BLOWOUT PREVENTER (BOP) RELIABILITY, AVAILABILITY, AND MAINTAINABILITY (RAM) ANALYSIS 1 FOR THE BUREAU OF SAFETY AND ENVIRONMENTAL ENFORCEMENT

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LIST OF CONTRIBUTORS:

ABS Consulting

Randal Montgomery
Kamran Nouri
Kamyar Nouri
David Montague

Industry Participants

OEM-1, DC-1, OP-1

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SUMMARY

As part of the Blowout Preventer (BOP) Maintenance and Inspection for Deepwater Operations study (BSEE Contract Number M11PC00027), the American Bureau of Shipping (ABS) and ABSG Consulting Inc. (ABS Consulting) performed a Reliability, Availability, and Maintainability (RAM) analysis of a typical BOP used in industry. Using a Reliability Block Diagram portraying the various combinations of component/subsystems required for successful BOP operation, failure data for the BOP system components, and maintenance, inspection and test data for a typical system, the analysis team estimated the availability of the BOP system. Availability, as used in this study, is the probability the BOP system functions properly on demand. This report presents the results for one of the Industry Participant's BOP design.

This report represents a portion of Deliverable F for the studies associated with Tasks 6.2.3, 6.2.3.1, and 6.2.3.2, as outlined in the above referenced contract. This report presents the objective and scope of the RAM study, analysis process, analysis assumptions, results summary, and conclusions/ observations.

The objective of RAM analysis is to determine the impact of Maintenance, Inspection and Testing (MIT) activities on the overall availability of BOP system manufactured by one Original Equipment Manufacturer participating in the MIT project. This was accomplished by (1) developing an Reliability Block Diagram (RBD) model representing the BOP system; (2) analyzing the model, for the three different operating scenarios, using a simulation method in order to estimate the availability of the BOP system during operation periods (on well); and (3) developing and analyzing two design variances and two what-if scenarios (regarding changes to MIT intervals and improved reliability of a few BOP system components) to assess the impact of these selected changes on BOP availability.

The analysis team estimated BOP availability using component failure events and failure data collected primarily from industry participants (IPs) participating in this study. The failure events were analyzed during a separate project data analysis task (BSEE Data Analysis) and are used as input to the base model for the RAM analysis. These data were supplemented with failure data from published industrial component failure data references when information was unavailable from the IPs. Availability results were estimated for the base design, two variations to this design, and two what-if scenarios.

Table S-1, BOP Availability Results Summary summarizes the RAM model results. This table presents mean availability results for three BOP operating scenarios and the results for each scenario based on five BOP analysis cases: base case, two design change cases, and two what-if cases. The three BOP operating scenarios are:

- Operating Scenario A – Considers the on-well operation of the BOP until a system failure occurs (i.e., all redundancies failure so that the BOP is no longer available to control a well kick) and prevents the BOP from being capable of controlling a well kick via at least one well control measure (e.g., annular, pipe ram, shear ram). Specifically, this scenario assumes all failures go undetected or not repaired until the entire system is unable to sufficiently operate to control a kick. This scenario results represent the BOP system availability relative to controlling a well kick via at least one well control system. The estimated mean availability of BOP system during drilling operation (on well) ranged from 0.9937 to 0.9995.

- Operating Scenario B – Considers the on-well operation of the BOP relative to maintaining all BOP functions with the ability to perform corrective maintenance of surface and subsea components without the securing of the well and the pulling of the BOP stack. Specifically, this scenario models performing corrective maintenance per the industry regulation (i.e., performing corrective maintenance any time a BOP component failure is detected) with the unavailable time being based on the mean-time-to-repair (MTTR) for the failed component. These scenario results provide the BOP availability for all functions operating assuming repairs do not require securing of the well and pulling of the subsea systems for repair. These results represent the upper bound estimate of the BOP system availability for all functions. The estimated mean availability of BOP system during drilling operation (on well) ranged from 0.9871 to 0.9912.

- Operating Scenario C – Considers the on-well operation of the BOP relative to maintaining all BOP functions with the requirement that the well must be secured and the BOP pulled to the surface in order to perform corrective maintenance on all subsea system components. (Note: This scenario does not require the securing of the well and the pulling of the BOP stack to perform corrective maintenance on surface BOP system components). Specifically, this scenario models performing corrective maintenance to the industry regulation (i.e., performing corrective maintenance any time a BOP component failure is detected) with the unavailable time being based on (1) the average time to secure the well for failed subsea components and (2) the MTTR for the failed surface components. (Note: Based on input from the industry participants, the average time to secure well was set at 96 hours.) These scenario results provide the BOP availability for all functions operating assuming all subsea component repairs require securing of the well and pulling of the subsea systems for repair. These results represent the lower bound estimate of the BOP system availability for all functions. The estimated mean availability of BOP system during drilling operation (on well) ranged from 0.9835 to 0.99.

Table S-1: BOP Availability Results Summary

BOP Analysis Cases	Operating Scenario A	Operating Scenario B	Operating Scenario C
	Mean Availability for Drilling Operation Period (On Well) with at Least One Well Control Function Remaining to Control a Well Kick	Mean Availability for Drilling Operation Period (On Well) While Maintaining **All** BOP Well Control Functions Assuming Corrective Maintenance (CM) Performed Without Pulling of the Stack	Mean Availability for Drilling Operation Period (On Well) While Maintaining **All** BOP Well Control Functions Assuming Any Subsea CM Performed Requires Securing of the Well and Pulling of the Stack
Base Case: All Well-Control Functions	.9991	.9902	.9835
Design Change 1 (Lower Marine Riser Package [LMRP] Annular(s) & Pipe Rams Only)	.9946	.9881	.9882
Design Change 2 (LMRP Annular(s) Only)	.9937	.9876	.9878
What-If Case 1 (4 week test interval)	.9995	.9871	.984
What If Case 2 (Improved reliability of select components)	.9993	.9912	.99

The results presented here consider BOP surface and subsea controls and the stack equipment. While detected failures on the BOP stack may result in the BOP to be pulled, the subsystems located on the rig will be repaired without having to pull the BOP stack.

Based on the analysis results, the team made the following observations:

- Operating Scenario A results represent the BOP availability to control a well kick by at least one well control function, which is a better measure of the BOP system availability relative to its overall safety operation.

- Operating Scenarios B and C represent the BOP availability relative to maintaining all BOP well control functions while on the well (i.e., it models the regulatory requirement relative to maintaining all BOP functions at all times while on the well) relative to the regulatory requirement. These results measure the availability for two differing corrective maintenance responses to subsea component failures: (1) on-the-well repair and (2) pulling-of-the-stack repair. While actual operations likely result in a combination of these two responses, these models provide upper and lower bounds for actual operation relative to maintaining all BOP functions.

- While the BOP system is constructed with many subsystems that internally have multiple layers of redundancy, the BOP also has single component failure points in its design. These single failures are the dominant contributors to the estimated BOP probability of failure on demand. Based on these RAM results, the dominant contributors to the estimated BOP failure on demand probability are the two single failure points: LMRP connector failure, and Well Head Connector failure. Combined, these two component failures contribute over 99% to the estimated unavailability of the BOP system during "on well." In the calculations, these two components have an equal contribution to the estimated unavailability of the BOP system.

(Note: These dominant contributors were identified based on the total failure rate data for these devices for all failure modes without any differentiation to unsafe and safe failure fraction of the respective failure modes.)

- Due to a lack of available data from the industry, common cause failures of redundant subsystems were not included in the BOP system model for the RAM analysis. Such failures may be significant contributors to subsystem failures that are designed with redundant components. Considering the highly redundant features in much of the BOP system design, further investigation into sources of failure data for BOP common cause failures should be considered.

- To demonstrate the contribution of the component failures associated with non-shearing control measures (i.e., pipe rams and annulars), BOP system availability considering pipe rams and annular(s), and annular(s) only operating were evaluated (i.e., design changes 1 and 2). While these results indicate that the removal of the shear rams and pipe rams (design change 2 only) had little impact on BOP system availability, this results because the remaining component failures, especially the two single point of failure items, have a more significant impact on the BOP system availability than the impact of the removed items on the system availability. However, readers are cautioned to not draw the conclusion that these results indicate the redundancy provided by the removed well control items are not important. The shear and pipe rams are considered important part of the BOP system and provide the required redundancy and essential functions for controlling the well.

- What-If Case 1 analysis indicate the system availability is not significantly changed by the extending of the test interval for all operating scenarios, with an average availability reduction of 0.2% for Operating Scenarios B and C. Specifically, the no change in Operating Scenario A availability was expected since this scenario is based on allowing the BOP functionality to degrade until the BOP can't sufficiently function to control a kick (i.e., no inspection and test are performed). As for Operating Scenarios B and C, the BOP availability for all operating configurations is reduced for one case. The result for the remaining case may indicate no change or drop in availability, but due to model rounding of the results, it is not possible to determine the significance between the results, 0.9835 and 0.984.

- What-If Case 2 analysis shows that improving the reliability performance of a few selected components in the BOP system caused a slight improvement in the estimated BOP availability in all three operating scenarios. The four components selected for improvement were identified in the BSEE Data Analysis Study (ref. 1) as less reliable BOP components. However, the BOP system design includes redundant features for these particular components and thus their failures were small contributors to the BOP system failure probability.

- Improving the reliability of, or gaining better understanding of unsafe and safe failure fractions for, the single point of failure components and other components, which were the major contributors to the BOP estimated unavailability, should cause a significant improvement in BOP availability. Improvements might be achieved through better construction/quality assurance of these items, better item design, and/or reducing detection/repair time of the items.

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LIST OF ACRONYMS

ABS	–	American Bureau of Shipping
ABS Consulting	–	ABSG Consulting Inc.
BOP	–	Blowout Preventer
BSEE	–	Bureau of Safety and Environmental Enforcement
CM	–	Corrective Maintenance
FMECA	–	Failure Mode Effect and Criticality Analysis
HPU	–	Hydraulic Power Unit
IP	–	Industry Participant
LMRP	–	Lower Marine Riser Package
MIT	–	Maintenance, Inspection and Test
MTTF	–	Mean Time to Failure
MTTR	–	Mean Time to Repair
MUX	–	Multiplex
OEM	–	Original Equipment Manufacturer
PM	–	Preventive Maintenance
RAM	–	Reliability, Availability, and Maintainability
RBD	–	Reliability Block Diagram
SPM	–	Sub Plate Mounted (Valve)
TRIMM	–	Tool for Reliability Inspection and Maintenance Management

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1.0 INTRODUCTION

As part of the Blowout Preventer (BOP) Maintenance and Inspection for Deepwater Operations study (BSEE Contract Number M11PC00027), the American Bureau of Shipping (ABS) and ABSG Consulting Inc. (ABS Consulting) performed a Reliability, Availability, and Maintainability (RAM) study of a typical BOP system used in industry. The analysis team developed a Reliability Block Diagram (RBD) model and used BOP system failure events data and maintenance, inspection, and test (MIT) data to estimate BOP system availability. This report represents a portion of Deliverable F for the studies associated with Tasks 6.2.3, 6.2.3.1, and 6.2.3.2, as outlined in the contract.

Two RAM models were developed for BOP systems from two different original equipment manufacturer (OEM) designs. This report presents the RBD model for one of the OEM BOP system design. This analysis is based on a class VI BOP configuration with five rams and a single annular.

This report presents the objective and scope of the RAM study and analysis process and discusses the analysis assumptions, results summary, analysis details, and conclusions.

1.1 OBJECTIVES

The objective of RAM analysis is to determine the impact of MIT activities on the overall availability of a BOP system manufactured by one OEM participating in the MIT project. This was accomplished by (1) developing an RBD model representing the BOP system; (2) analyzing the model using a simulation method in order to estimate the availability of the BOP system during operation periods (on well); and (3) developing and analyzing two design variances and two what-if scenarios (regarding changes to MIT intervals and improved reliability of a few BOP components) to assess the impact of these selected changes on BOP availability.

1.2 ANALYSIS SCOPE

The physical scope of the RAM analysis was limited to a selected BOP system and associated equipment designed by one OEM and used by a drilling contractor and operator participating in the study. The selected BOP system design met the following criteria:

- Operation Location **–** Gulf of Mexico (majority of the operation and maintenance to be from the Gulf of Mexico)
- Operating Depth **–** 5,000 Feet and Deeper
- BOP Configuration of a Class VI**,** five ram configuration and single annular or a four ram and dual annular

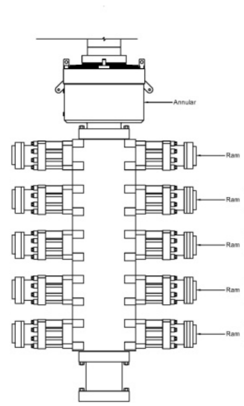

Figure 1-1 Class VI BOP

The analytical scope for the RAM analysis considered all eleven functions defined in a related FMECA study. The BOP system functions considered in developing the RBD model used for analysis are the following:

1. Close and seal on the drill pipe and allow circulation on demand.
2. Close and seal on open hole and allow volumetric well control operations on demand.
3. Strip the drill string using the annular BOP(s).
4. Hang-off the drill pipe on a ram BOP and control the wellbore.
5. Controlled operation – Shear the drill pipe and seal the wellbore.
6. Emergency Operation – Auto-Shear – Shear the drill pipe and seal the wellbore.
7. Emergency Operation – Emergency Disconnect System – Shear the drill pipe and seal the wellbore.
8. Disconnect the LMRP/BOP.
9. Circulate the well after drill pipe disconnect.
10. Circulate across the BOP stack to remove trapped gas.
11. Connect BOP and LMRP at landing.

The RBD model logically shows the interaction of BOP equipment required during a normal operation to successfully provide blowout protection. The model shows how the BOP system can call upon various redundant features to control a pressure kick in the event the situation worsens or BOP subsystems fail. Using this model and failure data for the equipment elements in the model, one can estimate the BOP system availability in the event of a pressure kick.

This analysis encompasses surface and subsea control systems and the BOP Stack equipment as per the BOP design drawings provided in Appendix B. Appendix D lists the individual block and component failure data input into the simulation.

1.3 INTENDED USE

Failure and repair data used in this reliability and availability analysis were partly based on published industry data and as well as data collected as part of this effort. Therefore, it is recommended to use the numerical results as a relative measure of BOP system performance rather than as an absolute measure of performance. In this context, the numerical results from the reliability block diagram and the detail component results can be used to identify the critical components having the most impact on BOP availability.

Ultimately, the results from this assessment are intended to provide a better understanding of BOP system reliability and availability with respect to the existing maintenance, inspection, and test policies.

1.4 RAM Analysis and Meeting Schedule

The analysis team for each study included personnel from two industry participants (IPs), the American Bureau of Shipping (ABS), and ABSG Consulting Inc. (ABS Consulting). The IPs participating included one or more representatives from an OEM and a drilling contractor. These individuals provided knowledge of the design, engineering, operation, and maintenance of the BOP system being evaluated. Table 1-1 lists the functional positions for the IP personnel who participated in this study.

Table 1-1: IP RAM Team Members

IP Organization	Position/Expertise
BOP OEM	Engineering Manager, Drilling Products
	Manager, Reliability Engineering/Drilling and Production
	Electrical Engineering Manager, Drilling and Production
	Sub Section Manager, Stacks, Mechanical Controls and Risers
Drilling Contractor	Subsea Operation Manager
	Subsea Superintendent
	Subsea Multiplex (MUX) System SME
Operator	Engineer Operations, Drilling and Completions

In addition to the IP representatives, personnel from ABS and ABS Consulting participated in the several RAM meetings. Specifically, ABS personnel provided knowledge of the overall BOP operations and class society and regulatory requirements applicable to BOP design and operation. ABS Consulting personnel developed the RBD model, facilitated teleconference and meetings with IPs to refine the RBD model and component failure data, performed the analysis, and documented the RAM study. Table 1-2 lists the ABS and ABS Consulting personnel participating in this study.

To prepare for the RAM studies, ABS and ABS Consulting held a kickoff meeting with the IPs on August 14 and 15, 2012. The purposes of the kickoff meeting were to discuss the FMECA and RAM analysis approaches and the analyses scope to help ensure that all participants have the same level of understanding of the FMECA & RAM procedures.

Table 1-2: ABS and ABS Consulting RAM Team Members

Name	Organization	Title	Study Role
David Cherbonnier	ABS	Staff Consultant, Corporate Offshore Technology	Subsea Engineer
Bibek Das	ABS	Senior Engineer II, Corporate Shared Technology	Senior Engineer II (Risk and Reliability), Corporate Technology
Randy Montgomery	ABS Consulting	Senior Director, Integrity Management	Project Technical Lead
Kamyar Nouri	ABS Consulting	Senior Risk and Reliability Engineer	Risk and Reliability Analyst (model & logic development)
Kamran Nouri	ABS Consulting	Senior Risk and Reliability Engineer	Risk and Reliability Analyst (review and documentation)

In addition to the kickoff meeting, the analysis team held several teleconferences and meetings with the IPs from December 2012 to March of 2013. During these sessions, the RAM team members were provided an introduction to RBD methodology and collaborated on the RBD model logic for the base case, the two design alternatives, and the two “what–if” cases. BOP functions were defined in a related Failure Mode Effect and Criticality Analysis (FMECA) study and were incorporated into the model. All BOP system functions were considered during the development of various analysis cases.

1.5 REPORT ORGANIZATION

Section 2 of this report provides an overview of the methodology used to create RBDs and to estimate the BOP system’s availability for the base case, alternate design cases, and what-if cases. Section 3 discusses the analysis assumptions. Section 4 discusses the results of the effort.   Section 5 discusses the analysis conclusions and observations. Appendices A, B, C and D provide a list of references, drawings, the failure and repair data, the BOP reliability block diagram and detailed block and component information.

2.0 *RELIABILITY AND AVAILABILITY ANALYSIS PROCESS*

To estimate the availability of the BOP system, the analysis team developed an RBD model of this system. The RBD shows the logical interaction of BOP subsystems and equipment required for successful system operation. The RBD model consists of series and parallel trains of components and subsystems required for successful BOP system operation.

The analysis team identified a baseline BOP system (base case) according to one OEM design and one configuration used by one of the drilling contractors participating in the MIT project. The base-case model was used to estimate the reliability and availability of the BOP system for the three operating scenarios. In addition to the base-case model, several alternative designs and what-if scenarios were evaluated (for all three operating scenarios) based on input from the IP.

For the BOP system analysis, the team used BOP component/subsystem failure and maintenance data provided by the IPs. The team developed the RBD model and performed the availability calculations as described in Section 2.1.The BOP system RAM characteristics estimated is:

- Mean Availability for Drilling Operation Period (on well)

2.1 ANALYSIS APPROACH

The basic fundamentals of RBD modeling are to logically show the interaction of subsystems and components required for successful operation of the system. Or conversely, to show combinations of component/subsystem failures that lead to system failure (unavailability or probability of failure on demand).

Figure 2-1 depicts a sample RBD made up of two subsystems, each containing three components. Subsystem 1 contains three series blocks and subsystem 2 contains a combination of parallel and series blocks. In subsystem 1, any component failure will translate to system failure. Subsystem 2, however, has redundant components D and E and thus can withstand a single failure of D or E without suffering system failure. In subsystem 2, component F is in series with all other components and it is a single point of failure for the system.

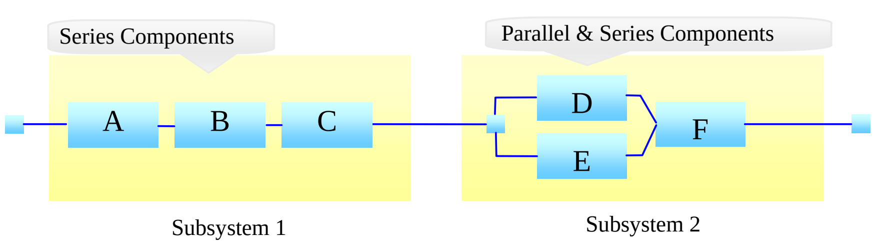

Figure 2-1 RBD Example 1

More complex relationships like ‘K’ out of ‘N’ components and cross relationships can exist and are modeled, if necessary (Figure 2-2).

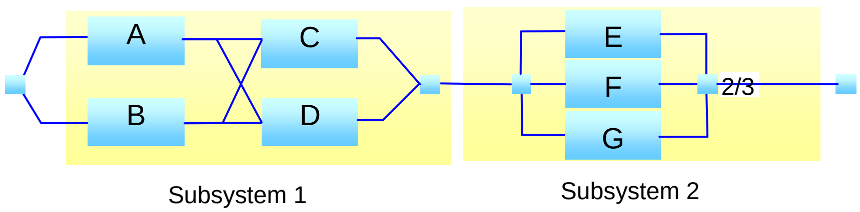

Figure 2-2 RBD Example 2

In both examples, each component is analyzed with respect to failure characteristics and its functional relationship to other components. The component’s failure characteristics are used to determine the component’s time of failure. This information is then passed on to the subsystem and subsequently to the system level, using the RBD as a roadmap for determining how to mathematically combine this information and arrive at system level failure characteristics

After the logic model development, component failure and maintenance data are required for logic model quantification. The analysis team collected equipment/component failure, inspection, test and maintenance data based on available industry data and this project’s data analysis study (BSEE Data Analysis). The reliability data included time-based or “running” failure rates and associated repair and restoration times for identified failure modes.

Monte Carlo simulation using a preset number of iterations was used to estimate system-level results. In this simulation, each component’s failure distribution is sampled each iteration for input into the system calculation until such time that the simulation results converge to a steady state result for the system.

2.2 Analysis Procedures

This section summarizes the procedures used in performing the RAM analysis. The RAM analysis began with the team collecting the documents, drawings, and related information. They then executed the following steps:

1. Reviewed the drawings listed in Appendix B.
2. Identified the specific system boundaries.
3. Reviewed detailed equipment lists.
4. Reviewed the operating requirements and procedures.
   a. Developed a two-phase approach to corrective maintenance (CM) and preventive maintenance (PM) activities covering drilling operation time versus time when the BOP is on the rig.

5. Defined the operating environment.
6. Developed an RBD model for the base case BOP system.
7. Developed an RBD models for the each of the BOP's major functions as per the FMECA study.
8. Performed a reliability and availability analysis (i.e., run the Monte Carlo simulation).
9. Developed an RBD model for the alternate BOP design cases and run the analysis.
10. Performed what-if analyses.
11. Documented the results.

