Bureau of Safety and Environmental Enforcement

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Decision Support for Dynamic Barrier Management: Joint Industry Project for a Plug and Abandonment Barrier Case Study

Final Report

Argonne NATIONAL LABORATORY

DYNAMIC BARRIER MANAGEMENT

Decision Support for Dynamic Barrier Management: Joint Industry Project For a Plug and Abandonment Barrier Case Study Final Report

Argonne National Laboratory

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EXECUTIVE SUMMARY

This JIP furthers introduction to the "barrier-success path approach"- a fresh way of thinking about process safety in the Oil and Gas Industry [1]. It focuses on the question "Can we improve the safety and the economics of off-shore operations by looking at our work in a different way?" This focus lies in identifying the physical barriers that prevent environment and safety events of significant negative consequence caused by unintended hydrocarbon release, and the necessary support functions that enable the barrier to succeed.

Offshore oil projects involve exploration and production companies (operators), drilling contractors, and service companies, all seeking to produce oil and gas efficiently and safely. While regulators are primarily interested in the safety of these activities, they recognize the need for efficiency.

In 2015, BSEE requested that a JIP focused around physical barrier study be coordinated with Argonne National Laboratory (ANL).

On September 15, 2016, this JIP, organized by Argonne National Laboratory (ANL) in collaboration with DNV GL, assembled a team of twenty-seven executives and subject matter experts from the oil and gas industry who were willing to perform a case study to test whether the barrier-success path approach could help improve performance and safety. This was the 'kick-off' meeting for this project.

The JIP selected a deepwater operation case study to identify the physical barriers and success paths associated with it. The case study selected was a plug and abandonment (P&A) scenario —both for temporary and for permanent well abandonment—where the physical barriers are cement plugs installed in the well.

The approach uses the combination of Physical Barriers and Success Paths to describe and manage risks. The Success Path is a systematic way to identify the key functions and elements needed to ensure the success of a given physical barrier. For the oil and gas industry, this means maintaining asset integrity and preventing loss of containment while maintaining productivity of operations.

Typical P&A activities discussed and evaluated in this JIP include 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, TX, on October 10-11, 2016. It was attended by twenty-seven subject matter experts with expertise in offshore operations, including P&A and cementing. A typical P&A scenario was presented and discussed. Breakout sessions were conducted to begin the development of success paths for installation of the lower cement plug, and, at a later time, the upper plug that would be used for permanent abandonment. Groups worked in separate sessions to develop success paths for:

- Successful Plug Design
- Successful Plug Installation
- Testing and Verification of the Plug

The teams identified and described the key elements (hardware) and activities (human actions and related procedures) needed to conduct these activities in a safe and successful manner. Clear decision-making criteria (i.e. success criteria) and actions were defined for the success paths developed. Group sessions worked towards the definition of a generic success path and decision-making criteria with the goal of

achieving consensus among the workshop participants. An iterative process was used in all cases to discuss and refine the various success paths.

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.

The results of the Phase 1 JIP provide evidence that the barrier-success path approach could provide significant benefits to the offshore oil and gas industry, as summarized below:

- ***Well integrity, well control, and P&A.*** The barrier-success path approach provides a systematic process for applying process safety concepts and barrier management to well design, well construction, well control, and P&A activities. A significant benefit is seen in the ability to pre-identify alternatives for unexpected conditions, which can streamline response to unexpected situations that normally require re-evaluation and re-planning. This can add significant value to the project bottom line when compared to current practices, because a significant amount of time is typically spent identifying alternatives after encountering unexpected conditions. The benefit is significant savings when the average cost of rig time and spread costs can exceed $1 Million/day for an ultra deepwater well for the period when alternatives are being identified and decisions for action are being made.
- ***Cross-industry communication for performance and compliance.*** The barrier-success path approach provides a "common language" that can be used to communicate barrier and risk management information within organizations and across the global industry and regulatory authorities. This enables enhanced safety culture and organizational process safety performance both within individual organizations and across the industry.
- ***Human factors, decision making, and situation awareness.*** The barrier-success path approach promotes common situation awareness during coordination of work activities amongst operators, drilling contractors, and service companies; and provides clear guidance for responding to unexpected conditions including barrier or success path degradation. It is the combination of the engineering and the social science approaches in this concept which allows systematic assessment of risk informed decision support on human performance, risk awareness, process safety culture, and organizational performance.
- ***Qualification and regulatory approval of new technologies***. The visual format of the barrier-success path approach illuminates risk hence it is beneficial for comparison of a new technology with an existing one especially when operating outside defined envelopes, e.g., high pressure-high temperature (HPHT) conditions. It also facilitates qualification and regulatory approval of the new technology and facilitates discussion between the regulator and the industry stakeholder/ vendor.
- ***Barrier monitoring and management.*** The barrier-success path approach, when integrated with real-time support systems, can provide means to know the current condition of barriers and the success paths that are used to design, construct, operate, and maintain them.
- ***Process safety and risk management.*** The barrier-success path approach enables integration of human and organization factors with risk management of operations thereby improving process safety.

1 INTRODUCTION

The barrier-success path approach is formed by merging concepts developed by DNV GL in industry projects on the topic "Decision Support for Dynamic Barrier Management" with the Argonne National Laboratory Multiple Physical Barrier (MPB) Approach. Both approaches are presented in **Appendix 1** and **Appendix 2** respectively.

The barrier-success path approach has the potential to significantly enhance the safety and productivity of offshore oil and gas operations. The combination of physical barriers for preventing and mitigating events that can lead to downtime, asset damage, or major accidents with success paths, which provide guidance for achieving success in both safety and performance measures, provides a powerful framework for managing performance and risk. This combination has proven significant in the US nuclear power industry since the Three Mile Island (TMI) accident in 1979. The Phase 1 Joint Industry Project (JIP) titled, "Decision Support for Dynamic Barrier Management" was organized to test the value of the barrier-success path approach for the offshore oil and gas industry by applying it to a specific offshore operation. This entire effort is considered to be Phase 1. Future Phases are to be decided upon at a later time.

This report summarizes the results of the Phase 1 JIP and provides guidance for potential follow-on activities that will enable the effective application of barrier-success path approach for the benefit of the industry.

1.1 Background of the Joint Industry Project

In 2011, DNV GL supported an offshore operator in evaluating critical human factor issues highlighted by the Macondo event. A workshop was organized to apply the combination of barriers used in the offshore industry with success path concepts used the nuclear power industry. As a result of this workshop, decision-making was identified as a critical human factors issue. Based on the insights gained from this project, DNV GL organized an internal research project in 2012 titled, "Critical Decision Making for Well Control and Blowout Prevention" with the objective to develop industry partnerships for pilot applications of the combined barrier-success path approach. As a result, two pilot projects were performed with industry partners in the period from 2013 to the present:

- Development of a decision support concept for erosion integrity management for an offshore production facility in partnership with an offshore operator and the Norwegian Center for Integrated Operations in the Petroleum Industry [2].
- In partnership with a drilling contractor and an offshore operator, success paths, response trees, and decision criteria were developed for diagnostics and automatic reconfiguration of a next-generation blowout preventer (BOP) control system. This project also included development of a regulatory compliance logic tree for assessment of regulatory compliance for initial approval of the BOP control system as well as continuous compliance assessment and communication with Bureau of Safety and Environmental Enforcement (BSEE) during drilling operations [3].

Beginning in 2014, DNV GL began the process to define and develop support for a Joint Industry Project entitled "Decision Support for Dynamic Barrier Management." As part of this process, more than 140 industry experts representing approximately 60 different organizations were contacted to introduce the barrier-success concept and to solicit their interest in forming a JIP.

In late 2015, BSEE expressed their formal support and requested that the JIP be coordinated with Argonne National Laboratory (ANL) because of the similarities between the DNV GL approach for dynamic barrier management and the ANL Multiple Physical Barrier (MPB) approach [1]. Subsequently ANL arranged to sponsor the Phase 1 JIP activities.

1.2 Phase 1 objectives and scope

The primary objective of the Phase 1 JIP was to assess the value of the barrier-success path approach to reduce the risks of offshore operations. This objective has been accomplished by identification of critical industry issues for the management of barriers to prevent and mitigate major offshore accidents, and application of the barrier-success path approach to an industry-defined case study focusing on plug & abandonment (P&A) activities. Plug and abandonment was selected for the case-study purpose because of the increasing number of offshore facilities that are coming to their end of producing life and would be subject to decommissioning. It also allowed the assessment of the benefits of the barrier-success path approach for operational risk management and industry-regulator communication.

1.3 Phase 1 organization and participants

Figure 1 shows the organization of the Phase 1 JIP and the participating organizations. As shown in the figure, significant effort was made to involve diverse international industry organizations and regulatory authorities, such as Pemex, SENER (Mexico Ministry of Energy), and the Norwegian Petroleum Safety Authority (PSA).

The Phase 1 JIP was sponsored by Argonne National Laboratory who in turn was sponsored by the Bureau of Safety and Environmental Enforcement (BSEE) task order. This support made it possible to bring together an excellent mix of organizations even during difficult economic conditions. The distribution of the participating organizations amongst operators, drilling contractors, service companies, and regulators made it possible for the Phase 1 JIP to serve as a "laboratory" for application of physical barrier and success path concepts and assess their value for facilitating cross-industry and industry-regulator communication.

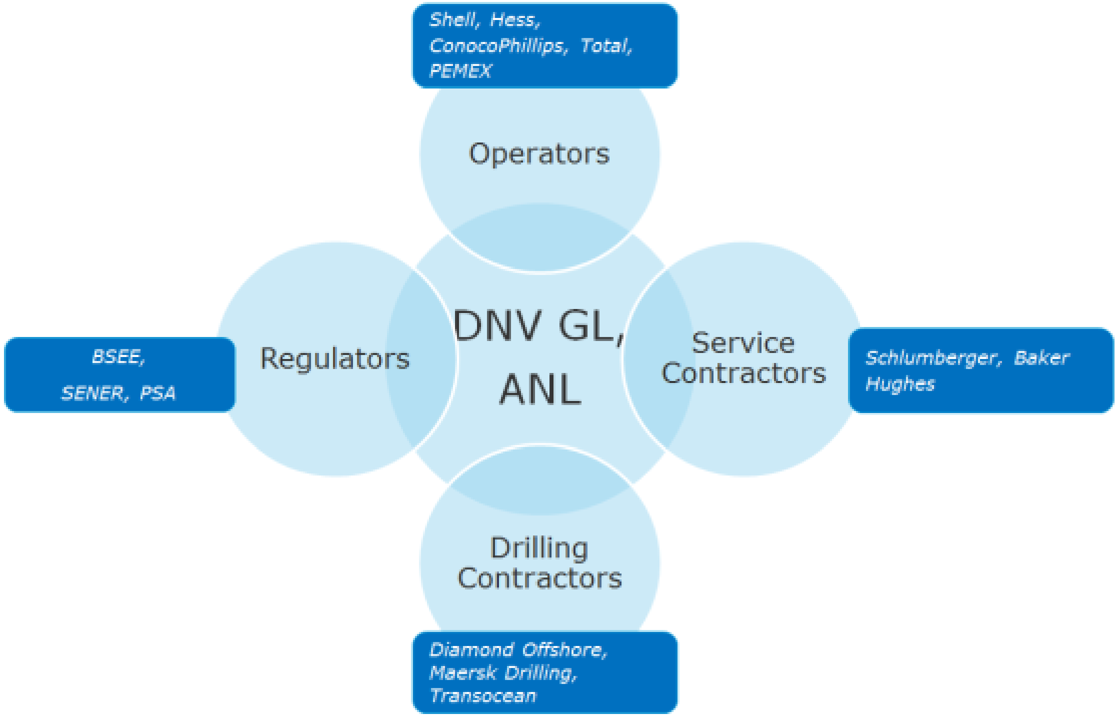

Figure 1: Organization and Participants of Phase 1 JIP

1.4 Phase 1 activities

The main activities of the Phase 1 JIP are summarized in the following sections. This entire effort is considered to be Phase 1. Future Phases are to be decided upon at a later time.

1.4.1 Kickoff Meeting

The Phase 1 JIP kickoff meeting was held on September 15, 2016. This meeting was attended by 27 decision makers representing wells and HSE functions from the participating industry and regulator organizations. During the meeting, the JIP background and objectives were presented, as well as the JIP organizational structure, participating organizations, and roles. An anonymous survey instrument was used to allow JIP kickoff meeting participants to provide input regarding the critical safety issues currently facing the offshore industry. A summary of the identified issues is presented in Appendix 3.

The background and technical overview of the barrier-success path approach were also presented to the participants to further illustrate the overall objective of the JIP. The proposed Phase 1 activities were summarized as well as the structure, participants, and logistics for the case study workshops. An outline of the proposed P&A case study was presented and feedback received from the meeting participants. Finally, the kickoff meeting attendees were tasked to return to their organizations and identify subject matter experts (SMEs) to participate in the case study workshops.

1.4.2 Case Study Workshops

Two case study workshops were held and were attended by 27 subject matter experts representing a broad cross-section of the four kinds of organizations: offshore operators, drilling contractors, service companies, and regulatory authorities, with the following areas of expertise:

- Cementing operations
- Offshore P&A operations
- Risk management
- Regulatory compliance assessment

Both case study workshops were structured to serve as a "laboratory" for collaboration and communication across the stakeholder groups, so the application of the approach could be tested in an environment representative of real-world activities.

The main activities of the first workshop held on October 10-11, 2016 were:

- **Present the barrier-success path methodology.**

The SMEs were presented with a summary of the barrier-success path approach, which set the framework for making good decisions based on the current conditions of barriers and success paths. They were also presented with a generic template for organizing information to identify key physical elements, decisions, and actions for cement plug installation.

- **Develop success paths for the P&A case study.**

The P&A case study was presented and discussed, after which breakout sessions were conducted to begin the development of a success path for installation of the lower cement plug. An iterative process was used to discuss the success paths as they were developed by each of the four breakout groups and refined during reconciled group sessions to work towards defining a generic success path with consensus of the workshop participants.

- **Perform information requirements analysis and decision support analysis for the P&A case study.**

On the second day, the process for information requirements analysis and decision support analysis was applied to identify the following:

    - **Success criteria -** Specific criteria that are used to determine whether the requirements have been satisfied.
    - **Actions -** Specific actions that should be taken if the success criteria are not satisfied
    - **Alternatives -** Specific pre-determined actions that should be taken if the success criteria cannot be achieved within an acceptable time frame or require taking an entirely different path.

  Once again, an iterative process was used to develop consensus on the success criteria, actions and alternatives to be taken if the success criteria are not achieved.

The main activities of the Second workshop held on October 31 - November 1, 2016 were:

- **Continued discussion of information requirements analysis and decision support analysis for the P&A case study to identify the following :**
    - **Source of information -** Statement of where the specified information can be obtained

- **Decision maker -** Personnel responsible for making the decision and communicating with other personnel either within the organization or externally to another organization.

Once again, an iterative process was used to develop consensus on the success criteria, actions and alternatives to be taken if the success criteria are not achieved.

- **Present Regulatory Compliance Tree.**

The proposed regulatory compliance success tree developed by DNV GL was presented and discussed briefly. Time limitations prevented reaching consensus on this success tree, but all agreed that it shows promise. DNV GL subsequently received comments from BSEE on the regulatory success tree which will be incorporated into the proposed regulatory success tree.

- **Identify potential visualization methods and potential methods for implementation to support decision making for dynamic barrier management.**

A group discussion was used to obtain participant feedback on potential applications of success paths within the stakeholder organizations, as well as for communication and coordination across stakeholder organizations. Breakout sessions were used to solicit potential concepts for visualization and communication of success path concepts, and the desirable methods for delivery of success path concepts for application within the stakeholder organizations.

- **Solicit participant perspectives on the value of the barrier-success path approach within their organization and for the industry as a whole.**

Workshop participants were provided an opportunity to comment on their impressions regarding the workshop process and the potential value of the barrier-success path approach for their organization and the industry. An open discussion was held to obtain participant comments and feedback on potential applications of the barrier-success path approach and the plans for the closeout meeting were discussed.

The results of the P&A case study workshops are presented in results of the Case Study Workshops, see Section 4.

