On the Development of the Blowout Preventer PRA Model

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Abstract: Specialized well control equipment is used in Oil and Gas (O&G) drilling operations to manage formation fluid influxes from geological formations. It is important to manage these undesired influxes (or kicks), for, if uncontrolled, they could lead to a loss of containment with serious safety and environmental consequences. The central component of the well control system is the blowout preventer (BOP). This equipment controls flow from the well using pipe shearing and wellbore sealing mechanisms. The effectiveness of these mechanisms, an important focus of the O&G industry, is the subject of this exercise. This paper describes how Probabilistic Risk Assessment (PRA) methodology has been applied to the BOP, a safety critical piece of equipment.

Keywords: PRA, Oil and Gas, Blowout Preventer, BOP, offshore operations, risk analysis.

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1. INTRODUCTION

Well control is an essential part of oil & gas drilling operations. Two different methods, primary and secondary, are used to control well pressures and are applied differently depending on the needs during normal operation and emergencies.

Primary well control is accomplished using the drilling fluid, called mud, to maintain a hydrostatic pressure above the formation pressure. To maintain primary control, the mud weight is adjusted as drilling progresses. These adjustments are necessary to promote safe and efficient operations in varying geological conditions.

Secondary well control relies on a blowout preventer (BOP). The BOP is used when the formation pressure exceeds the mud pressure and a kick occurs. A kick is an unplanned, uncontrolled flow of formation fluids (water, gas and oil) into the wellbore that, if not addressed, could lead to a loss of containment. The BOP is a safety critical mechanical device that uses shearing and sealing mechanisms to shut in the well, preventing a loss of containment.

Both regulatory requirements and industry standards address BOP design and operation. For example, the Code of Federal Regulations (30 CFR 250) and the American Petroleum Institute (API) standards (i.e., API 16A [1] for design and API STD 53 [4] for operations) contain detailed requirements for BOP design, testing, and operation, including risk assessment. Qualitative risk assessments, such as Bow-ties, FMEAs, HazIDs, and HAZOPs have been traditionally conducted on the BOP and other equipment to improve safety, reliability, and minimize downtime.

A recent opportunity presented itself to an oil and gas (O&G) operator to use PRA early in the equipment design process to evaluate the equipment and to communicate the quantified risk internally and to regulatory bodies. Although widely accepted in nuclear and aerospace industries, historically, very few attempts have been made to apply PRA to offshore drilling systems [1].

Recently, Anadarko Petroleum Corporation (APC) conducted a multi-phase project to develop PRA models of offshore drilling systems. A first of a kind BOP PRA model was developed, using the latest generation of BOP and MODU (Mobile Offshore Drilling Unit) configurations, followed by a Class 3 Dynamic Positioning System (DPS) PRA, and finally an Integrated PRA model. The PRA models were

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generic in nature and will serve as a starting point for modeling various specific drilling rig configurations.

The BOP PRA model presented here is the result of a collaboration between APC and NASA Johnson Space Center. The purpose of this paper is to present the BOP PRA model development process, preliminary findings, and lessons learned.

2. SYSTEM DESCRIPTION

The subsea BOP is a complex assembly of control systems and mechanical devices that is installed on a subsea wellhead (see Figure 1). Subsea BOPs consist of two main sections, a Lower Marine Riser Package (LMRP) and the BOP Stack. A riser connects the subsea BOP system to the ship, using a flex joint that allows for lateral movement. At the bottom of the riser is the LMRP, which typically includes annular BOPs and subsea BOP control systems. The LMRP connects to the BOP stack, which consists of various ram preventers and the choke and kill valves.

To function the BOP, hydraulic power is supplied through a rigid conduit line that runs along the riser. In deep water applications, (more than about 4,000 ft) electrohydraulic multiplex (MUX) systems are used to close the rams in a timely manner. The MUX system uses electrical signal communications to function the BOP with the hydraulics supplied from the rigid conduit lines. There are also subsea accumulators that serve as backup to the primary hydraulic supply for emergency BOP functions.

During a rig positioning emergency the crew activates the Emergency Disconnect Sequence (EDS) that secures the well by closing the blind shear rams on the BOP stack. Then, to prevent the structural damage to the riser and the well, the riser and LMRP are automatically disconnected from the BOP stack.

The BOP allows for passage of a drill string and tools, provides a conduit for circulation, and has the ability to control high formation pressure. The majority of rigs in the world are equipped with BOP systems rated to 15K or 15,000 psi.

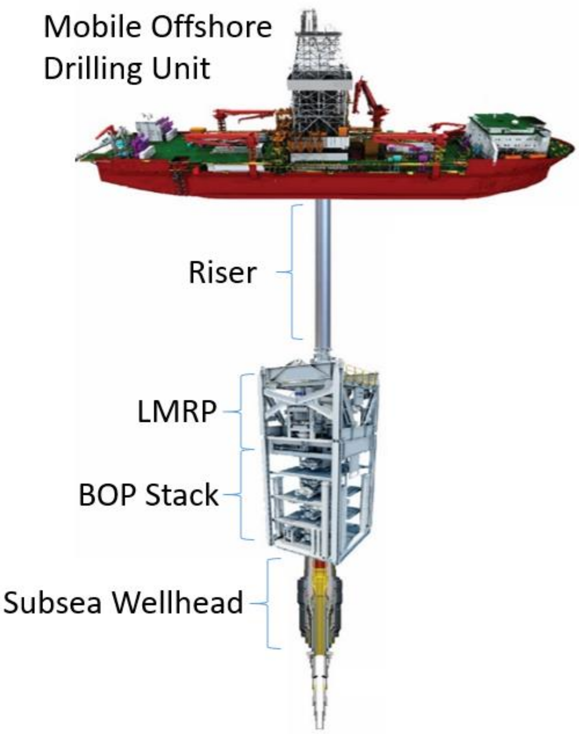

Figure 1: Subsea BOP and MODU

The BOP configuration has a high level of complexity because of the level of redundancies. Additional factors include the ability to close and seal on pipe, on casing, or on an open hole and shearing ability.