2.3 DATA COLLECTION AND PROCESSING

The collection and analysis of reliability data includes both the compilation of available component/subsystem failure and maintenance data from historical BOP operations data and industry generic data for similar components. With the help of IPs and ABS subject matter experts, the analysis team identified and collected the information and documentation needed to perform the reliability and availability analysis. The information collected included:

- A high-level system diagram
- Component/equipment detail drawings
- Operating environment information
- Available component/equipment reliability data from the Tool for Reliability Inspection and Maintenance Management (TRIMM) database and related data analysis (part of this project, referred to as BSEE Data Analysis)
- Industry data when historical BOP component data were unavailable. These data were used to augment the reliability data from TRIMM, providing a more complete dataset for the analysis

The analysis team reviewed the available information to determine whether any additional information is needed for BOP RBD model development and analysis. The information was used to establish component failure rates and associated repair times. Processing of the collected data involved assessing the applicability of the data to the failure modes of interest in the RAM study.

2.4 OPERATING SCENARIOS

In order to evaluate the BOP performance and evaluate the impact of BOP MIT, the RAM study involved the evaluation of the following three operating scenarios:

- Operating Scenario A – Considers the on-well operation of the BOP until a system failure occurs (i.e., all redundancies failure so that the BOP is no longer available to control a well kick) and prevents the BOP from being capable of controlling a well kick via at least one well control measure (e.g., annular, pipe ram, shear ram). Specifically, this scenario assumes all failures go undetected or not repaired until the entire system is unable sufficiently operate to a control a kick. This scenario results represent the BOP system availability relative to controlling a well kick via at least one well control system.

- Operating Scenario B – Considers the on-well operation of the BOP relative to maintaining all BOP functions with the ability to perform corrective maintenance of surface and subsea components without the securing of the well and the pulling of the BOP stack. Specifically, this scenario models performing corrective maintenance per the industry regulation (i.e., performing corrective maintenance any time a BOP component failure is detected) with the unavailable time being based on the MTTR for the failed component. These scenario results provide the BOP availability for all functions operating assuming repairs do not require the securing of the well and the pulling of the subsea systems for repair. These results represent the upper bound estimate of the BOP system availability for all functions.

- Operating Scenario C – Considers the on-well operation of the BOP relative to maintaining all BOP functions with the requirement that the well must be secured and the BOP pulled to the surface in order to perform corrective maintenance on all subsea system components. (Note: This scenario does not require the securing of the well and the pulling of the BOP stack to perform corrective maintenance on surface BOP system components). Specifically, this scenario models performing corrective maintenance to the industry regulation (i.e., performing corrective maintenance any time a BOP component failure is detected) with the unavailable time being based on (1) the average time to secure the well for failed subsea components and (2) the MTTR for failed surface components. (Note: Based on input from the IPs, the average time to secure well was set at 96 hours.) These scenario results provide the BOP availability for all functions operating assuming all subsea component repairs require the securing of the well and the pulling of the subsea systems for repair. These results represent the lower bound estimate of the BOP system availability for all functions.

2.5 BASE-CASE MODEL AND ANALYSIS

The base-case RBD model developed reflects successful operation of the BOP system design per the drawings listed in Appendix B. and includes both the surface and subsea control systems and the BOP stack. The base-case RBD model is used to estimate the reliability and availability of the BOP system as it is designed and operated at the time of this project. This model includes control and stack subsystems that are involved in sealing, shearing, and balancing the well. The following subsection outlines the details and parameters considered in the simulation and analysis of the base-case RBD model.

Base-Case Simulation Details

BlockSim 7 software was used to perform the Monte Carlo simulations of the BOP RBD model. Figure 2-3 presents the base-case model set-up, indicating we specified an expected lifetime of 5 years (43,825 hours) before a major system overhaul and a maximum of 100 simulations.

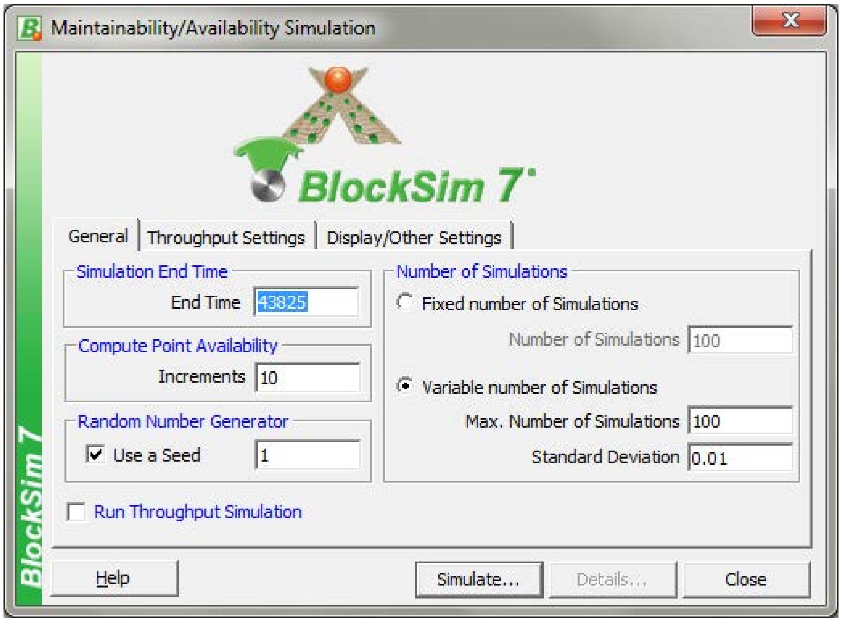

Figure 2-3 Simulation Settings

Since the BOP is not operated continuously throughout the year, the BOP operation has been divided into two main phases "On Well" and "On Rig." The "On Well" phase is the operational phase where the BOP is providing protection against well blowouts and "On Rig" is the maintenance phase (see Figure 2-4). To complete the 5-year profile simulation, each phase is cycled through multiple times based on the given time duration for each phase

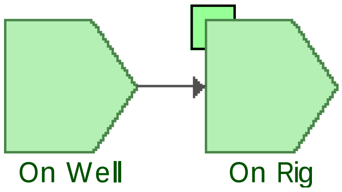

Figure 2-4 Two Phases of the BOP

Figure 2-5 presents the "On Well" operation phase settings. The "On Well" operational phase was set to 8 weeks (1,344 Hours), followed by the maintenance phase "On Rig." During the simulation process, the simulation will switch to the maintenance phase if any failures occur during the operational phase simulation.

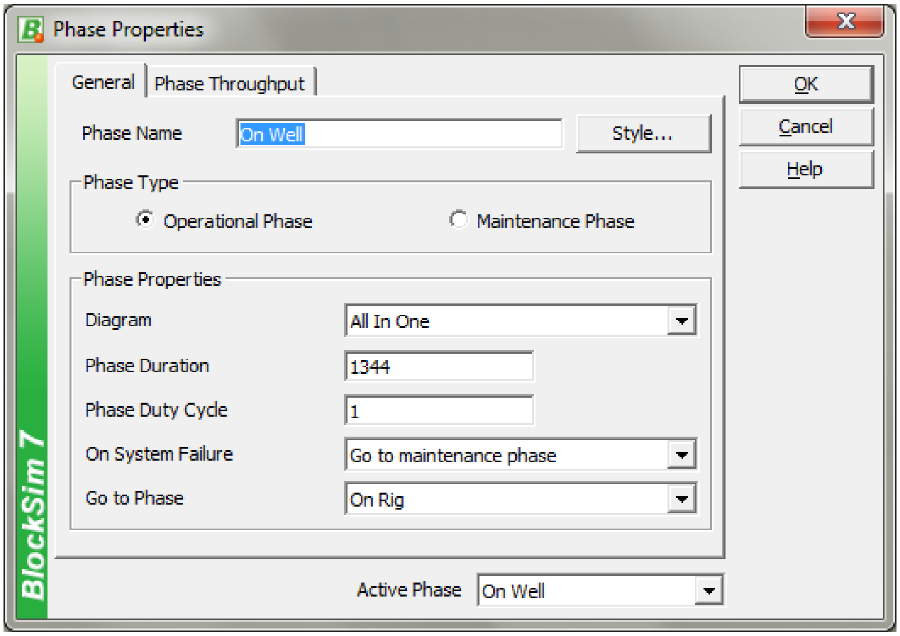

Figure 2-5 "On Well" Operation Phase Settings

Figure 2-6 presents the "On Rig" maintenance phase settings. The "On Rig" maintenance phase contains a maintenance template which dictates which equipment/components are maintained, under CM or PM.

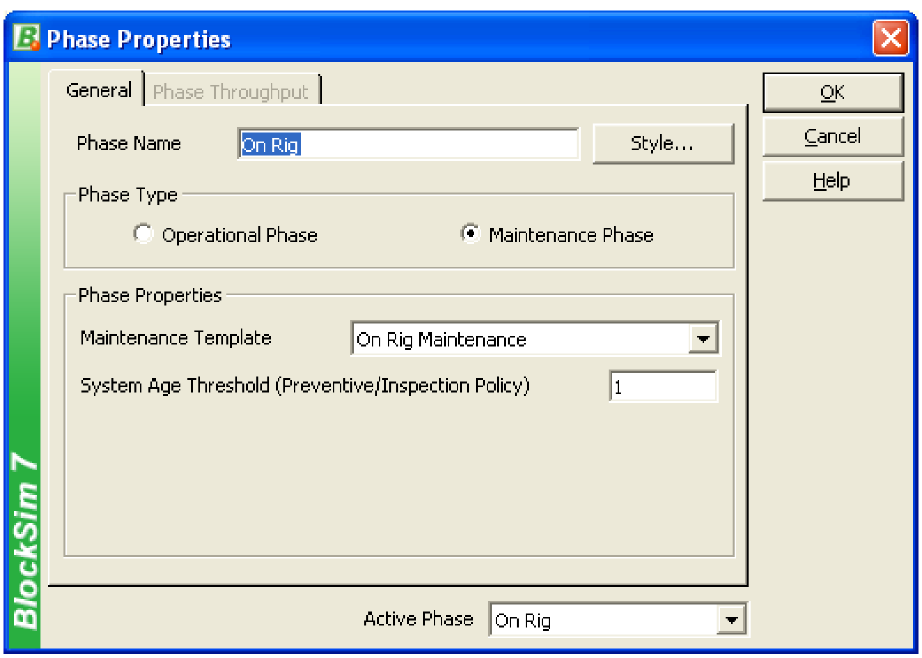

Figure 2-6 "On Rig" Maintenance Phase Settings

Figure 2-7 presents the corrective maintenance policy. Other considerations for the simulation include how CM, PM and Inspection (pressure and function test) are performed. CM always brings the system down, and, therefore, counts against the overall mean availability of the system (on well and on rig periods combined). For CM, a maintenance policy was defined to perform CM upon failure:

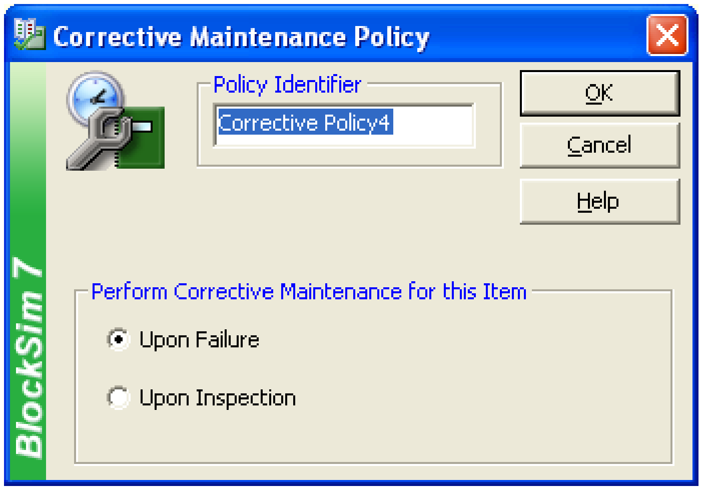

Figure 2-7 Corrective Maintenance (CM) Policy

Figure 2-8 presents the preventive maintenance policy. PMs are performed during non-operational phase "On Rig." For PM, the maintenance policy was defined to only take place during a maintenance phase:

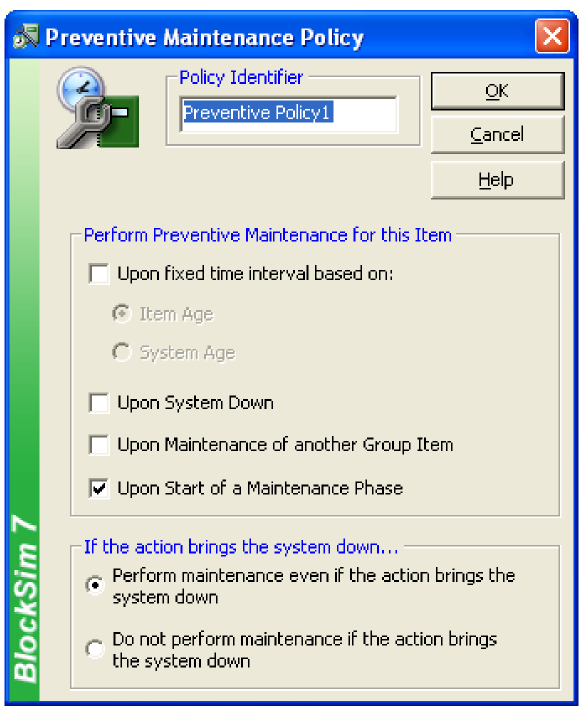

Figure 2-8 Preventive Maintenance (PM) Policy

Figure 2-9 presents the inspection policy. For the purpose of this simulation, the inspection facility of the BlockSim 7 was used to emulate the 14-day tests. The inspection (pressure and function test) interval was embedded in an inspection policy with an interval of 14 days (336 hours). The tests are performed on the well, taking time away from drilling time and therefore reducing the mean availability for all events but not counting against the reliability of the system.

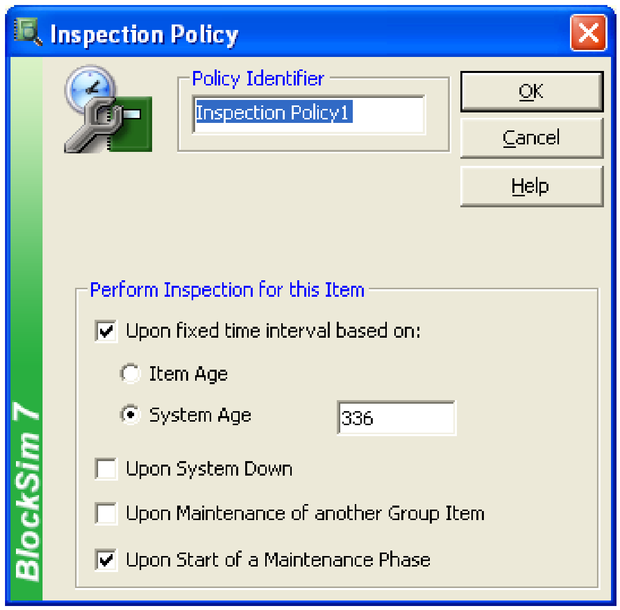

Figure 2-9 Inspection Policy to Emulate the 2-Week Tests

2.6 Alternate Designs and What-If Case Models

After developing and analyzing the base-case model, the analysis team developed two design variation cases and two what-if cases for further analyses. The identified test cases, developed in collaboration with the IPs, were used to evaluate the impact of system design changes, test/inspection frequency changes, and selected component improvement changes on the BOP system's availability. In each test case, only a single design change or specified parameter was modified; all other parameters stayed the same as the base-case RBD model.

1. Design Change 1 **– LMRP and Pipe Rams Only –** It is assumed the BOP system does not have a shear ram(s) in the stack of devices for isolating the well.
2. Design Change 2 **– LMRP Only –** It is assumed the BOP system only has the LMRP in the stack of devices for isolating the well. The Pipe Rams and Shear Ram(s) have been removed from the design.
3. What-If Change 1 - **Test Frequency** - The period between inspections and testing of the BOP system is extended from two weeks to four weeks.
4. What If Change 2 - **Component Reliability** - Based on the project data analysis results and several detailed discussions with the IPs, the team "improved" the reliability performance of four BOP components.

Using the project data analysis, the team identified 4 dominant components with the highest failure rates or the largest number of failures that should be considered for improvement. Next, the subcomponents with the highest number of reported failures within each major component were selected. Additionally, the top failure modes (including the failure modes that could be associated with quality and possible training) were selected. The reliability of the component in terms of its failure rate or mean time to failure (MTTF) that was impacted by component quality and possibly the training of the personnel performing the MIT tasks were selected for improvement. Table 2-1 presents the selected major components and associated failure modes selected for this case.

Table 2-1: Selected BOP Major Components and Percentage of Improvement

BOP Major Component	Highest Number of Component Failure	Component Failure Modes	Percent of Failure	Percentage of Improvement
Blue and Yellow Subsea Control System	Sub Plate Mounted (SPM) Valve & Manifolds	External Leak	42%	52%
		Component out of specification	3%	
		Substandard workmanship	7%	
Choke & Kill Valves and Lines	Connection and Spool Pieces	External Leak	55%	83%
		Component out of specification	5%	
		Substandard workmanship	23%	
MUX Control System	CCU	Processing Error	28%	48%
		Component out of specification	11%	
		Substandard workmanship	9%	
Pipe and Test Ram	All inclusive	Mechanical Failure	26%	58%
		Component out of specification	6%	
		Substandard workmanship	26%	

The improvement made for each major component was to eliminate the failure modes that largely contributed to a component's failure. For example, if Component X had three failure modes that accounted for 70% of the component's failure rate, we would artificially lower the failure rate by 70% to reflect the improvement in the What-If analysis.

3.0 ANALYSIS ASSUMPTIONS

In performing the RBD simulation to estimate BOP system availability characteristics, the analysis team made several assumptions.

3.1 GENERAL ASSUMPTIONS

- All spare parts are available at the rig; the average repair time for components does not include any time for obtaining spare parts from onshore suppliers
- All specialized crews needed to make necessary BOP repairs are available at the rig
- Human errors introducing failures into the BOP system during test, inspection and/or maintenance are not included model; however, they were indirectly considered via improving the reliability of selected components in What-If Case 2.
- Common cause failure of BOP subsystems with redundant components was not included in the analysis due to insufficient data.

The system availability results presented in this report are only based on the estimated time that is required to perform the PM and CM tasks, assuming that the spare parts and the specialized crew are available to perform the necessary tasks. However, the absence of the required spare parts and specialized maintenance crew could result in additional time to perform the maintenance tasks, hence reducing the estimated system availability.

3.2 SPECIFIC ASSUMPTIONS

- The lifetime of the BOP is 5 years (for analysis purposes).
- Failures of any BOP components located in the stack forces the model to switch to maintenance. phase and counts against the on-well availability (availability without PM and inspection).
- Failures of any BOP components located on the rig will not count against the on-well availability (availability without PM and inspection) unless all redundancies have been exhausted.
- Failures of any BOP components located on the rig are assumed to be correctable without the introducing any downtime. In other words corrective maintenance of equipment located on the rig does not require the system to be down. The only exception to this is simultaneous failures of redundant components.
- All subsea subsystems can only be repaired once the BOP brought up to the rig.
- All BOP preventive maintenance takes place on the rig.
- Choke and kill systems are both required for BOP successful operation.
- The use of shear rams is considered as an emergency action in which the well will be abandoned. In reality, there are two other situations where the shear rams may be activated but these events are not considered in the model:
    - Accidental shear by the operator
    - Shear due to rig loss of position control

- A failure in one of the SPM valve "open" circuits effectively disable the corresponding SPM valve closure circuit, eliminating this circuit ram closure signal.
- Hydraulic accumulators provide redundant backup to the hydraulic pumps.
- Average time the BOP is on well (i.e., not on the rig for MIT) is 8 weeks.
- Pressure tests occur at 2-week intervals.
- Duration of each test is 10 hours which is based on an average test durations reported by the IPs. The BOP is available for operation, if needed, during testing.
- Once a failure occurs, the failed BOP component will undergo CM and PM.
- For the purpose of this RAM study, the time duration for pressure and function testing were combined. The test time includes actual test time and any preparation before testing begins.

The pressure and function test duration or test time was determined after discussing several test situations with the IPs. Test duration for the BOP depends on many conditions and variables. The actual test time could be less than an hour. However, time to prepare the well and BOP equipment for testing are impacted by the BOP configuration (such as number of RAMS including blind shear and test ram), availability of test equipment, the drilling depth and the well condition and pressure at the time of testing. Given these variables and potential issues occurring during the test procedures, BOP test duration might range from 1 to 24 hours. A sampling of the recent reported test durations included times of 1, 2, 6, 8, 10, 12, 14, 16 and 24 hours. The team, with input from the IPs, selected 10 hours as the minimum test duration for this study based on the average of some of the recent/reported test duration.

The selected test time (10 hours) is only minimum/reasonable amount of time for testing the BOP system only during ***normal routine operation***, given the fact that the BOP stack is latched on to the wellhead and initial BOP system testing after installation is satisfactory.

3.3 BLOCKSIM 7 ANALYSIS PARAMETERS

In performing the RBD simulation of the BOP system, the analysis team specified the following parameters for the analysis:

- Simulation Factors:
  Simulation End Time: 43,825 Hours or 5 Years
  Number of Simulations: 100
- Corrective maintenance takes place upon a failure for Operating Scenarios B and C.
- Preventive maintenance occurs only when the BOP is on the RIG.
- BlockSim's inspection facility is used to emulate the 14-day tests.

4.0 RESULTS SUMMARY

Using two separate component failure datasets and considering several design alternatives and what-if scenarios, fifteen separate analyses of the BOP system were performed. These fifteen separate analyses included the analysis of the three operating scenarios as detailed in Section 2.4 for the five analysis cases outlined in Table 4-1. In each case the input MTTF values are obtained from the BSEE Data Analysis Report, supplemented with data from industrial data references (IEEE STD 497, OREDA 2009) where data gaps existed.

Table 4-1: List of Analysis Cases

Analysis Case	Description
Base Case - All functions; IP Data	This configuration considers all BOP well control system capabilities, including annular, pipe Rams, shear rams, auto shear and emergency disconnect systems and associated controls and choke and kill components.
Design Change 1 LMRP Annular & Pipe Rams Only; IP Data	This configuration considers BOP well control system capabilities, associated with annular, pipe rams only and their associated controls and choke and kill components.
Design Change 2 - LMRP Annular Only; IP Data	This configuration considers BOP well control system capabilities associated with annular only and its associated controls and choke and kill components.
What If Case 1; Test Interval 4 weeks; IP Data	This What-If case evaluates the impact of increasing the inspections interval form 2 weeks to 4 weeks. The base-case BOP configuration is used for this What-If case.
What If Case 2; Improved reliability of select components; IP data	This What-If case evaluates the impact of improving the reliability of more frequently failing BOP components, based on the data analysis results. Specifically, this What-If case includes reliability improvement of the (1) blue and yellow subsea control system, (2) choke & kill valves and lines, (3) MUX control system, and (4) pipe and test ram. The base-case BOP configuration is used for this What-If case. Reliability input data was adjusted based on Table 2-1.