1.4.3 Closeout Meeting

The JIP Phase 1 closeout meeting will be held February 2, 2017. Attendees will include the decision makers from the kickoff meeting and the SMEs that participated in the case study workshops. The SMEs will be given the opportunity to report on their experience from the case study workshops and their views regarding the value of the barrier-success path approach for their organizations and for the industry as a whole. Then the group will discuss the overall outcomes for the Phase 1 and determine the scope, organization, and resources for follow-on activities. A Phase 2 JIP could be organized involving some or all of the Phase 1 participants, or perhaps a set of smaller focused activities involving those organizations interested in specific activities. Several preliminary ideas for follow-on activities are discussed in 7.2

2 TECHNICAL APPROACH

2.1 The barrier-success path approach

The barrier-success path approach is formed by merging concepts developed by DNV GL in industry projects on the topic "Decision Support for Dynamic Barrier Management" with the Argonne National Laboratory Multiple Physical Barrier (MPB) Approach. Both development efforts have been underway independently for the past five years with the same motivation—to integrate the strengths of the success paths concept of the nuclear power industry with physical barrier-based risk management approaches from the offshore oil & gas industry.

See Appendix 1 for a summary of the DNV GL approach for Decision Support for Dynamic Barrier Management and, Appendix 2 for a description of the ANL MPB Approach.

3 JIP PHASE 1 CASE STUDY WORKSHOPS

The main activities of the workshops are outlined in section 1.4.2.

3.1 Description of the P&A case study

The P&A case study involved placement of three cement plugs for temporary and permanent abandonment of a hypothetical well in the Gulf of Mexico. The final desired configuration of the well is shown in Figure 2. Given the limited time available, the workshop discussions focused on design, installation, and testing of the lower cement plug.

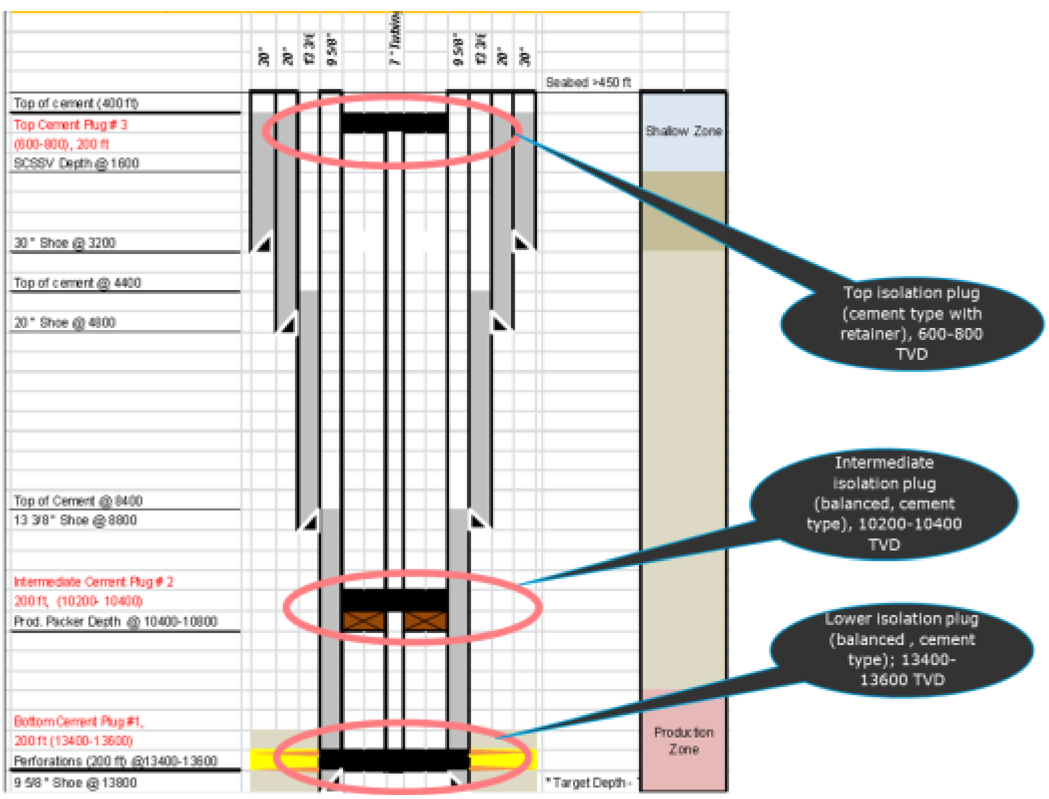

Figure 2: Final Well Configuration for P&A Case Study

4 RESULTS OF THE CASE STUDY WORKSHOPS

4.1 Process of developing success paths and decision support for the P&A case study

The following steps were performed in the JIP case study to develop the success paths, decision support information, and regulatory compliance assessment for the specified P&A scenario. It should be noted that the resulting success paths and decision support information are generic for installation of a cement plug for this specific scenario, which may not represent all the specificities required to develop a success path for a particular P&A project. The intent of this workshop is to develop a generic approach based on industry consensus of SMEs that can then be taken back to each organization and adapted for a specific project.

The steps used to develop the P&A success paths are summarized in the following.

4.1.1 Identify P&A project phases to structure success paths

The first step was to identify the phases of the P&A project that would be the focus of the success paths. In general, any specific system or installation can be described in terms of the acronym DCOM—Design, Construction (includes Installation and Testing/Verification), Operation, and Maintenance. Since the cement plug barrier used for the case study is not usually subject to "operation" or "maintenance" in the usual sense of an active system, it was adequate to focus on following two phases:

1. Design of the cement plug
2. Construction of the cement plug
    - Installation of the cement plug
    - Testing/verification of the cement plug

Success paths were developed for each i.e. Design, Installation and Testing/Verification of the cement plug.

4.1.2 Identify end states

In the process of success path development, it is very easy to think in terms of "activities" or "procedure steps" when developing the list of items that are needed for success. When this occurs, the added value of the success path concept is lost, and the effort becomes an exercise in procedure writing. Instead the approach presented during this JIP proposes a mindset of "end states" or conditions that must be achieved in order to achieve success. These end states may be sequential or not. The key is to provide a "checklist" of end states that must be accomplished and verified. Thus, when all end states have been verified, the framework for the success path has been implemented, and it is ready for the next step.

4.1.3 Identify requirements for achievement of each end state

Next, the requirements for achieving each end state are identified. Each requirement is described in terms of quantitative or qualitative measures that can be conclusively verified.

4.1.4 Identify "showstoppers"

For the P&A case study, not all of the end states on the three success paths (Design, Install, and Test) were equally important. Therefore, a group discussion was focused on the "showstoppers" that—if not achieved—could introduce a barrier vulnerability thus threatening the accomplishment of the success path. While for other end states it would be sufficient to "keep working" to satisfy the requirements, for a showstopper, immediate action would be needed to identify an alternative.

4.1.5 Develop consensus for success paths

The Design, Install, and Test success paths were developed in breakout sessions and then subjected to the discussion by the whole group in order to obtain consensus. In addition, the success paths that were developed in Workshop 1 were then discussed at the beginning of Workshop 2. In this way, the resulting success path diagrams represent the consensus of the group, with time for reflection and internal discussions within their home organizations between the workshops.

4.1.6 Identify success criteria, actions, and alternatives for each node of the success path

The backbone of decision support for dynamic barrier management is to define the content and application of information that is needed to:

- Assess the health of each barrier;
- Assess the availability of each success path;
- Assess the performance of a success path in supporting the barrier;
- Decide when an alternate success path should be implemented for maintaining the effectiveness of a specific barrier; and
- Decide when a barrier has failed and give attention to the performance of a different barrier, and implement success path(s) to ensure its effectiveness.

A general approach has been developed for capturing this information and organizing it to support the assessments and decisions described above. That is, for each node of the success tree the following categories of information are identified:

- **Success criteria -** Specific criteria that are used to determine whether the requirements have been satisfied. The success criteria are defined in terms of specific parameters, thresholds that must be satisfied, and (when needed) the logical combinations of criteria that define success.
- **Actions -** Actions that should be taken if the success criteria are not satisfied, with the goal to satisfy the success criteria within an acceptable time frame.
- **Alternatives -** Actions that should be taken if the success criteria cannot be achieved within an acceptable time frame. In many cases, this will consist of selection and implementation of an alternate success path for a given barrier, or (when needed) shifting attention to a different barrier and its associated success paths.

For a full implementation of the barrier-success path approach, this assessment would include identification of the sources of all the necessary information—whether "live," real-time instruments or periodic or on-demand audits/inspections.

4.1.7 Review and revise P&A compliance assessment tree

The technical assessment of barrier health and success path status can be used to inform the assessment of regulatory compliance. For compliance assessment of a mechanical system such as a BOP control system—

where the requirements (e.g. API STD 53) are largely streamlined—it is relatively straightforward to translate the written requirements into a logic diagram using conventional Boolean *AND* and *OR* gates to define the logical relationship among success tree elements. However, in many circumstances, the regulations and industry standards can be indistinct, and capturing them in a logic diagram becomes more challenging. However, even in such circumstances, development of the compliance assessment logic diagram presents an opportunity for industry and regulatory organizations to engage in a discussion and reach consensus on how the requirements for compliance should be interpreted. This could mean reaching an agreement in advance and assessing compliance more rapidly and accurately during abnormal operating conditions.

For the P&A case study, a regulatory compliance assessment tree was developed by DNV GL prior to the workshops. It was then reviewed during the workshop by the group of SMEs, and BSEE provided comments after the workshops. Additional discussion by the full group is still needed to ensure that consensus has been reached.

The proposed regulatory assessment diagram for the P&A case study is discussed in Section 4.4.

4.1.8 Develop template for decision support and structure for P&A "dashboard"

Development of a success tree in a workshop setting is a free-form process, including the development of a logic model using *AND* and *OR* gates. It can be beneficial to define a template to allow for a common structure to organize information on barriers and success paths, and a "dashboard" that can be used to present and visualize the current conditions of barriers, success paths, and recommended actions during operations.

A preliminary concept for such a dashboard has been developed based on the workshop results and is discussed in Section 5.1.

4.2 Success paths for plug and abandonment case study

4.2.1 Design of the lower cement plug

Figure 3 shows the complete success path for the design of the lower cement plug. Figures 3a and 3b provide enlarged views of portions of the full tree. As shown in the figure, the objective of the plug design is "Successful barrier design fulfills isolation requirements." There are five major elements required for the successful design of a cement plug:

- *Initial state of well supports isolation*
  The initial state of the well must have the adequate mechanical integrity to support well access, adequate provisions for well control to support intervention and isolation, and adequate mechanical integrity to support well isolation.

- *Intervention and plug installation equipment supports design*
  Required characteristics of the intervention and installation equipment include adequate rig, pumping setup, flow and density measurement, bulk system cement unit, onsite lab equipment and personnel, and logistics.

- *Cement design and testing*
  For achievement of cement design and testing requirements the long-term cement design criteria and the job-specific cement, the lab must support isolation.
- *Placement design supports isolation*
  Achievement of adequate placement design requires adequate spacer, cement and displacement fluid volumes and rates; placement sequence that honors the fluid density and rheology hierarchy, and mechanical separation devices.
- *Requirements for barrier verification are established*
  The plug design should include a definition of testing requirement.

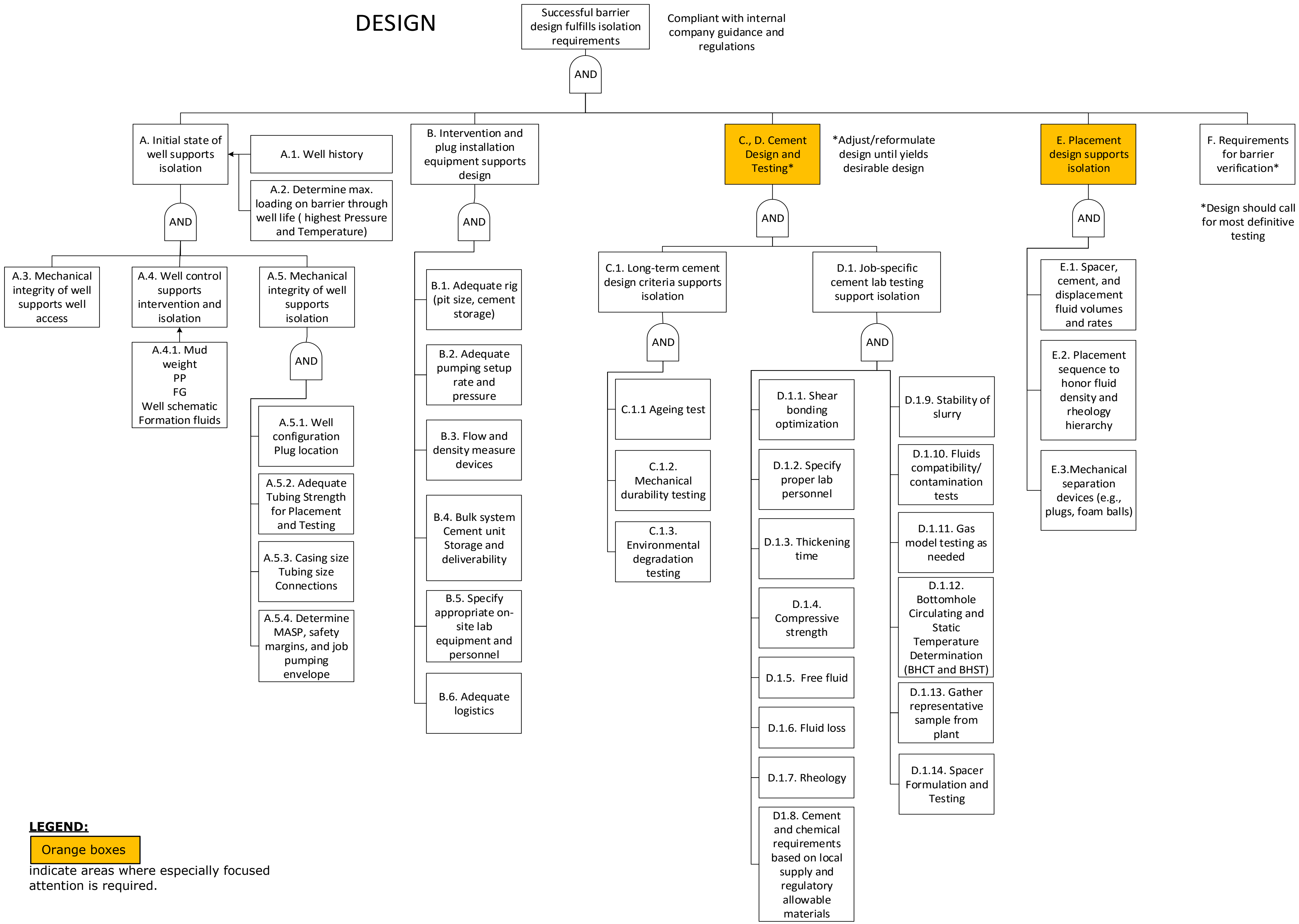

Figure 3: Success Path for Plug Design (Full)