The BOP arrangement used in this PRA model is based on a generic configuration for deepwater exploration drilling operations (see Figure 2). The stack is configured with; 1) two annular preventers, 2) one blind shear ram, 3) one casing shear ram, and 4) three pipe rams. The test ram was not included in the model, as it cannot be used to control well fluids.

The Deadman and Autoshear are safety functions on the BOP that automatically activate functions on the BOP to secure the well. Both the Deadman and Autoshear functions were modeled based on the conditions required to activate those functions. The Autoshear operates after the LMRP is disconnected from the BOP stack. For the purposes of the model, the Deadman function is based on a parting of the riser that leads to the loss of BOP control communications and hydraulic power. The simultaneous loss of control communications and hydraulics were not specifically modeled, outside of the riser parting scenario.

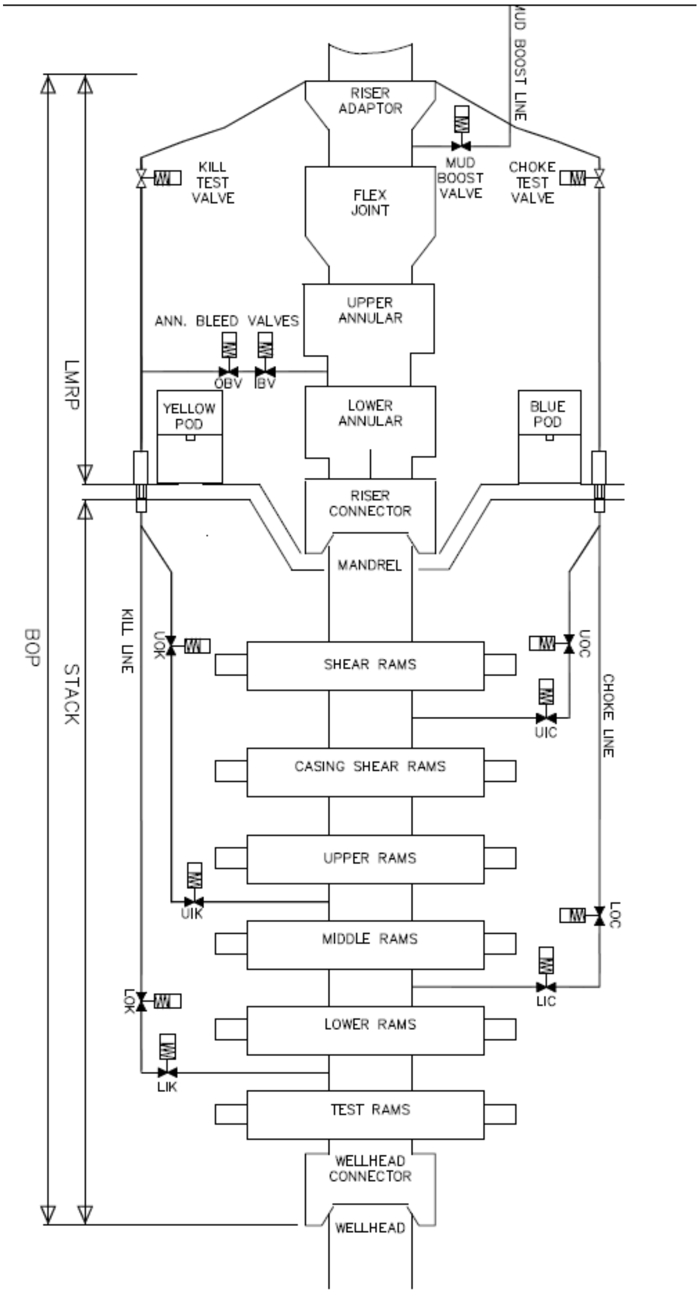

Figure 2: Simplified BOP Diagram

The surface hydraulics and electronics were included to complete the BOP system. The surface controls, including hydraulics and electronics, were developed with the help of BOP subject matter experts (SMEs) to represent a typical configuration. The choke and kill valves were modeled only as potential leak paths after an emergency disconnect and not in response to a well kick. For the purposes of this model, the BOP software has been sufficiently tested, to catch any software bugs, and therefore is not included.

2.1 Elements of the Blowout Preventer

The detailed BOP system diagrams, with component identifiers, were created to define system functions and the model boundaries. The analysis also accounted for the latest version of the associated API standards and requirements, including API Standard 53 [4] and API Specification 16D [3]. The following sections describe the main BOP subsystems analyzed with the model.