Table 4-2 tabulates the simulation results for the three operating scenarios and the above analysis cases. The reliability block diagrams for these analysis cases are provided in Appendix D.

Table 4-2: Results Summary

BOP Analysis Cases	Operating Scenario A	Operating Scenario B	Operating Scenario C
	Mean Availability For Drilling Operation Period (On Well) With At Least One Well Control Function Remaining to Control a Well Kick	Mean Availability for Drilling Operation Period (On Well) While Maintaining **All** BOP Well Control Functions Assuming CM Performed Without Pulling of the Stack	Mean Availability for Drilling Operation Period (On Well) While Maintaining **All** BOP Well Control Functions Assuming Any Subsea CM Performed Requires Securing of the Well and Pulling of the Stack
Base Case: All Well-Control Functions	.9991	.9902	.9835
Design Change 1 (LMRP Annular(s) & Pipe Rams Only)	.9946	.9881	.9882
Design Change 2 (LMRP Annular(s) Only)	.9937	.9876	.9878
What-If Case 1 (4 week test interval)	.9995	.9871	.984
What If Case 2 (Improved reliability of select components)	.9993	.9912	.99

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5.0 OBSERVATION AND CONCLUSIONS

The simulation calculated report the availability figures of merit for the Bop system without PM and inspection activity (i.e., while in service "on well"). Since the BOP is a safety critical system the availability result without the PM and inspection is of interest.

The estimated availability of the BOP system for Operating Scenario A ranges from 0.9937 to 0.9995. (Note: Results of Operating Scenario A represent the BOP availability to control a well kick by at least one well control function, which is a better measure of the BOP system availability relative to its overall safety operation.) For operating scenarios B and C, the estimated availability for the BOP systems ranges from 0.9871 to 0.9912 and from 0.9835 to 0.99, respectively. A comparison of results of the Operating Scenario A to the results of Operating Scenarios B and C reflects the expected outcome that the BOP availability for at least one well control function operating is significantly higher (i.e., approximately one order of magnitude improvement) than the BOP availability for all well control functions.

In addition to the above observation, the team made the following observations:

- While the BOP system is constructed with many subsystems that internally have multiple layers of redundancy, the BOP also has single component failure points in its design. These single failures are the dominant contributors to the estimated BOP probability of failure on demand. Based on these RAM results, the dominant contributors to the estimated BOP failure on demand probability are the two single failure points: LMRP connector failure, and Well Head Connector failure. Combined, these two component failures contribute over 99% to the estimated unavailability of the BOP system during "on well." In the calculations, these two components have an equal contribution to the estimated unavailability of the BOP system.

  (Note: These dominant contributors were identified based on the total failure rate data for these devices for all failure modes without any differentiation to unsafe and safe failure fraction of the respective failure modes.)

- Due to a lack of available data from the industry, common cause failures of redundant subsystems were not included in the BOP system model for the RAM analysis. Such failures may be significant contributors to subsystem failures that are designed with redundant components. Considering the highly redundant features in much of the BOP system design, further investigation into sources of failure data for BOP common cause failures should be considered.

- To demonstrate the contribution of the component failures associated with non-shearing control measures (i.e., pipe rams and annulars), BOP system availability considering pipe rams and annular(s), and annular(s) only operating were evaluated (i.e., design changes 1 and 2). While these results indicate that the removal of the shear rams and pipe rams (design change 2 only) had little impact on BOP system availability, this results because the remaining component failures, especially the two single point of failure items, have a more significant impact on the BOP system availability than the impact of the removed items on the system availability. However, readers are cautioned to not draw the conclusion that these results indicate the redundancy provided by the removed well control items are not important. The shear and pipe rams are considered important part of the BOP system and provide the required redundancy and essential functions for controlling the well.

- What-If Case 1 analysis indicate the system availability is not significantly changed by the extending of the test interval for all operating scenarios, with an average availability reduction of 0.2% for Operating Scenarios B and C. Specifically, the no change in operating scenario A availability was expected since this scenario is based on allowing the BOP functionality to degrade until the BOP can't sufficiently function to control a kick (i.e., no inspection and test are performed). As for Operating Scenarios B and C, the BOP availability for all operating configurations is reduced for one case. The result for the remaining case may indicate no change or drop in availability, but due to model rounding of the results, it is not possible to determine the significance between the results, 0.9835 and 0.984.

- What-If Case 2 analysis shows that improving the reliability performance of a few selected components in the BOP system caused a slight improvement in the estimated BOP availability in all three operating scenarios. The four components selected for improvement were identified in the BSEE Data Analysis Study (ref. 1) as less reliable BOP components. However, the BOP system design includes redundant features for these particular components and thus their failures were small contributors to the BOP system failure probability.

- Improving the reliability of, or gaining better understanding of unsafe and safe failure fractions for, the single point of failure components and other components, which were the major contributors to the BOP estimated unavailability, should cause a significant improvement in BOP availability. Improvements might be achieved through better construction/quality assurance of these items, better item design, and/or reducing detection/repair time of the items.

APPENDIX A – LIST OF REFERENCES

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This appendix provides a list of relevant industry data sources used during the RAM analysis.

1- BSEE Data Analysis, BOP Failure Event and Maintenance, Inspection and Test (MIT) Data Analysis for BSEE (project related analysis), ABS Consulting Inc., 2013.
2- IEEE Std 493^{TM}, Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems, Institute of Electrical and Electronics Engineering, Inc., 2007.
3- OREDA 2009, Offshore Reliability Data 5th Edition, Volume 1 &2, SINTEF, 2009.
4- SINTEF Report 2012, Reliability of Deepwater Subsea BOP Systems and Well Kicks, SINTEF, 2012.

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APPENDIX B – LIST OF DRAWINGS

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This appendix provides a list of drawings used during the RAM analysis.

S/D, SCOPE OF SUPPLY
S/D, HYDRAULIC, LMRP
S/D, HYDRAULIC, STACK
S/D, HYDRAULIC, MUX POD
S/D, BLOCK DIAGRAM HYDRAULIC INTERCONNECT
S/D, HYDRAULIC POWER UNIT
S/D, FAMILY OF FUNCTIONS
S/D, SYSTEM CABLING BLOCK DIAGRAM

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APPENDIX C – FAILURE AND REPAIR DATA

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FAILURE AND REPAIR DATA INPUT TO RBD MODEL

The individual component reliability data was gathered from several sources and organized in the following table. The MTTF and MTTR values in this table were used to populate the RBD simulation model. Data from the BSEE Data Analysis study was used to the extent that they were available.

Table C-1: Reliability Data for Individual BOP Components

Subsystem / Component	Quantity	MTTF	Source	MTTR	Source	PM	Source	Inspection	Source
POWER Subsystem									
UPS	2	9,499,764	IEEE Std 493-2007	3.688	IEEE Std 493-2007	4.625	BSEE MIT Data Analysis	3.688	
POWER DIST PANEL	2	102,156	IEEE Std 493-2007	5.74	IEEE Std 493-2007	5.74		5.74	
SUBSEA XFMR	2	74,357,512	IEEE Std 493-2007	4.272	IEEE Std 493-2007	4.272		4.272	
CCU – Elect. Controls									
Remote Driller Panel	2	112,373	BSEE Data Analysis	5.9	BSEE MIT Data Analysis	2	BSEE MIT Data Analysis	4.406	
Driller's Panel	1	112,373	BSEE Data Analysis	5.9	BSEE MIT Data Analysis	2	BSEE MIT Data Analysis	4.406	
Remote Control Panel	1	112,373	BSEE Data Analysis	5.9	BSEE MIT Data Analysis	2	BSEE MIT Data Analysis	4.406	
Processor & Equipment Cabinets (CCU)	2	10,345	IEEE Std 493-2008	0.771	IEEE Std 493-2008	0.771		0.771	
Power Isolation J-Box	1	308,7252.6	IEEE Std 493-2008	2.519	IEEE Std 493-2008	2.519		2.519	
MUX System									
J-Box MUX Umbilical	2	308,7252.6	IEEE Std 493-2008	2.519	IEEE Std 493-2008	2.519		2.519	
Cable Reel	2	63,938	OREDA 2009	40	OREDA 2009	5		5	
Hydraulic Power Unit (HPU) – Hydraulic Controls									
HPU I/F Control Panel	1	112,373	BSEE Data Analysis	5.9	BSEE MIT Data Analysis	2	BSEE MIT Data Analysis	4.406	
Reservoir / Mixing Unit	1	126,420	BSEE Data Analysis	59.9	OREDA 2009	10		10	
Accumulator 180 GAL 16 Station 5K	1	1,820,448	BSEE Data Analysis	2.92	BSEE MIT Data Analysis	6.88	BSEE MIT Data Analysis	2	
Accumulator 285 GAL 20 Station 5K	2	1,820,448	BSEE Data Analysis	2.92	BSEE MIT Data Analysis	6.88	BSEE MIT Data Analysis	2	
Accumulator VM1	3	71,839	BSEE Data Analysis	16	OREDA 2009	2		2	
100 HP Pump	3	16,458	OREDA 2009	34	OREDA 2009	5		5	
Suction Strainer 100 Mesh	3	8,333,333	OREDA 2009	1		1		1	
Filtration Unit	1	8,333,333	OREDA 2009	1		1		1	
Hydraulic Hotline & Rigid Conduits									
Hotline Reel	2	2,439,024	OREDA 2009	2	OREDA 2009	2		2	
Rigid Conduit	1	2,439,024	OREDA 2009	2	OREDA 2009	2		2	
Stack									
LMRP Connector	1	126,420	BSEE Data Analysis	3.95	BSEE MIT Data Analysis	12.22	BSEE MIT Data Analysis	10	IP - See Assumption
Stack Accumulators (16 * 80 Gal)	1	1,820,448	BSEE Data Analysis	2.92	BSEE MIT Data Analysis	6.88	BSEE MIT Data Analysis	10	IP - See Assumption
Valve, 3WNC, SSUB X SSUB, SPM	32	958,131	BSEE Data Analysis	15.04	BSEE MIT Data Analysis	5.63	BSEE MIT Data Analysis	10	IP - See Assumption
Shear Seal Valve, Solenoid, 3WNC (6)	36	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
VALVE 3W DOUBLE PILOT (38)	2	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Shuttle Valve	16	2,073,288	BSEE Data Analysis	5.545	BSEE MIT Data Analysis	4.833	BSEE MIT Data Analysis	10	IP - See Assumption

Subsystem / Component	Quantity	MTTF	Source	MTTR	Source	PM	Source	Inspection	Source
LMRP Annular	1	36,120	BSEE Data Analysis	6.88	BSEE MIT Data Analysis	16.6	BSEE MIT Data Analysis	10	IP - See Assumption
Upper Shear Rams	1	63,210	BSEE Data Analysis	5.64	BSEE MIT Data Analysis	20.7	BSEE MIT Data Analysis	10	IP - See Assumption
Lower Shear Rams	1	63,210	BSEE Data Analysis	5.64	BSEE MIT Data Analysis	20.7	BSEE MIT Data Analysis	10	IP - See Assumption
Upper Pipe Rams	1	34,874	BSEE Data Analysis	5.64	BSEE MIT Data Analysis	20.7	BSEE MIT Data Analysis	10	IP - See Assumption
Middle Pipe Rams	1	34,874	BSEE Data Analysis	5.64	BSEE MIT Data Analysis	20.7	BSEE MIT Data Analysis	10	IP - See Assumption
Lower Pipe Rams	1	34,874	BSEE Data Analysis	5.64	BSEE MIT Data Analysis	20.7	BSEE MIT Data Analysis	10	IP - See Assumption
SSTV Rams	1	34,874	BSEE Data Analysis	5.64	BSEE MIT Data Analysis	20.7	BSEE MIT Data Analysis	10	IP - See Assumption
Auto Shear ARM Valve T4	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Hydraulic Autoshear Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Well Head Connector	1	126,420	BSEE Data Analysis	3.95	BSEE MIT Data Analysis	12.22	BSEE MIT Data Analysis	10	IP - See Assumption
Subsea Electronic Module	2	45,971	BSEE Data Analysis	0.77	OREDA 2009	0.77	OREDA 2009	10	IP - See Assumption
POD Pressure Regulator w/o POCV Y	2	140,467	BSEE Data Analysis	15.04	OREDA 2009	5.63	OREDA 2009	10	IP - See Assumption
POD Pressure Regulator including POCV B	2	137,913	BSEE Data Analysis	15.04	OREDA 2009	5.63	OREDA 2009	10	IP - See Assumption
Choke & Kill System									
Choke Line	1	42,528	SINTEF 2012	117	SINTEF 2012	5		10	IP - See Assumption
Kill Line	1	42,528	SINTEF 2012	117	SINTEF 2012	5		10	IP - See Assumption
Upper Inner Choke Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Lower Inner Choke Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Lower Inner Kill Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Upper Inner Kill Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Lower Outer Choke Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Upper Outer Choke Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Lower Outer Kill Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Upper Outer Kill Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Inner Bleed Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Outer Bleed Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Choke STAB	1	252,840	BSEE Data Analysis						
Kill STAB	1	252,840	BSEE Data Analysis						
Choke Test Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Kill Test Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Shuttle Valve	20	2,073,288	BSEE Data Analysis	5.545	BSEE MIT Data Analysis	4.833	BSEE MIT Data Analysis	10	IP - See Assumption
SPM VALVE	40	958,131	BSEE Data Analysis	15.04	BSEE MIT Data Analysis	5.63	BSEE MIT Data Analysis	10	IP - See Assumption
Shear Seal Valve, Solenoid, 3WNC (6)	40	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption

APPENDIX D – RELIABILITY BLOCK DIAGRAM

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BASE-CASE – ALL FUNCTIONS RELIABILITY BLOCK DIAGRAM

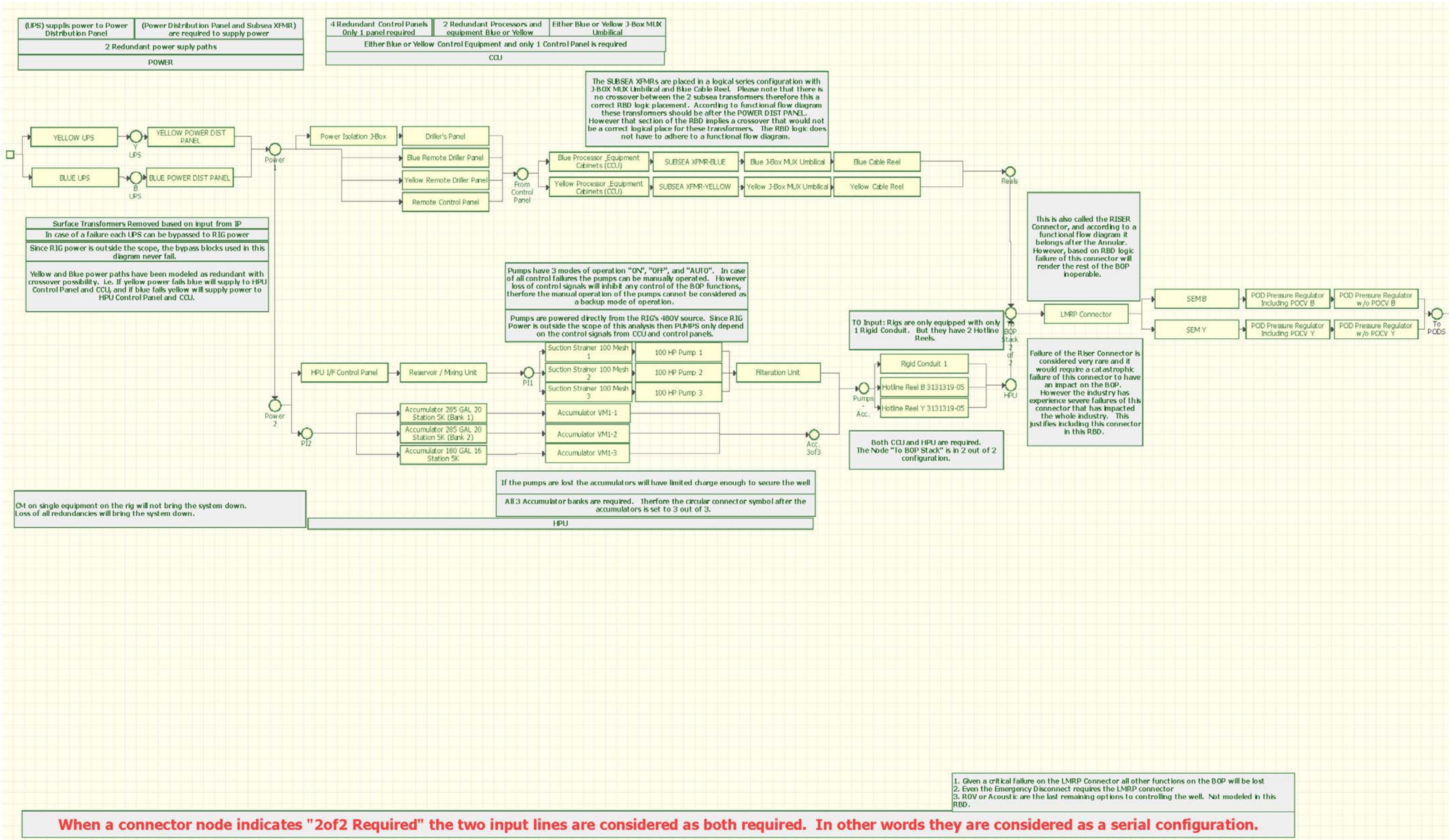

Figure D-1 All Functions Reliability Block Diagram (1 of 3)

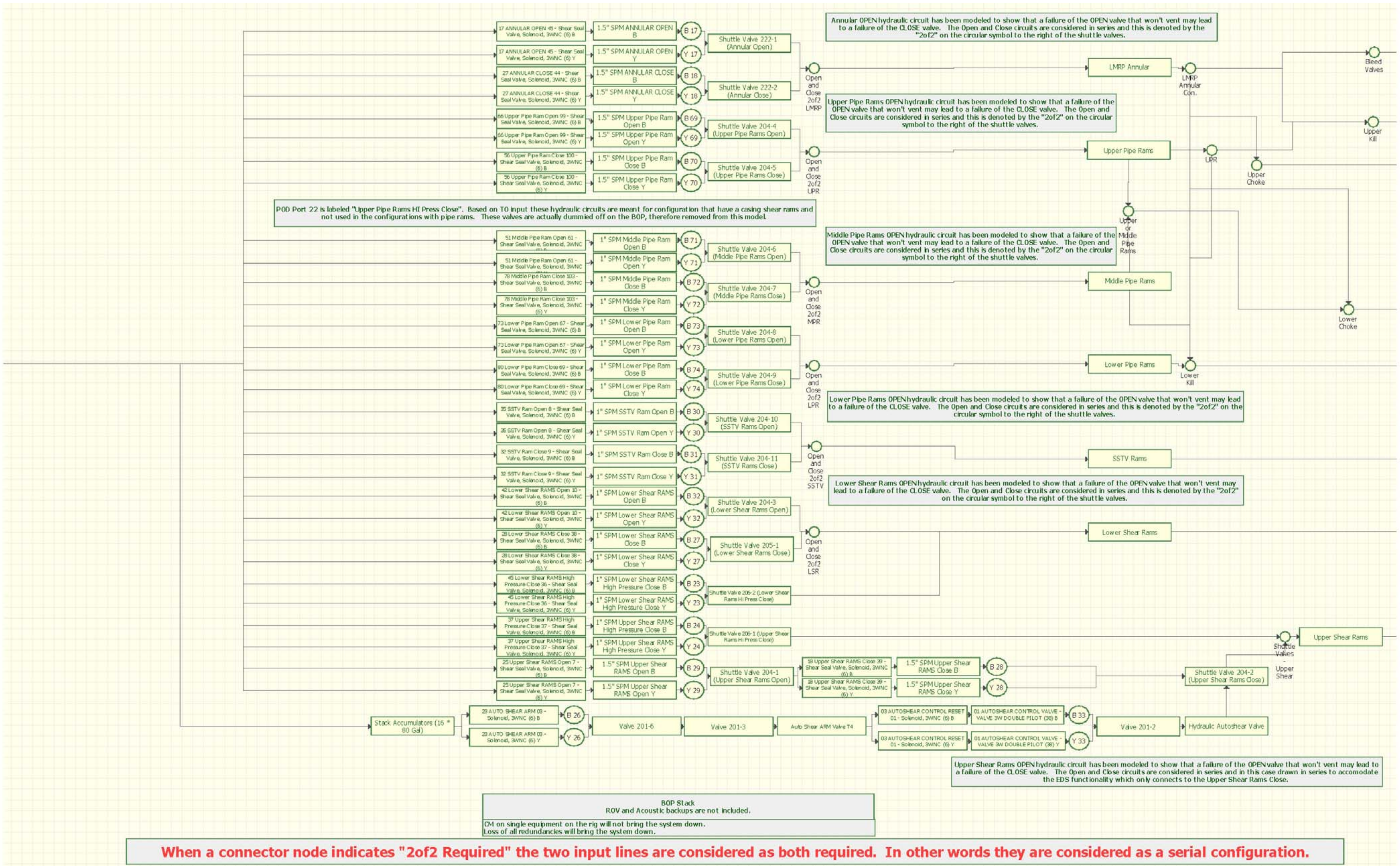

Figure D-1 All Functions Reliability Block Diagram (2 of 3)