Please note: The orange block represents "showstoppers". Refer section 4.1.4

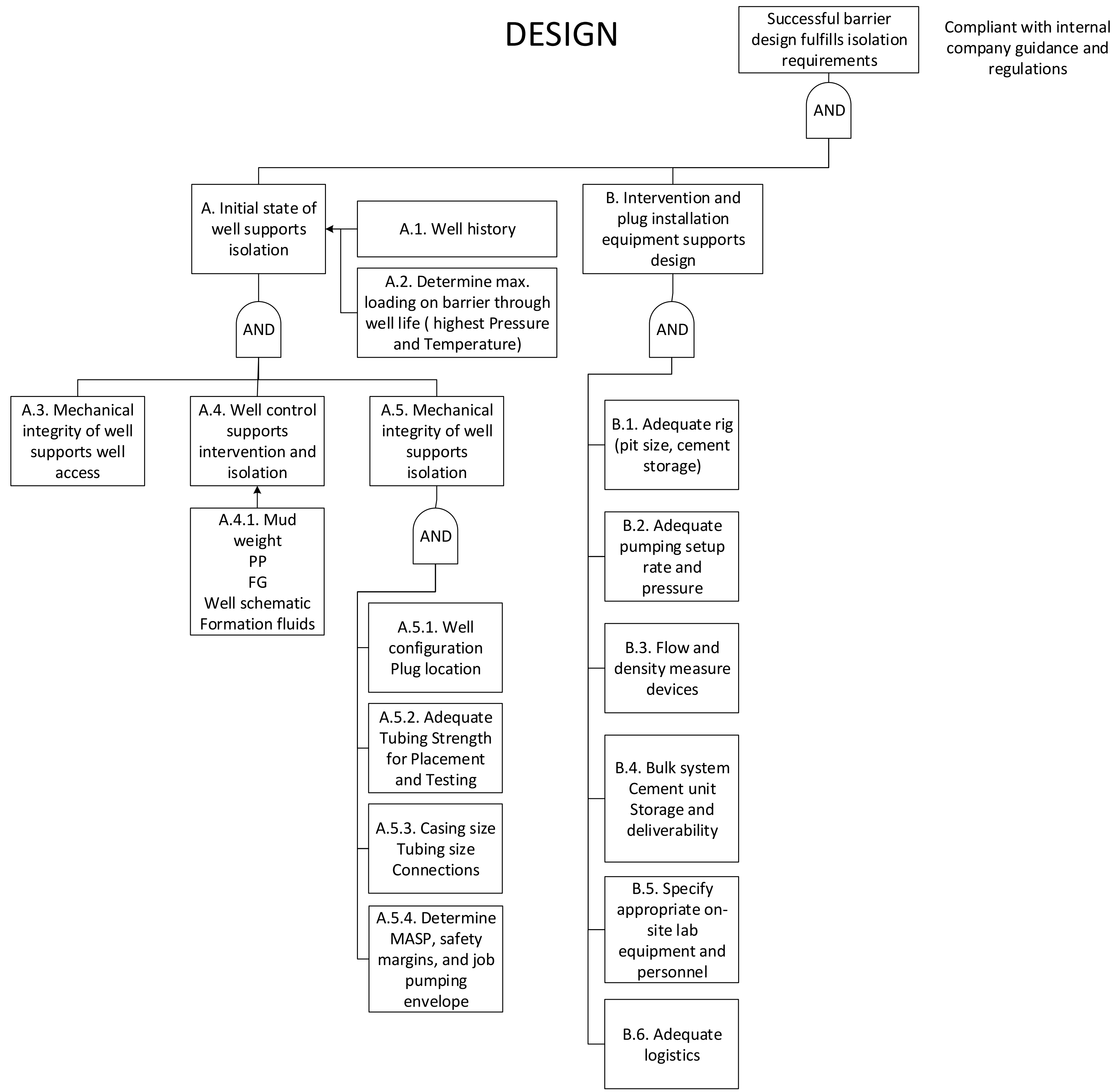

Figure 3a: "A and B" leg of the Success Path for Plug Design

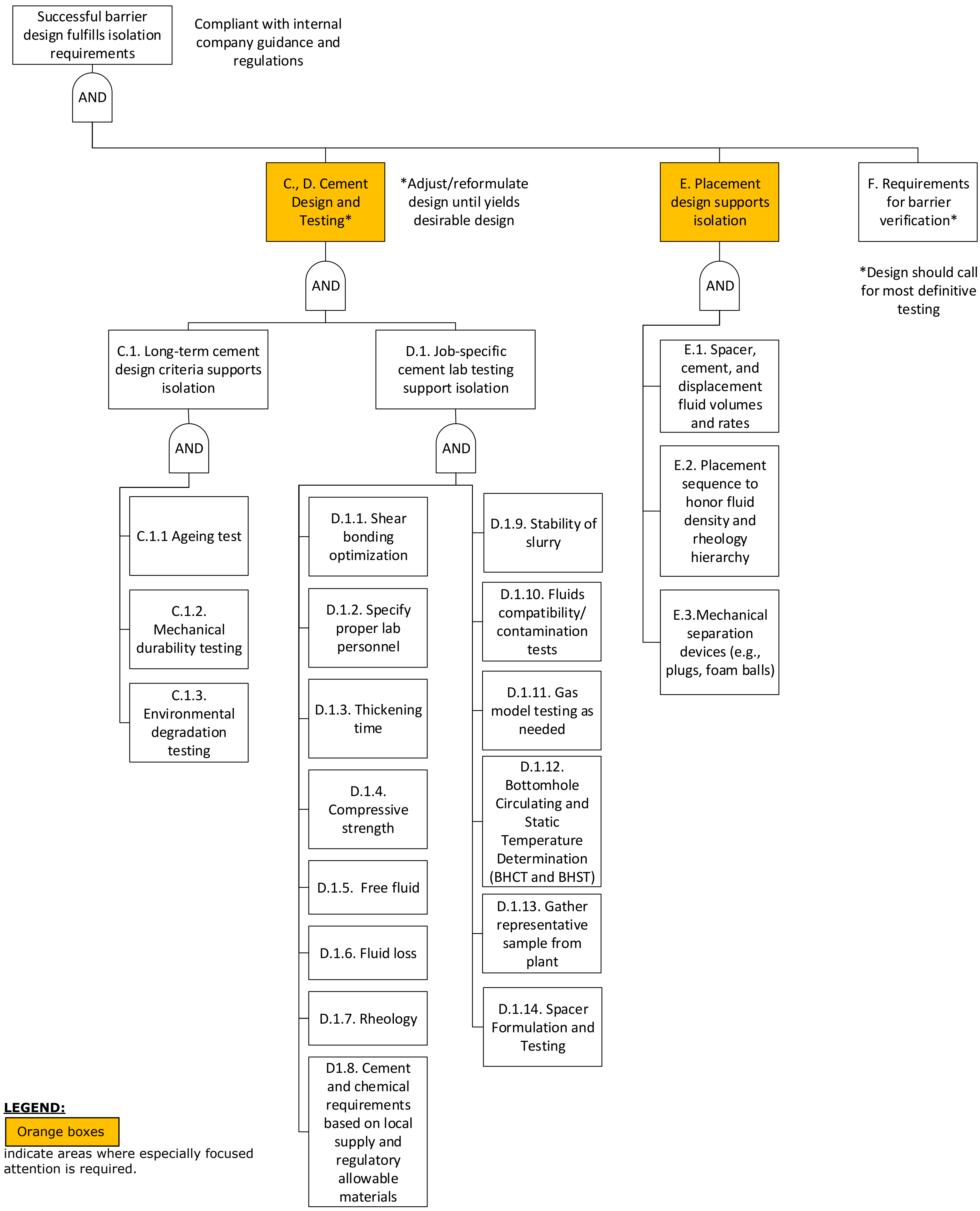

Figure 3b: "C, D, E, and F" leg of the Success Path for Plug Design

Please note: The orange block represents "showstoppers". Refer section 4.1.4

4.2.2 Installation of the lower cement plug

Figure 4 shows the complete success path for installation phase of the lower cement plug. Figures 4a and 4b show enlarged views of portions of the full success paths. The objective of this phase is to install the plug to meet the safety function—i.e. to provide hydraulic seals for isolation of pressure and flow in the well.

As shown in the figure, three major elements must be accomplished to achieve installation of the cement plug to meet the safety function:

- *Wellbore prepared to meet design criteria*
  In order to prepare the wellbore to meet design criteria, it is necessary to ensure that the well mechanical integrity meets design criteria, the injection test confirms the design criteria, and the well tubular surface is prepared for sealing.
- *Cement slurry mixed to design density*
  In order to ensure that the cement slurry meets the design density, it is necessary to verify that the equipment meets the slurry mixing requirements and that the slurry quality supports isolation.
- *Plug placement meets operational specification*
  To ensure that the plug placement meets operational specifications, it is necessary to verify that Top of Cement (TOC) is at the correct location according to design. This is accomplished through adequate displacement volume control, monitoring the fluid pumping schedule, verifying positive surface pressure indication, and ensuring wait on cement (WOC) time meets the design specification.

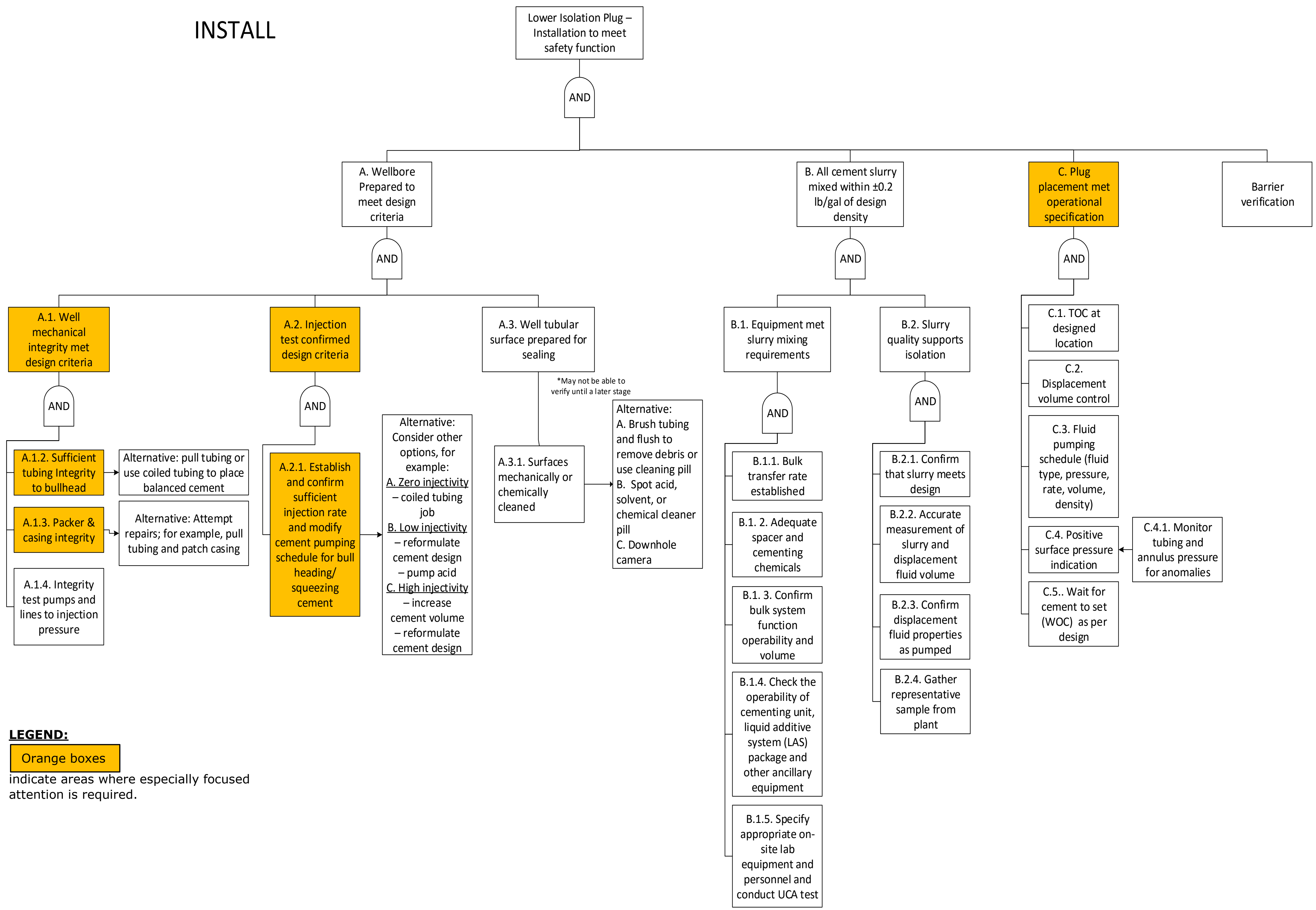

Figure 4: Success Path for Plug Installation (Full)

