Research Report by Argonne's Strategic Alliance for Global Energy Solutions (SAGES)

AUGUST | 2017

Risk-Based Evaluation of Offshore Oil and Gas Operations Using a Multiple Physical Barrier Approach

AUTHORS

Bruce P. Hamilton

Erna Gevondyan

Joseph C. Braun

Daniel M. Fraser

Edited by: Stephanie Hill

ACKNOWLEDGMENTS

The authors wish to acknowledge the enthusiastic participation of many Bureau of Safety and Environmental Enforcement (BSEE) staff for their help, suggestions, guidance and cooperation toward preparing this document, with special recognition for the time and contributions of Michael Pittman, Jarvis Abbott, and Kelly Griggs – BSSE HQ, Sterling.

The authors would also like to recognize the efforts of David Grabaskas, Roy Lindley, Dennis Moore, Alex Sas-Jaworsky, and Mike Vander Staak for their technical contributions to several of the risk analysis studies discussed in this report.

EXECUTIVE SUMMARY

This report identifies a risk-analysis technique, developed by Argonne, that focuses on physical barriers in the offshore oil and gas industry. It studies the careful design, construction, operation, and maintenance of physical barriers to provide a greater degree of safety and environmental protection.

The focus on physical barriers unifies safety and risk analyses across many industries. However, safety approaches in each industry must adapt to the unique features of that industry. Argonne's approach to offshore oil and gas risk analysis begins with the proper characterization of risk, and this characterization is reached by distinguishing process safety from industrial safety. To have a streamlined approach for process safety in the oil and gas industry, a consistent definition of *barriers* is needed. This report builds upon the fundamental definition of *physical barriers* and describes the system and the difference between industrial and process safety.

Currently, the oil and gas industry recognizes two meanings for the word *barrier*—the literal meaning and the figurative meaning. As a result, process safety and industrial safety are often conflated. The industry has demonstrated a very strong commitment to industrial safety in facilities. There has been a steady reduction in the loss of life and health from industrial accidents in facilities. However, most ***major*** industry incidents that involve multiple fatalities or permanent total disabilities, extensive damage to the structures, or severe impact to the environment are related to ***process integrity***.

These observations have led the Argonne team to develop the Multiple Physical Barriers (MPB) approach for evaluating process safety. In the MPB Approach, the only barriers are ***physical barriers***. Training, people, and procedures are important, but they are not barriers in their own rights. For example, failure to follow a correct procedure may cause a major accident, but only by means of its impact on the performance of a physical barrier.

How then do people in the industry ensure that physical barriers are performing their critical safety functions? The answer is to ensure that ***success paths***—systems, components, and human actions needed to ensure the success (of a barrier)—are in place and are capable of performing their functions in all expected conditions and circumstances. A collection of success paths is sometimes called a *success tree*.

This report summarizes the application of Argonne's approach, which includes identifying multiple physical barriers and developing success paths. The objective of this approach is to support BSEE's goal of enhancing safety in the offshore oil and gas industry. This approach helps implement key objectives such as the following:

- expanding BSEE's tools for enhanced oversight of high-risk activities and equipment by developing and implementing a systematic methodology to understand and manage high-risk areas

- facilitating BSEE's utilization of data to develop a variety of applications for MPB models; MPB models can be used as tools to visualize the critical barrier systems in offshore operations
- using the MPB and success path models to facilitate productive communication between operators and BSEE and to help all parties focus on improving safety outcomes on the Outer Continental Shelf (OCS).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
ANL	Argonne National Laboratory
APD	Application for Permit to Drill
API	American Petroleum Institute
BOEM	Bureau of Ocean Energy Management
BOEMRE	Bureau of Ocean Energy Management
BOP	Blowout Preventer
bopd	Barrels of Oil Per Day
BSEE	Bureau of Safety and Environmental Enforcement
BSR	Blind Shear Ram
CBHP	Constant Bottom-Hole Pressure
CBP	Choke Back Pressure
CCF	Common Cause Failure
CCU	Central Control Unit
CF	Circulating Friction
DMAS	Deadman/Autoshear System
DWOP	Deepwater Operation Plan
EDS	Emergency Disconnect System/Sequence

FG	Fracture Gradient
FMECA	Failure Modes and Effect Analysis
FOSV	Full-Opening Safety Valve
HP	High-Pressure
HPHT	High-Pressure, High-Temperature
HSE	Health, Safety, and Environmental
IEC	International Electrotechnical Commission
JIP	Joint Implementation Project
KDV	Kick Detection Volume
KRT	Kick Response Time
KWF	Kill Weight Fluid
LMRP	Lower Marine Riser Package
LOP	Leak-Off Pressure
MASP	Maximum Allowable Surface Pressure
MPB	Multiple Physical Barrier
MPD	Managed Pressure Drilling
MUX	Multiplex
MW	Mud Weight
NOG	Norwegian Oil and Gas Association
NRC	Nuclear Regulatory Commission
OCS	Outer Continental Shelf
PC	Pressure Category
PFD	Probability of Failure per Demand
PP	Pore Pressure
PRA	Probabilistic Risk Assessment
RCD	Rotating Control Device
ROV	Remotely Operated Vehicles
RP	Recommended Protocol
RRF	Risk-Reduction Factor
SBP	Surface Back-Pressure
SEM	Subsea Electronic Module
SIL	Safety Integrity Level
SME	Subject Matter Expert
SPM	Sub Plate Mounted
TIW	Texas Iron Works

INTRODUCTION

Safely exploring, developing, and producing oil and gas on the Outer Continental Shelf (OCS) is a long, multistep process that starts many years prior to the first production of oil and gas. The Bureau of Safety and Environmental Enforcement (BSEE) works throughout this process to reduce the risks of operating offshore. Argonne National Laboratory ("Argonne") provides technical assistance to BSEE in developing tools and capabilities that facilitate the utilization of a risk-based approach in BSEE's management and governance processes.

BACKGROUND

The Department of the Interior's Inspector General, as well as other external bodies (including the Transportation Safety Board, National Academy of Engineers, and the Oil Spill Commission), recommended that BSEE develop a dynamic, regulatory framework capable of incorporating data about the relative risks of regulated activities. These bodies highlighted the importance of an efficient, technically sound, and legally defensible regulatory approach. Such an approach would use risk-based analysis as a prioritizing tool and would include regulations that require risk analysis to assess operations defined as "high risk." Since the time of those recommendations, BSEE has embarked on an investment strategy to develop and implement tools and processes that support a more comprehensive approach to risk-informed regulatory activities such as regulation, inspection, permitting, and policy analysis.

Furthermore, BSEE and Argonne have developed a model for incorporating risk-informed decision-making principles through a Multiple Physical Barrier (MPB) identification and analysis methodology. BSEE and Argonne also recommend ways to incorporate risk analysis into BSEE's existing governance and approach to assessing and regulating high-risk activities such as drilling, well-completions, and well-workovers.

STUDY OBJECTIVES

Building on earlier MPB model-development efforts, BSEE enlisted the services of Argonne to provide technical assistance for the development and implementation of tools and processes that would support a more comprehensive and effective approach to risk-informed regulatory activities. This assistance includes the development of a risk-based screening methodology for identifying important barriers in offshore hydrocarbon development operations in a way that highlights critical barrier systems for consistent analysis and inspection. Argonne has also assisted BSEE in applying the MPB model to a range of production scenarios and safety systems; drilling scenarios with multiple rig types; and differing operational environments, such as deepwater and high-pressure, high-temperature (HPHT).

Specific examples of this work include the following:

- expanding BSEE's tools for enhanced oversight of high-risk activities and equipment by developing and implementing a systematic methodology to understand and manage high-risk areas, including pipelines, drilling, completions, and well-workovers

- facilitating BSEE's utilization of its data to develop a variety of applications of MPB models, which can be used as tools to visualize critical barrier systems in each of the operations described above
- using information and insights culled from interactions with operators and BSEE subject matter experts (SMEs), as well as an analysis of BSEE data on facility construction and operation, to develop MPB models that equip BSEE with tools to visually analyze critical barrier systems, related regulations, and industry standards all at once. This can help determine the inspectable characteristics that BSEE can focus on to improve safety outcomes on the OCS.

Argonne's technical assistance on risk-based management and governance for BSEE has yielded this report, which is organized in the following parts:

- introduction of the MPB Approach as a systematic, clear, and comprehensive approach for managing operational safety risks
- overview of MPB Applications conducted for offshore drilling, production, completions, and workover activities
- description of the research findings
- summary conclusions and recommendations

The report's appendix provides a collection of MPB models Argonne developed illustrating critical barriers that must be maintained to ensure safe operation for a variety of offshore operations and technologies.

MULTIPLE PHYSICAL BARRIER APPROACH TO OPERATIONAL RISK MANAGEMENT

ISSUE BACKGROUND

Argonne has been actively involved in assessing the safety of nuclear reactors since its inception in 1946. When asked to provide assistance for enhancing safety measures in the offshore oil and gas industry, Argonne developed the MPB Approach. The MPB Approach aims to enable the industry to move in the most direct and systematic fashion to a position where operational (or process) risks can be identified, evaluated, and acted upon to improve the safety of offshore operations.

The MPB Approach is based on key principles from nuclear power plant safety and also from other industries[1]. However, the nuclear industry and the upstream oil and gas industry could hardly be more dissimilar. Nuclear power plants remain in one place for their entire lifetimes and carry out a single mission of producing electricity for distribution over a land-based electrical grid. Because nuclear power plants spend all but a fraction of their time in a steady-state

[1] Since 2010 Argonne has been researching operational risk and comparing approaches from a variety of applications including nuclear, aviation, maritime, transportation, and chemical safety.

situation, the Nuclear Regulatory Commission (NRC) uses Probabilistic Risk Assessment (PRA) to estimate risk by *determining what can go wrong*, how likely malfunctions are to happen, and what the consequences of these malfunctions are.

In the oil and gas industry, however, offshore facilities perform many different functions, most notably drilling, completion, production, workover, and closure or abandonment of offshore subsea wells. Offshore facilities perform these functions under operating conditions that change from day to day. Hence, a major adaptation from the nuclear-style PRA approach is required to better address this dynamic environment in offshore oil and gas operations. The MPB Approach to operational risk (safety) management was born out of this necessity.

Argonne's MPB Approach enables effective risk management by *determining what must go right*. By focusing on success, this approach combines risk variables and prioritizes them so they become manageable. The approach is applied qualitatively at first, in order to delineate, characterize, and illustrate how critical safety functions are to be met. Analytical tools then help quantitatively assess risks associated with critical safety functions under a variety of scenarios and prioritize strategies that balance costs and benefits while managing risks.

PHYSICAL BARRIERS

The big accidents in the oil and gas industry have come not from failures of industrial safety, but from lapses in process safety.

Industrial Health, Safety, and Environmental (HSE) risks stem from a wide variety of hazards to people in the workplace. On the other hand, process, or operational safety, risks stem from the breach of; removal of; or failure to properly design, install, or maintain a required *physical barrier*. If all required physical barriers are in place and are effective, then there will be no operational safety incidents. For example, an effective cement plug barrier, fluid column barrier, or blowout preventer (BOP) barrier would have prevented a Macondo accident. If these barriers had been effective, there also would not have been any operational (or process) safety incidents in the Gulf, including explosions, loss of well-control events, and major environmental spills. Operational (or process) safety is about establishing and maintaining multiple physical barriers.

The concept of physical barriers is not foreign to the offshore oil and gas industry. Typical structures such as casing and cement, the fluid (or mud) column in a well, and operable valves in the well structure are all physical barriers. To achieve success in the design, construction, operation, and maintenance of a given system, *multiple physical barriers* must be in place and must be operational so that the failure of a single barrier cannot lead to failure of the entire system.

Upon looking at the oil and gas industry, Argonne has found a very strong commitment to industrial safety at facilities, and a historical record shows a consistent and steady reduction in the loss of life and health from industrial accidents.

Another finding is that big accidents in the oil and gas industry have come not from failures of industrial safety, but from lapses in process safety (called "operational risk" by the *IADC Deepwater Well Control Guidelines, 2nd Edition, 2015*).

As illustrated by the side-by-side lists in Figure 1, the term *barrier* has differing meanings when applied to process and industrial safety. In process safety, *barriers* are always physical barriers, and physical barriers (e.g., casing, cement, fluid column, BOPs, valves, and pipelines) have specific critical safety functions that they must perform.

In industrial safety, the word *barrier* is often used metaphorically to describe procedures, training programs, prejob briefings, people, and other conditions or situations that keep undesirable events from happening.

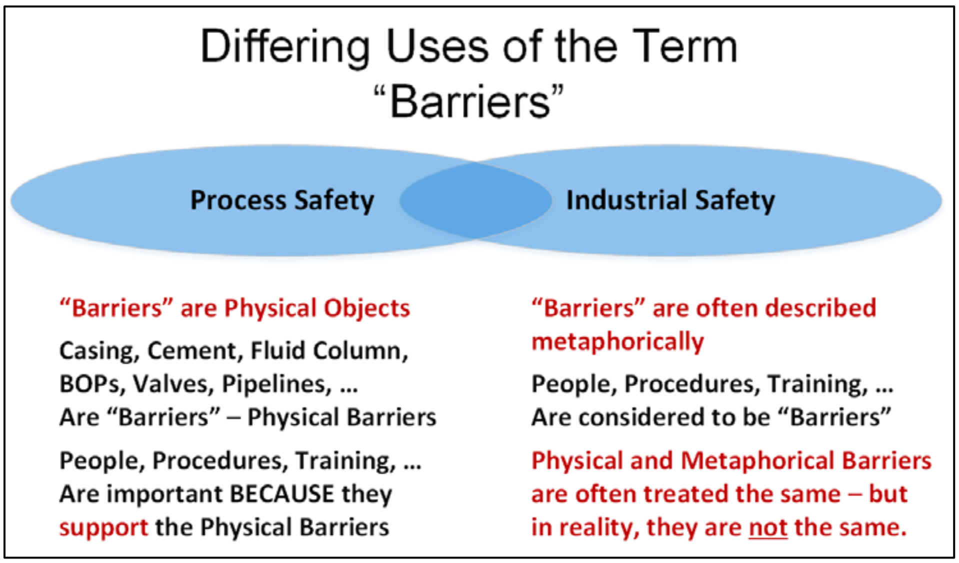


Figure 1: Uses of the Term *Barriers*.

In the MPB Approach, the only barriers are *physical barriers*. Training, people, and procedures are important, but they are not barriers in their own rights. For example, failure to follow a correct procedure may cause a major accident, but only by means of its impact on the performance of a physical barrier.

> ***In the Multiple Physical Barrier approach, the only barriers are physical barriers. Training, people, and*** procedures are important, but they are ***not barriers in their own rights.***

How then do people in the industry ensure that physical barriers are performing their critical safety functions? The answer is to ensure that *success paths*, which identify necessary components and actions to ensure success, are in place and are capable of performing their functions in all expected conditions and circumstances.

SUCCESS PATHS

A *success path* is a series or collection of equipment, procedures, software, processes, and human actions that ensure physical barriers are able to meet their critical safety functions.

Success path diagrams are used to characterize, delineate, and illustrate steps that must be taken to achieve success in the design, maintenance, and operation of each component in the system.

The development of a success path diagram focuses on two principal questions:

- What physical barriers are required for the operation at hand?
- What is needed to ensure that these physical barriers "succeed" in meeting their critical safety functions?

These questions marry two principles: the focus on physical barriers, which is foundational to the nuclear safety industry; and the ability to diagram and trace how critical systems function (e.g., performance qualification standards), which forms a key part of safety training for engineers and inspectors in the US Navy and the Coast Guard.

It is precisely the understanding of what needs to work correctly (especially for physical barriers) that paves the way toward elucidating failure modes. In effect, this approach is designed to help orchestrate a shift in operational awareness with the aim of improving operational risk management.

As will be illustrated, the use of success paths in the MPB Approach provides a number of key benefits, including the following:

- It is the fastest systematic mechanism for identifying the root cause of operational safety risks that lead to injury, downtime, and increased costs. This top-down approach starts with a high-level view of the system and enables systematic drill-downs for characterizing critical system components.
- It helps government agencies, as well as energy companies and other stakeholders, develop a common understanding of key safety risks and build consensus on cost-effective risk-mitigation measures.
- It provides a consistent, risk-informed communications framework for intuitively communicating with rig workers, senior executives, regulators, and everyone in between. Rig workers quickly identify their roles within the success paths and readily understand how their actions are integral to maintaining the success of the barrier.
- A well-charted success path enables decision makers to intuitively comprehend the key points required for success and to then participate intelligently in the discussion about risks and safety. Further, it provides a consistent and rigorous basis for defending decisions that have been made (for example, to senior executives or third parties). The foundations of this approach have been demonstrated to hold up in legal situations.

- It also serves as an optimal training tool that enables students to quickly and intuitively grasp key operational safety issues. Each physical barrier can be systematically analyzed to identify the foundational basis needed to safely manage the operational working environment on a rig.

Success path diagrams utilize a notation very similar to that of fault trees. However, unlike fault trees, possible failure modes for systems and components are not specified. Instead, the action that is necessary for system *success* is highlighted. An overview of success path notation is shown in Table 1. A box is used to group a collection of functions and intermediate steps or to designate a base event, a cone-shaped *AND* gate is used to indicate all inputs necessary for success, an arrow-shaped *OR* gate notes that any single input is adequate for success, a symbol of a person conveys that human action is required, and a triangular transfer gate is used to direct readers to a different success path diagram. Additional support systems are represented with triangular shapes colored yellow for primary rig AC power, orange for secondary rig AC power, read for subsea AC power, brown for a 3k accumulator, and green for a 5k surface hydraulic supply. A dashed line is used to indicate the order of progression for human actions or component actuation.

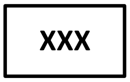
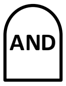
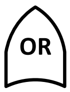
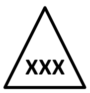
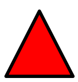
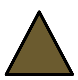
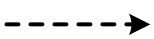
Symbol	***Name***	***Description***
	*System, Group, Function or Base Event*	*Name of a system, group of functions, intermediate steps, or base event*
	***AND*** *- Gate*	***All*** *of the inputs are necessary for success*
	***OR*** *- Gate*	***Any*** *of the inputs are adequate for success*
	***Transfer*** *- Gate*	*Transfer to a different success path diagram*
	***Human Action***	*Requires human action or operation*
	***Primary Power***	*Primary rig AC power*
	***Secondary Power***	*Secondary (UPS) rig AC power*
	***Subsea Power***	*Subsea AC power*
	***3k Accumulator***	*3k accumulator pilot supply*
	***5k Surface Hydraulic***	*5k surface hydraulic supply*
	***Actuation Progression***	*Indicates the order of progression for human actions or component actuation*

Table 1: Success Path Diagram Notation.

Typically, the formatting of a success path diagram presents the hierarchy of a system vertically (from high-level function or the system at the top to subsystems and components at the bottom), with the progression of system actuation (or sequence of events) moving from left to right. Subsystems and components that support the high-level function are connected by *AND* and *OR* gates. If an AND gate is used, then every element beneath it in the path must be present for the top element to succeed. If an OR gate is used, then any single element below it will be sufficient for success.

An application of the success path approach for any physical barrier would typically include the following four steps:

- Identify the physical barrier systems that need to be in place for a given operation and the associated critical safety function(s). (This is usually a statement of success, such as “Pumps deliver needed pressure and flow under all expected conditions.”)
- Ensure that the physical barrier support system(s) are designed and configured to perform their critical safety functions under all expected conditions.
- Monitor the performance of all critical equipment and implement preplanned actions and strategies for restoring barrier functions if one or more of the barrier systems fails or becomes degraded.
- Maintain all critical equipment in a condition to perform as needed during all expected conditions.

The following section provides examples of applying the Argonne MPB Approach to high-risk areas related to offshore oil and gas operations.

EXAMPLE APPLICATIONS OF THE MULTIPLE PHYSICAL BARRIER APPROACH

DRILLING

The following diagram (Figure 2) shows a simplified sketch depicting the physical barriers found during *drilling* operations:

The **fluid column** is the primary barrier that keeps hydrocarbons where they belong. It must be balanced to maintain a bottom-hole pressure that is higher than the pore pressure of the formation, but lower than the fracture gradient of the formation.

The **casing and cement** elements that line the sides of the well keep hydrocarbons from entering the well in an unwanted manner.

The **wellhead** binds all of the casing strings together and provides structural support for all of the casing below the well and all of the equipment located above the well.

The **BOP stack** surrounds the casing, annulus, and drill string. The stack includes several different types of rams, each with its own special function. The BOP includes annular preventers, pipe rams, shear rams, and choke-and-kill lines (not shown in Figure 2).

The **riser** connects the fluid column in the BOP stack to the floating rig.

The drill string has two important physical barriers: the **drill string check valve,** which prevents backflow up the drill pipe, and the **full opening safety valve (FOSV),** which is available for insertion at the top of the drill pipe and stops flow when the wellbore is open to the atmosphere.

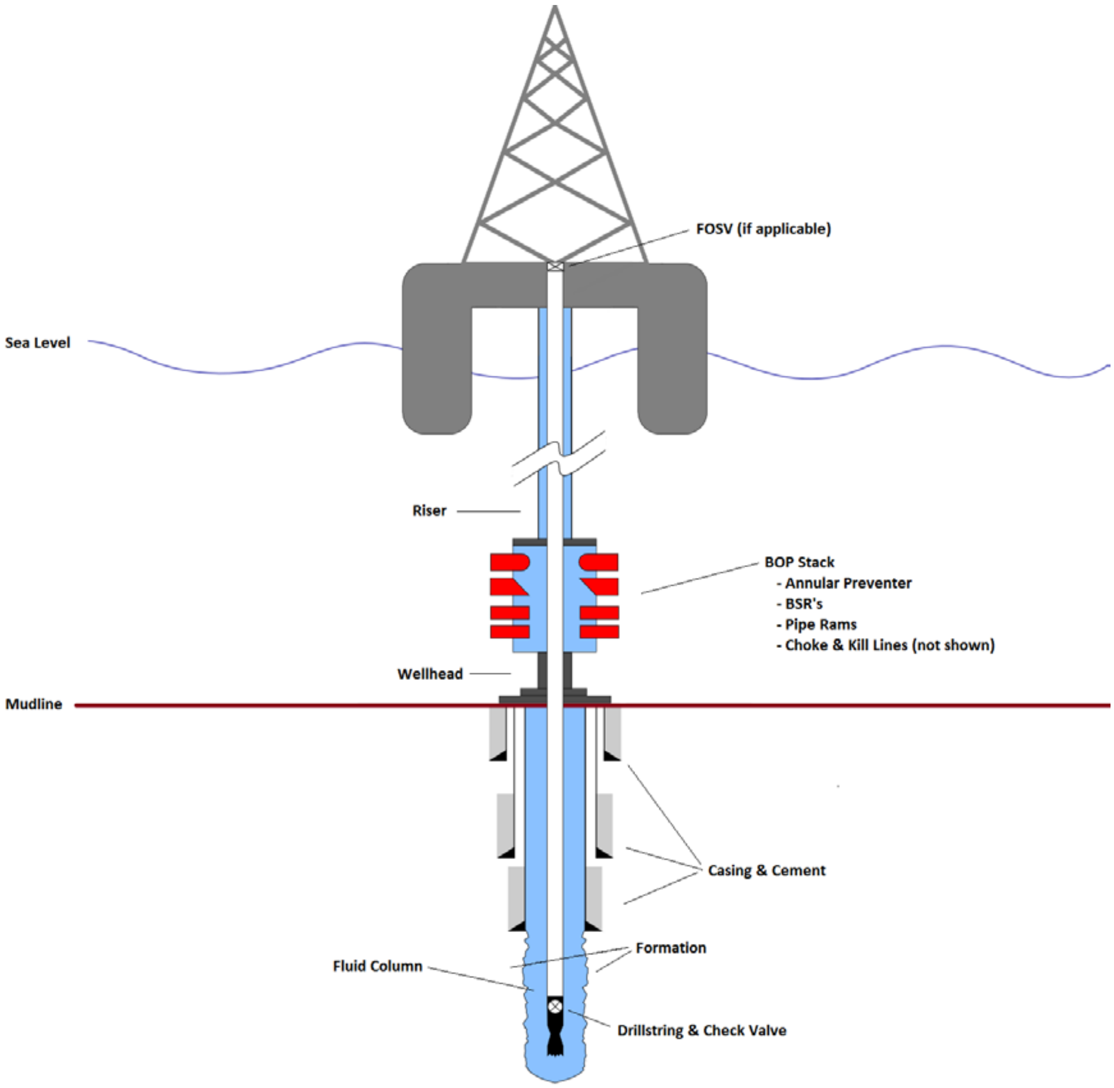


Figure 2: Sketch Depicting the Physical Barriers Found During Drilling Operations[2].

The first example application of the Argonne MPB Approach described in this report focuses on one physical barrier on a drilling rig: the FOSV.

FULL OPENING SAFETY VALVE

This example illustrates the analysis of a physical *barrier*, its *critical safety function*, and the *success paths* needed to achieve the safety function of an FOSV, which is sometimes referred to as a *stab-in safety valve* or *TIW (Texas Iron Works) valve*. We also present two actual examples of loss of well-control events that occurred when this success path was violated.

During a well-control situation, the FOSV (a valve weighing up to several hundred pounds) is

[2] SPE-174995-MS. D. Fraser, J. Braun, M. Cunningham, Argonne National Laboratory, D. Moore, Marathon Oil, A. Sas-Jaworsky, SAS Industries Inc.; J. Wilson, Transocean, *Operational Risk: Stepping Beyond Bow-Ties*, September 28-30, 2015, Houston.

screwed into the top of the drill pipe or tubing to prevent drilling fluids from flowing out of the drill pipe and onto the rig floor. Typically, the FOSV must be manually installed by the rig crew as quickly as possible once the command to begin well control has been issued.

Applicability. Figure 3 provides a completed MPB template for the FOSV. As noted in the first row of the template, this barrier analysis was specifically considered for operations of offshore drilling, completions, and workovers.

Success Path. The main body of the MPB template displays a success path for the FOSV with a concise statement of the barrier's purpose (in a rectangular box at the top of the diagram). This is the *critical safety function*. The noted critical safety function of an FOSV is to "keep fluids contained inside of drill pipe or tubular."

Directly below the critical safety function is an AND gate noting that both proper design and proper operation of the FOSV are essential to support fluid containment. The success path further demonstrates that, for the design and setup of the FOSV to be successful, the FOSV must be properly rated for pressures that could be produced by the well. (BSEE, for example, requires that the FOSV be rated at the same pressures as the BOP system.)

Similarly, this success path shows that not only must the FOSV be designed and set up properly, but a whole series of operational actions and monitoring actions must also take place. These operations are illustrated below the second AND gate as a set of individual boxes. Each box represents a specific action that must be observed and confirmed. These actions include the following:

- ensuring that the FOSV is readily available on the rig drill floor
- ensuring that the FOSV is in an OPEN state, since it could be very hard to install if closed (for example, think of screwing a cap on the end of a flowing garden hose)
- ensuring that the threads at the bottom of the FOSV are matched to the drill pipe or tubular used in the wellbore (in some cases, this can be accomplished by adding thread crossovers to the FOSV)
- ensuring that the special operating wrench for the FOSV is readily available so the valve can be closed once it's installed
- ensuring that the tool joint is at working height, so the rig crew can install the FOSV
- ensuring that the lifting device is available to lift the barrier into position
- ensuring that people adequately trained in FOSV installation are readily available at all times

Alternate Success Paths. In diagramming the success path, industry specialists are forced to systematically think through the entire operation of the physical barrier and identify items that are needed for the barrier to be successful. Below the success path is a box for specifying alternative success paths, which may be deployed if the current barrier fails. For example, if the FOSV fails to close, then shearing is a last resort.

Necessary Support Systems. The next block in the diagram is used to identify any functions that are needed to support the success path. In this case, electric power would be needed to operate an electrical hoist. If there is no power, the success path is not complete, and the barrier would not be operable. Carefully identifying these support systems is an important part of the MPB Approach. This step also helps identify “common cause” failures (such as the loss of power) that can impact multiple barriers.

Threat Scenarios. The final block, at the bottom of the MPB template, is used for “called-out” threats that may come from external events and that can impact the ability of the success path to perform its safety function. In the case of the FOSV, high temperatures or caustic fluids spraying from the drill pipe could prevent successful installation.

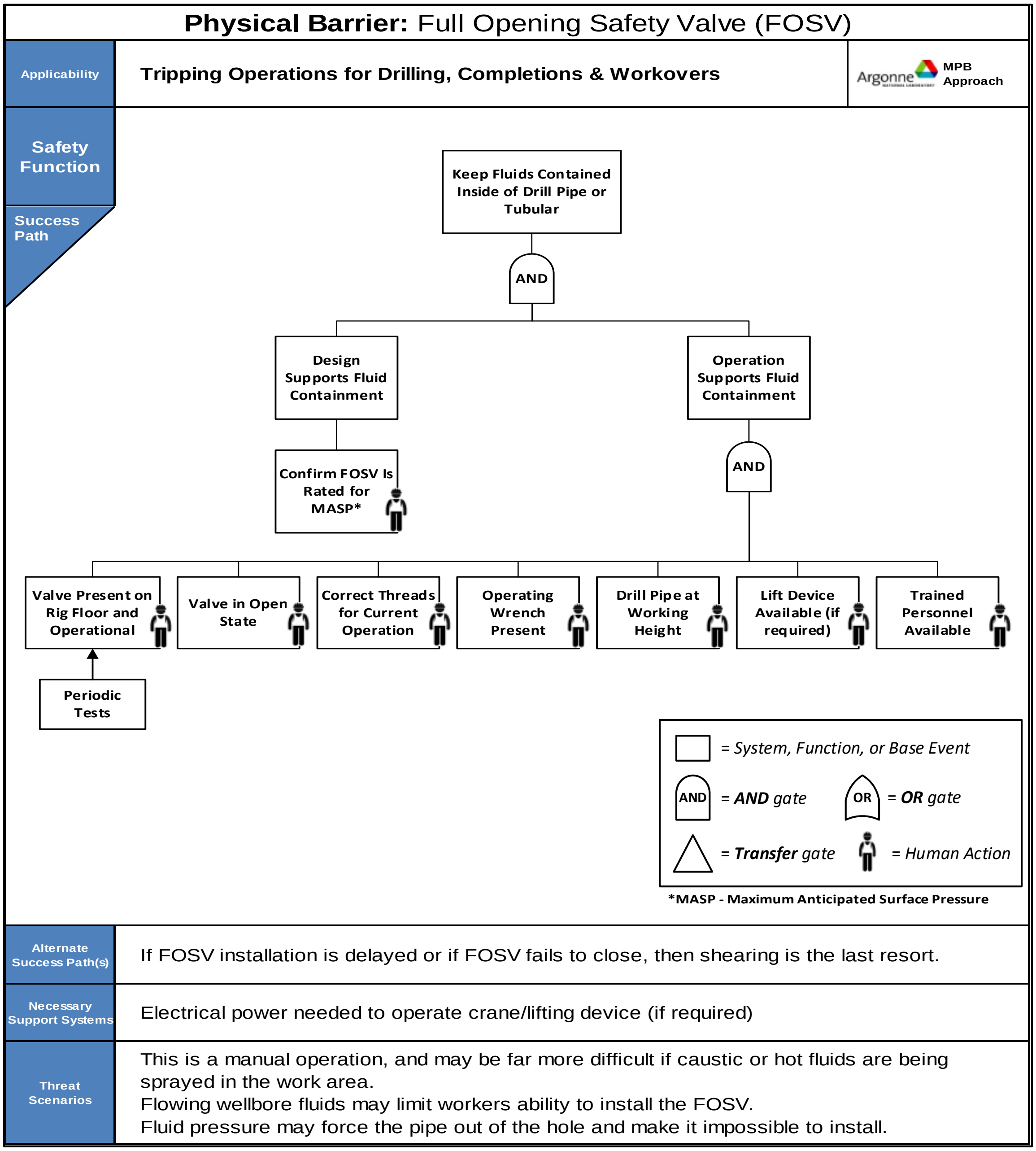


Figure 3: Argonne Multiple Physical Barrier Approach Template for FOSV.