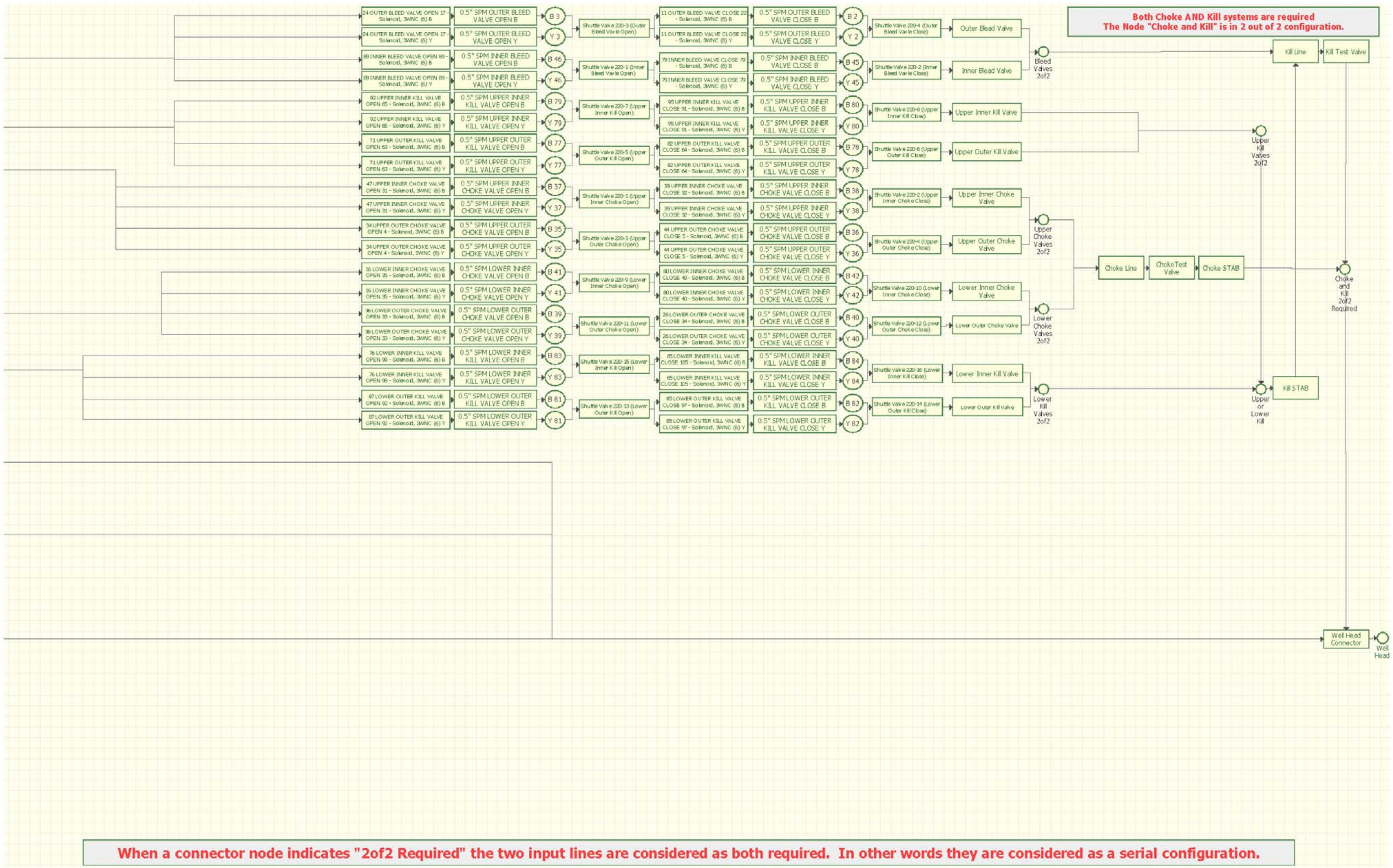

Figure D-1 All Functions Reliability Block Diagram (3 of 3)

Design Change 1 – LMRP ANNULAR & PIPE RAMS ONLY RELIABILITY BLOCK DIAGRAM

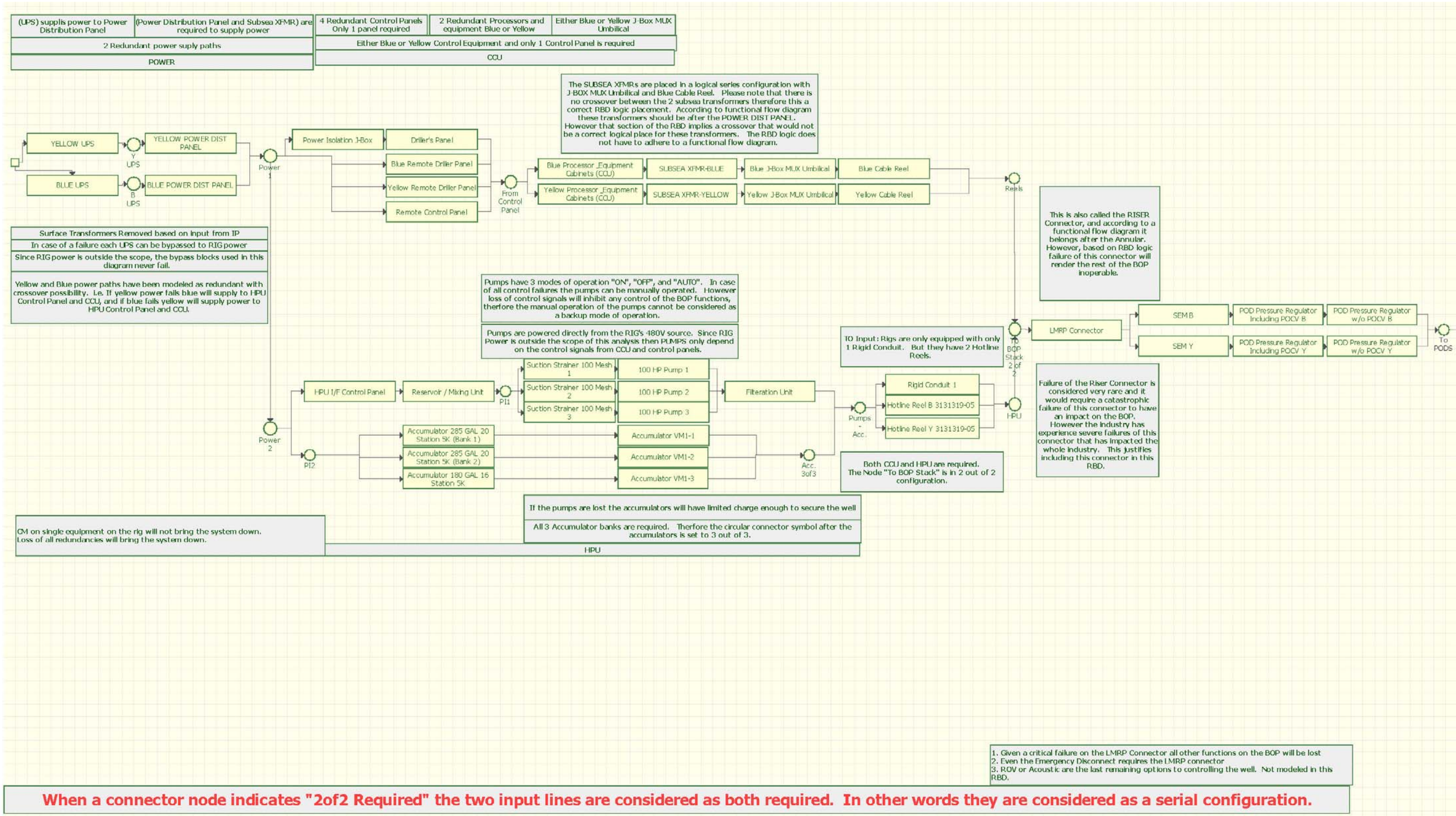

Figure D-2 LMRP Annular and Pipe RAMS Only Reliability Block Diagram (1 of 3)

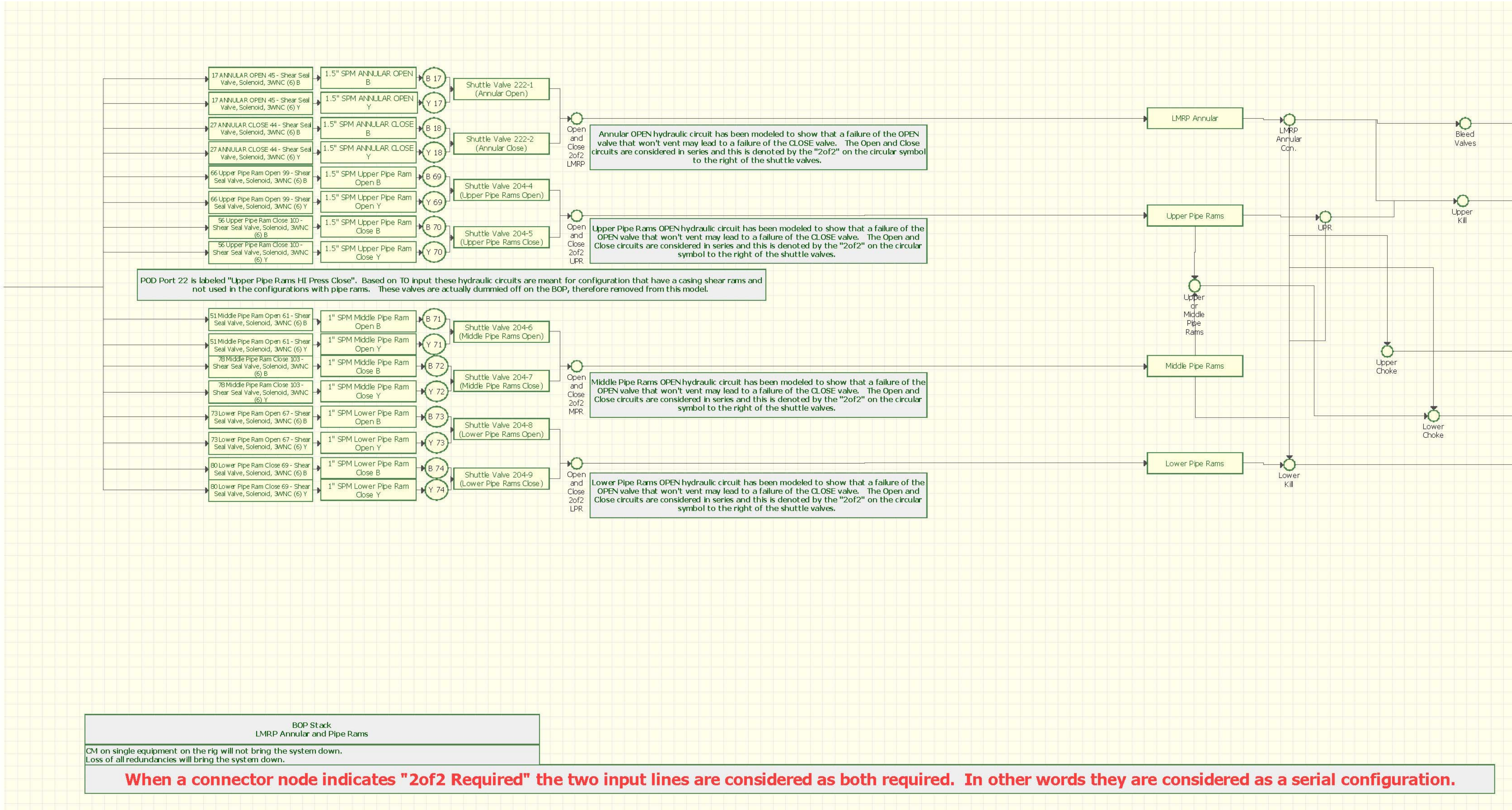

Figure D-2 LMRP Annular and Pipe RAMS Only Reliability Block Diagram (2 of 3)

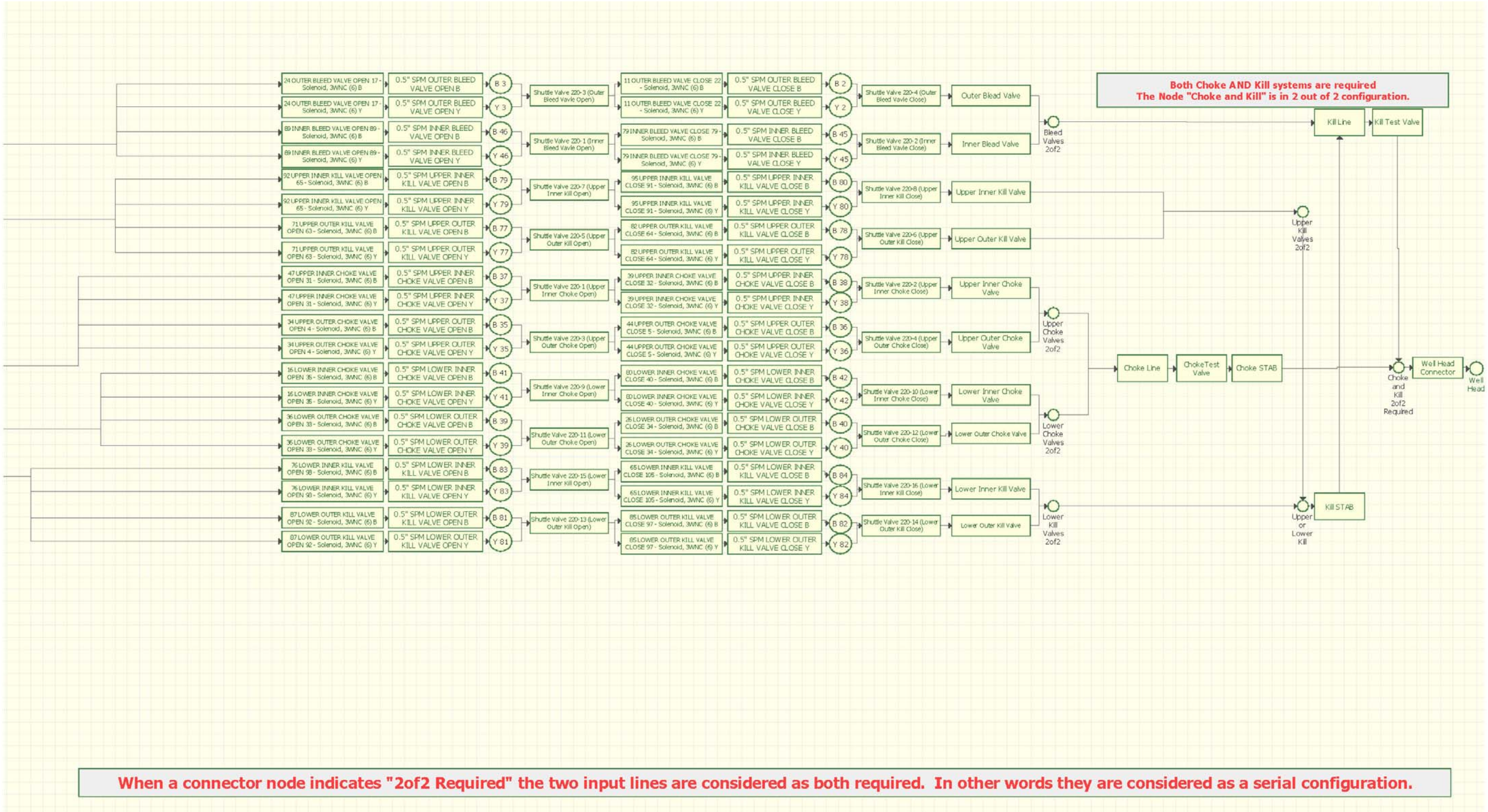

Figure D-2 LMRP Annular and Pipe RAMS Only Reliability Block Diagram (3 of 3)

Design Change 2 – LMRP ANNULAR ONLY RELIABILITY BLOCK DIAGRAM

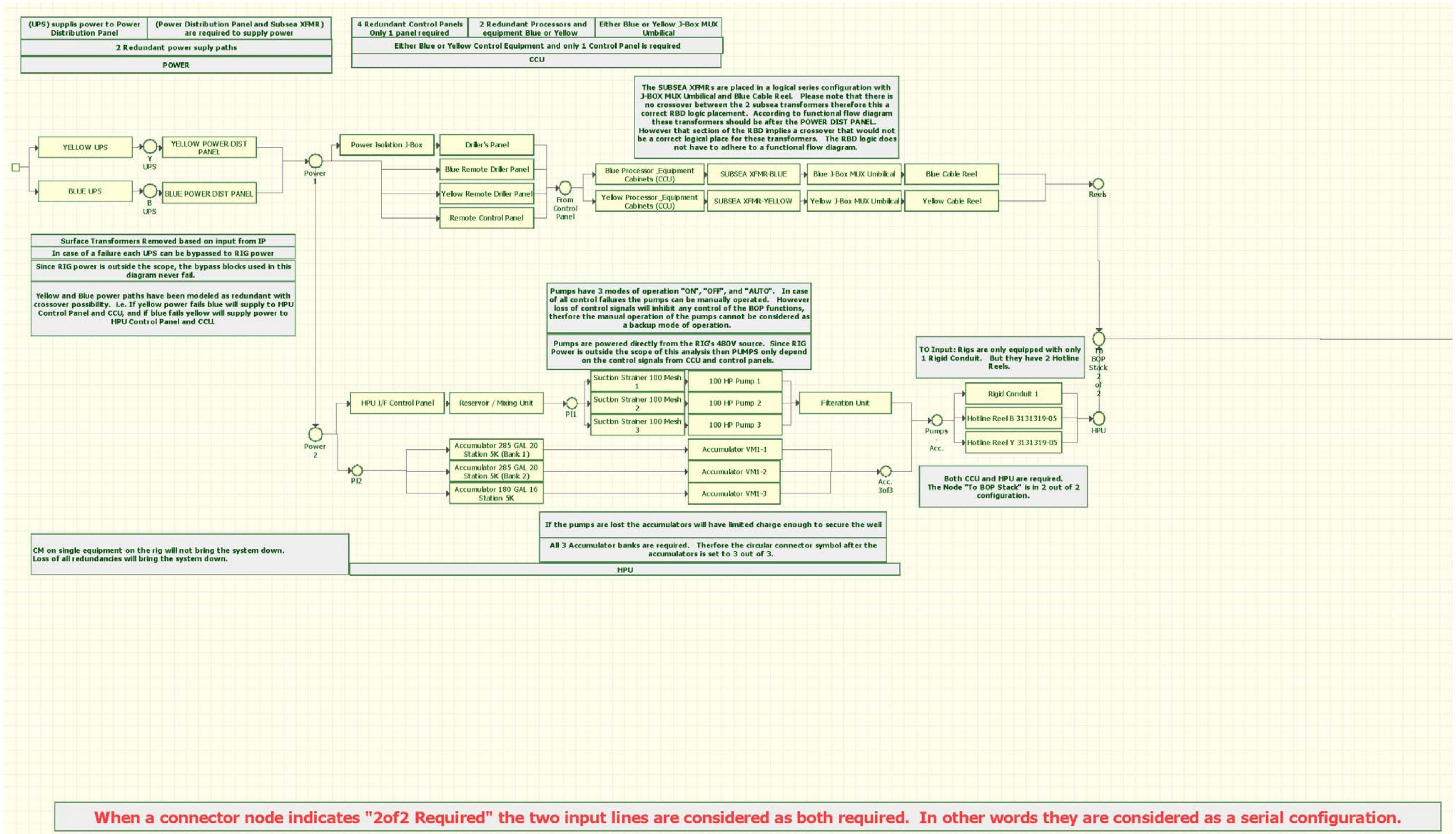

Figure D-3 LMRP Annular Only Reliability Block Diagram (1 of 3)

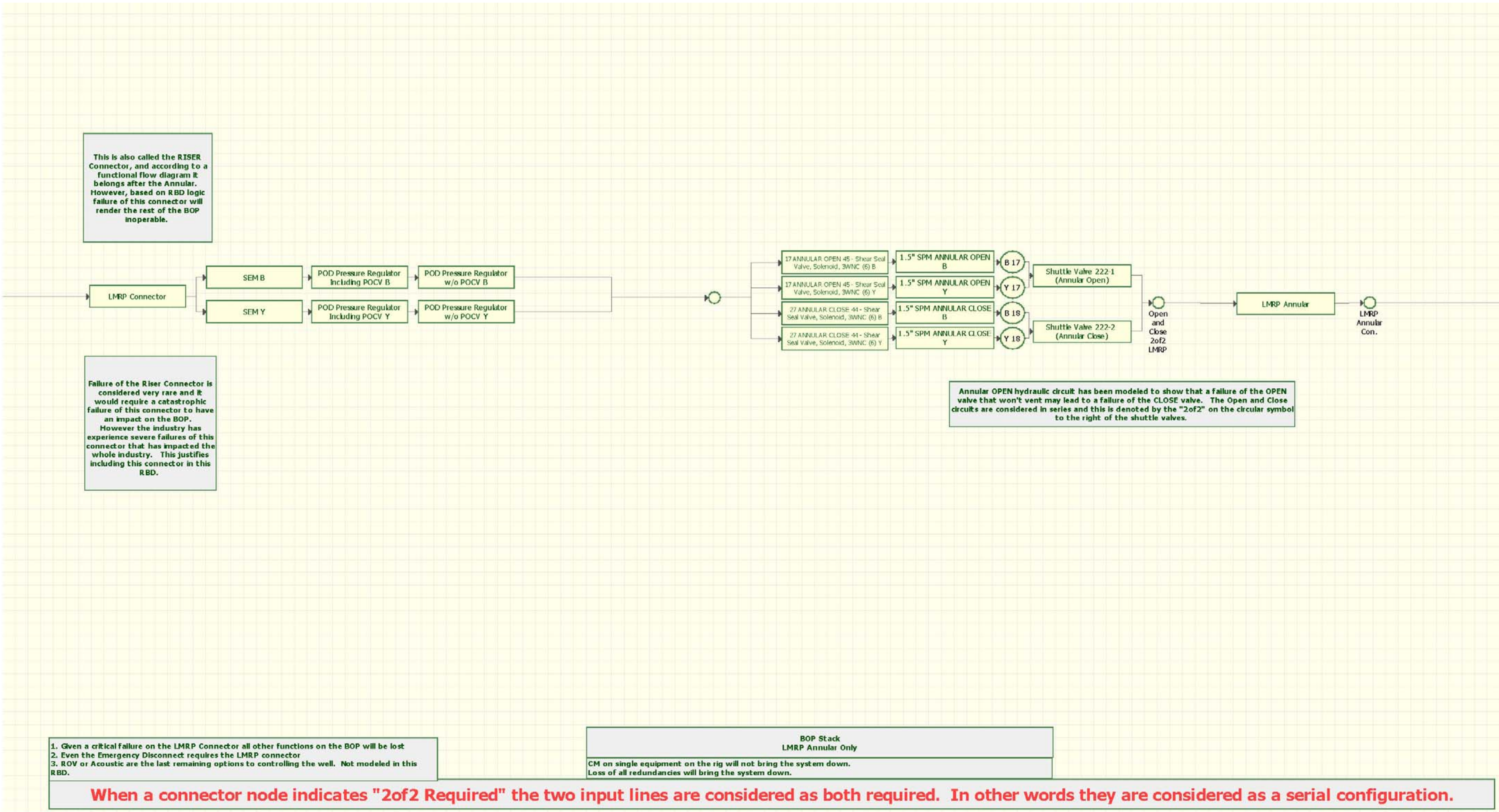

Figure D-3 LMRP Annular Only Reliability Block Diagram (2 of 3)