- Surface Accumulators – The surface accumulators are the primary hydraulic supply for the BOP. The model accounts for the accumulators individually at the basic event level and includes a common cause failure of the accumulators. The accumulators are modeled in racks with two banks each. Each bank has 10 accumulator bottles. It is assumed that the failure of one accumulator bottle is taking out the bank.
- Hydraulic Power Unit (HPU) – The HPUs are a series of pumps, filters and check valves which keep the accumulators at or near capacity and energized. The HPU is assumed to be a functional backup to the accumulators. While the primary function of the HPU is to keep accumulators energized, in the event of accumulator failure the HPUs are deemed capable to function the BOP at a degraded rate. The hydraulic fluid reservoir and mixing unit were not included in the model.
- Surface Hydraulics – Beyond the surface accumulators and HPUs are a series of filters, bypass valves and a pressure relief valve as part of the Surface Hydraulic Power System. This subsystem ends at the rigid conduit lines.
- Central Control Unit (CCU) – The CCUs are the primary computers and electronic controls for the BOP. They process the inputs and route the communication to the subsea controls. The CCUs are modeled as units at the basic event level and are not broken down further. There are two redundant CCUs, one on the yellow side and one on the blue side.
- Control System Displays – The control system displays are the panels that personnel use to function the BOP. The control system displays are modeled at the basic event level and were not broken down further. There are redundant displays placed in separate locations.
- Power System (Primary Rig Power and UPS) – The primary power is supplied from the vessel's generators. For the power requirements of the BOP, only one of the six generators is required. The Uninterrupted Power Supplies (UPS) are the backup power sources. They are charged by the rig's primary power system. There is a yellow side UPS and a blue side UPS. The UPSs do not provide power to the opposite sides for this model.
- Umbilicals – The umbilicals are lines that provide communications and electrical power from the surface to the subsea BOP controls. The umbilicals are modeled at the basic event level. There are redundant umbilicals, with one on the yellow side and one on the blue side.
- Lower Marine Riser Package – The LMRP consists of the primary BOP controls, including all of the solenoid valves, Subplate Mounted (SPM) valves, shuttle valves, Subsea Electronic Modules (SEMs), and the rigid conduit manifold. The LMRP also contains the two annular BOPs. The LMRP is modeled at a greater level of detail due to the complexity of the system and therefore has the greatest amount of fault trees associated with it.
  The annulars are considered redundant for the purposes of the model. Annulars normally have a lower pressure rating capability than the blind shear rams and pipe rams. Since there are operational constraints on annulars, the failure path on the event trees for the annulars also contains the scenarios where pressure exceeds the annulars capabilities.
- BOP Stack – The BOP stack provides the well control components used to close in and seal off the well at the maximum pressure ratings. The BOP stack is modeled with three pipe rams, a blind shear ram (the sealing element) and a casing shear ram (for shearing only). With the model

being generic, the pipe rams are considered redundant and all have the ability to seal off the well when the drill string is across the stack. Depending on the scenario, the blind shear ram may be the only component that can seal off the well.

2.2 Kick Detection System

A kick is defined as an influx of formation fluids from the rock formation into the wellbore due to the formation pressure being greater than the drilling fluids hydrostatic pressure. The drilling fluid, also known as mud, is being actively managed throughout the operation to control influxes of formation fluids. The mud system is a primary means of well control. The kick detection system alerts the driller of a kick and therefore allows him to respond by activating the BOP. The kick detection system modeled was also utilized in the development of the Human Reliability Analysis (HRA) for the crew's actions. The HRA focused on the crew detecting the kick and the recovery actions if the primary responsible party does not notice it right away.

The kick detection system, as modeled (see Figure 3), is a generic configuration based on industry standards. Maersk Training assisted in defining the system, which is based on the detection equipment for positive kick indicators. The complete mud system was not modeled because, by ground rules, the primary well barrier was not included in the BOP model.

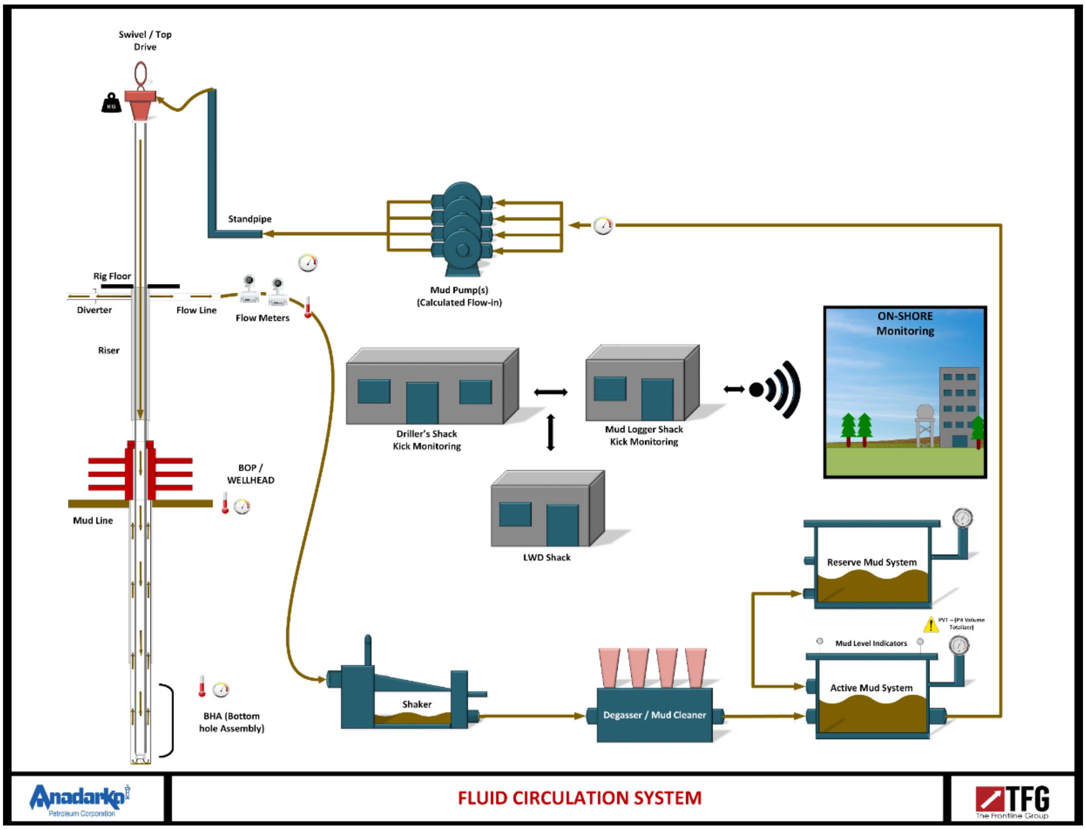

Figure 3: Generic Representation of the Kick Detection System Modeled

The kick detection system consists of a flow paddle, two mud level indicators and the information display. There are two separate systems, one for the driller and one for the mud logger. Both have the same equipment layout and are considered redundant for the purpose of this model. There is also a shore based real-time monitoring center which monitors the same information as the mud logger.