To truly understand the reliability and capability of a physical barrier, it is necessary to understand the reliability and capability of success paths that support the physical barrier. Success paths often use ordinary components and depend on the routine actions of workers. The "battle for safety" becomes one of helping all parties visualize and understand the importance of these components and their need to perform successfully.

The inability of a success path to function as intended is a significant element of risk. If an alternate success path is not available to perform the safety function, then the safety function is at risk, and the physical barrier cannot be expected to perform its intended job. Consider this example from a recent offshore incident report[3]:

On 27 September 2012, a well-control incident occurred (on a Gulf of Mexico location) ....*At the time of the incident, the platform rig was on a location contracted for recompletion work. As the rig was pulling 2 7/8" tubing out of the well, the well started flowing, and wellbore fluids spewed out to a height of 30–40 feet in the air. As the well was flowing, well-control procedures called for the stabbing of the TIW valve into the 2 7/8" tubing by using the hydraulic hoist on the rig floor; however, the hoist was unavailable at the time because it was being used to lower 2 7/8" tubing down the V-door. This resulted in an uncontrollable, timed event….*

Few people would think twice about using a hoist to lift a component on a drill floor, but when the hoist is not available to lift the FOSV into position for emergency insertion, the success path is invalidated, and there is no barrier. One method of mitigating the risk of similar barrier failure in the future could be to provide an alternate lifting mechanism for the FOSV. The device could be manufactured with suitable handles rig workers can use to manually place it in position. In this case, an alternative success path would be indicated by an OR gate in the success path diagram.

Sadly, in another incident in the Gulf of Mexico,

An FOSV was not adequately restored to operating condition after it was used for a cementing operation. When it was later called upon to operate in an emergency, it was blocked with sand and cement and could not be closed. The ensuing blowout caused the evacuation of the rig and a significant spill and contributed to the loss of a crew member[4].

In this example, there was an FOSV present on the rig floor. However, the valve was not in operational condition. Once again, the barrier failure can be mapped to either a box in the success path or to one of the limiting factors noted in the MPB template.

The value of the Argonne MPB Approach is that it focuses on identifying the physical barriers, their critical functions, and the success paths (both automated and human) needed to ensure full success and safety. The approach is sufficiently intuitive for everyday use, yet powerful enough for large-scale integration and the quantification of risks. When it comes to operational safety on offshore oil and gas facilities, the "devil is in the details," and the MPB Approach guides practitioners to systematically find and identify those details. The benefits are both for the operational team on its path toward intuitively understanding the safety implications of their roles and for the regulator through the identification of key areas for inspection.

As explained in the next example, the Argonne MPB Approach is also useful in applying risk-based techniques to compare and discuss alternative well-control techniques.

---

[3]http://www.bsee.gov/uploadedFiles/BSEE/Inspection_and_Enforcement/Accidents_and_Incidents/acc_repo/2012/HI%20A443%20Black%20Elk%2027%20Sep%202012.pdf.

4 OCS Report MMS 2002-062.

CONVENTIONAL DRILLING VERSUS MANAGED-PRESSURE DRILLING

Drilling fluid is one of the most dynamic and critical barriers used during the drilling process. The fluid barrier must be properly monitored and maintained at all times to be reliable. In this section, we will analyze fluid column barrier success paths to assess the benefits and limitations of the following alternative methods:

Drilling conventionally where well control is maintained solely via the use of a static or circulating drilling fluid column; and

Managed-pressure drilling (MPD), in which well control is maintained throughout the drilling operation by using a constant bottom-hole pressure (CBHP) method, sometimes also known as surface back-pressure (SBP).

In a barrier analysis, the fluid pressure barrier is sustained as long as fluid pressure remains between the pore pressure (PP) and the fracture gradient (FG) of the formation. This is the critical function of the barrier. In practice, the safety functions are realized quite differently.

The safety function of the fluid pressure barrier for conventional drilling is specified in two parts. First, the mud weight (MW) plus the circulating friction (CF) must be less than the FG. Initially, the FG is estimated. Later, leak-off pressure (LOP) at the weakest point in the wellbore is measured via a leak-off test. The safety function ensures that mud being circulated does not fracture the formation. Additionally, as a separate requirement, the pressure induced by the static MW must be greater than the PP. This way, the well will still be overbalanced when the pressure induced by the CF of the mud is eliminated as the pumps are stopped. When either of these limits is exceeded and when fluid is either being lost to the formation or a kick is occurring, the primary barrier is degraded, possibly to the extent that it is no longer effective.

The safety function of the MPD drilling scenario does not require that the static MW be greater than the PP, as in the conventional drilling scenario. Rather, it relies on the SBP from the MPD chokes to compensate for a reduced MW. The SBP can be used to either raise or lower the overall pressure. Furthermore, SBP pressure changes can be accomplished quickly, in a matter of seconds, unlike the conventional model of changing mud weight. This adds both precision and flexibility to the MPD drilling scenario, as will be seen in the success path discussion.

The success path in Figure 4 highlights a well-defined safety function for the conventional drilling fluid column and elucidates some key steps to support that safety function. Similarly, the success path in Figure 5 illustrates the safety function for MPD using a specific, constant bottom-hole pressure method with a pressure-containing rotating control device (RCD) located just below the riser tensioner. Key differences in the MPD diagram are highlighted in green. By comparing these two figures side by side, one can immediately see the similarities and differences in the two processes. This serves as a starting point for comparing the safety features of the two processes. A quick comparison is shown, for example, in Table 2.

Physical Barrier: Fluid Column

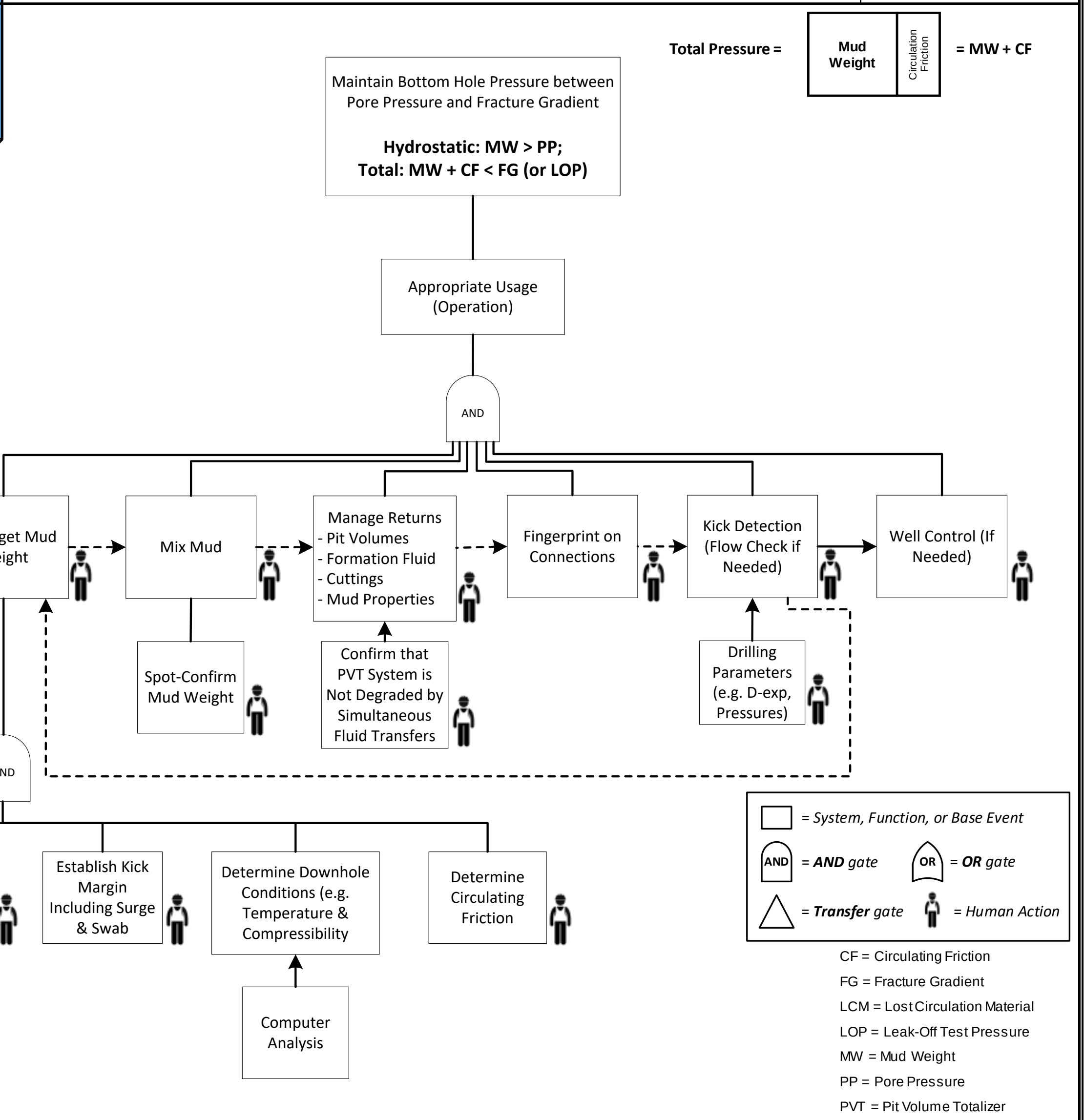
Applicability

Conventional Drilling

MPB Approach

Safety Function

Success Path



Alternate Success Path(s)

The BOP System

Necessary Support Systems

AC Power Needed for Pumps, Drilling and Dynamic Positioning
AC/DC Power Needed for Instrumentation + Monitoring

Threat Scenarios

Drilling into a high pressure zone can cause an underbalanced situation.

Figure 4: Fluid Column Success Path (Conventional Drilling).

Physical Barrier: Fluid Column (MPD)

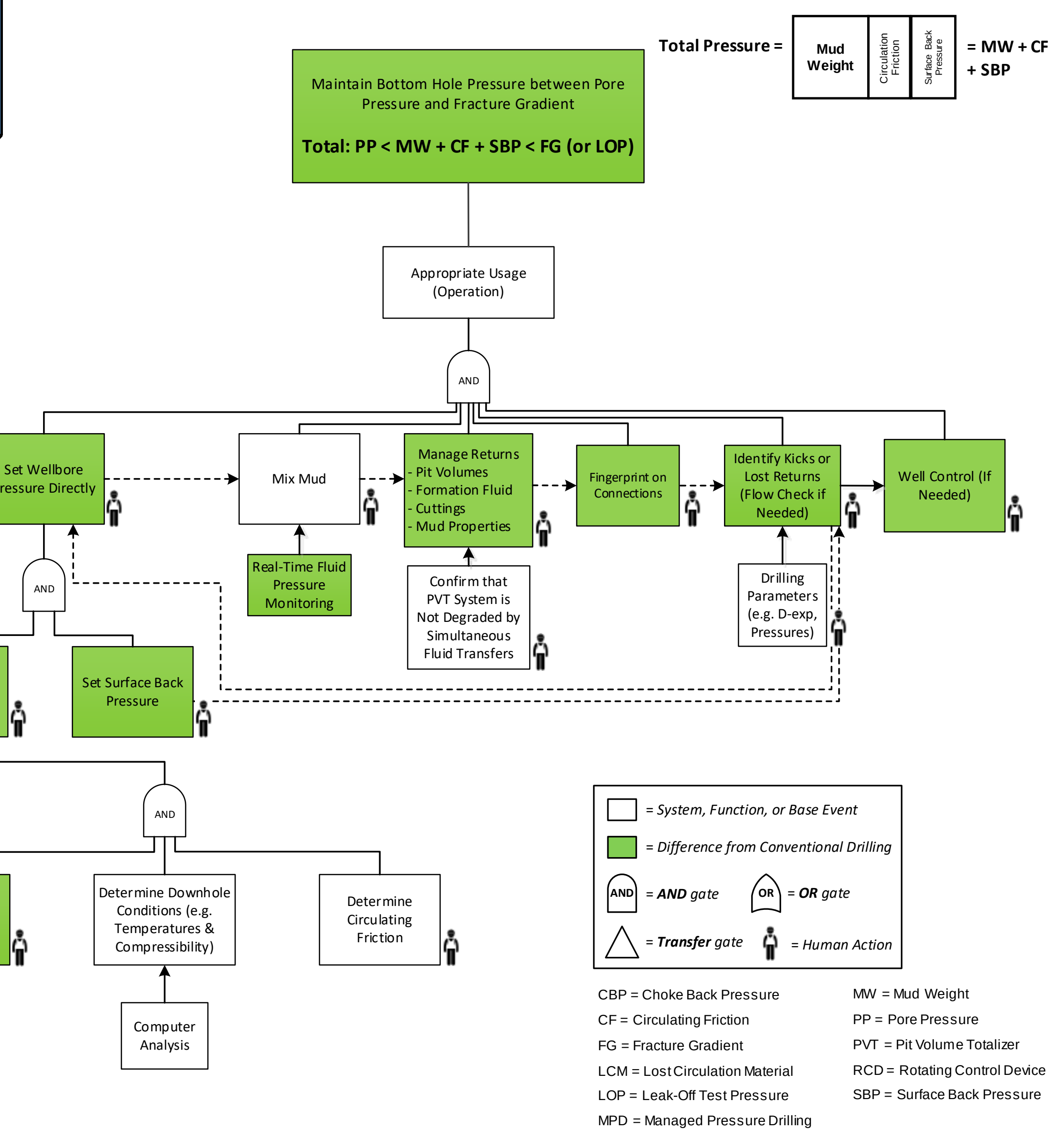
Applicability

Managed Pressure Drilling (MPD) - Constant Bottom Hole Pressure Method

Argonne MPB Approach

Safety Function

Success Path



Alternate Success Path(s)	If components fail or barrier degradation occurs the BOP system remains fully available.
Necessary Support Systems	- Pressure Control Equipment (e.g. RCD, MPD Choke) - AC Power Needed for Pumps, Drilling, Dynamic Positioning - AC/DC Power Needed for Instrumentation + Control
Threat Scenarios	- Coriolis meters can produce spurious results when gas is encountered. - If not monitored properly the riser joint and/or riser could become overpressured. - Wear/leak/failure of pressure control equipment.

Figure 5: Fluid Column Success Path (Managed-Pressure Drilling).

Technical Issue	Conventional Drilling (Figure 4)	Managed-Pressure Drilling (Figure 5)	Safety Difference
Safety function differences, wellbore pressure control	Uses only fluid weight and circulating friction (pressure)	Surface back pressure is used in addition to fluid weight and circulating friction	MPD improves safety by enabling near instantaneous and tightly controllable pressure maneuverability
Fluid pressure monitoring	Pressure/mud weight monitoring via sampling (>15 minute intervals): good to ± 0.1 avg. ppg at best	Coriolis in/out flow meters provide continuous monitoring: accuracy of: ± 0.01 ppg can be achieved	MPD improves safety by providing the driller with a more accurate wellbore fluid profile
Kick identification	Kicks / fluid losses normally detected by volume changes: detection limit ~10 bbl	Flow meters detect flow changes directly: detection within 2–3 bbl., often less	MPD improves safety by detecting kicks earlier, thereby giving crews more time to respond
Determination of wellbore parameters: pore pressure (PP) and fracture gradient (FG)	Information comes primarily from estimates and relatively few point measurements	Measurements can be made regularly and directly without stopping drilling	MPD can improve safety by giving accurate PP and FG measurements to the driller as often as needed
Compensation for swab, surge, and changing circulation pressures	Fluid weight must be set conservatively to allow for dynamic changes in wellbore pressure	Wellbore pressure can be held relatively constant by adjusting surface back pressure	MPD improves safety by reducing the number of kicks that occur due to wellbore pressure changes (e.g., when making connections)
Threat scenario: drilling into a high-pressure zone	Inaccurate estimates of wellbore parameters, as well as inaccurate averages of fluid weight, could result in an underbalanced situation	Threat is greatly reduced because of early kick detection and ability to quickly stop flow using surface back pressure	MPD improves safety by significantly reducing threat likelihood and impact
Threat scenario: Excess surface back pressure in the riser	--	Monitoring needed to control amount of surface back pressure; also pressure-relief systems may need to be incorporated into the system	This new threat is exclusive to MPD and raises the overall risk slightly
Threat scenario: Coriolis meters can produce spurious results when gas is encountered	--	Although gas is not normally circulated through the Coriolis meters, monitoring for gas in the outflow system continues to be prudent	This threat does not change the risk since conventional fluid-management parameters continue to be reported

Threat scenario: Wear / leak / failure of the rotating control device (RCD)		Monitoring needed to respond to leaks or failure of the RCD	This new threat is exclusive to MPD and raises the overall risk slightly

Table 2: Using the MPB Approach to Compare Conventional and Managed-Pressure Drilling[5].

As demonstrated in the above comparison, the Argonne MPB Approach provides a systematic and repeatable process for illustrating, understanding, and comparing different technology systems and weighing the pros and cons of each. Differences that impact operational risk can be readily seen in the comparison.

This research was extended by combining the pressure control success paths with estimated variances and kick performance indicators[6] to aid in the evaluation of alternative drilling scenarios. Figure 6 displays the barriers, safety functions, and success paths for the three evaluated scenarios.

[5] SPE-174995-MS. D. Fraser, J. Braun, M. Cunningham, Argonne National Laboratory, D. D. Moore, Marathon Oil, A. Sas-Jaworsky, SAS Industries Inc.; J. Wilson, Transocean, *Operational Risk: Stepping Beyond Bow-Ties*, September 28-30, 2015, Houston.

[6] SPE 170756-MS. D. Fraser, R. Lindley, Argonne National Laboratory, D. Moore, Marathon Oil, M. Vander Staak, Hess Corp., *Early Kick Detection Methods and Technologies*, October 27-29, 2014, Amsterdam.

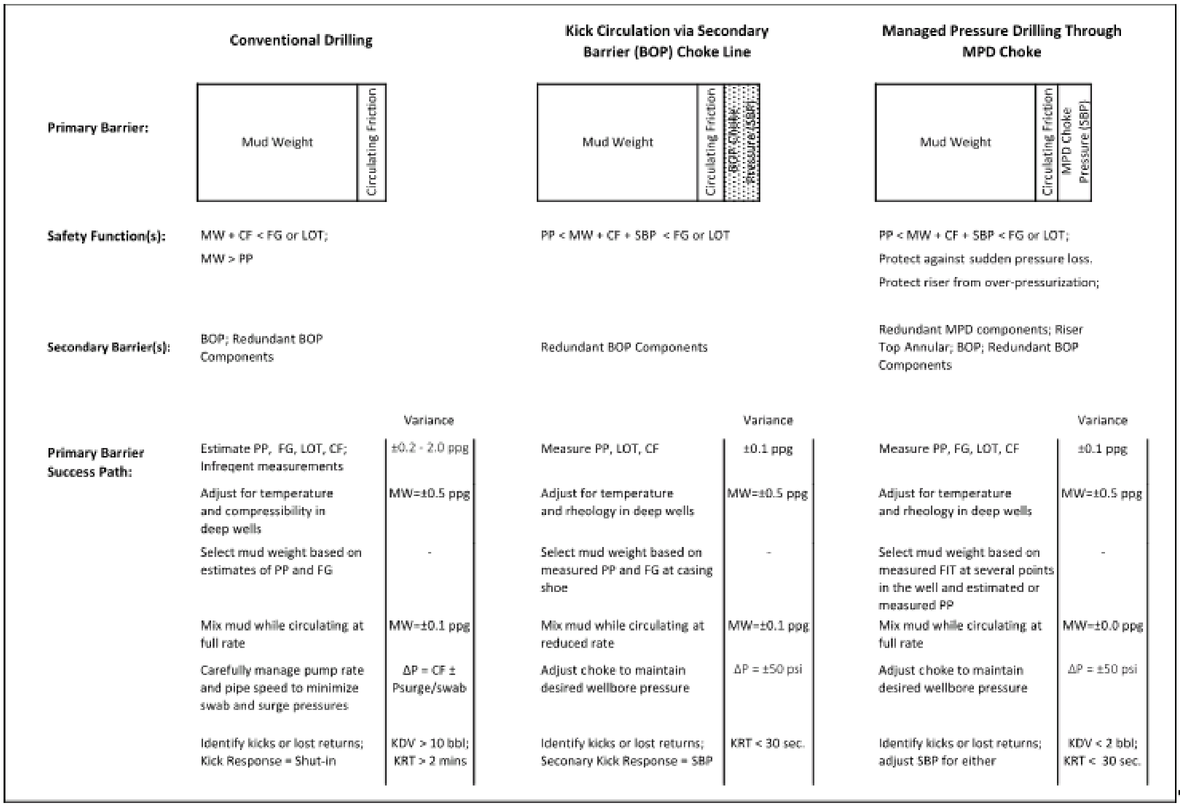


Figure 6: Illustration of Barriers, Safety Functions, and Success Paths for Three Drilling Scenarios[7].

Results of the multiple physical barrier analysis strongly suggests that MPD has substantial benefits over conventional drilling techniques in terms of improved accuracy in measurement of kick detection volumes (KDVs), reduced kick response times (KRTs), and ability to maintain a constant bottom-hole pressure. These advantages assume however that the driller is well trained in the application of MPD, is familiar with the tools at his disposal, and uses each one to its fullest capability.

To increase understanding of techniques commonly used in MPD, success paths were developed for key elements of the system. Appendix I includes success paths for use of choke and lines, shown in Figure I-6, to maintain bottom-hole pressure, and use of a Rotating Control Device (RCD), shown in Figure I-7, provide a seal between the drill-string and annulus, allowing pipe movement to occur under pressure during drilling, tripping, and circulating operations.

The next sample application of the MPB Approach demonstrates how success paths allow both a qualitative and quantitative evaluation of system reliability.

BLOWOUT PREVENTER SYSTEM RELIABILITY

The BOP system is often thought of as the last line of defense during a loss of well control.

[7] SPE/IADC-173153-MS. D. Fraser, Argonne National Laboratory, D. D. Moore, Marathon Oil, and M. Vander Staak, HESS Corp., *A Barrier Analysis Approach to Well Control Techniques*, March 17-18, 2015, London.

However, as a complex electromechanical system subject to extreme environmental conditions, ensuring high-functional reliability of the BOP can be challenging. The Argonne MPB Approach was applied to evaluate the impact of BOP performance on operational risk. The focus of this study was on successful operation of the Blind Shear Ram (BSR), which is the only BOP element that can cut drill pipe and seal the wellbore. The BOP system reliability study report[8] is summarized below.

Success paths were created to outline the systems, components, and actions necessary for successful BSR actuation[9]. For the BSR, there are five possible actuation pathways, which result in the top success path shown in Figure 7. Here, the top event is the successful High Pressure (HP) Close Operation of the BSR. There is an OR gate below the top event, as any of the five actuation pathways (manual close, emergency disconnect, deadman/autoshear, ROV actuation, or acoustic actuation) is adequate to result in an HP Close Operation of the BSR. The acoustic actuation pathway is highlighted with a dashed line, as it is optional. Each of the actuation pathways is represented with a transfer gate, as each has its own success path. The following success path development focuses on the first pathway (Manual HP Close).

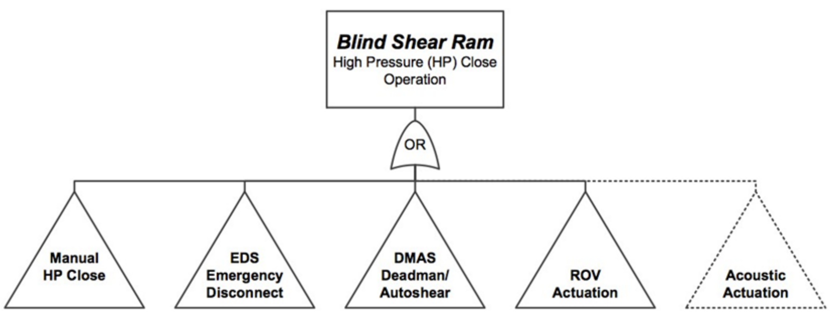


Figure 7: BSR HP Close Top Level Success Path.

The ***Manual HP Close*** actuation pathway is composed of six main systems, as shown in Figure 8, and requires two support systems. The manual actuation begins with the command signal from a human on the rig pressing the “BSR HP Close” button on the driller’s or toolpusher’s panel. This signal is sent to the surface control system, and then is sent subsea by the MUX system. Once subsea, the signal is processed by the LMRP subsea control pods, which transfer hydraulic fluid to the BOP shuttle valves, and finally to the BSR ram hardware.

[8] Grabaskas, D., Fraser, D. and R. Lindley, "Blowout Preventer System Reliability: Success Path Assessment," Prepared for the Bureau of Safety and Environmental Enforcement, 2015.
[9] This study evaluated the reliability of BSR actuation. Whether the BSR properly cuts the drill pipe and seals the wellbore was not investigated, as it is highly dependent on the individual system design and scenario conditions.

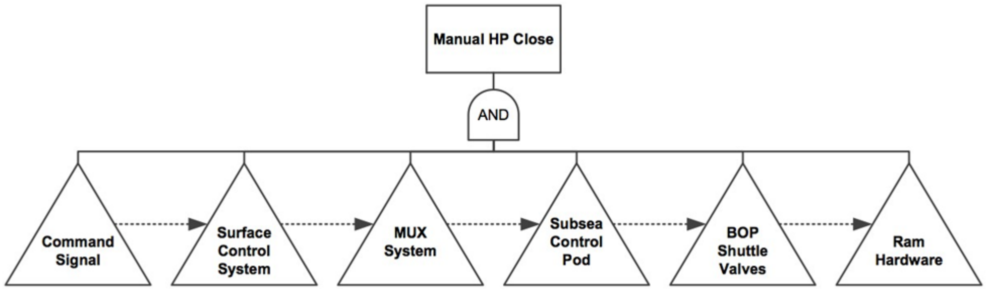


Figure 8: Manual HP Close Success Path Overview.

The ***command signal*** originates at the driller's or toolpusher's panel. Actuation from either panel is sufficient, but AC power is necessary for either panel to function, as shown in Figure 9.

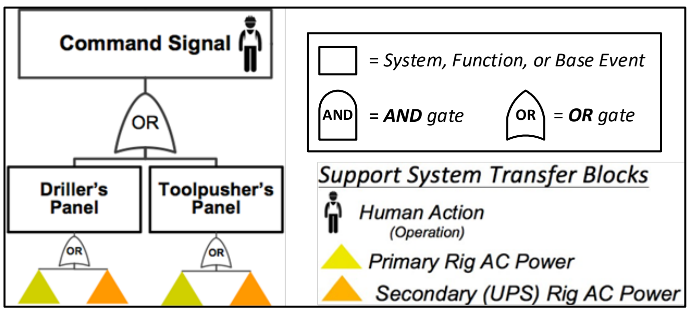


Figure 9: Manual HP Close – Command Signal.

The ***surface control system*** is comprised of the CCU and fiber optic modem, as shown in Figure 10. The CCUs process the command signal, while the fiber optic modems prepare the signal to be sent in the MUX cables. Both components have hardware redundancies. However, common software on the redundant CCUs presents a possible common cause failure (CCF) pathway. Both the CCUs and fiber optic modems require AC power.

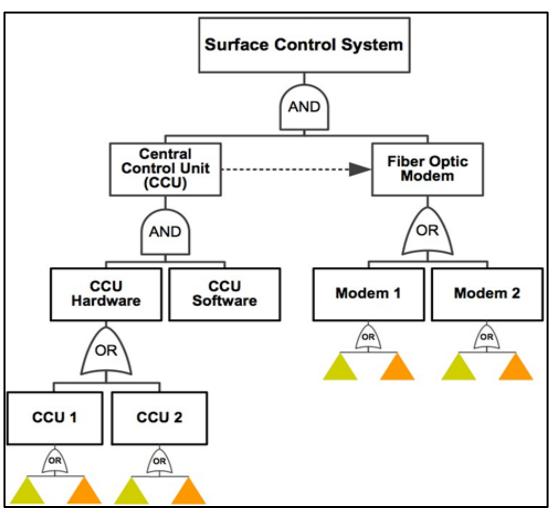


Figure 10: Manual HP Close – Surface Control System.

The MUX system, shown in Figure 11, is comprised of redundant MUX cables and associated

MUX cable reels. The reels provide the connection for the fiber optic signal (along with AC power) from the rig to the MUX cable. The MUX cable reels require AC power.

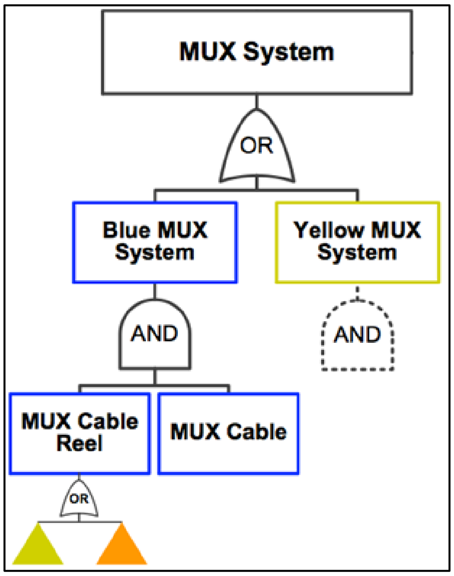


Figure 11: Manual HP Close – MUX System[10].

The LMRP ***subsea control pods*** are the most complex system of the manual HP close actuation pathway, as shown in Figure 11. The control pods can be broken down into three main components. First, the redundant subsea electronic modules (***SEMs***) process the signal from the surface and send electrical signals to the necessary solenoid valves. In the ***pod upper package***, the solenoids actuate and direct pilot hydraulic fluid to the required sub plate mounted (SPM) valves. In the ***pod lower package***, the SPM valves direct power hydraulic fluid to the BOP.

There is redundancy with two SEMs per pod, but surface ***AC power*** is required for their operation (assuming ***manual HP Close function***). The SEM also conducts a ***signal confirmation*** with the surface. This "handshake" confirms that the BSR HP Close signal was not sent spuriously and is required for further operation. The solenoid valves require ***DC electrical power*** and ***pilot hydraulic fluid***. The SPM valves require ***high-pressure power hydraulic fluid***, along with the ability to ***vent the hydraulic fluid*** in the opposing chamber of the SPM. For example, to move a SPM valve from position 1 to position 2, the hydraulic fluid in the chamber for position 1 must evacuate the SPM valve before the valve can move to position 2.

[10] The dashed AND gate under the "Yellow MUX System" indicates identical redundancy to the blue MUX system.