Please note: The orange block represents "showstoppers". Refer section 4.1.4

INSTALL

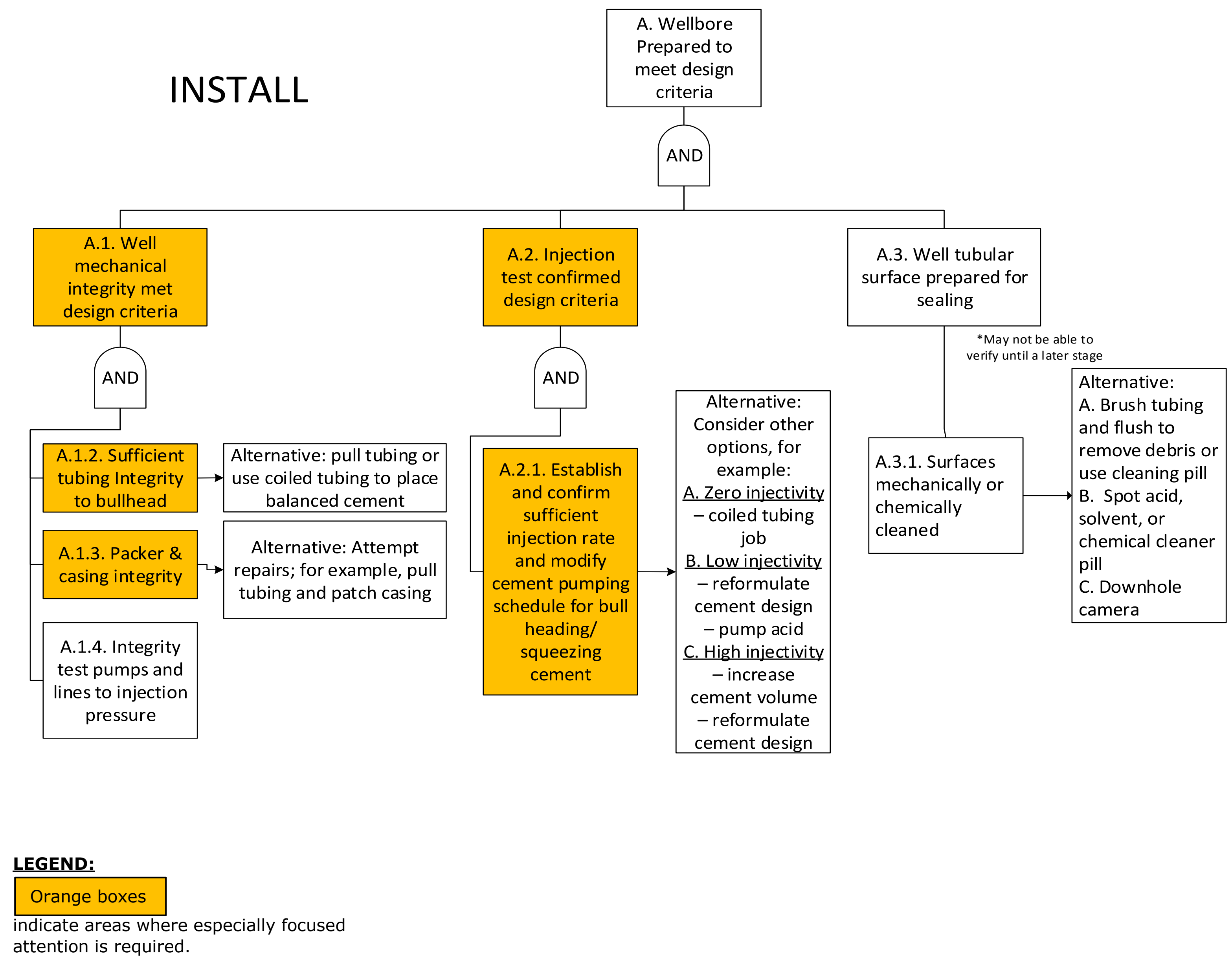

Figure 4a: "A" leg of Success Path for Plug Installation

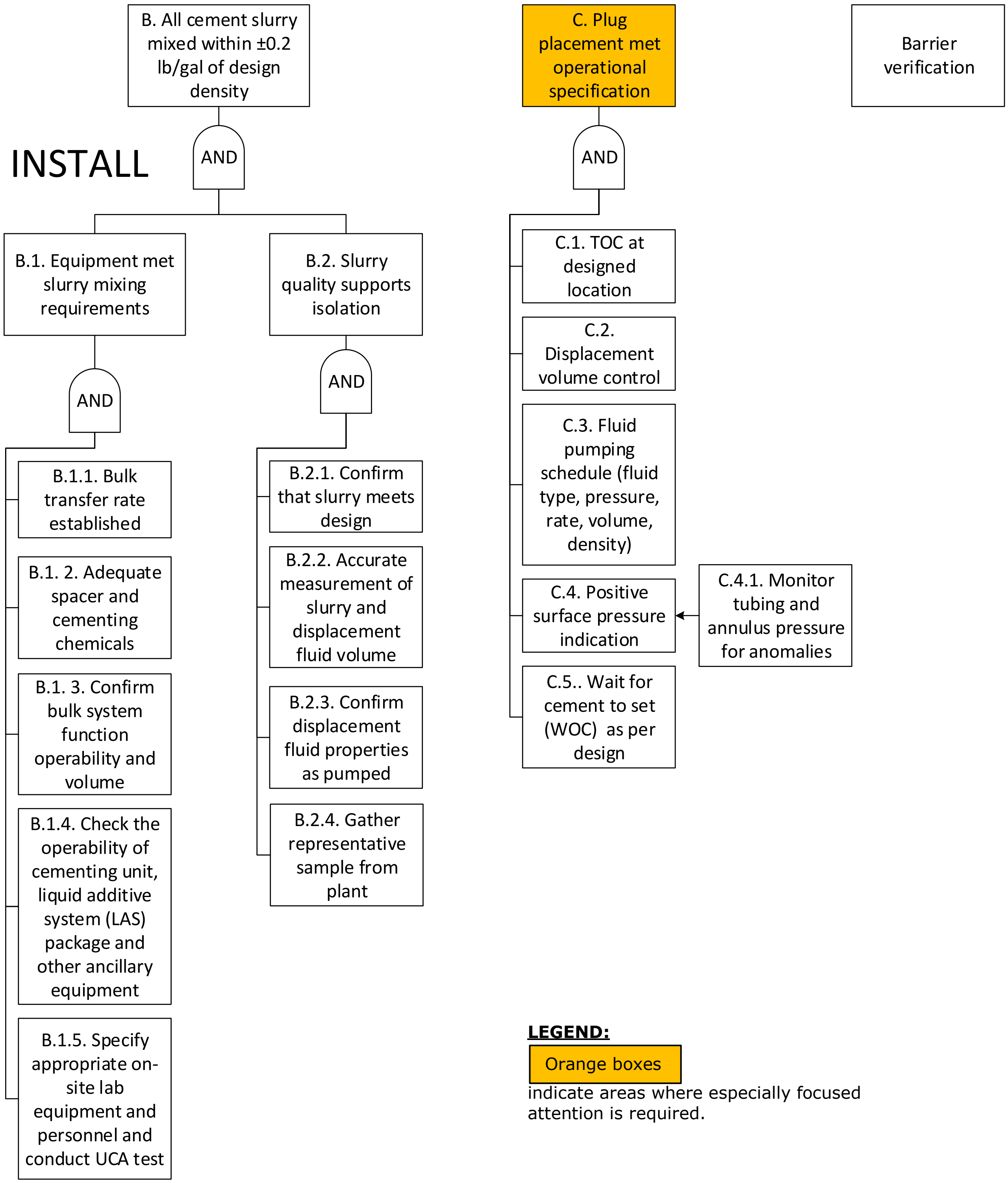

Figure 4b: "B and C" leg of Success Path for Plug Installation

4.2.3 Installation of the lower cement plug

Figure 5 shows the success path for testing and verification of the lower cement plug. In order to ensure that the plug is tested and verified to accomplish the safety function, it is necessary to confirm resistance of the plug to flow and pressure transmission and to confirm correct cement placement.

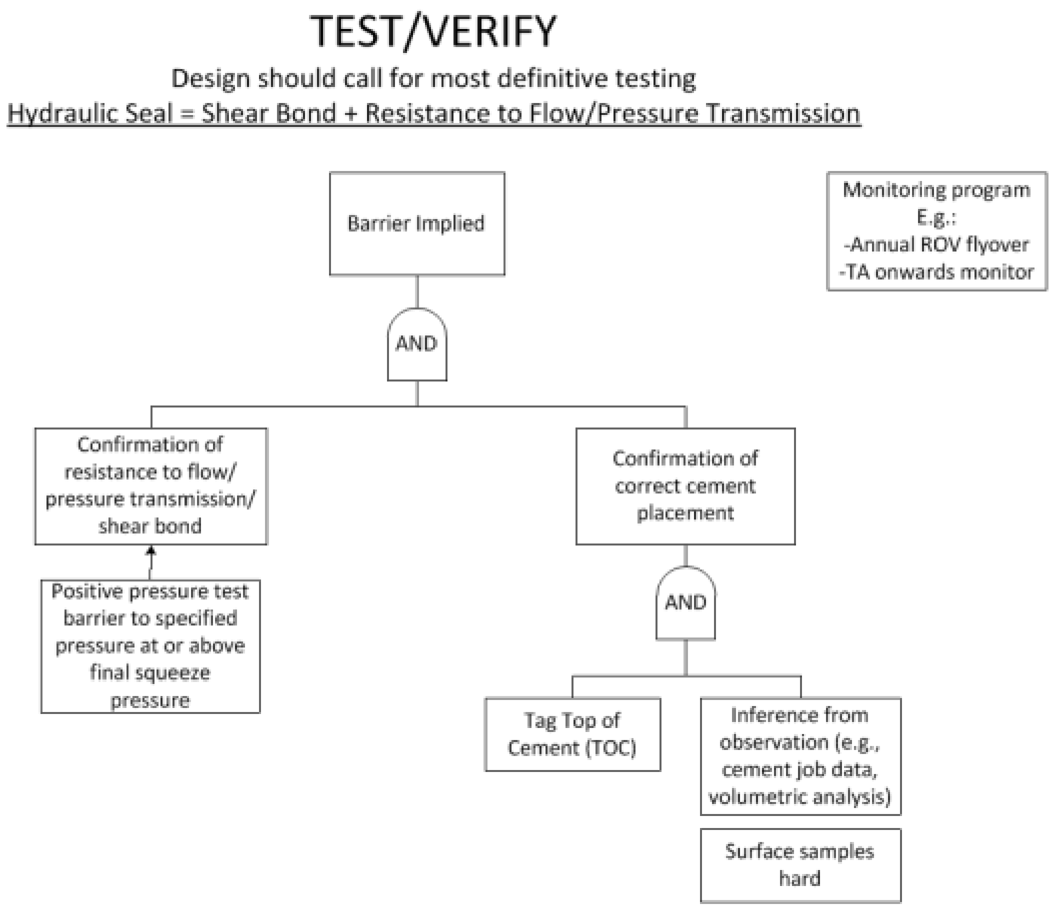

Figure 5: Success Path for Plug Test and Verification

4.3 Decision support analysis for the case study

Table 1 shows the structure of the spreadsheet for the decision support analysis used for the P&A case study workshops. For each node on the success path, the table is used to identify:

- **Success criteria (IF) -** Clear criteria for determining the successful performance of the barrier, completion of the Design, Install, or Test activities for P&A, or successful accomplishment of the End State for the success path. The success criteria are typically expressed in terms of the logical (e.g. Boolean) combination of predetermined thresholds for the relevant parameters i.e. If success criteria/criterion is met then desired requirement for each end state has been achieved.

- **Action (IF NOT THEN) -** Clear description of the actions that should be taken if the Success Criteria have not been met to achieve the same end state i.e. **IF** success criteria is not met **THEN** actions to be taken to achieve the desired requirement for each end state.
- **Alternative -** Clear statement of pre-determined actions that should be taken if the success criteria cannot be achieved within a pre-determined time frame to achieve the same end state. This could include activation of an alternate success path for the current barrier, activation of a success path for a different barrier or transition into a different success tree to achieve an alternate end state such as for showstoppers (see section 4.1.4).
- **Source of information -** Statement of where the specified information can be obtained, either from a direct source (e.g. instrumentation, audit/inspection or test results, etc.) or indirect source (e.g. inferred or calculated from other information).
- **Decision maker -** Personnel responsible for making the decision and communicating with other personnel either within the organization or externally to another organization. The specified personnel can be denoted according to the following categories:
    - Responsible (R)
    - Accountable (A)
    - Consulted (C)
    - Informed (I)

The use of this systematic approach for information requirements and decision support analysis forms the foundation of a comprehensive decision support concept for dynamic barrier management, including definition of instrumentation and possibilities for automatic reconfiguration depending on status of barriers and success paths.

A full information requirements analysis was not performed during the JIP Phase 1 P&A case study workshops. In particular, information regarding Information Sources and Decision Makers was not gathered. Table 1 shows some example results for the success criteria, actions, and alternatives for the plug installation success path.

Table 1: Spreadsheet for Decision Support

Success Criteria, Actions, and Alternatives for Install Leg of Success Tree (Lower Isolation Plug)

		SUCCESS CRITERIA (IF)	ACTION (IF NOT THEN)	ALTERNATIVE	SOURCE OF INFORMATION		DECISION MAKER & COMMUNICATION							
Requirement on Success Tree	***Ref. No.***				***Direct***	***Indirect***	***Internal***				***External***			
Sufficient tubing Integrity to bullhead	A.1.2.	No annular pressure = tubing pressure/ Tubing Pressure Test & Caliper / set plug in top packer with Wireline, pressure test tubing to x % of premium pipe (formation leak off DATA +_ 1000 PSI)	Pull tubing, use coiled tubing/ Set cement Balance Plug / Pull tubing out of hole	pull tubing or use coiled tubing to place balanced cement			R	A	C	I	R	A	C	I
Packer & casing integrity	A.1.3.	No annular pressure = tubing pressure / pressure test annulus to whatever tubing pressure test was		Attempt repairs; for example, pull tubing and patch casing										
Establish and confirm sufficient injection rate and modify cement pumping schedule for bull heading/squeezing cement	A.2.1.	Injection rate & pressure consistent with design / rate < 2bpm the x volume, if rate > 3 bpm then Vt = x + 50%, if rate > 6 bpm then Vt = x+ 100%	Reevaluate options and modify design/ Reevaluate options and modify design	Alternative: Consider other options, for example: A. Zero injectivity – coiled tubing job B. Low injectivity – reformulate cement design – pump acid C. High injectivity – increase cement volume – reformulate cement design										
Surfaces mechanically or chemically cleaned	A.3.1	analyze production samples and design spacer accordingly / circulation not possible then run brush and go with that	confirm at final pressure test	A. Brush tubing and flush to remove debris or use cleaning pill B. Spot acid, solvent, or chemical cleaner pill C. Downhole camera										

4.4 Regulatory Compliance assessment tree

Figure 6 shows the complete regulatory compliance assessment tree for plug and abandonment as developed by DNV GL. Figures 6a and 6b show enlarged views of portions of the tree. The logic tree represents the BSEE requirements of 30 CFR 250.1715.

As shown on the diagram, BSEE regulations require multiple plugs for pressure and flow isolation in a well. Detailed requirements are given for demonstrating that plugs provide isolation for:

- Zones in open hole;
- Zones in open hole below casing;
- Perforated zones that are currently open and not previously squeezed and isolated;
- Casing stubs where the stub end is within the casing;
- Casing stubs where the stub end is below the casing;
- Annular spaces that communicate with the open hole and extend to the mudline;
- Subsea well with unsealed annulus; and
- Wells with casing.

The regulations also include requirements for fluid left in the hole between plugs, plug length (plugs must be at least 100 feet long at the base of the deepest casing string), retrievable or permanent bridge plugs and cement plugs, and obstructions above the mudline.

This preliminary draft model is an example of a starting point for discussion between industry stakeholders and regulatory authorities to reach agreement on success criteria for regulatory compliance of P&A projects. It also provides a good basis for addressing “What if?” type of queries from regulatory authorities and industry stakeholders and can discuss the decision criteria and actions to demonstrate the particular contingency has been considered and pre-planning has taken place.

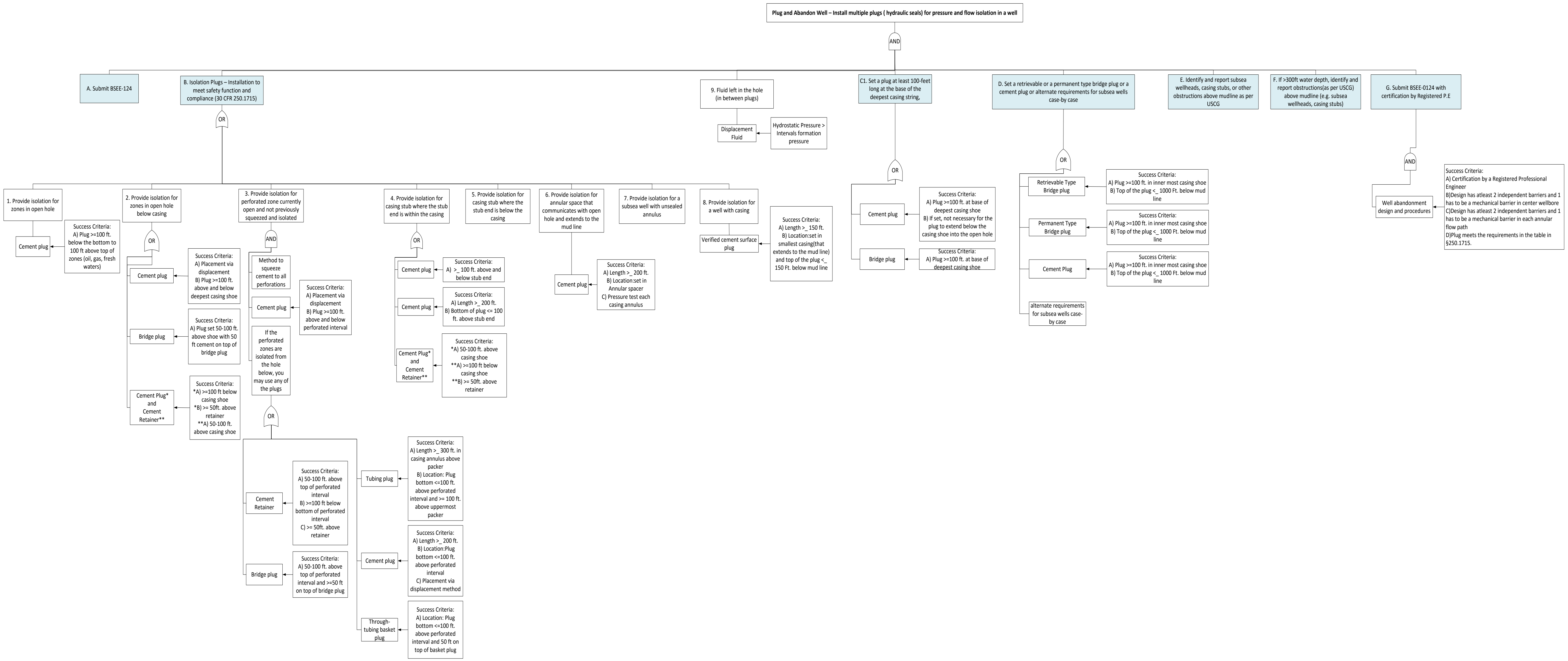

Figure 6: Regulatory Compliance Assessment Tree for P&A (Full)