The kick detection components are utilized in detection of a kick through positive indicators. A positive kick indicator is when there is an increased flow rate (above the mud pump rate) as identified by the flow paddle or by an increase in the fluid level in the mud tanks. For other kick scenarios (e.g., tripping pipe), other detection means are required, such as the trip tank. This model does not incorporate the trip tank or other kick detection devices.

2.3 Success Criteria

Establishing success criteria is an essential step in the probabilistic risk assessment of complex systems. The success criteria are focused on the system configuration and its required response during off nominal events. The criteria describe the minimum functional or equipment requirements for the system success for a given scenario. There may be different equipment functions required for a kick or loss of position initiating events, which can affect the success criteria. Table 1 provides an example list of the BOP success criteria.

Table 1: Example Success Criteria

Subsystem / Component	Success Criteria
Surface Accumulator Racks	3-out-of-4
Hydraulic Power Unit	1-out-of-2
Surface Hydraulic Filter	1-out-of-2
Surface Bypass Check Valve	1-out-of-2
Central Control Unit	1-out-of-2
Control System Displays	1-out-of-2
Umbilicals	1-out-of-2
Annulars	1-out-of-2
Pipe Rams	1-out-of-3
LMRP Control Pod	1-out-of-2
Kick Detection System	1-out-of-2

4. MODEL DEVELOPMENT

There was an internal project focused on the design and development of equipment to support a field with a high pressure high temperature environment. The project needed an enhanced risk assessment methodology to assure the safety of the newly designed equipment and regulatory compliance. The PRA methodology was selected based on its history of making positive impacts in both nuclear and aerospace industries.

The work presented in this paper is a result of a collaborative effort with NASA Johnson Space Center (JSC). It was a phased approach that allowed time for learning and refining the model. The effort involved multiple iterations. A series of smaller projects assured a better understanding of the PRA applications and increased collaboration between the NASA JSC PRA experts and the internal PRA team. The engagement with NASA JSC took place through the Space Act Agreement, which allows NASA to work with commercial entities.

The internal PRA team was comprised of Cogoto, Inc. and The Frontline Group experts. Cogoto, Inc. provided expertise in the PRA, knowledge of the O&G systems, and experience of working with NASA on the Space Shuttle and Constellation Program PRAs. The Frontline Group provided expertise in the offshore systems operations and hazard analysis. This expertise, combined with the internal process and equipment system SMEs, allowed for an efficient coordination of the PRA modeling process.

4.1 BOP PRA Model

The first PRA attempt was focused on modeling a generic subsea BOP stack and subsea controls. It was a steep learning curve for both the NASA PRA team, who had no previous O&G experience, and internal SMEs, who had no PRA experience. The NASA team went through a thorough process of familiarization with the offshore systems and operations as well as the O&G specific language and culture. The SMEs had to learn principles of the PRA methodology, nomenclature, and mathematical basis of the PRA.

The NASA team started building the first BOP model using the system definition and data sources provided by the SMEs. The idea was to obtain an unbiased evaluation of the BOP risks. This team consisted of a PRA analyst, data analyst and BOP subject matter expert. The subject matter expert spent a majority of time at the NASA facility. The intent with this was to help NASA with a better and more thorough understanding of the BOP system, O&G terms and concepts. There was planned up front time dedicated to system familiarization. Not only did this relate to the equipment design, but also included the purpose and the operations of the equipment. A series of informative meetings with NASA occurred and a BOP facility tour was conducted to further the understanding of the equipment and operations.

The initial model development was constrained to the subsea BOP. The high-level assumptions were that a kick occurred, the person responds to the kick, and then activates the BOP. The model also included the emergency disconnect function of the BOP with the assumption that the vessel has already lost position and, therefore, the model did not include any of the DPS failures. The two initiating events used in the analysis were a well kick and loss of vessel position. The end state of this analysis was a loss of containment. During the model development phase, the data collection and analysis started. NASA started collecting data from O&G sources, and, where the sources were limited, they incorporated data from other industries and open sources. Upon completion of the initial work, the model was validated at NASA, with the BOP SME, for accuracy. After completion of the validation, NASA generated a report documenting this analysis. Leading up to this phase of work, the internal team took a hands-off approach to get an unbiased view point.

In parallel, the internal PRA team was established to coordinate the PRA activities, validate the PRA models, and ultimately adapt these models to a specific rig's configurations and needs. With the original hands-off approach, the internal PRA team became fully engaged with the model validation only when the first draft of the report was created. As a result of this approach, the conceived BOP PRA model required multiple revisions to properly reflect the BOP system's logic and drilling operations. The report required additional collaboration between NASA and the internal team to incorporate the proper O&G terminology and better describe the nuances of the offshore system operations and procedures. Also, the model scrutiny highlighted aspects of the model that required updates. These updates were later utilized as the starting point for the subsequent analysis. However, this project was an excellent learning opportunity and, in spite of the extra work that had to be invested, it provided some interesting insights proving the value of the PRA methodology.