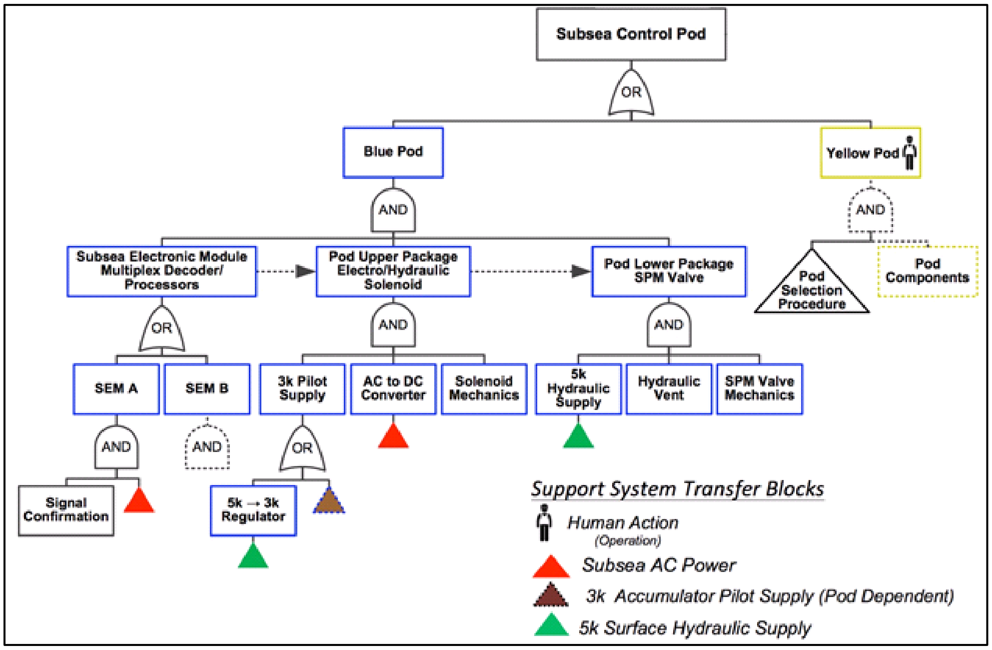


Figure 12: Manual HP Close – Control Pod.

Power hydraulic fluid is transferred from the LMRP to the BOP shuttle valves. These shuttle valves, shown in Figure 13, merge possible sources of hydraulic power, such as from the blue and yellow pods, ROV, and DMAS. The number of shuttle valves the hydraulic fluid must pass through is highly dependent on the particular BOP design and can range anywhere from a single shuttle valve to six or more.

Lastly, the power hydraulic fluid enters the BSR ram hardware. As shown in Figure 14, the BSR must vent the hydraulic fluid in the open chamber of the ram to prevent a hydraulic lock. Also, the ram operator seals must work correctly to prevent leakage of hydraulic fluid (and pressure) from the close chamber of the ram.

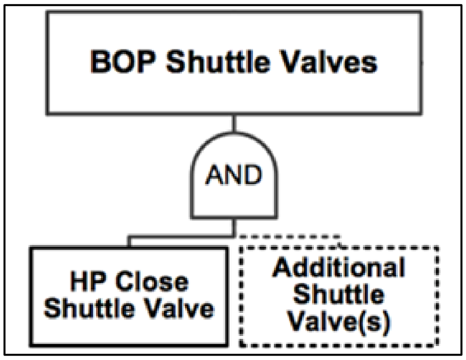


Figure 13: Manual HP Close – BOP Shuttle Valves.

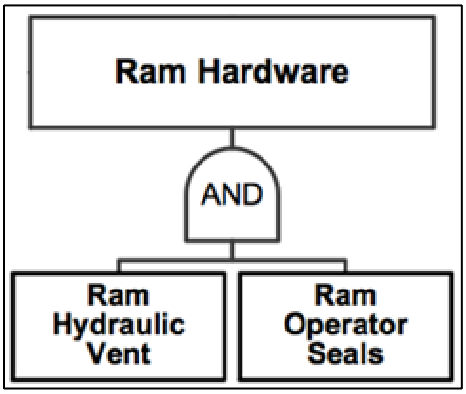


Figure 14: Manual HP Close – Ram Hardware.

The success paths outlined above (and similar success paths developed for the other four actuation pathways, which are displayed in Appendix A) provide the framework for both qualitative and quantitative assessments of BOP reliability. An initial qualitative reliability analysis, which sought to identify general weaknesses or single points of failure in the BOP system, identified failure points in the following components: BSR shuttle valves; BSR operator seals; BSR hydraulic vent; CCU software; surface accumulators; subsea signal confirmation; BOP 5k accumulators; and DMAS components.

Following the qualitative reliability assessment, a quantitative assessment utilizing the success paths was performed to provide insight into the BOP safety integrity level (SIL). The SIL is a measure of risk reduction provided by a component or system, as defined by IEC 61508. SIL is often compared to component/system reliability or unavailability, although the meaning is slightly different. The SIL is not just a reliability estimate for a component/system, but describes the relative change in risk (particularly of dangerous failures) when the component/system is included or absent. This change in risk level equates to the risk reduction provided by the component/system.

Table 3 provides an overview of the four SIL categories, as defined by IEC 61508. As can be seen, the probability of failure per demand (PFD) and risk-reduction factor (RRF)s are closely linked. For example, a component/system that reduces the risk of a dangerous failure by one in 10 would be classified as SIL – 1.

SIL	*PFD*	*PFD (power)*	*RRF*
1	*0.1-0.01*	10^{-1} - 10^{-2}	*10-100*
2	*0.01-0.001*	10^{-2} - 10^{-3}	*100-1000*
3	*0.001-0.0001*	10^{-3} - 10^{-4}	*1000-10,000*
4	*0.0001-0.00001*	10^{-4} - 10^{-5}	*10,000-100,000*

Table 3: SIL Category Overview IEC 61508[11].

[11] International Electrotechnical Commission, "61508:2010 Function Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems," IEC 61508:2010, 2010.

Determining the SIL is just one component of ensuring functional safety, but since it is a quantitative measure, it is a popular metric among standards, regulators, and industry. For example, NOG Guideline 070[12] (a Norwegian national guideline) establishes minimum SIL requirements for common offshore safety instrumented functions, rather than the full risk-based approach described in IEC 61508[13]. Regarding the annular/pipe ram and blind shear ram, NOG 070 states:

The success paths were utilized to estimate the probability of failure on demand for the BOP system, providing an approximation of the system SIL category.

The required PFD/SIL for the BOP function for each specific well should be calculated and a tolerable risk level set as part of the process of applying for consent of exploration and development of the wells. As a minimum, the SIL for isolation using the annulus function should be SIL 2 and the minimum SIL for closing the blind/shear ram should be SIL 2.

The BSR HP Close Operation success path model allowed a quantitative estimation of the PFD for the BSR HP Close function. Making the PFD estimate is similar to establishing a SIL. However, as mentioned at the beginning of this section, the SIL indicates a level of risk reduction for dangerous failures, rather than a reliability estimation. While the results presented here provide insight into the approximate SIL category of the BSR system, this analysis does not represent the scope necessary for a complete functional safety analysis of a "safety instrumented system", as prescribed by IEC 61508.

Data on BOP control system component reliability is sparse, resulting in uncertainty in the quantitative results.

The analysis determined a PFD for the three main BSR HP Close actuation pathways (manual, EDS, and DMAS), along with a PFD for the BSR HP Close system as a whole using the three actuation pathways. An overview of the calculation results is presented here. It is important to note that data on the reliability of BOP control system components is fairly sparse. While data on some components is available, uncertainty can be large. For other components, no data is available, and expert judgment is needed to provide reasonable reliability estimates.

The results of the PFD analysis for the BSR HP Close function can be found in Table 4 for each of the three main actuation pathways, along with the total PFD for the BSR HP Close system. This evaluation does not consider the success of shearing the drill pipe or sealing the wellbore, but only the successful actuation of the BSR HP Close function.

It is important to note that the results in Table 4 are mean value results. Typically, for a SIL calculation, a 70 percent upper confidence interval value is preferred over a point estimate or mean. Individually, the Manual HP Close and EDS are approximately SIL– 1, with a PFD of ~1 × 10. In "deadman" mode, the DMAS is also SIL – 1, but the "autoshear" function is SIL – 2.

[12] Norwegian Oil and Gas Association (NOG), "Norwegian Oil and Gas Association Application of IEC 61508 and IEC 61511 in the Norwegian Petroleum Industry," NOG Guideline 070, 2004.
[13] SINTEF, "Barriers to Prevent and Limit Acute Releases to Sea," SINTEF A20727, 2011.

This difference is due to the fact that fewer components are necessary to activate the autoshear function, in comparison to the deadman function. Taken together, the BSR HP Close PFD is within the SIL – 2 category[14].

Actuation Pathway	*Probability of Failure per Demand (PFD)*	*Odds of Failure per Demand*	*Approximate SIL*
Manual HP Close	*1.24×10^{-2}*	*1 in 81*	*1*
EDS	*1.58×10^{-2}*	*1 in 63*	*1*
DMAS			
Deadman	*1.45×10^{-2}*	*1 in 69*	*1*
Autoshear	*9.51×10^{-3}*	*1 in 105*	*2*
Total[15]	***5.60×10^{-3}***	***1 in 179***	***2***

Table 4: BSR HP Close Failure Probability Estimates.

While the actuation pathway and total BSR system PFD provide an approximate level of risk reduction, perhaps a more important result, from an operational standpoint, is the effect on the BSR system PFD when a component is unavailable. Argonne performed a sensitivity analysis to determine the effect on BSR system reliability when a component or system was unavailable. The study revealed the following major findings:

First, success paths provided an intuitive and accessible approach to assess the reliability of the complex BOP system. Interpreting BOP schematics required a variety of industry experts, but the success path notation aided the communication of essential BOP functionality and allowed the identification of vital components and systems without the need for detailed, fault-based analyses.

Second, the qualitative success path evaluation of BOP blind shear ram reliability indicated several potential weaknesses and single points of failure within the system. These include the BOP shuttle valve stack, the blind shear ram functionality, and the control system software (among others).

Third, the quantitative success path evaluation to determine a probability of failure on demand of the high-pressure close of the blind shear ram appears to indicate a SIL – 2 for the blind shear ram system as a whole.

Increasing the SIL to a higher category, such as SIL – 3, would likely require significant changes to the BOP control system to achieve the necessary level of reliability, in addition to redundancy in the blind shear ram, as it serves as a single point of failure for the system (assuming a BOP configuration with a single blind shear ram).

[14] Since the three activation pathways share many systems/components (i.e., they are not independent), the total *BSR* PFD is *not* equal to the product of PFDs for the *Manual HP Close*, *EDS*, and *DMA* despite the fact that only one pathway is necessary for successful operation.
[15] Only considering manual, EDS, and DMAS, and assuming “Deadman” mode for DMAS

COMPLETION AND PRODUCTION

Once a well has been drilled, completion operations must be undertaken to prepare the well for production. The following section discusses an application of the Argonne MPB Approach to support safe *completion* and *production* operations — installing and deinstalling a production packer.

INSTALLING AND DEINSTALLING A PRODUCTION PACKER

A seal bore production packer is used to demonstrate the versatility of utilizing success paths to examine risks for passive barriers. As seen in Figure 14, the success path acts as a framework for lifecycle management (e.g., design, construction, installation, operational monitoring, and removal).

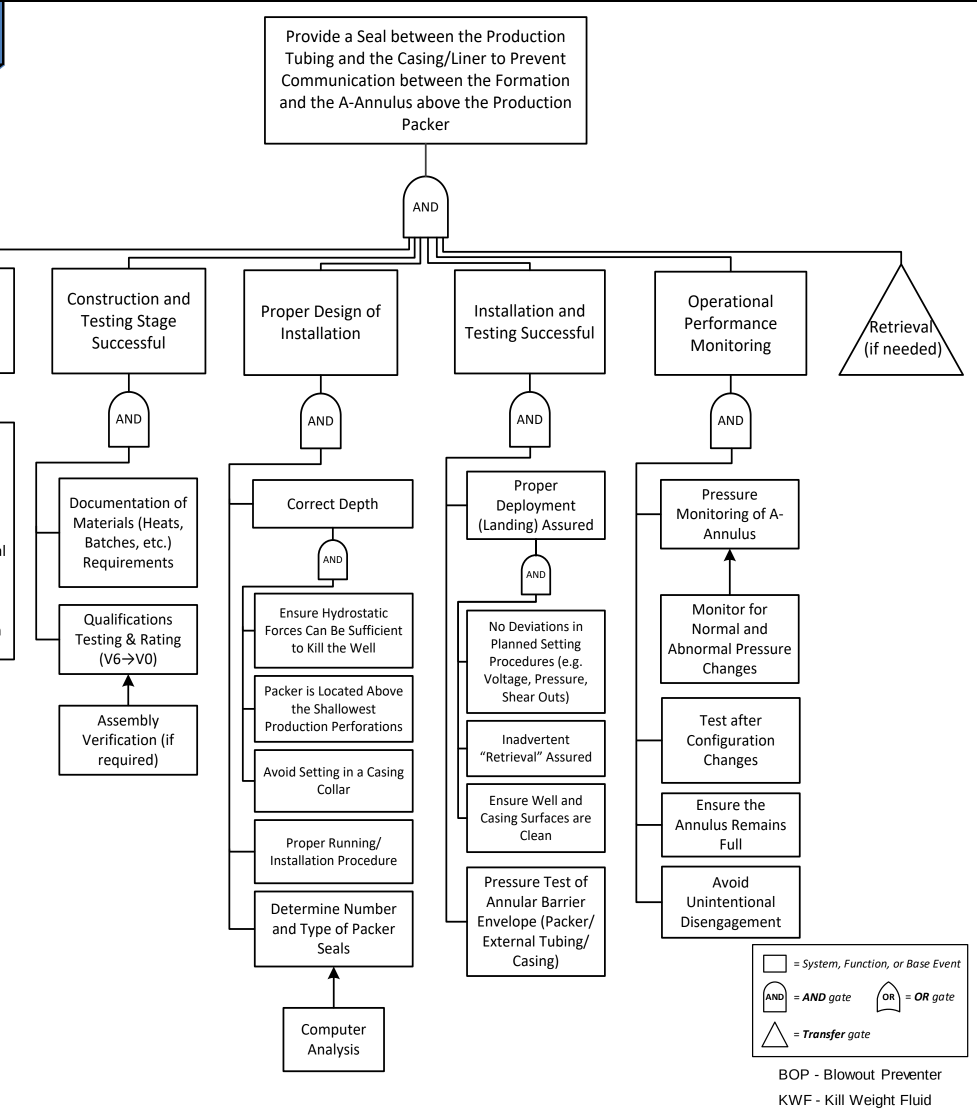
The use of packers is generally well understood and widely used in the oil and gas industry during well completions. The packer specification is described in ANSI/API SPEC 11D1 (second edition, July 2009). Packers are *passive* barriers and place more emphasis on design, installation, and monitoring. Note the intermediate design phase for the packer installation process. As with all barriers, packers must be monitored for system integrity. In this case, the operational monitoring consists of monitoring the A-annulus of the well for abnormal pressure changes. Normally, the A-annulus is filled with weighted brine that contains additives to inhibit corrosion. Temperature effects at the bottom of the well can have a significant impact on the packer. Significant temperature differentials between the production tubing and the well casing can cause contraction or elongation of the production tubing and can even cause some packers to release unintentionally. This gives rise to an important barrier threat scenario, as noted in the template.

Physical Barrier: Seal Bore Production Packer/No Gas Lift

Applicability	**Installed in completion phase: used in completion and production phases.**	Argonne MPB Approach

Safety Function

Success Path



Alternate Success Path	Wellhead Seals and Casing; BOP during installation/workover
Necessary Support Systems	Passive systems usually require no support systems.
Threat Scenarios	- Large temperature variations Any high temperature event that could cause elongation of the production tubing could impose excessive axial stresses on the packer and push it beyond it's operating envelope. Conversely, any operation that cools the tubing (such as a stimulation acid job) could contract the tubing and cause the tubing seals to disengage from the packer or the tubing could part (depending on the packer type and condition of the seals which sometimes become stuck inside the packer over time). - Inability to maintain hole full of fluid

Figure 15: Success Path for a Seal Bore Production Packer.

The removal of barriers in general, and in this case the retrieval of a packer, represents an area of high risk. Figure 15 illustrates the success path for packer retrieval. Here, the MPB Approach assumes that there is pressure under the barrier unless it can be “proven” otherwise. If there are no impediments to adding kill weight fluid (KWF), then the engineer can simply use KWF to kill the well and then follow the recommended removal practice of the manufacturer.

However, it may sometimes be the case that the production tubing is intentionally blocked (e.g., with a bridge plug) or unintentionally blocked with debris. In this scenario, it is not possible to add KWF by means of the production tubing, and the blockage must be removed so that the well can be killed.

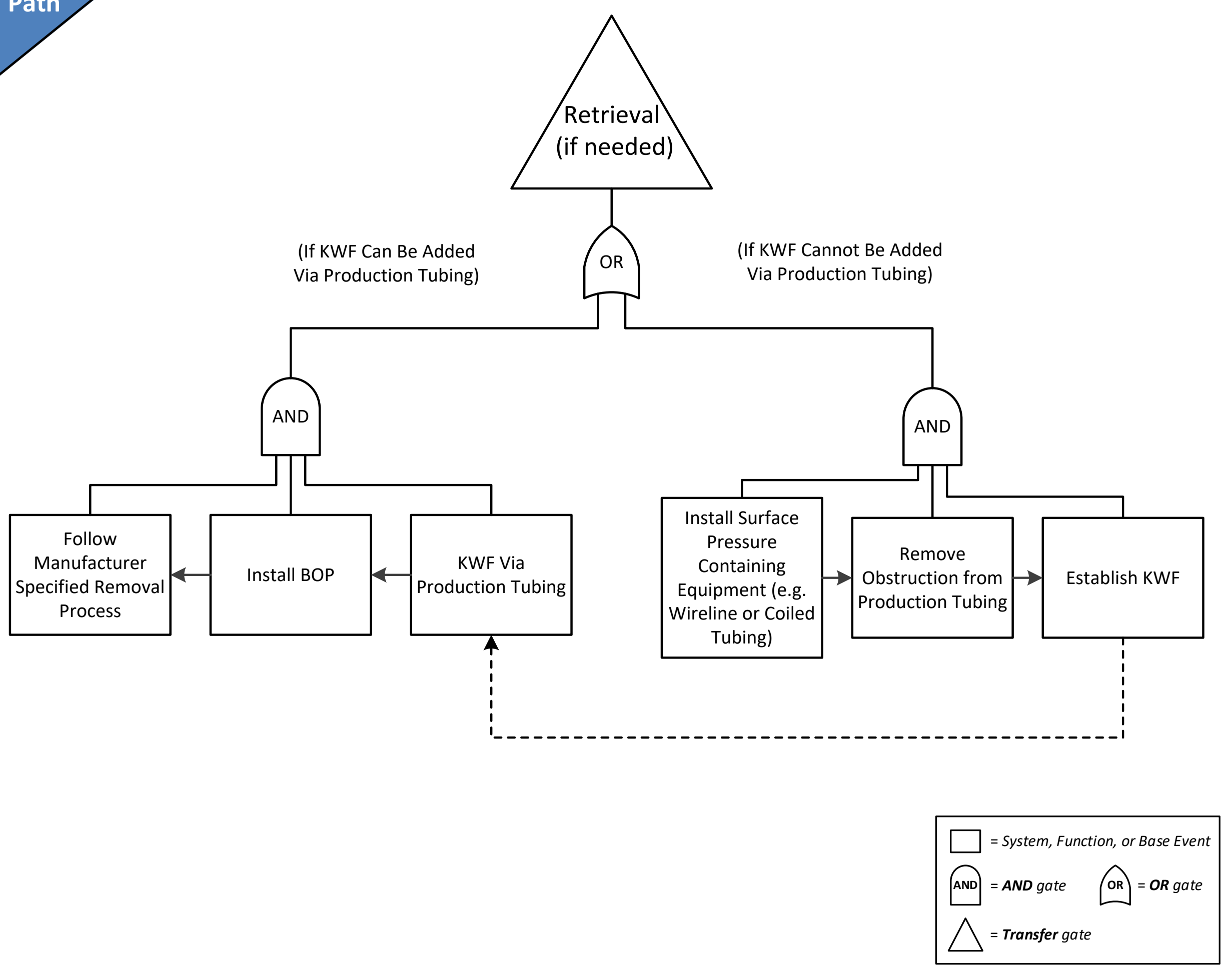
In such a case, surface pressure holding equipment, such as a wire-line system or a coil tubing system, is brought into place. Because these systems are capable of holding pressure at the surface, they form a barrier to replace the barrier that is being removed (e.g., the blockage). (Pressure holding equipment is mandatory unless the well can be proven to not contain pressure.) Once the plug or obstruction is removed, it becomes possible to add KWF via the production tubing and fully kill the well. The surface pressure containing equipment can be safely removed, a BOP can be added, and the packer(s) can then be safely removed by the recommended removal practice of the manufacturer. *There are events in the BSEE database that demonstrate how unexpected pressure can produce loss of well control events when pressure holding equipment is not used to open a pressurized well.*

This success path illustrates one of the key and essential elements of the MPB concept – that there must always be multiple physical barriers in place to keep the hydrocarbons where they belong.

Physical Barrier: Sealbore Production Packer/No Gas Lift

Applicability	**Packer Retrieval**
Safety Function	

Success Path



BOP - Blow-Out Preventer
KWF - Kill Weight Fluid

Alternate Success Path	There are several ways to add surface pressure containing equipment. The basic idea is to add another barrier while working on the production tubing.
Necessary Support Systems	All systems used to support surface pressure containment system.
Threat Scenarios	•Inability to maintain kill weight fluid column •Inability to operate BOP or surface pressure containing equipment •Loss of AC power to vital components

Figure 16: Success Path for Packer Retrieval.

WORKOVER

The Argonne MPB Approach is also used to support improved safety in *workover* activities — operations done on, within, or through the wellbore after the initial completion.

COILED TUBING EQUIPMENT SAFETY ANALYSIS

In 2016, Argonne began working with a Joint Implementation Project (JIP) consisting of coiled tubing SMEs and industry representatives to update the current version of API RP 16ST by developing a thorough FMECA for coiled tubing technology that can be used for well intervention on offshore and onshore wells. Argonne's expertise in developing FMECAs in the past for the nuclear industry proved key in ensuring the quality of this work. Additionally, Argonne's experience of closely studying the safety of coiled tubing technology helped develop a *barrier-based* FMECA.

Argonne recommended beginning the analysis by identifying the necessary physical barriers required for each equipment configuration. One of the key discoveries in this effort was the necessity to perform safety analysis for a number of barrier configurations dependent on well *pressure category*. The API has historically focused on the transition toward risk-based decision-making approaches.[16] Based on this goal, the API RP 16ST committee recommended various safety equipment configurations that corresponded to the properties of the well. Together with the SMEs, Argonne identified 19 different stack configurations that corresponded to the minimum number of barriers needed for each pressure category. A summary of these barrier configurations is provided in Table 5.

Pressure Category	**Minimum Number of Barriers per API RP 16ST**	**Barrier Configuration Option Name**	**List of Barriers or Barrier Components**
PC-0: No pressure at surface	1	Option A	Pipe Ram, Coiled Tube, Flow-Check Assembly
		Option B	Blind Ram, Shear Ram
		Option C	Shear-Blind Ram (XSBR)
PC-1: 1 psig–1,500 psig and PC-2: 1,501 psig–3,500 psig	2	Option A	Pipe Ram, Coiled Tube, Flow-Check Assembly
		Option B	Blind Ram, Shear Ram
			Pipe Ram, Coiled Tube, Flow-Check Assembly
		Option C	Shear-Blind Ram (Combi) Blind Ram, Shear Ram
			Shear-Blind Ram (XSBR)
		Option D	Shear-Blind Ram (Combi in a working stack with a single-pipe ram and a single-slip ram)
			Shear-Blind Ram (XSBR)
		Option E	Shear-Blind Ram (Combi in a working stack with a combination pipe-slip ram)
			Shear-Blind Ram (XSBR)

[16] An example is the barrier-based analysis used in API RP 16D for drilling operations.

		Option F	Combination Pipe-Slip Ram, Coiled Tube, Flow-Check Assembly
			Shear-Blind ram (Combi)
PC-3: 3,501 psig–7,500 psig and PC-4: 7,501 psig–12,500 psig	3	Option A	Pipe Ram, Coiled Tube, Flow-Check Assembly
			Blind Ram, Shear Ram
			Shear-Blind Ram (XSBR)
		Option B	Pipe Ram, Coiled Tube, Flow-Check Assembly
			Shear-Blind Ram (Combi)
			Shear-Blind Ram (XSBR)
		Option C	Blind Ram, Shear Ram
			Shear-Blind Ram (Combi)
			Shear-Blind Ram (XSBR)
		Option D	Shear-Blind Ram (Combi in a working stack with a single-pipe ram and a single-slip ram)
			Shear-Blind Ram (XSBR)
		Option E	Shear-Blind Ram (Combi in a working stack with a combination pipe-slip ram)
			Shear-Blind Ram (XSBR)
		Option F	Combination Pipe-Slip Ram, Coiled Tube, Flow-Check Assembly
			Shear-Blind Ram (Combi)
			Shear-Blind Ram (XSBR)

Table 5: Summary of the Coiled Tubing Barrier Configurations for Each Pressure Category.

Figure 17 illustrates an example barrier configuration diagram for a given well. In this example, the pressure category of the well is 3 (hence, “PC-3”), which means the pressure in the well is between 3,501 and 7,500 psig. According to the recommendation in API RP 16ST, a coiled tubing stack configured for PC-3 must have at least three redundant barriers (with an exception in PC-3 Option D, where two SBRs are installed). Argonne designed these logical diagrams for each pressure category to identify the proper barriers needed.

The series of barrier diagrams are the outcome of reaching a consensus on necessary safety elements present in the system. The diagrams are also the basis for developing coiled tubing barrier success paths and the barrier-based FMECA. This FMECA will become the foundation for the updated version of API RP 16ST by serving as justification for the shift toward a risk-based decision-making approach.

Argonne’s effort in helping the industry, as well as other stakeholders, reach consensus on the most viable barrier configurations has helped reach further agreements regarding the consequences of specific component failures on barriers. Thinking about barriers makes it easier to see how failure that affects a specific barrier, altering it defective or inoperable, has a less severe failure consequence if there are other barriers installed to ensure the safety of the overall system.

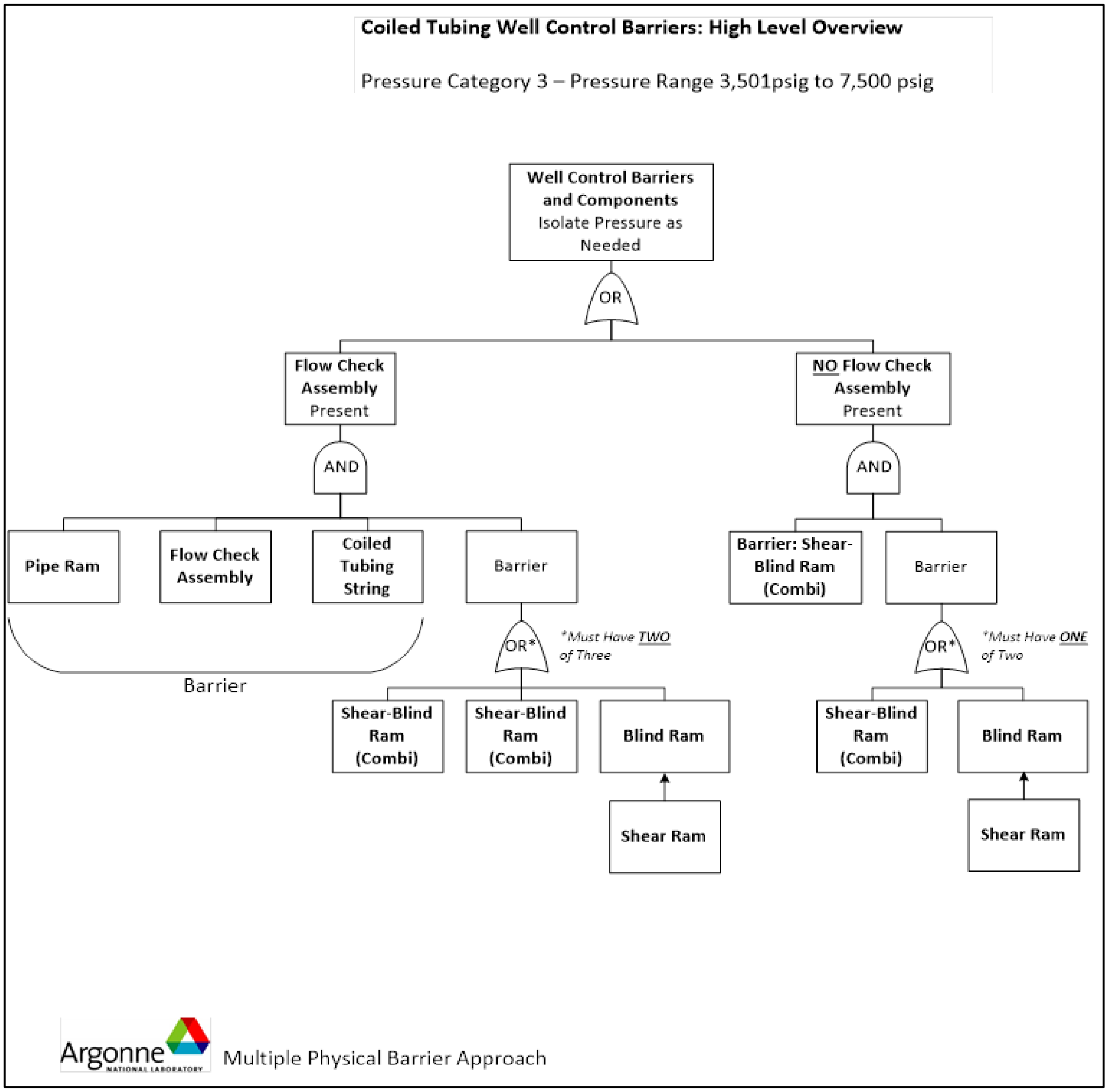


Figure 17: Example Barrier Configuration Diagram for a PC-3 Well.

COILED TUBING INSPECTION WORKSHOP – A RISK-BASED APPROACH

The development of the documents described in the previous section also helped Argonne work with BSEE on creating a risk-based coiled tubing inspection workshop. In this workshop, which will take place beginning in July 2017, Argonne will transfer the risk-based approach to BSEE participants. The modules of this workshop will be designed by Argonne together with BSEE to ensure that the goals of BSEE in facilitating risk-based coiled tubing inspection programs are met.

The goal of this workshop is to ensure safety and to protect the environment by helping stakeholders adopt a common approach to understanding and evaluating critical safety functions without the requirement for new regulations.

PLUG AND ABANDONMENT

On September 15, 2016, a Joint Industry Project (JIP), organized by Argonne National Laboratory (ANL) in collaboration with DNV GL, assembled a team of 27 executives and subject matter experts from the oil and gas industry willing to perform a case study and test whether the barrier-success path approach could help improve performance and safety.

The JIP selected a deepwater operation case study to identify the barriers and success paths associated with it. The operation selected was the plugging and abandonment (P&A) process — both for temporary and for permanent well abandonment.

Typical P&A activities discussed and evaluated in this JIP included the cement barrier design, the placement and testing process, risk evaluation and management, and regulatory compliance.

The first P&A case study workshop was held in Katy, Texas, on October 10–11, 2016. It was attended by 27 subject matter experts with expertise in offshore operations, including P&A and cementing. Gulf of Mexico P&A regulations were proposed and discussed to assess their value to stakeholder-regulator communication.

The results of the phase 1 JIP provide evidence that the barrier-success path approach could provide significant benefits to the offshore oil and gas industry, in the following areas:

- well integrity, well control, and P&A
- cross-industry communication for performance and compliance
- human factors, decision making, and situation awareness
- qualification and regulatory approval of new technologies
- barrier monitoring and management
- process safety and risk management

The second workshop was held October 31–November 1, 2016. Success paths and success criteria developed in the first workshop were revised to identify alternative success paths and “showstoppers” based on feedback and comments from the participants.

