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Global Energy Solutions Group

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Risk-Based Evaluation of Offshore Oil and Gas Operations Using a Success Path Approach

2018 UPDATE

This document was originally published in 2017 under the title *Risk-Based Evaluation of Offshore Oil and Gas Operations Using a Multiple Physical Barrier Approach*. It was revised in 2018 to reflect expanded application of Success Paths by industry stakeholders and as a tool for BSEE oversight programs.

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EXECUTIVE SUMMARY

This report presents a systematic study of process safety in offshore oil and gas operations and introduces a risk-analysis methodology, called the Success Path Approach, developed by Argonne National Laboratory. This methodology leverages more than 50 years of expertise derived from assessing the reliability of nuclear reactors, but adapted to the operational conditions of the offshore oil and gas industry. The technique is framed around the design, construction, operation and maintenance of systems, components, and processes to provide a rigorous, yet practical, quantitative way to measure safety and the level of 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 Success Path Approach for evaluating process safety. In the Success Path 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 systems (e.g., physical barriers) are performing their critical safety functions? The answer is to ensure that *Success Paths*—hardware, software, and human actions needed to ensure safe operation of a system or component—are always in place and are capable of performing their functions in all expected conditions and circumstances.

This report describes how Success Paths provide a “**chain of causality**” illustrating what must go right to ensure safe operations of barriers, workers, and processes. Visualizing what must go right helps us **understand, manage, and respond to** what can fail.

This report summarizes Argonne's approach of identifying multiple physical barriers and assessing the relevant Success Paths. The objective is to support BSEE's goal of enhancing safety in the offshore oil and gas industry by:

- Expanding BSEE's tools to enhance oversight of high-risk activities and equipment by developing and implementing a practical and systematic methodology to understand, analyze, and manage high-risk areas.
- Creating a practical and adaptable framework for offshore operators and contractors that is easily deployable and understandable.
- Enabling all offshore operation stakeholders to leverage and utilize operational data to develop a variety of analytical Success Path models for assessment, diagnostics, prognosis, and clear visualization of the critical barrier systems in offshore operations.
- Utilizing Success Paths to facilitate productive communication between operators and BSEE and to help all parties focus on improving safety outcomes on the Outer Continental Shelf.
- Expanding application of the Success Path Approach to inspections, standards development, identification of gaps in regulations, and other oversight programs.

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ACRONYMS AND ABBREVIATIONS

AC	ALTERNATING CURRENT
AI	ARTIFICIAL INTELLIGENCE
ANSI	AMERICAN NATIONAL STANDARDS INSTITUTE
APD	APPLICATION FOR PERMIT TO DRILL
API	AMERICAN PETROLEUM INSTITUTE
BOEM	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
CT	COILED TUBING
DMAS	DEADMAN/AUTOSHEAR SYSTEM
DSATS	DRILLING SYSTEMS AUTOMATION TECHNOLOGY SECTION
DWOP	DEEPWATER OPERATION PLAN
EDS	EMERGENCY DISCONNECT SYSTEM/SEQUENCE
FG	FRACTURE GRADIENT
FMECA	FAILURE MODE, EFFECTS, AND CRITICALITY 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 INDUSTRY 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
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
RIDM	RISK-INFORMED DECISION-MAKING
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 begins 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 a risk-based approach in BSEE's management and governance. The proposed methodologies leverage more than 50 years of experience from nuclear reactor safety, but are adapted to the unique operational conditions of the offshore oil and gas environment.

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 operational 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," such as drilling, well completions, and well workovers. 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 across several of the bureau's mission areas, including inspections, permitting, regulation, technology research, and standard development.

As a result of this effort, BSEE and Argonne developed a model to incorporate risk-informed decision-making through the identification of multiple physical barriers and the application of a Success Path Approach to understand, analyze, and manage safety risks.

STUDY OBJECTIVES

Leveraging more than 50 years of experience assessing safety and system reliability for the nuclear industry, BSEE enlisted the services of Argonne to provide technical assistance in developing and implementing tools and processes to support a more comprehensive and effective approach to risk-informed regulatory activities. This assistance includes the development of a risk-based screening methodology to identify important barriers in offshore hydrocarbon development operations in a way that highlights critical barrier systems for consistent analysis, quantifiable assessment, and inspection. The study also applies the Success Path model to a range of production scenarios and safety systems, drilling scenarios with multiple rig types, and differing operational environments, such as deepwater drilling and high-pressure, high-temperature (HPHT) wells.

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 and enabling BSEE’s utilization of operational data to develop a variety of Success Path applications to analyze, diagnose, and visualize critical barrier systems in each of the operations described above.
- Analyzing information and insights culled from interactions with operators and BSEE subject matter experts (SMEs), as well as BSEE operational data on facility construction and operation, to develop Success Path models that equip BSEE to visually analyze critical barrier systems, related regulations, and industry standards in an integrated fashion within a practical framework. This can help determine the inspectable characteristics that BSEE can focus on to improve safety outcomes on the OCS.
- Adapting a successful risk-based methodology for the offshore oil and gas environment by creating a framework within which the entire industry can communicate and continuously improve operational integrity.

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

- Introduction of the Success Path Approach to operational risk management. The material is structured to provide an insightful background of this systematic, clear, and comprehensive approach for managing operational safety risks in offshore oil and gas operations.
- Overview of Success Path applications conducted for offshore drilling, production, completions, and workover activities.
- Description of the research findings.
- Summary conclusions and recommendations.

The report’s appendices provide a collection of Success Path models Argonne developed in partnership with the BSEE and industry, illustrating critical barriers that must be maintained to ensure safe operation for a variety of offshore operations and technologies.

SUCCESS PATH APPROACH TO OPERATIONAL RISK MANAGEMENT

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 Success Path Approach. This 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 safety of offshore operations.

The Success Path Approach is based on key principles from nuclear power plant safety and from other industries¹ with safety critical applications. However, the nuclear industry and the upstream oil and gas industry are dissimilar in several ways. Nuclear power plants remain in one place for their entire lifetimes and carry out a single mission: 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, 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 a variety of operating conditions that change over time, and there is a large degree of variation in terms of well formation and operational conditions such as water depth, temperature of operation, marine currents, and other weather conditions. Hence, a major adaptation from the nuclear-style PRA approach is necessary to better address the dynamic environment of offshore oil and gas operations. The Success Path Approach to operational risk (safety) management was born out of this necessity.

Another major difference from the offshore oil and gas industry is that the degree of instrumentation used in the equipment is limited in scope to cover only the main elements of the operational envelope. This is driven by the challenges of using sensing devices in extreme water depths or extraordinarily difficult pressure and temperature regimes inside the wellbore. This lack of instrumentation limits the observability of the process and hinders the applicability of mainstream risk assessment methodologies.

Argonne's Success Path 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. In addition, a key aspect of this approach is that it provides the regulator, operators, and contractors a common communications framework to delineate the "successful" safety operational landscape. In practice, it is very easy to define what success means; however, depending on the stakeholder, failure has many degrees of meaning because each stakeholder has a different definition of mission, but all share a common outcome.

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.

The Success Path Approach is deployed in two sequential steps. First, a qualitative phase focuses on delineating, characterizing, and illustrating how the critical safety functions are to be met. Second, analytical tools quantitatively assess risks associated with critical safety functions under a variety of scenarios and prioritize strategies that balance costs and benefits while managing risks. This assessment is performed under the framework of “achieving success” in the operations.

PHYSICAL BARRIERS

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 the Macondo accident. If these barriers had been effective, there also would not have been any operational (or process) safety incidents in the Gulf, including loss of life, loss of well control, and major environmental spills. Operational (or process) safety is about establishing and maintaining multiple physical barriers designed to cover the relevant operational envelope.

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

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* are necessary. These barriers support system operation in a coordinated fashion. They must be in place and operational so that the failure of a single barrier cannot lead to failure of the entire system.

Within the oil and gas industry, Argonne found a very strong commitment to industrial safety at facilities, and the historical record shows a consistent and steady reduction in the loss of life and health as a result of industrial accidents. A focus on performing casual analyses of incidents has advanced progress toward incident-free operations. The Success Path Approach enables the industry to assess the level of success proactively. Moreover, it allows the development of operational health models that help anticipate key elements that can change the current level of success and enable the operator to change course before an operational incident occurs.

Argonne’s studies revealed that large accidents in the oil and gas industry have come not from failures of industrial safety, but from lapses in process safety that could have been mitigated by the proper design, deployment, and assessment of process physical barriers (called “operational risk” by the *IADC Deepwater Well Control Guidelines, 2nd Edition, 2015*).

A key aspect to highlight in this analysis is the discovery that the term *barrier* has different meanings when applied to process and industrial safety. Figure 1 illustrates the different meanings

of the term *barrier* 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, pre-job briefings, people, and other conditions or situations that keep undesirable events from happening.

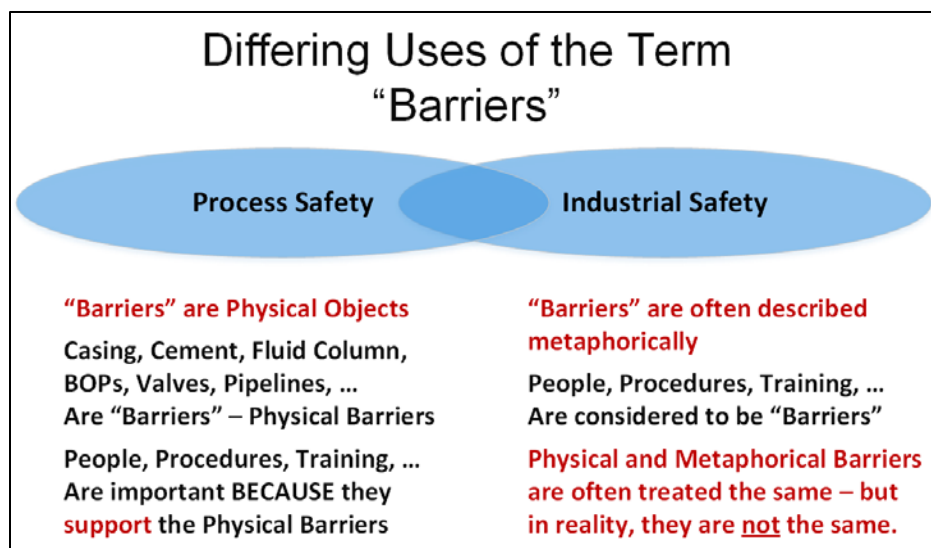


Figure 1: Uses of the Term *Barriers*

The Success Path Approach follows a process safety centric focus; the only barriers are *physical barriers*. Training, people, and procedures are important aspects of the process, 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.

To ensure that physical barriers are performing their critical functions in a particular industrial application, the necessary components, subsystems, interfaces and command and control actions need to be in place. The framework that ensures the coordination of these elements are Success Paths.

In the Success Path approach, the only barriers are physical barriers. Training, people, and procedures are important, but they are not barriers in their own rights.

SUCCESS PATHS

A Success Path is a series or collection of equipment, procedures, software, processes, and human actions that ensure physical barriers can meet the critical safety functions defined within the scope of operational conditions. To identify Success Paths, key process parameters are characterized and the system functional status is assessed for each safety-critical function.

Success Path diagrams delineate and illustrate steps that must be taken to achieve success in the design, maintenance, and operation of each system component. The development of a Success Path diagram focuses on two principal questions:

- What physical barriers are required for the operation at hand?
- What is necessary 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 other safety critical industries; and the ability to diagram and trace how critical systems function (e.g., performance qualification standards), which forms a key part of safety training.











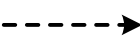
It is precisely the understanding of what needs to work correctly for a physical barrier that paves the way toward elucidating failure modes. In effect, this approach is designed to help orchestrate a shift in operational awareness in order to improve operational risk management. In practical oil and gas use, the Success Path Approach eliminates the uncertainty of personnel assessing a fault and helps put the focus on the key elements that define success. The level of uncertainty when defining success is much narrower than the uncertainty space that defines faults.

As will be illustrated in the next section, application of the Success Path Approach provides a number of key benefits, including the following:

- It is the fastest systematic mechanism to identify 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 to characterize 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. Furthermore, it enables incremental definition of a system, providing scalable ways to enable communications among multiple oil and gas stakeholders.
- 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 comprehend the key points required for success, which facilitates informed 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 grasp key operational safety issues. Each physical barrier can be systematically analyzed to identify the foundational basis for the safe management of the working environment on a rig.
- It mitigates the challenges of using other well-established methodologies requiring the use of precise statistical operational data for the success of such methods. For the digital enablement maturity of the oil and gas industry these methods are impractical

Success Path diagrams use notation that is very similar to that of fault trees. However, unlike fault trees, Success Path diagrams do not specify possible failure modes for systems and components. Instead, they highlight the action that is necessary for system *success*. Table 1 provides an overview of Success Path notation. A box groups a collection of functions and intermediate steps or to designate a base event, a cone-shaped *AND* gate indicates 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 directs readers to a different Success Path diagram. Additional support systems are represented by triangles: yellow for primary-rig AC power, orange for secondary-rig AC power, red for subsea AC power, brown for a 3k accumulator, and green for a 5k surface hydraulic supply. A dashed line indicates the order of progression for human actions or component actuation.

Table 1: Success Path Diagram Notation

Symbol	Name	Description
	<i>System, Group, Function or Base Event</i>	<i>Name of a system, group of functions, intermediate steps, or base event</i>
	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

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 critical system or component would typically include the following four steps:

- Identify the critical safety function(s) and associated hardware, software, and human actions needed to ensure successful operation. This is usually a statement of success, such as “Pumps deliver needed pressure and flow under all expected conditions.”
- Ensure that the required 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 Success Path Approach to high-risk areas related to offshore oil and gas operations.

OFFSHORE OIL AND GAS APPLICATIONS OF THE SUCCESS PATH APPROACH

The Success Path Approach developed by Argonne covers the most relevant applications for offshore oil and gas operations. However, this methodology was fine-tuned for drilling operations. This section describes key use cases within drilling, where the approach was studied.

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.

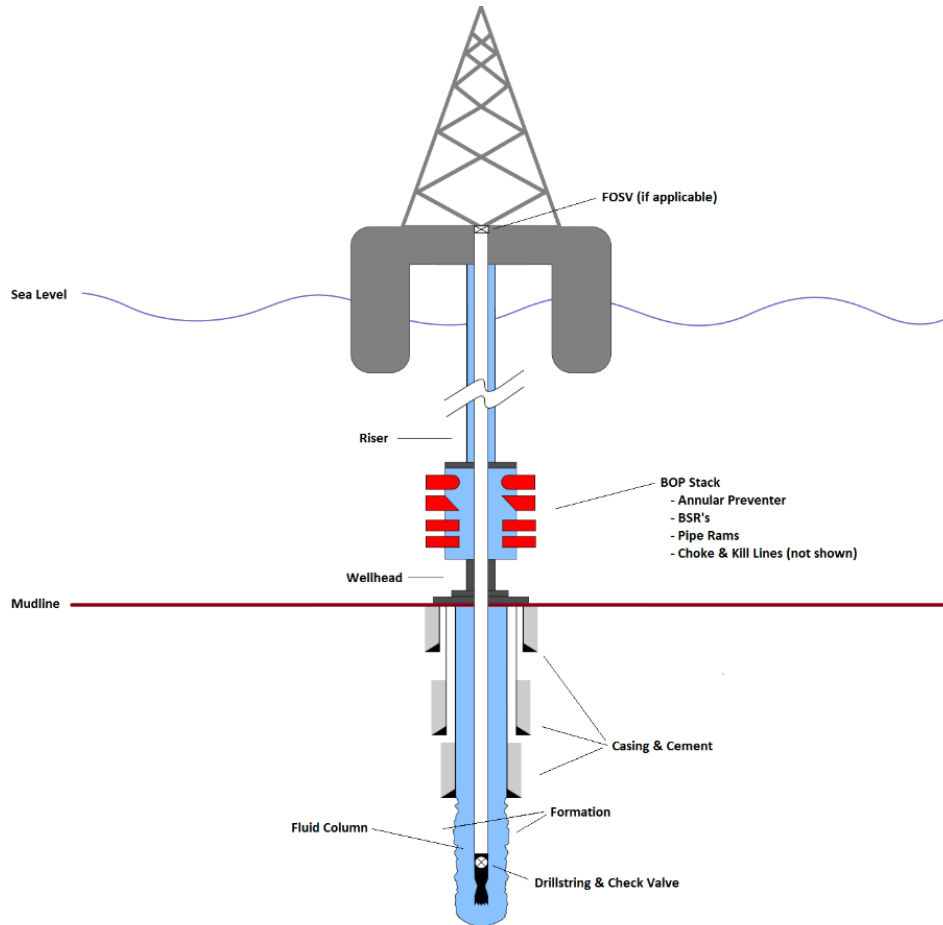


Figure 2: Sketch Depicting the Physical Barriers Found During Drilling Operations²

The first example application of the Argonne Success Path 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 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.

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.

Applicability. Figure 3 provides a completed Success Path 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 Success Path 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 Success Path

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 Success Path 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.

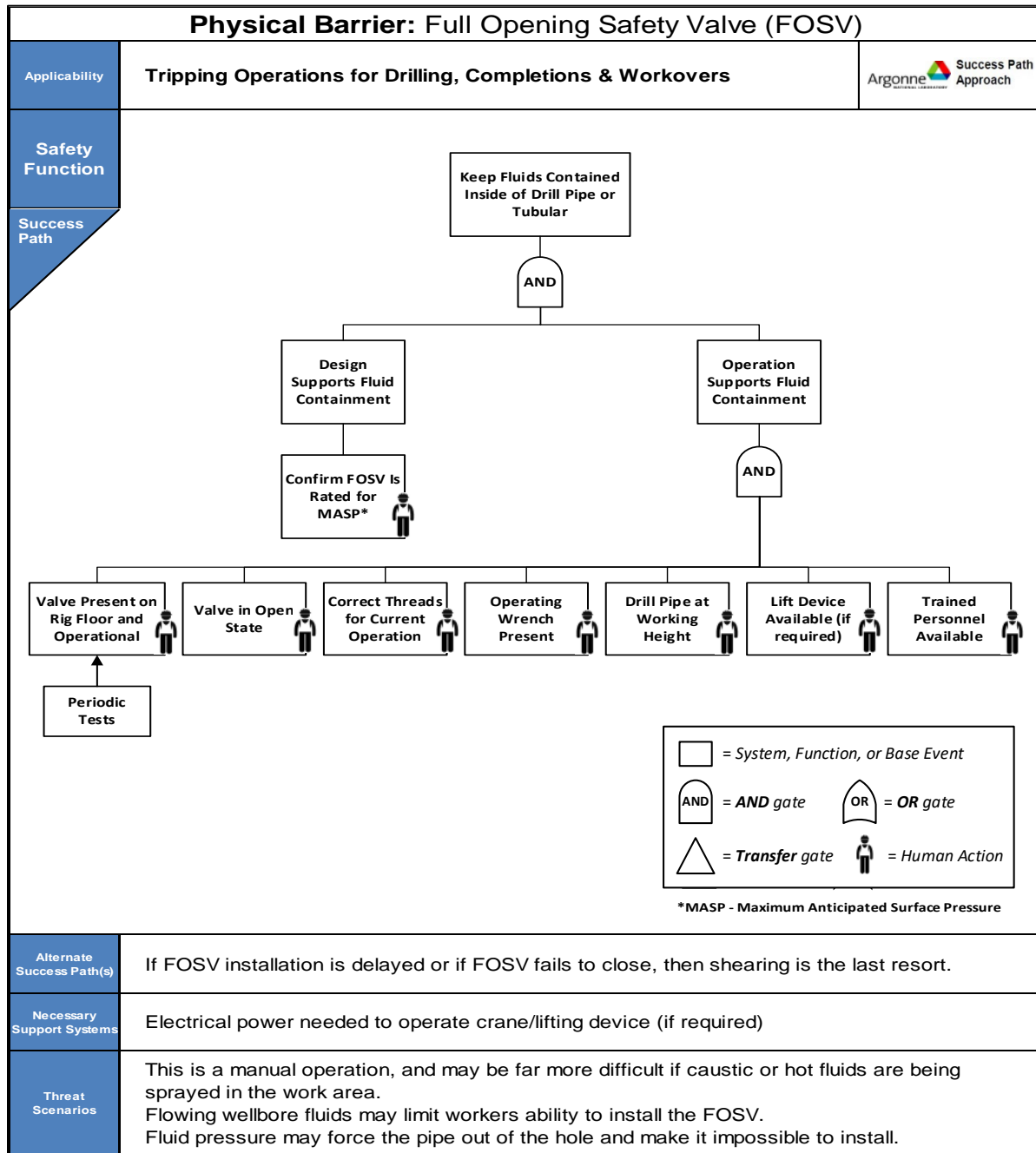


Figure 3: Argonne Success Path Approach Template for FOSV

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 report³:

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 member⁴.

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 Success Path template.

The value of the Argonne Success Path 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 Success Path Approach

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.

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 Success Path Approach is also useful in applying risk-based techniques to compare and discuss alternative well-control techniques.

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

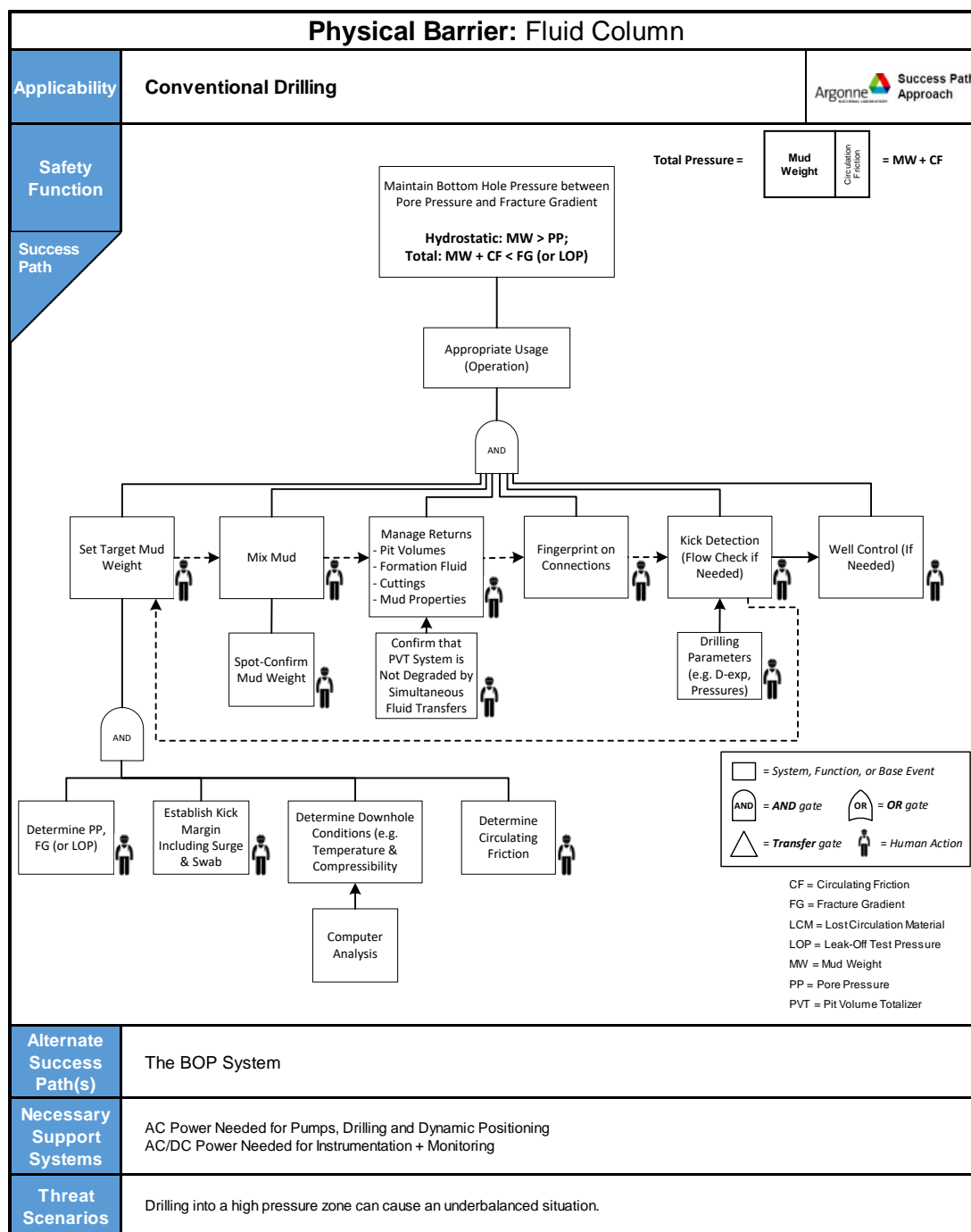


Figure 4: Fluid Column Success Path (Conventional Drilling)

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 in Table 2.

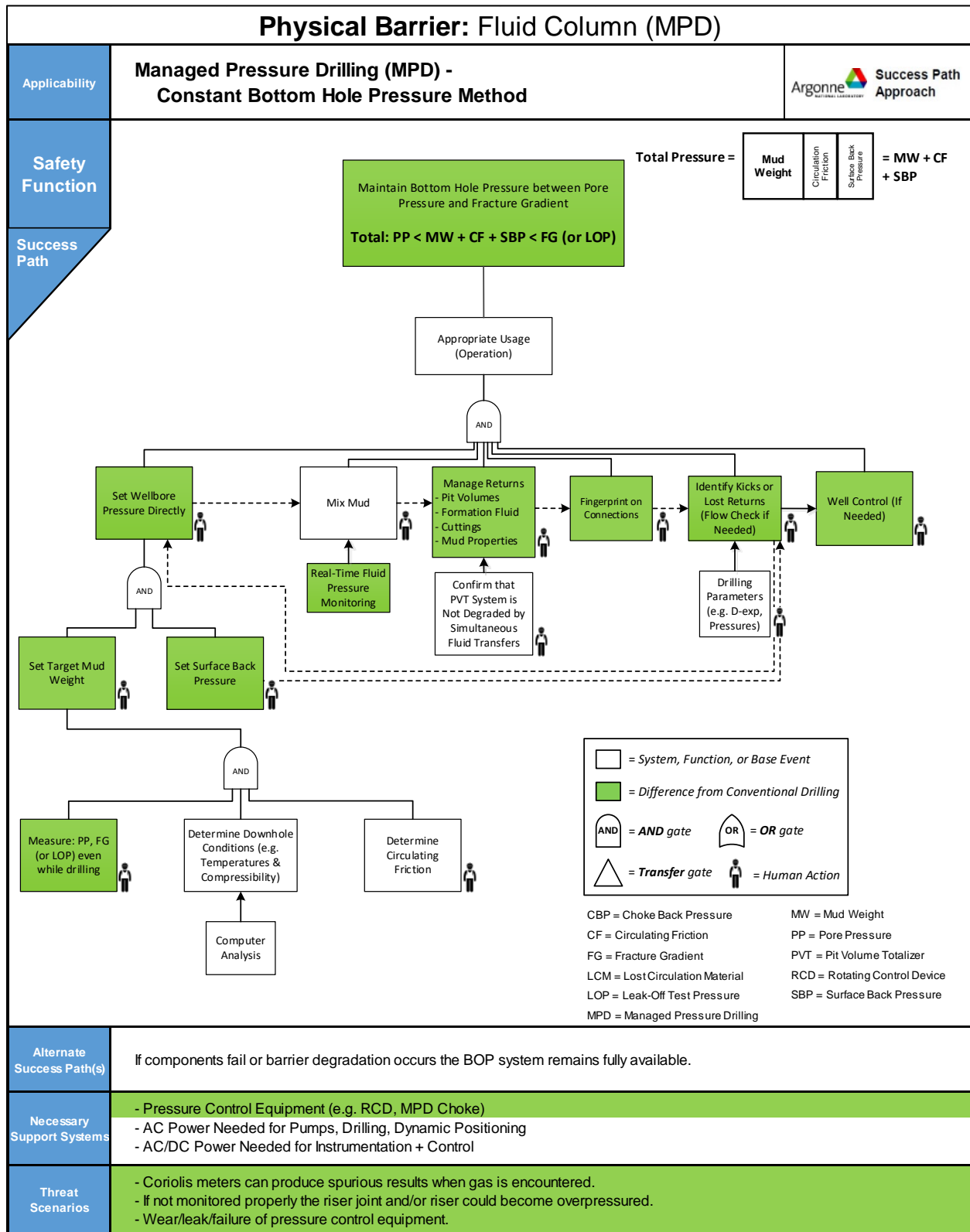


Figure 5: Fluid Column Success Path (Managed-Pressure Drilling)

Table 2: Using the Success Path Approach to Compare Conventional and Managed-Pressure Drilling⁵

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

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.

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

As demonstrated in the above comparison, the Argonne Success Path 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 indicators⁶ to aid in the evaluation of alternative drilling scenarios. Figure 6 displays the barriers, safety functions, and Success Paths for the three evaluated scenarios.

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.

	Conventional Drilling	Kick Circulation via Secondary Barrier (BOP) Choke Line	Managed Pressure Drilling Through MPD Choke																																										
Primary Barrier:																																													
Safety Function(s):	MW + CF < FG or LOT; MW > PP	PP < MW + CF + SBP < FG or LOT	PP < MW + CF + SBP < FG or LOT; Protect against sudden pressure loss. Protect riser from over-pressurization;																																										
Secondary Barrier(s):	BOP; Redundant BOP Components	Redundant BOP Components	Redundant MPD components; Riser Top Annular; BOP; Redundant BOP Components																																										
Primary Barrier Success Path:	<table border="1"> <thead> <tr> <th></th> <th>Variance</th> </tr> </thead> <tbody> <tr> <td>Estimate PP, FG, LOT, CF; Infrequent measurements</td> <td>±0.2 - 2.0 ppg</td> </tr> <tr> <td>Adjust for temperature and compressibility in deep wells</td> <td>MW=±0.5 ppg</td> </tr> <tr> <td>Select mud weight based on estimates of PP and FG</td> <td>-</td> </tr> <tr> <td>Mix mud while circulating at full rate</td> <td>MW=±0.1 ppg</td> </tr> <tr> <td>Carefully manage pump rate and pipe speed to minimize swab and surge pressures</td> <td>ΔP = CF ± P_{surge/swab}</td> </tr> <tr> <td>Identify kicks or lost returns; Kick Response = Shut-In</td> <td>KDV > 10 bbl; KRT > 2 mins</td> </tr> </tbody> </table>		Variance	Estimate PP, FG, LOT, CF; Infrequent measurements	±0.2 - 2.0 ppg	Adjust for temperature and compressibility in deep wells	MW=±0.5 ppg	Select mud weight based on estimates of PP and FG	-	Mix mud while circulating at full rate	MW=±0.1 ppg	Carefully manage pump rate and pipe speed to minimize swab and surge pressures	ΔP = CF ± P _{surge/swab}	Identify kicks or lost returns; Kick Response = Shut-In	KDV > 10 bbl; KRT > 2 mins	<table border="1"> <thead> <tr> <th></th> <th>Variance</th> </tr> </thead> <tbody> <tr> <td>Measure PP, LOT, CF</td> <td>±0.1 ppg</td> </tr> <tr> <td>Adjust for temperature and rheology in deep wells</td> <td>MW=±0.5 ppg</td> </tr> <tr> <td>Select mud weight based on measured PP and FG at casing shoe</td> <td>-</td> </tr> <tr> <td>Mix mud while circulating at reduced rate</td> <td>MW=±0.1 ppg</td> </tr> <tr> <td>Adjust choke to maintain desired wellbore pressure</td> <td>ΔP = ±50 psi</td> </tr> <tr> <td>Identify kicks or lost returns; Secondary Kick Response = SBP</td> <td>KRT < 30 sec.</td> </tr> </tbody> </table>		Variance	Measure PP, LOT, CF	±0.1 ppg	Adjust for temperature and rheology in deep wells	MW=±0.5 ppg	Select mud weight based on measured PP and FG at casing shoe	-	Mix mud while circulating at reduced rate	MW=±0.1 ppg	Adjust choke to maintain desired wellbore pressure	ΔP = ±50 psi	Identify kicks or lost returns; Secondary Kick Response = SBP	KRT < 30 sec.	<table border="1"> <thead> <tr> <th></th> <th>Variance</th> </tr> </thead> <tbody> <tr> <td>Measure PP, FG, LOT, CF</td> <td>±0.1 ppg</td> </tr> <tr> <td>Adjust for temperature and rheology in deep wells</td> <td>MW=±0.5 ppg</td> </tr> <tr> <td>Select mud weight based on measured FIT at several points in the well and estimated or measured PP</td> <td>-</td> </tr> <tr> <td>Mix mud while circulating at full rate</td> <td>MW=±0.0 ppg</td> </tr> <tr> <td>Adjust choke to maintain desired wellbore pressure</td> <td>ΔP = ±50 psi</td> </tr> <tr> <td>Identify kicks or lost returns; adjust SBP for either</td> <td>KDV < 2 bbl; KRT < 30 sec.</td> </tr> </tbody> </table>		Variance	Measure PP, FG, LOT, CF	±0.1 ppg	Adjust for temperature and rheology in deep wells	MW=±0.5 ppg	Select mud weight based on measured FIT at several points in the well and estimated or measured PP	-	Mix mud while circulating at full rate	MW=±0.0 ppg	Adjust choke to maintain desired wellbore pressure	ΔP = ±50 psi	Identify kicks or lost returns; adjust SBP for either	KDV < 2 bbl; KRT < 30 sec.
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Figure 6: Illustration of Barriers, Safety Functions, and Success Paths for Three Drilling Scenarios⁷

Results of the Success Path analysis strongly suggests that MPD has substantial benefits over conventional drilling techniques in terms of improved accuracy in measurement of kick detection volumes (KDV), 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 II includes Success Paths for use of choke and lines, shown in Figure II-6, to maintain bottom-hole pressure, and use of a Rotating Control Device (RCD), shown in Figure II-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 Success Path Approach demonstrates how Success Paths allow both a qualitative and quantitative evaluation of system reliability.