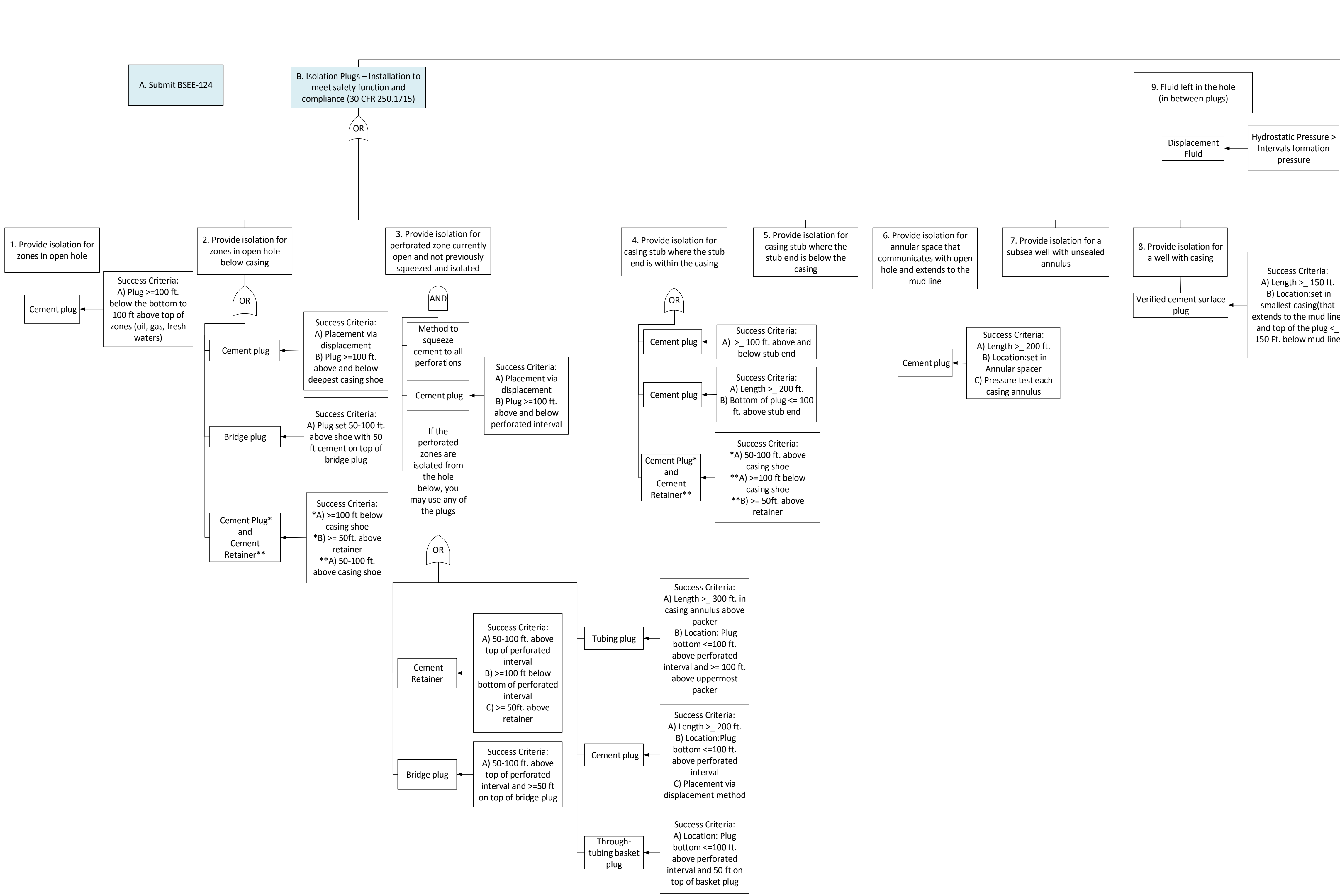

Figure 6a: "A and B" leg of the Regulatory Compliance Assessment Tree for P&A

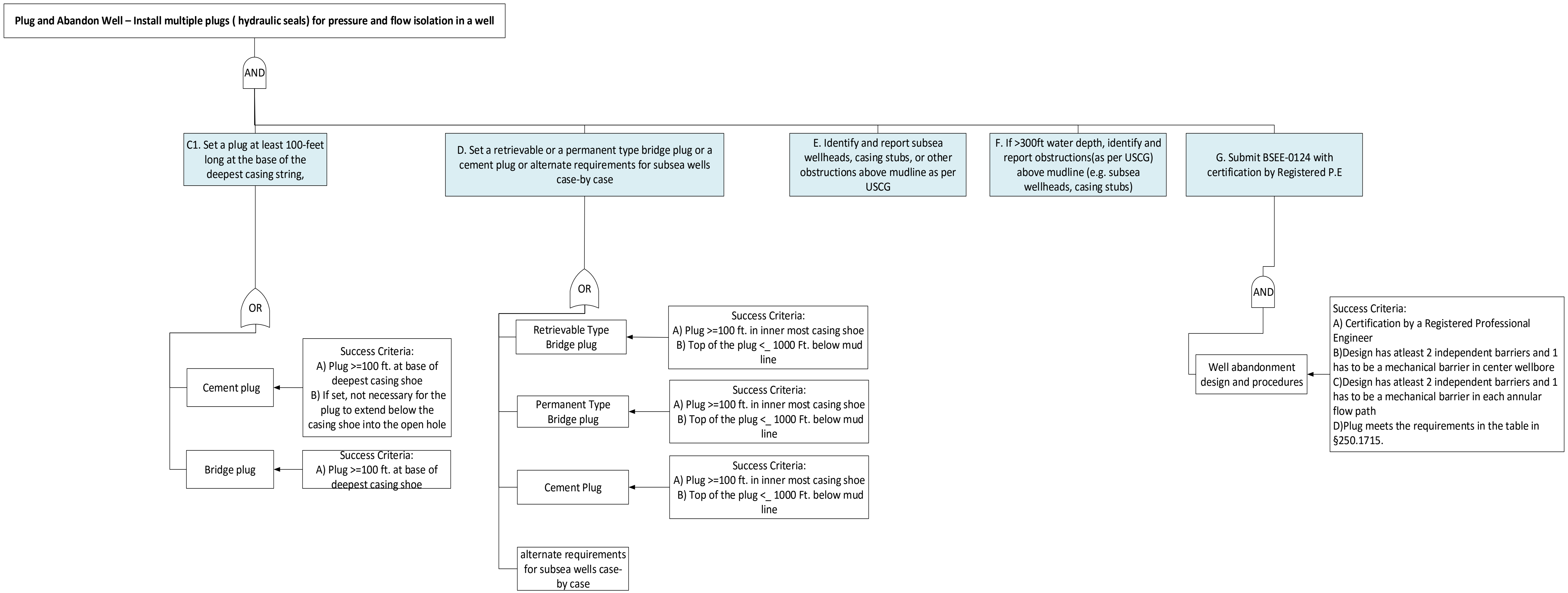

Figure 6b: "C, D, E, F, and G" leg of the Regulatory Compliance Assessment Tree for P&A

4.5 Feedback from case study workshop participants

At the end of the second case study workshop, participants were given the opportunity to provide input on the value of the barrier-success path concept for application to P&A and other types of offshore operations. The feedback obtained from the workshop participants is summarized in the following sections.

4.5.1 Potential applications of the barrier-success path concept

Participants identified many potential applications for the barrier-success path concept, as summarized in the following paragraphs.

- The success path approach could be used as the starting point for the development of operating procedures that would be effective in ensuring that the relevant barriers are established, monitored, and maintained which is different from current industry approach of procedural writing with a focus on task rather than barriers. In the development of procedures, success paths could be used to ensure that all steps are clearly identified and to ensure that steps that are critical to maintaining the barriers are not omitted. This could, in particular, be applied to the design, construction, and testing phases of cement barriers for P&A and could significantly improve project performance.
- The approach could also be applied to planning and implementing activities for in-between well maintenance for drilling operations. The success path development process and implementation could be shared across the companies involved in the projects, including clear identification of roles and responsibilities of the participating organizations and personnel.
- Barrier and success path concepts could be used in training, to ensure that employees understand the role and functions of the critical physical barriers.
- The success path models could be directly interfaced to real-time monitoring instrumentation to ensure that current conditions are used to inform the assessment of barrier status and recommended actions.
- A barrier-success path framework could be used to support incident investigation and root cause analysis by focusing on the performance of the barriers during the incident, and how well equipment response and human decision making supported the effective performance of the barriers. The framework could also be used to interpret operating experience across incidents to identify and prioritize attention to barriers that could be enhanced.
- In order to institutionalize the benefits of the barrier-success path approach, workshop participants envision operationalizing the process and linking it to the management system and business governance to manage enterprise risk.
- The barrier and success path models could be used to support high-level communication and consensus between industry organizations and regulatory authorities. For example, a regulatory compliance tree could be designed according to an agreement between the industry and the regulator on barrier success criteria and further actions mitigate degrading barriers.

4.5.2 Potential visualization and delivery methods

Workshop participants were asked to develop ideas on how to best visually represent the success paths, barrier conditions, and actions to be taken for communication purposes and following suggestions were made:

- Visualization Methods

Visual representation of current well conditions such as a dynamic well barrier schematic and use of color coding / status for each critical barrier element (see

Figure 8).

  - A success path logic diagram showing current conditions of each element, whether success criteria are satisfied, and recommendations for actions that are needed. The incorporation of the barrier-success path approach into a digital application could be used to take this information into the field and for real-time updates and communication of current conditions within the organization and across the industry.

- Delivery Methods

  - The most popularly identified delivery method was an application (e.g., a mobile app or cloud based service) that could be used to develop success paths and monitor them real-time in the field (onshore/ offshore). This application could be connected to a common database such that could store this information for use within the organization or across the industry.
  - Another suggested method of delivery was the publication of an industry best practice or a guideline for application of barrier and success path concepts. Prior to the development of a consensus best practice, the methodology and guidance for implementation should be published. Some guidance for methodology and implementation is has been shared in SPE published papers. See references [1] and [2].
  - The results of the application of barrier-success path analytics could be shared, and the concepts incorporated in training and knowledge sharing programs.
  - Inclusion of the visual barrier-success path diagram into company documents/ processes such as Permit To Work (PTW) and pre-tour meetings to create a basis for discussion during approvals and inform user of critical human actions or interfaces in order to reduce human errors.
  - Inclusion into training programs and use for onboard training to explain impact of not following success paths, communications and decision making (see column “Decision maker and communication” in Table 1).

4.5.3 Value of the barrier-success path approach

Workshop participants were asked about their views regarding the value of the barrier-success path approach. They commented that the approach helps to focus on success and identification of things that must go right for planning projects and managing safety barriers. A significant benefit is seen in the ability to pre-identify alternatives for unexpected conditions, which can streamline response to unexpected situations that normally require re-evaluation and re-planning. This can add significant value to the project bottom line when compared to current practices, because a significant amount of time is typically spent identifying alternatives after encountering unexpected conditions. The benefit is significant savings when the average cost of rig time and spread costs can exceed $1 Million/day for an ultra deepwater well for the period when alternatives are being identified and decisions for action are being made.

In the domain of barrier management, the combined barrier-success path approach can simplify bow tie diagrams so that they focus on the critical physical barriers while the success path highlights the supporting equipment, procedures, and human actions that are needed to make sure the physical barriers successfully utilized for well control or other threatening situations. This information can be distilled in the systematic framework in the written manuals and procedures, to focus on the critical elements (e.g., training, maintenance, etc.) that must be performed properly. The same information framework can be used to identify the required instrumentation and decision algorithms for automating processes and equipment when appropriate. Maximum attention can be given to areas where failures are known to occur as part of defining success paths and procedures for specific jobs.

5 ADDITIONAL THOUGHTS AND IDEAS FOR IMPLEMENTATION

5.1 Proposed P&A Dashboard concept

Once the barriers and success paths are identified and the decision support information—including success criteria, actions, and alternatives—is established, it is possible to create a standardized representation that can be used to continuously monitor the status of the barriers and success paths. Figure 7 shows a preliminary concept for a "dashboard" for continuous barrier and success path monitoring for plug and abandonment.

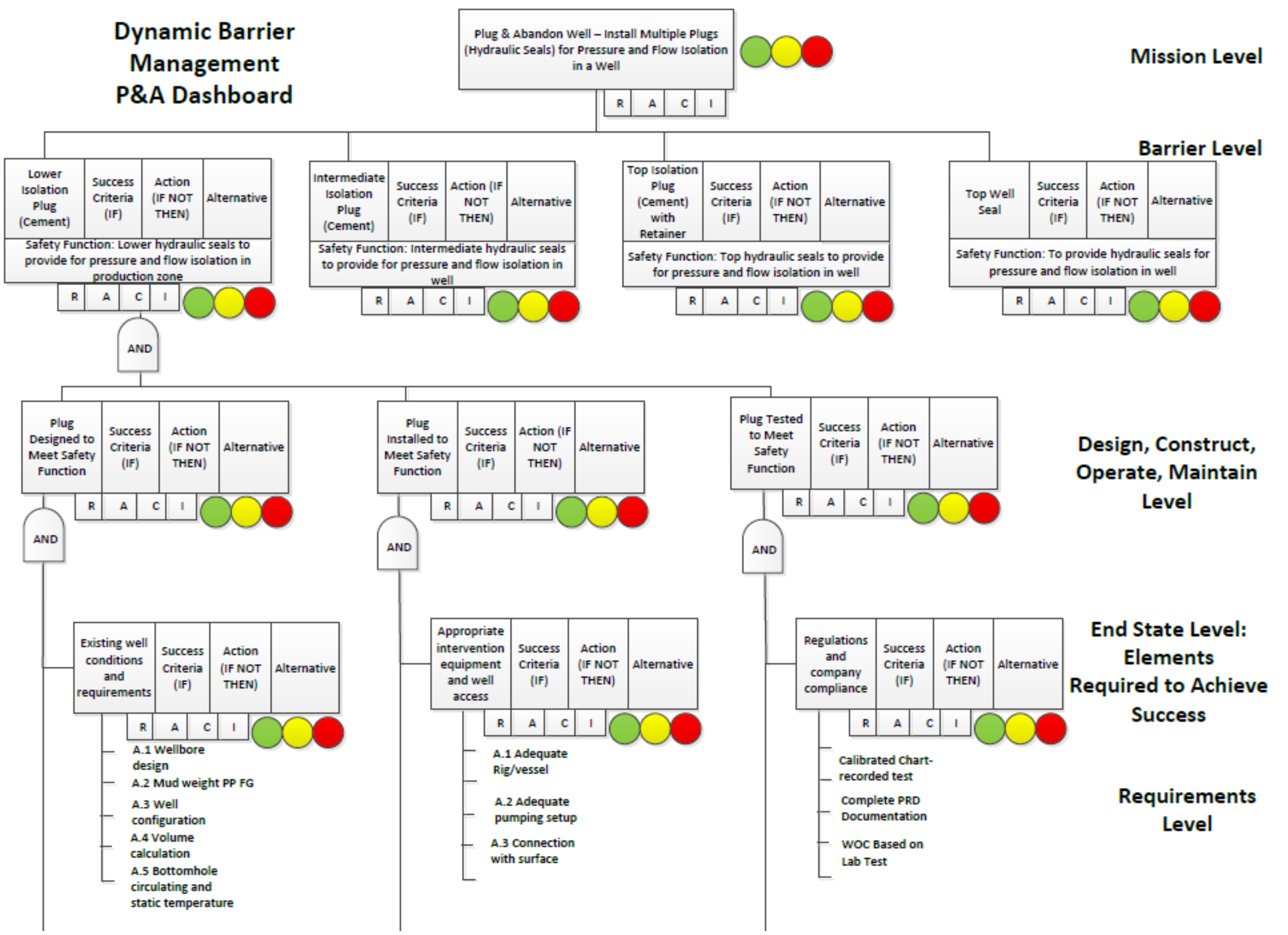

Figure 7: P&A Dashboard Concept for Barrier and Success Path Monitoring

As shown in the figure, the proposed dashboard consists of five levels to systematically organize information for decision making:

1. Mission Level

The Mission level highlights the overall mission for the activity. For the P&A case study, this is to install multiple plugs (hydraulic seals) for pressure and flow isolation in a well.

2. Barrier Level

The Barrier level delineates the four different barriers that will be deployed during the P&A project: the lower isolation plug, intermediate isolation plug, the top isolation plug, and the top well seal.

3. Design, construct, operate, maintain level

This level highlights that each major project includes four major types of activities: Design, Construction, Operation, and Maintenance. For the purposes of the P&A case study this can be condensed to three activities:

- Design of the cement plug
- Installation of the cement plug
- Testing of the cement plug

As discussed previously, success paths were defined during the workshops for each of these three activities.

4. End State Level

This shows the major End States that must be achieved to carry out the complete process for design, construction, operation, and maintenance of the barrier. As discussed previously, it can be helpful to think in terms of End States rather than activities/procedures to highlight specific goals that must be satisfied. While there are many similar characteristics and success paths and procedures, the success path focuses on those elements that must be provided in order to achieve success. Once the success path is defined, the development of corresponding procedures to ensure that each End State is achieved becomes streamlined.

5. Requirements Level

The Requirements Level sets out those requirements that must be satisfied in order to achieve the associated End State.

Each element on the template clearly specifies the information that is required for decision making i.e. Success Criteria (IF), Action (IF NOT THEN), Alternative, Source of Information (not shown in figure above) and Decision Maker and Communication.

Green/Yellow/Red traffic lights are provided for each node of the tree to indicate whether the associated success criteria have been satisfied.