A regulatory compliance success tree, based on the US Gulf of Mexico P&A regulations, was proposed and discussed to assess its value to stakeholder-regulator communication.

RESEARCH FINDINGS

The applications of the Argonne MPB Approach described in this report and success paths in Appendix I demonstrate the value of this tool for enhanced management and oversight of high-risk activities and equipment. The approach provides a *systematic process* for applying process safety concepts and barrier management to understand, assess, and regulate drilling, completion, production, workover, and decommissioning activities.

The MPB Approach begins with a qualitative assessment focused on identifying the physical barriers, their critical functions, and the success paths that are needed to ensure full success and safety. This logical chain of cause and effect logic also forms the basis of a detailed *operational risk analysis* for a specific well, rig, or facility. When quantification is incorporated with quality data, the *safety significance of any component, system or set of human actions* can be numerically evaluated and compared. Similarly, the approach can be used to compare and evaluate the *safety significance of existing or proposed regulations*.

Through the use of success paths, the MPB Approach provides a *common language* for communicating barrier and risk management information within organizations and across the global industry and regulatory authorities. The combination of engineering and social science concepts in this approach allows systematic assessment of risk informed decision support on technology safety, human performance, process safety culture, and organizational performance.

A well-charted success path enables a wide variety of stakeholders to *intuitively comprehend* the key points required for success and then participate intelligently in the discussion about risks and safety. Further, it provides a *consistent and rigorous basis* for defending the decisions that have been made whether to senior executives or third parties. The foundations of this approach have been demonstrated to hold up in legal situations.

OBSERVATIONS

While the Argonne MPB Approach helps identify physical barriers, their critical functions, and elements needed for the success of an operation, it is the management system that must incorporate these factors to add the greatest value.

At its core, the role of the management system is to *ensure that equipment and personnel perform as expected.* Every element of a success path can (and should) be incorporated into the management system. The MPB Approach can be applied to help systematically organize operational programs and demonstrate to management and rig crews that “all of the boxes are checked.” When problems occur, success paths can be used to help guide root-cause analyses and keep track of near-miss failures.

APPLICATION OF THE MPB APPROACH TO BSEE OPERATIONS AND GOVERNANCE

As identified in the BSEE FY 2016 – FY 2019 Strategic Plan[17], BSEE seeks to demonstrate *operational excellence* through the achievement of safety, environment, and conservation goals; and *organizational excellence* with a focus on people, information, and transparency. The following subsections describe how use of the Argonne MPB Approach in planned BSEE initiatives can markedly contribute to the successful implementation of identified strategies and achievement of goals for operational and organizational excellence.

STRATEGY 1: ENSURE A CONSISTENT, NATIONAL APPROACH TO DETECTION OF NONCOMPLIANCE AND INCIDENT INVESTIGATION

By providing a consistent taxonomy and systematic process for getting at the root cause of operational safety risks, the Argonne MPB Approach is well suited for *use in investigations to increase BSEE's capacity to identify and reduce unsafe conditions offshore*.

The MPB Approach provides a mechanism for rigorously demonstrating and evaluating the severity potential of violations, and offers a risk-informed communication framework for *promoting common understanding and effective dialogue among inspectors, operators, and contractors pertaining to offshore performance*.

STRATEGY 2: EXAMINE THE FULL LIFE CYCLE OF OFFSHORE OPERATIONS AND ADAPT TO CHANGING CONDITIONS

One of the most important challenges BSEE faces today is the evaluation of Application for Permit to Drill (APD) permits and Deepwater Operation Plan (DWOP) permits. When evaluating various permitting requests, BSEE needs to know the operational risks involved. While APD and DWOP permit applications often include risk assessments, practitioners of this analysis do not have a consistent interpretation of barriers — nor do they utilize a common method for evaluating barrier safety. This leads to confusion both for the industry and for BSEE.

Process accidents only happen when a physical barrier is impacted. Hence, risk assessment must focus on physical barriers. Ultimately, the failure to recognize this concept means that risks are not appropriately understood or communicated. Training, meetings, and procedures are important, but should not be discussed on the same level as physical barriers. Instead, these elements are part of the success paths needed to set up or maintain these barriers. As noted above, accidents are the result of physical barriers that were breached, removed, or not properly installed or maintained.

BSEE is in the position, especially with its risk team, to address this fundamental area and

[17] https://www.bsee.gov/who-we-are/history/strategic-plan

provide key guidance to industry. This would immediately reduce confusion and begin standardizing how risks are communicated and reported. The MPB Approach provides an ideal mechanism for use by BSEE and industry to *evaluate an operator's ability to perform operations on the OCS in a safe and environmentally sound manner*.

Barrier success paths provide the means for safe permitting and justification of decisions using a risk-based approach. By considering success paths provided with every APD and DWOP, BSEE would know the exact types of questions to ask concerning the proposed approach and associated technologies. Based on early discussions and partial vetting with the industry, this approach is expected to be well received[18]. It does not introduce additional cost to the industry, and the benefits can be significant, primarily because of increased insights into operational safety.

STRATEGY 3: FURTHER INCORPORATE RISK-BASED DECISION MAKING INTO CORE SAFETY FUNCTIONS

The BSEE risk team is currently implementing a *risk-based inspections* approach for platforms on the OCS. This approach utilizes a numerical analysis model developed by Argonne, coupled with an in-depth analysis of past performance and other company intelligence. This approach helps identify which platforms have the highest amounts of risk and thereby should be considered higher priority. The Argonne MPB Approach now takes this one step further by helping identify what specifically should be looked at once inspectors are aboard the platform.

As described in the comparison of conventional drilling and managed pressure drilling[19], the Argonne MPB Approach can be applied to *incorporate risk-based decision making into the evaluation of new technologies*. By comparing success paths, new technologies can be readily evaluated once inspectors understand which dependencies have been eliminated and whether any new dependencies have been added.

STRATEGY 4: DEVELOP AND SUSTAIN A WELL-TRAINED, HIGH-PERFORMING AND DIVERSE WORKFORCE

The Argonne MPB Approach serves as an optimal tool for *technical training* of BSEE personnel. Education on required barriers and the success paths needed to maintain those barriers, will enable students to quickly and intuitively grasp the key operational safety issues and prepare engineers and inspectors to effectively evaluate operators' submissions and perform inspections on platforms and rigs.

By enabling both technical and nontechnical audiences to intuitively comprehend the key points required for success, the MPB Approach can also *facilitate collaboration across the bureau* on rulemaking and minimize barriers to productivity.

[18] See for example SPE/IADC-173153-MS. D. Fraser, ANL, D. D. Moore, Marathon Oil, M. Vander Staak, Hess Corp., A Barrier Analysis to Well Control Techniques, March 17-19, 2015, London.

[19] SPE/IADC-173153-MS. D. Fraser, Argonne National Laboratory, D. D. Moore, Marathon Oil, and M. Vander Staak, HESS Corp., *A Barrier Analysis Approach to Well Control Techniques*, March 17-18, 2015, London.

STRATEGY 5: ENHANCE BSEE'S DECISION MAKING THROUGH THE COLLECTION, MANAGEMENT, AND ANALYSIS OF HIGH QUALITY INFORMATION

One of the main benefits of the MPB Approach lies in the ability to *integrate risk management and business intelligence into sound risk-informed input to BSEE decision making*. Argonne used information and insights culled from interactions with operators and BSEE subject matter experts, as well as an analysis of BSEE data on facility construction and operation, to develop success paths and equip BSEE with tools to visually analyze critical barrier systems, related regulations, and industry standards all at once. This approach facilitates a quantitative risk assessment, when suitable industry data is available, and identifies where efforts to collect high quality information would have maximum benefit.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The MPB Approach provides a systematic, clear, and comprehensive approach for managing safety risks. Success paths are used to characterize, delineate, and illustrate the steps that must be taken to achieve success in the design, maintenance, and operation for each component of the system

This approach can help government agencies, energy companies, and other stakeholders in building consensus on key safety risks; identifying cost-effective risk mitigation measures; and establishing enhanced methods for testing, inspection, and data-driven decision making.

RECOMMENDATIONS

In response to these research findings and conclusions, the Argonne research team has the following recommendations:

- Continue to apply the MPB Approach in cases where the advantages to stakeholders are both evident and beneficial.
- Seek to build teams of regulators and stakeholders to jointly develop success paths and success trees for specific industry applications. This will allow the concept to gradually gain acceptance in the industry and will stimulate the creativity of technical people in both the industry and the regulatory agency.
- "Experiment" with different applications of the approach on to see how well it works in different areas with different types of people.
- Seek situations where quantification of risk can be used in applications where both risks and costs are high – (e.g., BOPs). In other industries, this combination is where risk-informed decision making (RIDM) has added the most value. In cases of this type, higher costs of quantification are usually justified by quality of the ultimate quantitative decisions that result.

- Seek to expand risk-based thinking and RIDM to all parts of the BSEE organization. This new technology promotes collaboration, common understanding, effective dialogue, and sound input to support the development and implementation of risk-based regulations.

APPENDIX I

SUCCESS PATH DIAGRAMS FOR VARIETY OF OFFSHORE OIL AND GAS TECHNOLOGIES AND OPERATIONS

SUCCESS PATH NOTATION

In the Argonne Multiple Physical Barrier (MPB) approach to safety, *success path* diagrams are developed for safety-critical technologies and high-risk operations to depict what systems, components, and actions are necessary for success. These diagrams utilize a common notation to illustrate steps that must be taken to achieve success in the design, maintenance, and operation of each component in the system. An overview of success path notation is shown in Table I-1.

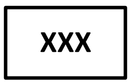
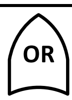
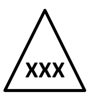
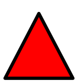
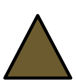
Symbol	Name	Description
	*System, Group, Function or Base Event*	*Name of a system, group of functions, intermediate steps, or base event*
	***AND*** *- Gate*	***All*** *of the inputs are necessary for success*
	***OR*** *- Gate*	***Any*** *of the inputs are adequate for success*
	***Transfer*** *- Gate*	*Transfer to a different success path diagram*
	***Human Action***	*Requires human action or operation*
	***Primary Power***	*Primary rig AC power*
	***Secondary Power***	*Secondary (UPS) rig AC power*
	***Subsea Power***	*Subsea AC power*
	***3k Accumulator***	*3k accumulator pilot supply*
	***5k Surface Hydraulic***	*5k surface hydraulic supply*
	***Actuation Progression***	*Indicates the order of progression for human actions or component actuation*

Table I-1: Success Path Diagram Notation.

The following subsections provide examples of success paths developed by Argonne.

DRILLING SUCCESS PATHS

When applying the MPB Approach to offshore *drilling*, Argonne developed success paths for several physical barriers found during a typical drilling operation. Success paths developed for the FOSV, fluid column, managed pressure drilling system, blind shear ram component of a BOP, and secondary support systems (e.g., electricity, and hydraulic power) are provided below.

FOSV SUCCESS PATH

As shown in Figure I-1, the FOSV success path requires an extensive amount of human action.

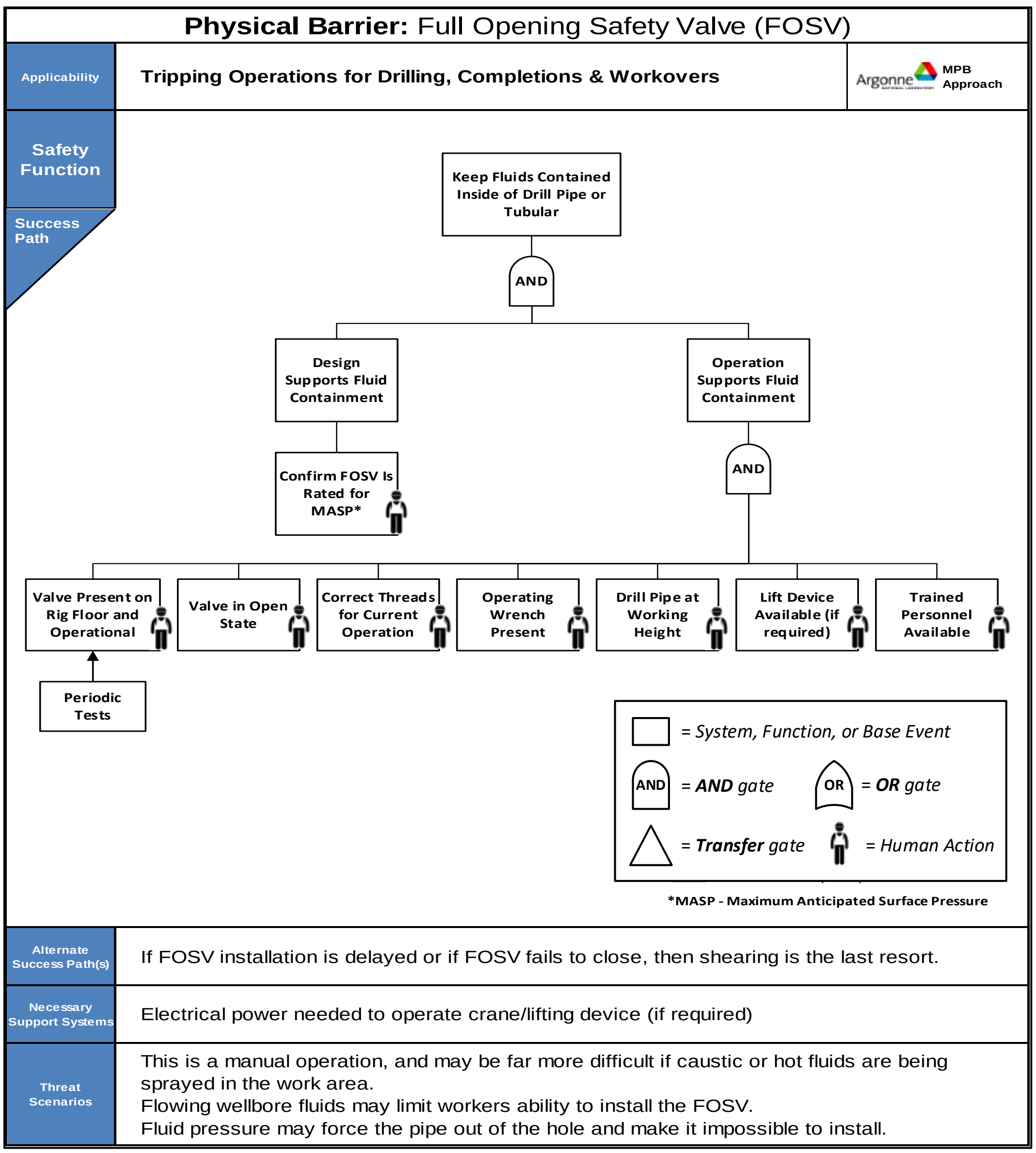


Figure I-1: Success Path for a Full Opening Safety Valve.

FLUID COLUMN SUCCESS PATHS

Drilling fluid ("mud") is one of the most dynamic and critical barriers used during the drilling process. The fluid pressure barrier is sustained as long as the fluid pressure lies between the pore pressure and the fracture gradient of the formation. This is the critical safety function of the barrier. The Argonne MPB Approach was applied to evaluate and compare pressure control techniques for three scenarios of drilling operation. Success paths shown in Figure I-2, Figure I-3, and Figure I-4 illustrate vital steps identified for sustaining the fluid pressure barrier under each scenario.

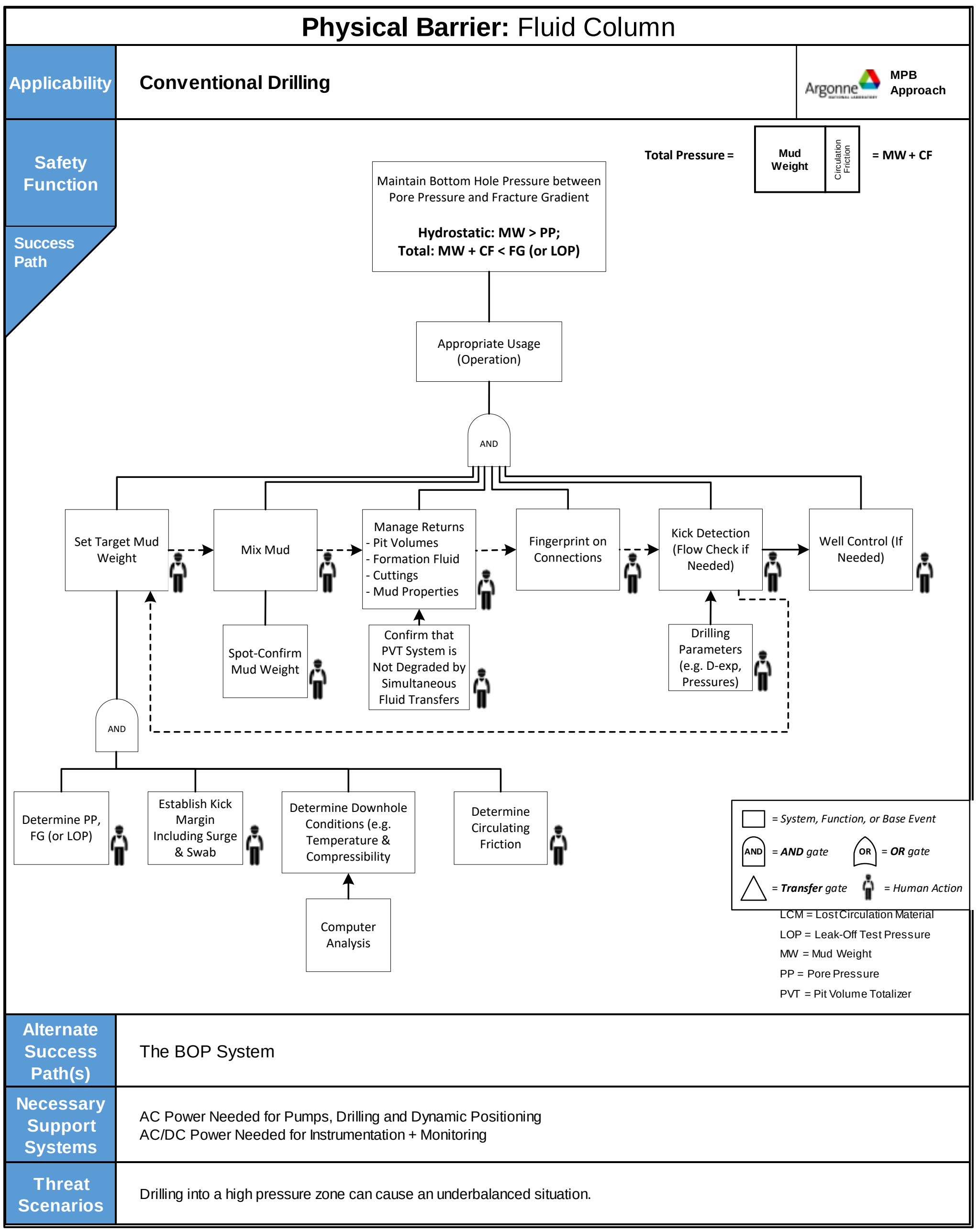


Figure I-2: Success Path for a Fluid Column in Conventional Drilling.

Physical Barrier: Fluid Column (MPD)

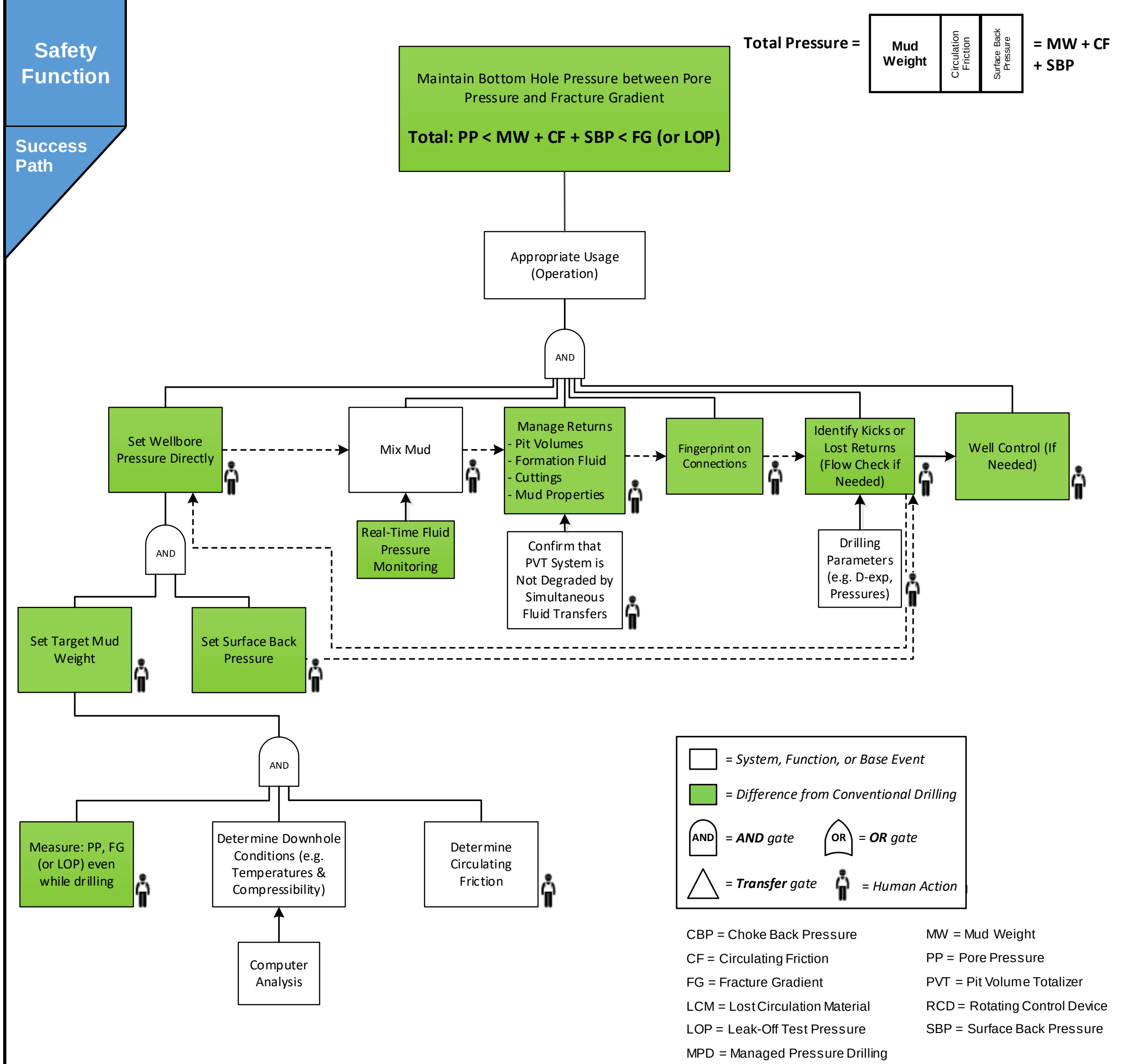
Applicability

Managed Pressure Drilling (MPD) - Constant Bottom Hole Pressure Method

MPB Approach

Safety Function

Success Path



Alternate Success Path(s)	If components fail or barrier degradation occurs the BOP system remains fully available.
Necessary Support Systems	- Pressure Control Equipment (e.g. RCD, MPD Choke) - AC Power Needed for Pumps, Drilling, Dynamic Positioning - AC/DC Power Needed for Instrumentation + Control
Threat Scenarios	- Coriolis meters can produce spurious results when gas is encountered. - If not monitored properly the riser joint and/or riser could become overpressured. - Wear/leak/failure of pressure control equipment.

Figure I-3: Success Path for a Fluid Column in Managed Pressure Drilling.

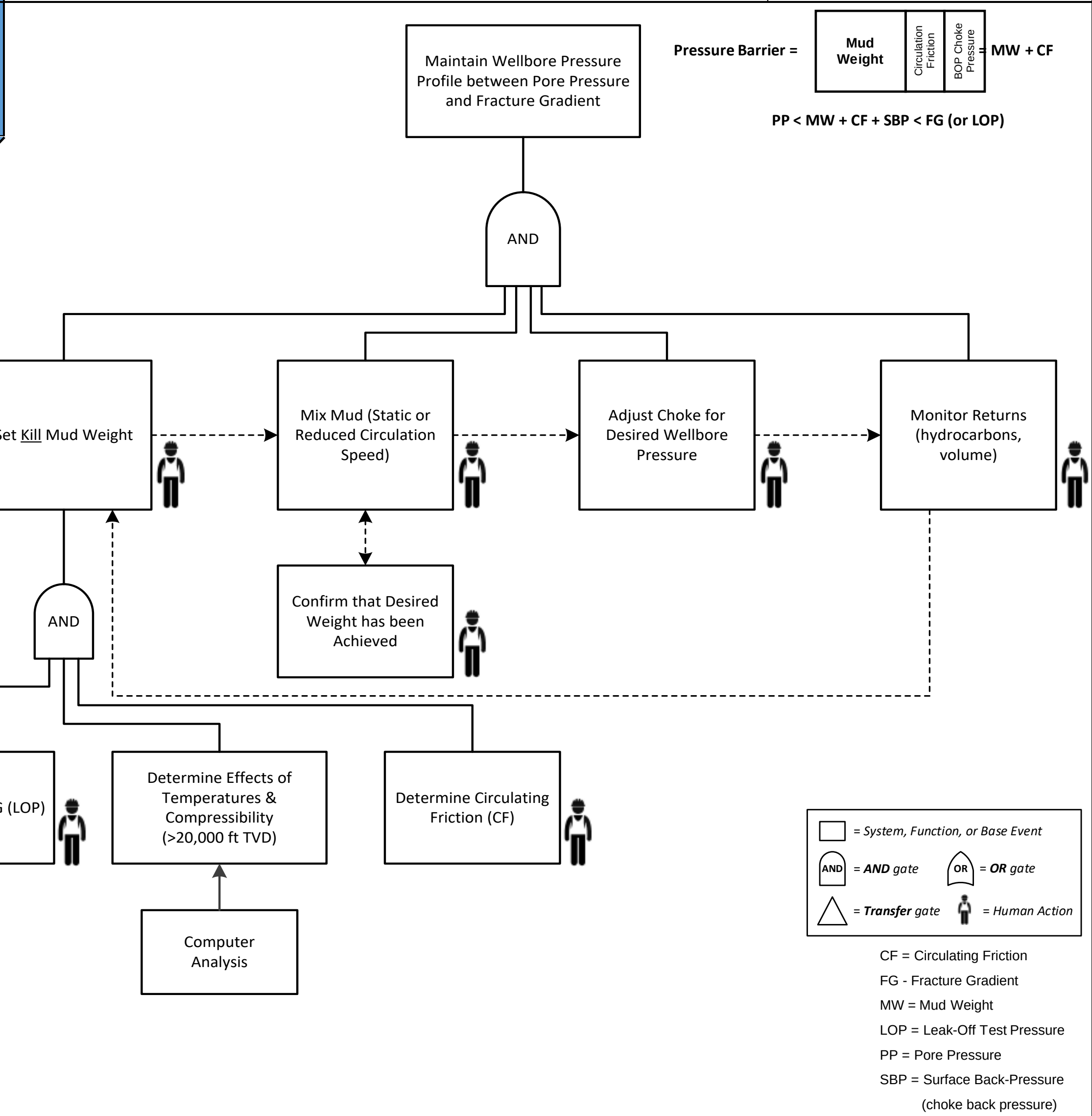
Physical Barrier: Fluid Column (Kick Circulation Via Choke Line)

Applicability	**Conventional Drilling:**	• **BOP Closed** • **Not Drilling** • **Kick Circulation Via Choke**

Argonne

Critical Safety Function

Success Path



Alternate Success Path(s)	Circulation with increase weight drilling fluid.		
Critical Support Systems	AC Power Needed for Pumps, Drilling + Choke Control	AC/DC Power Needed for Instrumentation + Control	BOP Must Remain Shut Until Intentionally Opened
Limitations	This is shown to be a process that is continuous in time. Continuous monitoring and information updates are integral to this process.		

Figure I-4: Success Path for a Fluid Column in Kick Circulation Via Choke Line.

The pressure control success paths were combined with variances and kick performance indicators to aid in the evaluation of alternative drilling scenarios. Figure I-5 displays the barriers, safety functions, and success paths for the three evaluated scenarios.

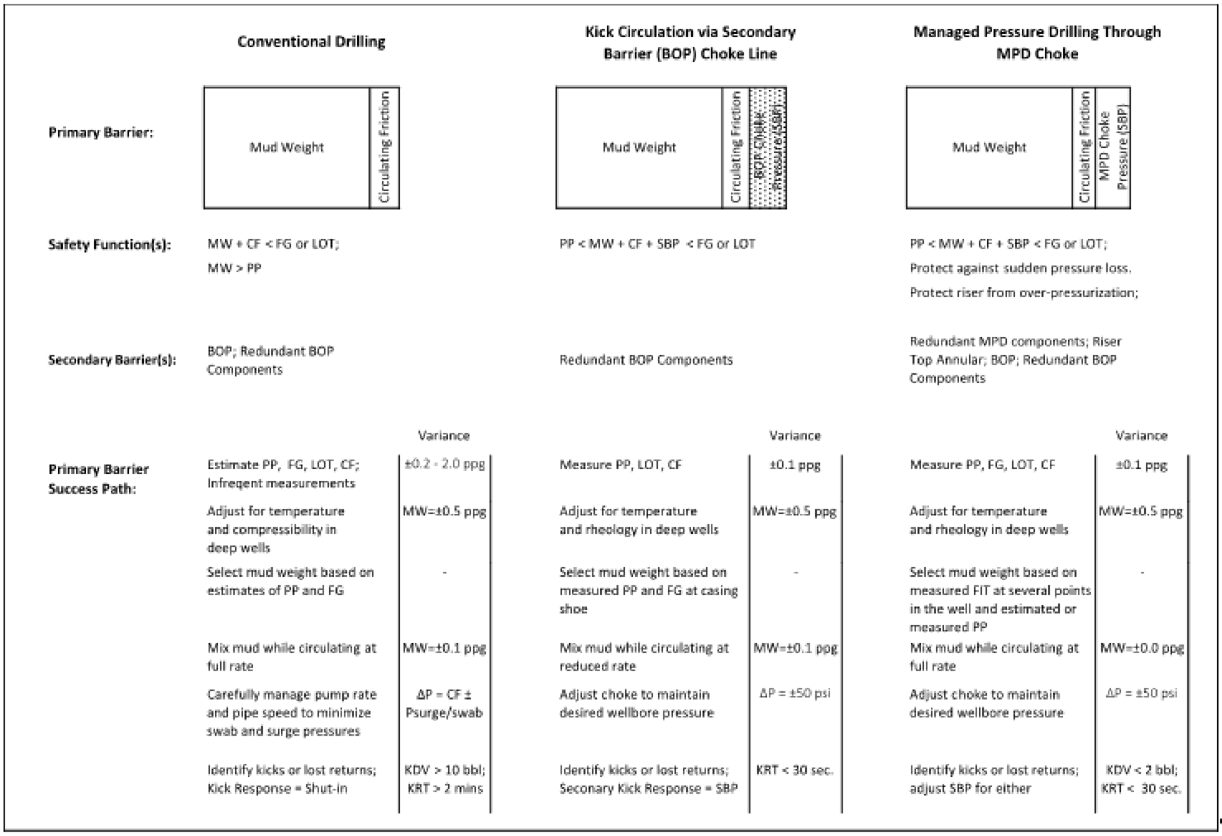


Figure I-5: Illustration of Barriers, Safety Functions, and Success Paths for Three Drilling Scenarios.