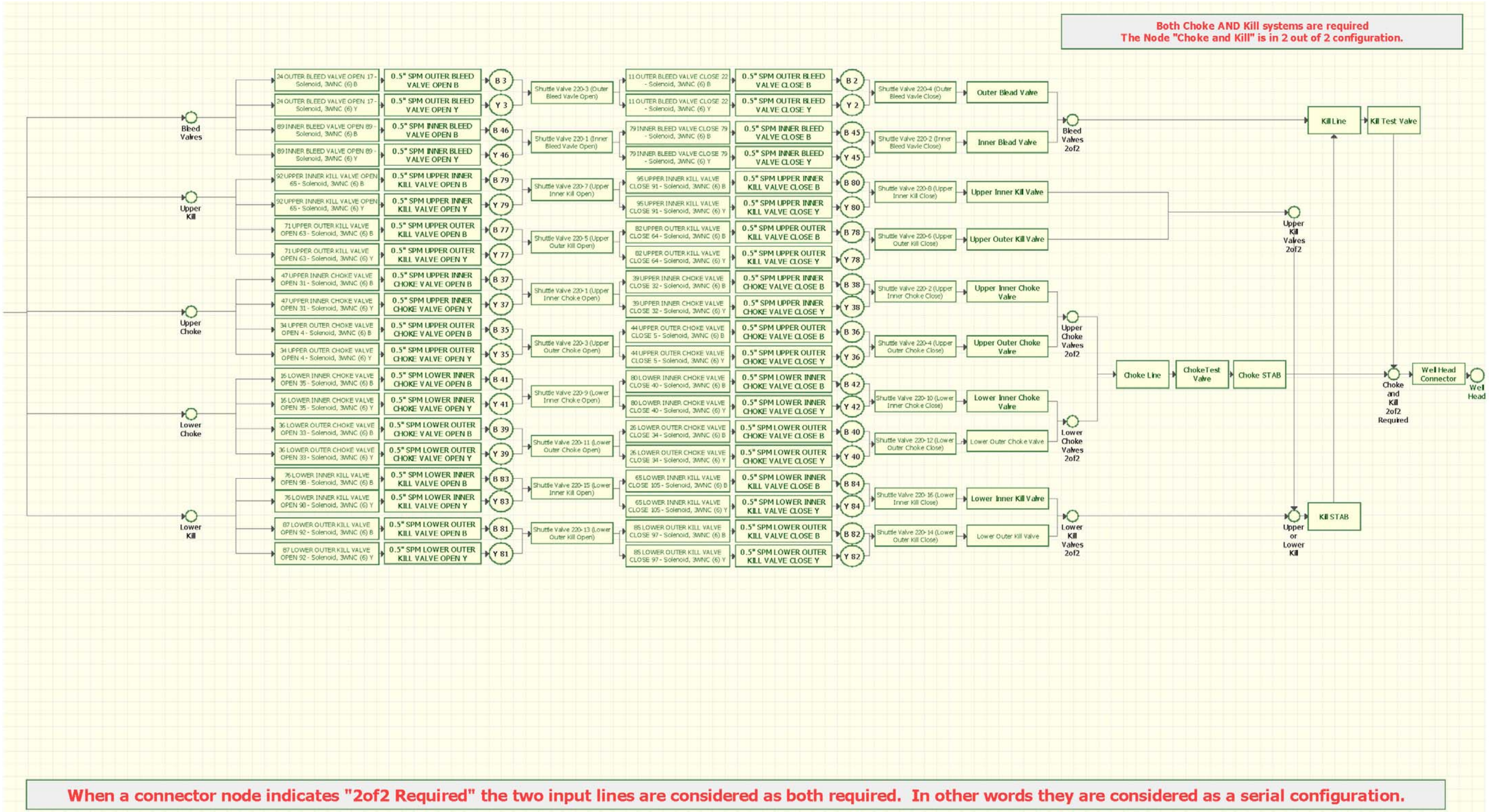

Figure D-3 LMRP Annular Only Reliability Block Diagram (3 of 3)

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BLOWOUT PREVENTER (BOP)
RELIABILITY, AVAILABILITY, AND
MAINTAINABILITY (RAM) ANALYSIS 2
FOR THE
BUREAU OF SAFETY AND ENVIRONMENTAL ENFORCEMENT

2650788-RAM-1-F2	2	Final Report for Issue to BSEE	6/27/2013
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June 2013

This work was performed by American Bureau of Shipping and ABSG Consulting Inc. for the Bureau of Safety and Environmental Enforcement (BSEE) under the terms of BSEE contract number M11PC00027

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<u>LIST OF CONTRIBUTORS:</u>

ABS Consulting
Randal Montgomery
Kamran Nouri
Kamyar Nouri
David Montague

Industry Participants
OEM#2, DC#3, and OP#3

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SUMMARY

As part of the Blowout Preventer (BOP) Maintenance and Inspection for Deepwater Operations study (BSEE Contract Number M11PC00027), the American Bureau of Shipping (ABS) and ABSG Consulting Inc. (ABS Consulting) performed a Reliability, Availability, and Maintainability (RAM) analysis of a typical BOP used in industry. Using a Reliability Block Diagram portraying the various combinations of component/subsystems required for successful BOP operation, failure data for the BOP system components, and maintenance, inspection and test data for a typical system, the analysis team estimated the availability of the BOP system. Availability, as used in this study, is the probability the BOP system functions properly on demand. This report presents the results for one of the Industry Participant's BOP design.

This report represents a portion of Deliverable F for the studies associated with Tasks 6.2.3, 6.2.3.1, and 6.2.3.2, as outlined in the above referenced contract. This report presents the objective and scope of the Reliability Availability Maintainability (RAM) study, analysis process, analysis assumptions, results summary, and conclusions/observations.

The objective of RAM analysis is to determine the impact of Maintenance, Inspection and Testing (MIT) activities on the overall availability of BOP system manufactured by one Original Equipment Manufacturer participating in the MIT project. This was accomplished by (1) developing an Reliability Block Diagram (RBD) model representing the BOP system; (2) analyzing the model for the three different operating scenarios, using a simulation method in order to estimate the availability of the BOP system during operation periods (on well); and (3) developing and analyzing two design variances and two "what-if" scenarios (regarding changes to MIT intervals and improved reliability of a few BOP system components) to assess the impact of these selected changes on BOP availability.

The analysis team estimated BOP availability using component failure events and failure data collected primarily from industry participants (IPs) participating in this study. The failure events were analyzed during a separate project data analysis task (BSEE Data Analysis) and are used as input to the base model for the RAM analysis. These data were supplemented with failure data from published industrial component failure data references when information was unavailable from the IPs. Availability results were estimated for the base design, two variations to this design, and two what-if scenarios.

Table S-1, BOP Availability Results Summary summarizes the RAM model results. This table presents mean availability results for three BOP operating scenarios and the results for each scenario based on five BOP analysis cases: base case, two design cases, and two what-if improvement cases. The three BOP operating scenarios are:

- Operating Scenario A – Considers the on-well operation of the BOP until a system failure occurs (i.e., all redundancies failure so that the BOP is no longer available to control a well kick) and prevents the BOP from being capable of controlling a well kick via at least one well control measure (e.g., annular, pipe ram, shear ram). Specifically, this scenario assumes all failures go undetected or not repaired until the entire system is unable to sufficiently operate to control a kick. These scenario results represent the BOP system availability relative to controlling a well kick via at least one well control system. The estimated mean availability of BOP system during drilling operation (on well) ranged from 0.9928 to 0.9994.

- Operating Scenario B – Considers the on-well operation of the BOP relative to maintaining all BOP functions with the ability to perform corrective maintenance of surface and subsea components without the securing of the well and the pulling of the BOP stack. Specifically, this scenario models performing corrective maintenance per the industry regulation (i.e., performing corrective maintenance any time a BOP component failure is detected) with the unavailable time being based on the mean-time-to-repair (MTTR) for the failed component. These scenario results provide the BOP availability for all functions operating assuming repairs do not require securing of the well and pulling of the subsea systems for repair. These results represent the upper bound estimate of the BOP system availability for all functions. The estimated mean availability of BOP system during drilling operation (on well) ranged from 0.9863 to 0.9913.

- Operating Scenario C – Considers the on-well operation of the BOP relative to maintaining all BOP functions with the requirement that the well must be secured and the BOP pulled to the surface in order to perform corrective maintenance on all subsea system components. (Note: This scenario does not require the securing of the well and the pulling of the BOP stack to perform corrective maintenance on surface BOP system components). Specifically, this scenario models performing corrective maintenance to the industry regulation (i.e., performing corrective maintenance any time a BOP component failure is detected) with the unavailable time being based on (1) the average time to secure the well for failed subsea components and (2) the MTTR for the failed surface components. (Note: Based on input from the IPs, the average time to secure well was set at 96 hours.) These scenario results provide the BOP availability for all functions operating assuming all subsea component repairs require securing of the well and pulling of the subsea systems for repair. These results represent the lower bound estimate of the BOP system availability for all functions. The estimated mean availability of BOP system during drilling operation (on well) ranged from 0.9822 to 0.9882.

Table S-1: BOP Availability Results Summary

BOP Analysis Cases	Operating Scenario A	Operating Scenario B	Operating Scenario C
	Mean Availability for Drilling Operation Period (On Well) With At Least One Well Control Function Remaining to Control a Well Kick	Mean Availability For Drilling Operation Period (On Well) While Maintaining **All** BOP Well Control Functions Assuming Corrective Maintenance (CM) Performed Without Pulling of the Stack	Mean Availability for Drilling Operation Period (On Well) While Maintaining **All** BOP Well Control Functions Assuming Any Subsea CM Performed Requires Securing of the Well and Pulling of the Stack
Base Case: All Well-Control Functions	.9991	.9875	.9843
Design Change 1 (Lower Marine Riser Package [LMRP] Annular(s) & Pipe Rams Only)	.9943	.9875	.9869
Design Change 2 (LMRP Annular(s) Only)	.9928	.9873	.9867
What-If Case 1 (4 week test interval)	.9991	.9863	.9822
What If Case 2 (Improved reliability of select components)	.9994	.9913	.9882

The results presented here consider BOP surface and subsea controls and the stack equipment. While detected failures on the BOP stack may result in the BOP to be pulled, the subsystems located on the rig will be repaired without having to pull the BOP stack.

Based on the analysis results, the team made the following observations:

- Operating Scenario A results represent the BOP availability to control a well kick by at least one well control function, which is a better measure of the BOP system availability relative to its overall safety operation.

- Operating Scenarios B and C represent the BOP availability relative to maintaining all BOP well control functions while on the well (i.e., it models the regulatory requirement relative to maintaining all BOP functions at all times while on the well) relative to the regulatory requirement. These results measure the availability for two differing corrective maintenance responses to subsea component failures: (1) on-the-well repair and (2) pulling-of-the-stack repair. While actual operations likely result in a combination of these two responses, these models provide upper and lower bounds for actual operation relative to maintaining all BOP functions.

- While the BOP system is constructed with many subsystems that internally have multiple layers of redundancy, the BOP also has single component failure points in its design. These single failures are the dominant contributors to the estimated BOP probability of failure on demand. The dominant contributors to the estimated BOP failure on demand probability are the two single failure points: the LMRP connector failure and the Well Head Connector

failure. Combined, these two component failures contribute over 99% to the estimated unavailability of the BOP system during “on well.” In the calculations, these two components have an equal contribution to the estimated unavailability of the BOP system.
(Note: These dominant contributors were identified based on the total failure rate data for these devices for all failure modes without any differentiation to unsafe and safe failure fraction of the respective failure modes.)

- Due to a lack of available data from industry, common cause failures of redundant subsystems were not included in the BOP system model for the RAM analysis. Such failures may be significant contributors to subsystem failures that are designed with redundant components. Considering the highly redundant features in much of the BOP system design, further investigation into sources of failure data for BOP common cause failures should be considered.

- To demonstrate the contribution of the component failures associated with non-shearing control measures (i.e., pipe rams and annulars), BOP system availability considering pipe rams and annular(s), and annular(s) only operating were evaluated (i.e., design changes 1 and 2). While these results indicate that the removal of the shear rams and pipe rams (design change 2 only) had little impact on BOP system availability, this is because the remaining component failures, especially the two single point of failure items, have a more significant impact on the BOP system availability than the impact of the removed items on the system availability. However, readers are cautioned to not draw the conclusion that these results indicate the redundancy provided by the removed well control items are not important. The shear and pipe rams are considered important part of the BOP system and provide the required redundancy and essential functions for controlling the well.

- What-If Case 1 analysis indicate the system availability is not significantly changed by the extending of the test interval for all operating scenarios with an average availability reduction of 0.2% for Operating Scenarios B and C. Specifically, the no change in Operating Scenario A availability was expected since this scenario is based on allowing the BOP functionality to degrade until the BOP can’t sufficiently function to control a kick (i.e., no inspection and test are performed). As for Operating Scenarios B and C, the BOP availability for all operating configurations is reduced for all analysis cases, as expected.

- What-If Case 2 analysis shows that improving the reliability performance of a few selected components in the BOP system caused a slight improvement in the estimated BOP availability in all three operating scenarios. The four components selected for improvement were identified in the BSEE Data Analysis Study (ref. 1) as less reliable BOP components. However, the BOP system design includes redundant features for these particular components and thus their failures were small contributors to the BOP system failure probability.

- Improving the reliability of, or gaining better understanding of unsafe and safe failure fractions for, the single point of failure components and other components, which were the major contributors to the BOP estimated unavailability, should cause a significant improvement in BOP availability. Improvements might be achieved through better construction/quality assurance of these items, better item design, and/or reducing detection/repair time of the items.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABS	–	American Bureau of Shipping
ABS Consulting	–	ABSG Consulting Inc.
BOP	–	Blowout Preventer
BSEE	–	Bureau of Safety and Environmental Enforcement
CM	–	Corrective Maintenance
FMECA	–	Failure Mode Effect and Criticality Analysis
HPU	–	Hydraulic Power Unit
IP	–	Industry Participant
LMRP	–	Lower Marine Riser Package
MIT	–	Maintenance, Inspection and Test
MTTF	–	Mean Time to Failure
MTTR	–	Mean Time to Repair
MUX	–	Multiplex
OEM	–	Original Equipment Manufacturer
PM	–	Preventive Maintenance
RAM	–	Reliability, Availability, and Maintainability
RBD	–	Reliability Block Diagram
SPM	–	Sub Plate Mounted (Valve)
TRIMM	–	Tool for Reliability Inspection and Maintenance Management

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1.0 INTRODUCTION

As part of the Blowout Preventer (BOP) Maintenance and Inspection for Deepwater Operations study (BSEE Contract Number M11PC00027), the American Bureau of Shipping (ABS) and ABSG Consulting Inc. (ABS Consulting) performed a Reliability, Availability, and Maintainability (RAM) study of a typical BOP system used in industry. The analysis team developed a Reliability Block Diagram (RBD) model and used BOP system failure events data and maintenance, inspection, and test (MIT) data to estimate BOP system availability. This report represents a portion of Deliverable F for the studies associated with Tasks 6.2.3, 6.2.3.1, and 6.2.3.2, as outlined in the contract.

Two RAM models were developed for BOP systems from two different original equipment manufacturer (OEM) designs. This report presents the RBD model for one of the OEM BOP system design. This analysis is based on a class VII BOP configuration with five rams and dual annular.

This report presents the objective and scope of the RAM study and analysis process and discusses the analysis assumptions, results summary, analysis details, and conclusions.

1.1 OBJECTIVES

The objective of RAM analysis is to determine the impact of Maintenance, Inspection and Testing (MIT) activities on the overall availability of a BOP system manufactured by one OEM participating in the MIT project. This was accomplished by (1) developing an RBD model representing the BOP system; (2) analyzing the model using a simulation method in order to estimate the availability of the BOP system during operation periods (on well); and (3) developing and analyzing two design variances and two what-if scenarios (regarding changes to MIT intervals and improved reliability of a few BOP components) to assess the impact of these selected changes on BOP availability.

1.2 ANALYSIS SCOPE

The physical scope of the RAM analysis was limited to a selected BOP system and associated equipment designed by one OEM and used by a drilling contractor and operator participating in the study. The selected BOP system design met the following criteria:

- Operation Location **–** Gulf of Mexico (majority of the operation and maintenance to be from the Gulf of Mexico)
- Operating Depth **–** 5,000 Feet and Deeper
- BOP Configuration of a Class VII**,** five ram configuration and dual annular or a six ram and single annular

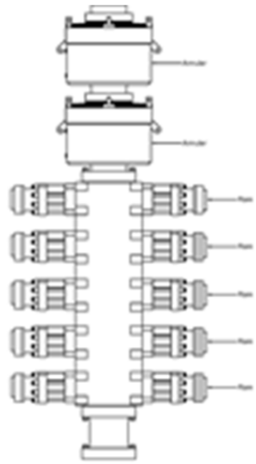

Figure 1-1 Class VII BOP

The analytical scope for the RAM analysis considered all fourteen functions defined in a related FMECA study. The BOP system functions considered in developing the RBD model used for analysis are the following:

1. Close and Seal on the Drill Pipe and Allow Circulation on Demand
2. Close and Seal on Open Hole and Allow Volumetric Well Control Operations on Demand
3. Strip the Drill String Using the Annular BOP(s)
4. Hang-Off the Drill Pipe on a Ram BOP and Control the Wellbore
5. Controlled operation – Shear the Drill Pipe and Seal the Wellbore
6. Emergency Operation – Auto-Shear – Shear the Drill Pipe and Seal the Wellbore
7. Emergency Operation – Emergency Disconnect System – Shear the Drill Pipe and Seal the Wellbore
8. Disconnect the Lower Marine-Riser Package (LMRP) from BOP Stack
9. Circulate the Well after Drill Pipe Disconnect
10. Circulate across the BOP Stack to Remove Trapped Gas
11. Connect BOP and LMRP at Landing
12. Power System
13. Secondary – Acoustic
14. Secondary – Remotely Operated Vehicle

The RBD model logically shows the interaction of BOP equipment required during a normal operation to successfully provide blowout protection. The model shows how the BOP system can call upon various redundant features to control a pressure kick in the event the situation worsens or BOP subsystems fail. Using this model and failure data for the equipment elements in the model, one can estimate the BOP system availability in the event of a pressure kick.

This analysis encompasses surface and subsea control systems and the BOP Stack equipment as per the BOP design drawings provided in Appendix B. Appendix D lists the individual block and component failure data input into the simulation.

1.3 INTENDED USE

Failure and repair data used in this reliability and availability analysis were partly based on published industry data and as well as data collected as part of this effort. Therefore, it is recommended to use the numerical results as a relative measure of BOP system performance rather than as an absolute measure of performance. In this context, the numerical results from the reliability block diagram and the detail component results can be used to identify the critical components having the most impact on BOP availability.

Ultimately, the results from this assessment are intended to provide a better understanding of BOP system reliability and availability with respect to the existing maintenance, inspection, and test policies.

1.4 RAM ANALYSIS AND MEETING SCHEDULE

The analysis team for each study included personnel from two industry participants (IPs), the American Bureau of Shipping (ABS), and ABSG Consulting Inc. (ABS Consulting). The IPs participating included one or more representatives from an OEM and a drilling contractor. These individuals provided knowledge of the design, engineering, operation, and maintenance of the BOP system being evaluated. Table 1-1 lists the functional positions for the IP personnel who participated in this study.

Table 1-1: IP RAM Team Members

IP Organization	Position/Expertise
BOP OEM	Engineering Manager, Drilling Products
	Project Manager
Drilling Contractor	Subsea Operation Manager
Operator	Manager Deepwater Wells

In addition to the IP representatives, personnel from ABS and ABS Consulting participated in the several RAM meetings. Specifically, ABS personnel provided knowledge of the overall BOP operations and class society and regulatory requirements applicable to BOP design and operation. ABS Consulting personnel developed the RBD model, facilitated teleconference and meetings with IPs to refine the RBD model and component failure data, performed the analysis, and documented the RAM study. Table 1-2 lists the ABS and ABS Consulting personnel participating in this study.

Table 1-2: ABS and ABS Consulting RAM Team Members

Name	Organization	Title	Study Role
David Cherbonnier	ABS	Staff Consultant, Corporate Offshore Technology	Subsea Engineer
Bibek Das	ABS	Senior Engineer II, Corporate Shared Technology	Senior Engineer II (Risk and Reliability), Corporate Technology
Randy Montgomery	ABS Consulting	Senior Director, Integrity Management	Project Technical Lead
Kamyar Nouri	ABS Consulting	Senior Risk and Reliability Engineer	Risk and Reliability Analyst (model & logic development)
Kamran Nouri	ABS Consulting	Senior Risk and Reliability Engineer	Risk and Reliability Analyst (review and documentation)

To prepare for the RAM studies, ABS and ABS Consulting held a kickoff meeting with the IPs on August 14 and 15, 2012. The purposes of the kickoff meeting were to discuss the FMECA and RAM analysis approaches and the analyses scope to help ensure that all participants have the same level of understanding of the FMECA & RAM procedures.

In addition to the kickoff meeting, the analysis team held several teleconferences and meetings with the IPs from December 2012 to March of 2013. During these sessions, the RAM team members were provided an introduction to RBD methodology and collaborated on the RBD model logic for the base case, the two design alternatives, and the two "what–if" cases. BOP functions were defined in a related Failure Mode Effect and Criticality Analysis (FMECA) study and were incorporated into the model. All BOP system functions were considered during the development of various analysis cases.

1.5 REPORT ORGANIZATION

Section 2 of this report provides an overview of the methodology used to create RBDs and to estimate the BOP system's availability for the base case, alternate design cases, and what-if cases. Section 3 discusses the analysis assumptions. Section 4 discusses the results of the effort. Section 5 discusses the analysis conclusions and observations. Appendices A, B, C, and D provide a list of references, BOP system drawings, the failure and repair data, the BOP reliability block diagram and detailed block and component information.