5.2 Other Dashboard concepts

As illustrated in the

Figure 8, some other ideas for the proposed dashboard are as below:

1) Dynamic well barrier schematic with color coding to show health of barrier (left side of figure). This is similar to NORSOK D-010 well barrier schematic but is dynamic as barrier health status can be made available in real-time to monitor and support decision making during operations.

2) Barrier-success path and compliance assessment trees that show current status of success path elements and real-time compliance assessment (right side of figure).

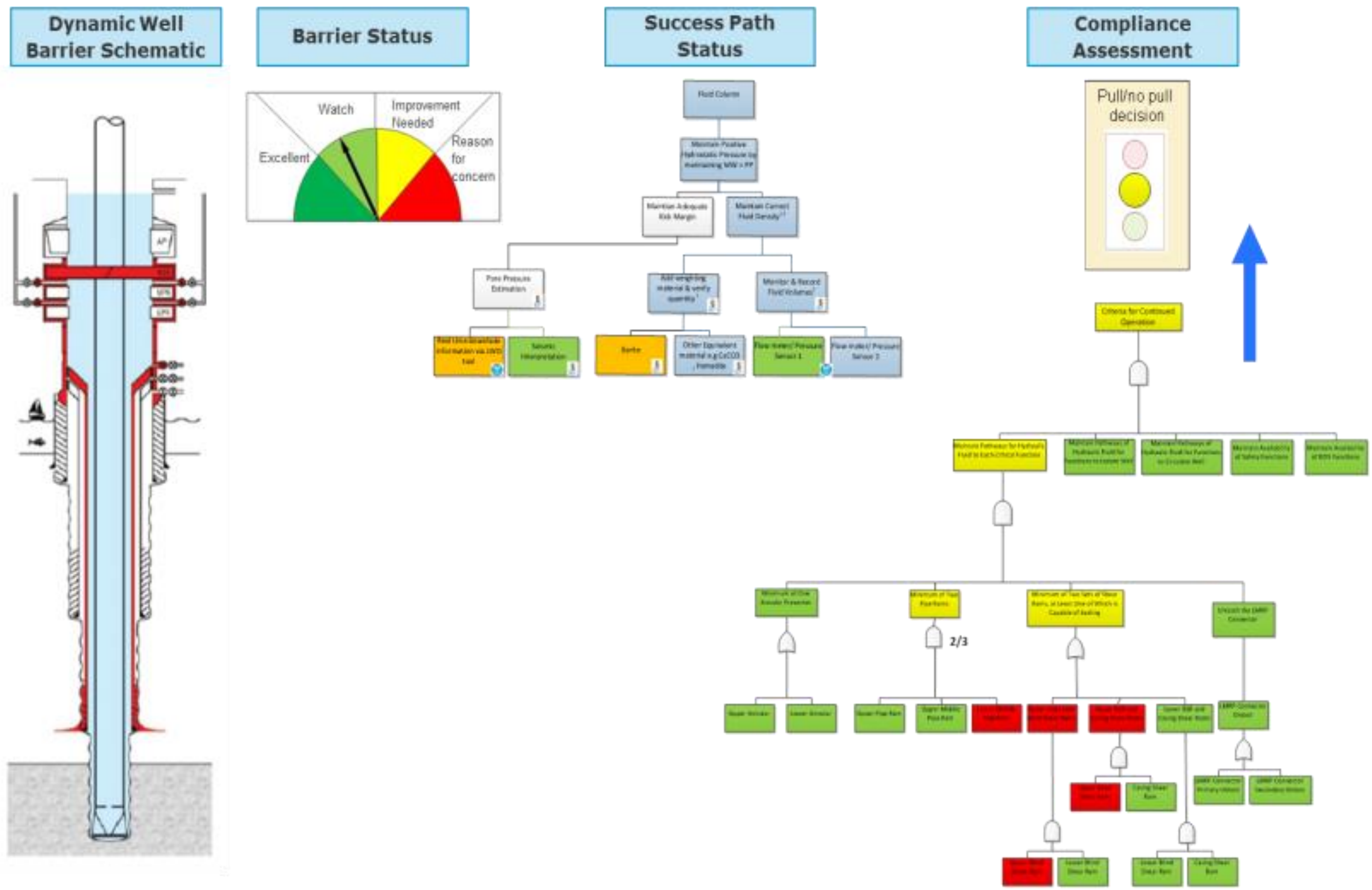

Figure 8: Other Concepts for Barrier and Success Path Monitoring

6 NOTABLE JIP INSIGHTS

The Phase 1 Joint Industry project brought together 15 organizations as a community to assess the value of the barrier-success path approach for operational risk management for the offshore oil & gas industry. The following sections provide a brief summary of the major learnings from the Phase 1 JIP.

6.1 Practical application of the approach

In post-workshop debriefings, participants stated that it took some time to grasp the success path concept and comprehend how it differs from current approaches for planning operations and managing risks. However, once the concept was understood, it became intuitive to begin developing the success paths. Guided discussion sessions were used to review, revise, and gain consensus on the success paths for design, installation, and testing of the cement plug for the P&A case study. The application of the approach in the workshop setting appeared to provide a meaningful framework and common language for exploring operational planning and risk management for P&A operations. Representatives of the different stakeholder groups (operators, service companies, drilling contractors, and regulatory authorities) were able to work together within their respective roles towards the common goal of developing success paths and decision support information for P&A operations. This included both the operational and regulatory compliance perspectives, although the regulatory compliance logic model and decision criteria were not fully evaluated during the two case study workshops.

6.2 Common language for communication and consensus

The barrier-success path approach was shown to be relevant as a framework and common language for communication across stakeholder groups. In post-workshop discussions, participants stated that it was "a miracle" that the diverse group of SMEs representing all the major industry stakeholder types was able to reach consensus in the development of the generic P&A success paths. Observation of discussions in the breakout sessions, as well as the group reconciliation sessions, provided evidence that the ability to simplify and visualize the concepts while focusing on the few elements of top importance required for success made it possible for the group to identify, discuss, and resolve issues while capturing the final success paths.

6.3 Added value of the success perspective

There was a significant discussion in the workshops regarding the added value of using the success perspective to complement the focus on failure modes that is normally applied in hazard assessments for offshore operations. It was recognized that while failure and success perspectives are essentially two sides of the same coin, the inherent notion that there are fewer ways for a system to succeed than fail provides a significant advantage for characterizing the processes and defining the critical requirements for success. In addition, the success perspective aligns more naturally with decision-making in operations, as the primary focus is, "What actions should I take now to ensure success?" rather than assessing the numerous failure pathways that could have led to the current situation.

6.4 Potential applications of the barrier-success path approach

Evaluation of the outcomes of the case study workshops suggests a number of potential applications of the barrier-success path approach in the offshore oil & gas industry. For example, offshore operating companies, drilling contractors, and service companies could use the barrier-success path concept for planning, conducting, and monitoring work. These processes could be effectively supported by building barrier and success path concepts into the policies and procedures in the Safety Management System. The barrier-success path approach can be directly used for monitoring the design, installation, and testing of well control and well integrity barriers such as the fluid column, BOP, casing, plugs, piping, and topside systems.

At the installation level, the barrier-success path approach can be used to supplement existing approaches in identifying and monitoring the barriers for prevention and mitigation of major accident hazards, and for compliance with Safety and Environmental Management Systems (SEMS) regulations.

In addition to the generic uses of the barrier-success path approach across the industry, specific types of stakeholder organizations can focus on its application to their specific needs. For example, Original Equipment Manufacturers (OEMs) can use the approach for the design of advanced equipment for drilling, completion, production, and decommissioning. In turn, the operating companies can use the approach to support regulatory approval and continuous regulatory compliance assessment of new technologies.

Service companies can apply the barrier-success path approach to the development, implementation, and monitoring of plans for work processes that are used to design, construct, operate, and maintain all types of safety barriers—including those for well integrity, well control, and prevention/mitigation of major accident hazards. They can also build the barrier and success path approach into their Safety Management Systems.

Regulatory authorities can apply the barrier-success path approach for assessment and approval of new technologies and work process for offshore operations, through the application of existing regulatory processes for alternate procedures and equipment. The approach can also be used as a framework for compliance monitoring during operations, and for assessment of incidents and identification of trends and issues across incidents and industry-wide operational experience. Internally, regulatory authorities can use the barrier-success path approach to prioritize and focus regulatory activities.

The barrier-success path approach holds significant promise for application across industry stakeholders. For example, operating companies, service companies, and service contractors could use the barrier-success path approach to develop, coordinate, and monitor projects where each organization has different roles and responsibilities for achieving success. The success path diagrams and barrier-success path dashboard could be customized to focus on activities for which each organization is responsible. The project could be continuously monitored using the traffic lights to highlight those activities that have been successfully accomplished and those where particular attention is required, including identification of actions that should be taken and by whom.

Finally, the barrier-success path concept could be used as a framework for organizing real-time monitoring of information within and across organizations, and for defining requirements for real-time monitoring and reporting to regulatory authorities.

7 NEXT STEPS

7.1 Phase 1 closeout meeting

The JIP Phase 1 closeout meeting will be held February 2, 2017. Attendees at this meeting will include the decision makers from each organization that were present at the kickoff meeting as well as the SMEs who participated in the case study workshops.

During the closeout meeting, workshop participants will be given the opportunity to provide feedback regarding their participation in the case study workshops as well as their opinions regarding the value of the barrier-success path approach for application within their organization and across the industry. Ideas for follow-on activities including the development of a potential Phase 2 JIP will be presented and discussed. Finally, scope, organization and potential financing for follow-on activities will be discussed and next steps identified.

7.2 Potential focus areas for follow-on activities

Potential follow-on activities for the Phase 2 JIP can include the following:

- ***Develop additional generic success paths***
  Additional consensus-based success paths could be developed using additional case studies focusing on different barrier types and operations—e.g., fluid column, production operations, etc.

- ***Treatment of human roles—e.g., decision making, communication, and consensus***
  An important benefit of the barrier-success path approach is the ability to explicitly model the human roles in design, construction, operation, and maintenance of barriers for preventing and mitigating major accidents. A critical need is to identify how the barrier-success path approach could be used to increase understanding of the human roles, to enhance human performance, and reduce human error.

- ***Transition to alternate success paths or barriers***
  The focus of the Phase 1 P&A case study workshops was on the design, installation, and testing of "passive" barriers such as cement plugs. Thus the application of the barrier-success path approach to support decision making for monitoring barrier status and transition to alternate success paths or barriers was not explored in depth. Different barrier types such as fluid barriers (e.g., the fluid column) and dynamic mechanical barriers (e.g., BOPs) have much more complex requirements for decision-making.
  Follow-on activities that focus on these barrier types could be used to expand the comprehensive application of the barrier-success path approach to all types of offshore operations.

- ***Focus on a digital success path tool development and application***
  While development and application of success paths using paper (e.g., flip charts) and graphical tools such as Visio was key to brainstorming and materializing the logical layout of barriers and other success path elements in these JIP workshops, these tools may not be sufficient in live or agile applications of this approach. Additional work to define the need and requirements for software tools for development of barrier-success path models and their implementation in the field, including a possible interface to real-time instrumentation and results of audits and inspections could be discussed.

- ***International regulatory perspectives and possible harmonization***
  There is significant interest in incorporating diverse international regulatory perspectives and exploring potential concepts for coordination and harmonization of barrier and success path approaches across regulatory regimes. Petroleum Safety Authority (Norway), Mexican regulatory authorities (e.g. CNH, SENER, and ASEA) and BSEE all have interest in the application of various risk-informed approaches to their regulatory activities.

- ***Real-time monitoring***
  The potential for use of the barrier-success path approach for providing a “neutral” framework for real-time monitoring and reporting across stakeholder groups could be evaluated.

- ***Cross-industry assessment of operational experience and incidents***
  Similarly, the application of the barrier-success path approach for assessment of cross-industry operating experience and identifying trends across incidents could be evaluated.

8 CONCLUSIONS

Throughout the workshop sessions of this JIP, it was evident that the level of interest in the workshop approach for success path examples was well received by the stakeholders. Some companies' representatives went back to their company and began successfully applying the approach presented in the workshop to their company operations.

The results of the Phase 1 JIP provide evidence that the barrier-success path approach could provide significant benefits to the offshore oil and gas industry, as summarized in the following.

- ***Well integrity, well control, and P&A.*** The barrier-success path approach provides a systematic process for applying process safety concepts and barrier management to well design, well construction, well control, and P&A activities.
- ***Cross-industry communication for performance and compliance.*** The barrier-success path approach provides a "common language" that can be used to communicate barrier and risk management information within organizations and across the global industry and regulatory authorities. When implemented as part of a protocol for real-time monitoring between land and offshore locations, it provides a neutral "translation" language for communication with regulatory authorities and enables regulatory approval and compliance during well operations.
- ***Human factors, decision making, and situation awareness.*** The barrier-success path approach promotes common situation awareness during coordination of work activities amongst operators, drilling contractors, and service companies; and provides clear guidance for responding to unexpected conditions including barrier or success path degradation.
- ***Qualification and regulatory approval of new technologies***. The visual format of the barrier-success path approach illuminates risk and therefore is beneficial for comparison of a new technology with an existing one especially when operating outside defined envelopes, e.g., high pressure-high temperature (HPHT) conditions. It also facilitates qualification and regulatory approval of the new technology and facilitates discussion between the regulator and the industry stakeholder/ vendor.
- ***Process safety and risk management.*** The barrier-success path approach enables integration of human and organization factors with risk management of operations thereby improving process safety. It also allows simplification of processes and procedures in order to reduce the occurrence of interruptions and re-planning while improving risk awareness across the operating, maintenance, and management teams.
- ***Barrier monitoring and management.*** The barrier-success path approach, when integrated with real-time support systems, can provide means to know the current condition of barriers and the success paths that are used to design, construct, operate, and maintain them. However, it must be recognized that, application of digital data to support real-time analytics and automation brings additional risks if not properly designed and integrated with existing technologies.

9 REFERENCES

[1] D. Fraser, et al., "Operational Risk: Stepping Beyond Bow-Ties," SPE-174995-MS, SPE Annual Technical Conference and Exhibition, Houston TX, September 28-30, 2015.

[2] N. Paltrinieri, S. Hauge, and W.R. Nelson, Dynamic barrier management: A case of sand erosion integrity, Safety and Reliability of Complex Engineered Systems, Podofillini et al. (Eds), London, Taylor & Francis Group, 2015.

[3] W.R. Nelson, "Improving Safety of Deepwater Drilling Through Advanced Instrumentation, Diagnostics, and Automation for BOP Control Systems, OTC-27188-MS," Offshore Technology Conference, Houston, TX, May 2-5, 2016.

APPENDIX 1: DNV GL APPROACH FOR DECISION SUPPORT FOR DYNAMIC BARRIER MANAGEMENT

DNV GL has been developing the concept of "Decision Support for Dynamic Barrier Management" since 2011, building on the combination of barrier concepts from the offshore oil and gas industry with critical safety functions and success path concepts from the nuclear power industry. The main concepts are summarized in the following sections.

Combining barriers and success paths

A bow tie diagram shows the barriers that can be used to prevent a major accident or to mitigate its consequences. Figure A1-1 shows an example bow tie diagram for deepwater drilling. The orange circle at the center of the diagram is the major accident or "Top Event" that is the focus of the assessment - in this case, Loss of Containment for the drilling operation. The blue rectangle on the left is the Threat - i.e. Pressurized Hydrocarbons - that can lead to Loss of Containment. The rectangles between the Threat and the Top Event are the barriers that can be used to prevent the Threat from leading to the Top Event - i.e. the fluid column and the blowout preventer (BOP). Barriers on the left side of the bow tie diagram are referred to as prevention barriers.

Similarly, the red rectangles on the right-hand side of the bow tie diagram are potential Consequences that can result if Loss of Containment occurs. Barriers are shown that can prevent or reduce the magnitude of the consequences. Barriers on the right-hand side of the bow tie diagram are called mitigation barriers.