Results of the multiple physical barrier analysis points to MPD having substantial benefits over conventional drilling techniques in terms of improved accuracy in measurement of KDVs, reduced KRTs, and ability to maintain a constant bottom-hole pressure.

To increase understanding of techniques commonly used in MPD, success paths were developed for key elements of the system. Figure I-6 shows a success path for use of choke and lines to maintain bottom-hole pressure, and the success path in Figure I-7 illustrates required actions when the RCD to provide a seal between the drill-string and annulus.

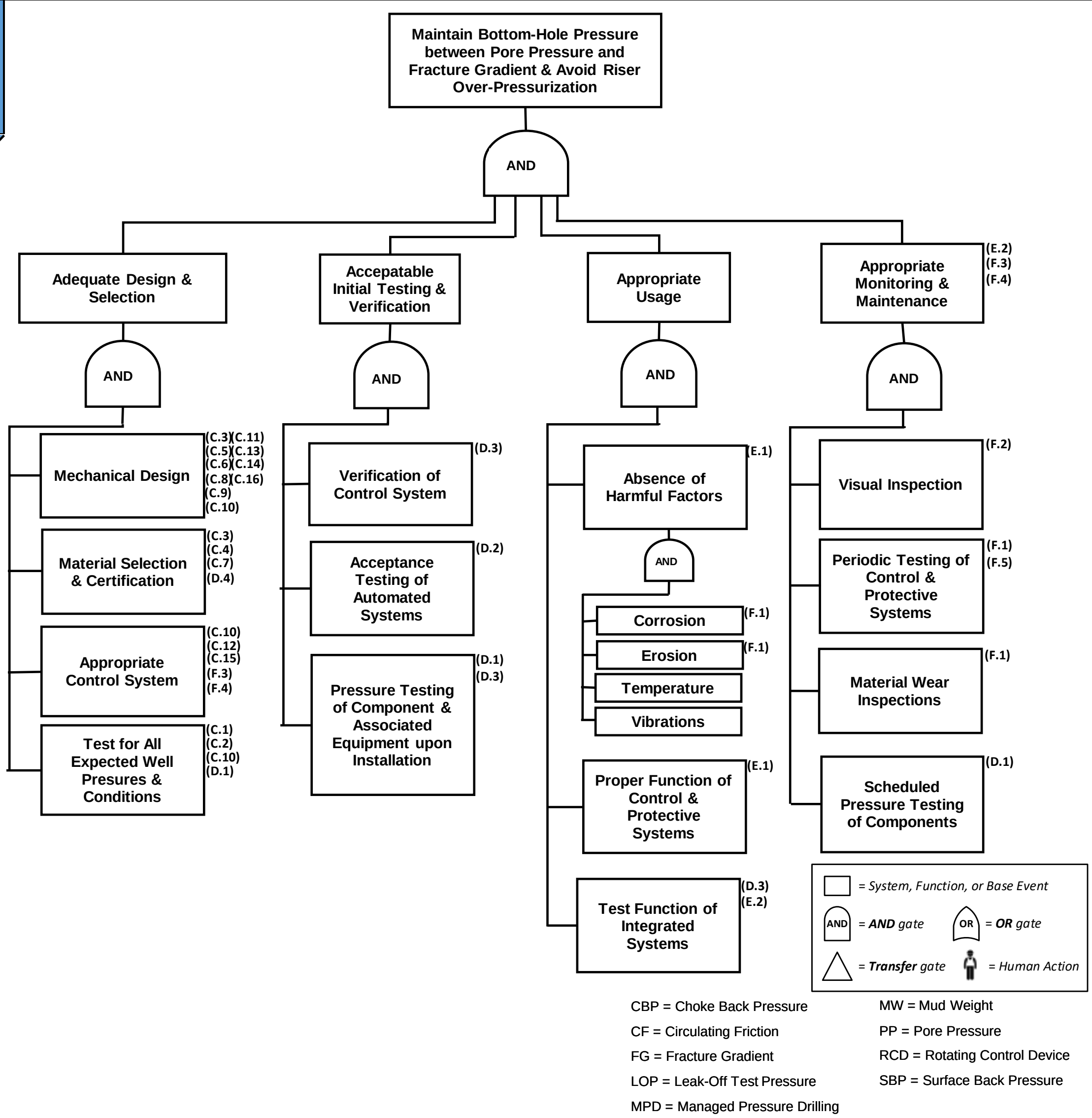
Physical Barrier: MPD Choke & Lines

Applicability: **Managed Pressure Drilling (MPD) - Constant Bottom-Hole Pressure Method**

Argonne MPB Approach

Critical Safety Function

Success Path



Alternate Success Path(s)	If choke fails in fixed position can control bottom-hole pressure by varying pump speed. Ultimate control is to shut Annular Preventer.
Critical Support Systems	AC Power Needed for Pumps, Drilling, Dynamic Positioning; AC/DC Power Needed for Instrumentation + Control; BOP Remains Fully Available in Case of Loss of Well Control
Limitations	A loss of pressure control could lead to a kick. In this case the BOP (Annular Preventer) and the choke would be used to control down hole pressure.
Notes	Parenthetic information refers to acceptance criteria found in Table 15.53 - UBD/MPD choke system of NORSOK D-010.

Figure I-6: Success Path for Choke and Lines in MPD.

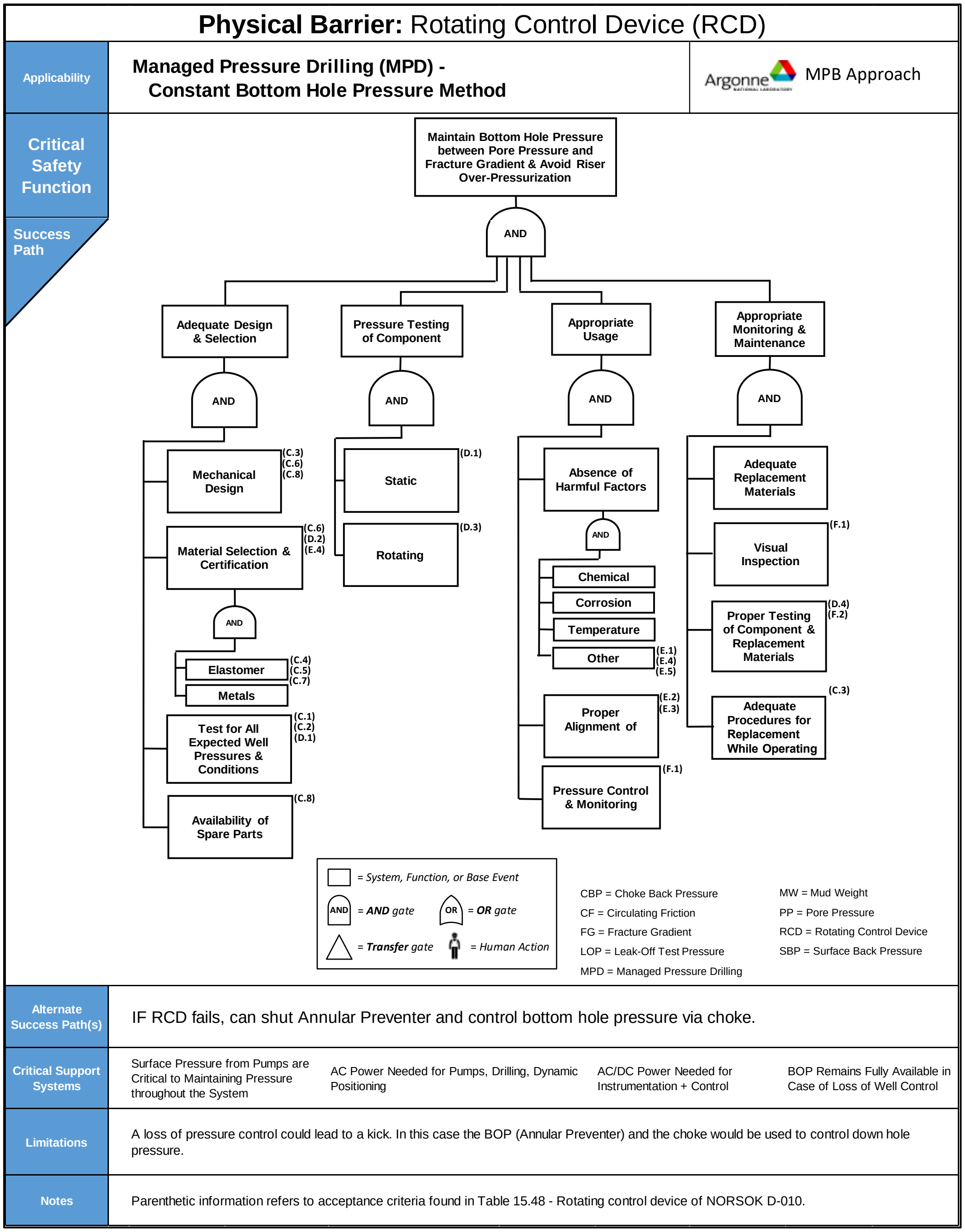


Figure I-7: Success Path for a Rotating Control Device in MPD.

BLIND SHEAR RAM SUCCESS PATH

With the assistance of many industry partners, Argonne developed success path diagrams depicting systems, components, and actions necessary for successful operation of the BSR HP Close function of a BOP. This subsection provides completed success paths for each of the three main BSR HP Close actuation systems (manual, EDS, and DMAS), and associated critical support systems (hydraulic power, AC power, MUX, and pod selection).

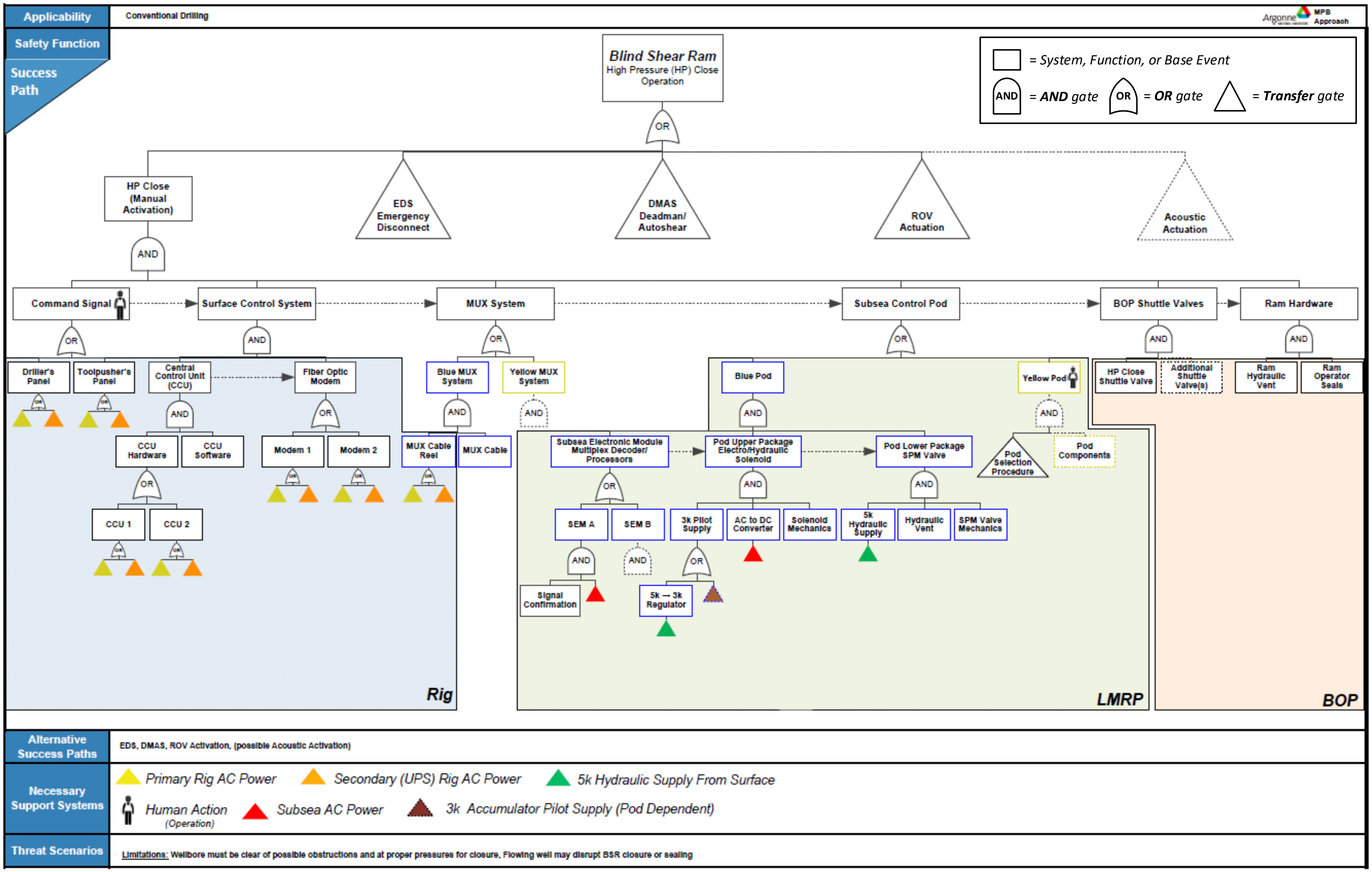


Figure I-8: Success Path for the Manual Actuation of BSR HP Close.

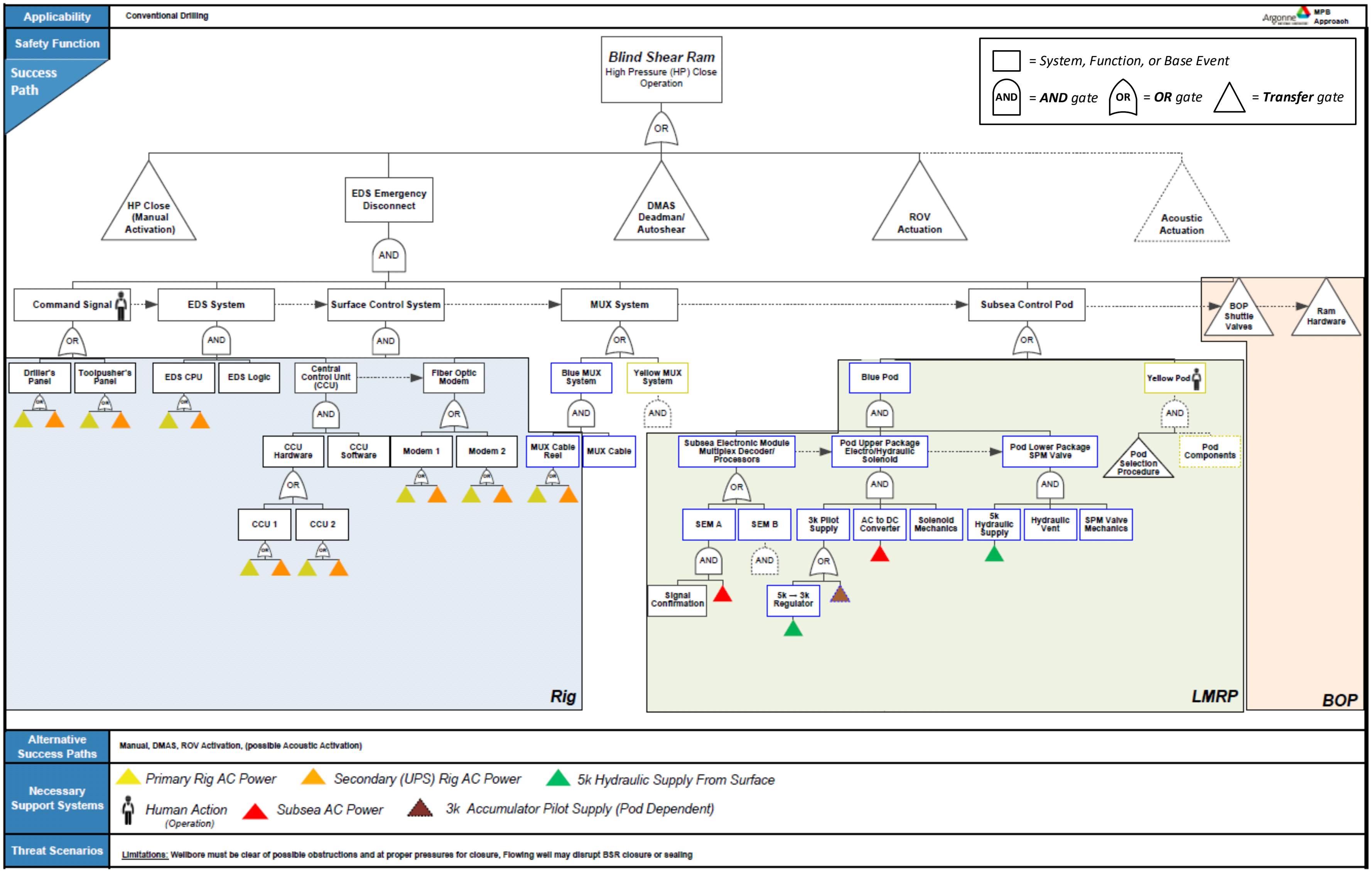


Figure I-9: Success Path for the Emergency Disconnect.

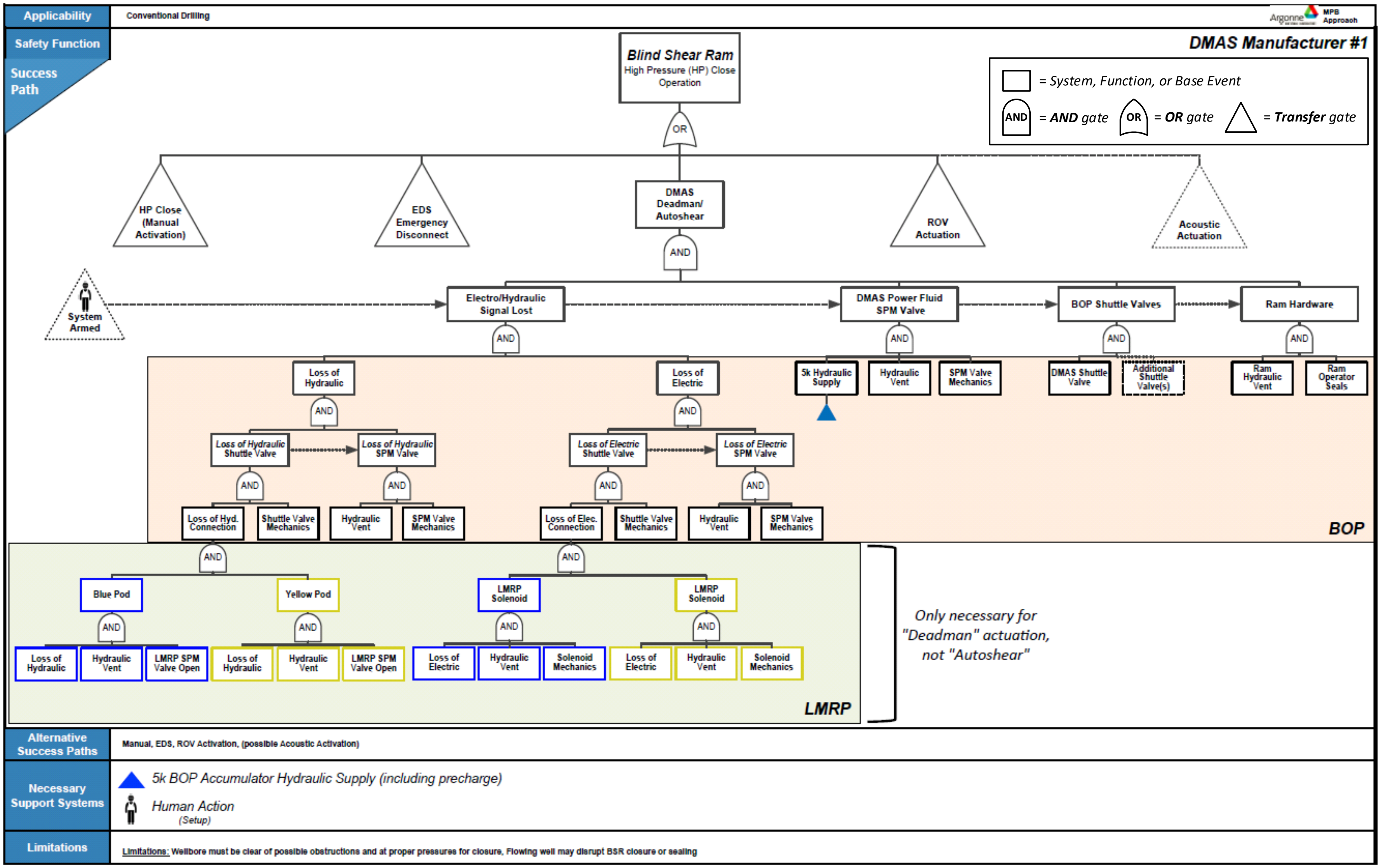


Figure I-10: Success Path for the DMAS of Manufacturer #1.

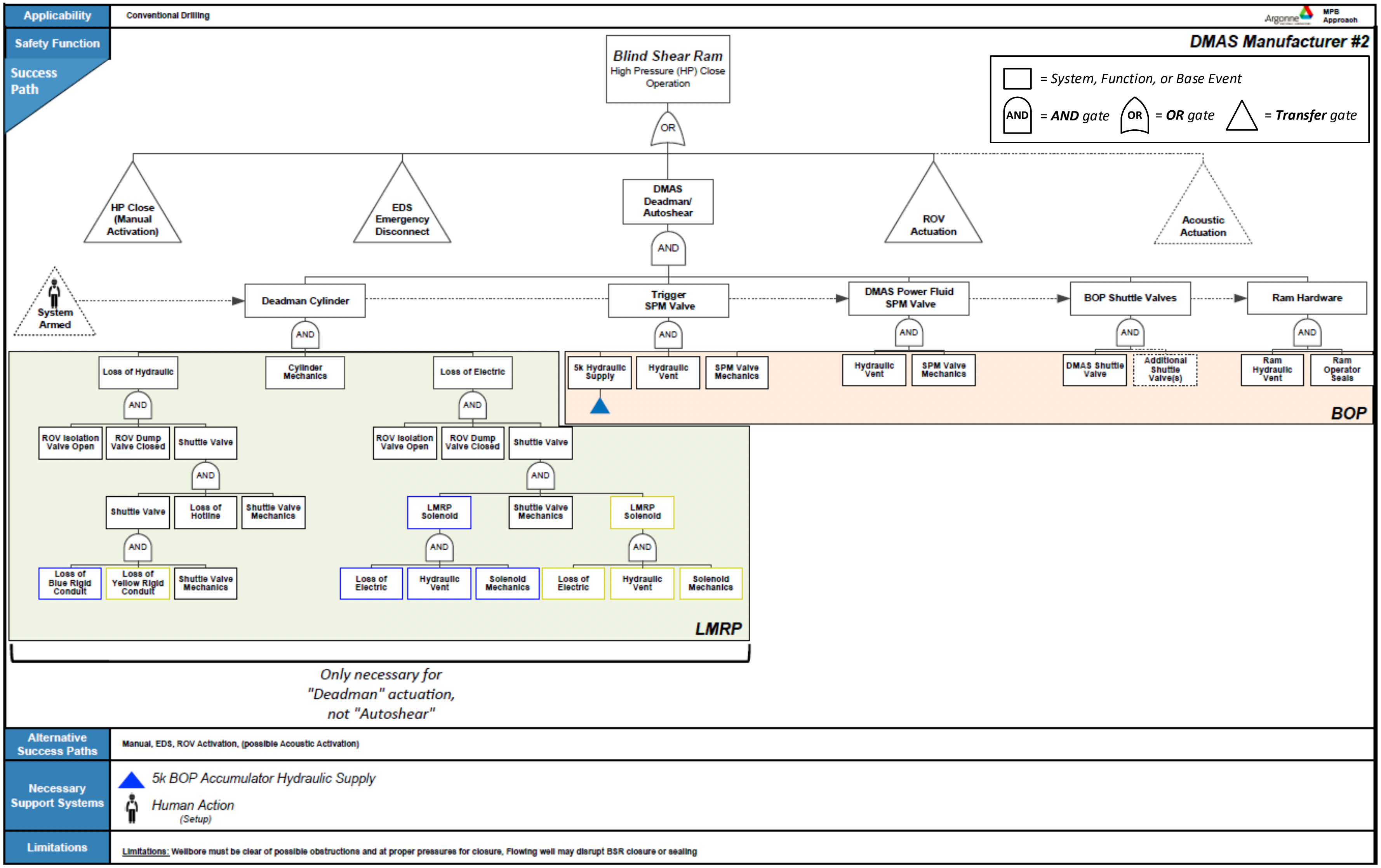
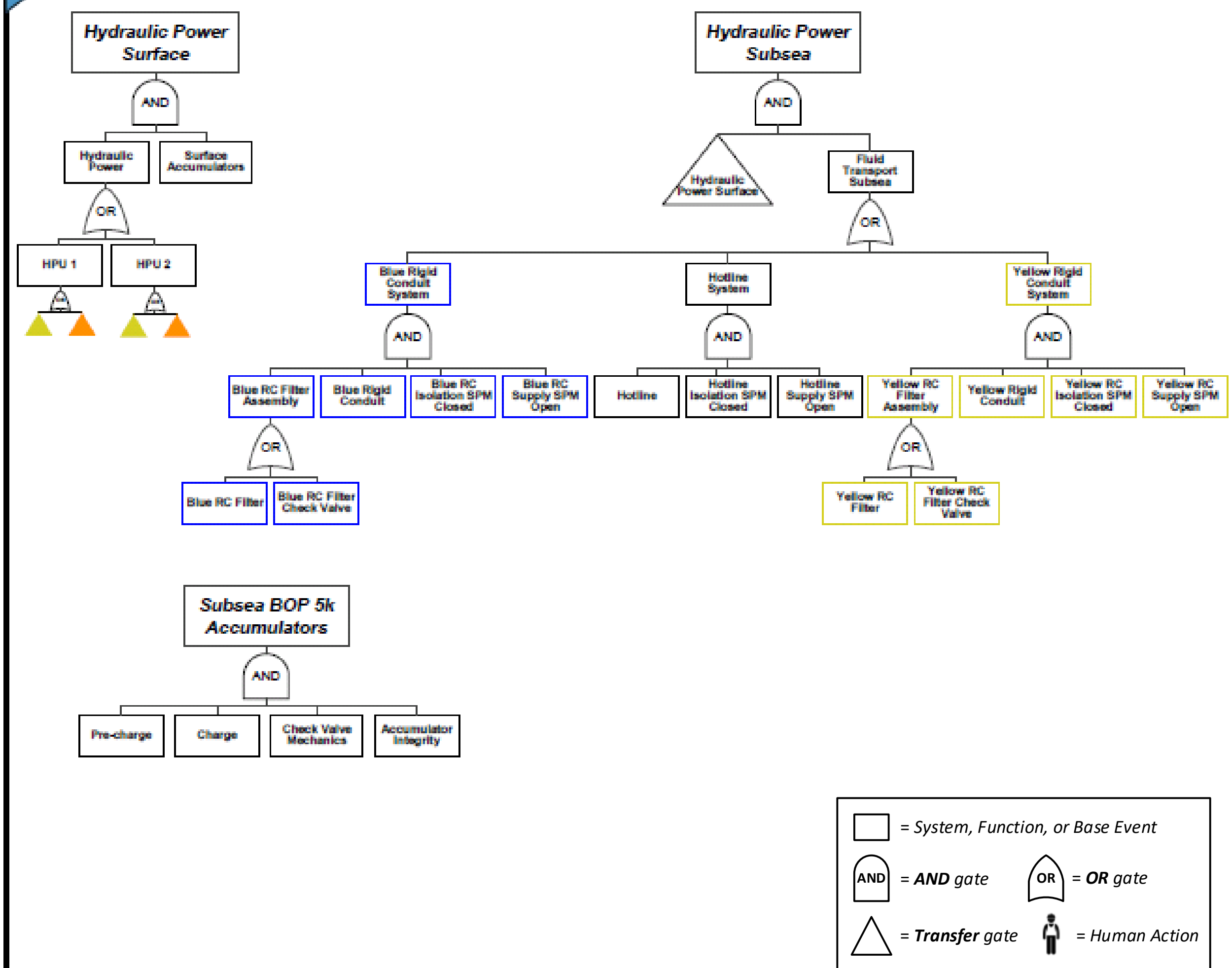


Figure I-11: Success Path for the DMAS of Manufacturer #2.

Applicability	Conventional Drilling
Safety Function	
Success Path	



Alternative Success Paths	
Necessary Support Systems	*Primary Rig AC Power* *Secondary (UPS) Rig AC Power*
Threat Scenarios	

Figure I-12: Success Path for a Hydraulic Power Support System.

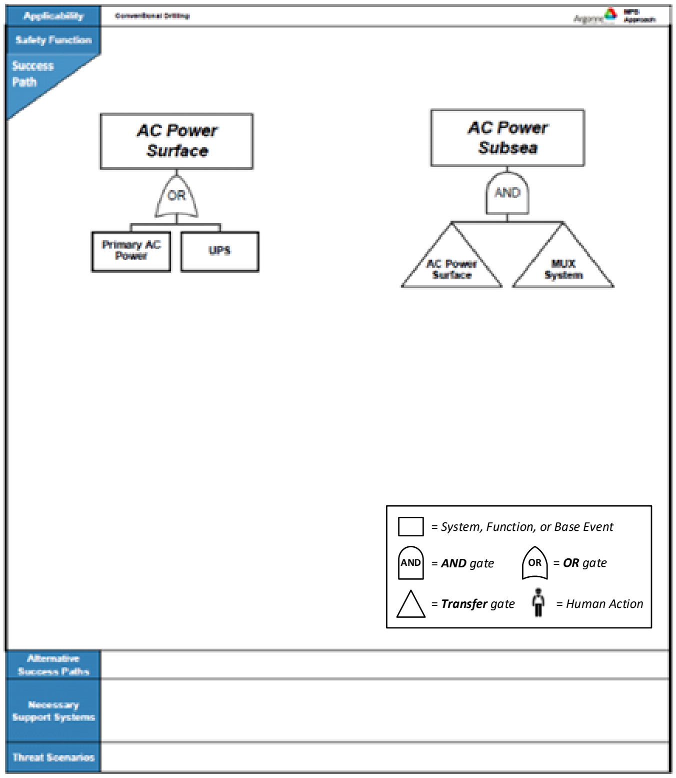


Figure I-13: Success Path for an AC Power Support System.

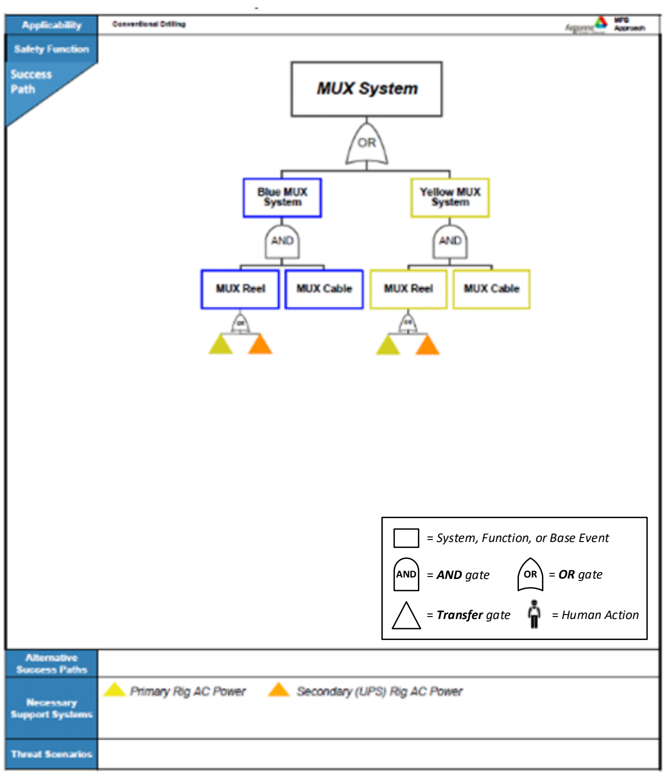


Figure I-14: Success Path for a MUX Support System.