2.0 *RELIABILITY AND AVAILABILITY ANALYSIS PROCESS*

To estimate the availability of the BOP system, the analysis team developed an RBD model. The RBD shows the logical interaction of BOP subsystems and equipment required for successful system operation. The RBD model consists of series and parallel trains of components and subsystems required for successful BOP system operation.

The analysis team identified a baseline BOP system (base case) according to one OEM design and one configuration used by one of the drilling contractors participating in the MIT project. The base-case model was used to estimate the reliability and availability of the BOP system for the three operating scenarios. In addition to the base-case model, several alternative designs and what-if scenarios were evaluated (for all three operating scenarios) based on input from the Industry Participants (IPS).

For the BOP system analysis, the team used BOP component/subsystem failure and maintenance data provided by the IPs. The team developed the RBD model and performed the availability calculations as described in Section 2.1. The BOP system RAM characteristics estimated is:

- Mean BOP Availability for Drilling Operation Period (on well)

2.1 ANALYSIS APPROACH

The basic fundamentals of RBD modeling are to logically show the interaction of subsystems and components required for successful operation of the system. Or conversely, to show combinations of component/subsystem failures that lead to system failure (unavailability or probability of failure on demand).

Figure 2-1 depicts a sample RBD made up of two subsystems, each containing three components. Subsystem 1 contains three series blocks and subsystem 2 contains a combination of parallel and series blocks. In subsystem 1, any component failure will translate to system failure. Subsystem 2, however, has redundant components D and E and thus can withstand a single failure of D or E without suffering system failure. In subsystem 2, component F is in series with all other components and it is a single point of failure for the system.

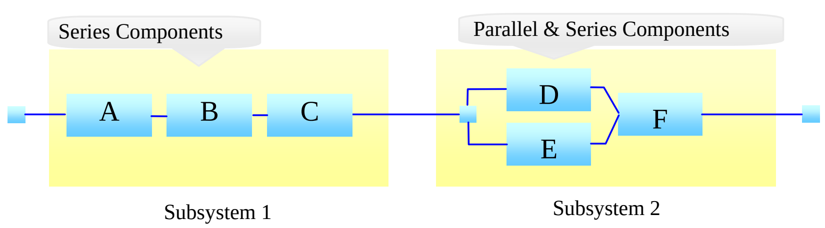

Figure 2-1 RBD Example 1

More complex relationships like ‘K’ out of ‘N’ components and cross relationships can exist and are modeled, if necessary (Figure 2-2).

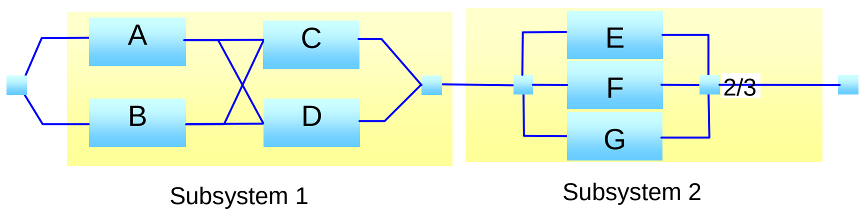

Figure 2-2 RBD Example 2

In both examples, each component is analyzed with respect to failure characteristics and its functional relationship to other components. The component’s failure characteristics are used to determine the component’s time of failure. This information is then passed on to the subsystem and subsequently to the system level, using the RBD as a roadmap for determining how to mathematically combine this information and arrive at system level failure characteristics

After the logic model development, component failure and maintenance data are required for logic model quantification. The analysis team collected equipment/component failure, inspection, test and maintenance data based on available industry data and this project’s data analysis study (BSEE Data Analysis). The reliability data included time-based or “running” failure rates and associated repair and restoration times for identified failure modes.

Monte Carlo simulation using a preset number of iterations was used to estimate system-level results. In this simulation, each component’s failure distribution is sampled each iteration for input into the system calculation until such time that the simulation results converge to a steady state result for the system.

2.2 ANALYSIS PROCEDURES

This section summarizes the procedures used in performing the RAM analysis. The RAM analysis began with the team collecting the documents, drawings, and related information. They then executed the following steps:

1. Reviewed the drawings listed in Appendix B.
2. Identified the specific system boundaries.
3. Reviewed detailed equipment lists.
4. Reviewed the operating requirements and procedures.
   a. Developed a two-phase approach to corrective maintenance (CM) and preventive maintenance (PM) activities covering drilling operation time versus time when the BOP is on the rig.
5. Defined the operating environment.

6. Developed an RBD model for the base case BOP system.
7. Developed an RBD models for the each of the BOP's major functions as per the FMECA study.
8. Performed a reliability and availability analysis (i.e., run the Monte Carlo simulation).
9. Developed an RBD model for the alternate BOP design cases and run the analysis.
10. Performed what-if analyses.
11. Documented the results.

2.3 DATA COLLECTION AND PROCESSING

The collection and analysis of reliability data includes both the compilation of available component/subsystem failure and maintenance data from historical BOP operations data and industry generic data for similar components. With the help of IPs and ABS subject matter experts, the analysis team identified and collected the information and documentation needed to perform the reliability and availability analysis. The information collected included:

- A high-level system diagram
- Component/equipment detail drawings
- Operating environment information
- Available component/equipment reliability data from the Tool for Reliability Inspection and Maintenance Management (TRIMM) database and related data analysis (part of this project, referred to as BSEE Data Analysis)
- Industry data when historical BOP component data were unavailable. These data were used to augment the reliability data from TRIMM, providing a more complete dataset for the analysis

The analysis team reviewed the available information to determine whether any additional information is needed for BOP RBD model development and analysis. The information was used to establish component failure rates and associated repair times. Processing of the collected data involved assessing the applicability of the data to the failure modes of interest in the RAM study.

2.4 OPERATING SCENARIOS

In order to evaluate the BOP performance and evaluate the impact of BOP MIT, the RAM study involved the evaluation of the following three operating scenarios:

- Operating Scenario A – Considers the on-well operation of the BOP until a system failure occurs (i.e., all redundancies failure so that the BOP is no longer available to control a well kick) and prevents the BOP from being capable of controlling a well kick via at least one well control measure (e.g., annular, pipe ram, shear ram). Specifically, this scenario assumes all failures go undetected or not repaired until the entire system is unable to sufficiently operate to control a kick. This scenario results represent the BOP system availability relative to controlling a well kick via at least one well control system.

- Operating Scenario B – Considers the on-well operation of the BOP relative to maintaining all BOP functions with the ability to perform corrective maintenance of surface and subsea components without the securing of the well and the pulling of the BOP stack. Specifically, this scenario models performing corrective maintenance per the industry regulation (i.e., performing corrective maintenance any time a BOP component failure is detected) with the unavailable time being based on the MTTR for the failed component. These scenario results provide the BOP availability for all functions operating assuming repairs do not require the securing of the well and the pulling of the subsea systems for repair. These results represent the upper bound estimate of the BOP system availability for all functions.

- Operating Scenario C – Considers the on-well operation of the BOP relative to maintaining all BOP functions with the requirement that the well must be secured and the BOP pulled to the surface in order to perform corrective maintenance on all subsea system components. (Note: This scenario does not require the securing of the well and the pulling of the BOP stack to perform corrective maintenance on surface BOP system components). Specifically, this scenario models performing corrective maintenance to the industry regulation (i.e., performing corrective maintenance any time a BOP component failure is detected) with the unavailable time being based on (1) the average time to secure the well for failed subsea components and (2) the MTTR for the failed surface components. (Note: Based on input from the industry participants, the average time to secure well was set at 96 hours.) These scenario results provide the BOP availability for all functions operating assuming all subsea component repairs require the securing of the well and the pulling of the subsea systems for repair. These results represent the lower bound estimate of the BOP system availability for all functions.

2.5 Base-Case Model and Analysis

The base-case RBD model developed reflects successful operation of the BOP system design per the drawings listed in Appendix B and includes both the surface and subsea control systems and the BOP stack. The base-case RBD model is used to estimate the reliability and availability of the BOP system as it is designed and operated at the time of this project. This model includes control and stack subsystems that are involved in sealing, shearing, and balancing the well. The following subsection outlines the details and parameters considered in the simulation and analysis of the base-case RBD model.

Base-Case Simulation Details

BlockSim 7 software was used to perform the Monte Carlo simulations of the BOP RBD model. Figure 2-3 presents the base-case model set-up, indicating we specified an expected lifetime of 5 years (43,825 hours) before a major system overhaul and a maximum of 100 simulations.

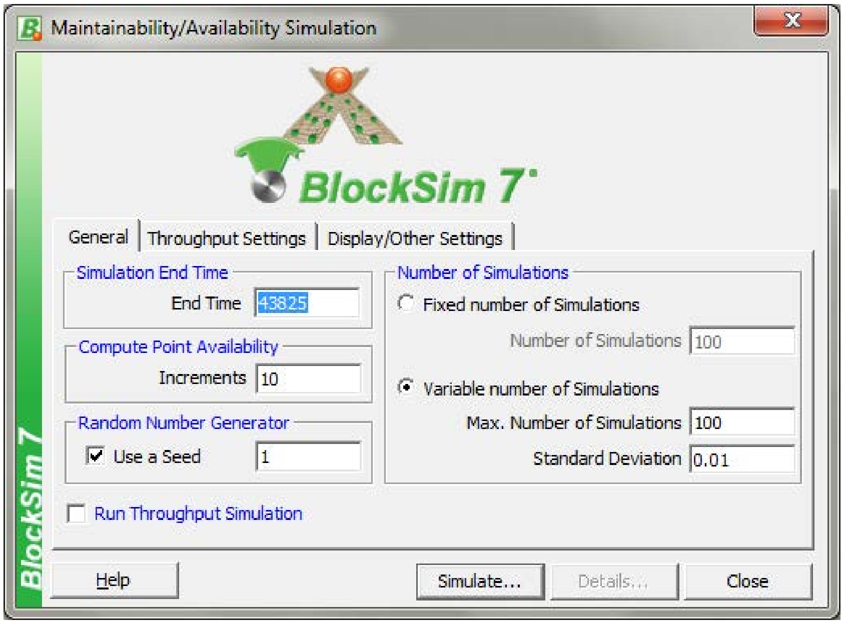

Figure 2-3 Simulation Settings

Since the BOP is not operated continuously throughout the year, the BOP operation has been divided into two main phases "On Well" and "On Rig." The "On Well" phase is the operational phase where the BOP is providing protection against well blowouts and "On Rig" is the maintenance phase (see Figure 2-4). To complete the 5-year profile simulation, each phase is cycled through multiple times based on the given time duration for each phase

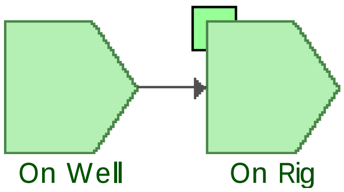

Figure 2-4 Two Phases of the BOP

Figure 2-5 presents the "On Well" operation phase settings. The "On Well" operational phase was set to 8 weeks (1,344 Hours), followed by the maintenance phase "On Rig." During the simulation process, the simulation will switch to the maintenance phase if any failures occur during the operational phase simulation.

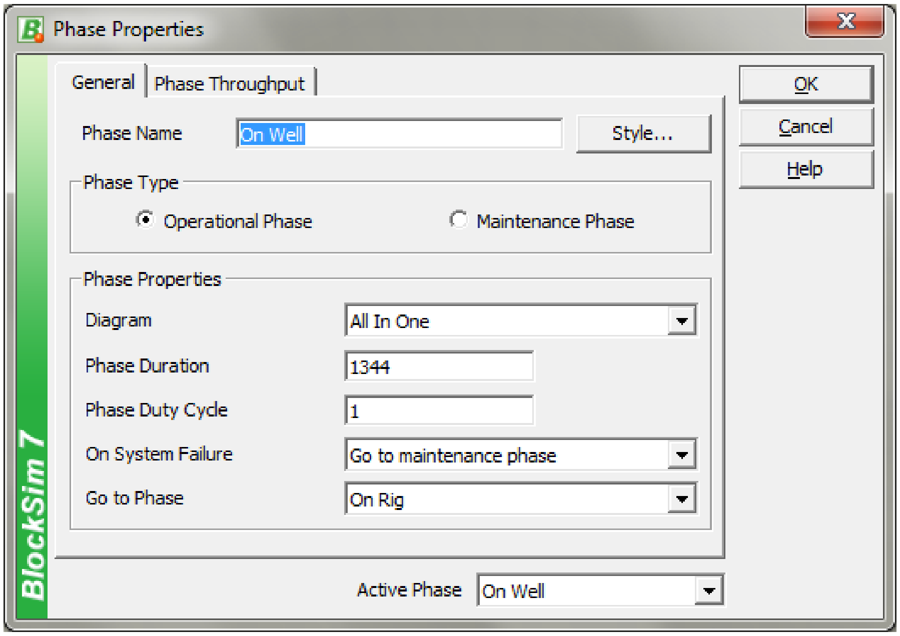

Figure 2-5 "On Well" Operation Phase Settings

Figure 2-6 presents the "On Rig" maintenance phase settings. The "On Rig" maintenance phase contains a maintenance template which dictates which equipment/components are maintained, under CM or PM.

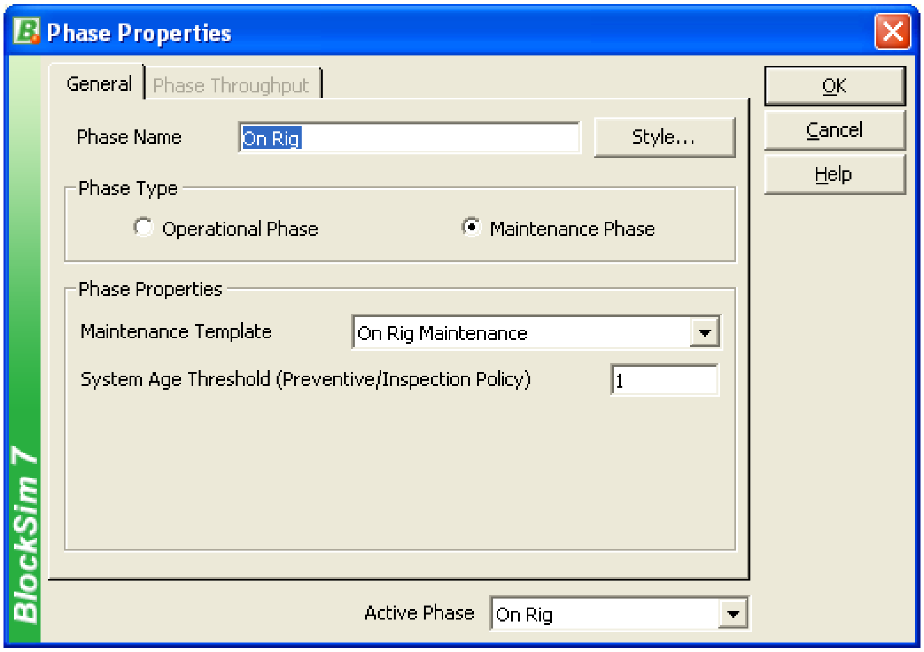

Figure 2-6 "On Rig" Maintenance Phase Settings

Figure 2-7 presents the corrective maintenance policy. Other considerations for the simulation include how CM, PM and Inspection (pressure and function test) are performed. CM always brings the system down, and, therefore, counts against the overall mean availability of the system (on well and on rig periods combined). For CM, a maintenance policy was defined to perform CM upon failure:

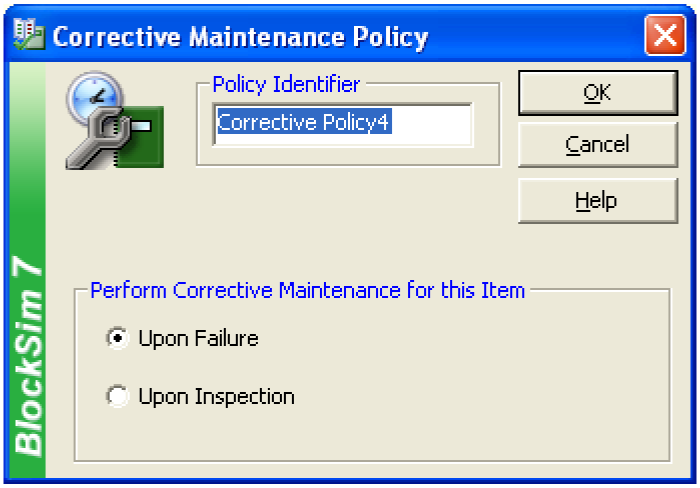

Figure 2-7 Corrective Maintenance (CM) Policy

Figure 2-8 presents the preventive maintenance policy. PMs are performed during non-operational phase "On Rig." For PM, the maintenance policy was defined to only take place during a maintenance phase:

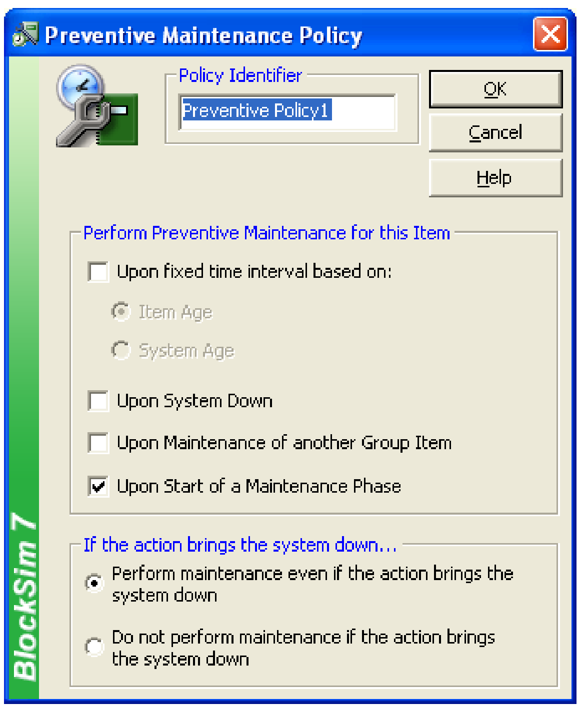

Figure 2-8 Preventive Maintenance (PM) Policy

Figure 2-9 presents the inspection policy. For the purpose of this simulation, the inspection facility of the BlockSim 7 was used to emulate the 14-day tests. The inspection (pressure and function test) interval was embedded in an inspection policy with an interval of 14 days (336 hours). The tests are performed on the well, taking time away from drilling time and therefore reducing the mean availability for all events but not counting against the reliability of the system.

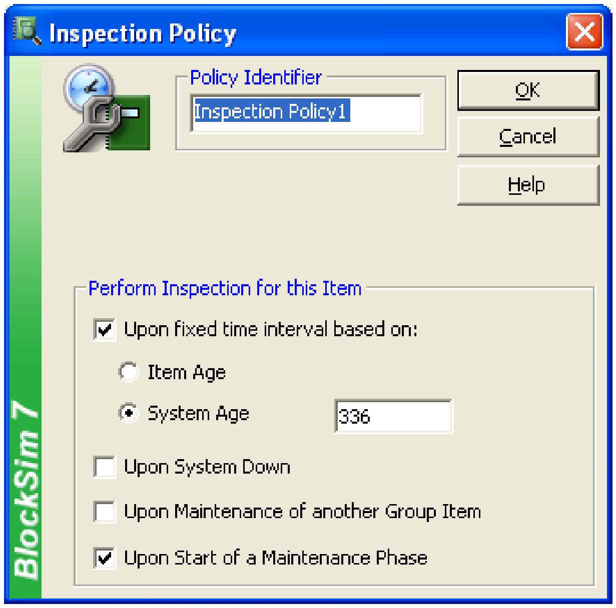

Figure 2-9. Inspection Policy to Emulate the 2-Week Tests

2.6 ALTERNATE DESIGNS AND WHAT-IF CASE MODELS

After developing and analyzing the base-case model, the analysis team developed two design variation cases and two what-if cases for further analyses. The identified test cases, developed in collaboration with the IPs, were used to evaluate the impact of system design changes, test/inspection frequency changes, and selected component improvement changes on the BOP system's availability. In each test case, only a single design change or specified parameter was modified; all other parameters stayed the same as the base-case RBD model.

1. Design Change 1 – **LMRP and Pipe Rams Only.** I t is assumed the BOP system does not have a shear ram(s) in the stack of devices for isolating the well.
2. Design Change 2 – **LMRP Only.** It is assumed the BOP system only has the LMRP in the stack of devices for isolating the well. The Pipe Rams and Shear Ram(s) have been removed from the design.
3. What-If Change 1 – **Test Frequency.** The period between inspections and testing of the BOP system is extended from two weeks to four weeks.
4. What If Change 2 – **Component Reliability.** Based on the project data analysis results and several detailed discussions with the IPs, the team "improved" the reliability performance of four BOP components.

Using the project data analysis, the team identified 4 dominant components with the highest failure rates or the largest number of failures that should be considered for improvement. Next, the subcomponents with the highest number of reported failures within each major component were selected. Additionally, the top failure modes (including the failure modes that could be associated with quality and possible training) were selected. The reliability of the component in terms of its failure rate or mean time to failure (MTTF) that were impacted by component quality and possibly the training of the personnel performing the MIT tasks were selected for improvement. Table 2-1 presents the selected major components and associated failure modes selected for this case.

Table 2-1: Selected BOP Major Components and Percentage of Improvement

BOP Major Component	Highest number of Component Failure	Component Failure Modes	Percent of Failure	Percentage of Improvement
Blue and Yellow Subsea Control System	Sub Plate Mounted (SPM) Valve & Manifolds	External Leak	42%	52%
		Component out of specification	3%	
		Substandard workmanship	7%	
Choke & Kill Valves and Lines	Connection and Spool Pieces	External Leak	55%	83%
		Component out of specification	5%	
		Substandard workmanship	23%	
Multiplex (MUX) Control System	CCU	Processing Error	28%	48%
		Component out of specification	11%	
		Substandard workmanship	9%	
Pipe and Test Ram	All inclusive	Mechanical Failure	26%	58%
		Component out of specification	6%	
		Substandard workmanship	26%	

The improvement made for each major component was to eliminate the failure modes that largely contributed to a component's failure. For example, if Component X had three failure modes that accounted for 70% of the component's failure rate, we would artificially lower the failure rate by 70% to reflect the improvement in the What-If analysis.

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3.0 ANALYSIS ASSUMPTIONS

In performing the RBD simulation to estimate BOP system reliability and availability characteristics, the analysis team made several assumptions.