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.

BLOWOUT PREVENTER SYSTEM RELIABILITY

The BOP system is often thought of as the last line of defense during a loss of well control. However, as a complex electromechanical system subject to extreme environmental conditions, ensuring high-functional reliability of the BOP can be challenging. The Argonne Success Path 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 report⁸ is summarized below.

Success Paths were created to outline the systems, components, and actions necessary for successful BSR actuation⁹. 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).

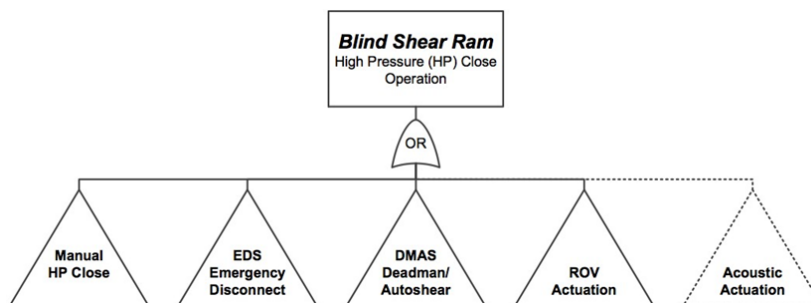


Figure 7: BSR HP Close Top Level Success Path

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.

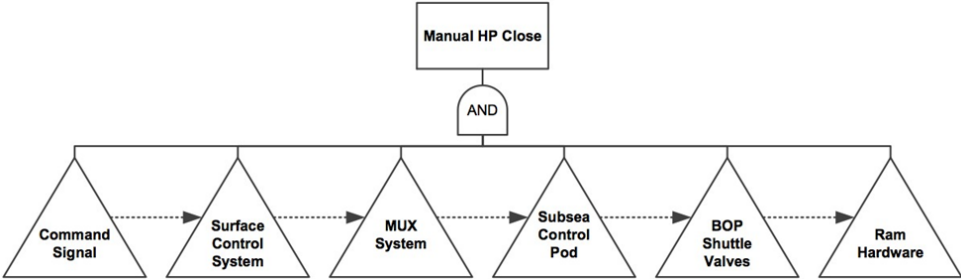


Figure 8: Manual HP Close Success Path Overview

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.

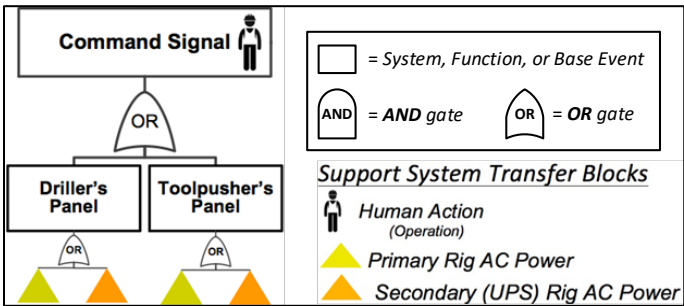


Figure 9: Manual HP Close – Command Signal

The *surface control system* is comprised of the Central Control Unit (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.

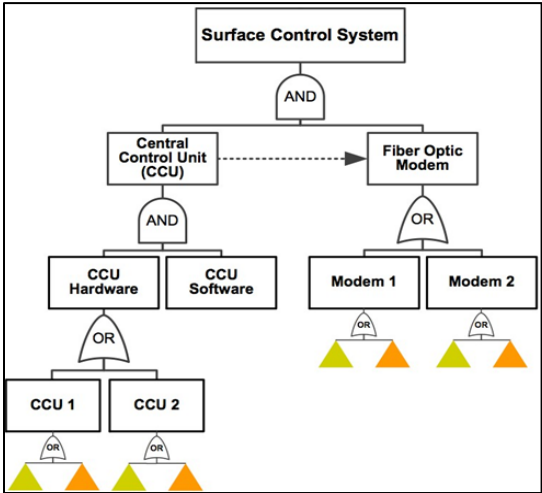


Figure 10: Manual HP Close – Surface Control System

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.

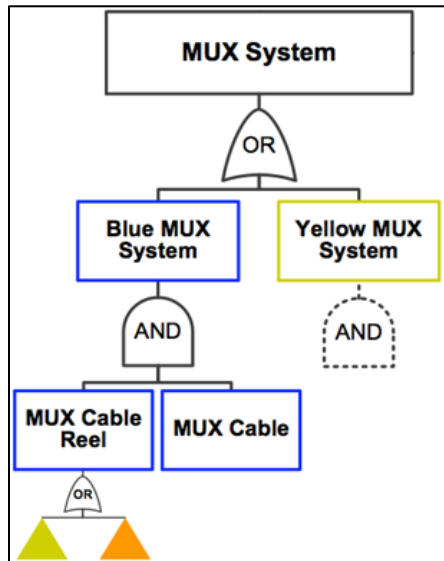


Figure 11: Manual HP Close – MUX System¹⁰

The Lower Marine Riser Package (LMRP) *subsea control pods* are the most complex system of the manual HP close actuation pathway, as shown in Figure 12. 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.

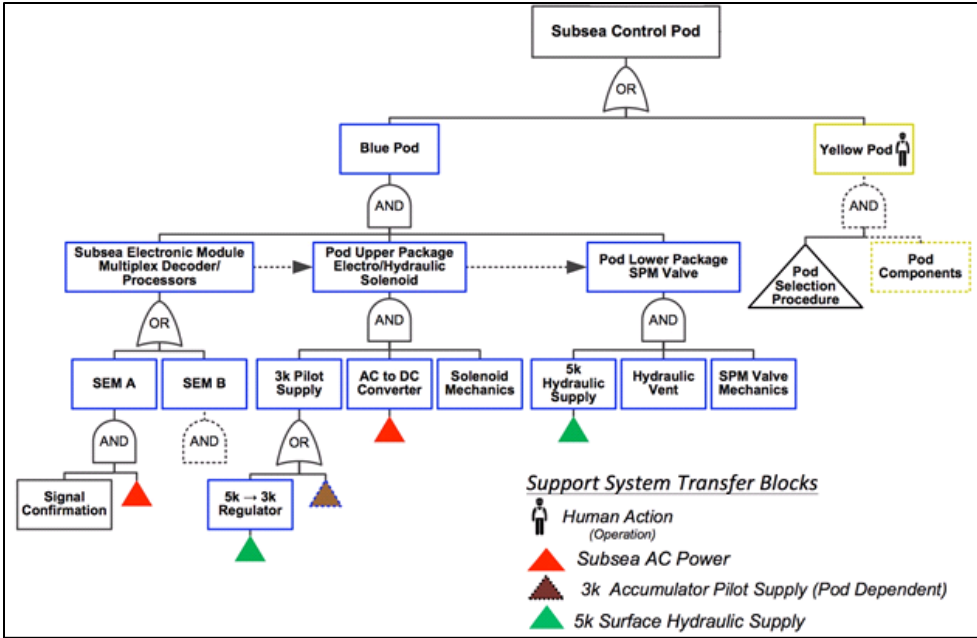


Figure 12: Manual HP Close – Control Pod

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, Remotely Operated Vehicles (ROV), and Dead Man Auto Shear (DMAS) system. 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.

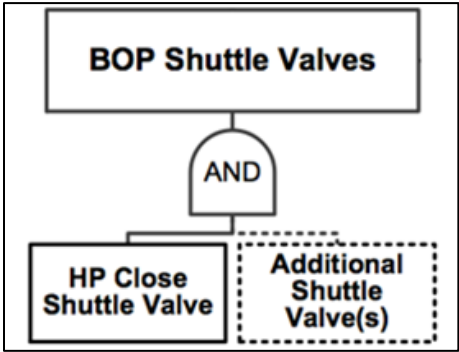


Figure 13: Manual HP Close – BOP Shuttle Valves

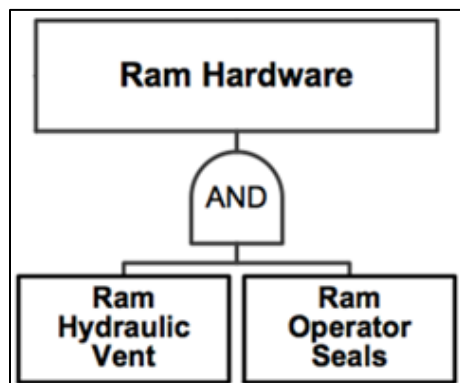


Figure 14: Manual HP Close – Ram Hardware

The Success Paths outlined above (and similar Success Paths developed for the other four actuation pathways, which are displayed in Appendix II) 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) 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.

Table 3: SIL Category Overview IEC 61508¹¹

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

¹¹ IEC 61508-1 ed.2.0, "Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 1: General requirements." Copyright © 2010 IEC Geneva, Switzerland. www.iec.ch

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 070¹² (a Norwegian national guideline) establishes minimum SIL requirements for common offshore safety instrumented functions, rather than the full risk-based approach described in IEC 61508¹³. Regarding the annular/pipe ram and blind shear ram, NOG 070 states:

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.

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 $\sim 1 \times 10$. In “deadman” mode, the DMAS is also SIL – 1, but the “autoshear” function is SIL – 2. This difference is due to the fact that fewer components are necessary to activate the autoshear function,

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.

in comparison to the deadman function. Taken together, the BSR HP Close PFD is within the SIL – 2 category.¹⁴

Table 4: BSR HP Close Failure Probability Estimates

Actuation Pathway	Probability of Failure per Demand (PFD)	Odds of Failure per Demand	Approximate SIL
<i>Manual HP Close</i>	1.24×10^{-2}	1 in 81	1
<i>EDS</i>	1.58×10^{-2}	1 in 63	1
<i>DMAS</i>			
<i>Deadman</i>	1.45×10^{-2}	1 in 69	1
<i>Autoshear</i>	9.51×10^{-3}	1 in 105	2
Total¹⁵	5.60×10^{-3}	1 in 179	2

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 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 Success Path 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 15, 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 American National Standards Institute (ANSI) / American Petroleum Institute (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.

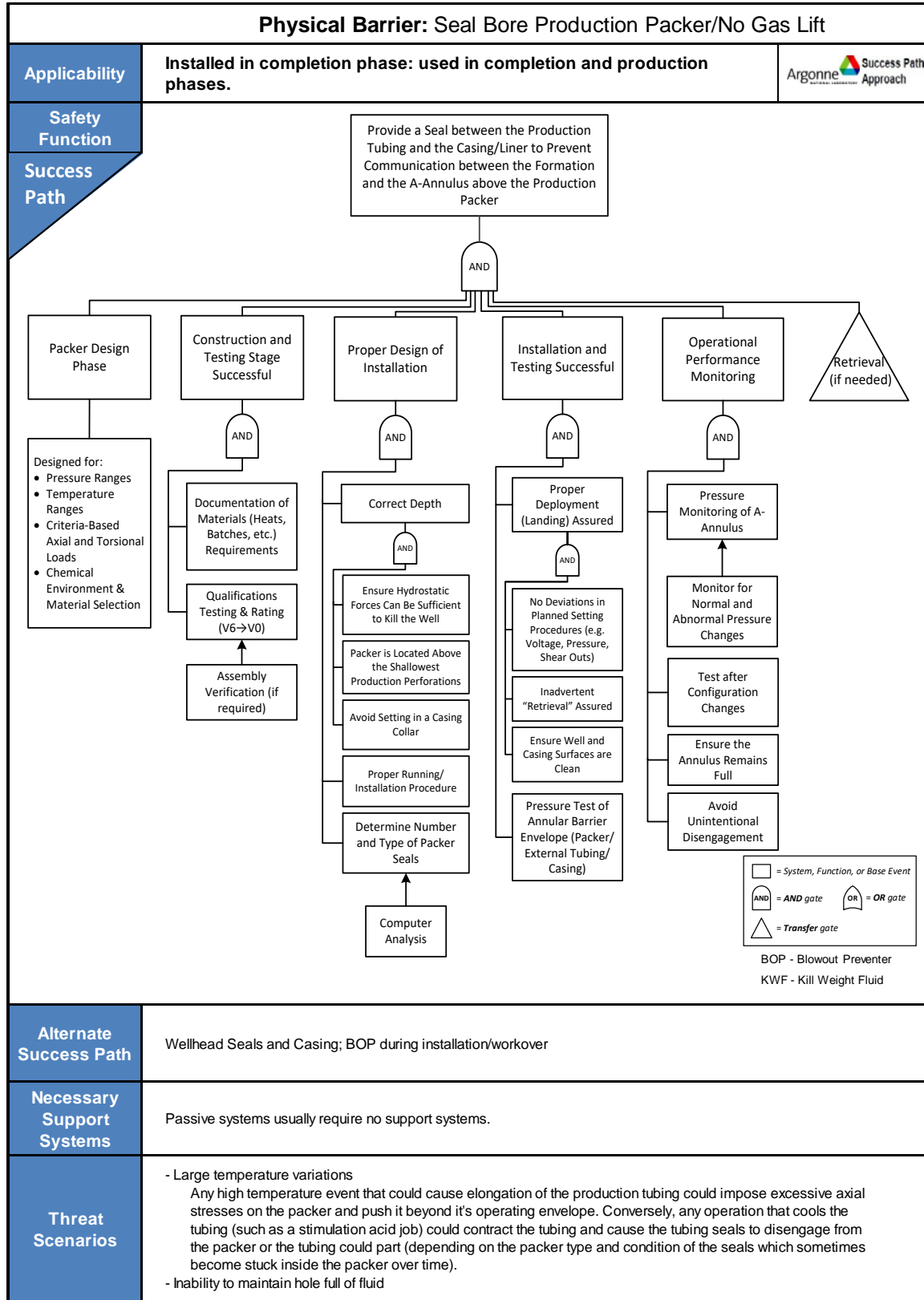


Figure 15: Success Path for a Seal Bore Production Packer

The removal of barriers in general, and in this case the retrieval of a packer, represents an area of high risk. Figure 16 illustrates the Success Path for packer retrieval. Here, the Success Path 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 Success Path concept – that there must always be Success Paths in place to keep the hydrocarbons where they belong.

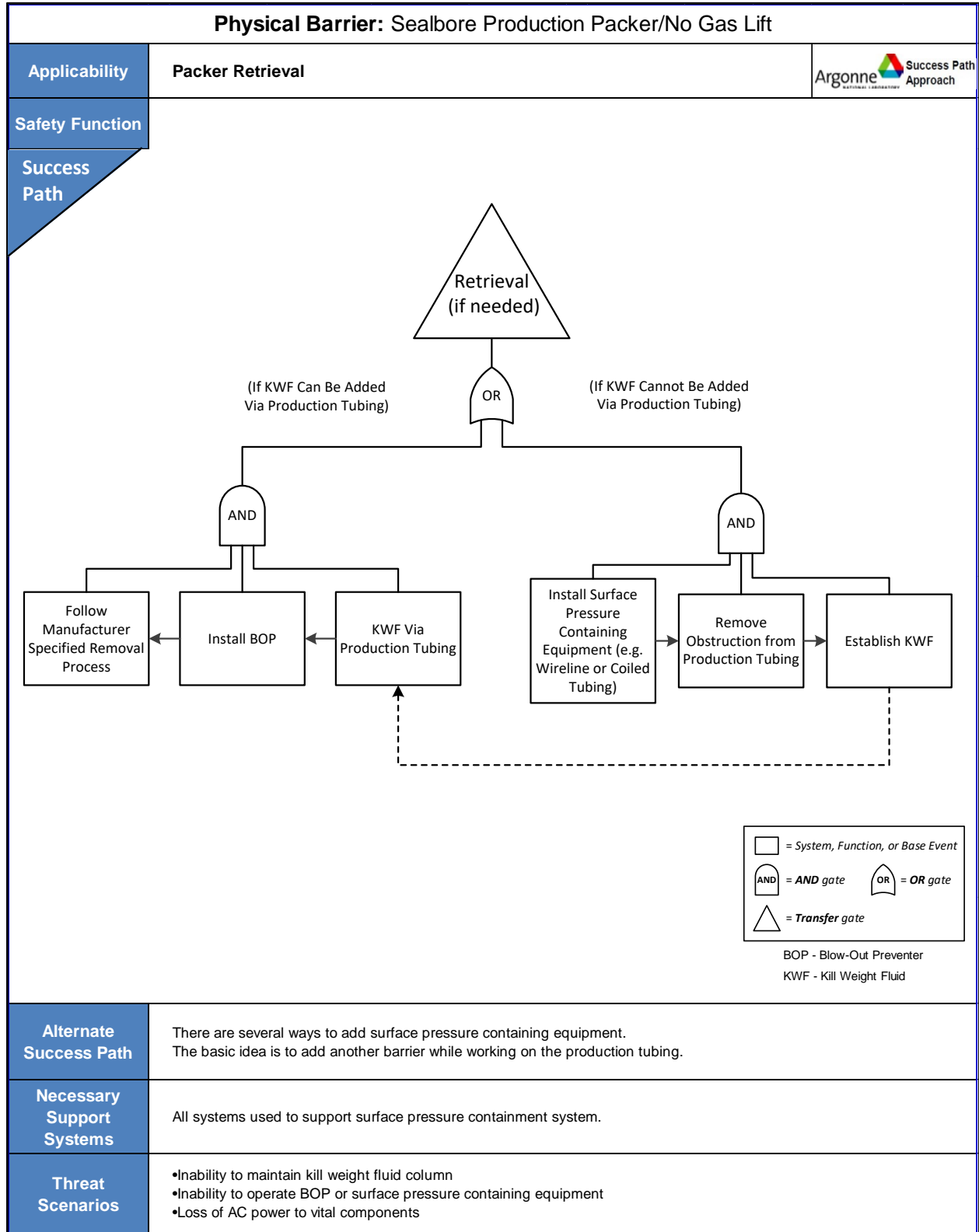


Figure 16: Success Path for Packer Retrieval

WORKOVER

The Argonne Success Path 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 2017, Argonne began work with BSEE to: (1) develop tools for risk-informed coiled tubing (CT) inspection and evaluation; and (2) use these tools and additional educational materials to train BSEE inspectors and engineers on safety-significant details related to coiled tubing operations. In support of this effort, Argonne worked together with a coiled tubing subject matter expert, Alexander Sas-Jaworsky, PE, to identify the physical barriers in coiled tubing equipment that create an envelope to contain hydrocarbons and other hazardous process fluids. The diagram in Figure 17 provides an example of a coiled tubing well control stack¹⁶ configuration that is compliant with the draft 2nd Edition of the API Recommended Practice (RP) 16ST barrier requirements for a pressure range from 3,501 to 7,500 psig (PC-3).

¹⁶ The relevant BSEE regulations refer to the physical barriers designed for well control in coiled tubing operations as “BOP” while this report has adopted the API RP 16ST definition, “well control stack.”

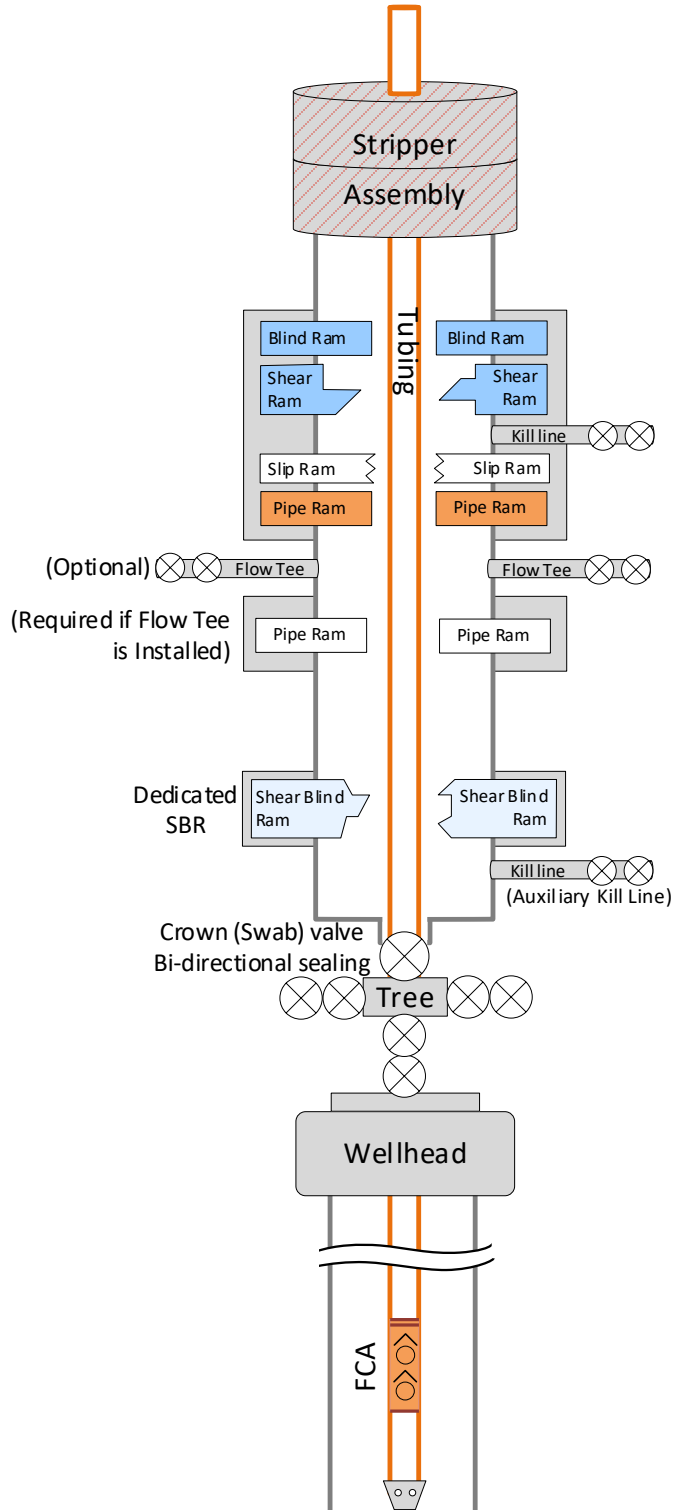


Figure 17: Example of a CT Well Control Stack Configuration Compliant with Draft 2nd Edition of API RP 16ST Barrier Requirements for PC-3

Once the critical physical barriers were identified, Argonne developed high-level Success Paths to illustrate the barrier requirements for coiled tubing equipment setup under specific pressure conditions. For example, Figure 18 depicts the options available to the operator for installing coiled tubing equipment in compliance with the proposed 2nd Edition of API RP 16ST,¹⁷ for PC-3, which allows a number of options for installed physical barrier elements in the coiled tubing well control stack.

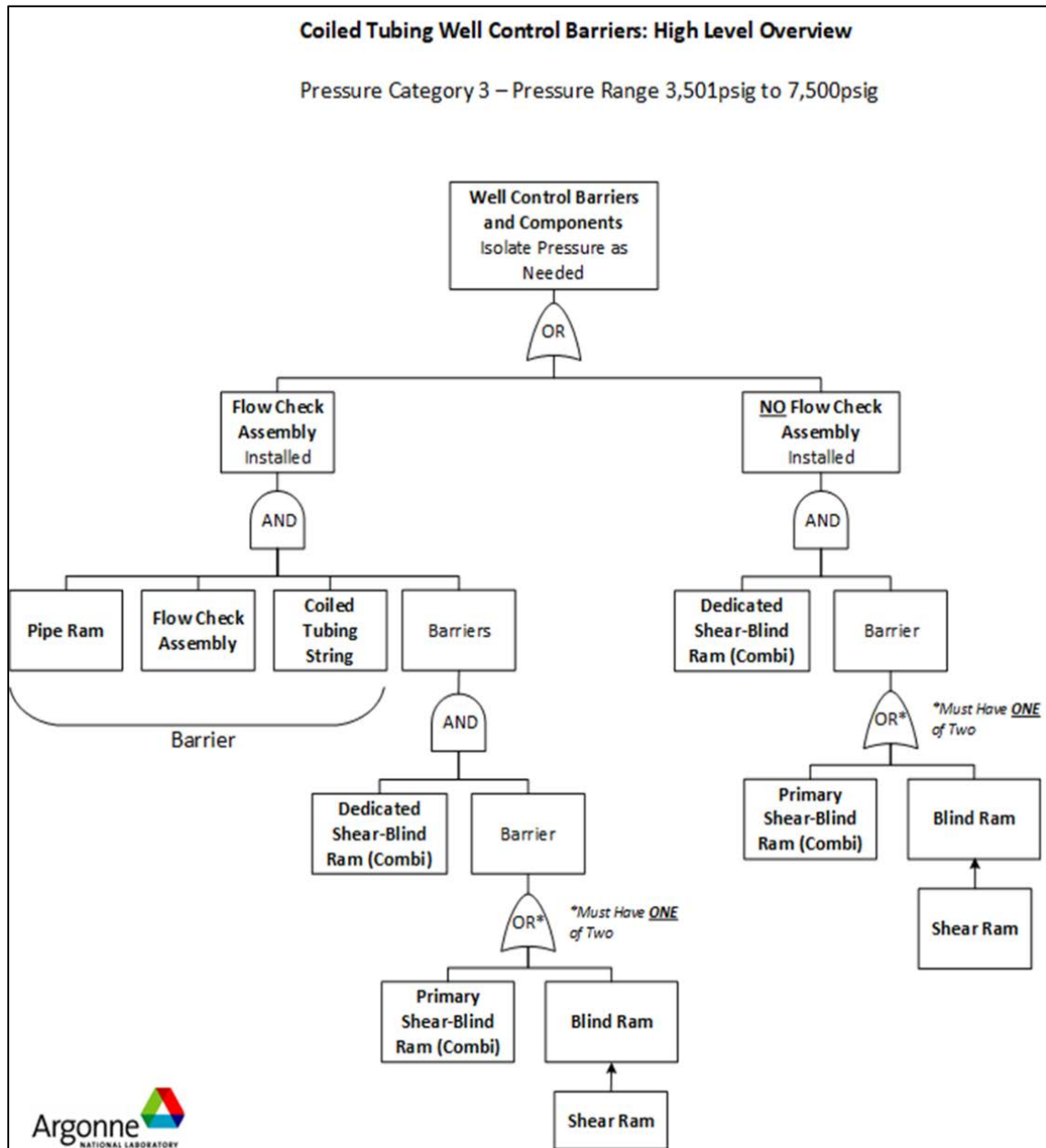


Figure 18: High-Level Success Path Diagram According to API RP 16ST PC-3

¹⁷ Per the CFR, a flow check is required (30 CFR 250.616(a)(4) or 30 CFR 250.1706(a)(4)). An alternate procedure or equipment request would be required to avoid installing one.

The Success Path development effort for PC-3 identified that, to conform with the API RP 16ST requirement to include a minimum of two barriers, an additional *dedicated* shear-blind ram is required. The word “dedicated” means that it is the shear blind ram that is installed as close as practical to the wellhead and must be able to shear the coiled tube and seal the well cavity to prevent hydrocarbons from reaching the facility and personnel. Note that the dedicated shear-blind ram is operated through a hydraulic power fluid system that is independent of that used for the primary well control stack rams.

In Figure 17, the required barriers¹⁸ are:

1. The combination of the flow check assembly, the coiled tubing string, and the pipe ram;
2. The combination of the shear ram and the blind ram; and
3. The dedicated shear-blind ram.

Table 5 describes the role of each barrier depicted in Figure 17 and provides brief information regarding its main function and the support equipment required to actuate it. The color coding for CT Barrier Components 1, 2, and 3 corresponds with the color coding in the barrier diagram in Figure 17—the CT barrier 1 components are orange; the CT barrier 2 components are dark blue, and CT barrier 3 is light blue. The items with no color (or white) are part of the coiled tubing equipment but are not relied upon in well control situations. The gray items, such as the wellhead components, are outside the scope of coiled tubing operations, pertinent regulations, and API RP 16ST.

¹⁸ Note that this list includes three required barriers instead of two. This is in accordance with API’s debate as of the time of publishing of this report on accepting the downhole flow check valve as a barrier given the fact that it can leak.

Table 5: Example of a List of Barriers, Their Functions, and Support Equipment for a Well Control Stack Configuration Described in Figure 18

Barrier (component) / Operational Equipment		Main Function	Support Equipment
CT Barrier 1 Components	Pipe Ram	Closes on Demand onto CT OD and Isolates Annulus Pressure	Hydraulic Power, Ram Lock(s)
	Downhole Flow Check Device	Seals and Isolates Annulus Pressure From CT ID Pressure	N/A - Passive Barrier Component
	Coiled Tubing String	Isolates CT ID Pressure/ Flow Path From Annulus Pressure/Flow Path	Injector, Support Systems
CT Barrier 2 Components	Blind Ram	Closes on Demand to Seal Across ID Bore of Stack and Contain Wellbore Pressure	Hydraulic Power, Ram Lock(s)
	Shear Ram	Closes on Demand to Shear the Tubing and Provides Means for Blind Ram to Properly Close and Seal Wellbore	Hydraulic Power
CT Barrier 3	Dedicated Shear-Blind Ram	Closes on Demand to Shear the CT and Seal Across ID Bore of Stack to Contain Wellbore Pressure	Hydraulic Power, Seals on Blades, Ram Locks
CT Operational Components	Stripper Assembly*	Contains Annulus Pressure at Surface During Normal Operation	Hydraulic Power
	Slip Ram	Secures CT Within Well Control Stack	Hydraulic Power, Ram Lock(s)
	Flow Cross (Flow Tee)	Allows for Fluid Circulation out of the Wellbore	Dual Pressure Isolation Valves on Each Branch
	Kill Line	Provides Access for Flow of Kill Fluid Down the CT ID Into the Well	Dual Pressure Isolation Valves on Line
	Flow Check Assembly	Isolates Annulus Pressure at CT BHA	N/A - Passive Barrier Component

*The stripper assembly is considered to be a continuously degrading operational component, and is classified as a pressure control device only when used for well control.

**Items below the Wellhead used to establish pressure containment (e.g. casing and cement) are critical well control components, but are beyond the scope of API RP 16ST.

Wellhead Components (Not Part of CT Barrier)	Crown Valve (Connection)	Provides Access to the Tree and Initial Pressure Control Point Below the CT Well Control Stack
	Xmas Tree	Provides Wellbore Pressure Isolation and Well Access
	Tubing Hanger Spool	Provides Pressure Isolation of Annulus Between Production Casing and Production Tubing
	Wellhead	Provides Means for Pressure Isolation of All Casing Annuli

The sequence of barrier actuation for this example is also shown in Table 6.

Table 6: Barrier Actuation Sequence in a Well Control Situation for the Configuration Discussed Above

Sequence	Well Containment Components
First	Pipe Ram + Flow Check Assembly + Coiled Tubing String
Second	Shear Ram + Blind Ram
Third	Shear-Blind Ram (“Dedicated” SBR)
Fourth (Beyond the scope of 16ST)	CT Drop Procedure + Close Xmas Tree

Within the scope of this project, Argonne also developed Success Paths for the well control barrier elements and their support equipment. These barriers and systems include (1) the stripper, (2) pipe ram, (3) coiled tubing string, (4) downhole flow check assembly, (5) blind rams as part of the shear and blind ram system, (6) shear rams as part of the shear and blind ram system, (7) primary combination shear-blind ram, (8) dedicated combination shear-blind ram, (9) hydraulic pump, (10) air-over hydraulic pump for the stripper, (11) primary accumulator system, (12) dedicated accumulator system, (13) injector, (14) tubing guide arch, and (15) service reel.

Figure 19 shows a Success Path that accompanies the operation of the pipe ram found in a typical coiled tubing well control stack configuration, including the one discussed above and depicted in Figure 17, which is designed to seal against the outer diameter of the coiled tube and isolate the annulus pressure. This figure illustrates that successful operation of a physical barrier element such as the pipe ram—defined by its critical *safety function*, “Pipe ram closes on demand and isolates annulus pressure”—requires a number of elements, hardware, software (in some cases), and human action to perform successfully. In addition, the information below the Success Path discusses alternate Success Paths (that call for alternative physical barriers) in the event that the pipe ram fails. The *critical support system* is noted as hydraulic power, and can often contain more than one element. Last, at the bottom of the Success Path template, the threat scenario provides information that can help the reviewer understand the impact of external factors on the physical barrier’s ability to perform its critical safety function. A framework of this type enables all involved parties to understand the components necessary to succeed—that is, the various Success Paths needed to achieve the critical function of closing and holding (in this case) annular pressure.