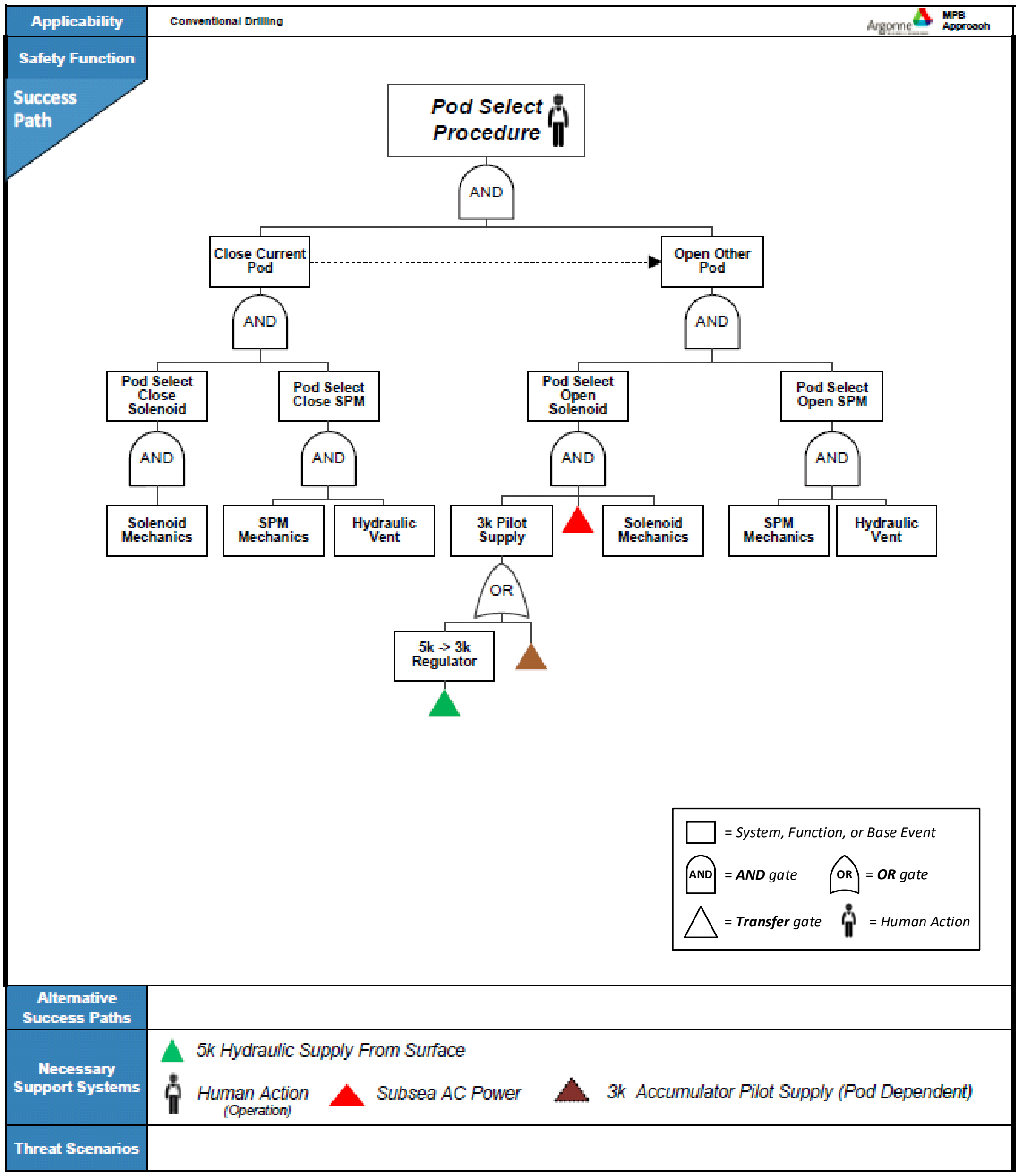


Figure I-15: Success Path for a Pod Select Support System.

CASING AND CEMENT SUCCESS PATHS

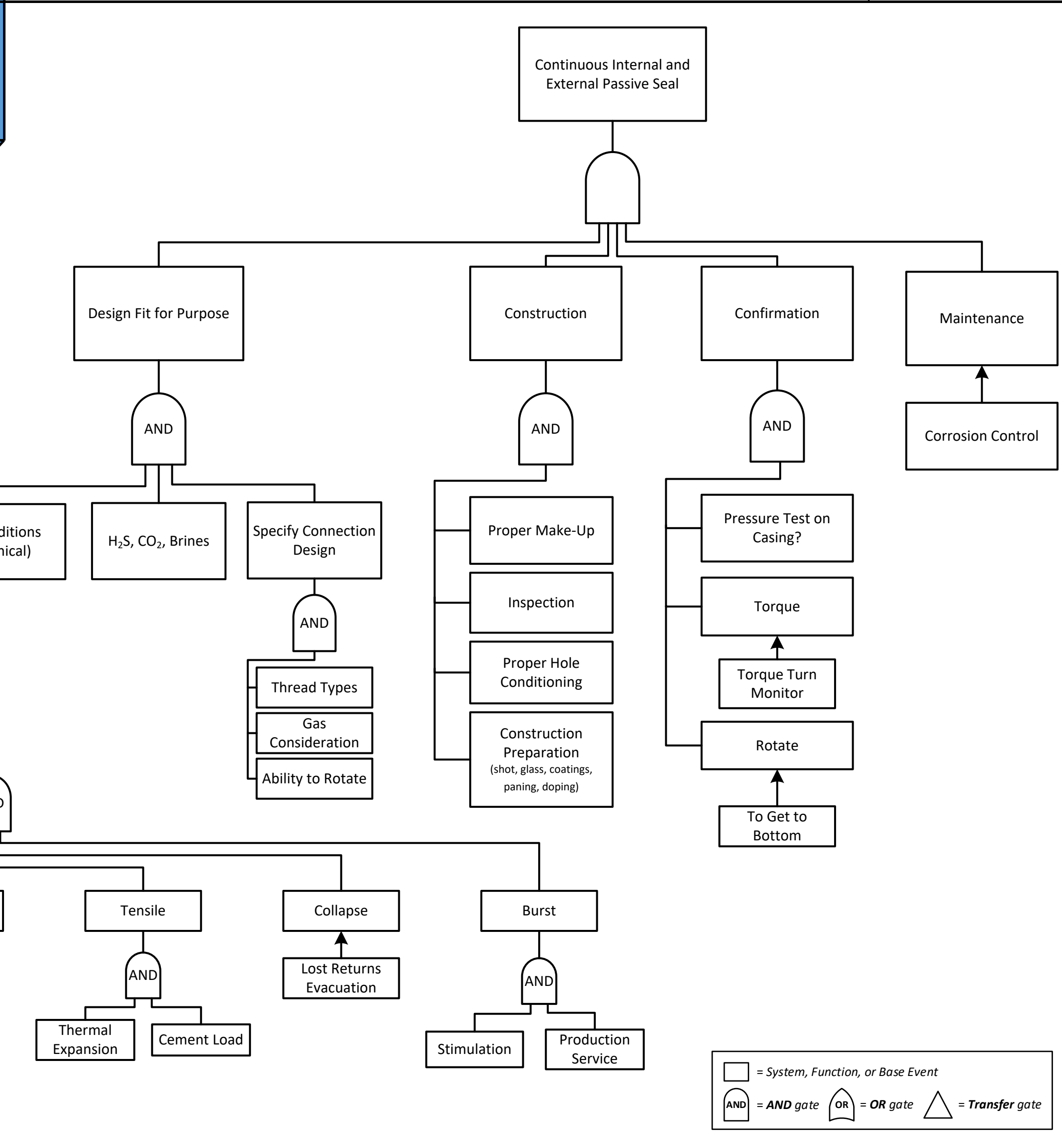
During the drilling process, casing is cemented in place to provide a continuous passive seal as an additional physical barrier against the loss of hydrocarbons. The success path for casing is shown in Figure I-16 and for cementing in Figure I-17.

Physical Barrier: Casing

Applicability	**Drilling Process**	MPB Approach

Safety Function

Success Path



Alternate Success Path(s)	BOP components can shut-in upper well components and elements.
Necessary Support Systems	
Threat Scenarios	Tripping with tools may cause wear of the casing and possible failure.
Notes	Casing is a passive physical barrier, and its performance is a result of actions taken, usually before hydrocarbons are reached.

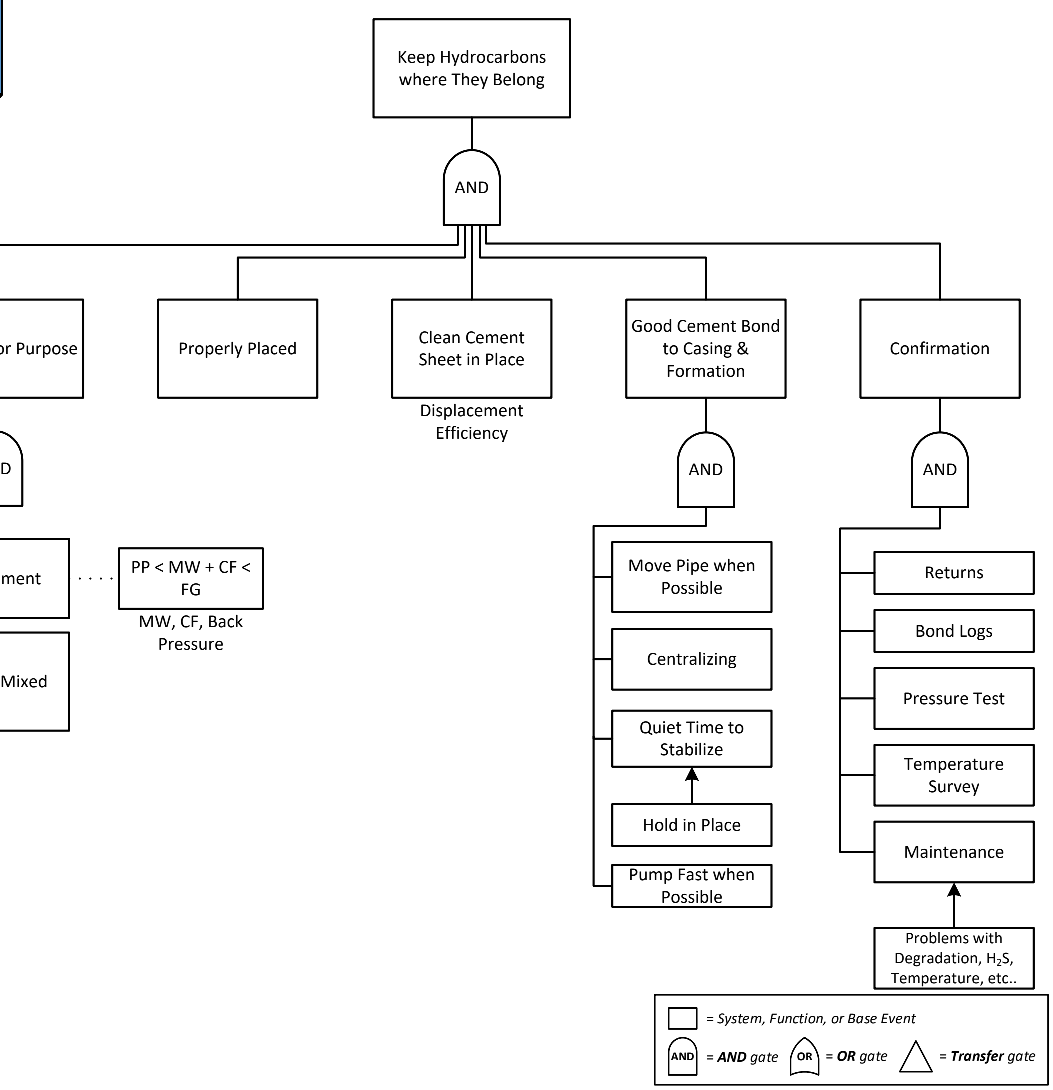
Figure I-16: Success Path for Casing.

Physical Barrier: Cement

Applicability	Drilling Process	MPB Approach

Safety Function

Success Path



Alternate Success Path(s)	BOP components can shut-in upper well components and elements.
Necessary Support Systems	
Threat Scenarios	
Notes	Cement is a passive physical barrier, and its performance is a result of actions taken, usually before hydrocarbons are reached.

Figure I-17:Success Path for Cement.

COMPLETION AND PRODUCTION SUCCESS PATHS

When applying the MPB Approach to support safe *completion* and *production* operations, Argonne developed success paths for several physical barriers found during a typical operation. The running in and cementing of casing, as described above, is sometimes performed in well-completion operations. Additional success paths developed for a seal bore production packer, and production pipeline are provided below.

SEAL BORE PRODUCTION PACKER SUCCESS PATHS

Packers are passive barriers and, as illustrated in the success path shown in Figure I-18, place emphasis on design, installation, and monitoring.

The removal of barriers in general, and in this case the retrieval of a packer, represents an area of high risk. Figure I-19 illustrates the success path for packer retrieval.

Physical Barrier: Seal Bore Production Packer/No Gas Lift

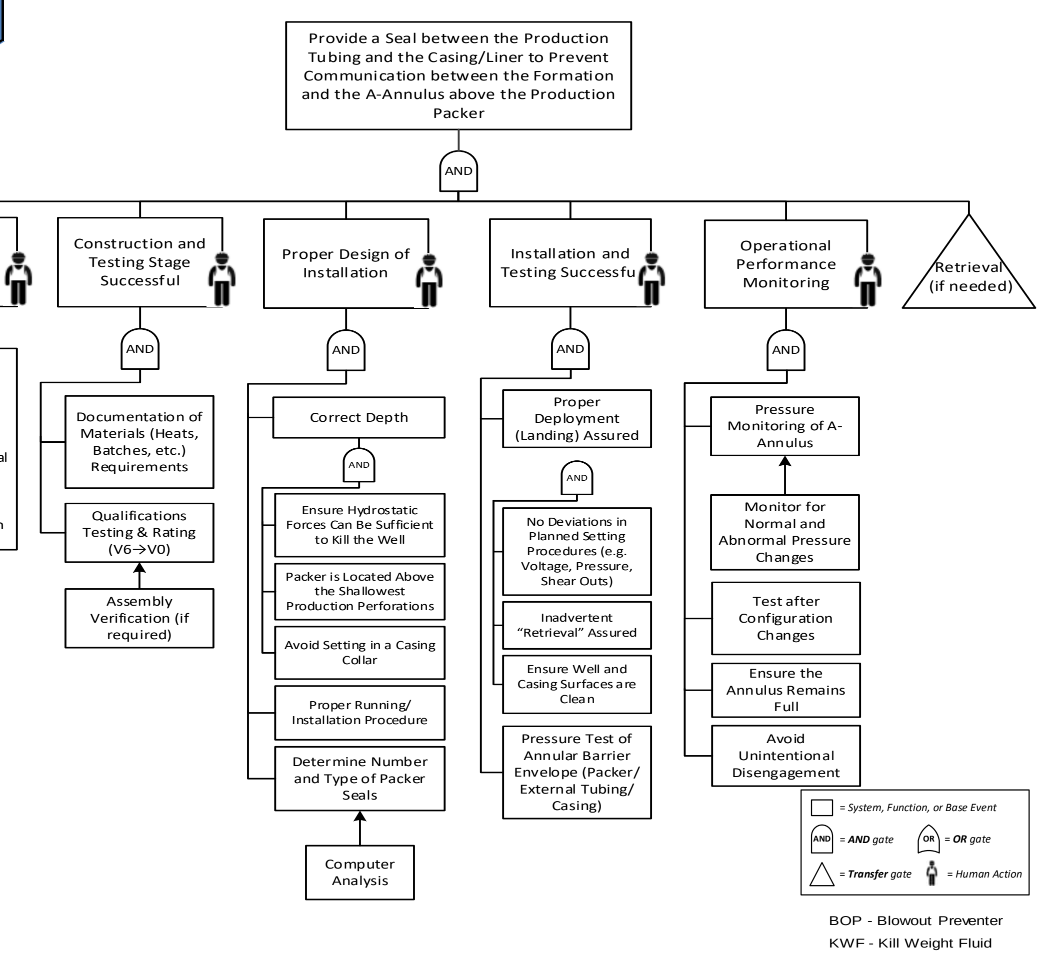
Applicability	**Installed in completion phase: used in completion and production phases.** Argonne MPB Approach
Safety Function / **Success Path**	
Alternate Success Path	Wellhead Seals and Casing; BOP during installation/workover
Necessary Support Systems	Passive systems usually require no support systems.
Threat Scenarios	- Large temperature variations Any high temperature event that could cause elongation of the production tubing could impose excessive axial stresses on the packer and push it beyond it's operating envelope. Conversely, any operation that cools the tubing (such as a stimulation acid job) could contract the tubing and cause the tubing seals to disengage from the packer or the tubing could part (depending on the packer type and condition of the seals which sometimes become stuck inside the packer over time). - Inability to maintain hole full of fluid

Figure I-18: Success Path for a Seal Bore Production Packer without Gas Lift.

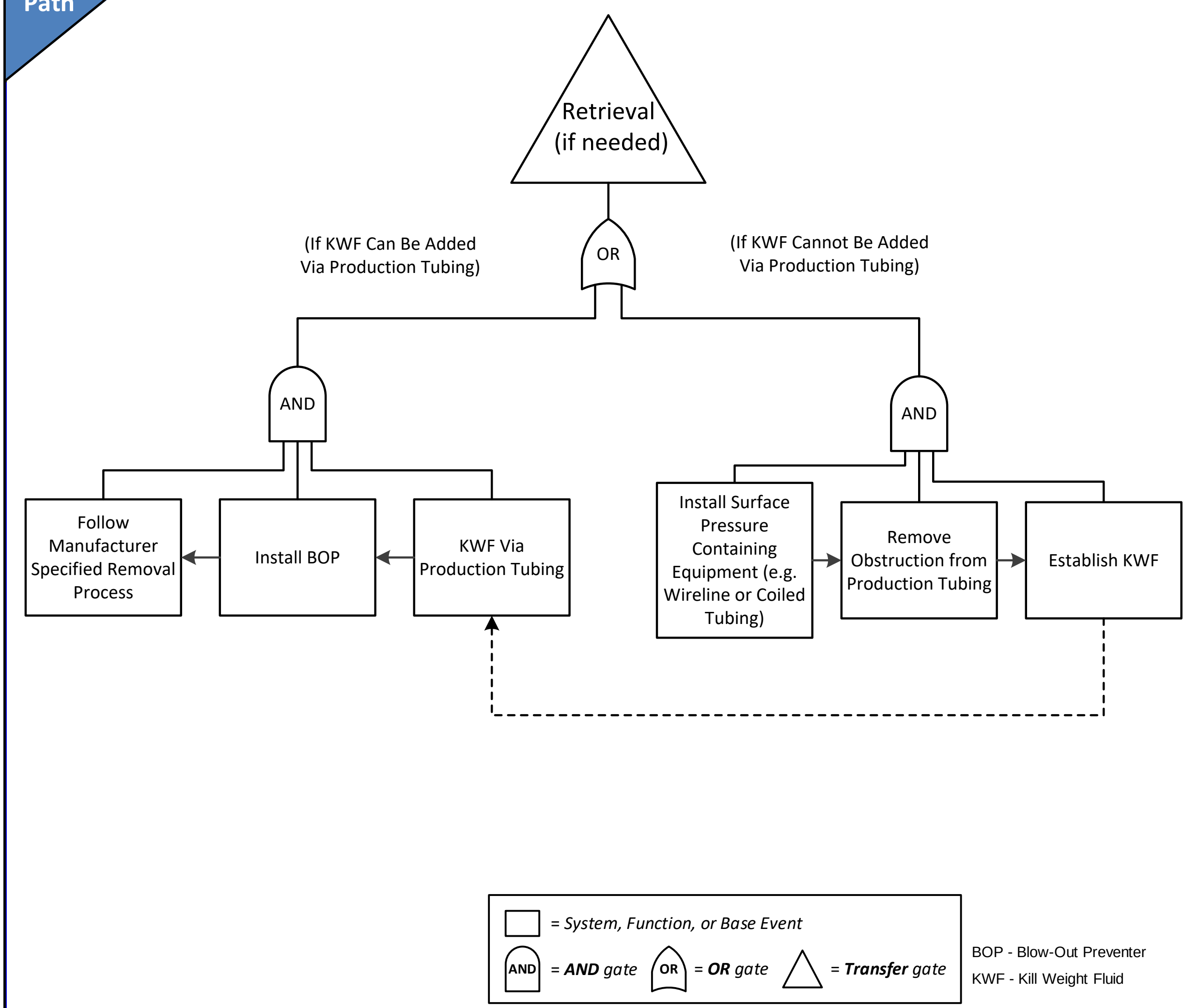
Physical Barrier: Sealbore Production Packer/No Gas Lift	
Applicability	**Packer Retrieval**
Safety Function	
Success Path	
Alternate Success Path	There are several ways to add surface pressure containing equipment. The basic idea is to add another barrier while working on the production tubing.
Necessary Support Systems	All systems used to support surface pressure containment system.
Threat Scenarios	•Inability to maintain kill weight fluid column •Inability to operate BOP or surface pressure containing equipment •Loss of AC power to vital components

Figure I-19: Success Path for Retrieval of a Seal Bore Production Packer without Gas Lift.

PRODUCTION PIPELINE SUCCESS PATH

When developing the success path in Figure I-20, it was discovered that a successful pipeline operation involves taking measures to protect the pipeline from erosion as well as from the corrosion effects that result from use.

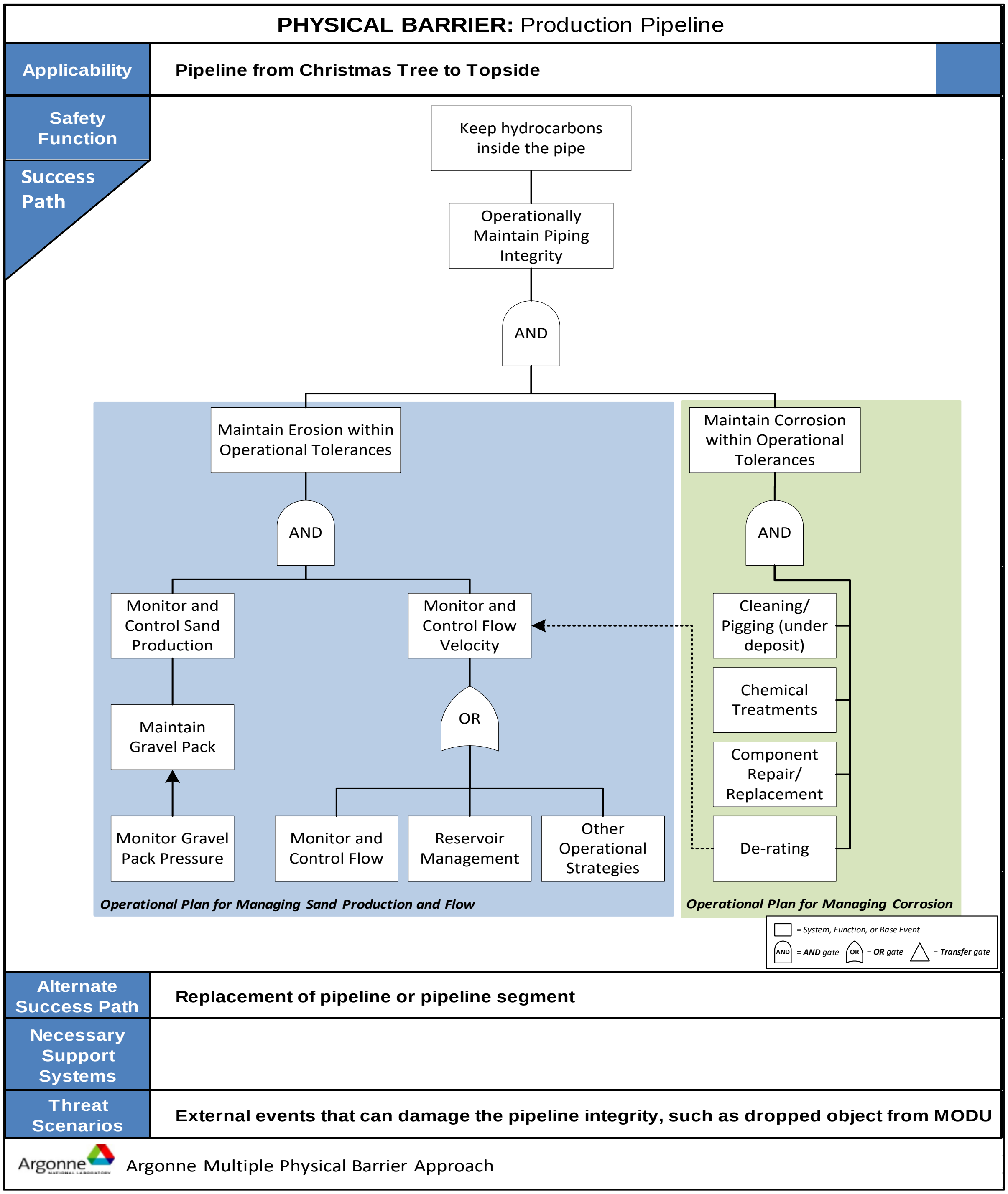


Figure I-20: Success Path for a Pipeline.

WORKOVER SUCCESS PATHS

When applying the MPB Approach to support improved safety in *workover* activities, Argonne collaborated with industry representatives to developed success paths for coil tubing equipment.

COILED TUBING SUCCESS PATHS

Argonne worked with coiled tubing SMEs and industry representatives to update the current version of API RP 16ST by developing a thorough FMECA for coiled tubing technology that can be used for well intervention on offshore and onshore wells. Argonne recommended beginning the analysis by developing success paths identifying the necessary physical barriers required for each equipment configuration. The resulting success path diagrams presented in this subsection were used to study safety of coiled tubing technology and helped develop a *barrier-based* FMECA.

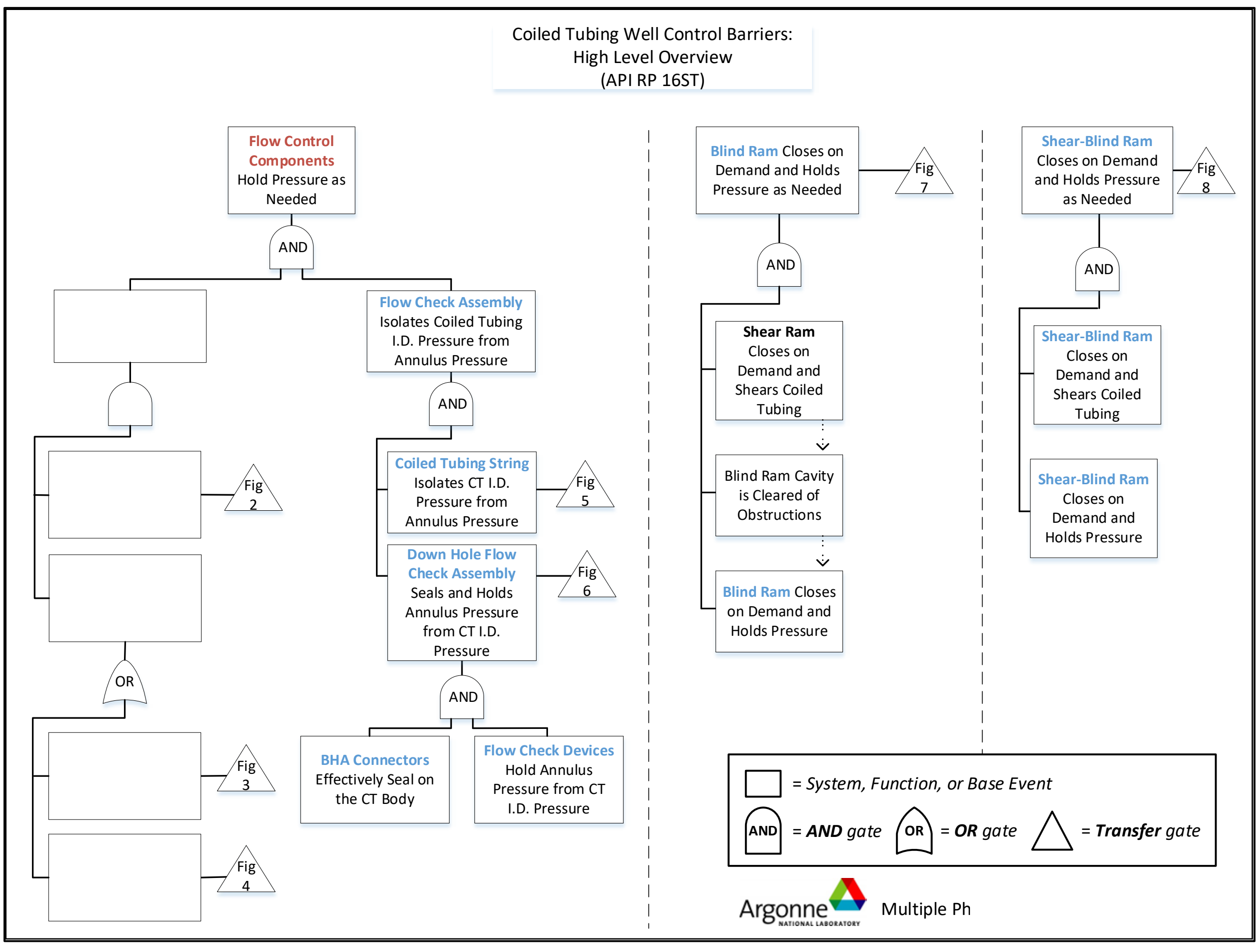
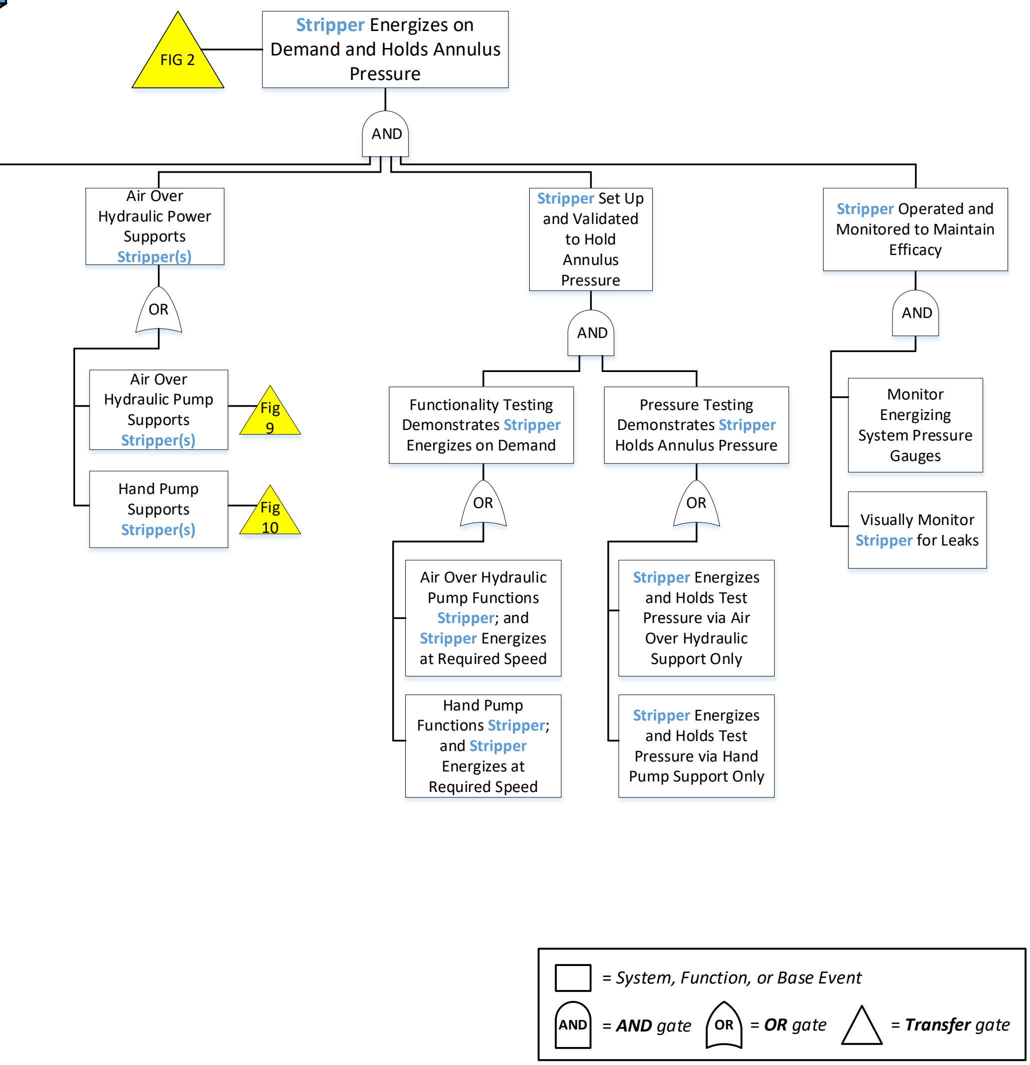


Figure I-21: Success Path for Coil Tubing Well Control Barriers.