4.2 DPS PRA Model

Because the first BOP model did not include any of the DPS logic, it was necessary to work on the DPS contribution to loss of containment. The MODU's DPS PRA model was the next analysis performed. The DPS is a system that maintains vessel position by the thrusters alone, with the help of position reference sensors, computers and the main power system. This system was modeled as part of a loss of containment scenario caused by a loss of vessel position. While this analysis is not the focus of this paper, it is mentioned here as it affects the BOP scenarios modeled. One benefit of this analysis was that a simplified naming convention was implemented following the BSEE PRA guide [6] which was in development at that time. Also, using the lessons learned from the first BOP PRA, there was a much closer collaboration between the NASA and the internal PRA teams that resulted in a much better model and final documentation.

4.3 System Integration PRA

The next project with NASA was on the integration of the BOP and the DPS PRA models developed in the earlier phases. In addition, the new scope included the BOP surface controls and the kick detection system, which were not previously modeled. This analysis resulted in a much more complete and mature model that incorporated all of the updates and lessons learned from the previous two phases of the project. The integrated PRA model development was a collaborative and iterative process (see Figure 4), that produced a high quality product.

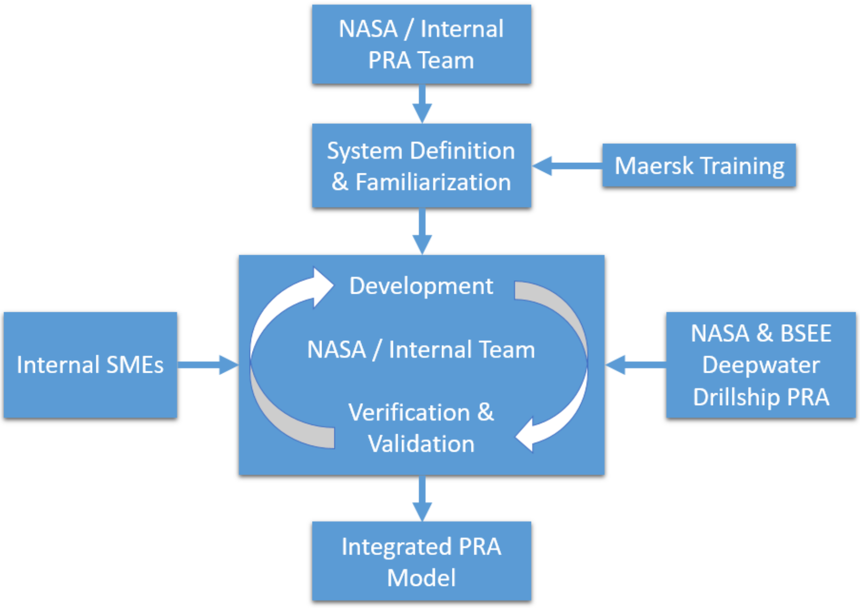

Figure 4: High Level Model Development Process for Integrated PRA

The internal PRA team worked in concert with the NASA analysts and SMEs to revise, update, and validate the model as it was being created. Regular collaborative sessions were held to discuss the model updates. This effort resulted in a high fidelity PRA model vetted by both O&G SMEs and PRA practitioners. While still generic, the integrated model is a good representation of the BOP and DPS currently in operation. Since this work supersedes the previously developed models, the following sections refer to the BOP PRA model created within the scope of the integrated model.

4.4 System Boundaries

The BOP system modeled includes the LMRP, the BOP stack, both subsea and surface control systems, the kick detection system, as well as the personnel making critical decisions, for example, initiating the EDS. The LMRP includes the annulars and subsea control systems, yellow and blue pods. The BOP stack has various ram preventers and the choke and kill lines. A top level diagram of the model boundaries and major system elements is shown in Figure 5.

The well kick and a vessel loss of position were the initiating events. Events such as a vessel collision, loss of vessel stability, dropped objects, or inadvertent BOP operation were not included. The model does not account for well control methods outside of closing the BOP. The primary end state for this analysis is loss of containment. There were additional end states included in the analysis for other operational consequences, which are beyond the scope of this paper.