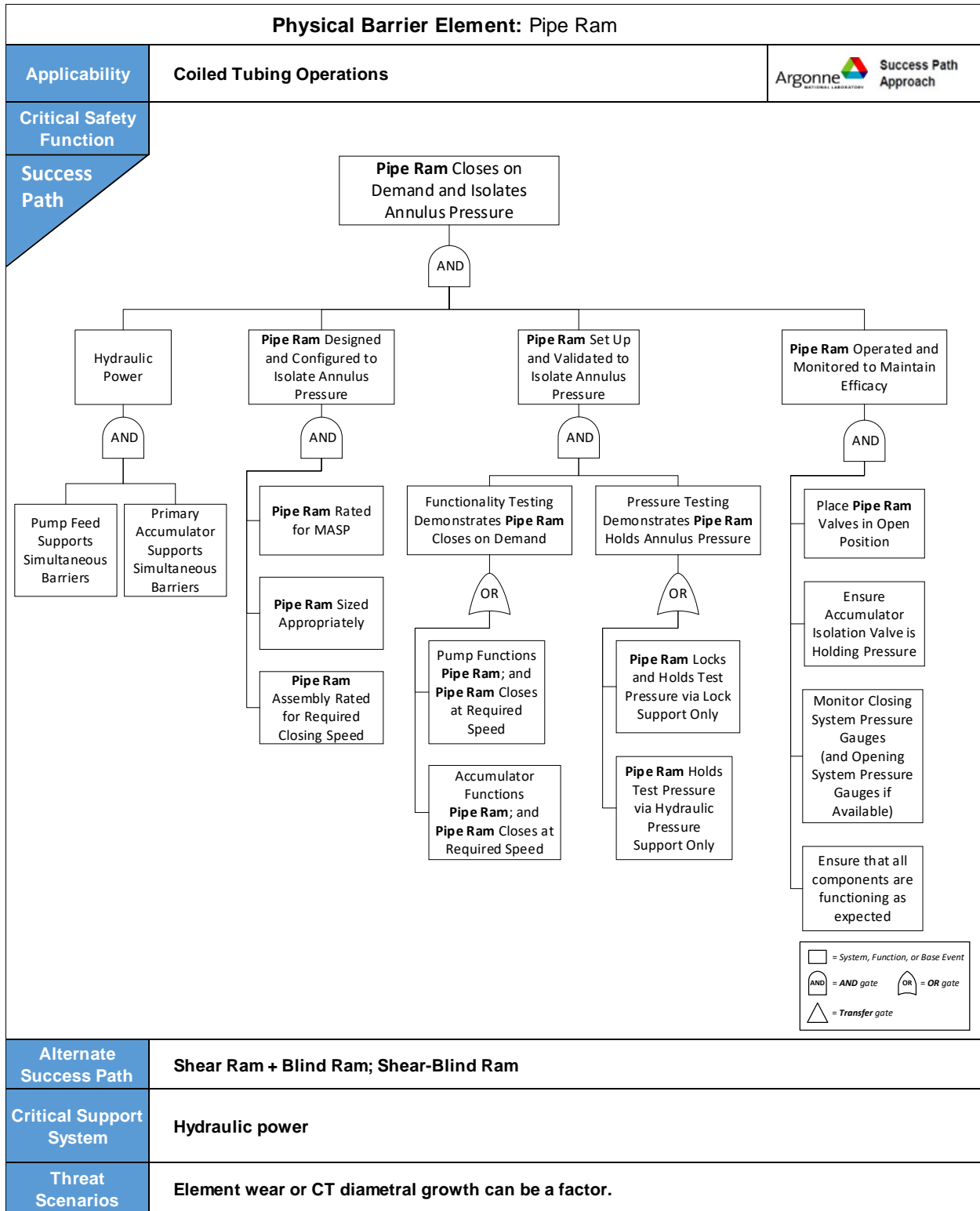


Figure 19: Pipe Ram Success Path

Coiled Tubing Equipment and Operations Inspection Checklist

Once the Success Paths for the physical barriers and the critical support system were developed, Argonne, together with Alexander Sas-Jaworsky, moved on to revising the coiled tubing equipment and operations inspection checklist. Despite its name, this checklist can potentially be used by BSEE not only for inspection, but also for confirming the compliance of the use of particular equipment proposed in a given application for permit to modify (APM), or it can have other uses for BSEE engineers. Although the contents of the checklist are far more specific and contain greater detail, each item on the checklist can be mapped back to elements on a pertinent Success Path and vice versa.

BSEE Coiled Tubing Equipment and Operations Training

Argonne and SAS Industries, Inc., built upon the coiled tubing Success Paths and inspection checklist to prepare educational material for use in a 32-hour training courses on the topic of coiled tubing equipment and operations. This material was designed to focus on application of the Success Path Approach and keeping in mind the process equipment—and the physical barriers—in making sure that the hydrocarbons and other process fluids remained properly contained and are not released into the environment. Furthermore, despite including considerable detail on the operation of coiled tubing equipment, the material was designed specifically for BSEE inspectors and engineers to be able to have sufficient knowledge to detect abnormal conditions with potential adverse safety consequences during an inspection or while reviewing an APM.

Prior to conducting the “live” training courses on coiled tubing equipment and operations, Argonne travelled to the BSEE Gulf of Mexico Region office to conduct a preliminary course, the purpose of which was to present the draft training material to the BSEE subject matter experts, and test the delivery of training to a group of BSEE inspectors and engineers who were asked to audit the course and provide feedback on necessary improvements.

Judging by the feedback received during the daily evaluations and the course-end survey, the material presented during the preliminary training was viewed by most as being of the appropriate operational and technical content. The level of complexity of the technical material and the presentation style was deemed conducive towards achieving a positive learning experience by BSEE participants. The retention of the learned material by most participants was evidenced through their avid participation in the exercises designed to test and reinforce the learning process. Following the successful training pilot, Argonne refined the training materials and conducted three “live” training sessions in three locations across the Gulf of Mexico Region during the first half of CY 2018.

Based on the successful application of the Argonne Success Path Approach for coiled tubing, BSEE decided to work with Argonne to develop a variety of Success Path protocols. These demonstrate the suitability of this approach for support risk-informed decision-making for a diverse set of barrier and non-barrier systems. Additional information on this effort is provided in Appendix I.

COILED TUBING FAILURE MODE, EFFECTS, AND CRITICALITY ANALYSIS (FMECA)

Argonne worked with API SC16 Task Group 5—which developed API RP 16ST “Coiled Tubing Well Control Equipment Systems”—on providing technical support to evaluating the robustness of the recommended safety elements. To ensure the integrity of the physical systems that support or comprise the physical barriers or other critical operational components, the Task Group members proposed performing a Failure Modes, Effects, and Criticality Assessment (FMECA), the results of which would be included in the justification of recommendations in the 2nd Edition of API RP 16ST that is expected to be balloted in CY 2018.

Argonne’s recommendation involved utilizing the FMECA to identify the effects of a component and/or system failure on the physical barriers; in other words, to clearly indicate the failure effect and other consequences in terms of potentially compromising the physical barriers that protect from release of hydrocarbons.

To demonstrate the relationship of the FMECA to the Success Paths, Argonne linked the two by including a requirement in the success trees to “Ensure that all relevant components are functioning as expected” as part of each physical barrier’s Success Path. This requirement can be interpreted as having an AND gate under it that contains individual key systems or components that must be in good working condition in order for this physical barrier to succeed. An example of the linking of the FMECA and to the Success Paths is provided in Figure 20.

The elements under the “Ensure that all relevant components are functioning as expected” AND gate are analyzed in the FMECA and evaluated in terms of the FMECA metrics discussed below.

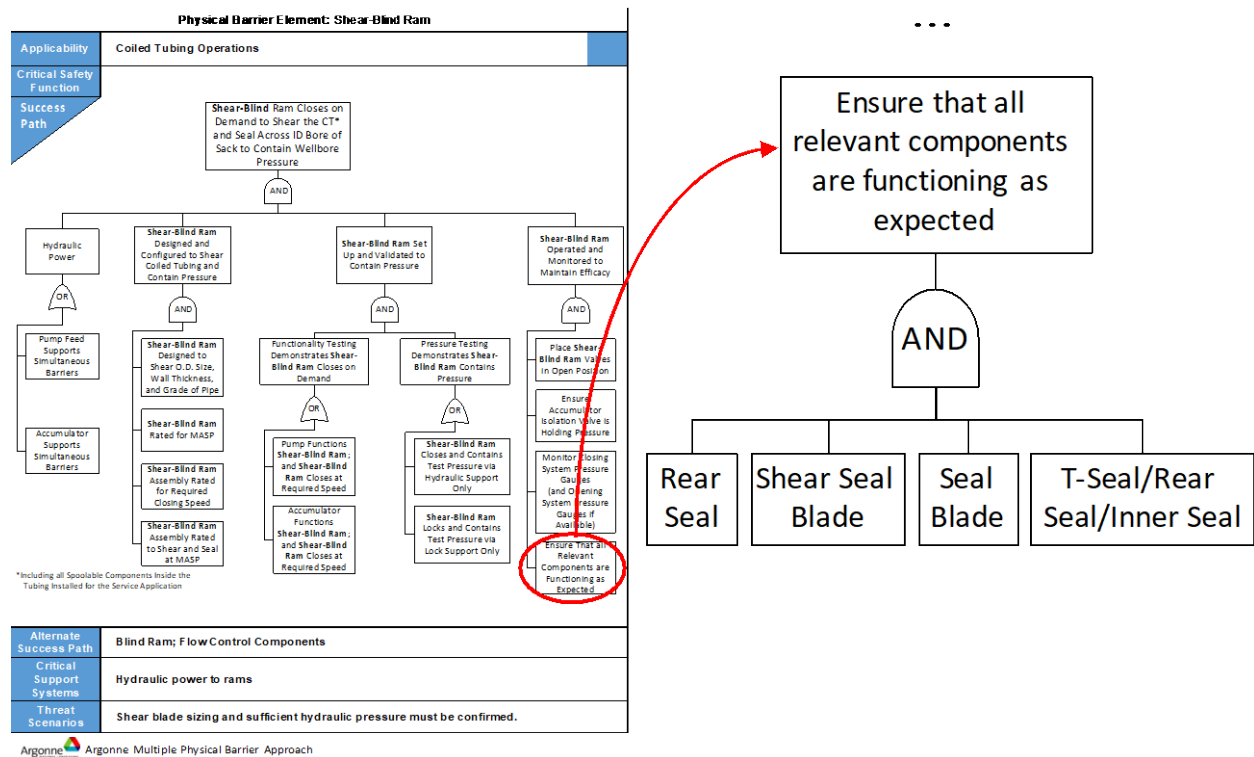


Figure 20: Example of the Relationship between a Barrier Success Path and Barrier Components Evaluated in the FMECA

The risk in terms of the safety and integrity of equipment and barriers included in the Success Path were determined using Argonne’s approach for the FMECA. This included evaluating the effects of component failures on barrier integrity by considering the following metrics for each component analyzed:

- Identifying component failure modes for each major component;
- Determining the local consequence of each failure mode;
- Determining the consequence of failure modes on the effected barrier(s);
- Identifying cause(s)/mechanism(s) of failure;
- Ranking the consequences of each failure mode in terms of its effects on barrier(s);
- Assigning an occurrence ranking for each failure mode (based on average failure data provided by the industry);
- Calculating a risk ranking for each failure mode (which is the product of consequence and occurrence ranking);
- Identifying failure detection mechanisms; and
- Identifying failure prevention controls.

The FMECA was developed within the API SC16 TG-5 Task Group, which included members from coiled tubing component vendors, operators, experts in the field, and representatives from Argonne, who served as the facilitators. When evaluating a given system, the group had to reach

a consensus on the value assigned to risk metrics for each failure mode (i.e., its consequence, occurrence, and risk rankings).

The *consequence ranking* scale suggested by Argonne is provided in Table 7. These rankings range from “1,” in which the failure being evaluated has no direct impact on the functionality of the barrier, to “5,” in which the final barrier to the environment has been disabled. Each failure mode identified was assigned a value from 1 to 5 based on a consensus of the FMECA group members.

Table 7: Example Failure Consequence Ranking

Consequence Ranking	
Rank	Description
1	System degraded but operational, no direct impact on barrier
2	System disabled but alternative system available, no direct impact on barrier
3	System disabled/degraded with barrier degraded but operational
4	Barrier disabled, but alternative barrier(s) remains
5	Barrier(s) disabled, no barriers remain

The *occurrence ranking* was also scaled to a 1 to 5 ranking system, where a ranking of 5 represented the most frequent types of events and a ranking of 1 represented the least frequent events. The actual frequency of each ranking was to be determined after representative data for the failure modes being considered in the FMECA were obtained. When no data were available for an event, the expectation was that expert judgment would be used to determine the occurrence ranking. While conducting the FMECA, it became apparent that sufficient data to determine the occurrence ranking of each failure was unavailable. Due to this lack of data, it was also difficult to reach consensus on an occurrence ranking based on expert judgment. Therefore, the FMECA evaluations were performed for all of the major components, but the occurrence ranking for each failure mode identified was assigned “to be determined (TBD).”

The *risk ranking* is the product of consequence and occurrence; in other words, a failure that occurs most frequently and has highest consequence in terms of barrier failure is calculated to have the highest risk ranking. Due to the consequence and occurrence ranking scales, the risk ranking values ranged from 1 to 25. Table 8 provides an example risk ranking reference structure, where a decision can be made for classifying component failure risk as Low, Medium, or High. These assignments are only provided as examples. The actual assignments were not determined during the FMECA due to the inability to assign occurrence rankings (explanation provided above in the “Occurrence Ranking” description).

Table 8: Example Failure Risk Ranking

		Risk Ranking				
		Occurrence Ranking				
		1	2	3	4	5
Consequence Ranking	1	1	2	3	4	5
	2	2	4	6	8	10
	3	3	6	9	12	15
	4	4	8	12	16	20
	5	5	10	15	20	25

Low	Medium	High
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Despite the lack of failure occurrence data, this study forced the SC16 TG-5 members to rethink the meaning of risk and safety and helped to develop a number of safety recommendations that are included in the 2nd Edition Draft of API RP16ST.

PLUG AND ABANDONMENT

On September 15, 2016, a Joint Industry Project (JIP), organized by Argonne National Laboratory 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.

Results of the JIP provide evidence of the significant benefits the Success Path Approach offers 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
- Aualification 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 Success Path Approach described in this report 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 Success Path 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 Success Path 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 Success Path 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 Success Path 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 SUCCESS PATH APPROACH TO BSEE OPERATIONS AND GOVERNANCE

As identified in the BSEE FY 2016 – FY 2019 Strategic Plan¹⁹, 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 Success Path 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 Success Path Approach is well suited for *use in investigations to increase BSEE's capacity to identify and reduce unsafe conditions offshore*.

The Success Path 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 provide key guidance to industry. This would immediately reduce confusion and begin standardizing how risks are communicated and reported. The Success Path Approach provides an ideal mechanism

¹⁹ <https://www.bsee.gov/who-we-are/history/strategic-plan>

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 received²⁰. 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 AND OPERATIONAL 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 Success Path 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 drilling²¹, the Argonne Success Path 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 with a common understanding of which dependencies have been eliminated and whether any new dependencies have been added.

The Success Path Approach can also be applied to create a foundation for proactive decision making at both safety and operations. By enriching the Success Path for a particular offshore oil and gas system with statistical methods – similar to those used in probability risk assessment (PRA) methodology, one can incrementally build safety and operational health models that would allow analytical methods to estimate the probability of success in the future. These predictive models can help guide operations to anticipate operational scenarios in which the performance of a physical barrier can be adversely impacted. The implementation of these predictive safety health models can leverage existing machine learning and artificial intelligence (AI) technologies that are becoming mainstream in other industrial sectors.

Success Paths allow to plan for successful operations but when augmented with predictive models the challenges posed by the dynamic operational conditions can be reduce, and decision making to obtain operational efficiency while preserving required levels of safety can be achieved.

²⁰ See for example SPE/IADC-173153-MS. D. Fraser, Argonne, D. D. Moore, Marathon Oil, M. Vander Staak, Hess Corp., *A Barrier Analysis to Well Control Techniques*, March 17-19, 2015, London.

²¹ 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.

Finally, for this strategy to be successful, it is required that standard Success Path predictive safety health metrics to be established. This could be orchestrated through task groups from open industrial partnerships or relevant professional societies such as the Society of Petroleum Engineers (SPE).

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

The Argonne Success Path 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 Success Path Approach can also facilitate collaboration across the bureau on rulemaking and minimize barriers to productivity.

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

One of the main benefits of the Success Path 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 Success Path Approach provides a systematic, comprehensive and practical approach for managing safety risks for the offshore oil and gas industry. The approach enables effective risk management by focusing on success metrics that defines the performance of the physical barriers. The methodology establishes a common framework for stakeholders – regulator, operators and contractors – for the design, analysis and overall assessment of operational safety. 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.

The Success Path Approach uses a top-down design, which makes its implementation scalable in scope and depth. It can be deployed in existing systems or used as guidance for new systems, following a systems engineering approach. The method is practical; it avoids the implementation challenges of other well-known statistic-based methodologies whose applicability is bounded to industries with a well-established industrial data management infrastructure.

The Success Path Approach can help government agencies, energy companies, and other stakeholders build consensus on key safety risks; identify cost-effective risk mitigation measures; and establish enhanced methods for testing, inspection, and data-driven decision making. Finally, Success Paths can create safety performance models of the system that allow stakeholders to anticipate events whose probability of occurrence can diminish the existing level of success. This together with fostering relevant professional societies for the standard definition of key safety performance metrics for Success Path predictive models could become a catalyst for a breakthrough in operational safety in the oil and gas industry.

RECOMMENDATIONS

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

- Seek to expand risk-based thinking and application of Success Paths to support BSEE's oversight programs, including inspections, permitting, regulation, technology research, and standard development. The Success Path Approach facilitates collaboration, common understanding, effective dialogue, and sound input to support the development and implementation of risk-based regulation.
- Use these tools to identify gaps in regulations and standards, and facilitate identification of suitable remedial actions.
- Continue to apply the Success Path 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 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 to see how well it works in different areas with different types of stakeholders.
- Define, develop, and implement anticipatory safety health models based on Success Paths. This can be achieved with the open participation of all stakeholders. We recommend engaging relevant professional societies such as SPE and/or fostering joint industrial collaborations to help define and identify key predictive metrics for these safety health models. In addition, it is recommended to leverage the SPE BOP Performance Capability Maturity Model subcommittee (part of the Drilling Systems Automation Technology Section (DSATS) Committee) to leverage the continuous safety performance metrics they are defining as part of the goals of this group.
- 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 has added the most value. In this type of case, higher costs of quantification are usually justified by the quality of the ultimate quantitative decisions that result.

APPENDIX I

SUCCESS PATH PROTOCOLS AS A TOOL FOR RISK-INFORMED DECISION-MAKING

SUCCESS PATH PROTOCOL DEVELOPMENT

Building on early success with use of the Success Path Approach for coiled tubing applications, BSEE decided to work with Argonne to demonstrate the broader applicability of Success Paths as a tool that supports risk-informed decision-making across several of the bureau's oversight programs, including: risk-based inspection, permitting, and identification of potential gaps in regulation or standards. Argonne used the Success Path Approach to develop protocols for evaluating five systems:

- Cranes,
- Electrical systems,
- Compression systems,
- Production well safety systems, and
- Maintenance involving breaking containment.

The development of Success Path Protocols involved the following steps:

1. Draw a Success Path to succinctly reflect the overall system by focusing on key items required for its safety and effectiveness.
2. Evaluate available incident and component failure data and categorize the incidents and failures by mapping them onto appropriate areas in the Success Path. This step may require a revision of the Success Path to account a potentially overlooked part.
3. Evaluate available BSEE enforcement tools, such as Potential Incidents of Noncompliance (PINCs), and map them onto the Success Path. This will indicate the areas of the system that are directly discussed or addressed in BSEE regulations or referenced industry standards, and are actively evaluated with. Inspection and regulatory the tools available to BSEE.
4. Determine areas of significant risk by determining areas on the Success Path that have a significant number of incidents associated with them but may not be specifically identified in the regulations or standards.
5. Based on the determination of elevated- or high-risk areas, develop conversation topics/questions to help guide an open-ended safety discussion during inspections, permit evaluations, rulemaking, and other similar applications.

The tools described above have been developed to provide the party utilizing them (BSEE or industry) the ability to evaluate the safety of a given system. They provide access to key variables, such as context and the influence one subsystem has on another, by modeling the whole system in a Success Path. They also show the historically risk-significant areas potentially in need of heightened attention.

The following subsections describe the Success Paths developed for each of the five systems named above, with incident and PINC data mapped where available. The figures demonstrating examples of Success Paths developed throughout this effort are meant to illustrate the breadth of applications of this approach.

CRANES

As an example of how Success Paths can be used to assess the safety of a critical piece of equipment, Argonne worked with BSEE to create a Success Path Protocol for safe crane operation. Figure I-1 depicts the high-level processes included in the crane Success Path. As illustrated by the boxes that connect to an *AND* gate, safe utilization of a crane requires proper specification, design, construction, operation, inspection, and maintenance.

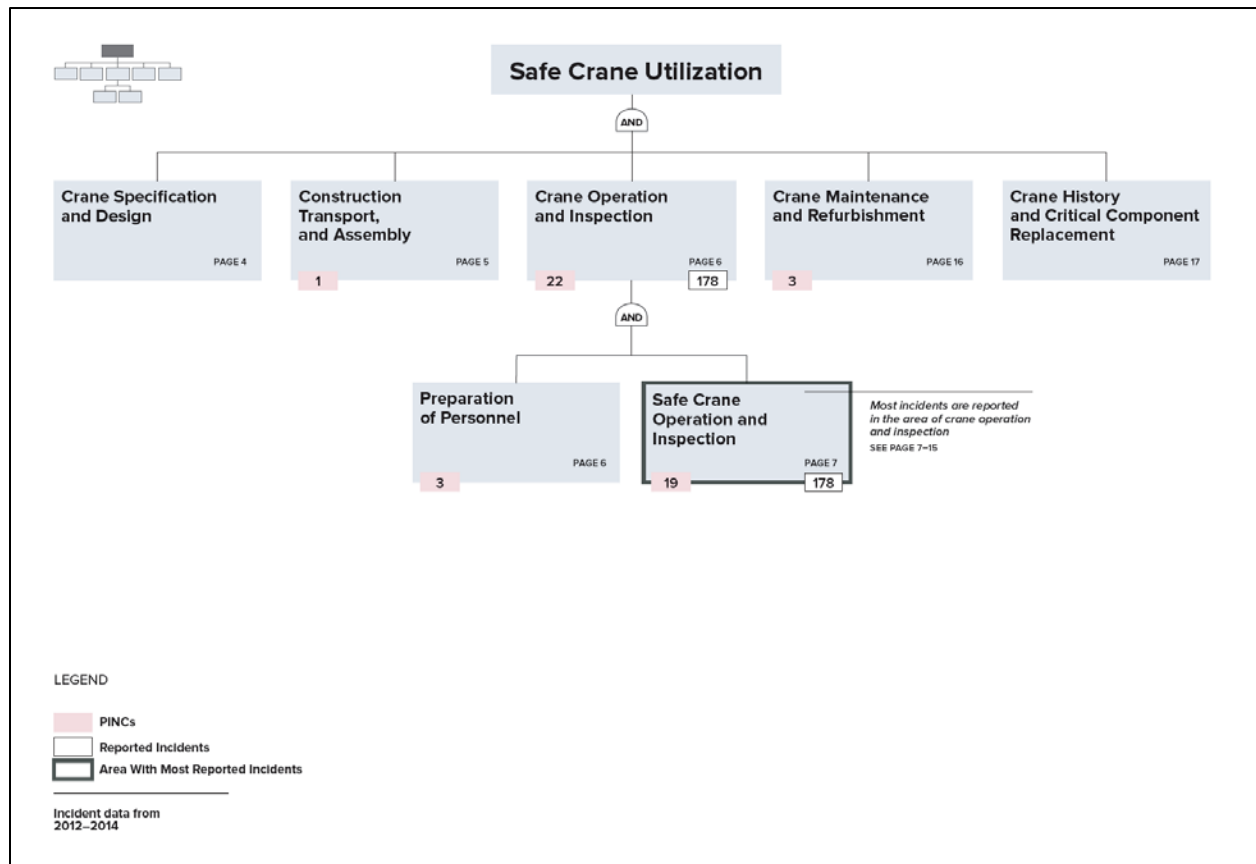


Figure I-1: High-Level Success Path for Safe Crane Utilization

BSEE publishes a PINC checklist of items that the bureau inspects to pursue safe operations on the Outer Continental Shelf.²² This list of inspection items is derived from all applicable BSEE regulations for safety and environmental standards.

Figure I-2 provides a Success Path for the operation and inspection component of safe crane utilization. For each component in this Success Path, Argonne used a circle to indicate the

²² See <https://www.bsee.gov/what-we-do/offshore-regulatory-programs/offshore-safety-improvement/potential-incident-of-noncompliance-pinc>.

associated number of component failure incidents, and a box to specify relevant PINCs, API standards, and recommended practice codes.

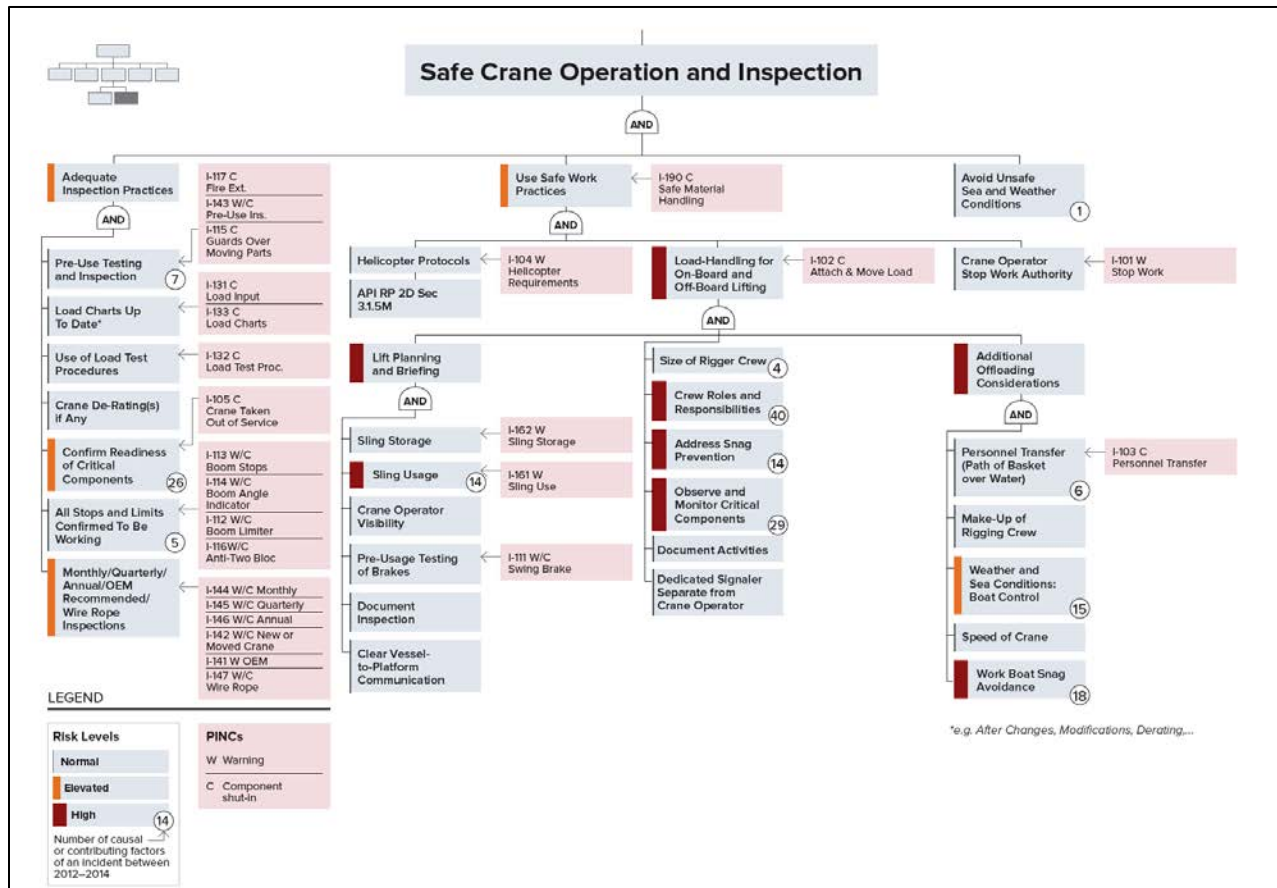


Figure I-2: Success Path for Safe Crane Operation and Inspection

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 operators during an inspection. These questions are open-ended and designed to lead to other questions, depending on the answers received from the operator. This effort focuses on overall strategy to make inspection programs more effective without additional regulation.

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

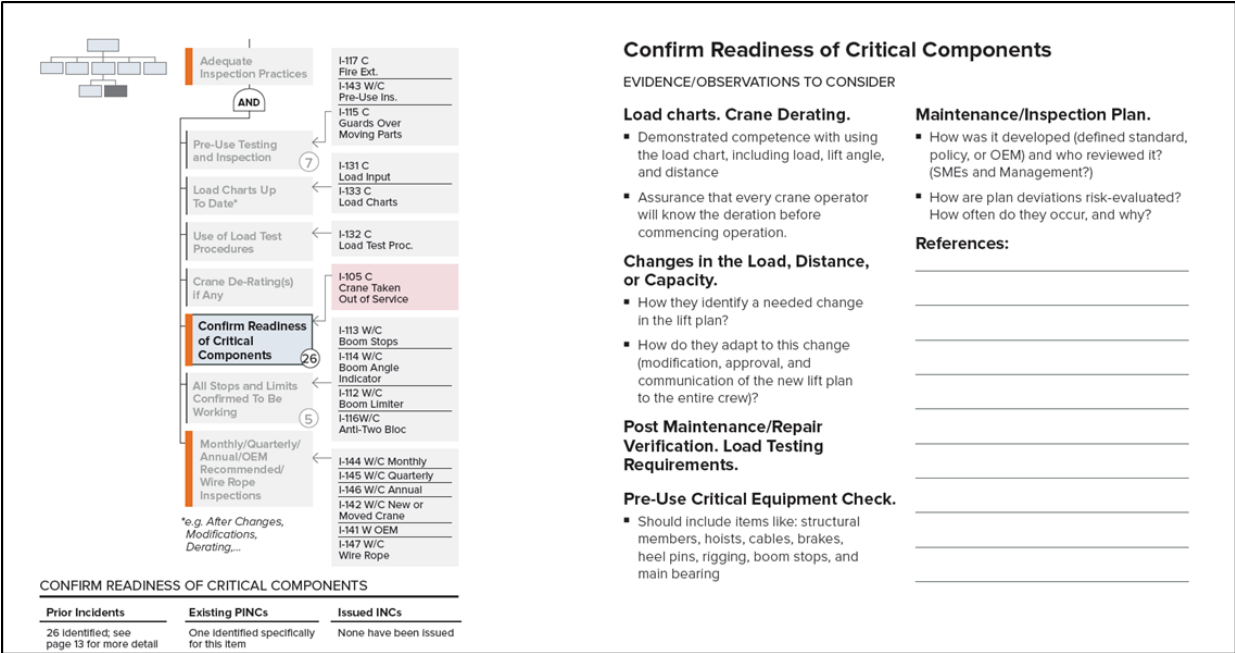


Figure I-3: Success Path for Inspections Component of Safe Crane Utilization

Confirm Readiness of Critical Components

EVIDENCE/OBSERVATIONS TO CONSIDER

Load charts. Crane Derating.

- Demonstrated competence with using the load chart, including load, lift angle, and distance
- Assurance that every crane operator will know the deration before commencing operation.

Maintenance/Inspection Plan.

- How was it developed (defined standard, policy, or OEM) and who reviewed it? (SMEs and Management?)
- How are plan deviations risk-evaluated? How often do they occur, and why?

Changes in the Load, Distance, or Capacity.

- How they identify a needed change in the lift plan?
- How do they adapt to this change (modification, approval, and communication of the new lift plan to the entire crew)?

References:

Post Maintenance/Repair Verification. Load Testing Requirements.

Pre-Use Critical Equipment Check.

- Should include items like: structural members, hoists, cables, brakes, heel pins, rigging, boom stops, and main bearing

ELECTRICAL SYSTEMS

Argonne worked with BSEE electrical engineers to design a Success Path Protocol to show requirements for a safe and sufficient electrical system on production facilities. This is an example of how Success Paths can be used to assess the safety integrity of an underlying critical support system. Figure I-4 illustrates how a safe electrical system can be represented by sufficient supply of primary electrical power and by having the ability to power safety-critical electrical systems with backup power.

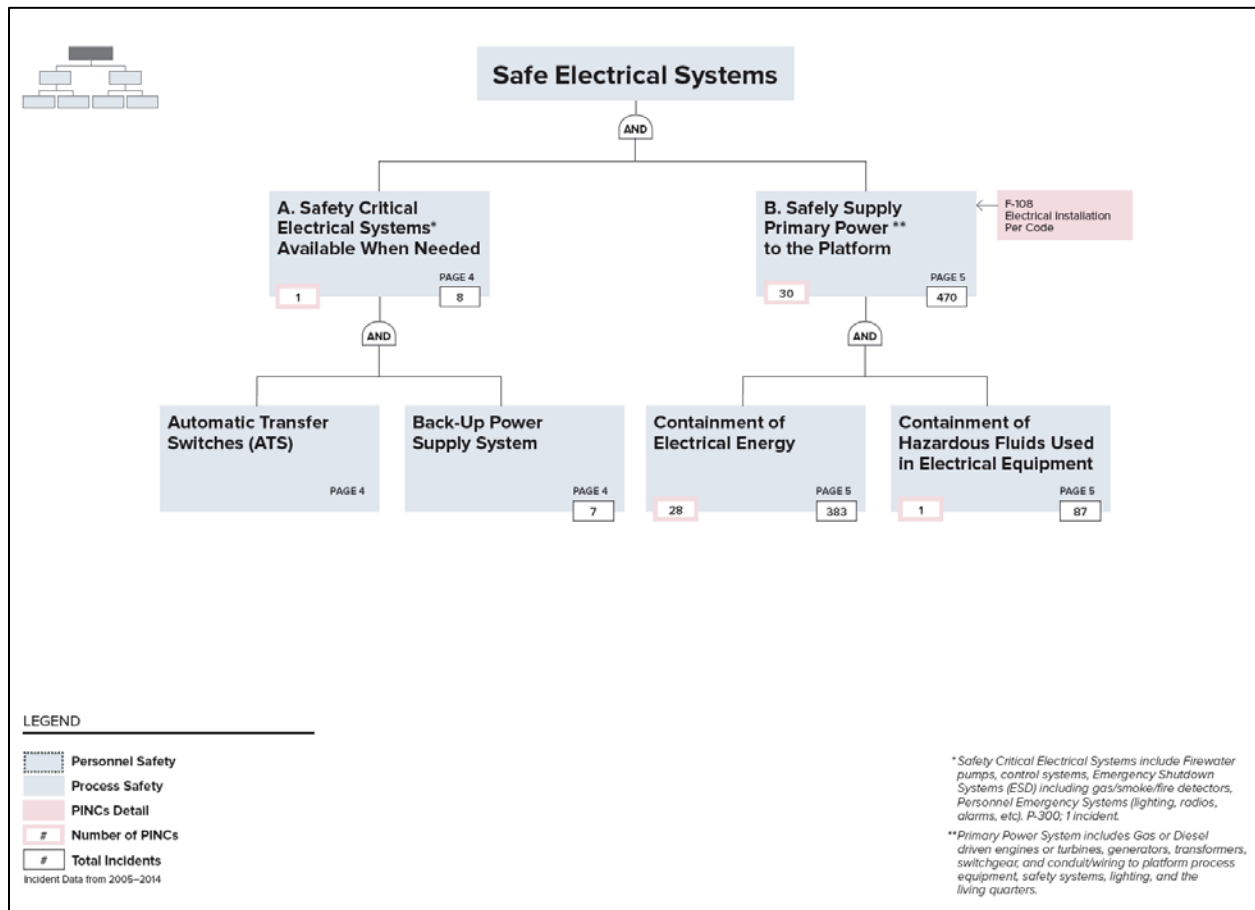


Figure I-4: Electrical Systems Success Path

As shown in Figure I-4, the left side of the Success Path calls for the availability of safety-critical systems. This is achieved by ensuring appropriate transfer from main power supply to the backup power supply, and the availability of the backup power supply itself. Despite its importance to the safety of the overall system, it is noteworthy that very few PINCs have been found for these systems. In addition, very few incidents have been recorded.