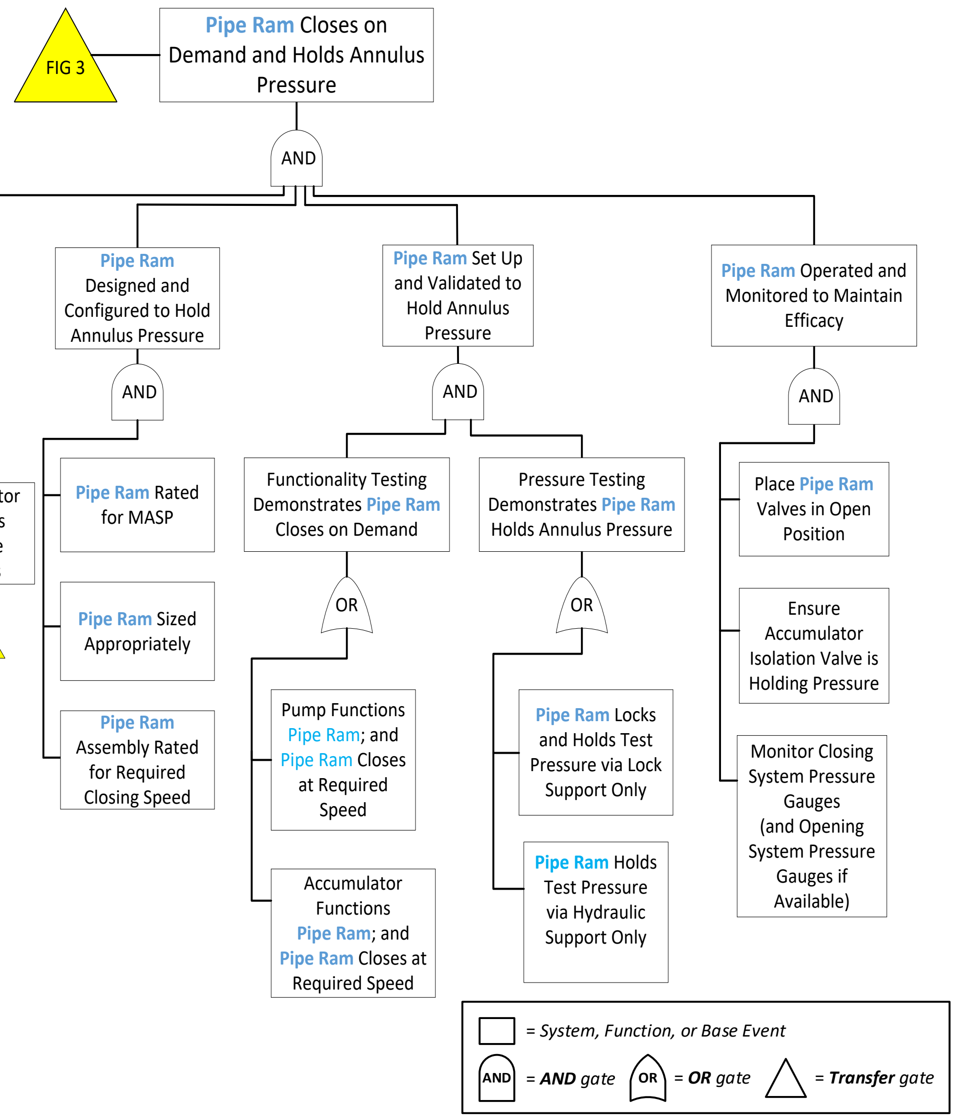
Physical Barrier Element: Stripper

Applicability	**Coiled Tubing Operations**	**8/28/2017**	**Figure 2**
Safety Function			
Success Path			
Alternate Success Path	**Pipe Ram; Annular Preventer; other barriers (e.g. Shear and Blind Ram)**		
Necessary Support Systems	**Hydraulic power for controls and CT Console**		
Threat Scenarios	**Stripper is constantly wearing. It should be anticipated to fail at any time.**		

Argonne Multiple Physical Barrier Approach

Figure I-22: Success Path for Stripper.

Physical Barrier Element: Pipe Ram			
Applicability	**Coiled Tubing Operations**	**8/28/2017**	**Figure 3**
Safety Function			

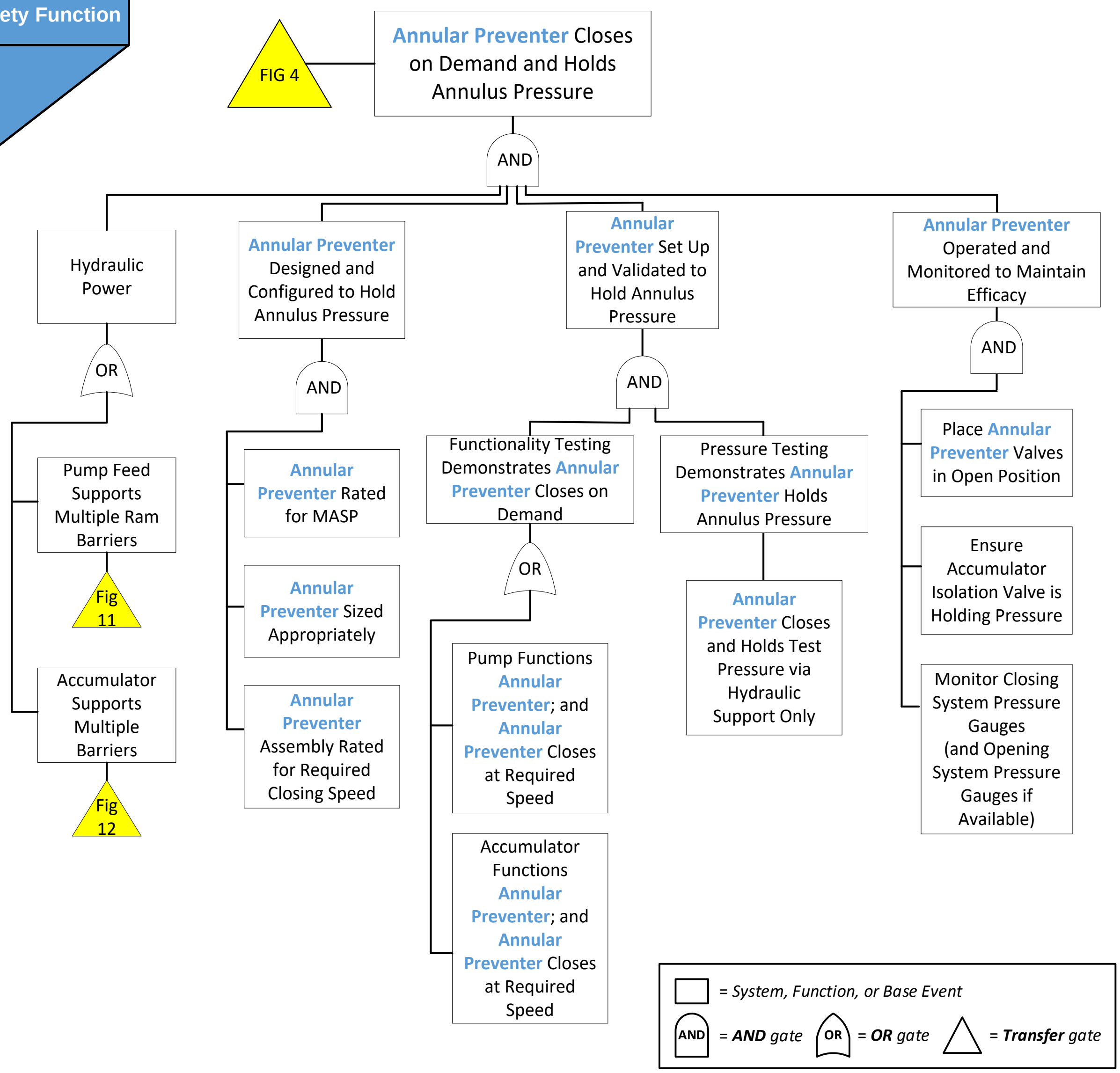


Alternate Success Path	**Stripper; Annular Preventer; Blind Ram; Shear-Blind Ram**
Necessary Support Systems	**Hydraulic power**
Threat Scenarios	**Element wear or CT diametral growth can be a factor.**

Argonne NATIONAL LABORATORY

Figure I-23: Success Path for Pipe Ram.

Physical Barrier Element: Annular Preventer		
Applicability	**Coiled Tubing Operations** **8/28/2017**	**Figure 4**
Safety Function		

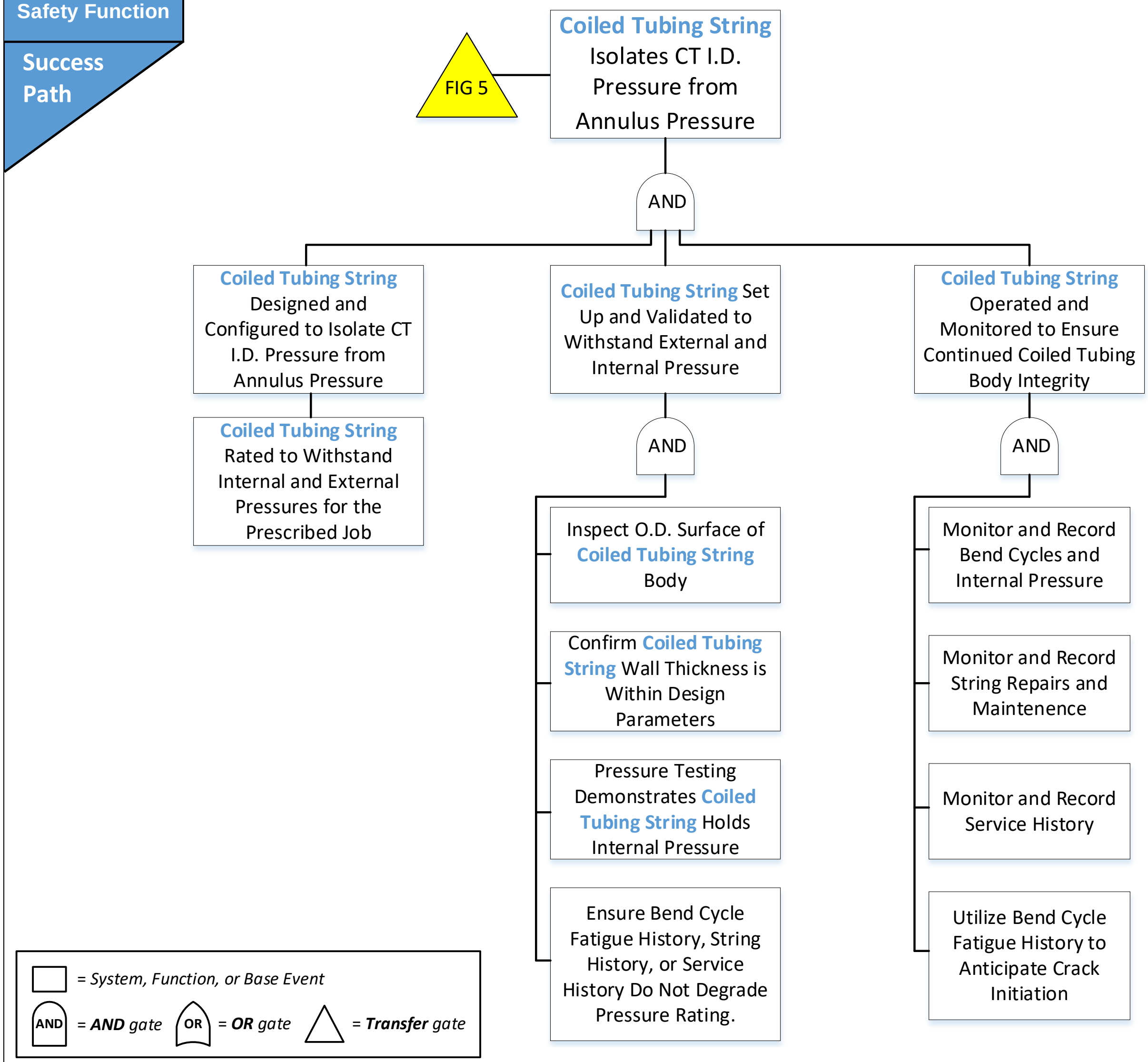


Alternate Success Path	**Stripper; Pipe Rams; Blind Ram System; Shear-Blind Ram**
Necessary Support Systems	**Hydraulic power**
Threat Scenarios	**Wear and distortion of rubber elements is a concern.**

Figure I-24: Success Path for Annular Preventer.

Physical Barrier Element: Coiled Tubing String

Applicability	**Coiled Tubing Operations** **8/28/2017**	**Figure 5**
Safety Function		
Success Path		



Alternate Success Path	**Surface Shear and Blind Ram or Shear-Blind Ram**
Necessary Support Systems	**CT Injector and support systems**
Threat Scenarios	**Surface defects, bend cycle fatigue, and mechanical damage are major factors.**

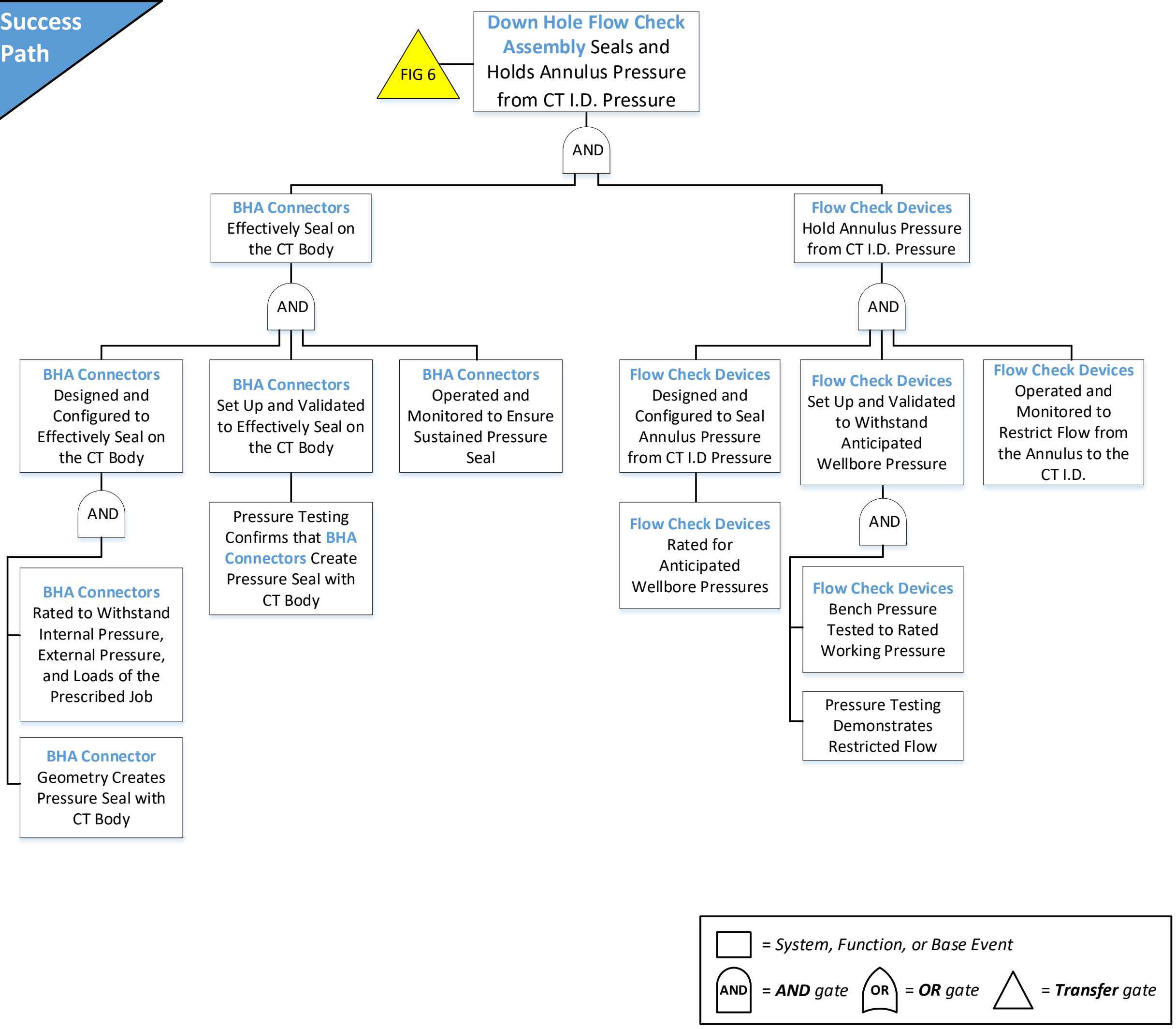
Argonne NATIONAL LABORATORY Argonne Multiple Physical Barrier Approach

Figure I-25: Success Path for Coiled Tubing String.

Physical Barrier Element: Down Hole Flow Check Assembly

Applicability	**Coiled Tubing Operations**	**8/28/2017**	**Figure 6**
Safety Function			

Success Path



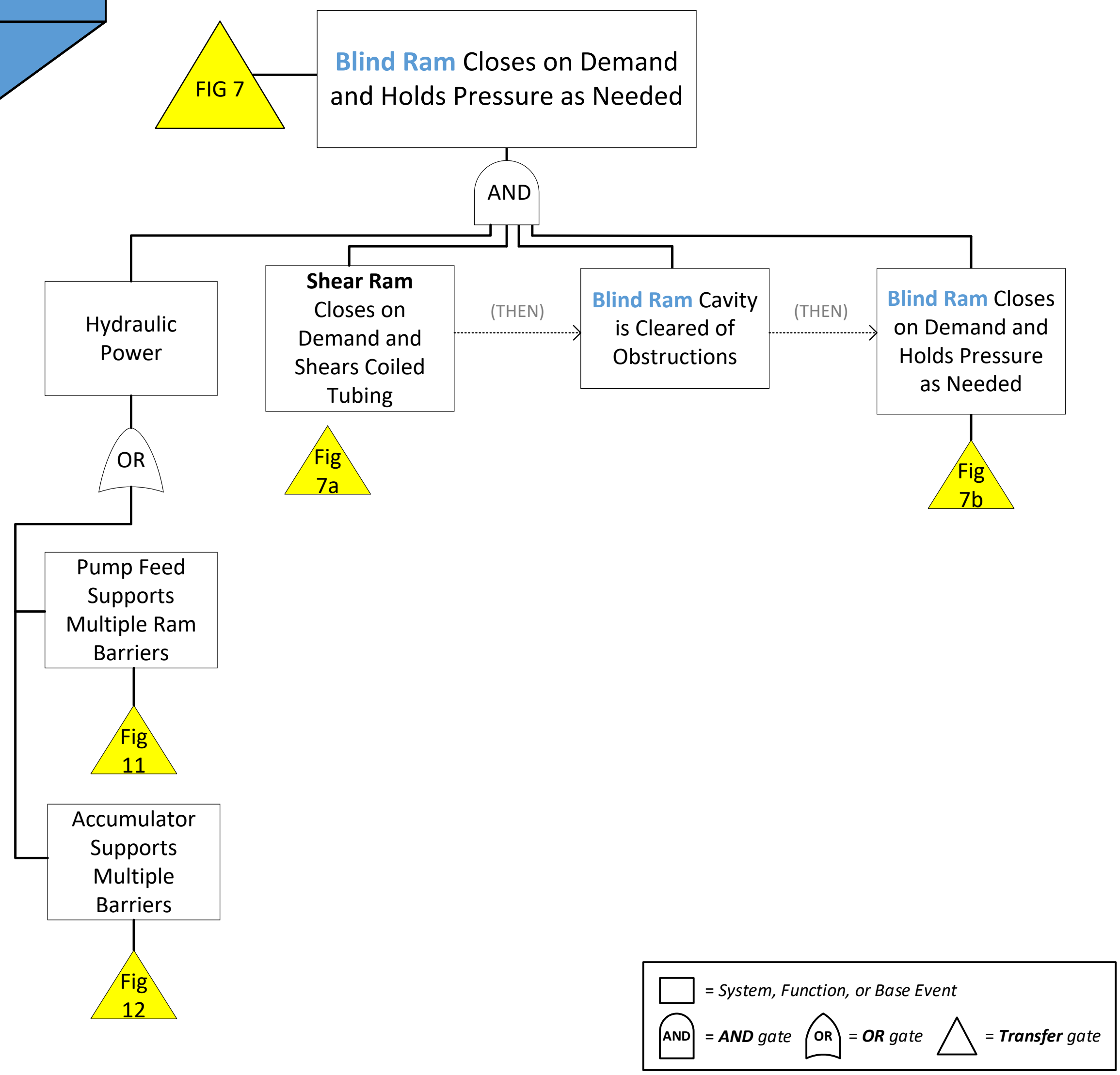
Alternate Success Path	**Blind Ram; Shear-Blind Ram**
Necessary Support Systems	**Hydraulic power for Surface Rams**
Threat Scenarios	**Gasket wear and fit can be factors.**

Argonne Multiple Physical Barrier Approach

Figure I-26: Success Path for Down-Hole Flow Check Assembly.

Physical Barrier Element: Blind Ram

Applicability	**Coiled Tubing Operations**	**8/28/2017**	**Figure 7**
Safety Function			



Alternate Success Path	**Shear-Blind Ram; Annular Preventer; Pipe Ram(s); Stripper**
Necessary Support Systems	**The shear ram must be used prior to closing the blind ram.** **Hydraulic power to rams and Injector (required for movement of pipe).**
Threat Scenarios	**Blind ram cavity must be cleared by injector action.** **Power Pack shutdown restricts Injector movement of pipe.**

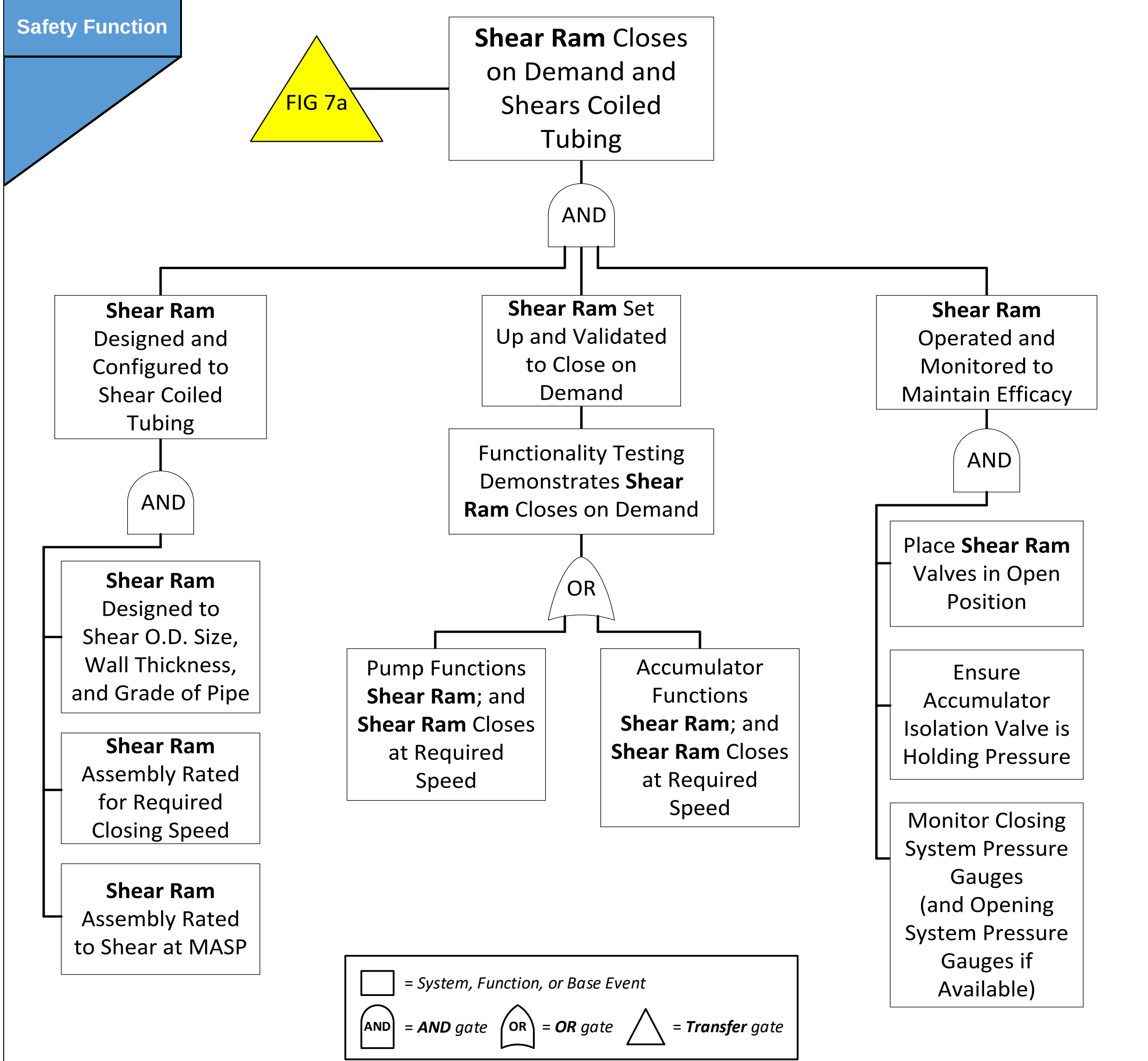
Argonne NATIONAL LABORATORY

Figure I-27: Success Path for Blind Ram.

Critical Support Element: Shear Ram as Part of Shear and Blind Ram System

Applicability	**Coiled Tubing Operations**	**8/28/2017**	**Figure 7a**

Safety Function



Alternate Success Path	**Shear-Blind Ram; Flow Control Components**
Necessary Support Systems	**Hydraulic power to rams and Injector.**
Threat Scenarios	**Sequence of Shear Ram closure/cavity clearance using Injector/Blind Ram closure is critical.**

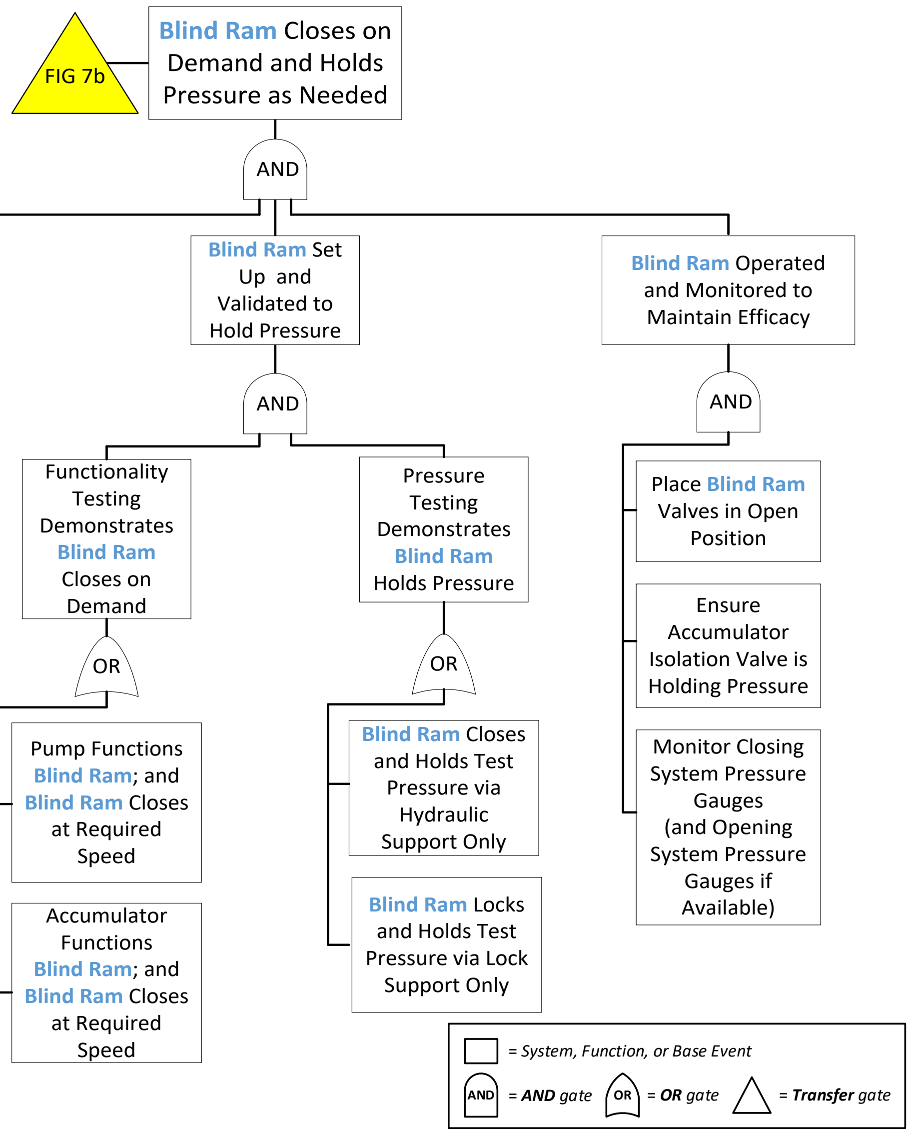
Argonne NATIONAL LABORATORY

Figure I-28: Success Path for Shear Ram as Part of Shear and Blind Ram System.