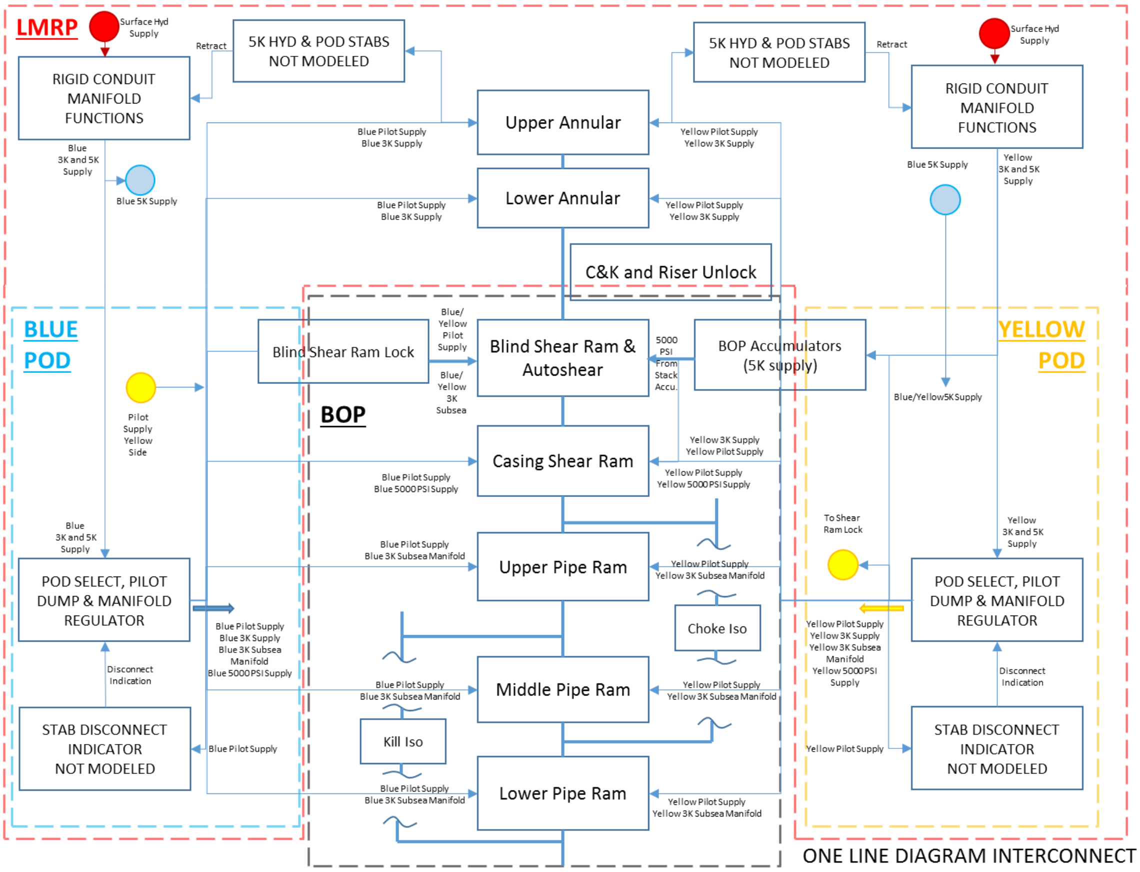

Figure 5: Top Level Subsea BOP System Boundaries

4.5 Event Trees

The event trees were developed, using a sequence of events defined in the operating procedures [5], to describe accident scenarios leading to a loss of containment. An example of a sequence of events involving mitigation of a well kick is shown in Figure 6.

Figure 6: The Well Kick while Drilling Sequence Diagram

The event sequences have a series of conditions that specify the state of the well during a well kick, to properly account for risk associated with various operations taking place with the BOP installed and the DPS being used to keep the vessel in position. The pre-processing event trees were needed to account for all the scenarios that would involve various combinations of the preventers to be activated depending on what was in the hole and the drilling operation in progress when the kick or loss of position occurred. Figure 7 shows the operational logic of a well kick scenario and Figure 8 shows how it was implemented in the model.