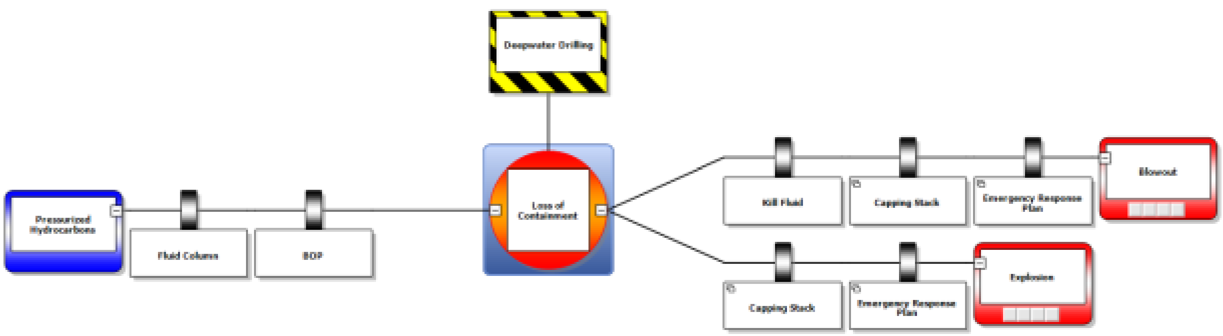

Figure A1-1: Bow tie diagram for deepwater drilling

Figure A1-2 shows a simplified response tree for the BOP barrier for deepwater drilling. Each pathway from the bottom of the tree to the top is a success path for implementing the BOP barrier. In this case, a success path represents a pathway for hydraulic fluid from the source (e.g. surface or subsea accumulators) to flow to the port of a BOP ram in order to close it to maintain well integrity when required by a well kick or other conditions indicating potential well flow.

The response tree is evaluated for the failure of the yellow pod and the crossover line between the pods, as indicated by the boxes with the orange color. Because of these failures, the success paths coded with the red color are no longer available for implementing the BOP barrier, while success paths colored green are available. Decision criteria have been established to select the recommended success path that is preferred for this failure scenario, as shown by the boxes colored light blue. This preferred path can be implemented either by manual action or by automated reconfiguration of the BOP control system.

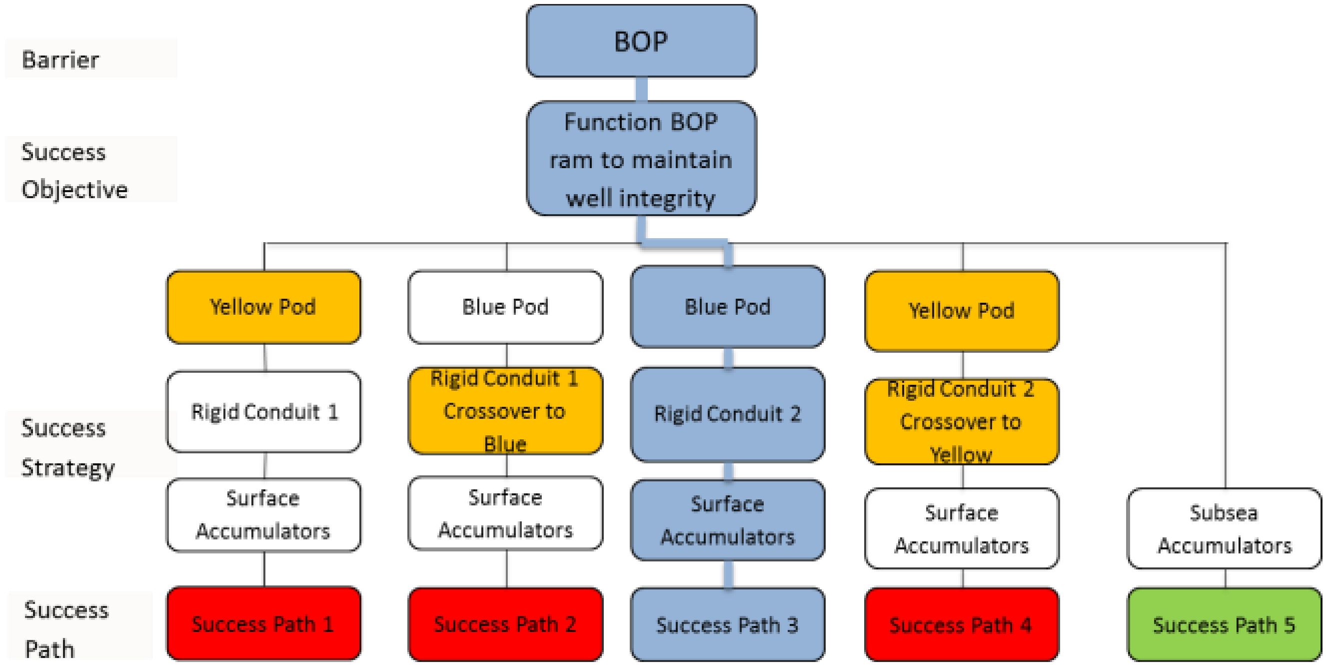

Figure A1-2: Response tree for the blowout preventer barrier for well integrity

Figure A1-3 shows how response trees and bow tie diagrams are combined to form the framework for decision support for dynamic barrier management. The diagram is based on the scenario where the fluid column barrier has failed. The BOP response tree is continuously monitored to determine the health of the BOP barrier for the Loss of Containment bow tie diagram. If a failure or degraded condition is detected in one of the elements of the BOP response tree, the tree is evaluated to determine which success paths are disabled due to the failure, which paths remain available, and based on the pre-established decision criteria, which success path should be used to reconfigure the BOP control system to restore the BOP barrier. Then the BOP control system is reconfigured to implement this success path, either through manual operator action or automatically using the automated functions of the BOP control system.

In combination, the barrier and success path concepts represent a robust framework for managing risk. Continuous monitoring of barrier health provides an indication when safety could be compromised by degradation of one or more barriers. Identification and continuous monitoring of success paths provide assurance that the elements required for successful barrier performance are always available. The response tree structure provides a systematic way to continuously ensure the availability of multiple success paths for supporting barrier performance.

Once the barrier-success path framework has been established, the next step is to define the information framework to support decision-making to determine when actions are required to respond to barrier degradation. The following section describes a systematic approach to establishing decision support for dynamic barrier management.

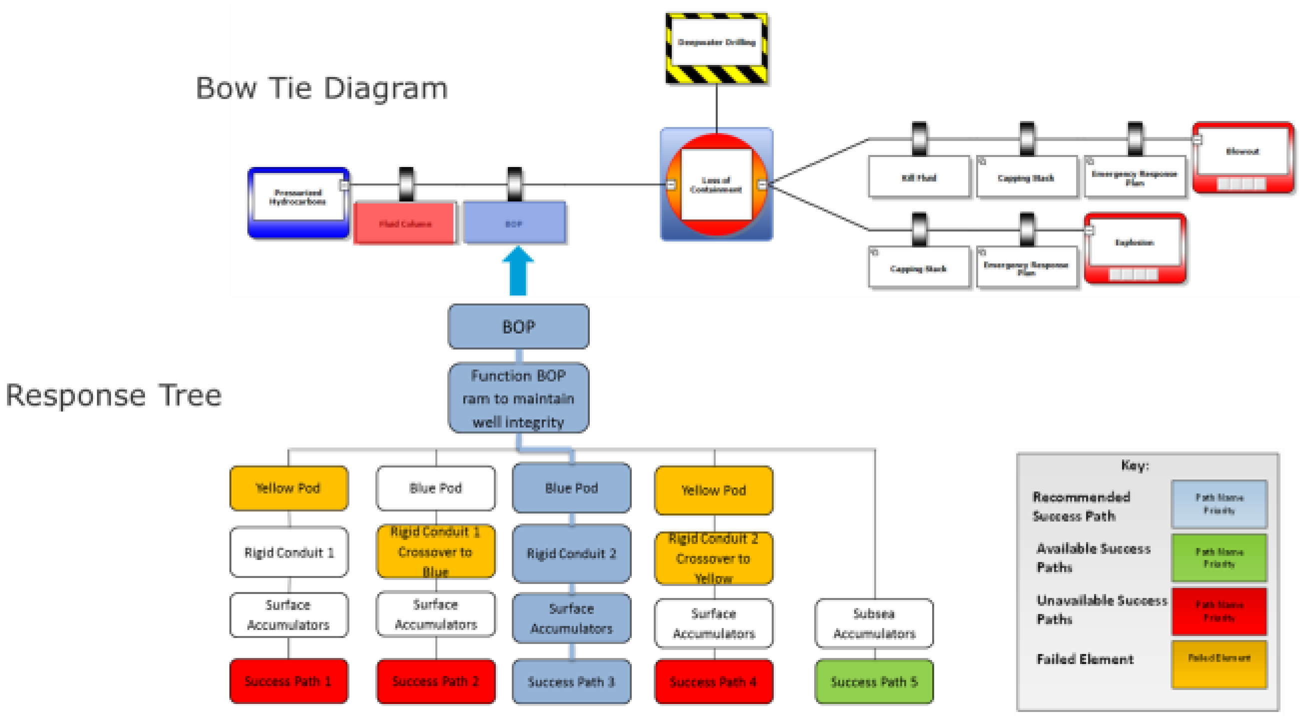

Figure A1-3: Combining bow tie diagrams and response trees for decision support for dynamic barrier management

Information requirements analysis and decision support

Table 1 shows how the information requirements, instrumentation requirements, and decision criteria are established for dynamic barrier management for the drilling example. The first column of the table shows the elements of the bow tie diagram, with the left to right flow of the bow tie diagram represented from the rows moving from the bottom to the top of the table:

- Threat
- Prevention barrier
- Prevention barrier success path
- Top event
- Mitigation barrier
- Mitigation barrier success path
- Consequence

The columns are then systematically filled out as follows:

- **Information requirement** - The information that is needed to determine the current condition of the Threat, Prevention Barrier, Prevention Barrier Success Path, Top Event, Mitigation Barrier, Mitigation Barrier Success Path, and Consequence.
- **Source of information** - Potential sources of the required information. These sources of information can either be direct information sources (e.g. sensors that directly monitor the parameter) or indirect information sources (e.g. measurements that can be calculated or otherwise inferred from directly monitored parameters).
- **Decision criteria (IF)** - Specific combinations of the parameters that indicate:
  - Occurrence or potential future occurrence of the threat
  - Degradation or failure of a prevention barrier
  - Occurrence or potential future occurrence of the Top Event
  - Degradation or failure of a mitigation barrier
  - Occurrence or potential future occurrence of the consequence
- **Response guidance (THEN)** - Actions to be taken when the decision criteria are satisfied.

The development of the information in this table forms the foundation for the decision support tool for dynamic barrier management.

Table A1-1: Information Requirements Analysis for Decision Support for Dynamic Barrier Management

	Information Requirement	Source of Information	Decision Criteria (IF)	Response Guidance (THEN)
Consequence: Oil Spill	Occurrence of oil spill	Visual observation	Oil on surface confirmed	Implement Emergency Response Plan
Mitigation Barrier Success Path: Inject kill fluid	Initiation criteria for kill fluid injection	- Volume and pressure of kill fluid source - Availability and position of valves in flow path	Uncontrolled well flow	Inject kill fluid
Mitigation Barrier: Kill Fluid	Functionality and Availability of Kill Fluid Flow Paths	- Availability of kill fluid source - Availability and position of valves in flow path	Loss of containment has occurred	Implement kill fluid success path
Top Event: Loss of Containment	Uncontrolled well flow	- Mud pit levels - Wellbore flow conditions	Uncontrolled well flow	- Function BOP ram control flow if possible - Inject kill fluid
Prevention Barrier Success Path: Function BOP ram to shear pipe and close well	Initiation criteria for BOP activation to shear pipe and close well	- Wellbore conditions - Kick margin	Underbalanced fluid column	Function BOP ram to shear pipe and close well
Prevention Barrier: BOP	Availability of hydraulic fluid pathways to function BOP rams	- Volume and pressure of hydraulic fluid source - Availability and position of valves in flow path	Availability of hydraulic fluid pathways does not meet operational and regulatory requirements	- Suspend drilling operations - Maintain BOP control system to restore required capability
Threat: Underbalanced fluid column	Hydrostatic pressure	Comparison of fluid column pressure to formation pressure	Inadequate kick margin	Restore kick margin

Regulatory compliance assessment

In addition to continuous monitoring of barriers and success paths, effective instrumentation and decision support can also be used to continuously assess compliance with regulatory requirements. The compliance assessment decision criteria can be represented in a success tree logic model to facilitate understanding of the current status of regulatory compliance and communication among operations, maintenance, and regulatory personnel.

Figure A1-4 shows a portion of the success tree decision criteria logic model for regulatory compliance assessment for a generic BOP control system. The logic model is a success tree structure based on the requirements of API STD 53 for the availability of BOP functions. The Top Event for the logic tree is "Criteria for Continued Operation." The basic premise is that as long as the availability of BOP functions at the lower levels of the tree is such that the Top Event is satisfied, drilling operations can continue. In this example, all the boxes are color coded green to illustrate normal conditions. If failures occur, the boxes will be coded yellow (function degraded) or red (function unavailable) to show the overall status of regulatory compliance.

This logic model is continuously monitored during drilling operations to determine if drilling operations can continue because the BOP control system complies with all regulatory requirements. If failures of BOP control system components result in a situation where the available BOP functions do not meet regulatory compliance requirements, this provides clear indication that the drilling operations must be suspended and the BOP must be pulled to the surface for maintenance. A major benefit of this regulatory compliance logic model is that decision criteria can be agreed in advance between operators and regulatory authorities such as BSEE.

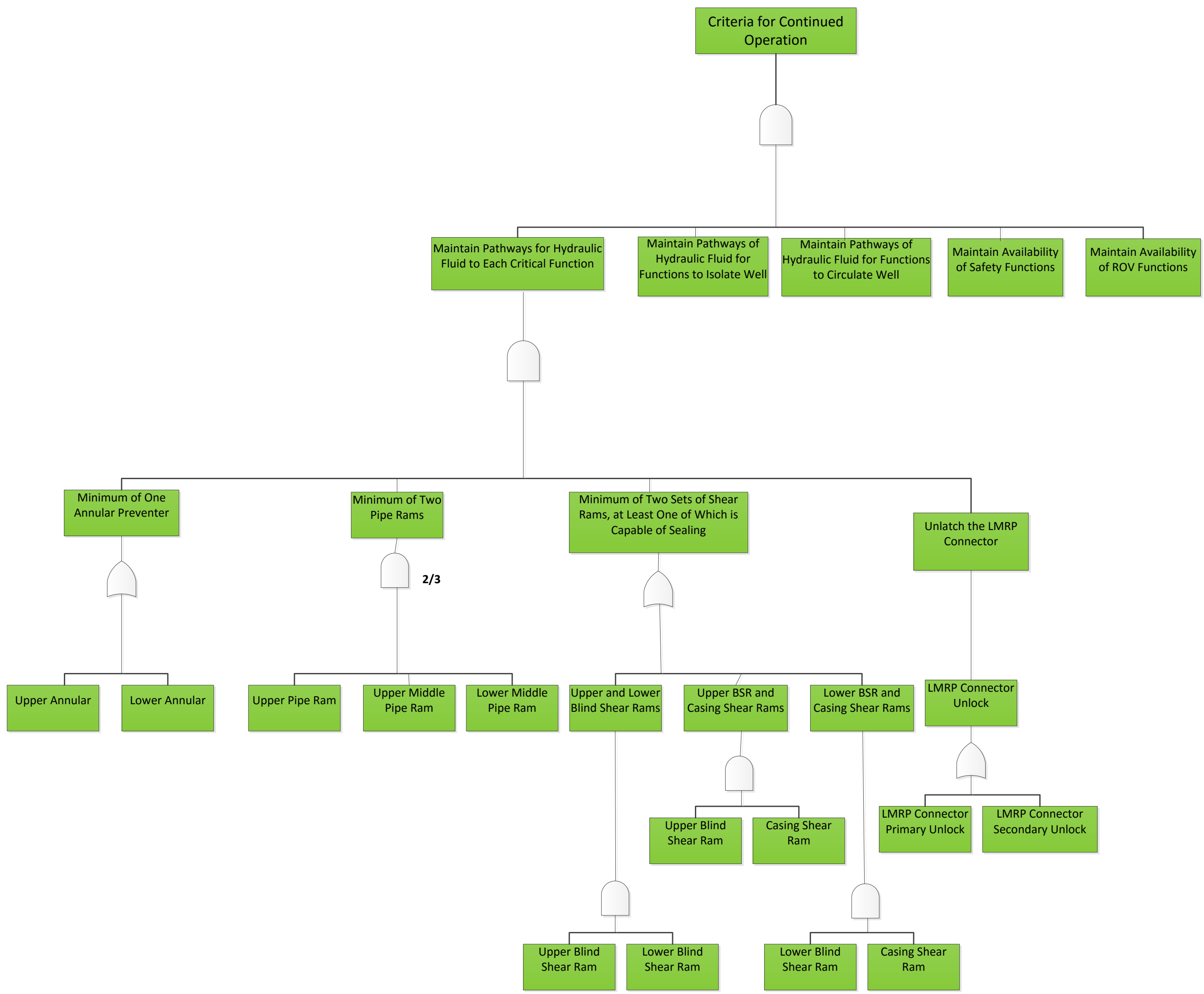

Figure A1-4: Regulatory Compliance Decision Criteria Logic Model for BOP Functions

APPENDIX 2: ARGONNE NATIONAL LABORATORY MULTIPLE PHYSICAL BARRIER APPROACH

Background

The Argonne National Laboratory (ANL) has been actively involved with the safety of nuclear reactors since its inception in 1946. When asked to provide assistance to the Offshore Oil and Gas Industry, ANL developed a "Physical Barrier" approach for improving the safety of offshore operations.