3.1 GENERAL ASSUMPTIONS

- All spare parts are available at the rig; the average repair time for components does not include any time for obtaining spare parts from onshore suppliers
- All specialized crews needed to make necessary BOP repairs are available at the rig
- Human errors introducing failures into the BOP system during test, inspection and/or maintenance are not included model; however, they were indirectly considered via improving the reliability of selected components in What-If Case 2.
- Common cause failure of BOP subsystems with redundant components was not included in the analysis due to insufficient data.

The system availability results presented in this report are only based on the estimated time that is required to perform the PM and CM tasks, assuming that the spare parts and the specialized crew are available to perform the necessary tasks. However, the absence of the required spare parts and specialized maintenance crew could result in additional time to perform the maintenance tasks, hence reducing the estimated system availability.

3.2 SPECIFIC ASSUMPTIONS

- The lifetime of the BOP is 5 years (for analysis purposes).
- Failures of any BOP components located in the stack forces the model to switch to maintenance. phase and counts against the on-well availability (availability without PM and inspection).
- Failures of any BOP components located on the rig will not count against the on-well availability (availability without PM and inspection) unless all redundancies have been exhausted.
- Failures of any BOP components located on the rig are assumed to be correctable without the introducing any downtime. In other words corrective maintenance of equipment located on the rig does not require the system to be down. The only exception to this is simultaneous failures of redundant components.
- All subsea subsystems can only be repaired once the BOP brought up to the rig.
- All BOP preventive maintenance takes place on the rig.
- Choke and kill systems are both required for BOP successful operation.
- The use of shear rams is considered as an emergency action in which the well will be abandoned. In reality, there are two other situations where the shear rams may be activated but these events are not considered in the model:
    - Accidental shear by the operator
    - Shear due to rig loss of position control

- A failure in one of the SPM valve "open" circuits effectively disable the corresponding SPM valve closure circuit, eliminating this circuit ram closure signal.
- Hydraulic accumulators provide redundant backup to the hydraulic pumps.
- Average time the BOP is on well (i.e., not on the rig for MIT) is 8 weeks.
- Pressure tests occur at 2-week intervals.
- Duration of each test is 10 hours which is based on an average test durations reported by the IPs. The BOP is available for operation, if needed, during testing.
- Once a failure occurs, the failed BOP component will undergo CM and PM.
- For the purpose of this RAM study, the time duration for pressure and function testing were combined. The test time includes actual test time and any preparation before testing begins.

The pressure and function test duration or test time was determined after discussing several test situations with the IPs. Test duration for the BOP depends on many conditions and variables. The actual test time could be less than an hour. However, time to prepare the well and BOP equipment for testing are impacted by the BOP configuration (such as number of RAMS including blind shear and test ram), availability of test equipment, the drilling depth and the well condition and pressure at the time of testing. Given these variables and potential issues occurring during the test procedures, BOP test duration might range from 1 to 24 hours. A sampling of the recent reported test durations included times of 1, 2, 6, 8, 10, 12, 14, 16 and 24 hours. The team, with input from the IPs, selected 10 hours as the minimum test duration for this study based on the average of some of the recent/ reported test duration.

The selected test time (10 hours) is only minimum/reasonable amount of time for testing the BOP system only during ***normal routine operation***, given the fact that the BOP stack is latched on to the wellhead and initial BOP system testing after installation is satisfactory.

3.3 BLOCKSIM 7 ANALYSIS PARAMETERS

In performing the RBD simulation of the BOP system, the analysis team specified the following parameters for the analysis:

- Simulation Factors:
  Simulation End Time: 43,825 Hours or 5 Years
  Number of Simulations: 100
- Corrective maintenance takes place upon a failure for Operating Scenarios B and C.
- Preventive maintenance occurs only when the BOP is on the RIG.
- BlockSim's inspection facility is used to emulate the 14-day tests.

4.0 RESULTS SUMMARY

Using two separate component failure datasets and considering several design alternatives and what-if scenarios, fifteen separate analyses of the BOP system were performed. These fifteen separate analyses included the analysis of the three operating scenarios as detailed in Section 2.4 and the 5 analysis cases outlined Table 4-1. In each case, the input MTTF values are obtained from the BSEE Data Analysis Report, supplemented with data from industrial data references (IEEE STD 497, OREDA 2009), where gaps existed.

Table 4-1: List of Analysis Cases

Analysis Case	Description
Base Case - All functions; IP Data	This configuration considers all BOP well control system capabilities, including annular, pipe rams, shear ram, auto shear and emergency disconnect systems and associated controls and choke and kill components.
Design Change 1 LMRP Annular & Pipe Rams Only; IP Data	This configuration considers BOP well control system capabilities, associated with annular, pipe rams only and their associated controls and choke and kill components.
Design Change 2 - LMRP Annular Only; IP Data	This configuration considers BOP well control system capabilities associated with annular only and its associated controls and choke and kill components.
What If Case 1; Test Interval 4 weeks; IP Data	This What-If case evaluates the impact of increasing the inspections interval form 2 weeks to 4 weeks. The base-case BOP configuration is used for this What-If case.
What If Case 2; Improved reliability of select components; IP data	This What-If case evaluates the impact of improving the reliability of more frequently failing BOP components, based on the data analysis results. Specifically, this What-If case includes reliability improvement of the (1) blue and yellow subsea control system, (2) choke & kill valves and lines, (3) MUX control system, and (4) pipe and test ram. The base-case BOP configuration is used for this What-If case. Reliability input data was adjusted based on Table 2-1.

Table 4-2 tabulates the simulation results for the three operating scenarios and the above various analysis cases. The reliability block diagrams for these analysis cases are provided in Appendix D.

Table 4-2: Results Summary

BOP Analysis Cases	Operating Scenario A	Operating Scenario B	Operating Scenario C
	Mean Availability for Drilling Operation Period (on Well) with at Least One Well Control Function Remaining to Control a Well Kick	Mean Availability for Drilling Operation Period (on Well) while Maintaining **All** BOP Well Control Functions Assuming CM Performed without Pulling of the Stack	Mean Availability for Drilling Operation Period (on Well) While Maintaining **All** BOP Well Control Functions Assuming Any Subsea CM Performed Requires Securing of the Well and Pulling of the Stack
Base Case: All Well-Control Functions	.9991	.9875	.9843
Design Change 1 (LMRP Annular(s) & Pipe Rams Only)	.9943	.9875	.9869
Design Change 2 (LMRP Annular(s) Only)	.9928	.9873	.9867
What-If Case 1 (4 week test interval)	.9991	.9863	.9822
What If Case 2 (Improved reliability of select components)	.9994	.9913	.9882

5.0 OBSERVATION AND CONCLUSIONS

The simulation calculated the availability figures of merit for the Bop system without PM and inspection activity (i.e., while in service "on well") Since the BOP is a safety critical system the availability result without the PM and inspection is of interest.

The estimated availability of the BOP system for Operating Scenario A ranges from 0.9928 to 0.9994. (Note: Results of Operating Scenario A represent the BOP availability to control a well kick by at least one well control function, which is a better measure of the BOP system availability relative to its overall safety operation.) For Operating Scenarios B and C, the estimated availability for the BOP systems ranges from 0.9863 to 0.9913 and from 0.9822 to 0.9882, respectively. A comparison of the results of Operating Scenario A to the results of Operating Scenarios B and C reflects the expected outcome that the BOP availability for at least one well control function operating is significantly higher (i.e., approximately one order of magnitude improvement) than the BOP availability for all well control functions.

In addition to the above observation, the team made the following observations:

- While the BOP system is constructed with many subsystems that internally have multiple layers of redundancy, the BOP also has single component failure points in its design. These single failures are the dominant contributors to the estimated BOP probability of failure on demand. Based on these RAM results, the dominant contributors to the estimated BOP failure on demand probability are the two single failure points: LMRP connector failure, and Well Head Connector failure. Combined, these two component failures contribute over 99% to the estimated unavailability of the BOP system during "on well." In the calculations, these two components have an equal contribution to the estimated unavailability of the BOP system.

  (Note: These dominant contributors were identified based on the total failure rate data for these devices for all failure modes without any differentiation to unsafe and safe failure fraction of the respective failure modes.)

- Due to a lack of available data from the industry, common cause failures of redundant subsystems were not included in the BOP system model for the RAM analysis. Such failures may be significant contributors to subsystem failures that are designed with redundant components. Considering the highly redundant features in much of the BOP system design, further investigation into sources of failure data for BOP common cause failures should be considered.

- To demonstrate the contribution of the component failures associated with non-shearing control measures (i.e., pipe rams and annulars), BOP system availability considering pipe rams and annular(s), and annular(s) only operating were evaluated (i.e., design changes 1 and 2). While these results indicate that the removal of the shear rams and pipe rams (design change 2 only) had little impact on BOP system availability, this results because the remaining component failures, especially the two single point of failure items, have a more significant impact on the BOP system availability than the impact of the removed items on the system availability. However, readers are cautioned to not draw the conclusion that these results indicate the redundancy provided by the removed well control items are not important. The shear and pipe rams are considered important part of the BOP system and provide the required redundancy and essential functions for controlling the well.

- What-If Case 1 analysis indicate the system availability is not significantly changed by the extending of the test interval for all operating scenarios, with an average availability reduction of 0.2% for Operating Scenarios B and C. Specifically, the no change in Operating Scenario A availability was expected since this scenario is based on allowing the BOP functionality to degrade until the BOP can’t sufficiently function to control a kick (i.e., no inspection and test are performed). As for Operating Scenarios B and C, the BOP availability for all operating configurations is reduced for all analysis cases, as expected.

- What-If Case 2 analysis shows that improving the reliability performance of a few selected components in the BOP system caused a slight improvement in the estimated BOP availability in all three operating scenarios. The four components selected for improvement were identified in the BSEE Data Analysis Study (ref. 1) as less reliable BOP components. However, the BOP system design includes redundant features for these particular components and thus their failures were small contributors to the BOP system failure probability.

- Improving the reliability of, or gaining better understanding of unsafe and safe failure fractions for, the single point of failure components and other components, which were the major contributors to the BOP estimated unavailability, should cause a significant improvement in BOP availability. Improvements might be achieved through better construction/quality assurance of these items, better item design, and/or reducing detection/repair time of the items.

APPENDIX A – LIST OF REFERENCES

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This appendix provides a list of relevant industry data sources used during the RAM analysis.

1. BSEE Data Analysis, BOP Failure Event and Maintenance, Inspection and Test (MIT) Data Analysis for BSEE (project related analysis), ABS Consulting Inc., 2013.
2. IEEE Std 493™, Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems, Institute of Electrical and Electronics Engineering, Inc., 2007.
3. OREDA 2009, Offshore Reliability Data 5th Edition, Volume 1 &2, SINTEF, 2009.
4. SINTEF Report 2012, Reliability of Deepwater Subsea BOP Systems and Well Kicks, SINTEF, 2012.

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APPENDIX B – LIST OF DRAWINGS

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This appendix provides a list of drawings used during the RAM analysis.

S/D, SCOPE OF SUPPLY
S/D, HYDRAULIC, LMRP
S/D, HYDRAULIC, STACK
S/D, HYDRAULIC, MUX POD
S/D, BLOCK DIAGRAM HYDRAULIC INTERCONNECT
S/D, HYDRAULIC POWER UNIT
S/D, FAMILY OF FUNCTIONS
S/D, SYSTEM CABLING BLOCK DIAGRAM

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APPENDIX C – FAILURE AND REPAIR DATA

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FAILURE AND REPAIR DATA INPUT TO RBD MODEL: The individual component reliability data were gathered from several sources and organized in Table C-1. MTTF and MTTR values in this table were used to populate the RBD simulation model. Data from the BSEE Data Analysis study were used to the extent available.

Table C-1 Reliability Data for Individual BOP Components

Subsystem / Component	Quantity	MTTF	Source	MTTR	Source	PM	Source	Inspection	Source
POWER Subsystem									
UPS	2	9,499,764	IEEE Std 493-2007	3.688	IEEE Std 493-2007	4.625	BSEE MIT Data Analysis	3.688	
SUBSEA XFMR	2	74,357,512	IEEE Std 493-2007	4.272	IEEE Std 493-2007	4.272		4.272	
CCU – Elect. Controls									
Drillers Control Panel	2	96,847	BSEE Data Analysis	5.9	BSEE MIT Data Analysis	2	BSEE MIT Data Analysis	4.406	
Rig Managers Panel	1	96,847	BSEE Data Analysis	5.9	BSEE MIT Data Analysis	2	BSEE MIT Data Analysis	4.406	
Subsea Engineer Panel	1	96,847	BSEE Data Analysis	5.9	BSEE MIT Data Analysis	2	BSEE MIT Data Analysis	4.406	
Central Control Console (CCC)	2	10,345	IEEE Std 493-2008	0.771	IEEE Std 493-2008	0.771		0.771	
MUX System									
MUX Cable Reel	2	63938	OREDA 2009	40	OREDA 2009	5		5	
Hydraulic Power Unit (HPU) – Hydraulic Controls									
HPU with Mixing System	1	102,264	BSEE Data Analysis	59.9	OREDA 2009	10		10	
Accumulator Banks	4	1,942,272	BSEE Data Analysis	2.92	BSEE MIT Data Analysis	6.88	BSEE MIT Data Analysis	2	
Accumulator VM1	4	1,942,272	BSEE Data Analysis	16	OREDA 2009	2		2	
100 HP Pump	3	16,458	OREDA 2009	34	OREDA 2009	5		5	
Suction Strainer 100 Mesh	3	8,333,333	OREDA 2009	1		1		1	
Filtration Unit	1	8,333,333	OREDA 2009	1		1		1	
Hydraulic Hotline & Rigid Conduits									
Hotline Reel	2	2,439,024	OREDA 2009	2	OREDA 2009	2		2	
Rigid Conduit	2	2,439,024	OREDA 2009	2	OREDA 2009	2		2	
Stack									
LMRP Connector	1	76,698	BSEE Data Analysis	3.95	BSEE MIT Data Analysis	12.22	BSEE MIT Data Analysis	10	IP - See Assumption
Stack Accumulators (16 * 80 Gal)	1	1,942,272	BSEE Data Analysis	2.92	BSEE MIT Data Analysis	6.88	BSEE MIT Data Analysis	10	IP - See Assumption
Valve, 3WNC, SSUB X SSUB, SPM	42	1,011,404	BSEE Data Analysis	15.04	BSEE MIT Data Analysis	5.63	BSEE MIT Data Analysis	10	IP - See Assumption
Shear Seal Valve, Solenoid, 3WNC (6)	40	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
VALVE 3W DOUBLE PILOT (38)	2	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Shuttle Valve	30	2,515,694	BSEE Data Analysis	5.545	BSEE MIT Data Analysis	4.833	BSEE MIT Data Analysis	10	IP - See Assumption
Upper Annular	1	40,083	BSEE Data Analysis	6.88	BSEE MIT Data Analysis	16.6	BSEE MIT Data Analysis	10	IP - See Assumption
Lower Annular	1	40,083	BSEE Data Analysis	6.88	BSEE MIT Data Analysis	16.6	BSEE MIT Data Analysis	10	IP - See Assumption

Table C-1 Reliability Data for Individual BOP Components (cont'd)

Subsystem / Component	Quantity	MTTF	Source	MTTR	Source	PM	Source	Inspection	Source
Shear Rams	1	61,358	BSEE Data Analysis	5.64	BSEE MIT Data Analysis	20.7	BSEE MIT Data Analysis	10	IP - See Assumption
Casing Shear Rams	1	61,358	BSEE Data Analysis	5.64	BSEE MIT Data Analysis	20.7	BSEE MIT Data Analysis	10	IP - See Assumption
Pipe Ram 1	1	40,035	BSEE Data Analysis	5.64	BSEE MIT Data Analysis	20.7	BSEE MIT Data Analysis	10	IP - See Assumption
Pipe Ram 2	1	40,035	BSEE Data Analysis	5.64	BSEE MIT Data Analysis	20.7	BSEE MIT Data Analysis	10	IP - See Assumption
Pipe Ram 3	1	40,035	BSEE Data Analysis	5.64	BSEE MIT Data Analysis	20.7	BSEE MIT Data Analysis	10	IP - See Assumption
Test Ram	1	40,035	BSEE Data Analysis	5.64	BSEE MIT Data Analysis	20.7	BSEE MIT Data Analysis	10	IP - See Assumption
Well Head Connector	1	76,698	BSEE Data Analysis	3.95	BSEE MIT Data Analysis	12.22	BSEE MIT Data Analysis	10	IP - See Assumption
Subsea Electronic Module	2	43,827	BSEE Data Analysis	0.77	OREDA 2009	0.77	OREDA 2009	10	IP - See Assumption
POD Pressure Regulator w/o POCV Y	2	117,997	BSEE Data Analysis	15.04	OREDA 2009	5.63	OREDA 2009	10	IP - See Assumption
POD Pressure Regulator including POCV B	2	115,047	BSEE Data Analysis	15.04	OREDA 2009	5.63	OREDA 2009	10	IP - See Assumption
Choke & Kill System									
Choke Line	1	42,528	SINTEF 2012	117	SINTEF 2012	5		10	IP - See Assumption
Kill Line	1	42,528	SINTEF 2012	117	SINTEF 2012	5		10	IP - See Assumption
Upper Inner Choke Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Lower Inner Choke Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Lower Inner Kill Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Upper Inner Kill Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Lower Outer Choke Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Upper Outer Choke Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Lower Outer Kill Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Upper Outer Kill Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Inner Gas Relief Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Outer Gas Relief Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Choke STAB	1	204,528	BSEE Data Analysis						
Kill STAB	1	204,528	BSEE Data Analysis						
Choke Test Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Kill Test Valve	1	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption
Shuttle Valve	24	2,515,694	BSEE Data Analysis	5.545	BSEE MIT Data Analysis	4.833	BSEE MIT Data Analysis	10	IP - See Assumption
SPM VALVE	48	1,011,404	BSEE Data Analysis	15.04	BSEE MIT Data Analysis	5.63	BSEE MIT Data Analysis	10	IP - See Assumption
Shear Seal Valve, Solenoid, 3WNC (6)	48	66,358	OREDA 2009	4.2	OREDA 2009	2		10	IP - See Assumption

APPENDIX D – RELIABILITY BLOCK DIAGRAM

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BASE-CASE – ALL FUNCTIONS RELIABILITY BLOCK DIAGRAM

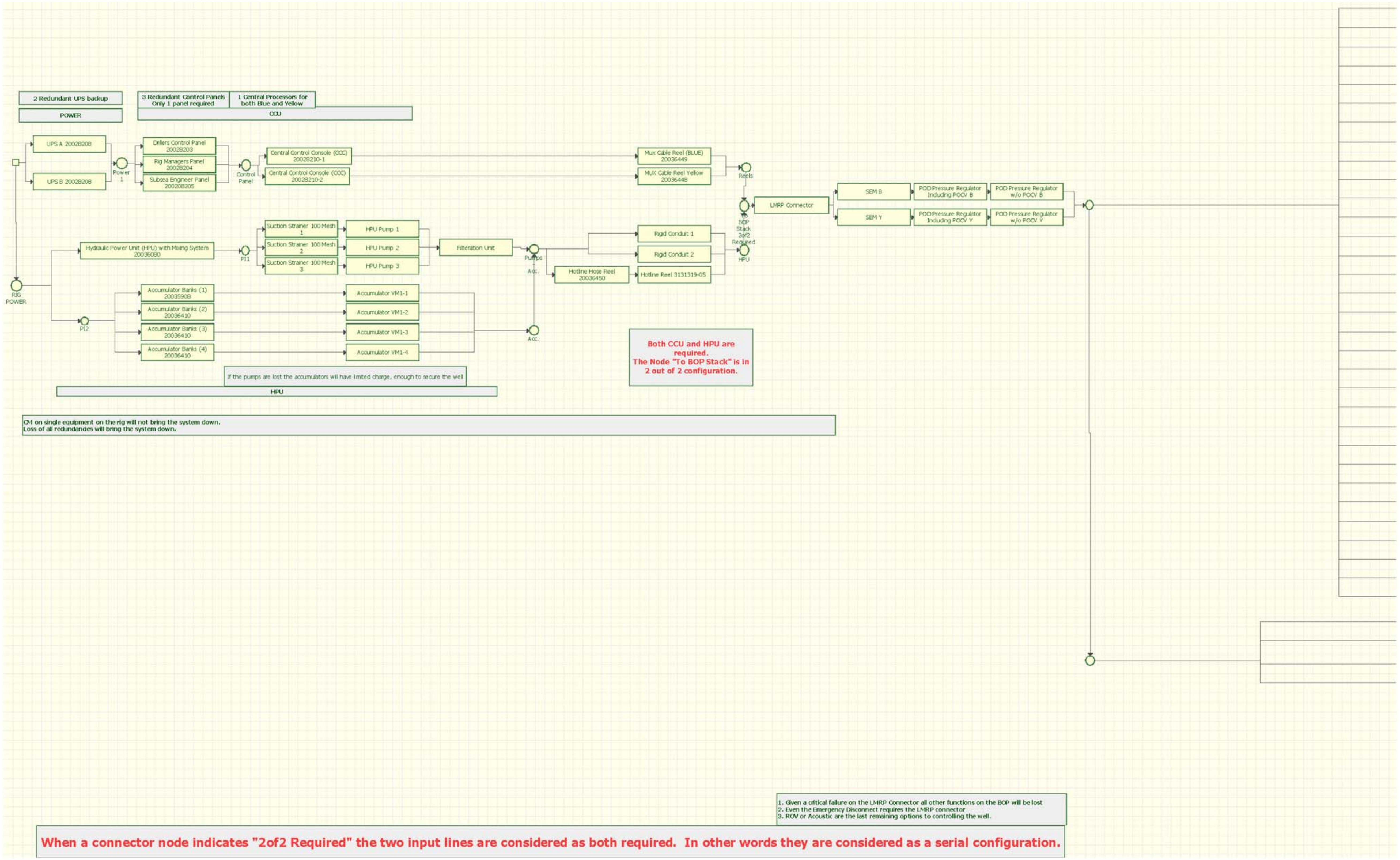

Figure D-1 All Functions Reliability Block Diagram (1 of 3)