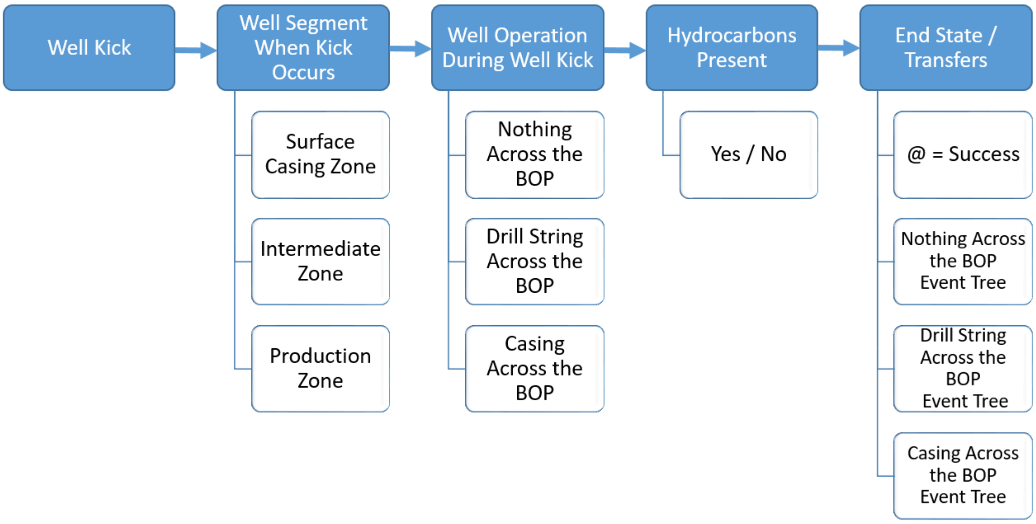

Figure 7: The Well Kick Operational Sequence Diagram

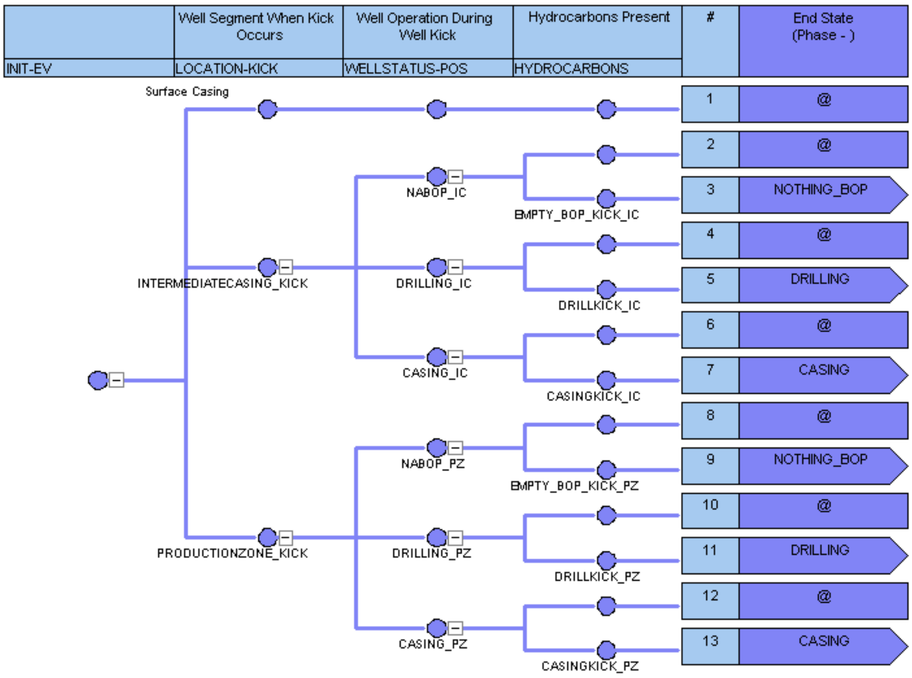

Figure 8: Implementation of the Well Kick Operational Logic

During a loss of position event the operational logic included:

- Classification of the loss of position event;
  - Drift off, which is caused by equipment failure/s leading to the system being unable to maintain position.
  - Drive off, which is caused by either a malfunction in the position reference system or caused by improper position inputs causing the vessel to rapidly move outside of the normal operating area.
  - Push off, which is caused by weather that exceeds the capability of a fully functional vessel.
- Well segment when the loss of position event occurs; surface casing, intermediate zone and production zone
- Well operation during the loss of position event; drilling, running casing or when there is nothing across the stack
- Whether hydrocarbons are present or not

- Whether the Emergency Disconnect Sequence is initiated or not

The conditional breakdown of the event trees allowed for the separate BOP event trees to be developed. As an example, when running larger casing size, the availability of specific functions on the BOP is limited to annulars, casing shear rams (non-sealing element) and blind shear rams. Whereas, when drilling, the available functions for the BOP include annulars, pipe rams, casing shear rams (non-sealing element) and blind shear rams. In the example event tree shown in Figure 9 when a kick occurs and there is nothing across the BOPs, closing the annulars may be sufficient to shut in the well. If the annulars fail, then the blind shear ram has a high chance of securing the well.

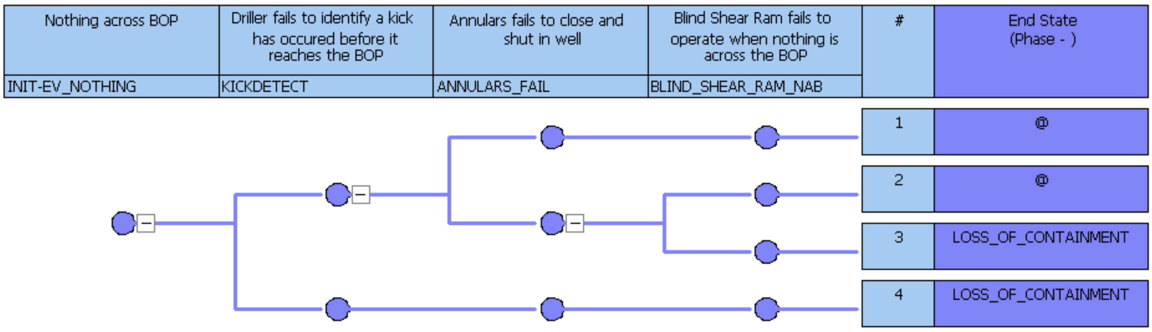

Figure 9: Example Event Tree

4.6 Fault Trees

The BOP's mitigative functions (annulars, pipe rams, blind shear rams, etc.) were modeled with fault trees down to the component level. The fault trees contain all the system logic, redundancies, common cause factors, maintenance, human reliability, and the data with the assigned uncertainty distributions for the basic events. The top fault trees utilized a number of sub-trees for the sub-systems that provided the same functions to various system that could be replicated. However, the basic events had unique names and always reflected specific components with distinctive identifiers. The following is an example of a fault tree for the middle pipe ram on the BOP.

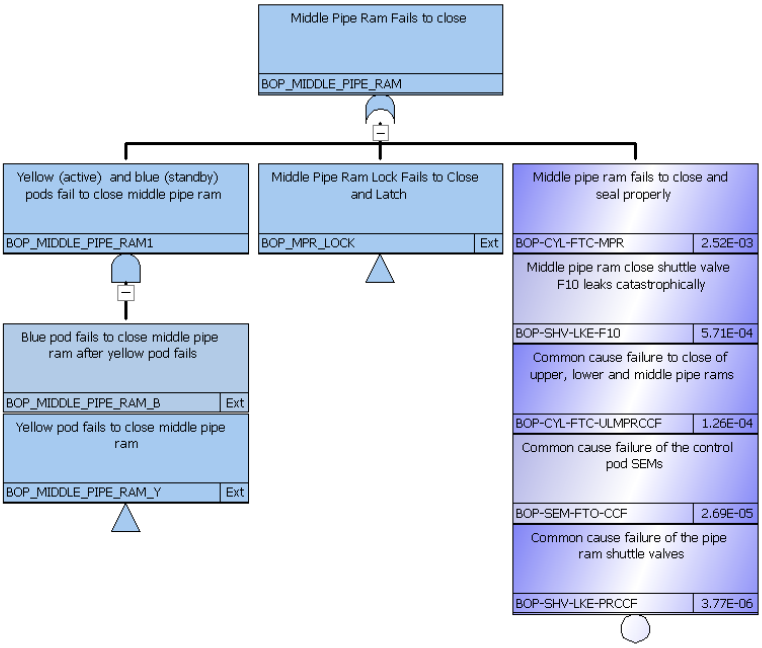

Figure 10: Example Fault Tree

4.7 Human Reliability Analysis

Human factors and HRA were an essential aspect of this PRA model. The HRA methodology applied was Cognitive Reliability and Error Analysis Method (CREAM) and was facilitated by NASA HRA experts utilizing the internal and Maersk Training subject matter experts. The primary HRA examined the response to positive kick indicators and accounted for the interactions among the driller, mud logger and the real time monitoring center. This HRA consisted of monitoring for a well kick and activation of the BOP. The subsequent activities related to closing in the well were assumed to be part of this HRA. There were other HRAs developed for this model, but the primary one was focused on the kick detection and response scenario.