The right side of the Success Path in Figure I-4 can be expanded to show the requirements for containment of electrical energy and containment of hazardous fluids used in electrical equipment, as demonstrated in Figure I-5.

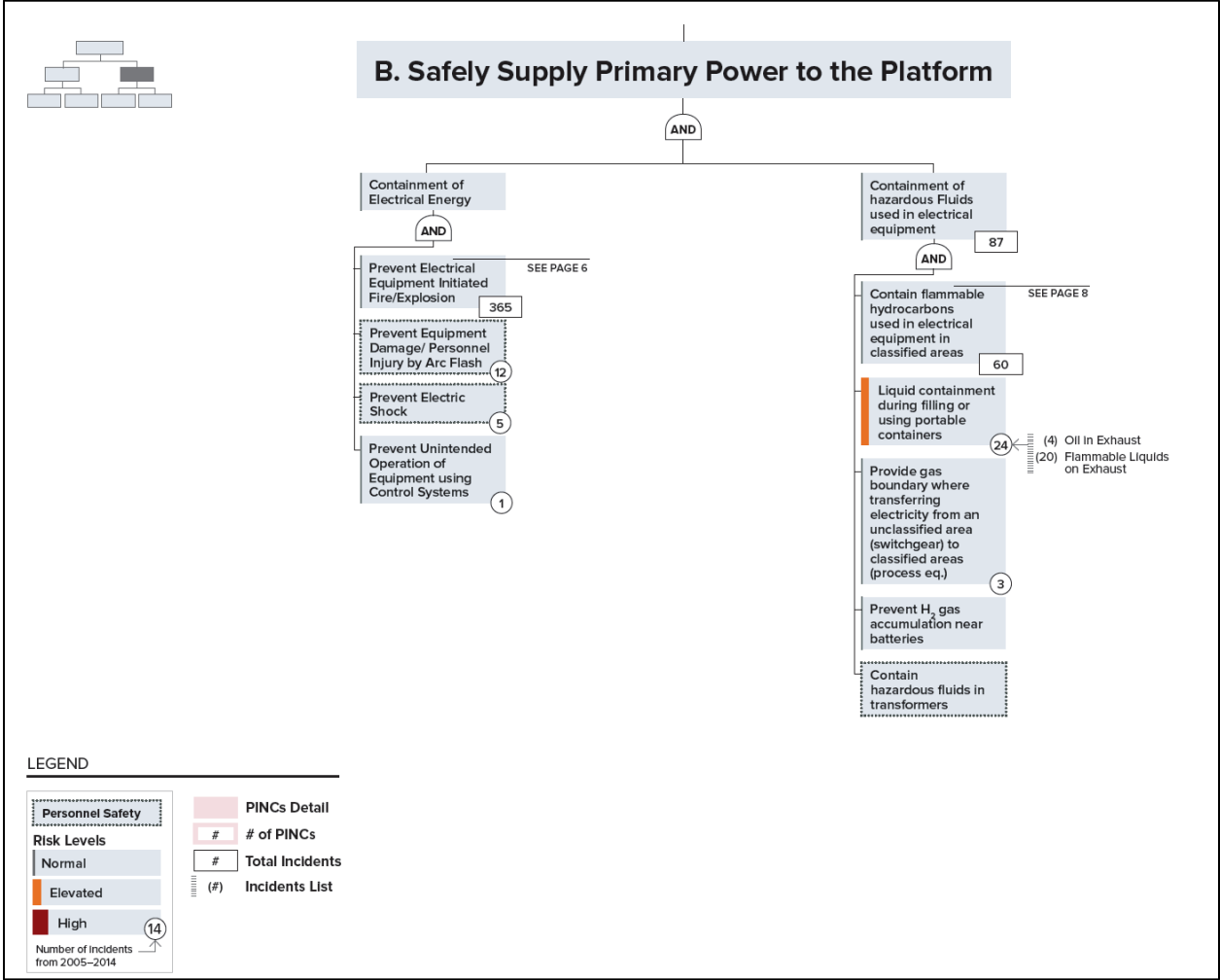


Figure I-5: Safe Primary Power Supply Success Path

One of the main concerns in this area is the prevention of electrical equipment-initiated fires and explosions. Therefore, this area is further expanded to show the safety-critical Success Path (Figure I-6 and Figure I-7).

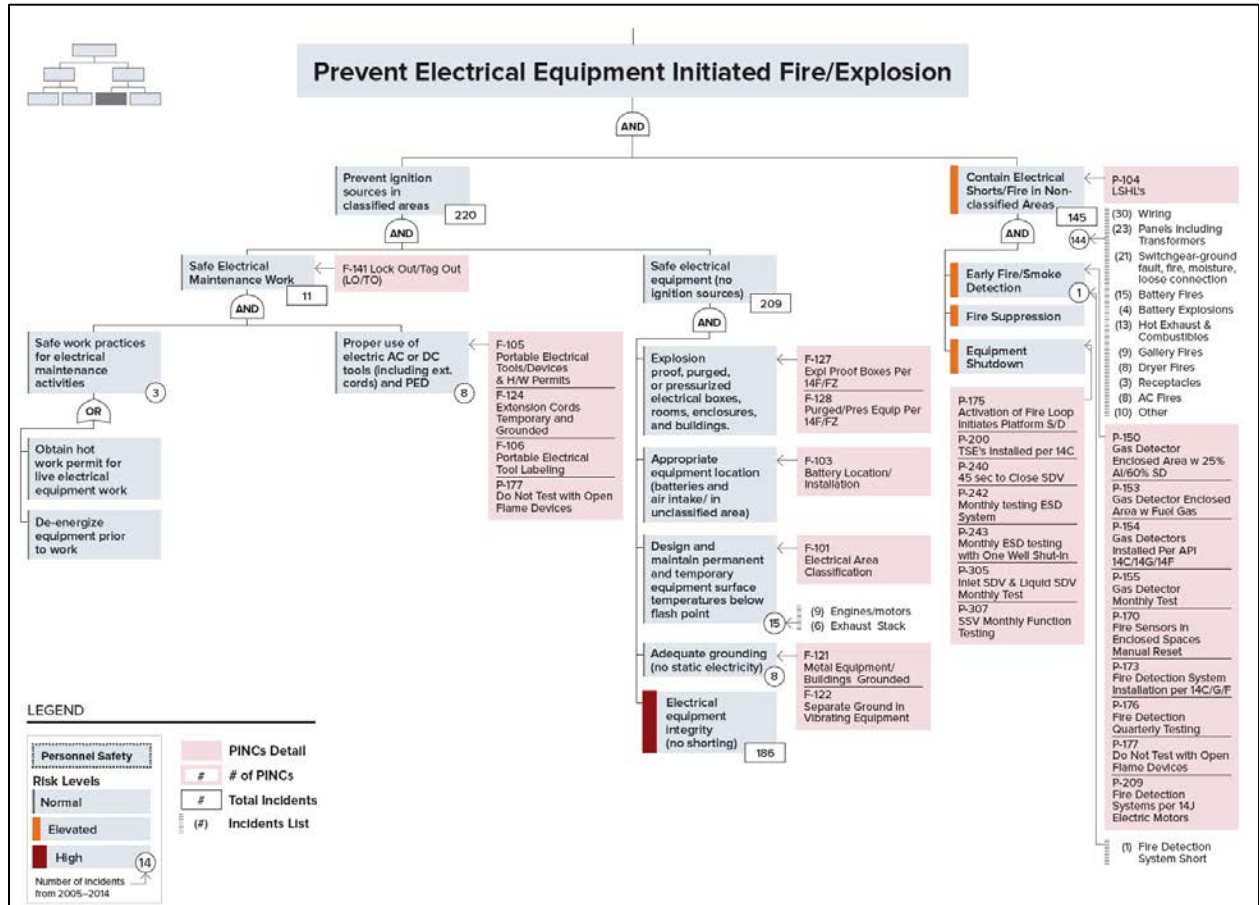


Figure I-6: Prevention of Electrical Equipment-Initiated Fire/Explosion Success Path

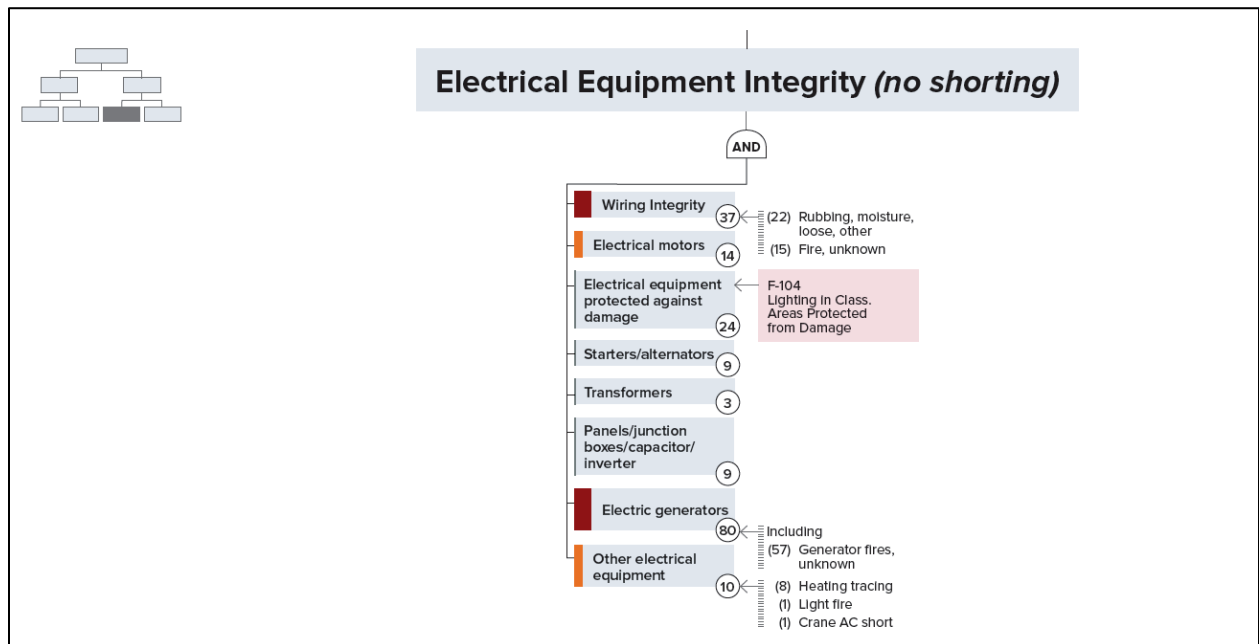


Figure I-7: Electrical Equipment Integrity Success Path

COMPRESSION SYSTEMS

Similar to the Cranes Success Path Protocol, Argonne created a Success Path for compression systems on production facilities, and mapped associated incident and PINC data. The high-level Success Path in Figure I-8 shows that the main forces behind a safe gas compression operation is the prevention of hydrocarbon ignition by containing hydrocarbons and eliminating ignition sources.

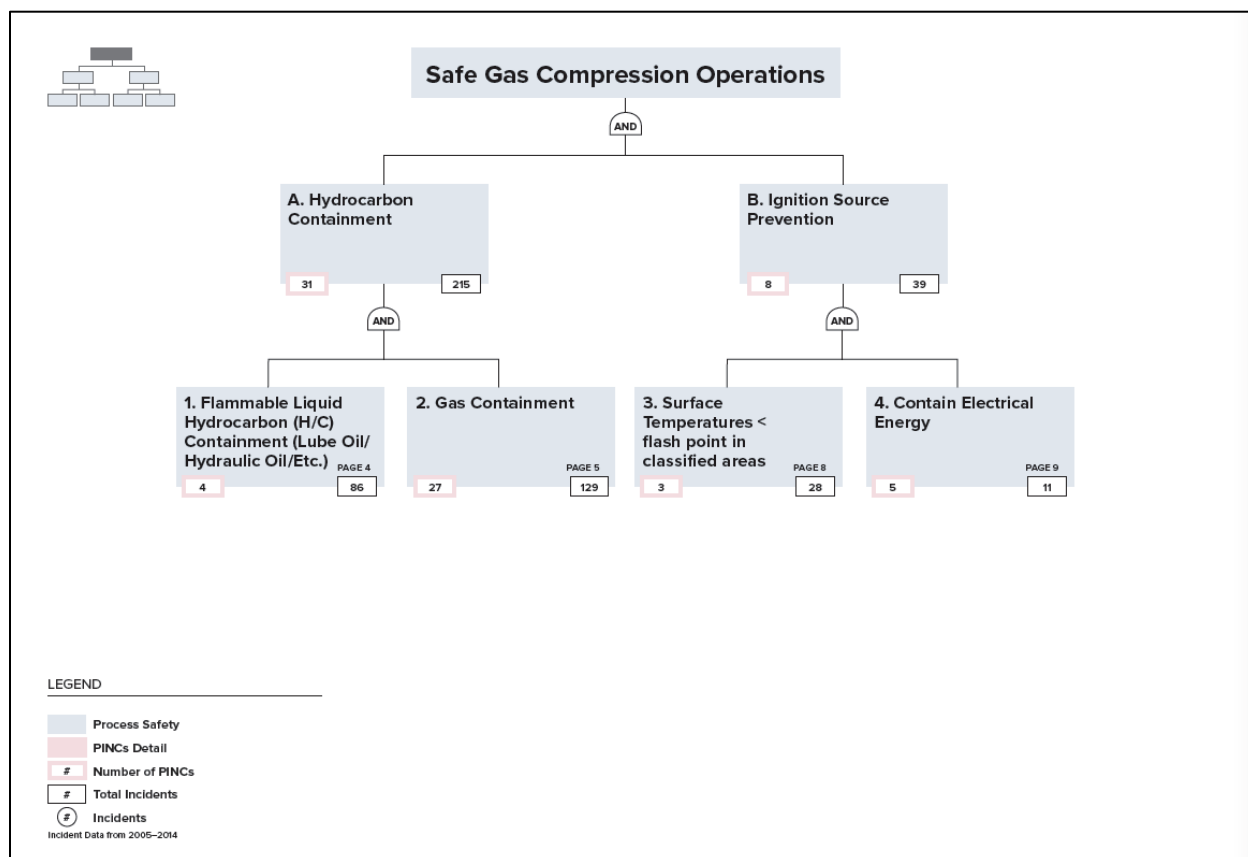


Figure I-8: Compression

These two parts in the Success Path break down further into containment liquid and gas hydrocarbons, maintaining surface temperatures below flash point, and containing electrical energy to avoid ignition sources. Each part offers additional insight by breaking down the Success Path further. For example, the Flammable Liquid Hydrocarbon Containment and Gas Containment branches expand to show the equipment and actions that are necessary to ensure these success states (Figure I-9 and Figure I-10, respectively).

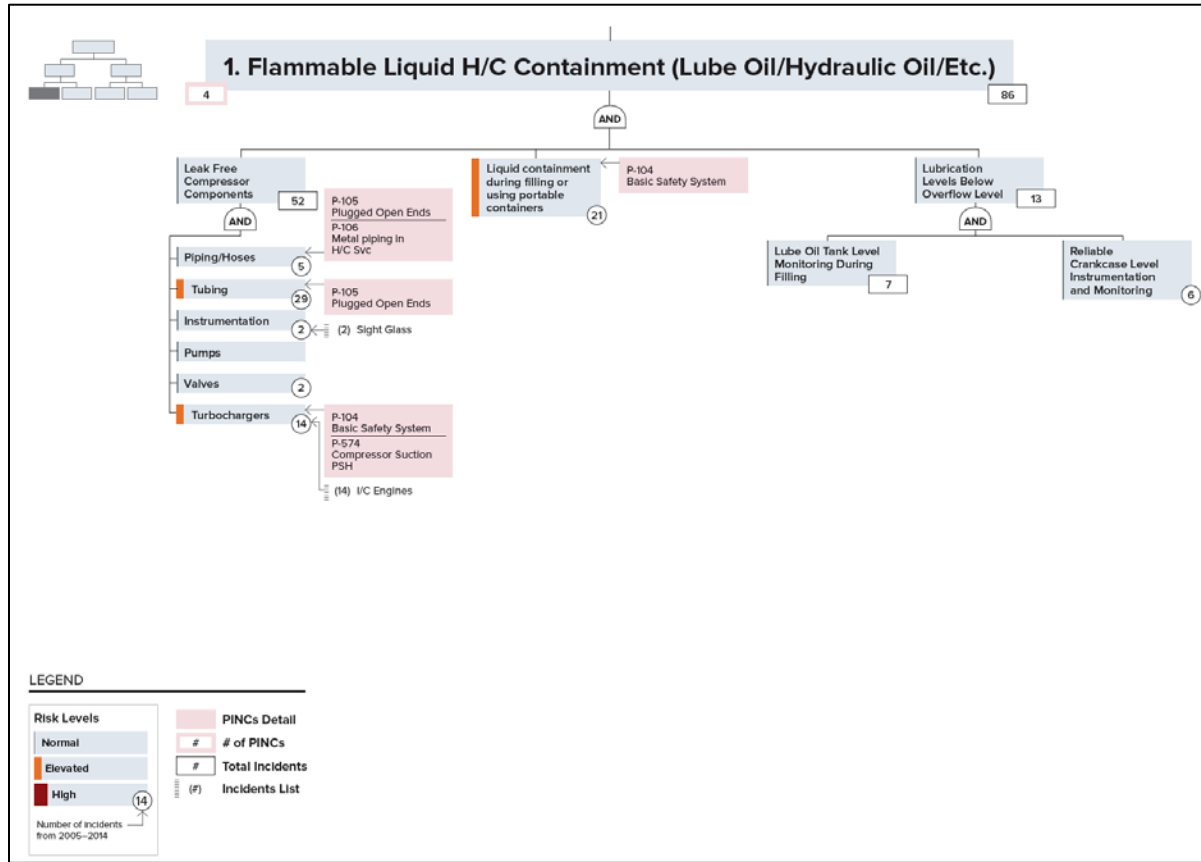


Figure I-9: Liquid Hydrocarbons

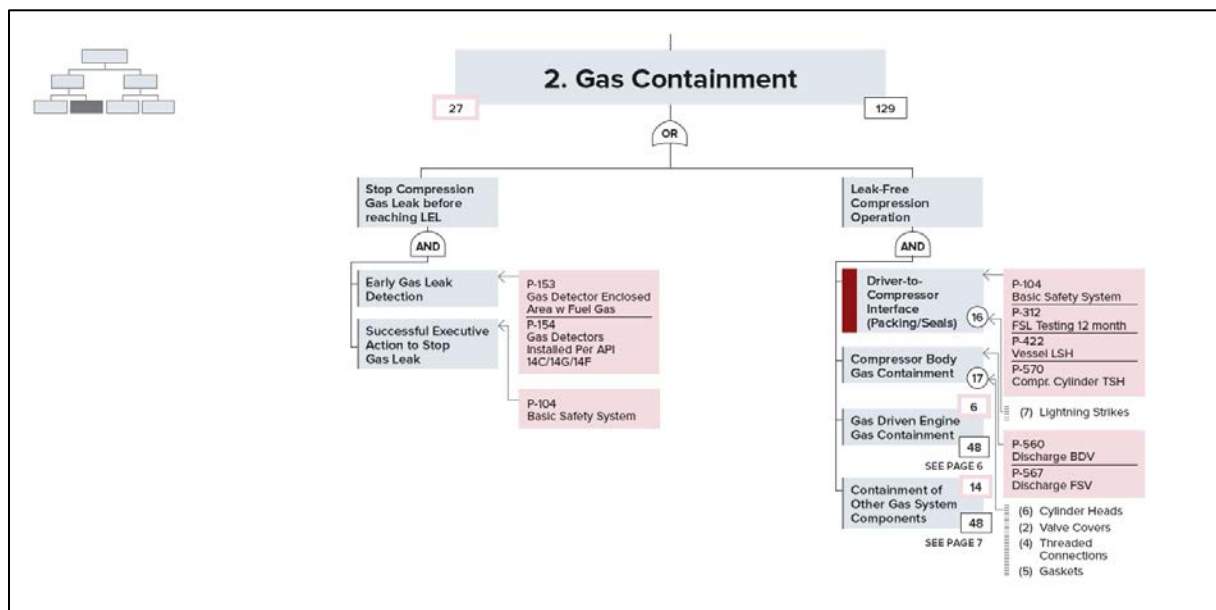


Figure I-10: Gas Containment

The other two branches of the Safe Gas Compression Operations Success Path expand to show the requirements to maintain surface temperatures below flash point and contain electrical energy, as illustrated in Figure I- 11.

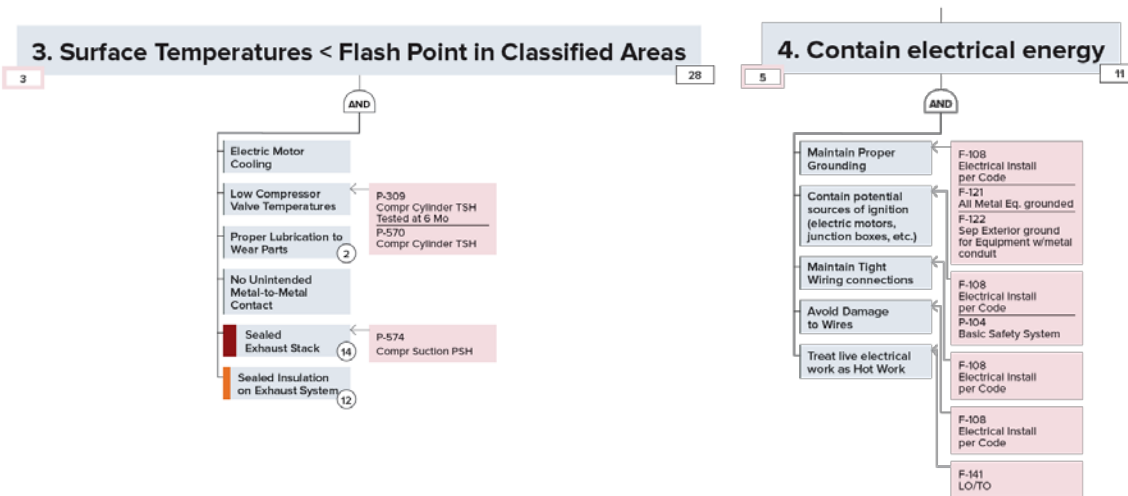


Figure I- 11: Prevention of Ignition Sources from Hot Surfaces and Electrical Energy

PRODUCTION WELL SAFETY SYSTEMS

The Production Well Safety System Success Path was developed with the physical barriers in mind. These are the physical barriers that prevent hazardous chemical exposure to personnel, contain hazardous fluids to the process equipment, and stop flow from the well in an emergency situation or for planned work. Figure I-12 outlines this process in a high-level Success Path.

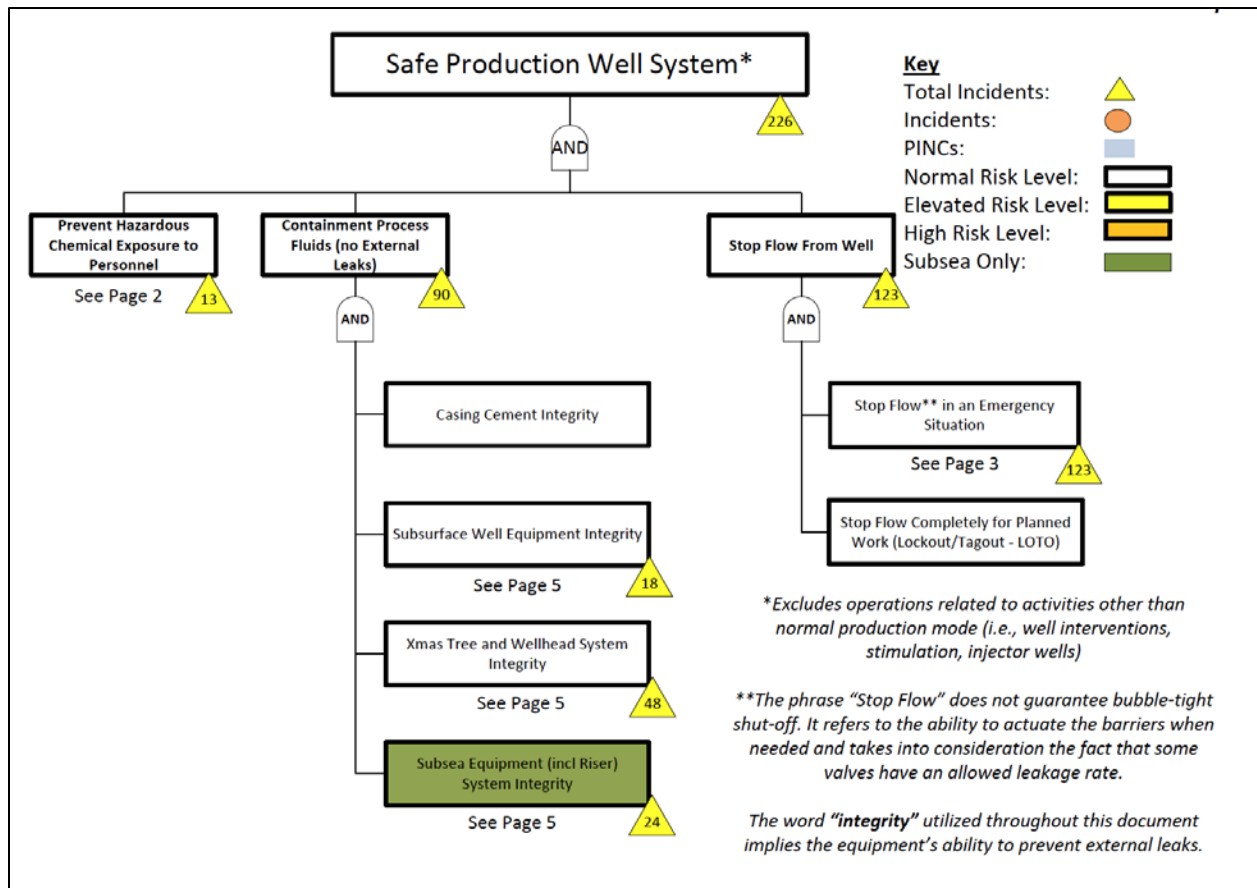


Figure I-12: Safe Production Well Success Path

The physical barriers required to stop flow in an emergency situation are comprised of an array of valves in the production process that must be able to close and seal (with an allowed leakage rate, in some cases) when called upon. The Success Path in Figure I-13 illustrates this requirement.

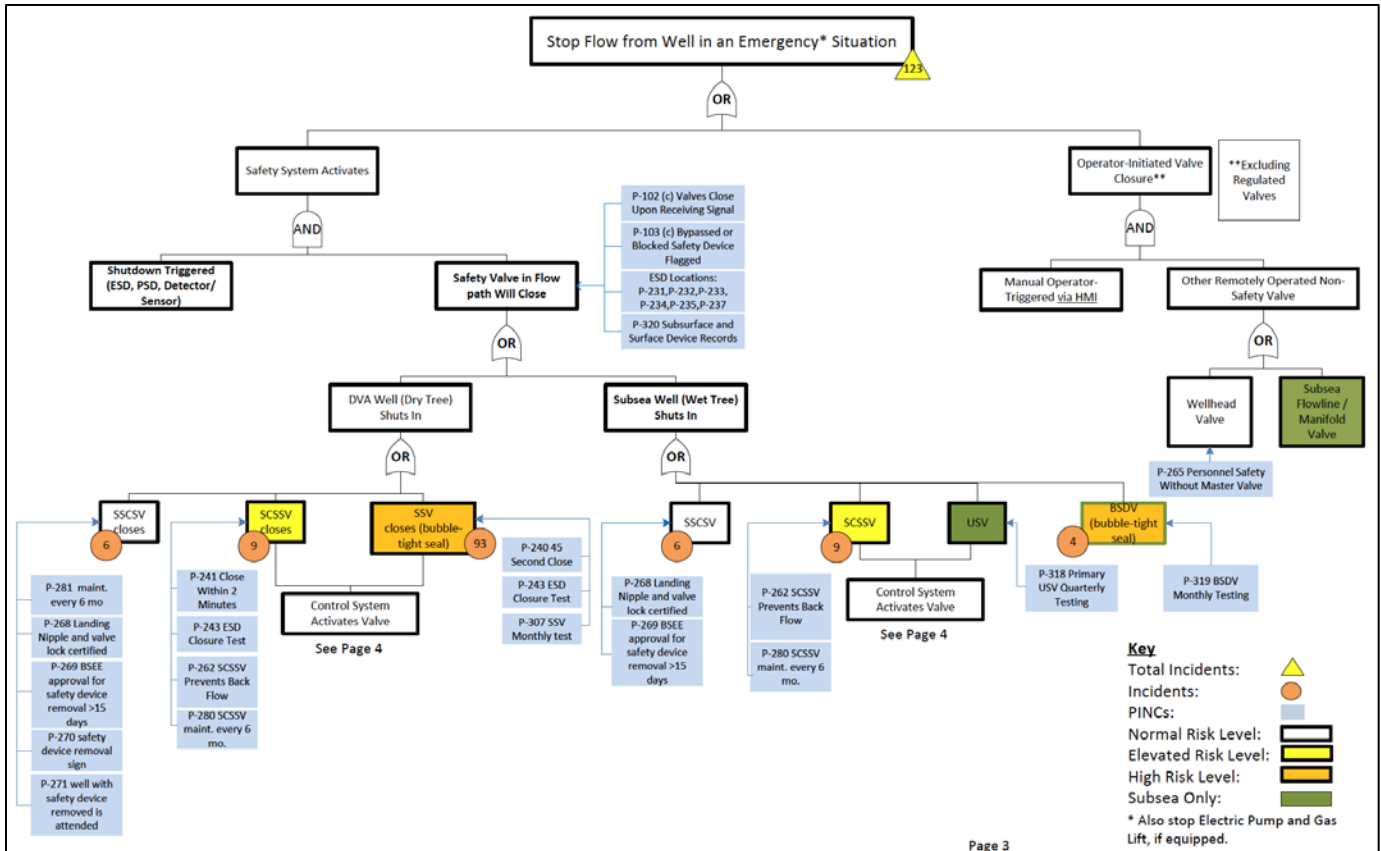


Figure I-13: Success Path to Stop Flow from the Well in an Emergency

MAINTENANCE INVOLVING BREAKING CONTAINMENT

The Success Path Approach has been applied to the process of purposefully breaking production system containment for maintenance, repair, testing, and other reasons. In this case, the high level Success Path in Figure I-14 shows the sequential process of planning to break containment for maintenance, performing the intended maintenance activity, sealing, verifying the containment after maintenance, and reinstating the equipment. Unlike the Success Paths described above, the one for this process focuses mainly on performing the planned activities in a safe manner such that the safety of the overall system is not jeopardized as a result. The four steps in this high-level Success Path are further broken down to show the steps necessary to carry each of them out. For example, the Success Path in Figure I-15 shows the process of performing equipment start-up or reinstatement.