Physical Barrier Element: Blind Ram as Part of Shear and Blind Ram System

Applicability	**Coiled Tubing Operations** **8/28/2017**	**Figure 7b**

Safety Function



Alternate Success Path	**Shear-Blind Ram**
Necessary Support Systems	**Hydraulic power to rams and Injector.**
Threat Scenarios	**Sequence of Shear Ram closure/cavity clearance using Injector/Blind Ram closure is critical.**

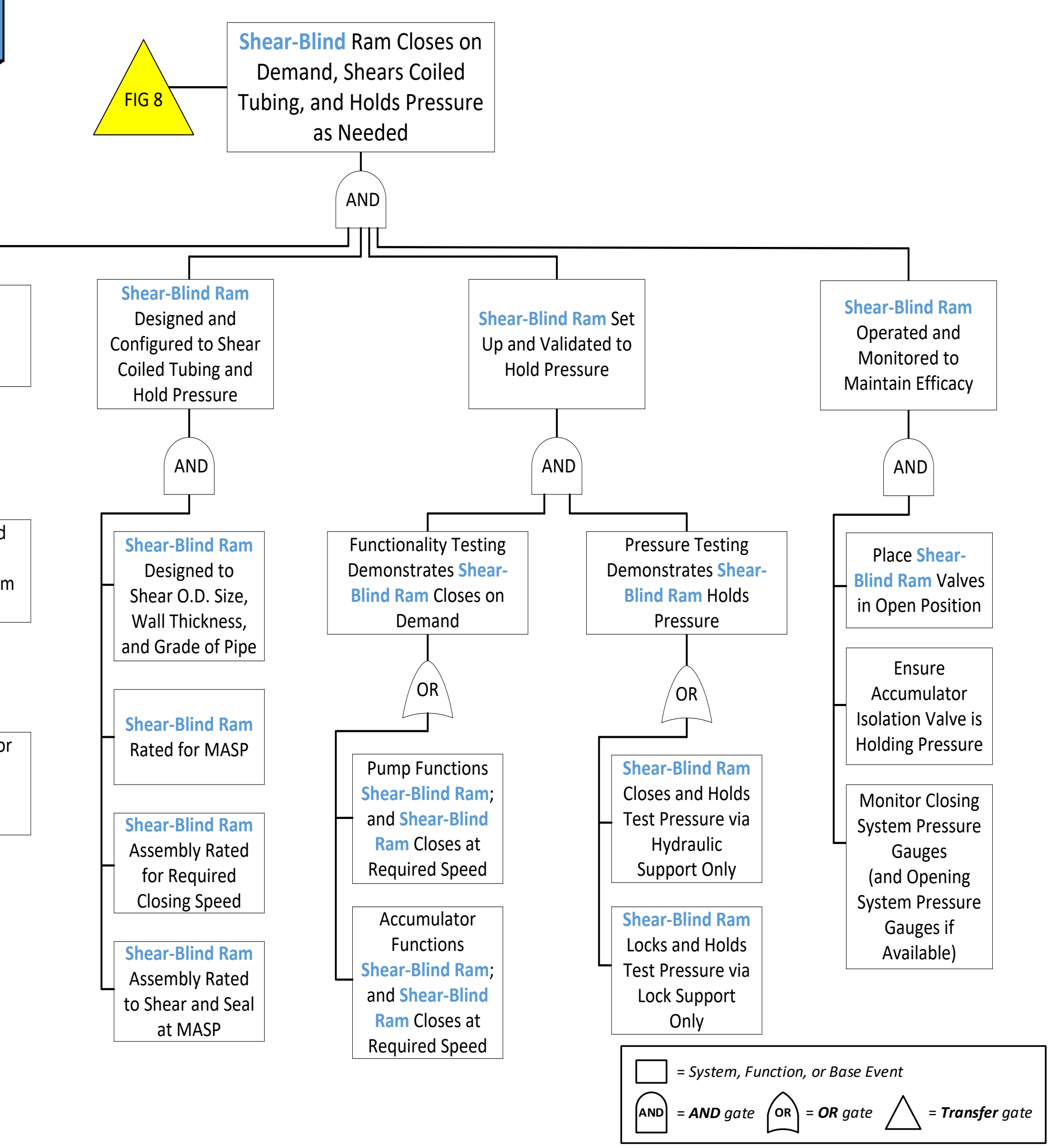
Argonne NATIONAL LABORATORY

Figure I-29: Success Path for Blind Ram as Part of Shear and Blind Ram System.

Physical Barrier Element: Shear-Blind Ram

Applicability	**Coiled Tubing Operations**	**8/28/2017**	**Figure 8**

Safety Function



Alternate Success Path	**Blind Ram; Flow Control Components**
Necessary Support Systems	**Hydraulic power to rams**
Threat Scenarios	**Shear blade sizing and sufficient hydraulic pressure must be confirmed.**

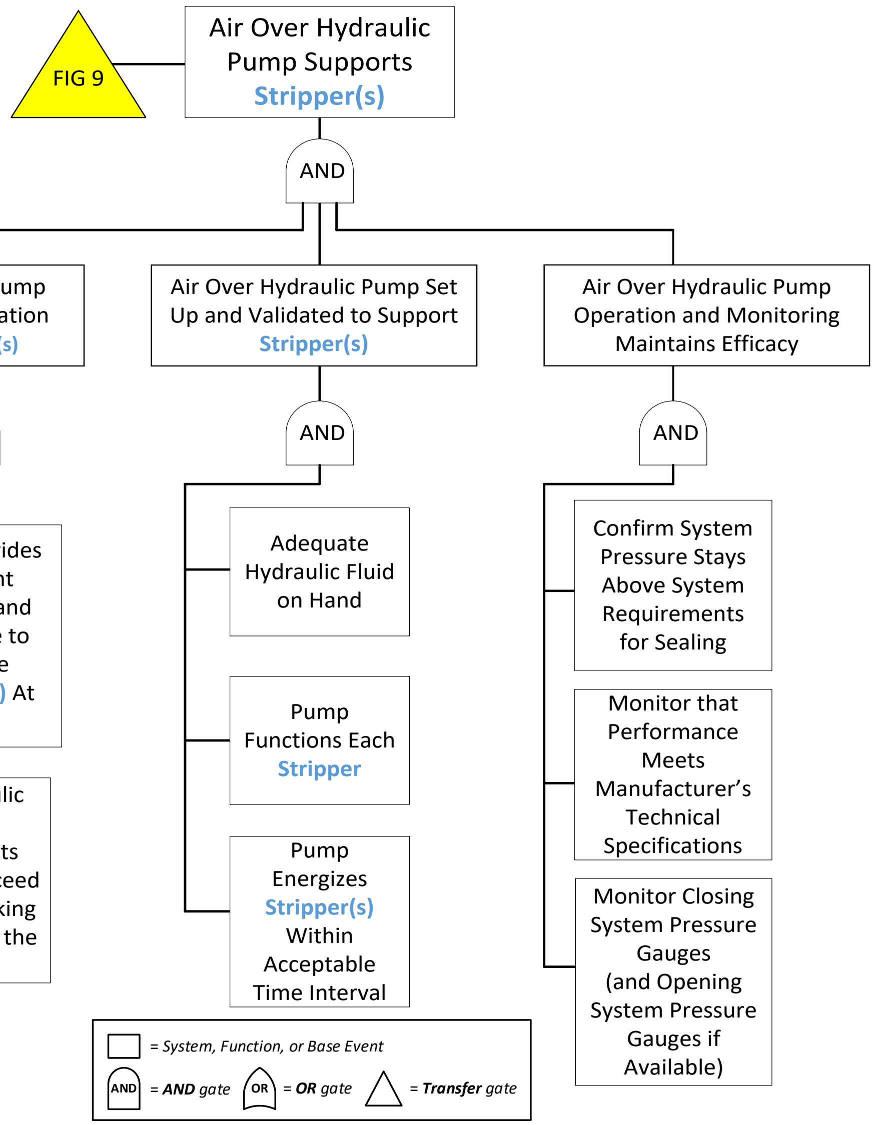
Argonne NATIONAL LABORATORY

Figure I-30: Success Path for Shear-Blind Ram.

Critical Support Element: Air Over Hydraulic Pump for Stripper

Applicability	**Coiled Tubing Operations**	**8/28/2017**	**Figure 9**

Safety Function



Alternate Success Path	**Pipe Rams or Annular Preventer using Accumulator power as source.**
Necessary Support Systems	**Back-up Hydraulic Pressure Supply**
Threat Scenarios	**Loss of air pressure is a possible issue.**

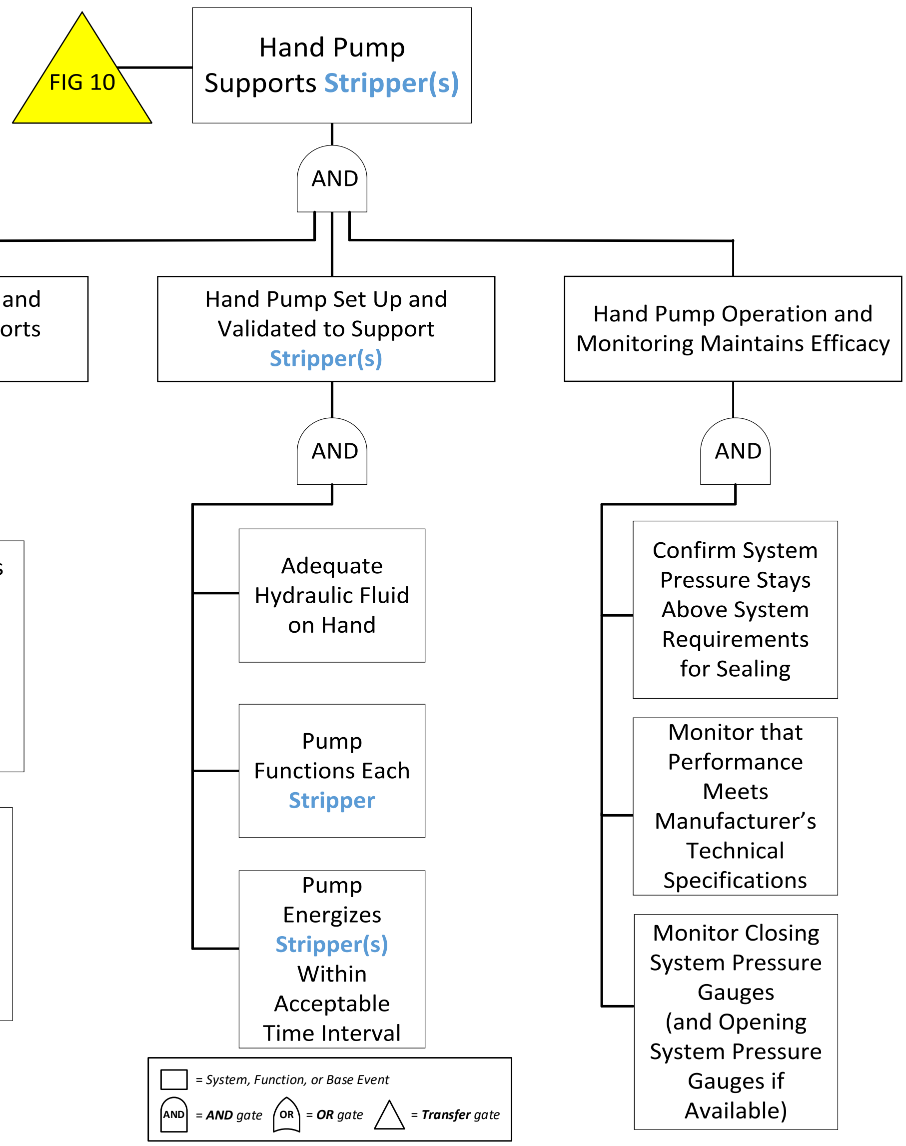
Argonne NATIONAL LABORATORY

Figure I-31: Success Path for Air Over Hydraulic Pump for Stripper.

Critical Support Element: Hand Pump for Stripper

Applicability	**Coiled Tubing Operations**	**8/28/2017**	**Figure 10**

Safety Function



Alternate Success Path	**Pipe Ram powered from Accumulator**
Necessary Support Systems	**Hand Pump mechanical integrity and total fluid volume available.**
Threat Scenarios	**Functionality of Hand Pump and Hydraulic Circuit routing is critical.**

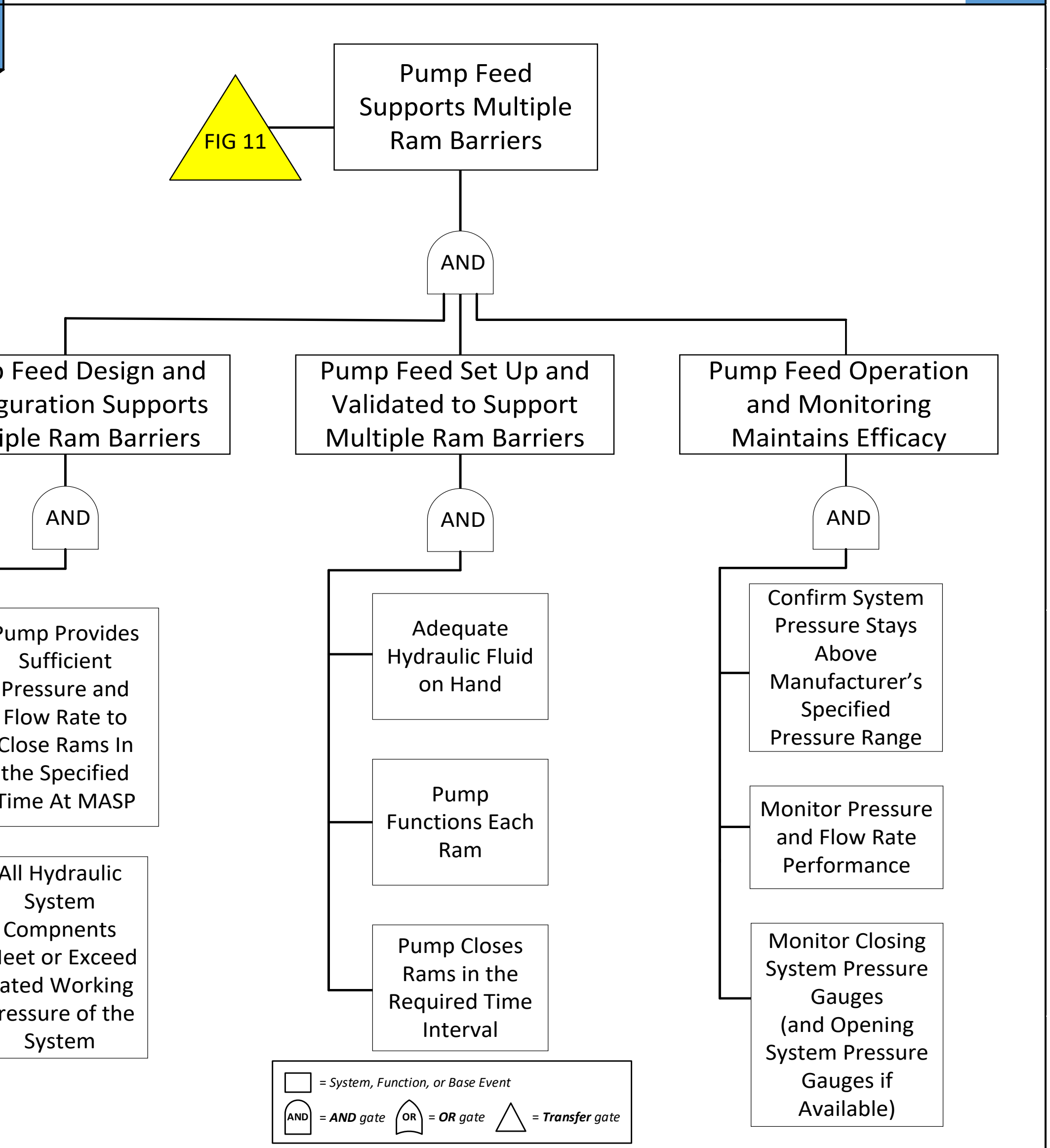
Argonne NATIONAL LABORATORY

Figure I-32: Success Path for Hand Pump for Stripper.

Critical Support Element: Hydraulic Pump

Applicability	**Coiled Tubing Operations**	**8/28/2017**	**Figure 11**

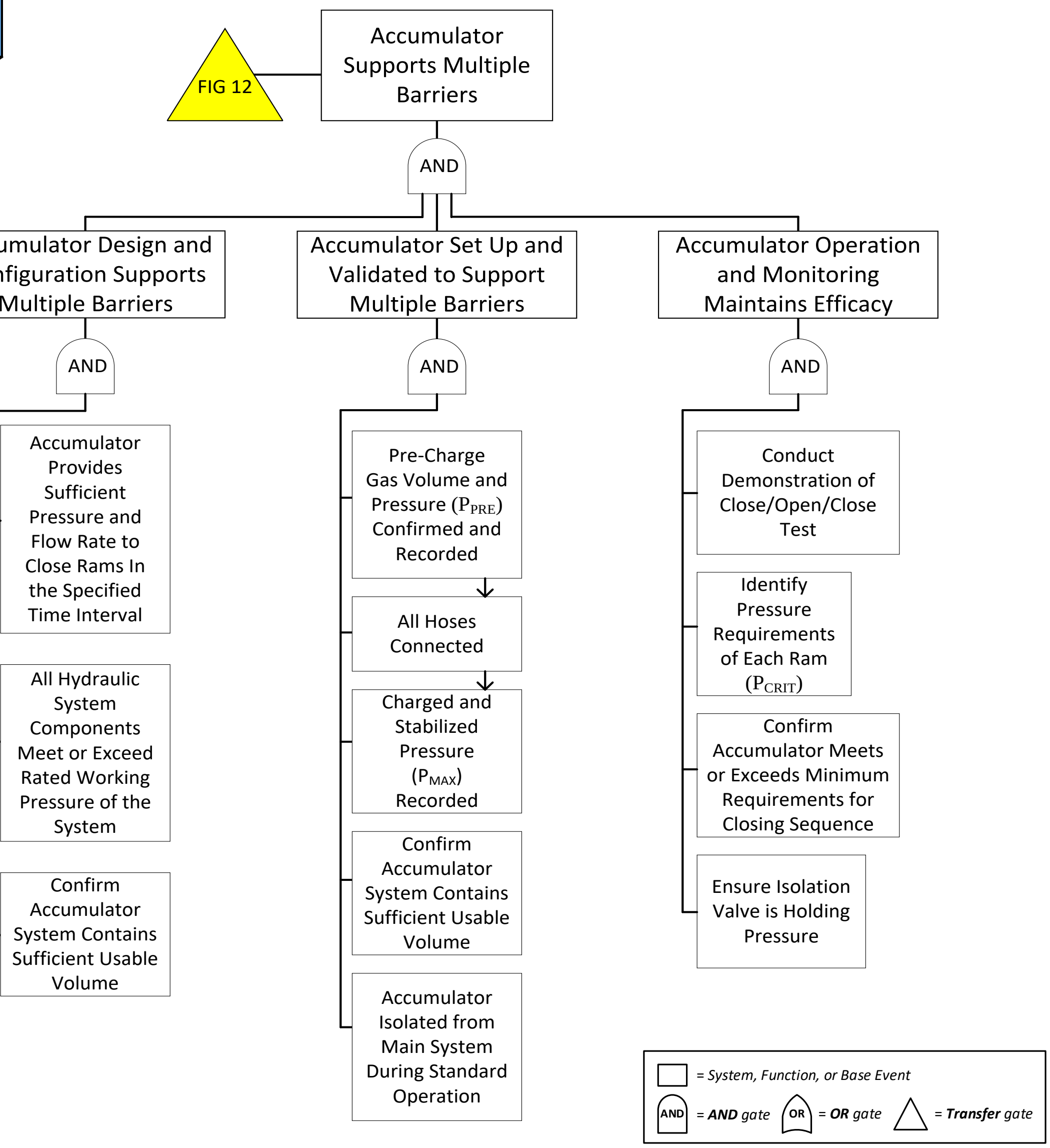
Safety Function



Alternate Success Path	**Accumulator Power**
Necessary Support Systems	**Accumulator System**
Threat Scenarios	**Pump wear and reduced pressure/delivery are issues.**

Argonne NATIONAL LABORATORY

Figure I-33: Success Path for Hydraulic Pump.

Critical Support Element: Accumulator System		
Applicability	**Coiled Tubing Operations** **8/28/2017**	**Figure 12**
Safety Function		
Alternate Success Path	**Hydraulic power from Power Pack**	
Necessary Support Systems	--	
Threat Scenarios	**Leakage within Accumulator System or Power Fluid Controls.**	

Argonne NATIONAL LABORATORY

Figure I-34: Success Path for Accumulator System.

USE OF SUCCESS PATHS IN RISK-BASED INSPECTION

Success paths can also be applied in risk based inspections as a common approach used by regulator and operators to understand and evaluate critical safety functions.

CRANE UTILIZATION SUCCESS PATH

Argonne has worked with BSEE to create a safe crane operation success path. Figure I-35 depicts the high-level processes included in the crane success path. As is illustrated with boxes connect to an *AND* gate, safe utilization of a crane requires proper specification, design, construction, operation, inspection, and maintenance.

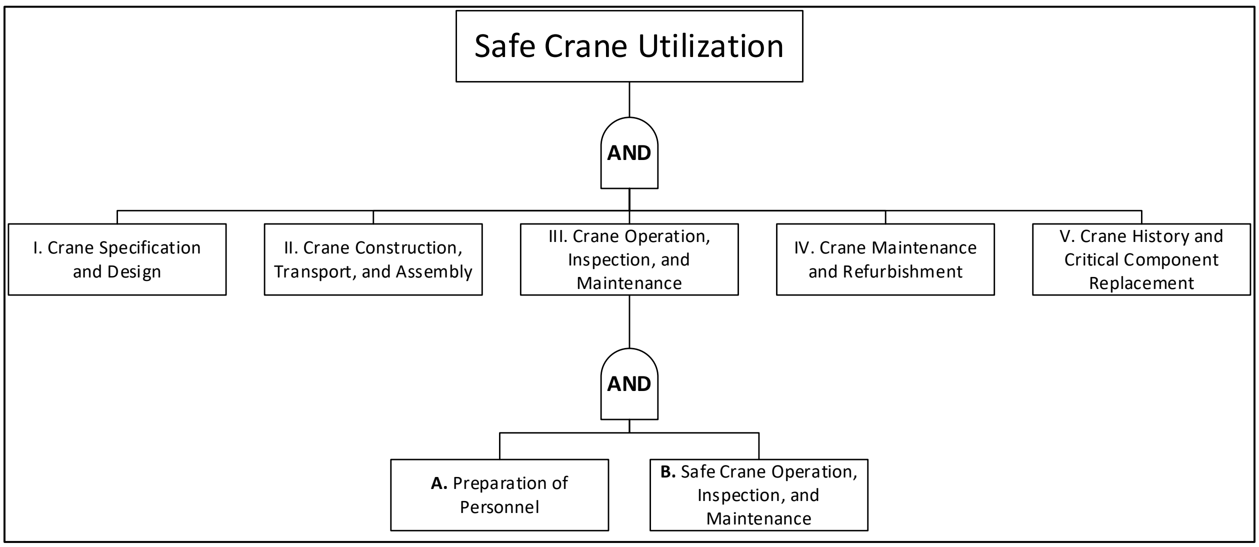


Figure I-35:High-Level Success Path for Safe Crane Utilization.

BSEE publishes a Potential Incident of Noncompliance, "PINCs," checklist of items which bureau inspects to pursue safe operations on the Outer Continental Shelf [20]. This list of inspection items is derived from all applicable regulations for safety and environmental standards.

Figure I-36 provides a success path for the operation and inspection component of the safe crane utilization. For each component in the success path, Argonne used a circle to note the associated number of component failure incidents, and a box to specify relevant PINCs, API standards, and recommended practice codes.

[20] https://www.bsee.gov/what-we-do/offshore-regulatory-programs/offshore-safety-improvement/potential-incident-of-noncompliance-pinc

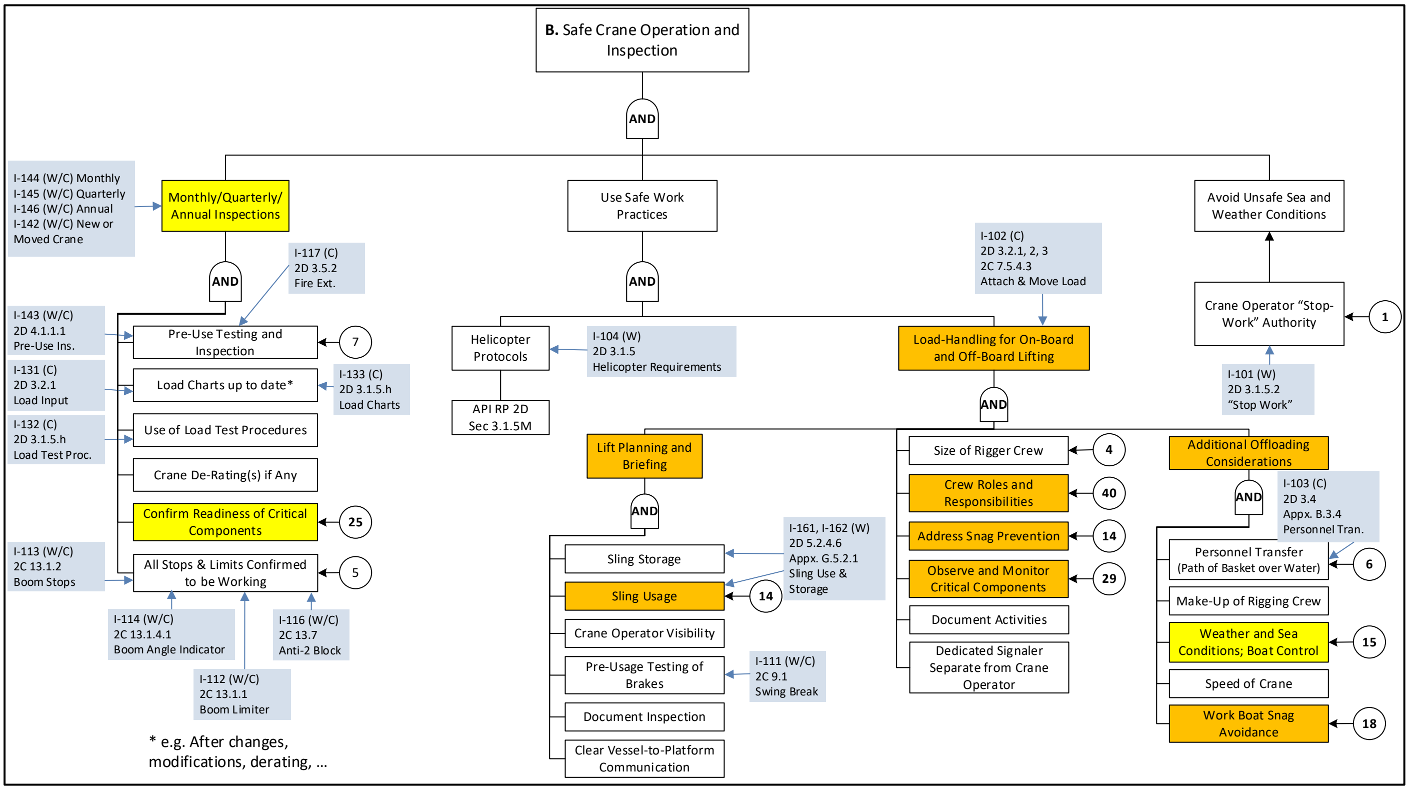


Figure I-36: Success Path for Safe Crane Operation and Inspection.

Based on this information, it is possible to develop a risk-based crane inspection program that focuses on the most vulnerable items in crane operation. To get started, Argonne worked with BSEE to create a list of relevant questions a BSEE inspector could potentially ask the operators during an inspection. These questions are open-ended in nature and are designed to lead to other questions, depending on the answers received from the operator. This effort is focused on the overall strategy to develop more effective inspection programs without additional regulation.

Figure I-3 shows an example of questions that an inspector could ask an operator to propagate an additional set of questions to pinpoint (or approximate) the underlying cause of equipment failure or process ineffectiveness.

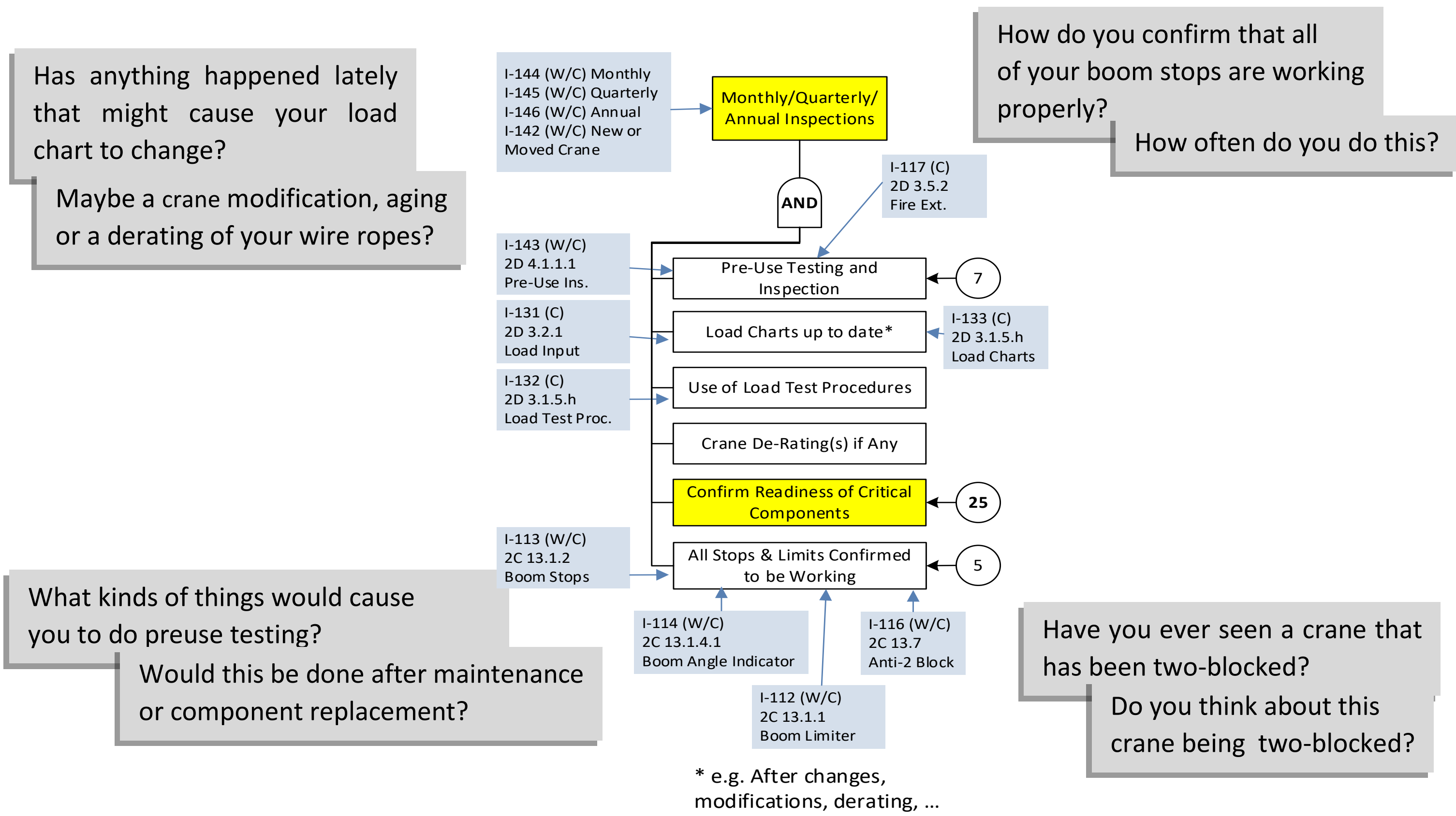


Figure I-37: Success Path for Inspections Component of Safe Crane Utilization.

About Argonne National Laboratory

Argonne is a U. S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

Disclaimer