4.8 Data

The main O&G data used in the model were from sources such as SINTEF, OREDA, and OGP. One of the benefits of using the PRA methodology in O&G application is that a variety of data sources can be utilized. Alternate data sources were used when no data was available from O&G. These sources included military, commercial or nuclear databases. The rationale for using data from other industries is that they had similar failure modes and comparable failure rates. The alternate data used in the model were from sources, such as NPRD, IEEE, etc.

5. RESULTS

The results shown below are based on a generic model and with some broad assumptions and surrogate data. There are a total of 9 Event Trees developed for this model with 170 separate Fault Trees and over 1100 basic events. This model produced about 17,000 cut sets for the loss of containment end state using a 1E-10 truncation limit. The overall risk of loss of containment is dominated by the human, followed by blind shear rams, regulators and shuttle valves.

The results of this analysis confirmed the O&G experience that the human is the one of the largest contributors to the overall risk. The human contribution to the risk is roughly 90%. Figure 11 shows the greatest percentage contributors to the overall risk.

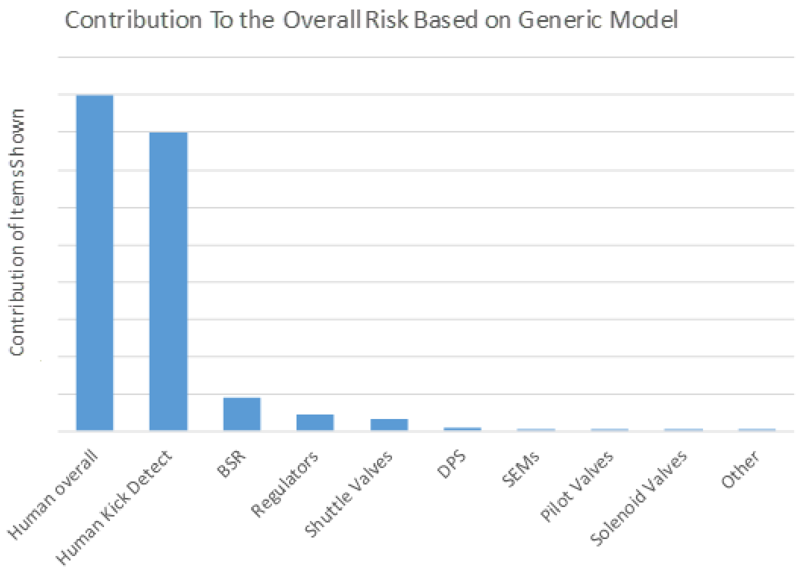

Figure 11: Major Contributors to the Risk of Loss of Containment

The higher contribution from the blind shear rams is justifiable due to the BOP configuration. Historically, based on O&G experience, the pilot valves and solenoid valves have higher failure reporting incidents due to being the most numerous parts on the BOP system. However, due to the level of redundancy of the components such as SEMs, pilot valves and solenoid valves, they do not contribute as much to the overall risk. While there are numerous other redundancies within the system, the single point failures and human error dominate the risk. Common cause was not a major contributor to the overall system's risk.

6. LESSONS LEARNED

There were a number of lessons learned during this BOP PRA model development. Some of the prominent lessons are described below.

For a new methodology implementation, each party needs to account for a fair amount of upfront time for the familiarization with both the system and the process. It is good to engage process experts from outside of the industry for a different perspective and internal experts with knowledge of both O&G and PRA methodology.

The BOP PRA required multiple updates and iterations to properly model the functions and operations of the BOP. It is essential to keep a detailed change log, with assigned responsibilities, to track and implement the changes.

The collaborative process developed by the team (see Figure 4), allowed both the internal and NASA PRA teams to work interactively, and proved to be one of the most efficient elements in the BOP PRA model development. This lead to a high quality product with minimal revisions. This collaborative process was developed as a result of learning from the previous phases of the project.

A standardized and simplified naming convention is necessary when it comes to the model. In conjunction with schematics, or diagrams, which uniquely identify all the necessary components and functions. Not only will this assist with validating the model, it also makes validating the results much easier, saving time in the process.

7. CONCLUSION

The model described in the paper focuses on a current generation BOP, with the configuration of upper and lower annulars, blind shear ram, casing shear ram and three pipe rams. It also includes control systems, EDS, and Autoshear functions. The two initiating events analyzed were a well kick and a loss of vessel position. The end state was a loss of well containment.

The results showed that, for the current model, the human is the largest contributor to the overall risk, thus confirming the O&G experience. The other main contributors were blind shear rams, regulators and shuttle valves. The pilot valves and solenoid valves have a higher level of redundancy therefore do not contribute noticeably to the overall risk. Given that this is a generic model, with data from numerous sources, the results are considered introductory and should be used as guidance only.

There was a phased approach to model development, utilizing a small internal team to coordinate the PRA process and engage NASA's expertise. The PRA, while complex, is not as onerous as originally thought. Just like any process, it requires the right team, creating the right model with the right data. It is essential to have the team with experience in both PRA methodology and the system being analyzed.

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