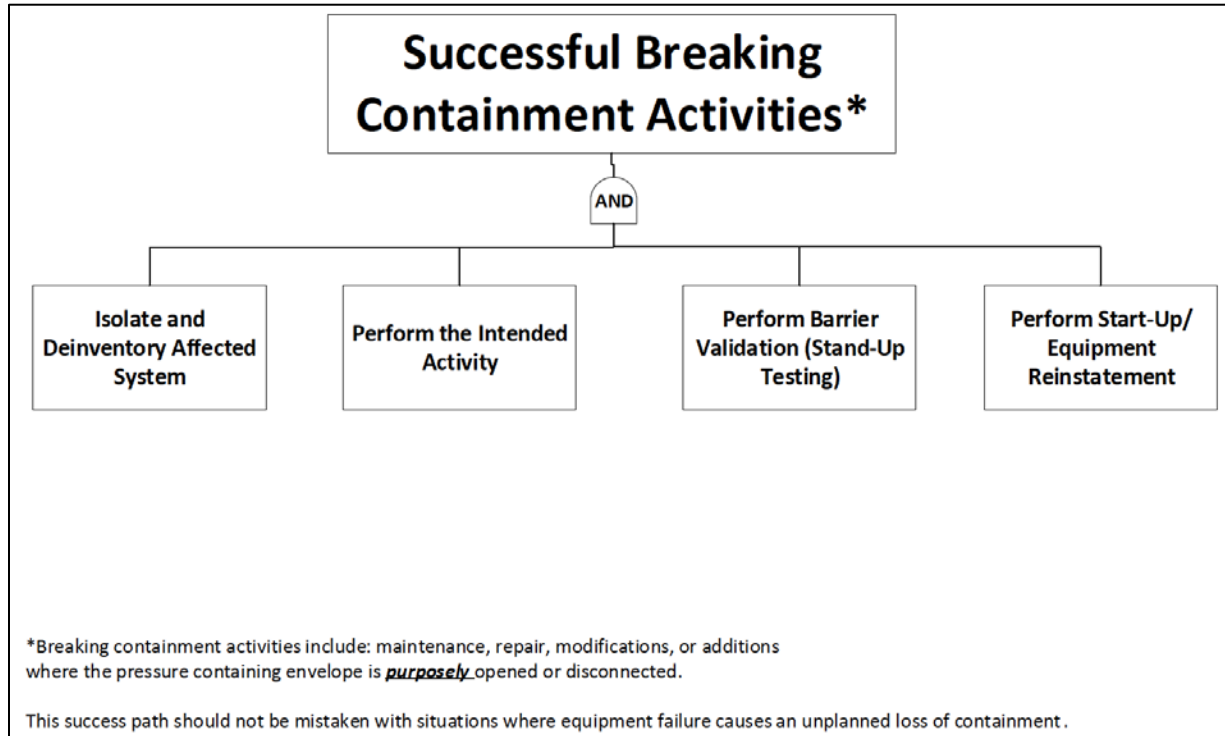


Figure I-14: Success Path for Breaking Containment Activities

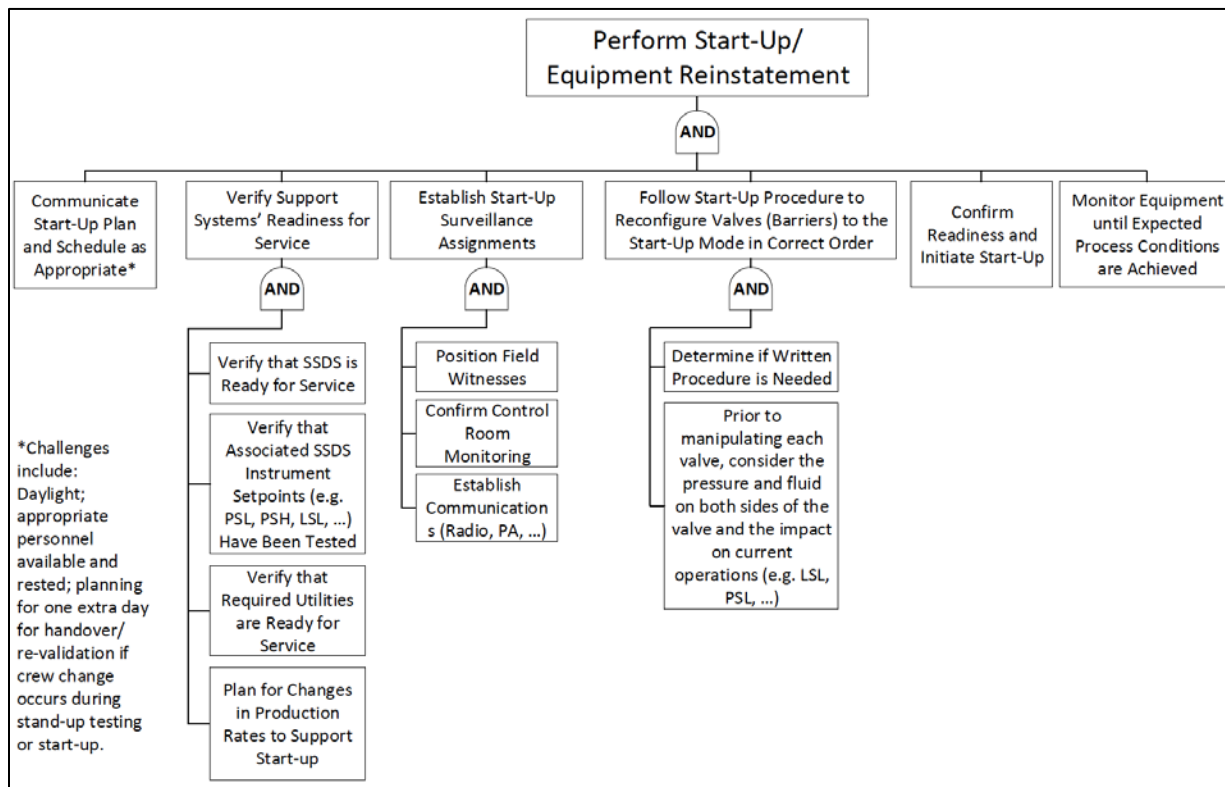


Figure I-15: Success Path for Performing Equipment Start-up/Reinstatement











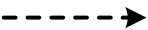
APPENDIX II

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

SUCCESS PATH NOTATION

In the Argonne Success Path 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 II-1.

Table II-1: Success Path Diagram Notation

Symbol	Name	Description
	<i>System, Group, Function or Base Event</i>	<i>Name of a system, group of functions, intermediate steps, or base event</i>
	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

The following subsections provide examples of Success Paths developed by Argonne.

DRILLING SUCCESS PATHS

When applying the Success Path 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 II-1, the FOSV Success Path requires an extensive amount of human action.

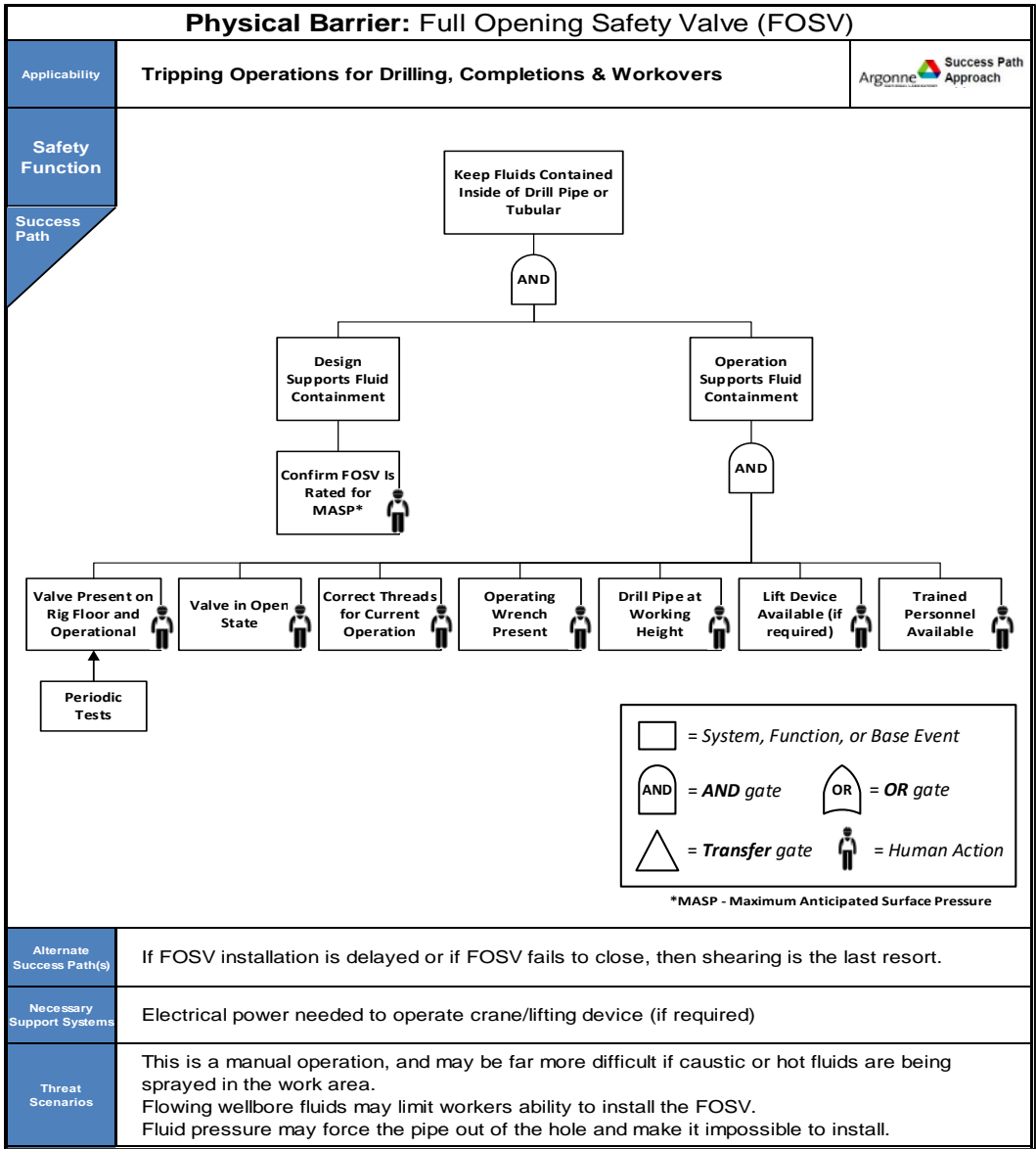


Figure II-1: Success Path for a Full Opening Safety Valve

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 fracture gradient of the formation. This is the critical safety function of the barrier. The Argonne Success Path Approach was applied to evaluate and compare pressure control techniques for three scenarios of drilling operation. Success Paths shown in Figure II-2, Figure II-3, and Figure II-4 illustrate vital steps identified for sustaining the fluid pressure barrier under each scenario.

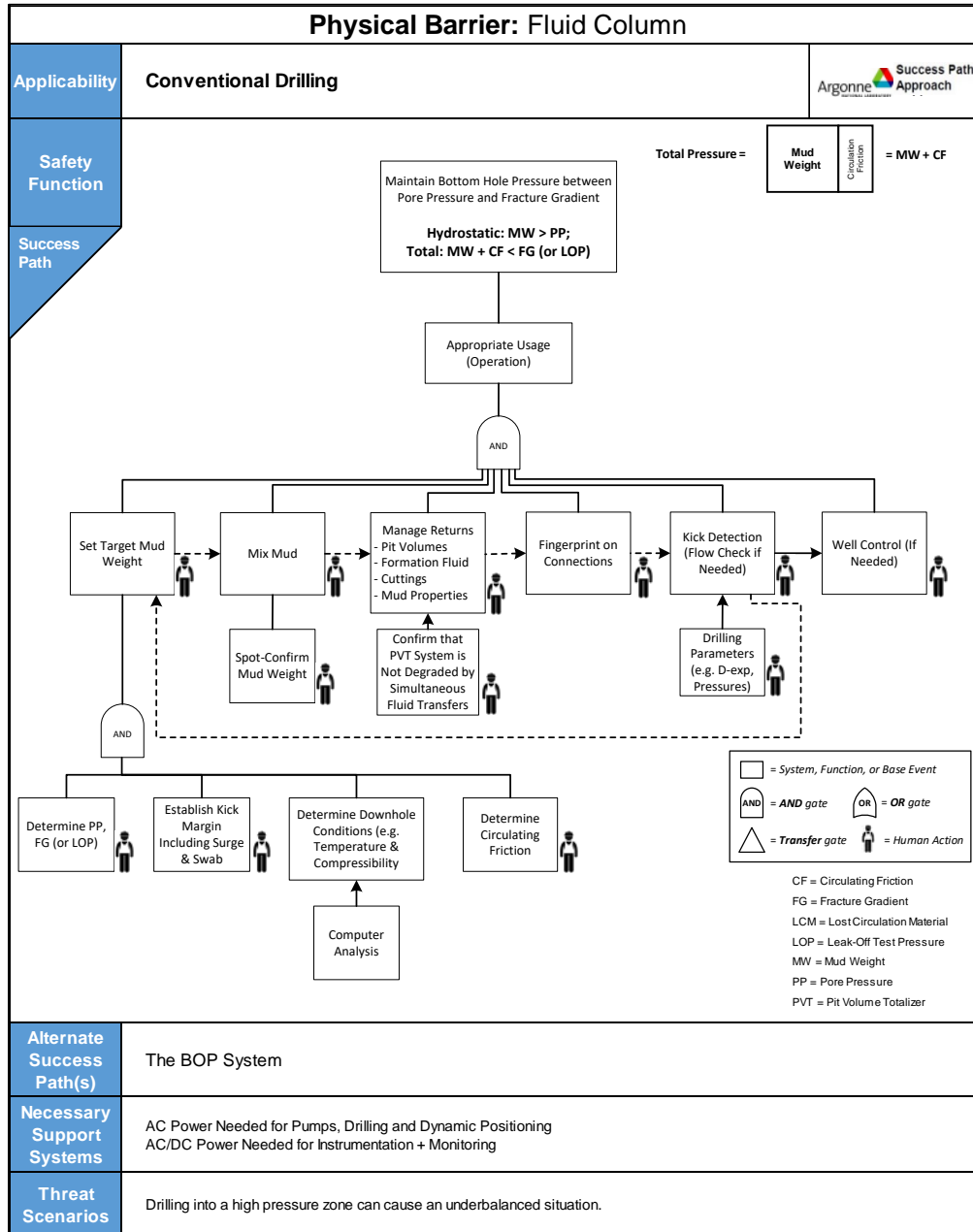


Figure II-2: Success Path for a Fluid Column in Conventional Drilling

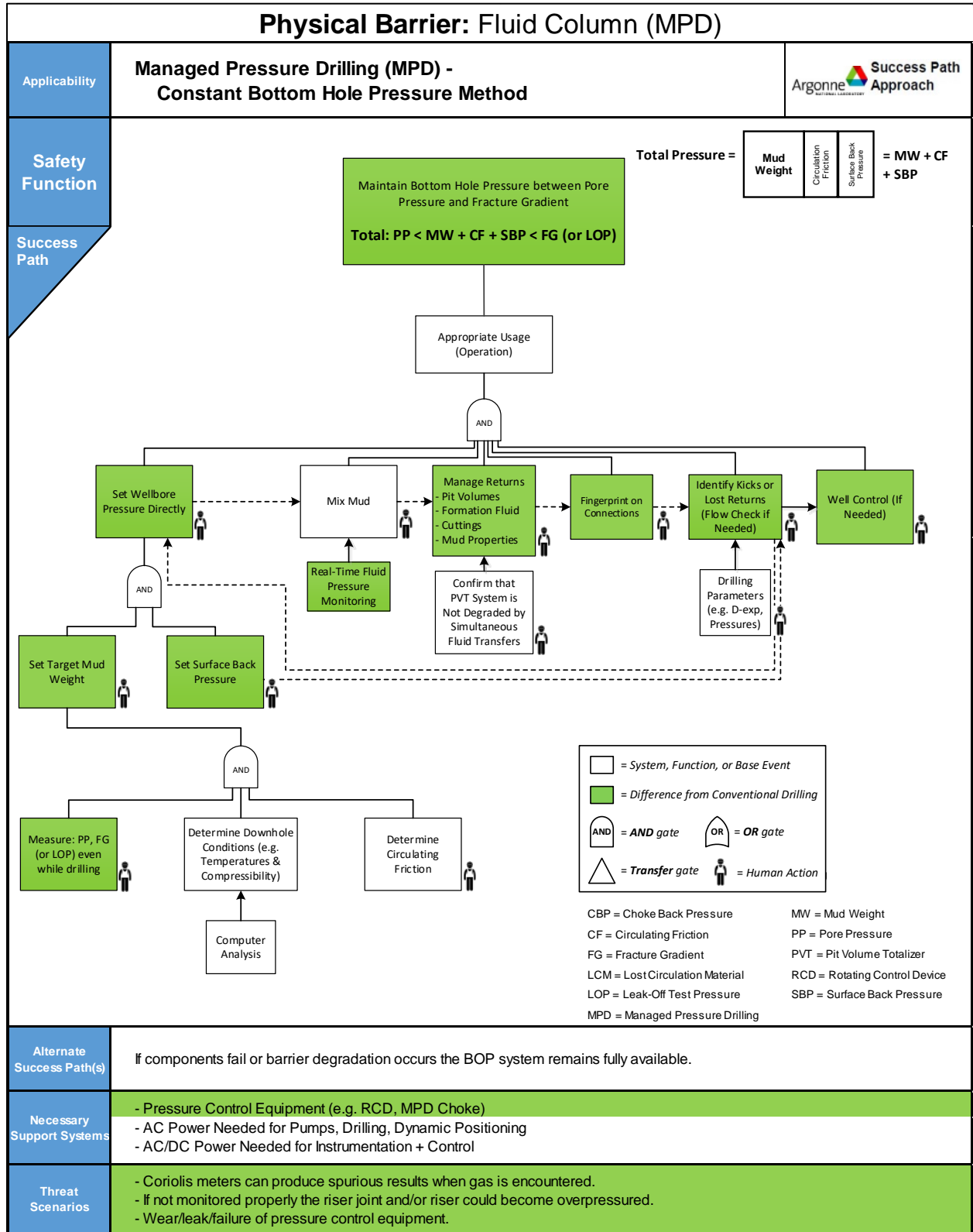


Figure II-3: Success Path for a Fluid Column in Managed Pressure Drilling

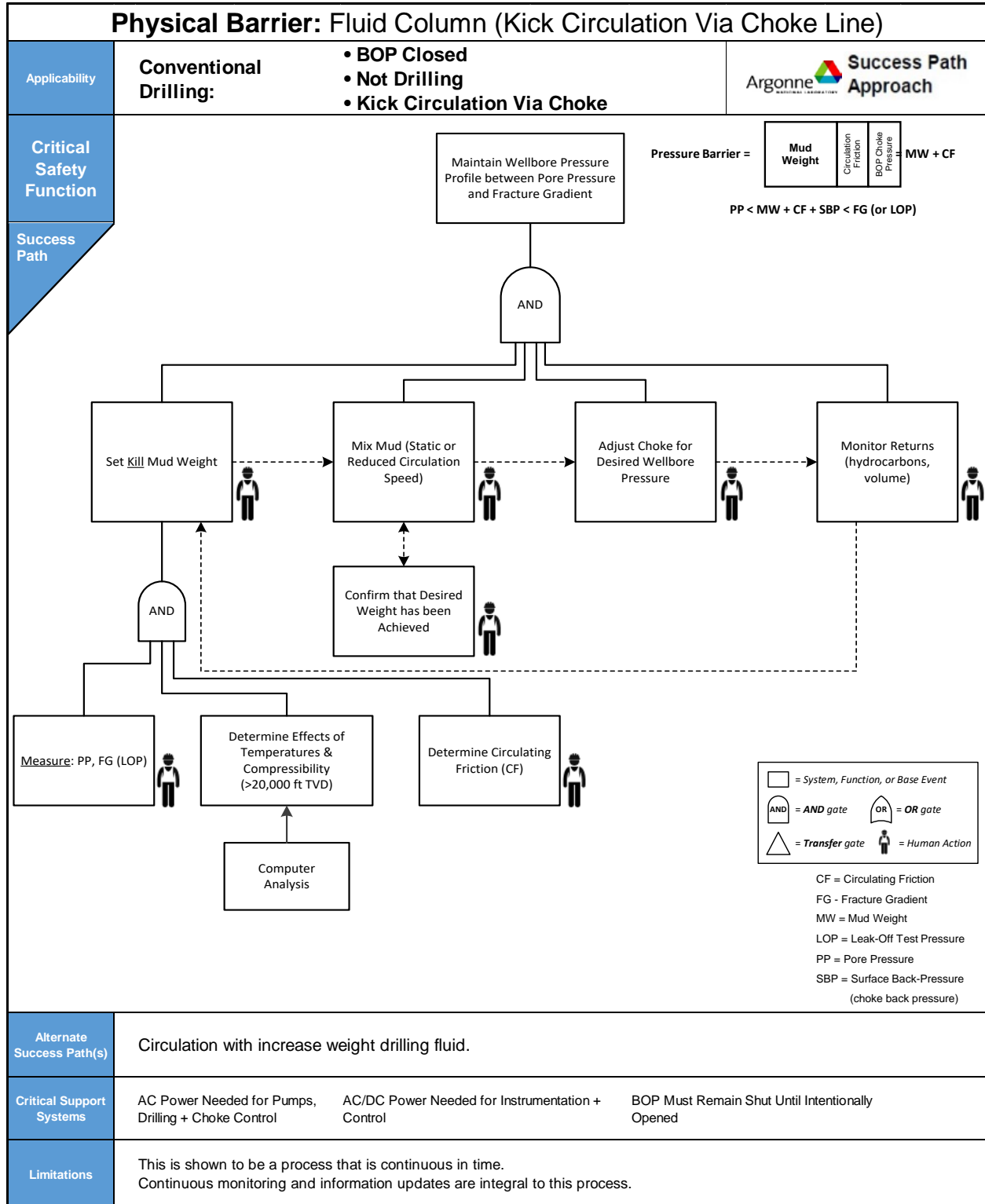


Figure II-4: Success Path for a Fluid Column in Kick Circulation via Choke Line

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

	Conventional Drilling	Kick Circulation via Secondary Barrier (BOP) Choke Line	Managed Pressure Drilling Through MPD Choke																																										
Primary Barrier:																																													
Safety Function(s):	MW + CF < FG or LOT; MW > PP	PP < MW + CF + SBP < FG or LOT	PP < MW + CF + SBP < FG or LOT; Protect against sudden pressure loss. Protect riser from over-pressurization;																																										
Secondary Barrier(s):	BOP; Redundant BOP Components	Redundant BOP Components	Redundant MPD components; Riser Top Annular; BOP; Redundant BOP Components																																										
Primary Barrier Success Path:	<table border="1"> <thead> <tr> <th></th> <th>Variance</th> </tr> </thead> <tbody> <tr> <td>Estimate PP, FG, LOT, CF; Infrequent measurements</td> <td>±0.2 - 2.0 ppg</td> </tr> <tr> <td>Adjust for temperature and compressibility in deep wells</td> <td>MW=±0.5 ppg</td> </tr> <tr> <td>Select mud weight based on estimates of PP and FG</td> <td>-</td> </tr> <tr> <td>Mix mud while circulating at full rate</td> <td>MW=±0.1 ppg</td> </tr> <tr> <td>Carefully manage pump rate and pipe speed to minimize swab and surge pressures</td> <td>ΔP = CF ± P_{surge/swab}</td> </tr> <tr> <td>Identify kicks or lost returns; Kick Response = Shut-in</td> <td>KDV > 10 bbl; KRT > 2 mins</td> </tr> </tbody> </table>		Variance	Estimate PP, FG, LOT, CF; Infrequent measurements	±0.2 - 2.0 ppg	Adjust for temperature and compressibility in deep wells	MW=±0.5 ppg	Select mud weight based on estimates of PP and FG	-	Mix mud while circulating at full rate	MW=±0.1 ppg	Carefully manage pump rate and pipe speed to minimize swab and surge pressures	ΔP = CF ± P _{surge/swab}	Identify kicks or lost returns; Kick Response = Shut-in	KDV > 10 bbl; KRT > 2 mins	<table border="1"> <thead> <tr> <th></th> <th>Variance</th> </tr> </thead> <tbody> <tr> <td>Measure PP, LOT, CF</td> <td>±0.1 ppg</td> </tr> <tr> <td>Adjust for temperature and rheology in deep wells</td> <td>MW=±0.5 ppg</td> </tr> <tr> <td>Select mud weight based on measured PP and FG at casing shoe</td> <td>-</td> </tr> <tr> <td>Mix mud while circulating at reduced rate</td> <td>MW=±0.1 ppg</td> </tr> <tr> <td>Adjust choke to maintain desired wellbore pressure</td> <td>ΔP = ±50 psi</td> </tr> <tr> <td>Identify kicks or lost returns; Secondary Kick Response = SBP</td> <td>KRT < 30 sec.</td> </tr> </tbody> </table>		Variance	Measure PP, LOT, CF	±0.1 ppg	Adjust for temperature and rheology in deep wells	MW=±0.5 ppg	Select mud weight based on measured PP and FG at casing shoe	-	Mix mud while circulating at reduced rate	MW=±0.1 ppg	Adjust choke to maintain desired wellbore pressure	ΔP = ±50 psi	Identify kicks or lost returns; Secondary Kick Response = SBP	KRT < 30 sec.	<table border="1"> <thead> <tr> <th></th> <th>Variance</th> </tr> </thead> <tbody> <tr> <td>Measure PP, FG, LOT, CF</td> <td>±0.1 ppg</td> </tr> <tr> <td>Adjust for temperature and rheology in deep wells</td> <td>MW=±0.5 ppg</td> </tr> <tr> <td>Select mud weight based on measured FIT at several points in the well and estimated or measured PP</td> <td>-</td> </tr> <tr> <td>Mix mud while circulating at full rate</td> <td>MW=±0.0 ppg</td> </tr> <tr> <td>Adjust choke to maintain desired wellbore pressure</td> <td>ΔP = ±50 psi</td> </tr> <tr> <td>Identify kicks or lost returns; adjust SBP for either</td> <td>KDV < 2 bbl; KRT < 30 sec.</td> </tr> </tbody> </table>		Variance	Measure PP, FG, LOT, CF	±0.1 ppg	Adjust for temperature and rheology in deep wells	MW=±0.5 ppg	Select mud weight based on measured FIT at several points in the well and estimated or measured PP	-	Mix mud while circulating at full rate	MW=±0.0 ppg	Adjust choke to maintain desired wellbore pressure	ΔP = ±50 psi	Identify kicks or lost returns; adjust SBP for either	KDV < 2 bbl; KRT < 30 sec.
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Figure II-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 II-6 shows a Success Path for use of choke and lines to maintain bottom-hole pressure, and the Success Path in Figure II-7 illustrates required actions when the RCD to provide a seal between the drill-string and annulus.

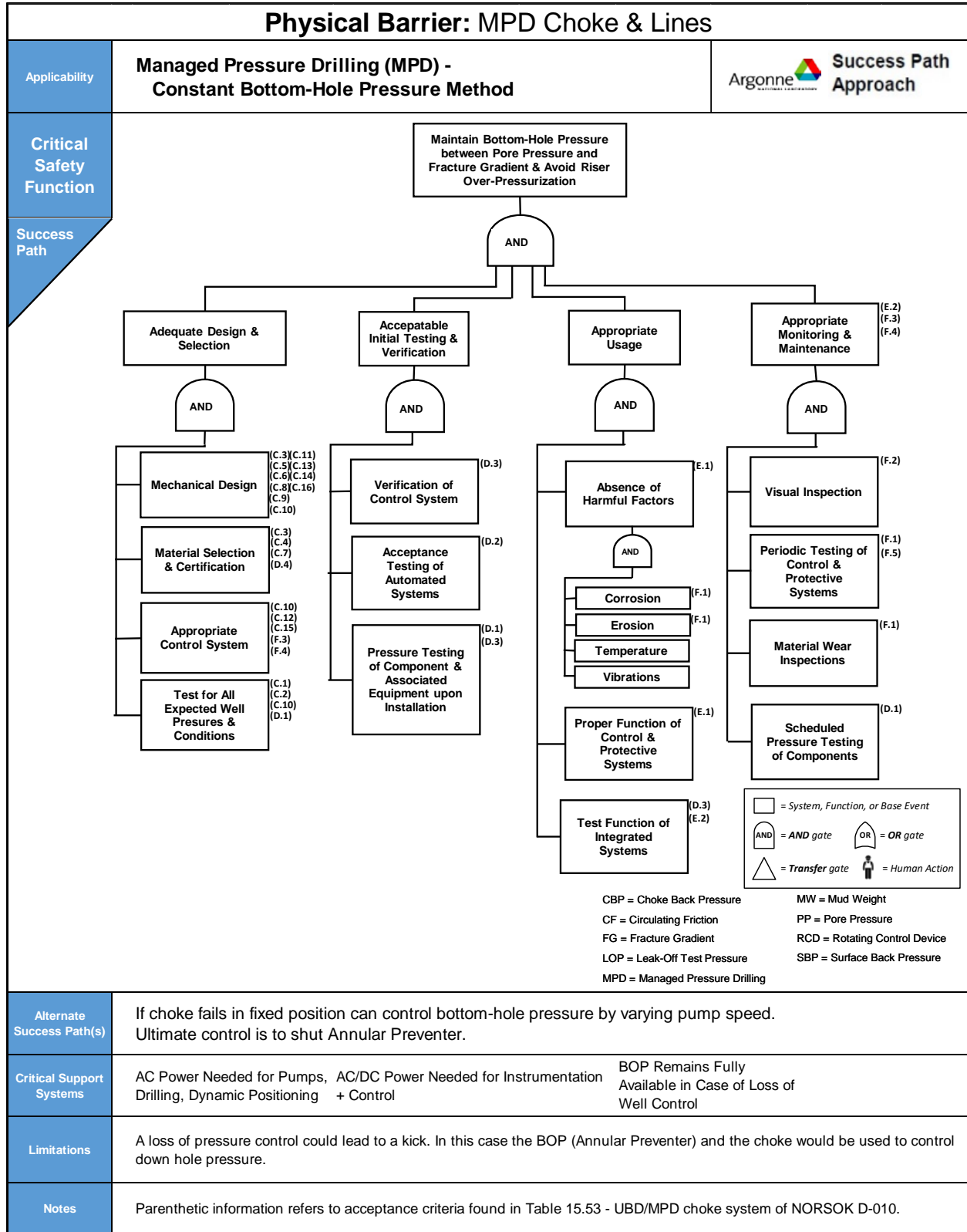
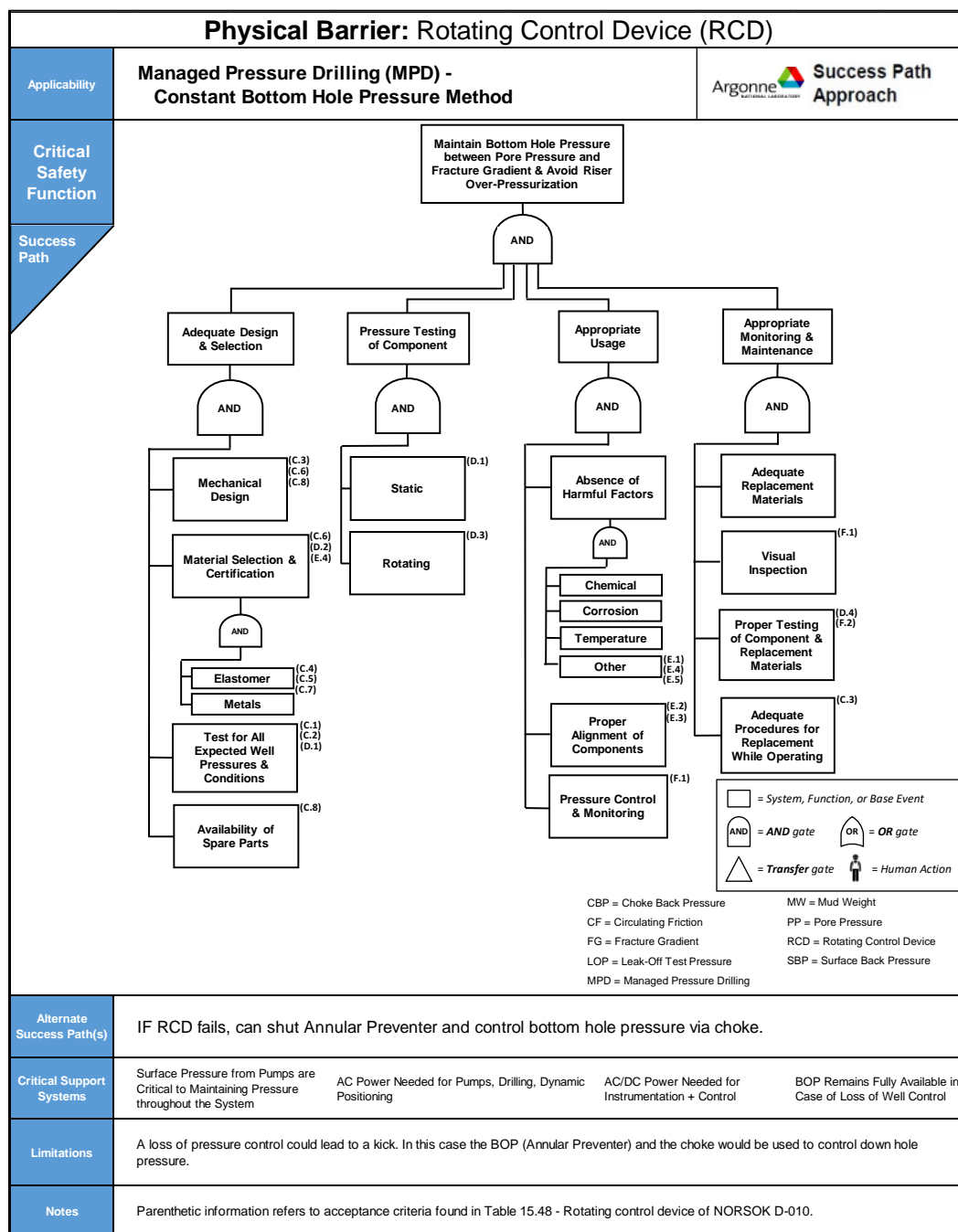


Figure II-6: Success Path for Choke and Lines in MPD



Appropriate Monitoring & Maintenance

AND

Adequate Replacement Materials

Visual Inspection (F.1)

Proper Testing of Component & Replacement Materials (D.4) (F.2)

Adequate Procedures for Replacement While Operating (C.3)

□ = System, Function, or Base Event

AND = AND gate OR = OR gate

△ = Transfer gate 👤 = Human Action

CBP = Choke Back Pressure MW = Mud Weight

CF = Circulating Friction PP = Pore Pressure

FG = Fracture Gradient RCD = Rotating Control Device

LOP = Leak-Off Test Pressure SBP = Surface Back Pressure

MPD = Managed Pressure Drilling

Figure II-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).