Nuclear power plants sit in one place for their entire lifetime and carry out a single mission of producing electricity for distribution over a land-based electrical grid.

Offshore oil facilities could not be more different. They are not land based; they perform many different missions, most notably Drilling, Completion, Production, Workover and Closure or Abandonment of offshore subsea wells. Yet there is a common element between the two – multiple physical barriers.

Physical Barriers

A nuclear plant employs multiple physical barriers between the radioactive nuclear fuel and the outside environment. Similarly, an offshore oil facility (rig or platform) utilizes multiple physical barriers to keep the hydrocarbons in the reservoir or in safely controlled containers and pipelines until they are safely moved to land-based facilities.

Although the barriers are different in character and design, the fundamental principle is the same - if one major barrier fails for any reason, another barrier is in place to hold or contain the hazardous materials so that they are not released to the environment.

Over time, there have been failures. The world knows about Chernobyl and Fukushima, and it also knows about Piper Alpha and Macondo. High hazard industries have learned from their failures and operations, and today, all of these industries, are safer than they have been in the past.

Upon looking at the Oil and Gas Industry, ANL has found a very strong commitment to Industrial Safety at all facilities, and a historical record that shows a consistent and steady reduction in loss of life and health from industrial accidents.

The big accidents in the Oil and Gas Industry have come, not from failures of Industrial safety, but from lapses in Process Safety or Process Integrity (*called "Operational Risk" by the IADC Deepwater Well Control Guidelines, 2nd Edition, 2015*). In these two different aspects of Safety, the word "barrier" is used differently. In Process Integrity or Process Safety, "barriers" are always seen as physical barriers, and each physical barrier has a specific 'critical safety function' that it 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 things from happening. This is illustrated in Figure A2-1.

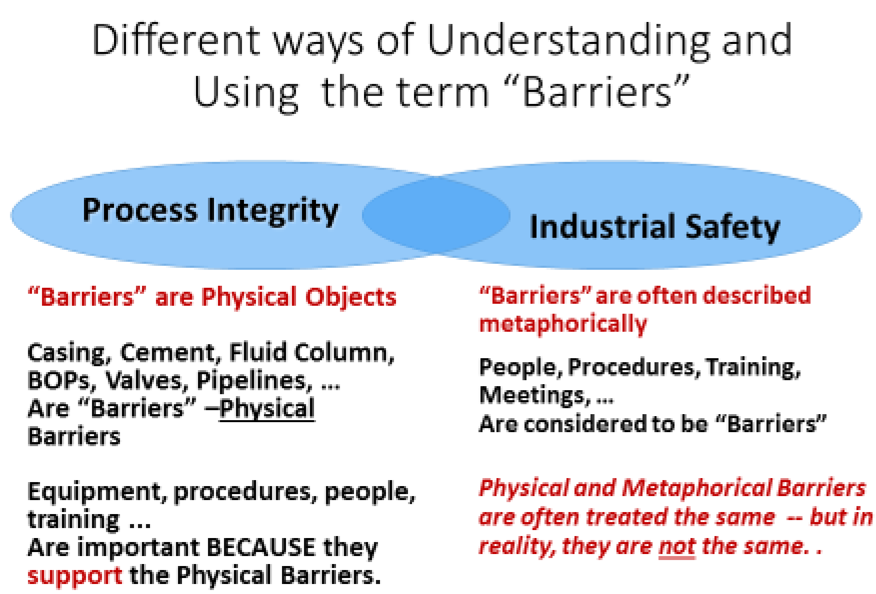

Figure A2-1: Uses of the Term "Barrier"

Success Paths

Figure A2-1 also identifies how people, procedures, training, etc. appear in Process Safety. They show up as parts of a "Success Path"—a series or collection of equipment, procedures, software, processes and human actions that are put in place to ensure that the physical barrier is able to meet its critical safety function. Success paths are important because they support the Physical Barriers.

The concept of multiple physical barriers in the nuclear industry is described by the term "Defense in Depth," which is the cornerstone for process safety in the nuclear industry.

The basic idea for Process Integrity or Process Safety in the Oil and Gas Industry is that process accidents only occur when a required Physical Barrier is missing, breached, or non-functioning.

Process Integrity is <u>always</u> about Physical Barriers.

Process Risk

Process Risk in the Oil and Gas Industry is directly related to Barrier Assurance – keeping the hydrocarbons where they belong.

Risk is actually a combination of two factors: the probability of a failure, and the consequences of a failure. It is sometimes written by the formula: $R = P_f \times C_f$. That is, the Risk is the Probability of a failure time the Consequences of a failure. This may be expressed in terms of dollars, or barrels of oil, or any other measure of value.

How then do we ensure that the physical barriers are performing their critical safety functions? The answer is to ensure that the Success Paths – the elements <u>needed</u> to ensure success – are in place and capable of performing their function in all expected conditions and circumstances. If a key element is missing, there is risk – an increased probability that the barrier will not succeed. If two key elements are missing, there is even more risk, etc.

Methods, Procedures and Process for Physical Barrier Success Paths

We have developed the habit of displaying Physical Barriers in the form of a Success Path Diagram, with the Physical Barrier or critical safety function as the top element, and success path or paths shown below it connected by "AND" and "OR" gates. The most general form of any success tree shows the elements of Design, Construction, Operation and Maintenance as the key elements needed for success. If an "AND" gate is used, then every element beneath it in the tree must be present in order for the top element to succeed. If an "OR" gate is used, then any single element below it will be sufficient for success.

Figure A2-2 shows the very basic conceptual version of a Success Tree with the four elements leading to the successful outcome. Each of the four elements of Design, Construction, Operation and Maintenance. (DCOM) can have its own success tree or trees associated with it.

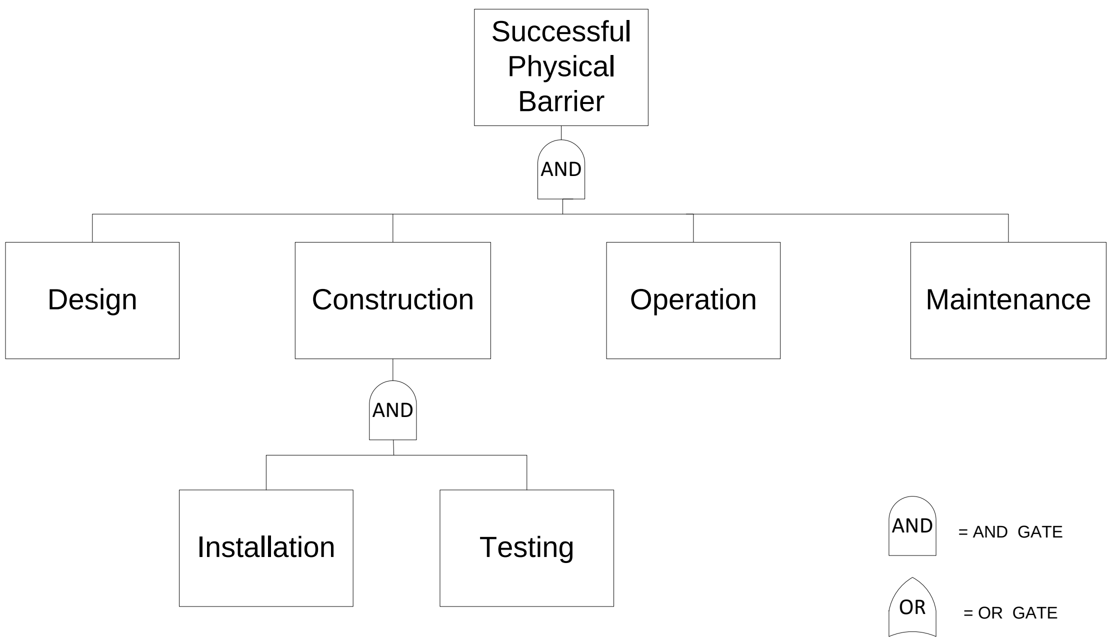

Figure A2-2: General Success Tree for a Physical Barrier

Figure 4 in Section 4.2.2 of this report shows a success tree for the "INSTALL" component of a bottom hole plug to be used in a "Plug and Abandon" scenario that is presented in that section. Note that this INSTALL component includes a broad spectrum of activities in the installation process: confirming that the wellbore is properly prepared; ensuring that the cement slurry is mixed to the proper density; and ensuring the proper placement of the cement plug.

What may seem like a relatively simple activity named INSTALL turns out to be a rather detailed and carefully laid out process. Skipping or missing an important step in this process could undermine the success of the barrier placement, and in turn increase the probability of the project not succeeding.

Similarly, the success path(s) for the "DESIGN" of the plug and the path(s) for "TESTING AND VERIFYING" the installation of the plug are comparably thorough and detailed.

An application of the Success Path approach for <u>any</u> Physical Barrier would typically include the following four steps:

1. Identify the Physical Barrier Systems that need to be in place for a given Operation and identify the critical Safety Function(s). (This is usually stated as a statement of success, e.g. "Pumps deliver needed pressure and flow under all expected conditions").

2. Ensure that the Physical Barrier Support System(s) are *designed* and configured (*constructed and installed*) to perform their critical Safety Functions under all expected conditions.

3. Monitor the performance of all critical equipment and Implement Pre-planned Actions and Strategies for restoring Barrier Functions if one or more of the Barrier Systems fails or becomes degraded (*operation*).

4. Maintain all critical equipment in a condition to perform as needed during all expected conditions.

If operating experience or other indicators suggest that equipment or processes may not perform reliably or give expected results, especially under abnormal conditions, it may be beneficial to examine the equipment, systems or processes more carefully. It is common practice in the oil and gas industry to conduct a Failure Modes and Effects Criticality Analysis (FMECA) to examine how individual components or subsystems perform under expected adverse conditions.

A systematic review of each component, performed in the context of its role in the success path, enables us to identify components that may underperform in critical situations. These components are candidates for replacement, upgrading, "hardening," or other measures to improve their performance or reliability.

Summary

Process Integrity focuses on Physical Barriers, critical Safety Functions, and Success paths.

Successful Barrier Performance depends on the performance of basic equipment and the supporting hardware, software and people through the Design, Construction (Installation and Testing), Operation (Monitoring) and Maintenance of this equipment.

FMECA analysis can identify how systems can be made more reliable, increasing both economic and safety performance.

APPENDIX 3: CRITICAL INDUSTRY ISSUES DEFINED BY THE PHASE 1 JIP PARTICIPANTS

Participants in the JIP kickoff meeting were asked to provide anonymous input regarding the critical issues currently facing the offshore industry. The issues that were identified are summarized in the following sections:

Process safety and risk management using barrier and success path approaches
Many issues must be addressed for effective safety and risk management in the offshore industry. Especially in today's challenging economic conditions, process safety must compete for management attention and resources with many other operational issues in the drive to maximize operating efficiency. There may be inadequate resources to maintain performance and reliability of facilities and equipment.

Process safety and risk management methods have not yet reached full maturity. While barrier management is becoming more common, integration with conventional methods can be challenging. Hazards and risks are not always effectively identified and managed. Treatment of human and organizational factors in risk and barrier management is still incomplete.

Integration of risk management with operations has not yet fully matured. Processes and procedures need to be simplified to reduce the occurrence of interruptions and replanning. In addition, methods to ensure risk awareness across the operating, maintenance, and management teams needs to be improved.

Barrier monitoring and management
Currently, barrier-based approaches for process safety and risk management are treated as analytic activities and not integrated with operations and maintenance. Operations, maintenance, and management personnel are not aware of the current condition of barriers and the success paths that are used to design, construct, operate, and maintain them. Information needed to make informed, analytically supported decisions regarding barrier performance is not readily available and may be out of date and poorly organized to support effective decision making. Assessment of barrier performance is mostly conducted following the occurrence of incidents rather than be used to identify and correct trends and transients that may cause barrier degradation or failure.

Barrier maintenance, inspection, and testing protocols are not effectively linked to complete understanding of performance, safety, and risk metrics. Currently, collected data is ineffectively organized and analyzed to support performance and risk optimization. Data collection and analysis shortcomings are especially critical for older, aging, and inadequately instrumented facilities. On the other hand, effective application of digital data to support real-time analytics and automation brings additional risks if not properly design and integrated with existing technologies. Current risk models may not adequately account for current facility and system configuration that has resulted from "engineering design creep" - i.e. design modifications that have been implemented to treat known failures and risks.

Communication within/across organizations and the industry
There is currently inadequate availability and consistency of quantifiable and accepted risk and safety management processes. In some organizations, there is a lack of communication and consistency across personal and process safety approaches and programs. This is even more significant in communication and application of process safety approaches across organizations. This is especially true regarding barrier management approaches - the methods have not yet been standardized across the industry. In addition,

regulatory approaches within the US and across international regulatory regimes have not been standardized to support effective communication and sharing of operational experience. A "common language" that can be used to communicate barrier and risk management information within organizations and across the global industry and regulatory regimes is a critical need. This needs to be implemented in protocols for real-time monitoring between land and offshore locations, and a neutral "translation" language for communication with regulatory authorities.

Human factors/training/competence/culture

Operations, maintenance, engineering, management, and even regulatory personnel have an inadequate awareness of process safety measures and their current condition. Risk and safety conditions and issues are poorly communicated across the organization, resulting in a significant lack of common situation awareness.

Adherence to operating and maintenance procedures is inadequate, as well as communication amongst work teams. Criteria for stopping work for risk and safety reasons are not clearly defined. Coordination of work activities amongst operators, drilling contractors, and service companies are poorly defined and implemented. Clear guidance must be provided for responding to unexpected conditions and barrier or success path degradation.

The current economic downturn and "great crew change" are leading to significant gaps in competence and understanding between experienced and new personnel. This is particularly critical for well control personnel and rig-site supervision. Competency and training programs need to incorporate more treatment of risk and safety decision making. Roles and responsibilities across disciplines and organizational boundaries and across the industry must be clearly defined to support timely and accurate decision making.

Communication and coordinating of process safety and risk management issues across global, multi-cultural workforces is very challenge.

Clear guidance for responding to barrier degradation and failure is inadequate.

Well integrity, well control, and P&A

Systematic processes are needed to apply process safety concepts and barrier management to well design, well construction, well control, and P&A activities. Well integrity and well control are especially challenging since well influx and anomaly detection are subject to significant uncertainty and currently accomplished using surface-based detection and analysis tools. The dynamics of each well are different and must be accounted for in well integrity management. Mechanical systems such as the BOP are complex and inadequately instrumented to support full health monitoring and diagnostics, resulting in unplanned downtime when the BOP must be pulled to the surface to investigate potential failures. Design, installation, and testing of cement plugs must account for the complexities of material behavior and interaction with the interfacing materials such as casing.

Regulatory approval and compliance

Application and adherence to current prescriptive standards and regulations are complex, especially when considering new technology and operating outside defined envelopes, e.g. high pressure - high temperature (HPHT) conditions. Awareness, compliance, and alignment with regulations across global regions are complex. Qualification and regulatory approval of new technologies that contribute to process safety barriers are challenging. Finally, current regulations can lead to inconsistent interpretation and application, so clear criteria must be developed.

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