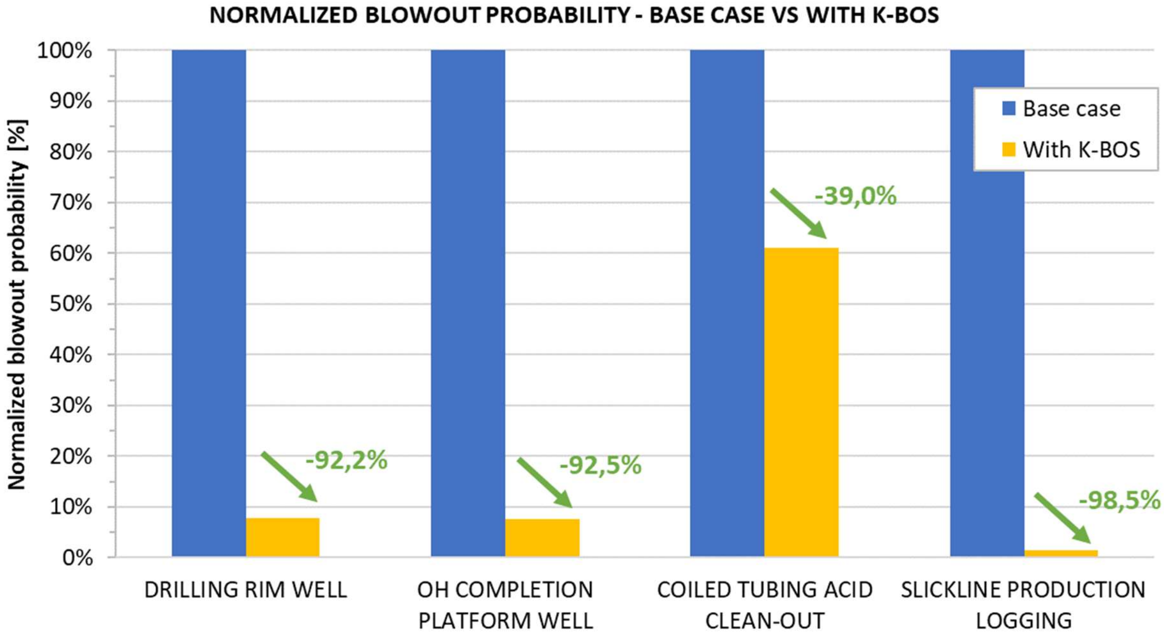


**Figure 29. Comparison of Normalized Blowout Probability for "Base case and "With K-BOS" PCE configurations**

## Summary and Conclusions

A blowout event in Kashagan is a Major Incident Hazard and main focus shall be on Prevention controls.

The analysis conducted and summarized in this paper demonstrated that K-BOS system is an excellent effort to further reduce the probability of a Well Emergency event. The quantitative risk assessment performed using the proprietary e-wise™ methodology showed that the application of the K-BOS ram during Drilling, Completion and Slickline operations significantly reduces the blowout probability by at least 1 order of magnitude (Figure 29).

No showstoppers were identified in utilizing the K-BOS ram in future Kashagan D&C and Workover operations. The maturation in the adoption of the K-BOS System during Kashagan operations will also allow to optimize, through ALARP demonstration, the Well Emergency Response readiness, potentially achieving also overall cost saving.

The improved shearing/sealing capacity and reduced closure time provided by the K-BOS enhance the risk profile for the oil and gas industry.

## Acknowledgments

The authors would like to thank NCOC, Eni and Kinetic Management for permission and encouragement to write and publish this paper. The authors also express their appreciation for the contributions of the NCSPSA Shareholders (KMG, Eni, ExxonMobil, Shell, Total, CNPC, Inpex) in addressing K-BOS as a good addition to improve barriers in Kashagan wells.

## Nomenclature

ALARP: As Low As Reasonably Practicable
AOF: Absolute Open Flow
API: American Petroleum Institute
BHA: Bottom Hole Assembly
BOP: Blowout Preventer
BSR: Blind Shear Ram
CCU: Control Unit
CHCD: Closed Hole Circulation Drilling
CT: Coil Tubing
D&C: Drilling and Completion
DD: Dangerous Detectable
DNV: Det Norske Veritas
DU: Dangerous Undetectable
e-wise™: Eni - Well Incident Systematic Evaluation
FMECA: Failure Modes Effects and Consequences Analysis
$H_2S$: Hydrogen Sulfide
HMI: Human Machine Interface
K-BOS: Kinetic Blowout Stopper
KEMS: Kinetic Energy Margin of Safety
MTTF: Mean Time to Failure
MTTR: Mean Time to Repair
N/D: Nipple Down
N/U: Nipple Up
PCE: Pressure Control Equipment
PFD: Probability of Failure on Demand
RCD: Rotating Control Head
SD: Safe Detectable
SIMOPS: Simultaneous Operations
SIL: Safety Integrity Level
SL: Slickline
$SO_2$: Sulfur Dioxide
SU: Safe Undetectable
FTA: Fault Tree Analysis
TVD: True Vertical Depth

## References

1. Gallagher, B., Dupal, K., Reese, J. “18 3/4" 15000 Psi Shear Anything KBOS for Subsea Well Applications”. Paper OTC-31048-MS presented at the Offshore Technology Conference, Virtual and Houston, Texas, August 2021. https://doi.org/10.4043/31048-MS
2. Gallagher, B., Juda, D., Gallagher, B., Angstmann, S. “Kinetic Blowout Stopper - The Airbag for the Oil and Gas Industry”. Paper SPE-194274-MS presented at the SPE/ICoTA Well Intervention Conference and Exhibition, The Woodlands, Texas, USA, March 2019. https://doi.org/10.2118/194274-MS

3. Zausa, F., Spelta, A., and Lorefice, R. "Comprehensive Methodology to Evaluate Blowout Probability Through the Combination of Geological Uncertainties, Human Errors and Equipment Reliability". Paper SPE-192934-MS presented at the Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, UAE, November 2018. https://doi.org/10.2118/192934-MS
4. Masi, S., Molaschi, C., Zausa, F., Michelez, J. “Managing Circulation Losses in a Harsh Drilling Environment: Conventional Solution vs. CHCD Through Risk Assessment”. Paper SPE-128225-MS presented at the IADC/SPE Drilling Conference and Exhibition, New Orleans, Louisiana, USA, February 2010. https://doi.org/10.2118/128225-MS