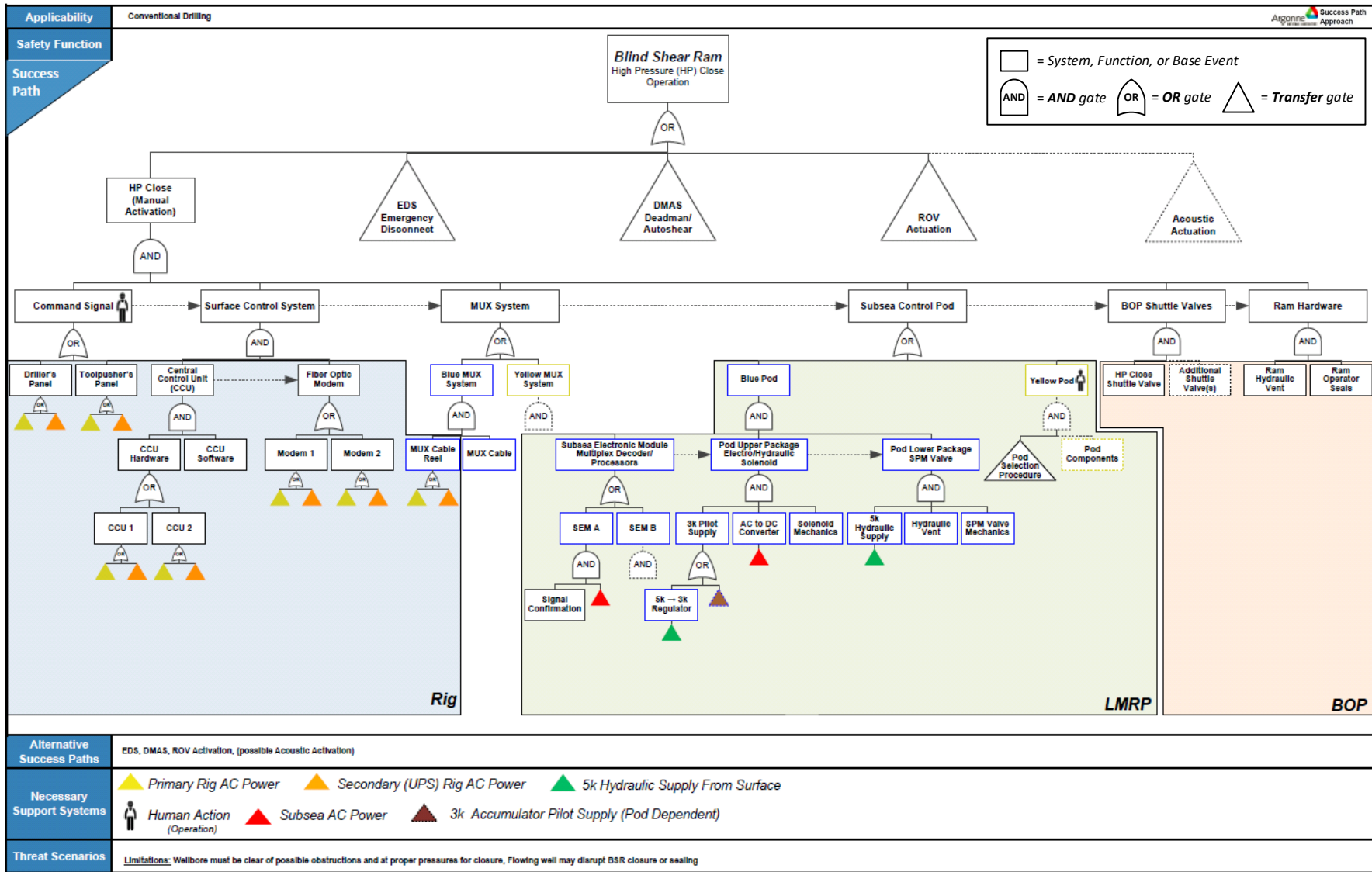


Figure II-8: Success Path for the Manual Actuation of BSR HP Close

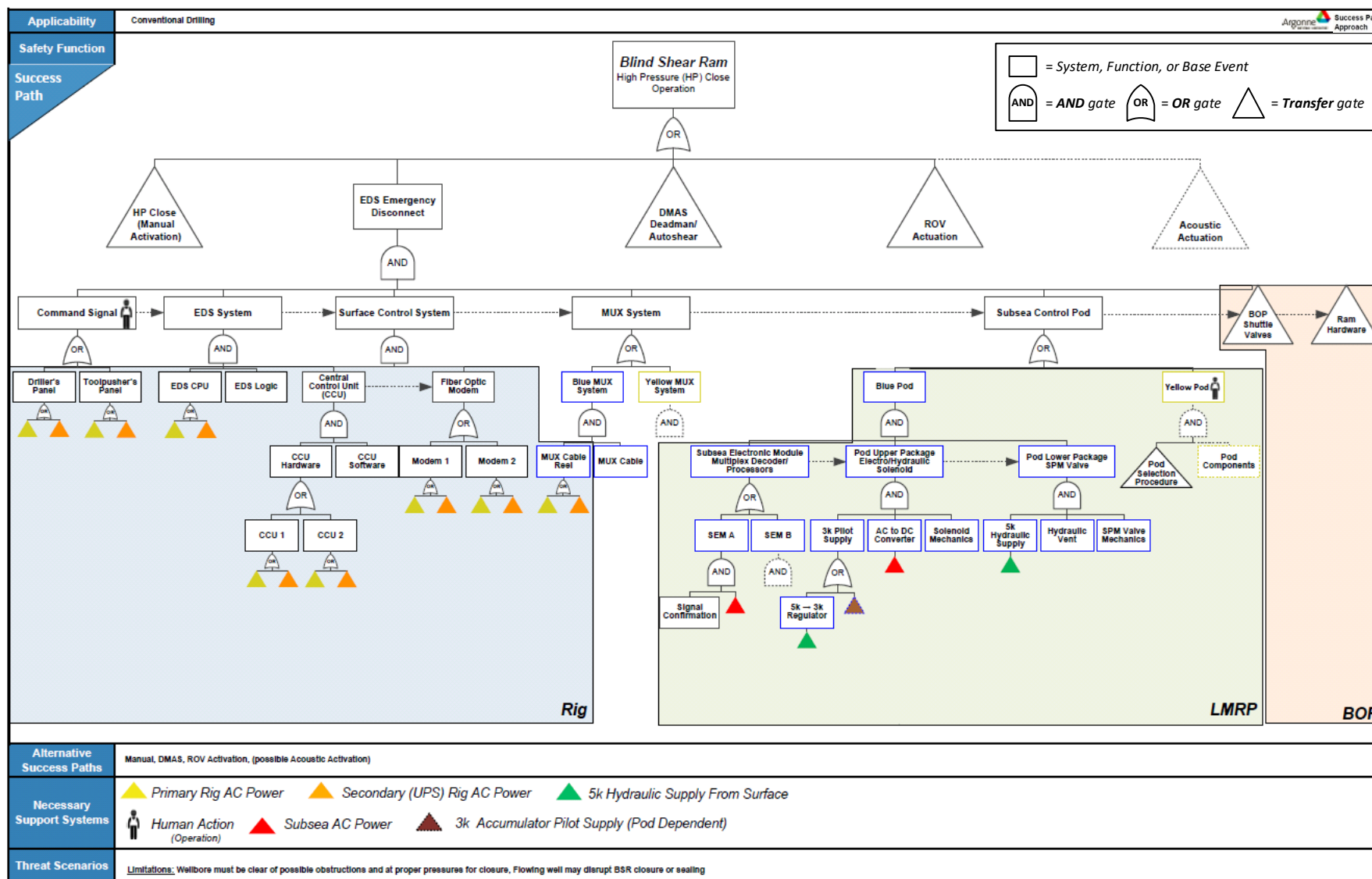


Figure II-9: Success Path for the Emergency Disconnect

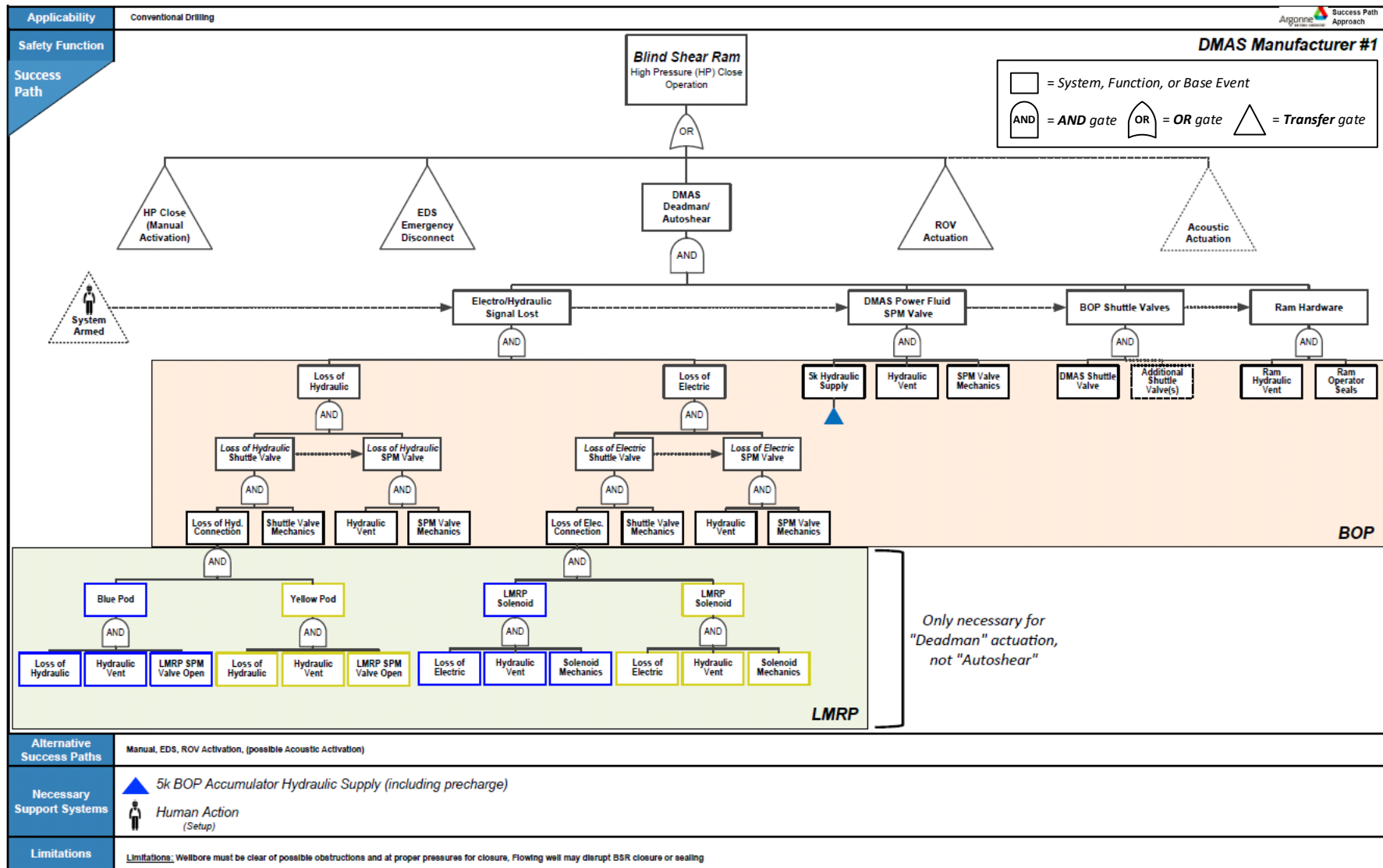


Figure II-10: Success Path for the DMAS of Manufacturer #1

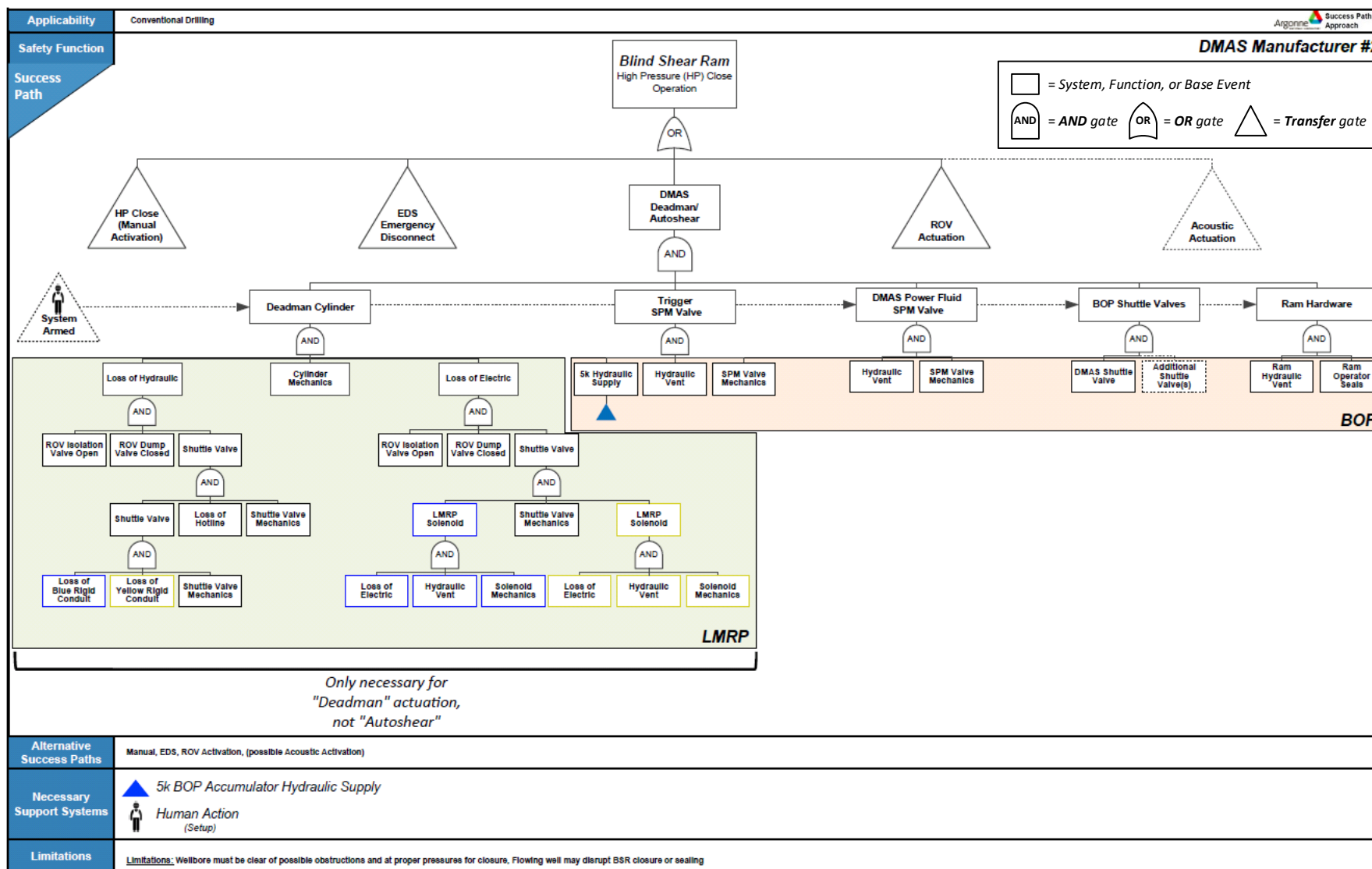


Figure II-11: Success Path for the DMAS of Manufacturer #2

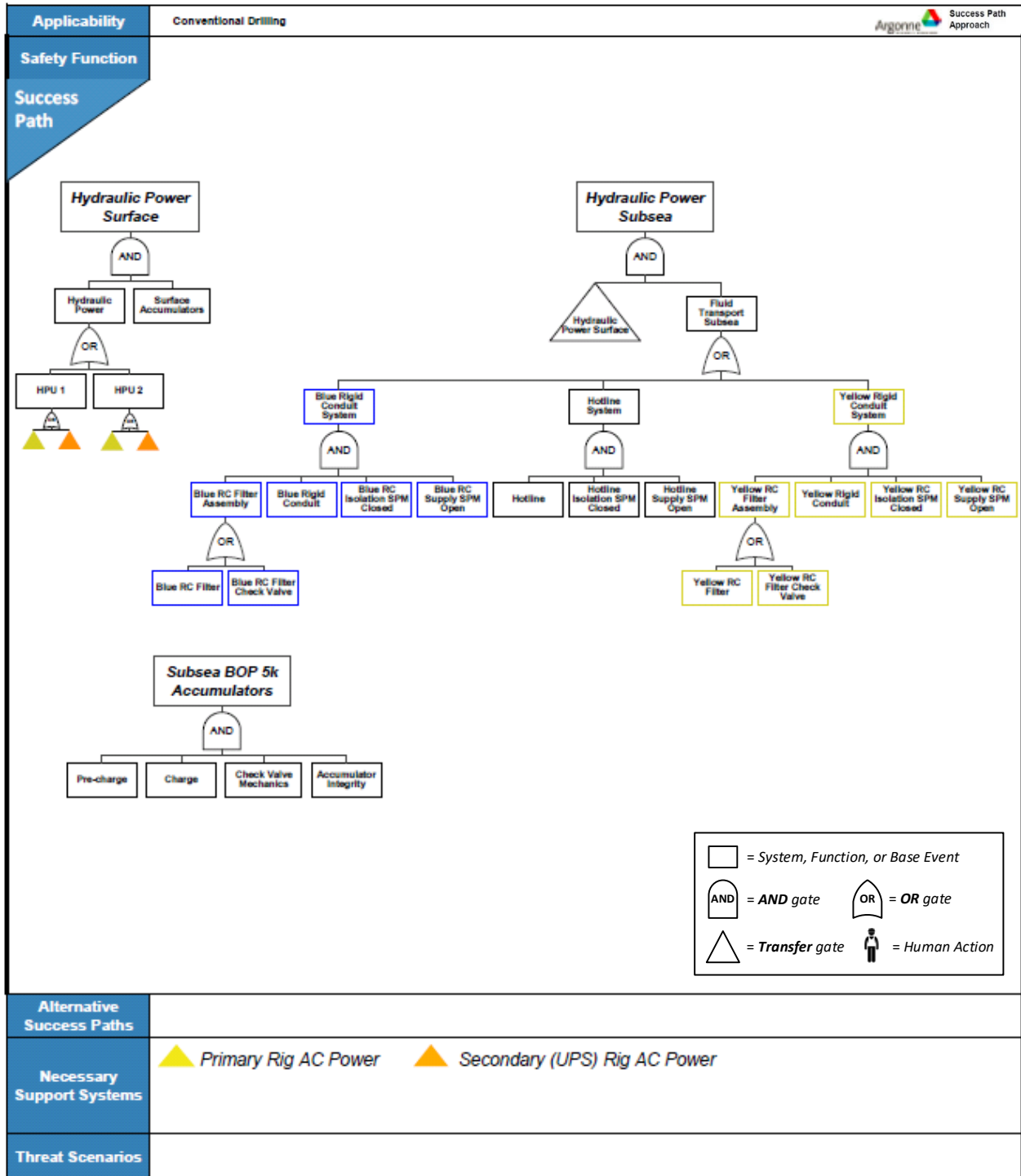


Figure II-12: Success Path for a Hydraulic Power Support System

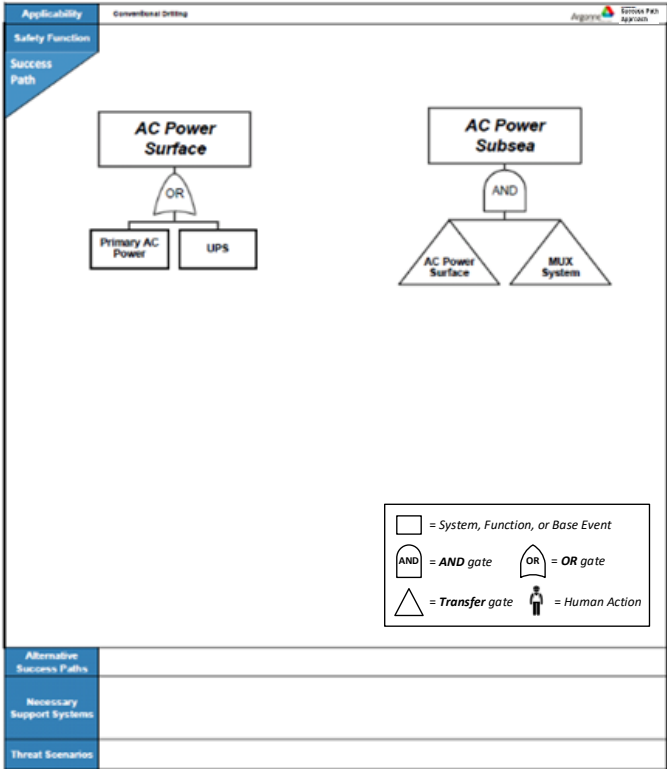


Figure II-13: Success Path for an AC Power Support System

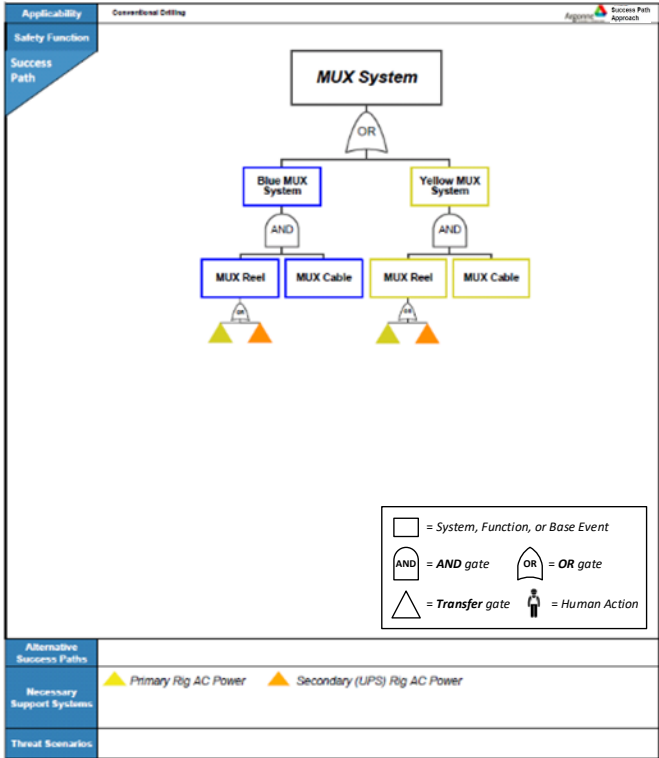
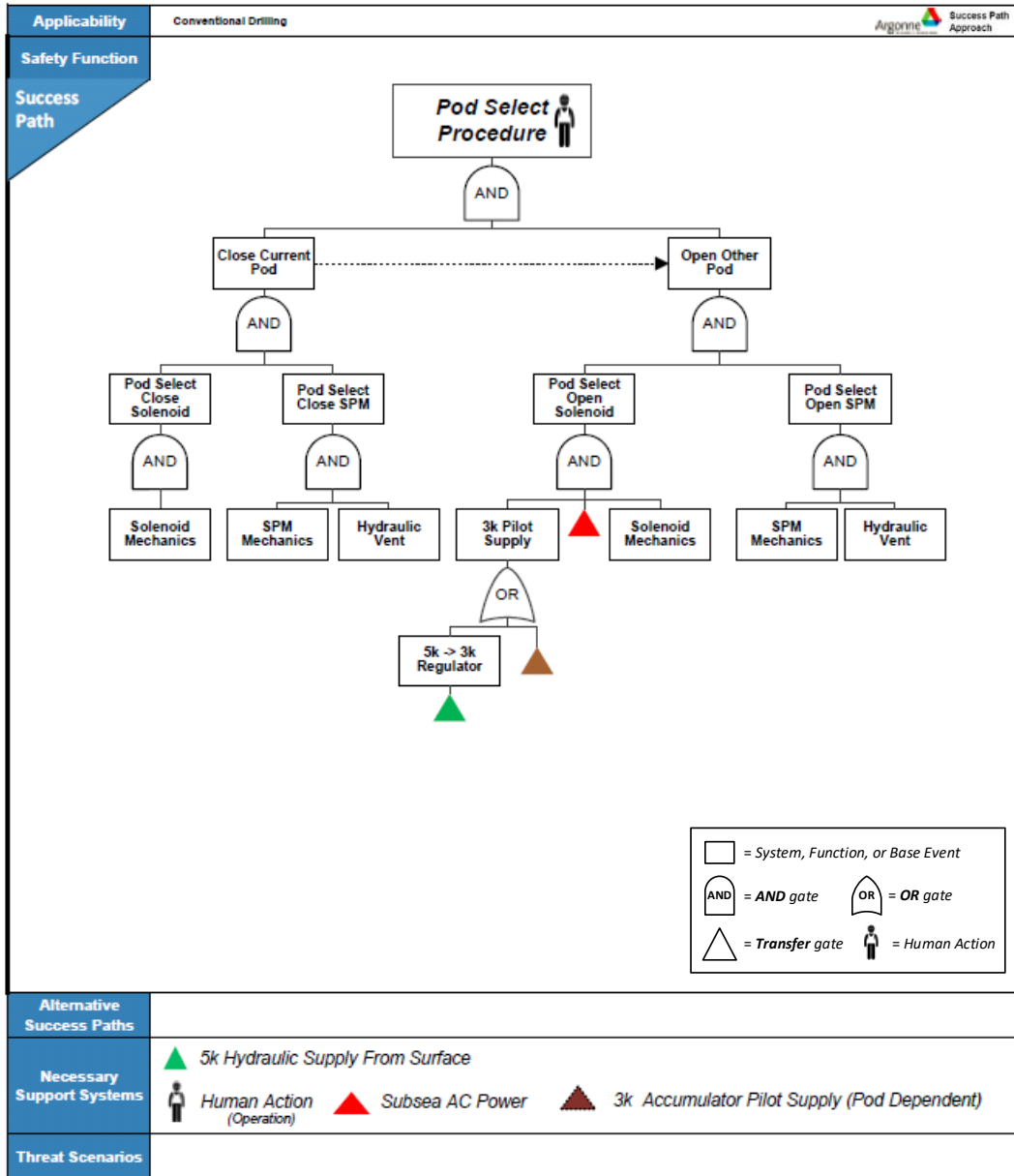


Figure II-14: Success Path for a MUX Support System



AND

Solenoid Mechanics

SPM Mechanics

3k Pilot Supply

Solenoid Mechanics

SPM Mechanics

Hydraulic Vent

AND

Pod Select Close Solenoid

Pod Select Close SPM

Pod Select Open Solenoid

Pod Select Open SPM

AND

Close Current Pod

Open Other Pod

AND

Pod Select Procedure

Figure II-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 II-16 and for cementing in Figure II-17.

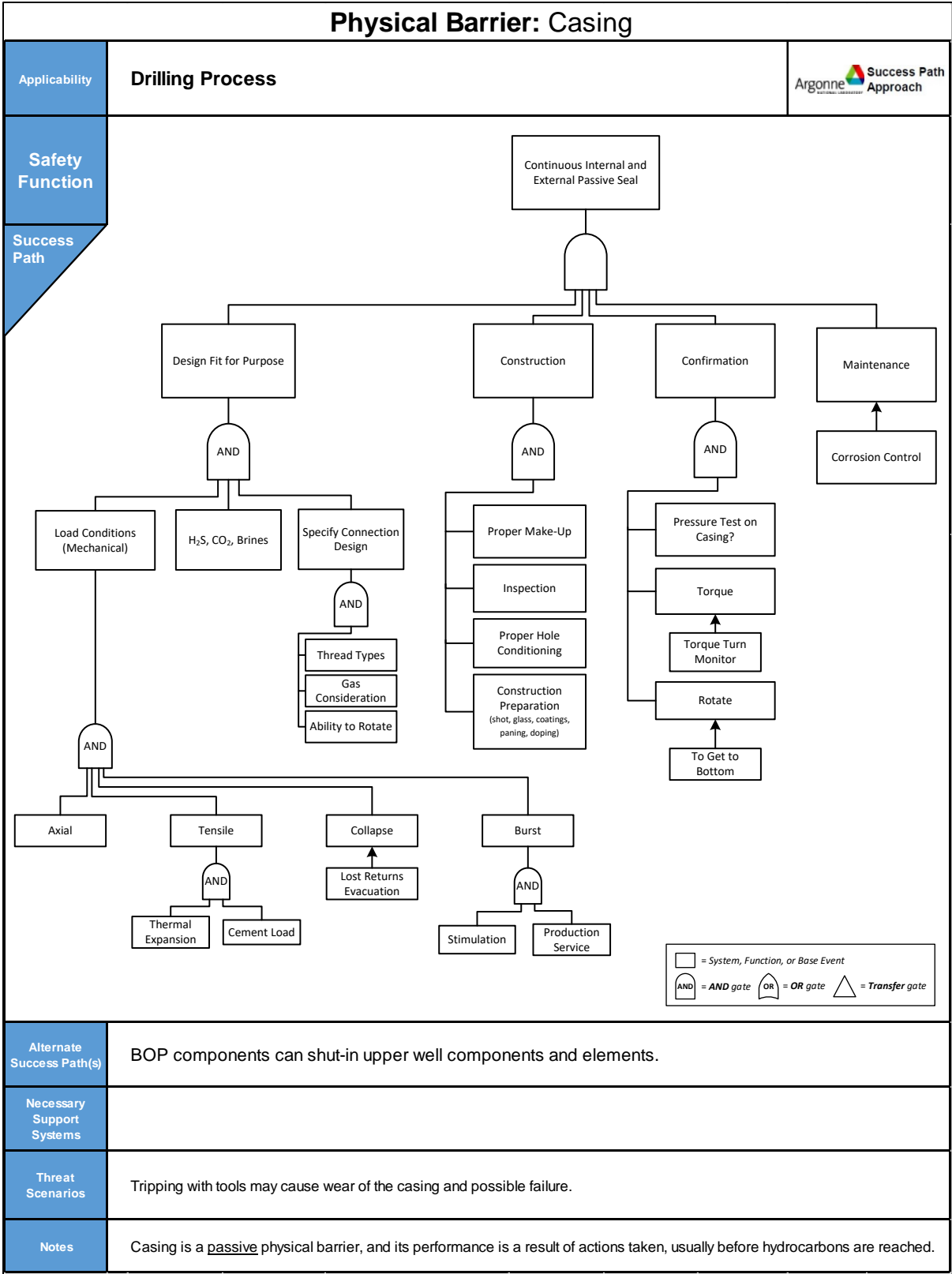


Figure II-16: Success Path for Casing

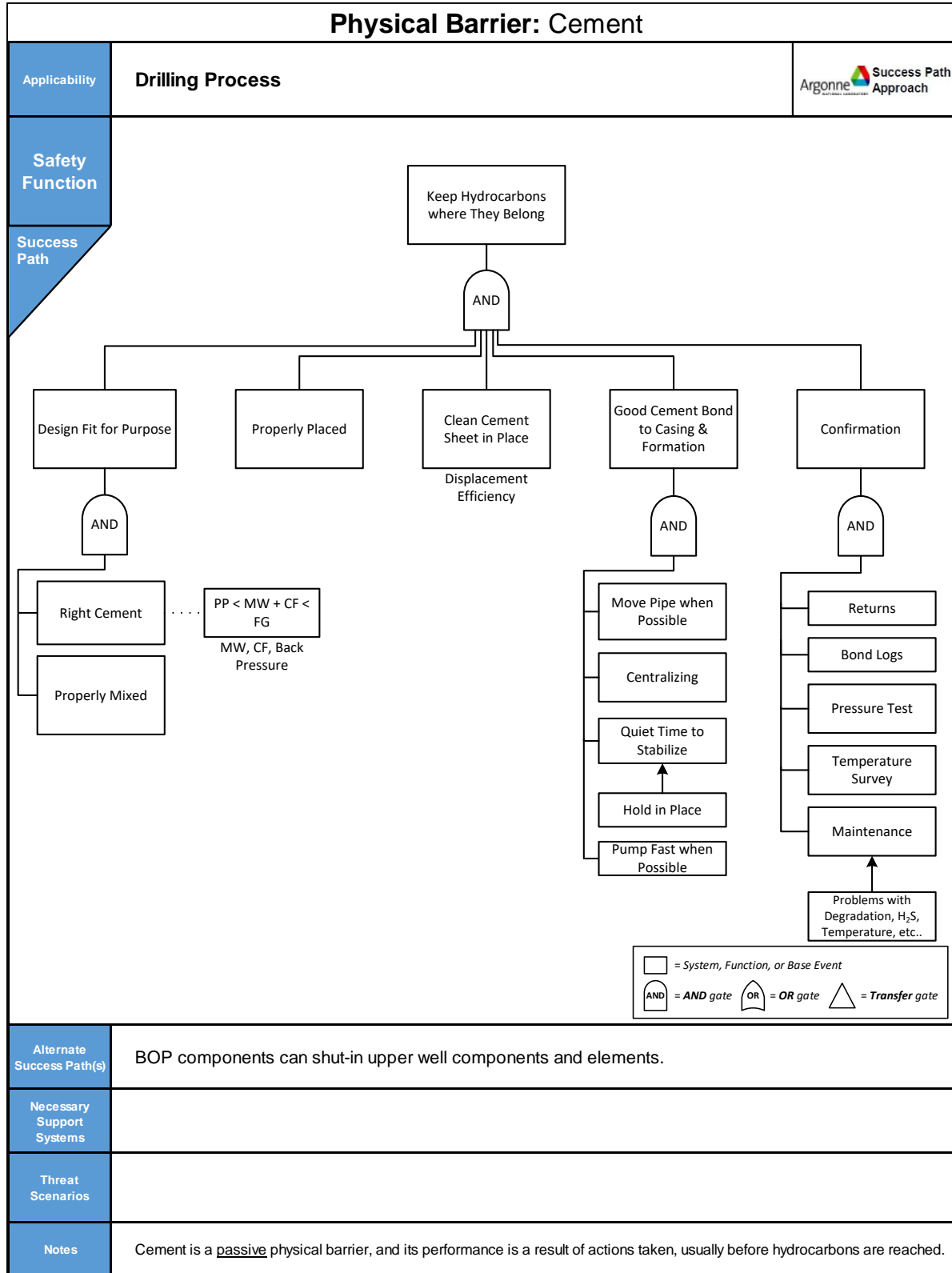


Figure II-17: Success Path for Cement

COMPLETION AND PRODUCTION SUCCESS PATHS

When applying the Success Path 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 II-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 II-19 illustrates the Success Path for packer retrieval.

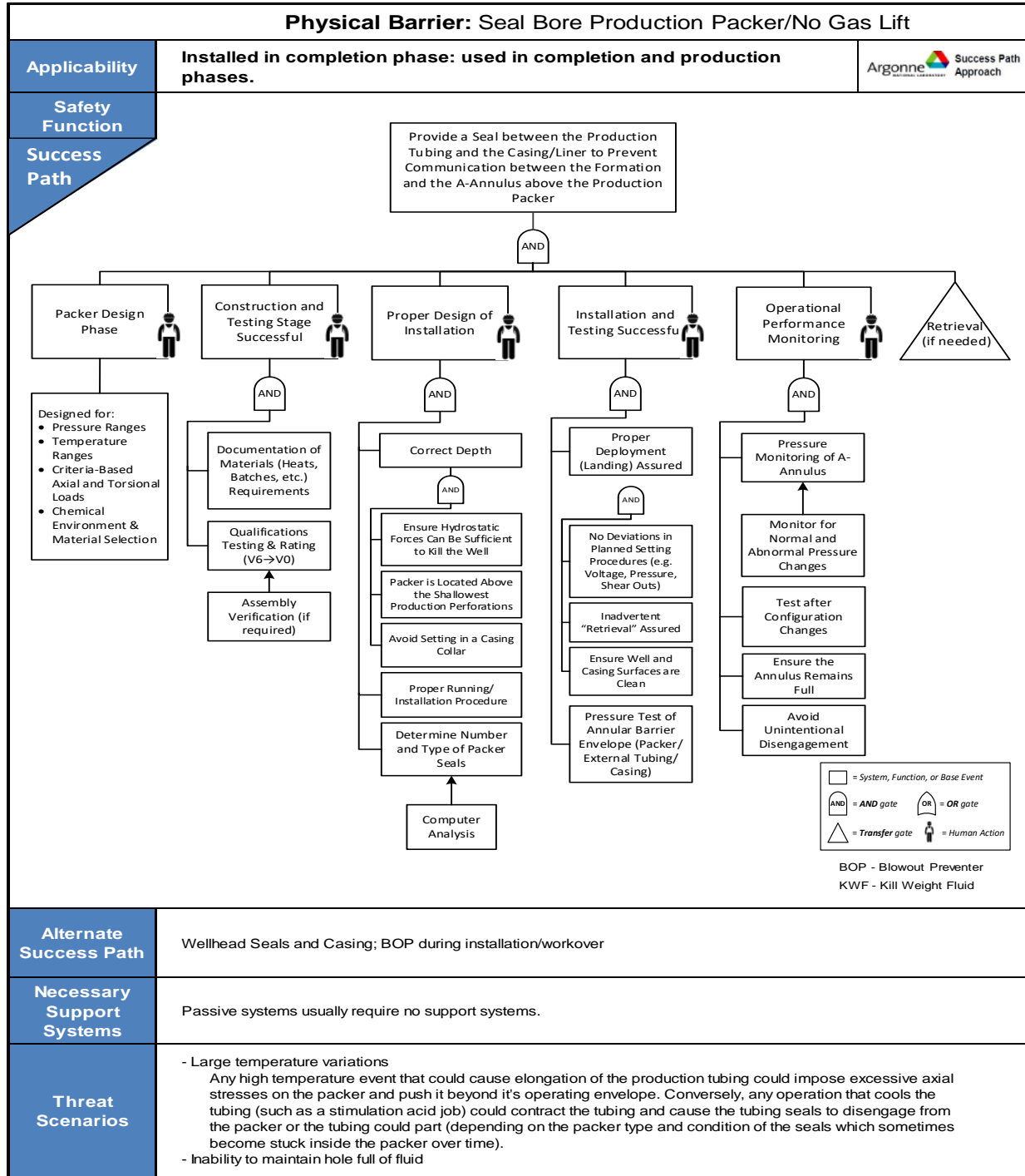


Figure II-18: Success Path for a Seal Bore Production Packer without Gas Lift

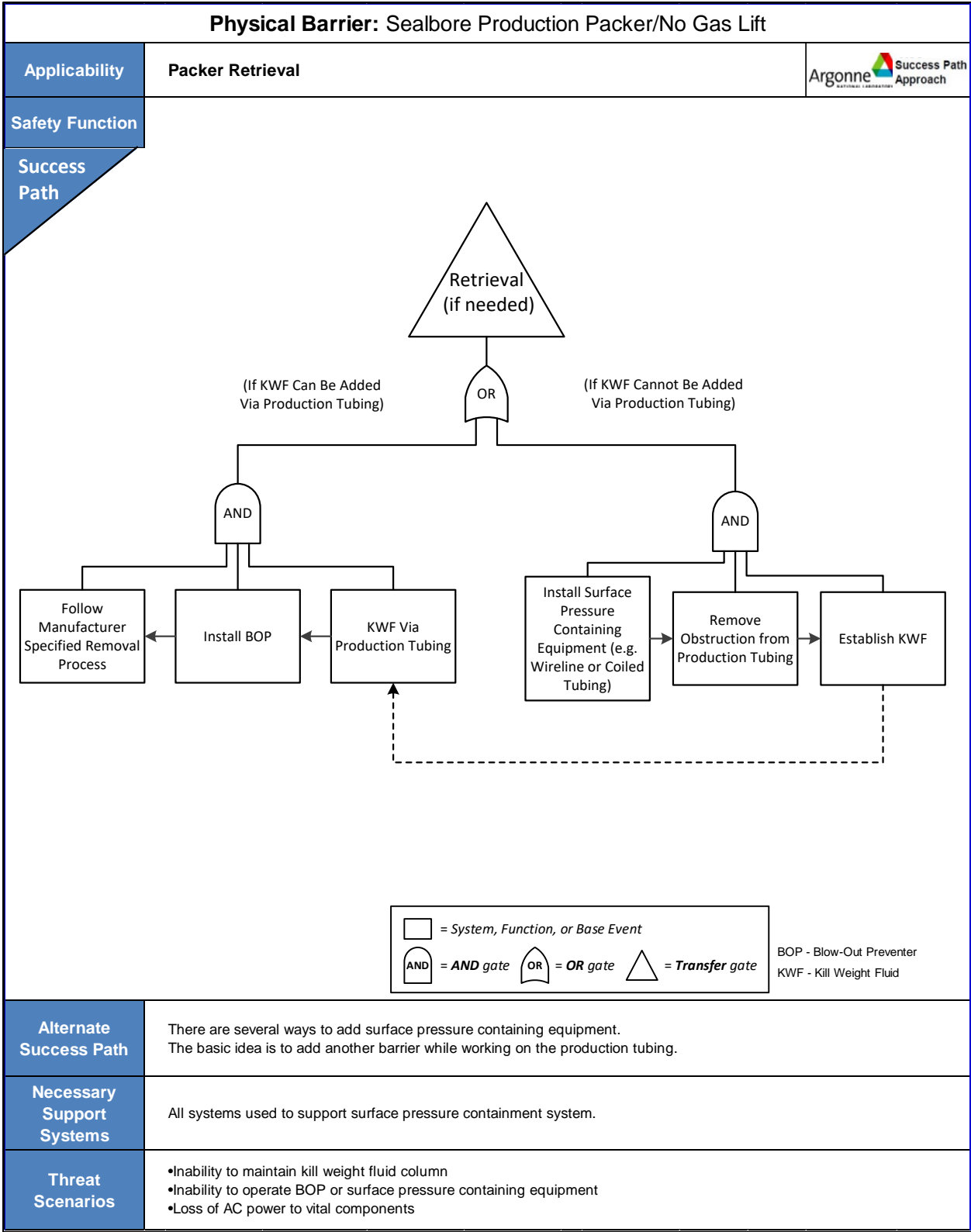


Figure II-19: Success Path for Retrieval of a Seal Bore Production Packer without Gas Lift

PRODUCTION PIPELINE SUCCESS PATH

When developing the Success Path in Figure II-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.

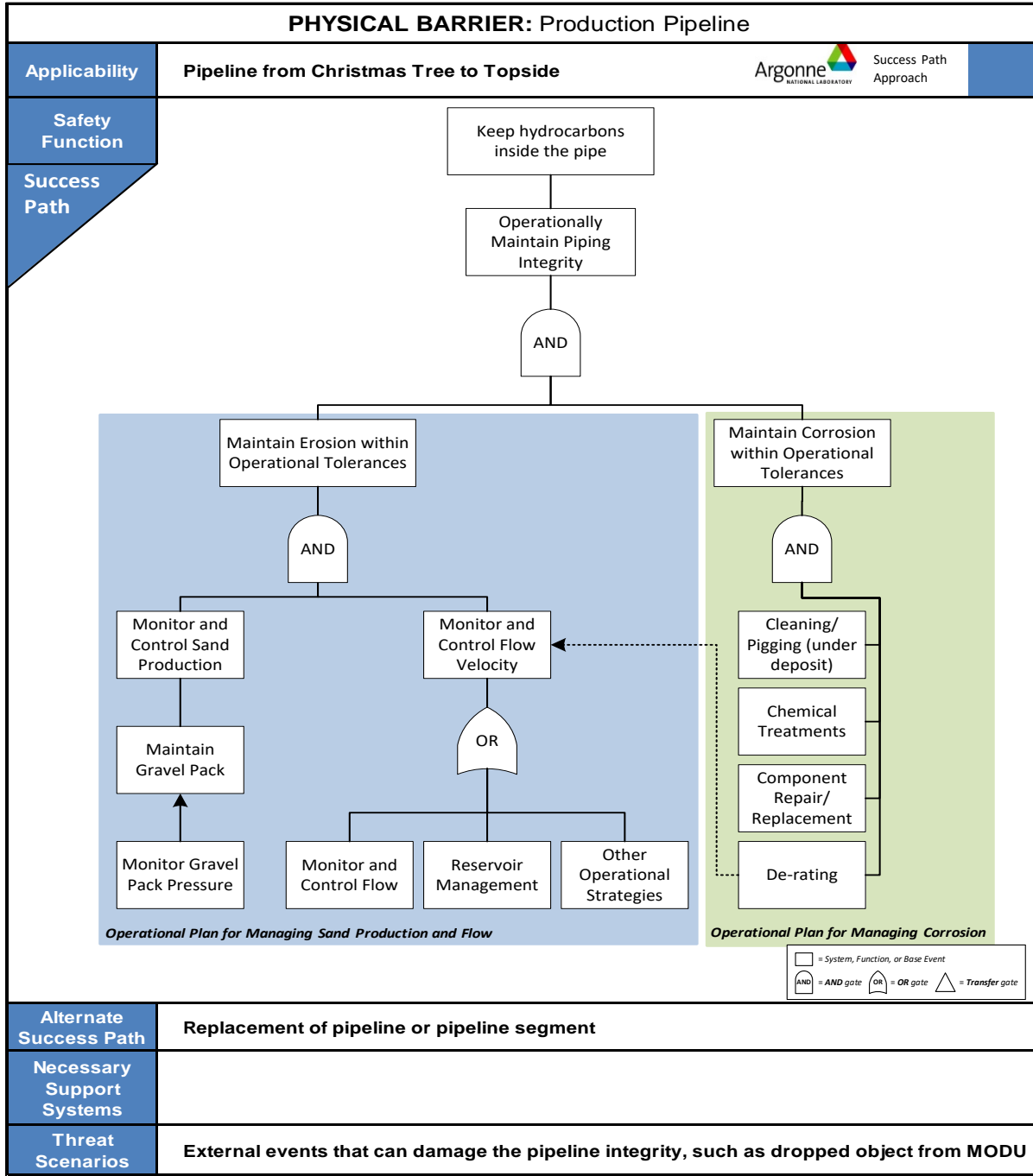


Figure II-20: Success Path for a Pipeline

WORKOVER SUCCESS PATHS

When applying the Success Path 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.

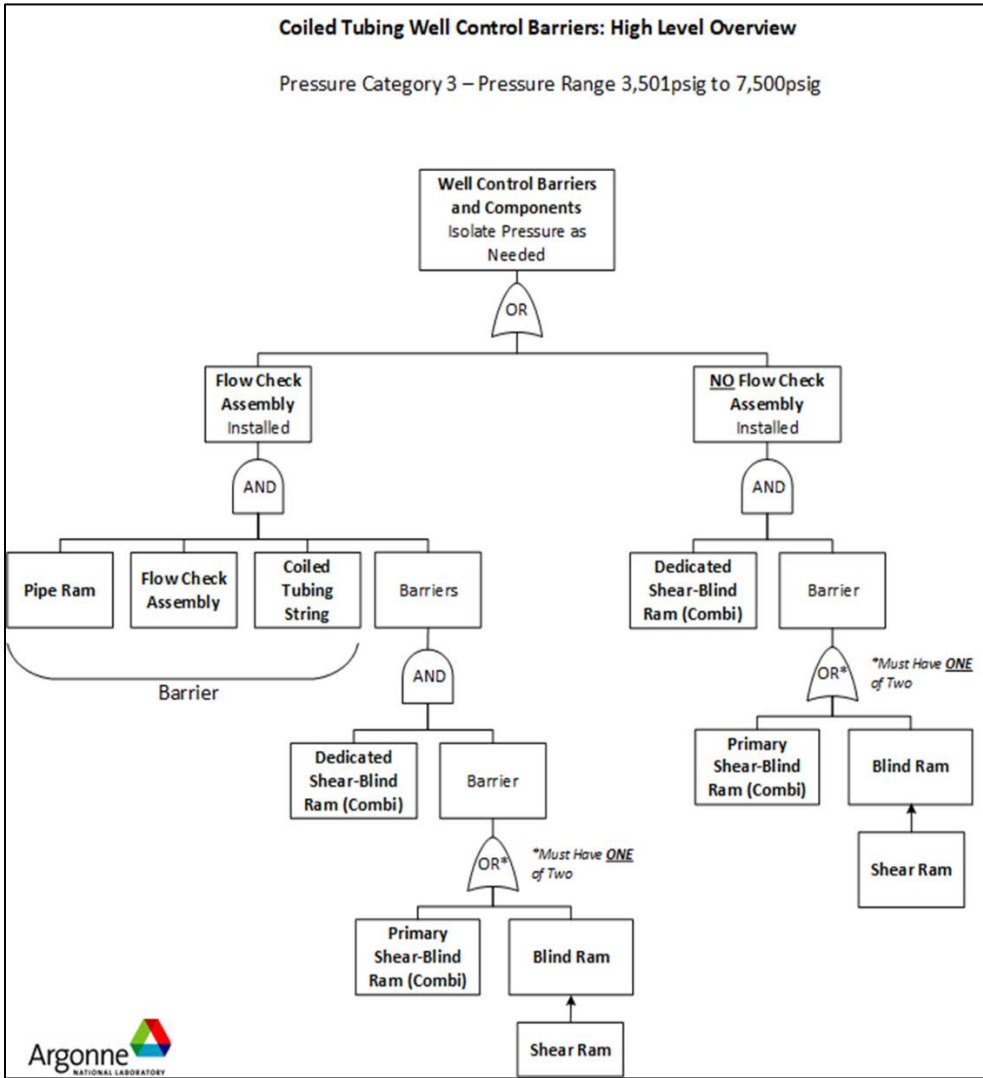


Figure II-21: Success Path for Coil Tubing Well Control Barriers

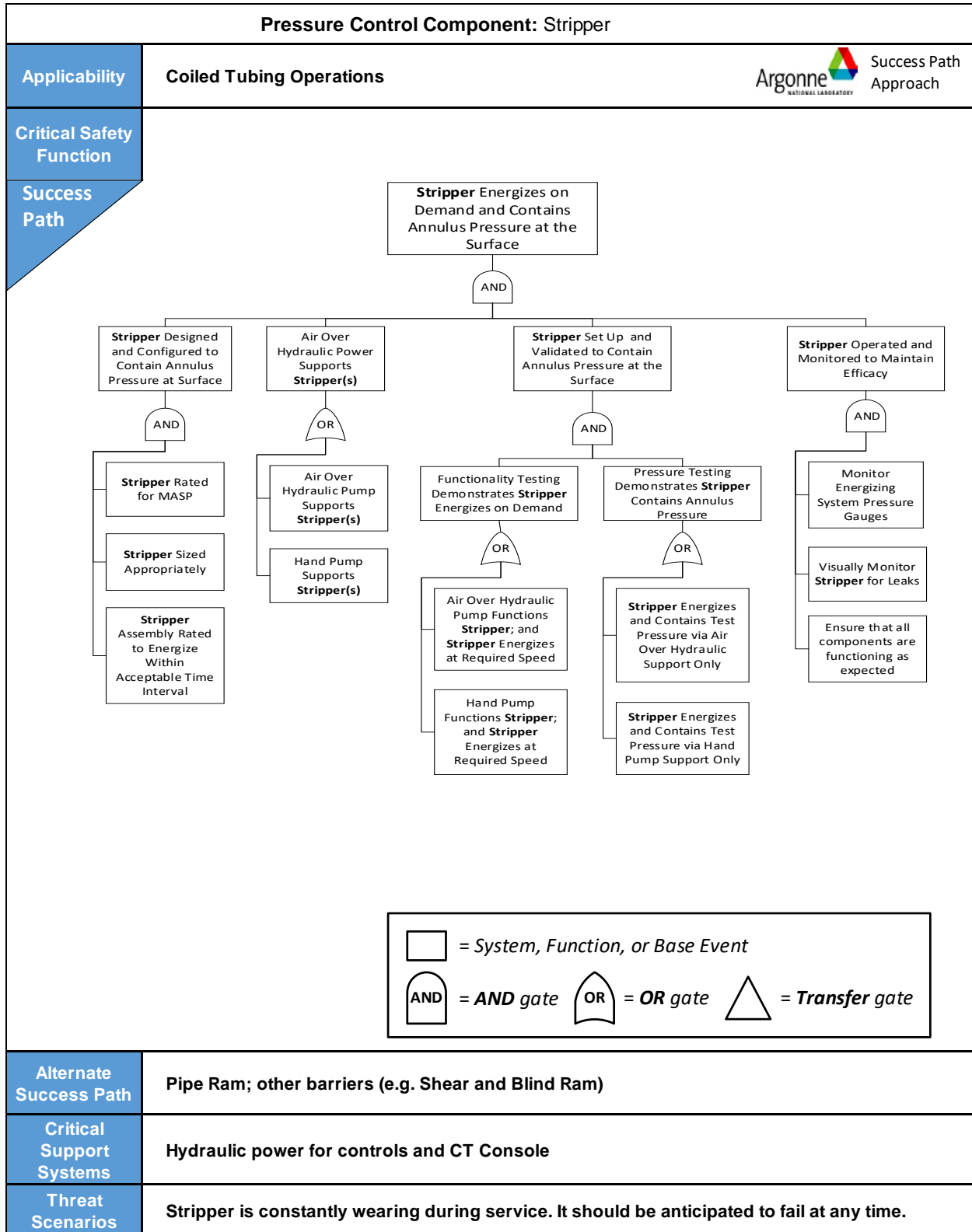


Figure II-22: Success Path for Stripper

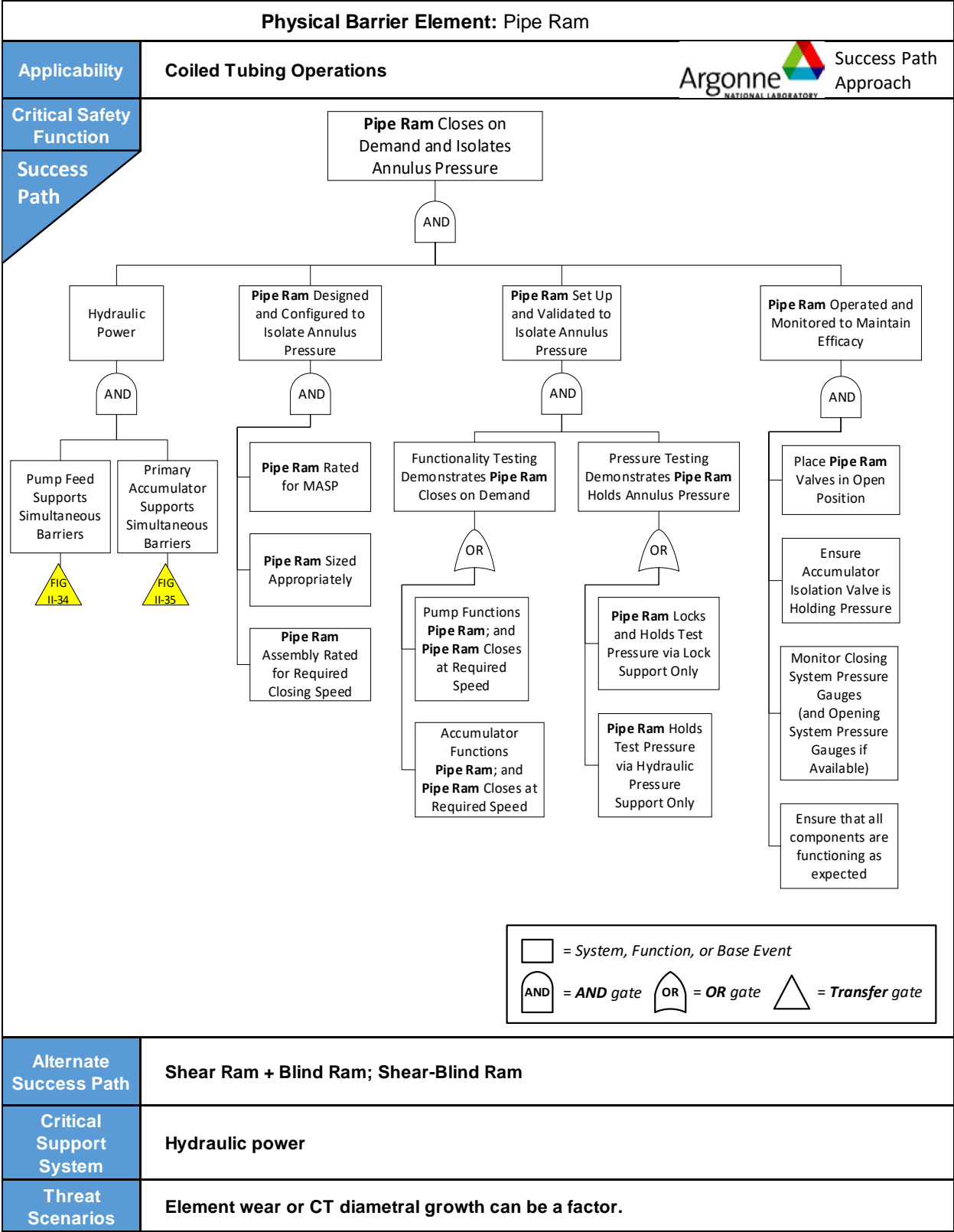


Figure II-23: Success Path for Pipe Ram

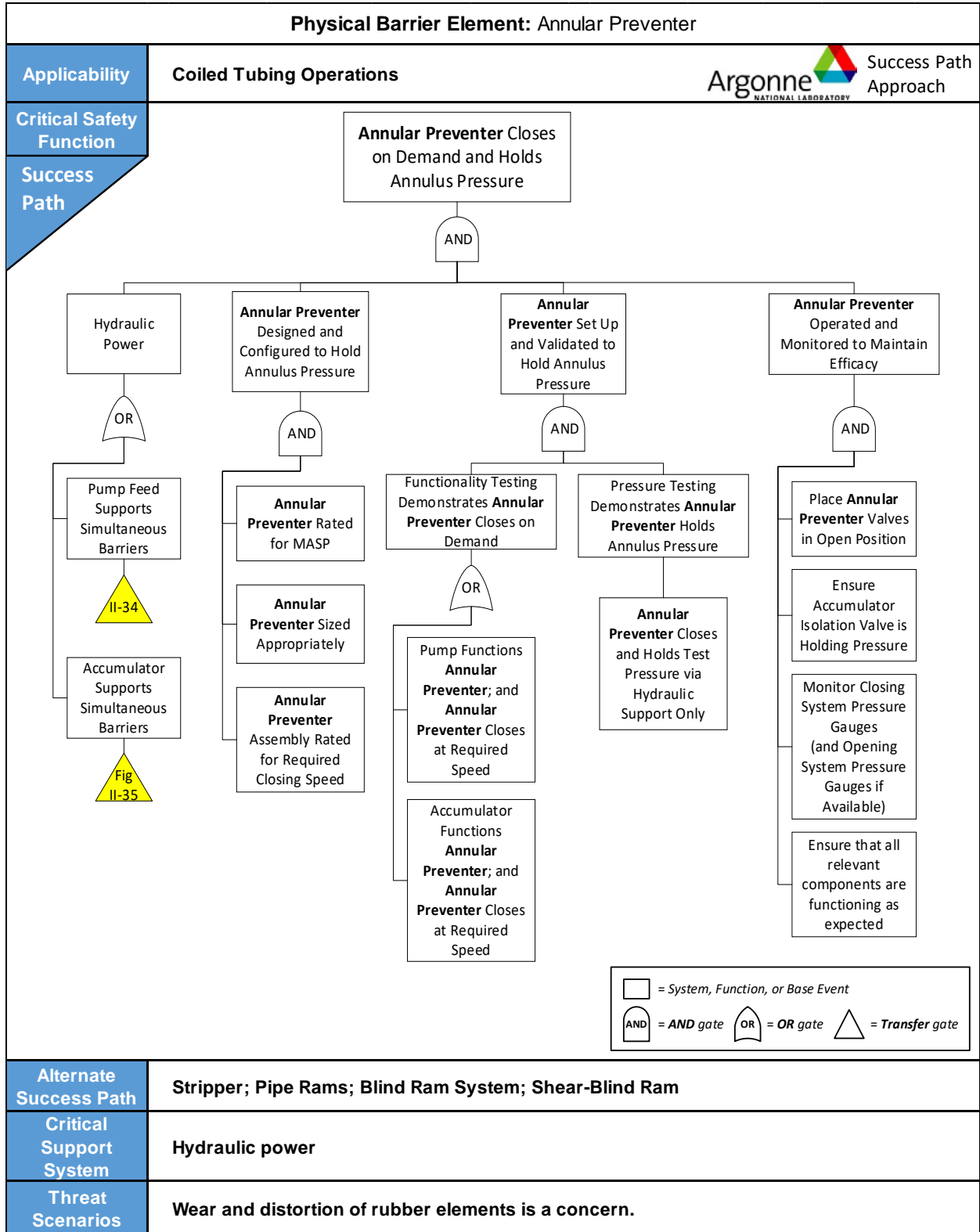


Figure II-24: Success Path for Annular Preventer

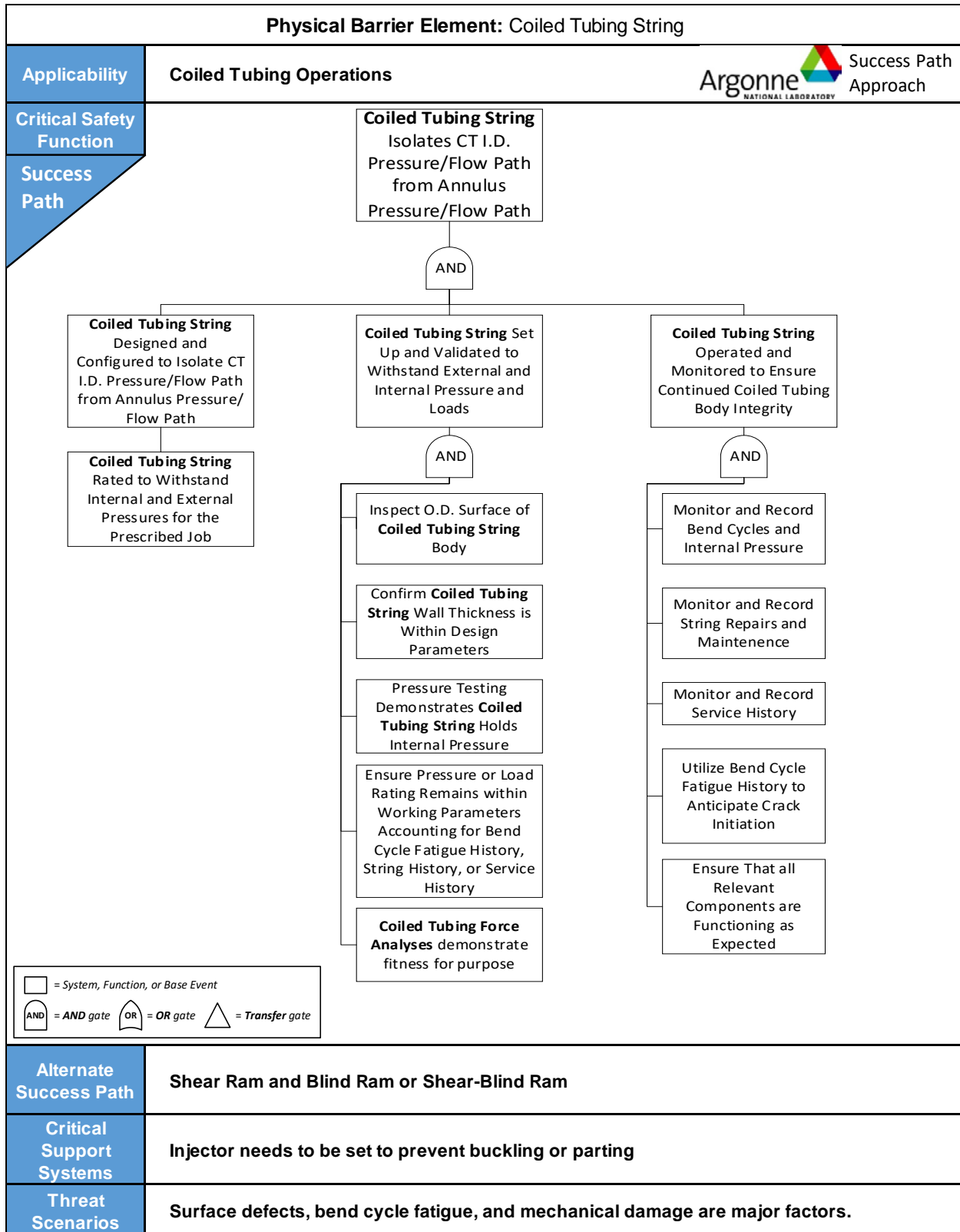


Figure II- 25: Success Path for Coiled Tubing String

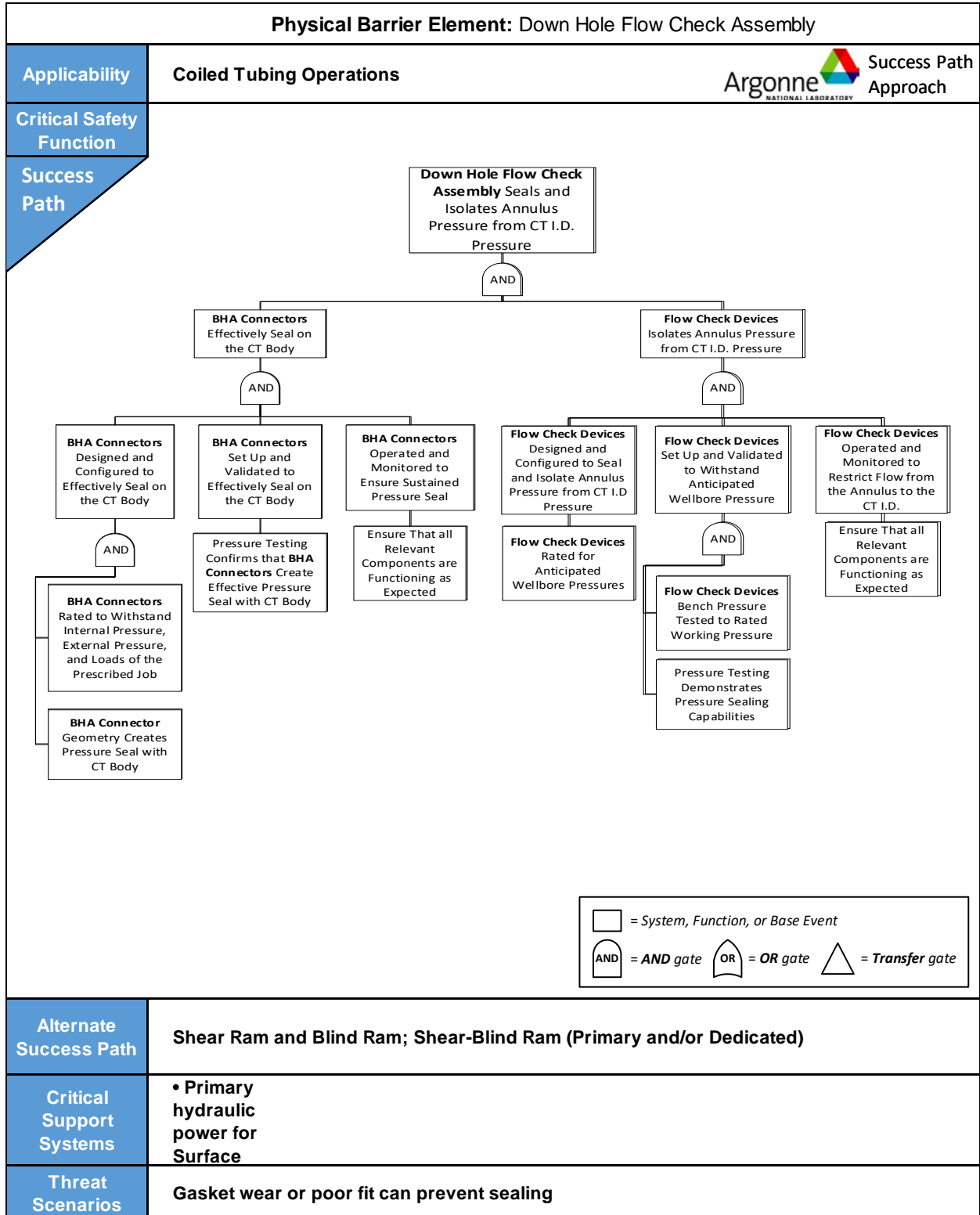


Figure II-26: Success Path for Down-Hole Flow Check Assembly

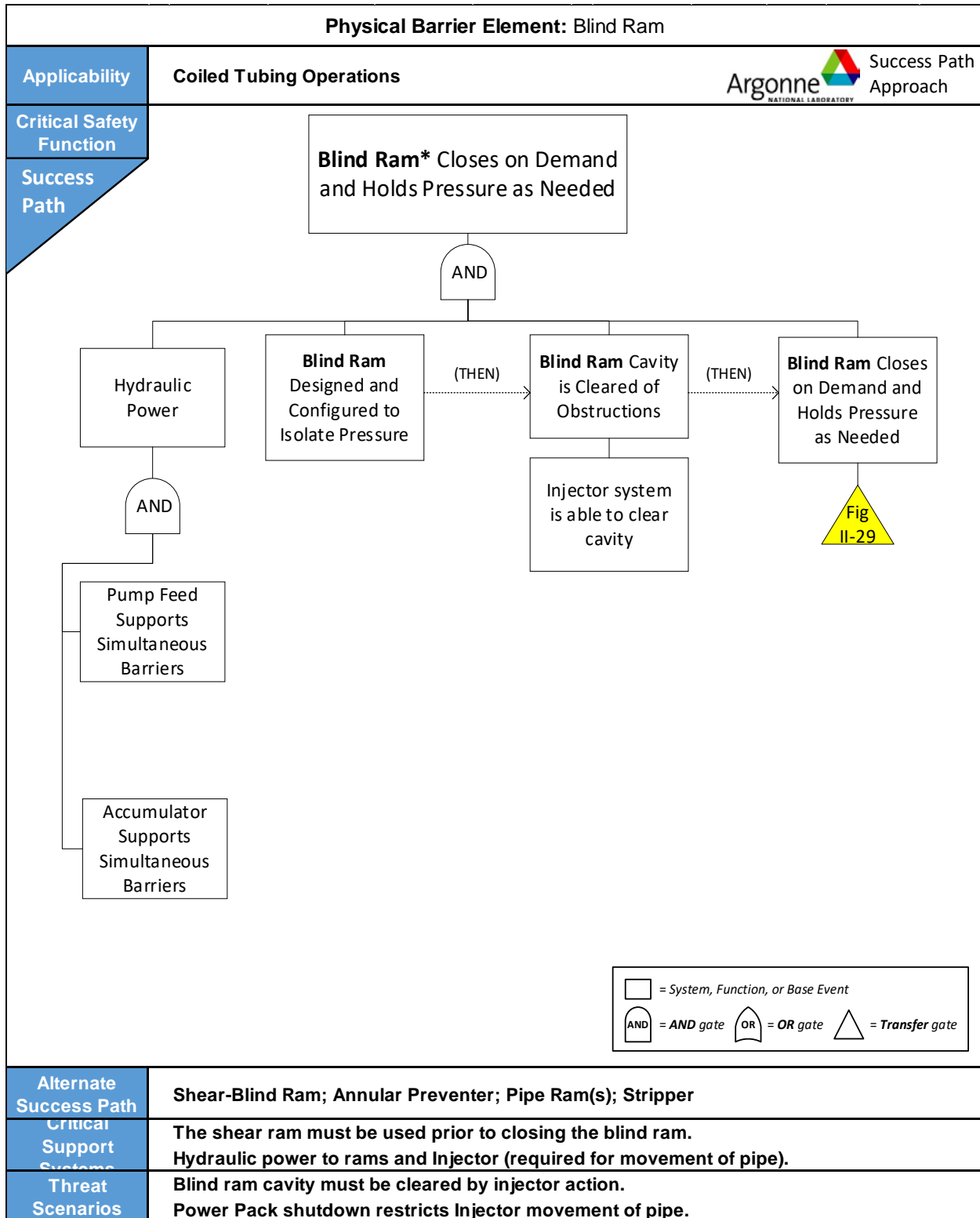


Figure II-27: Success Path for Blind Ram

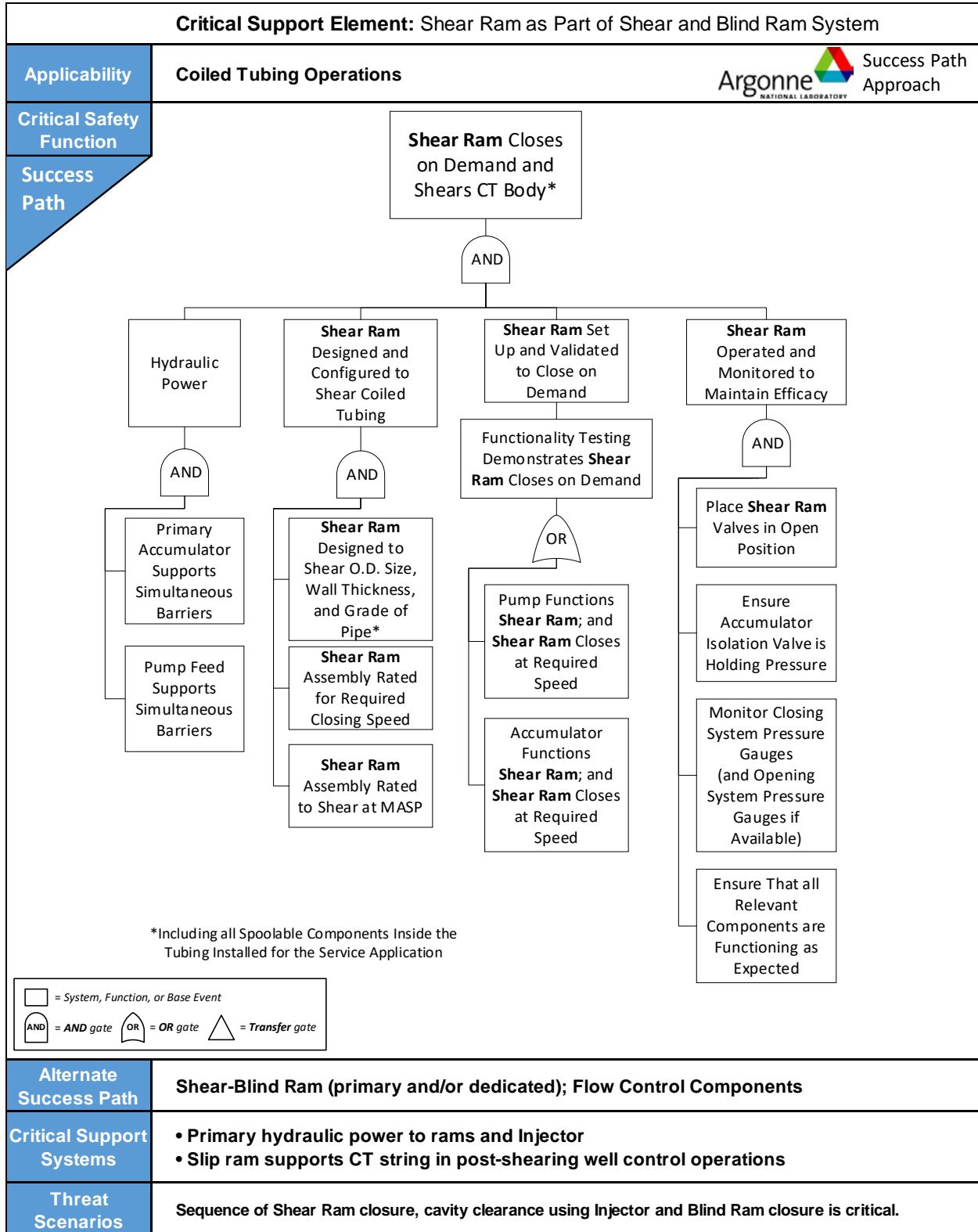


Figure II-28: Success Path for Shear Ram as Part of Shear and Blind Ram System

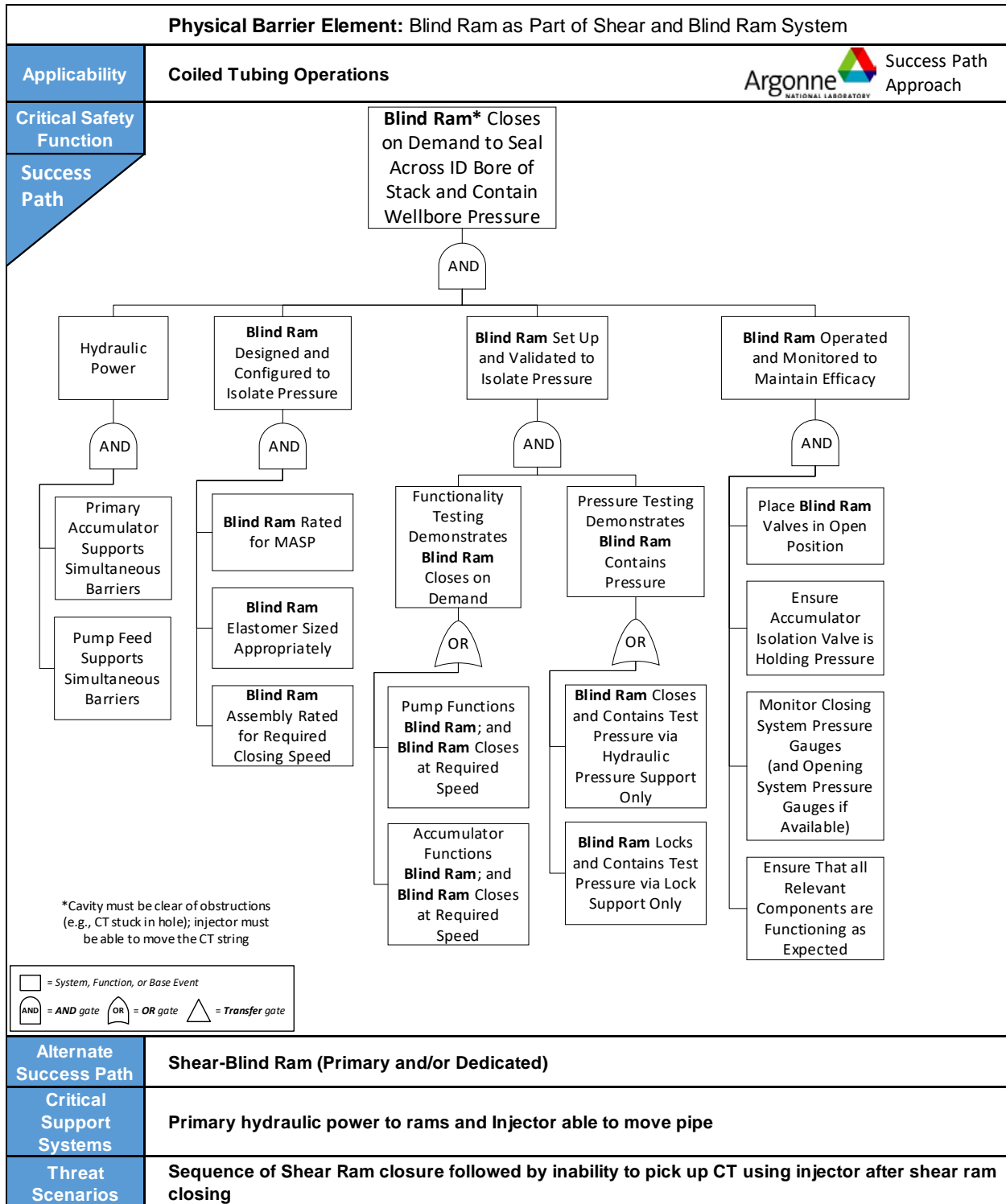


Figure II-29: Success Path for Blind Ram as Part of Shear and Blind Ram System

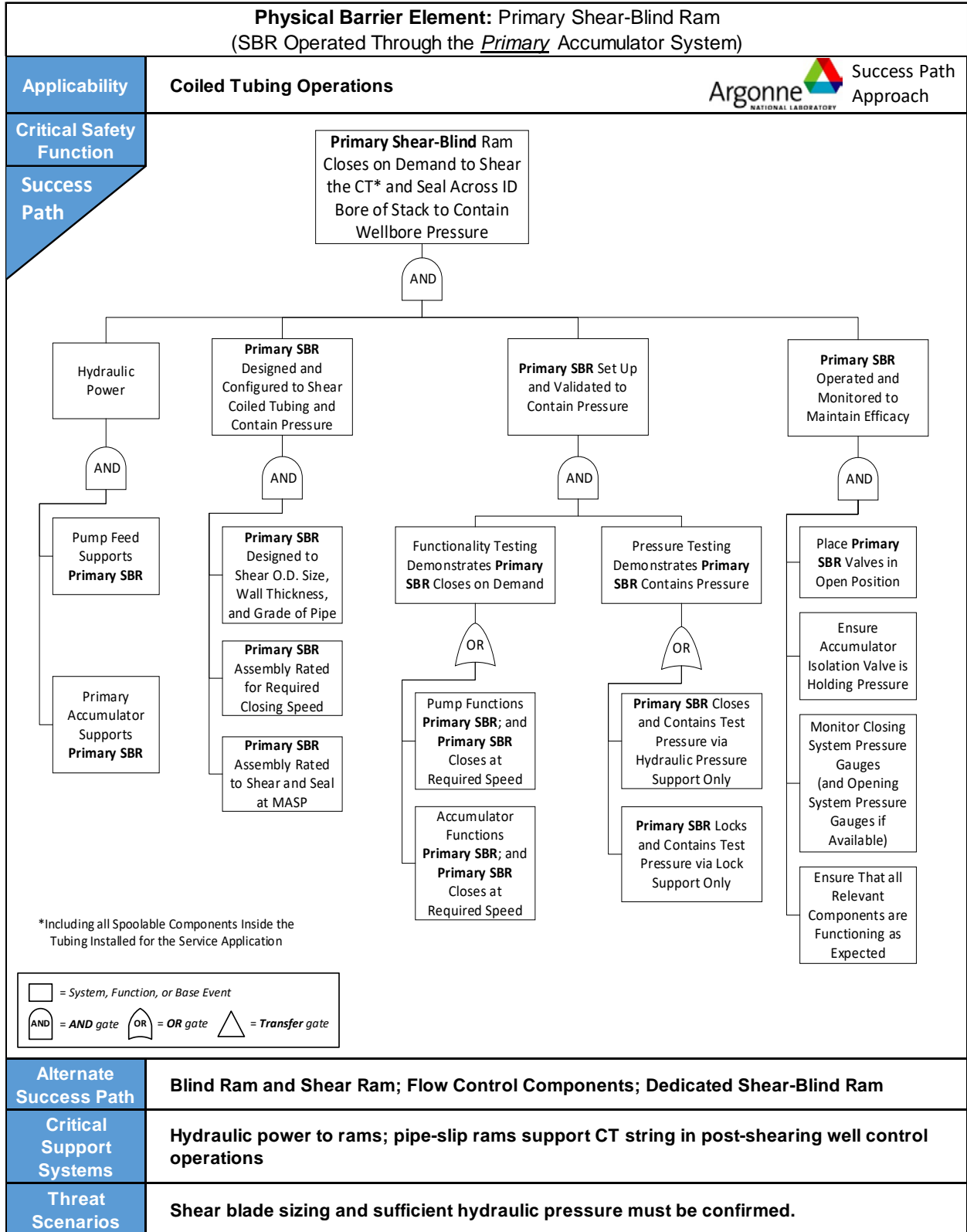


Figure II-30: Success Path for Shear-Blind Ram

Physical Barrier Element: Dedicated Shear-Blind Ram
 (SBR Operated Through the *Dedicated* Accumulator System - see p. 46)

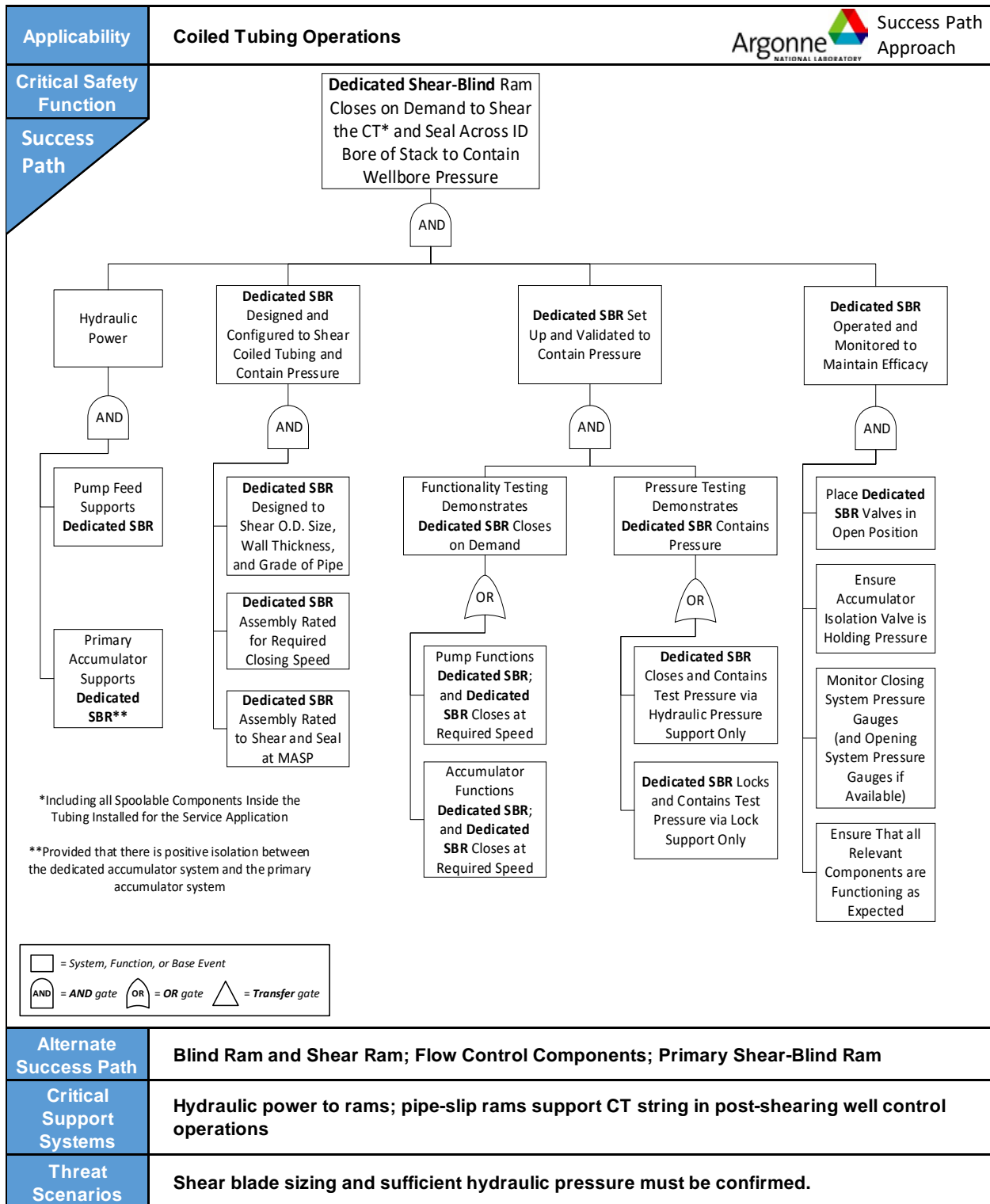


Figure II-31: Success Path for Dedicated Shear-Blind Ram

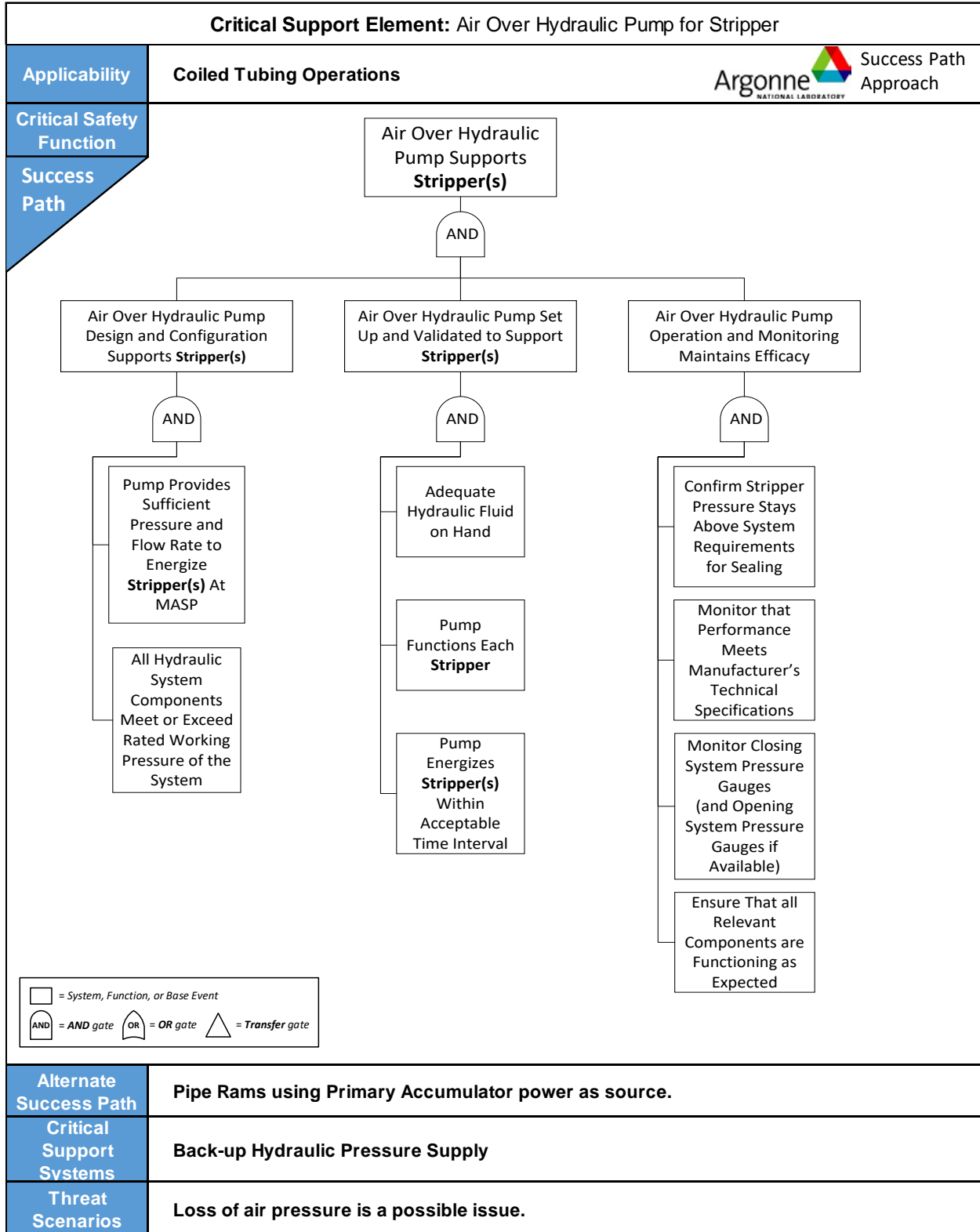


Figure II-32: Success Path for Air over Hydraulic Pump for Stripper

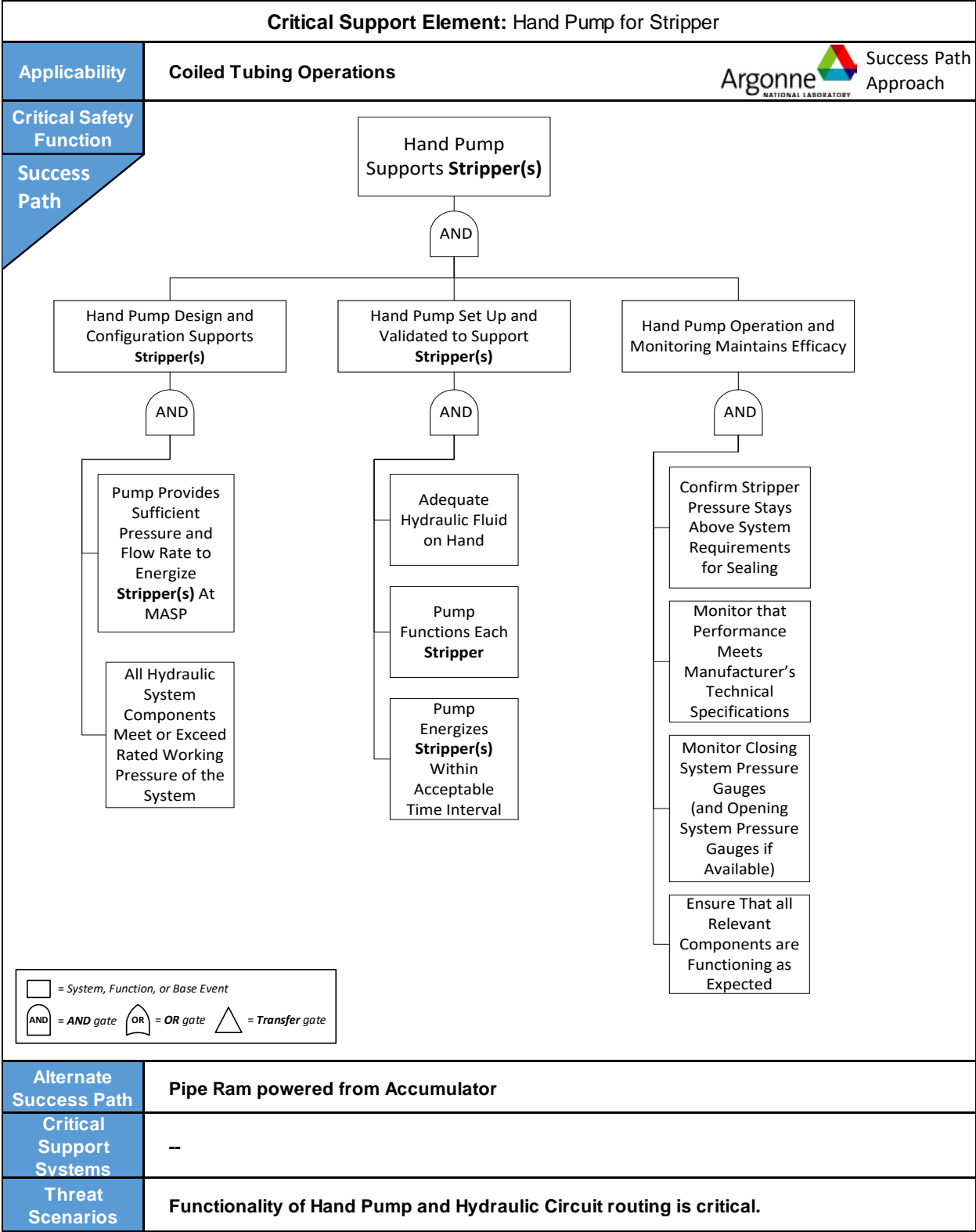


Figure II-33: Success Path for Hand Pump for Stripper

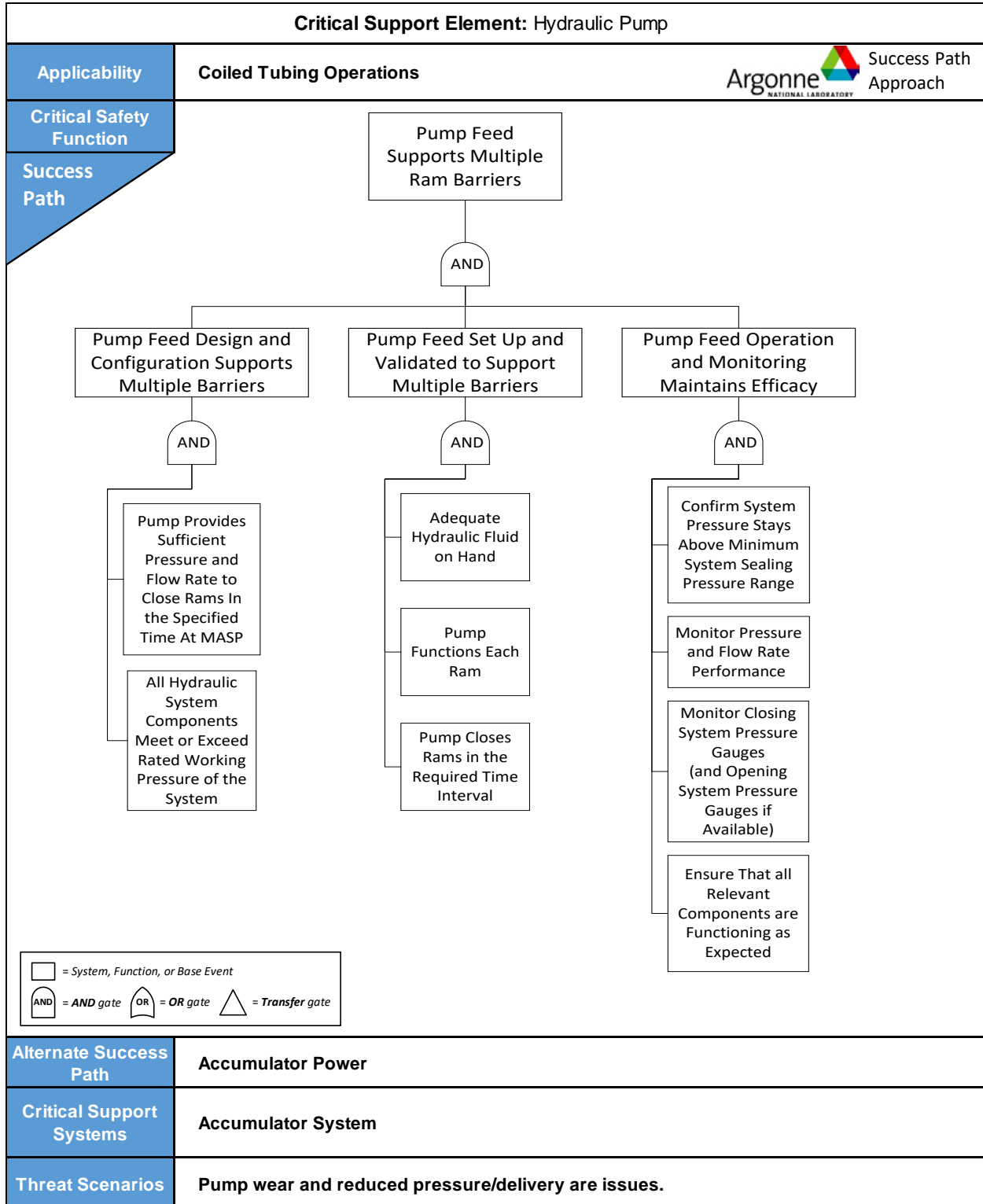


Figure II-34: Success Path for Hydraulic Pump

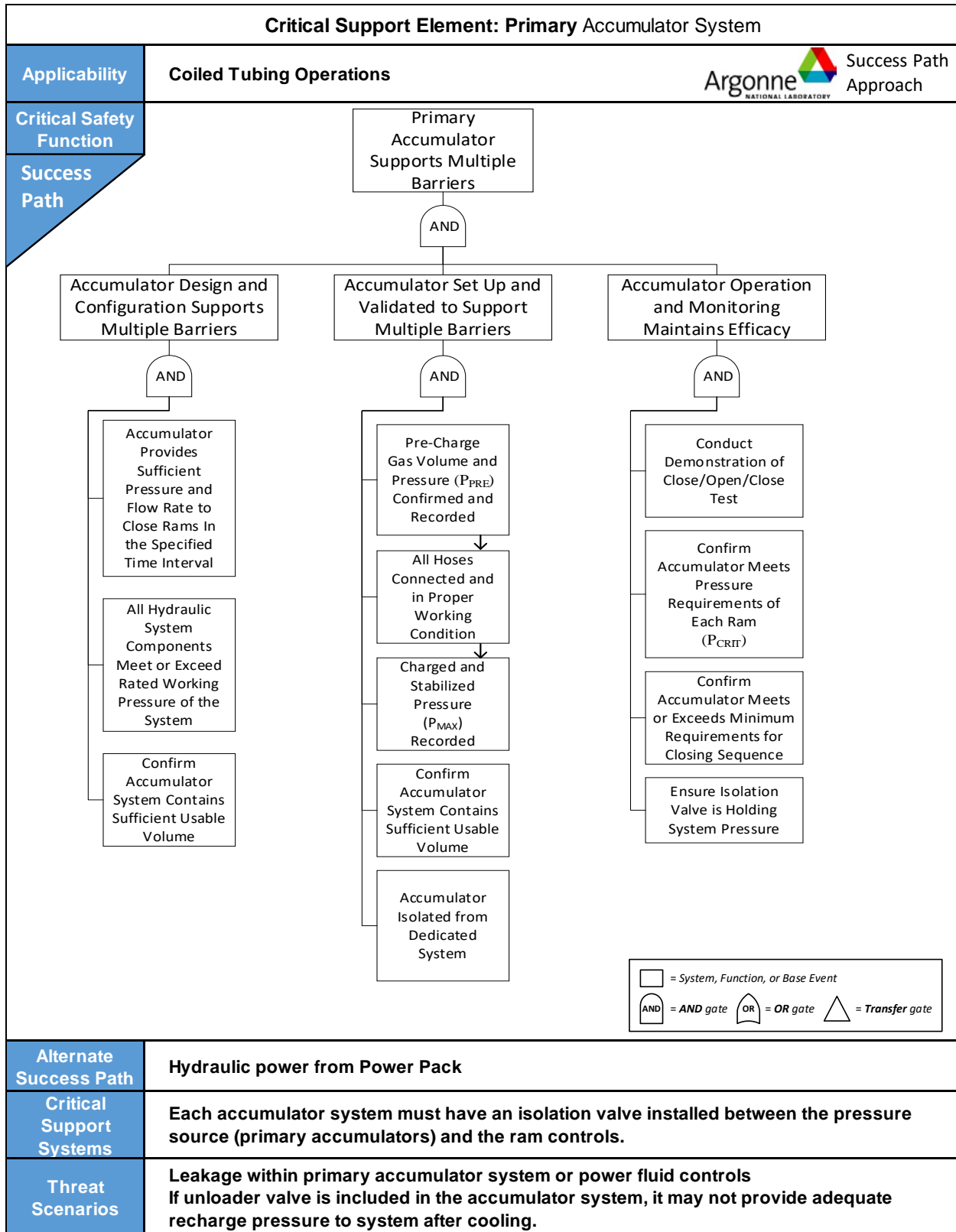


Figure II-35: Success Path for Accumulator System



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