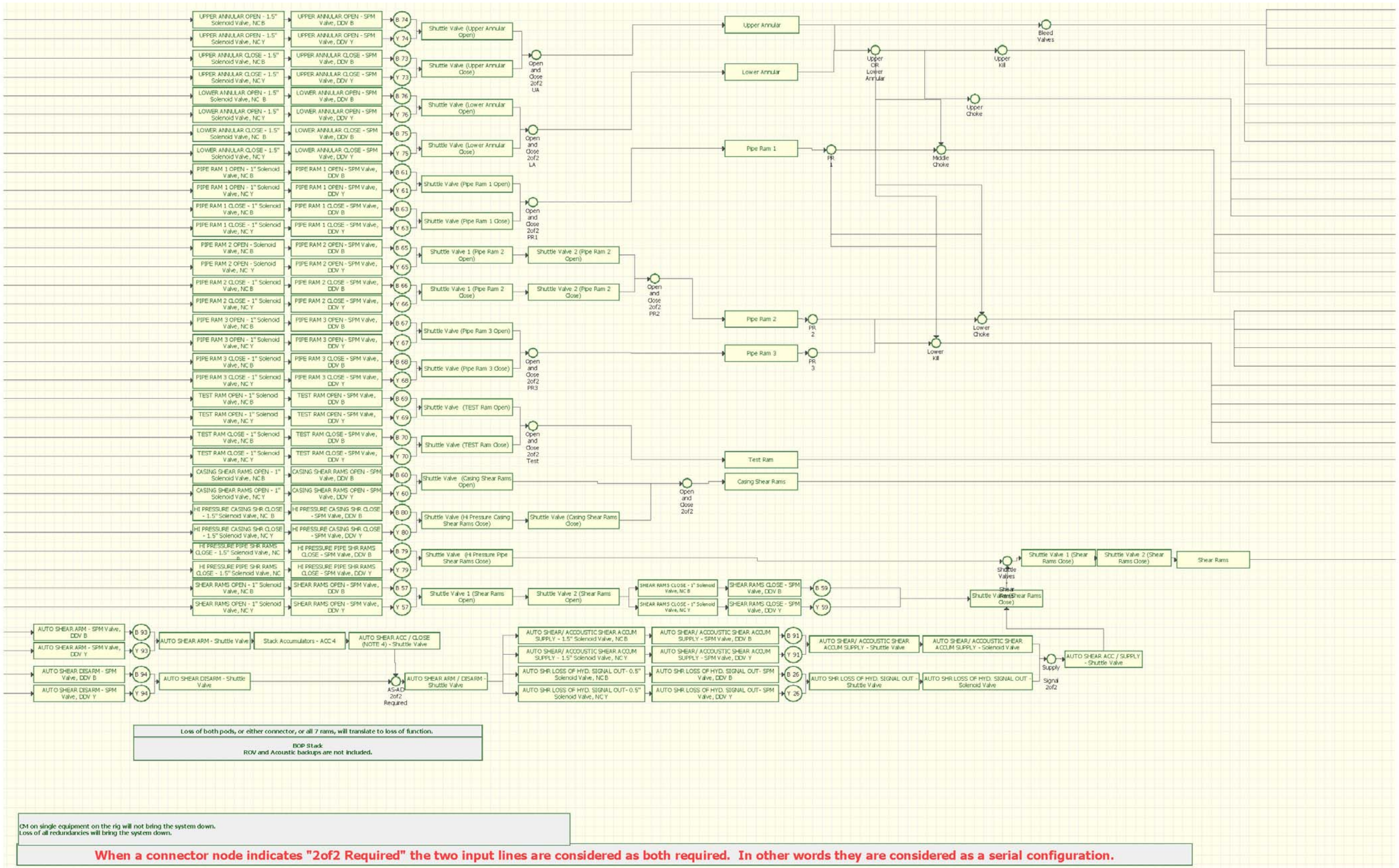

Figure D-1 All Functions Reliability Block Diagram (2 of 3)

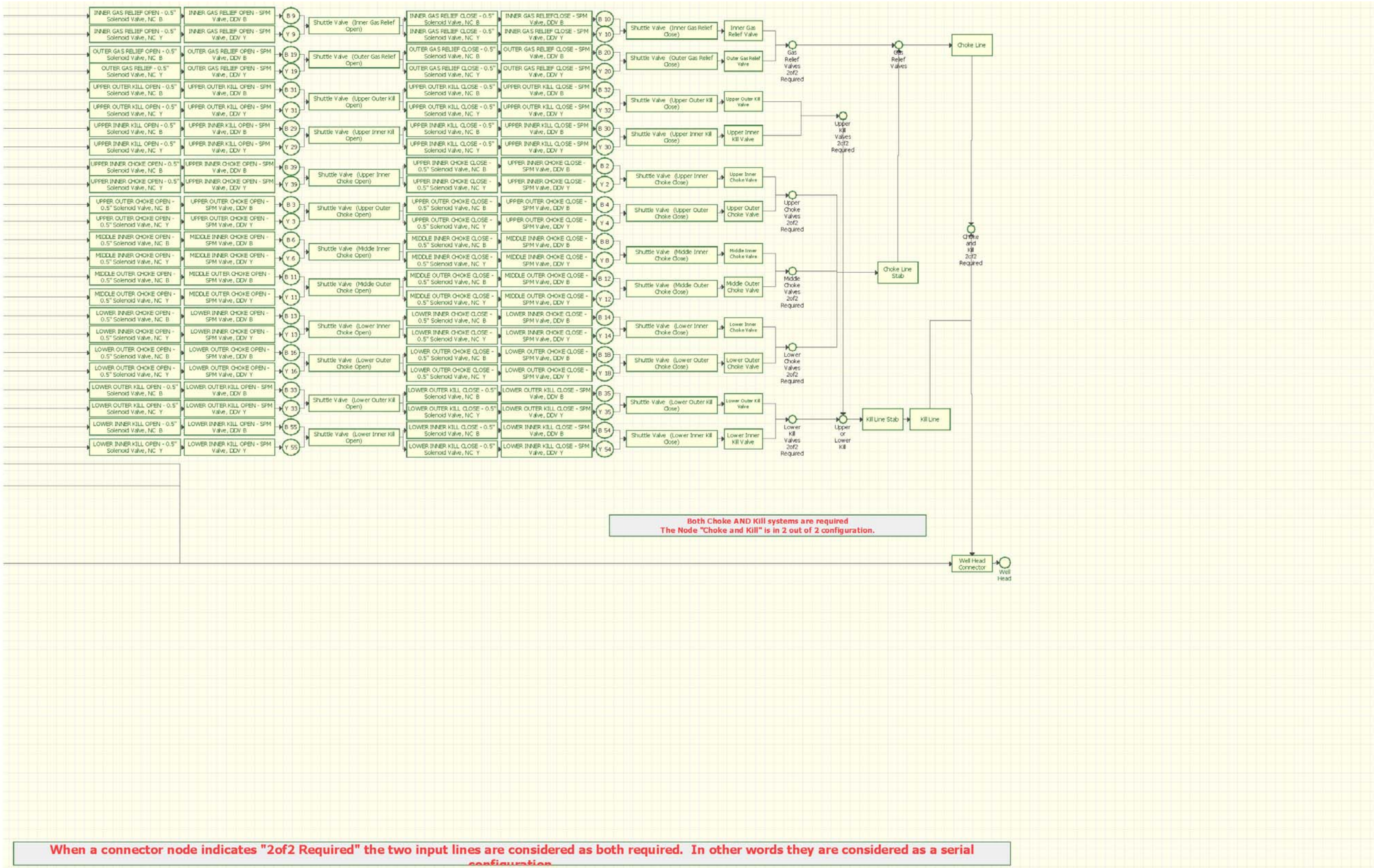

Figure D-1 All Functions Reliability Block Diagram (3 of 3)

Design Change 1 – LMRP ANNULAR & PIPE RAMS ONLY RELIABILITY BLOCK DIAGRAM

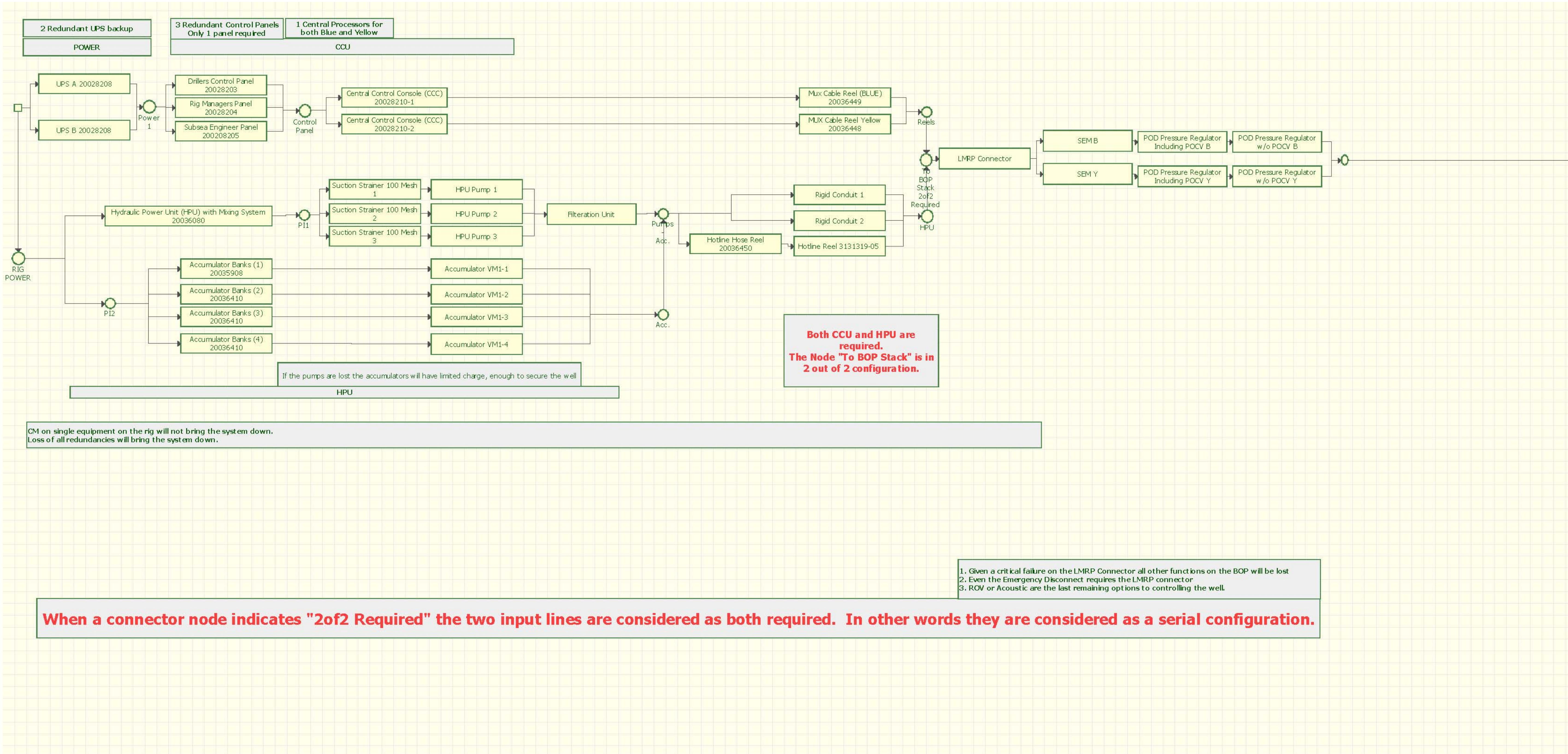

Figure D-2 LMRP Annular and Pipe RAMS Only Reliability Block Diagram (1 of 3)

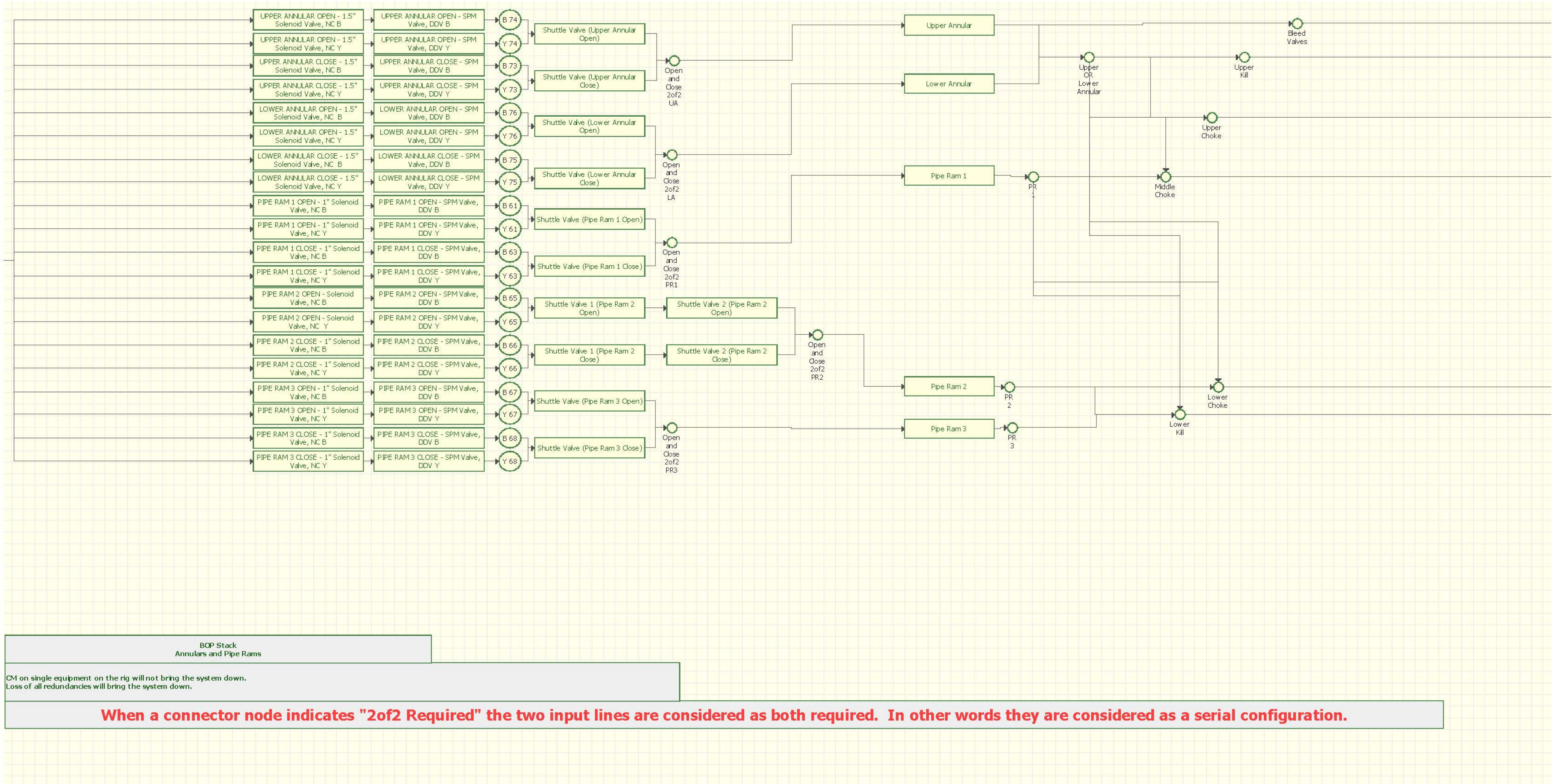

Figure D-2 LMRP Annular and Pipe RAMS Only Reliability Block Diagram (2 of 3)

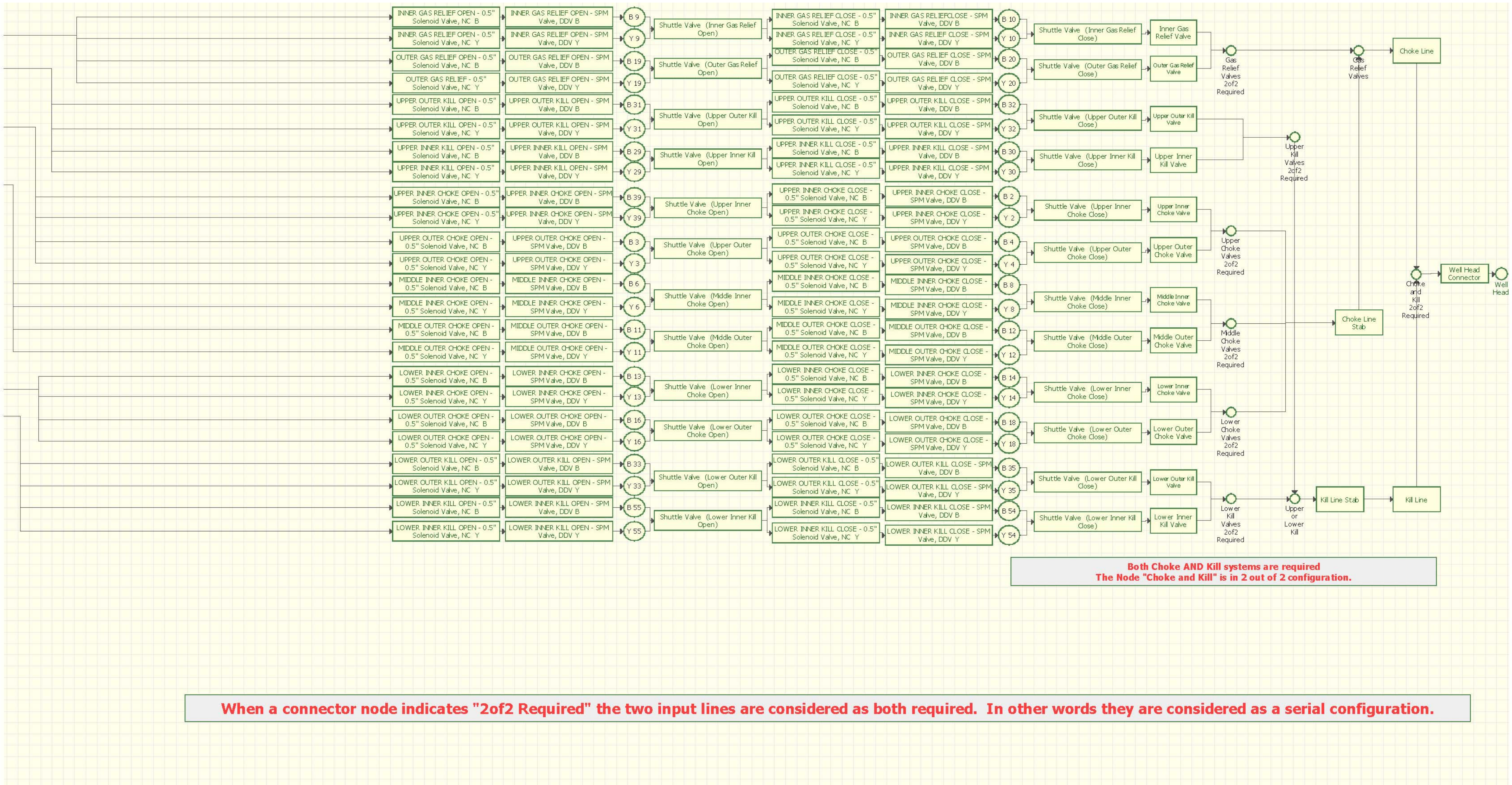

Figure D-2 LMRP Annular and Pipe RAMS Only Reliability Block Diagram (3 of 3)

Design Change 2 – LMRP ANNULAR ONLY RELIABILITY BLOCK DIAGRAM

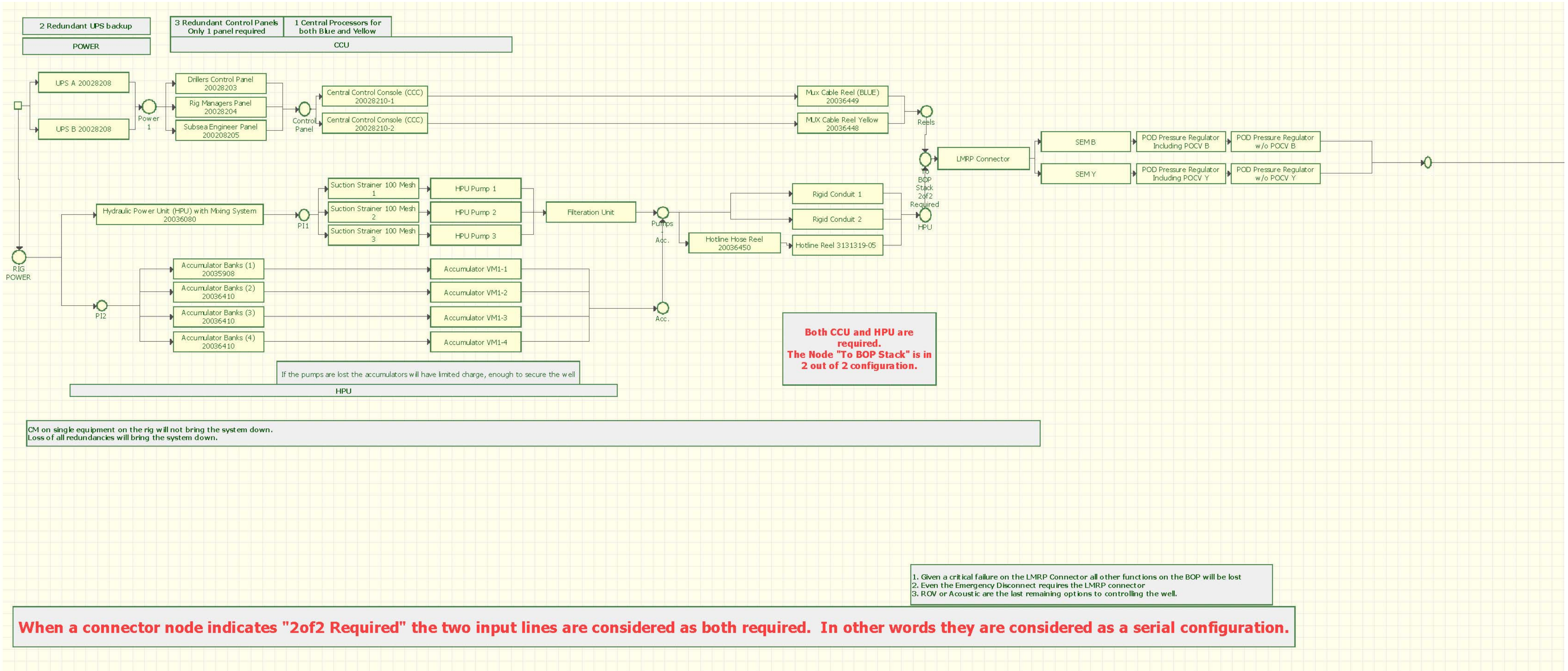

Figure D-3 LMRP Annular Only Reliability Block Diagram (1 of 3)

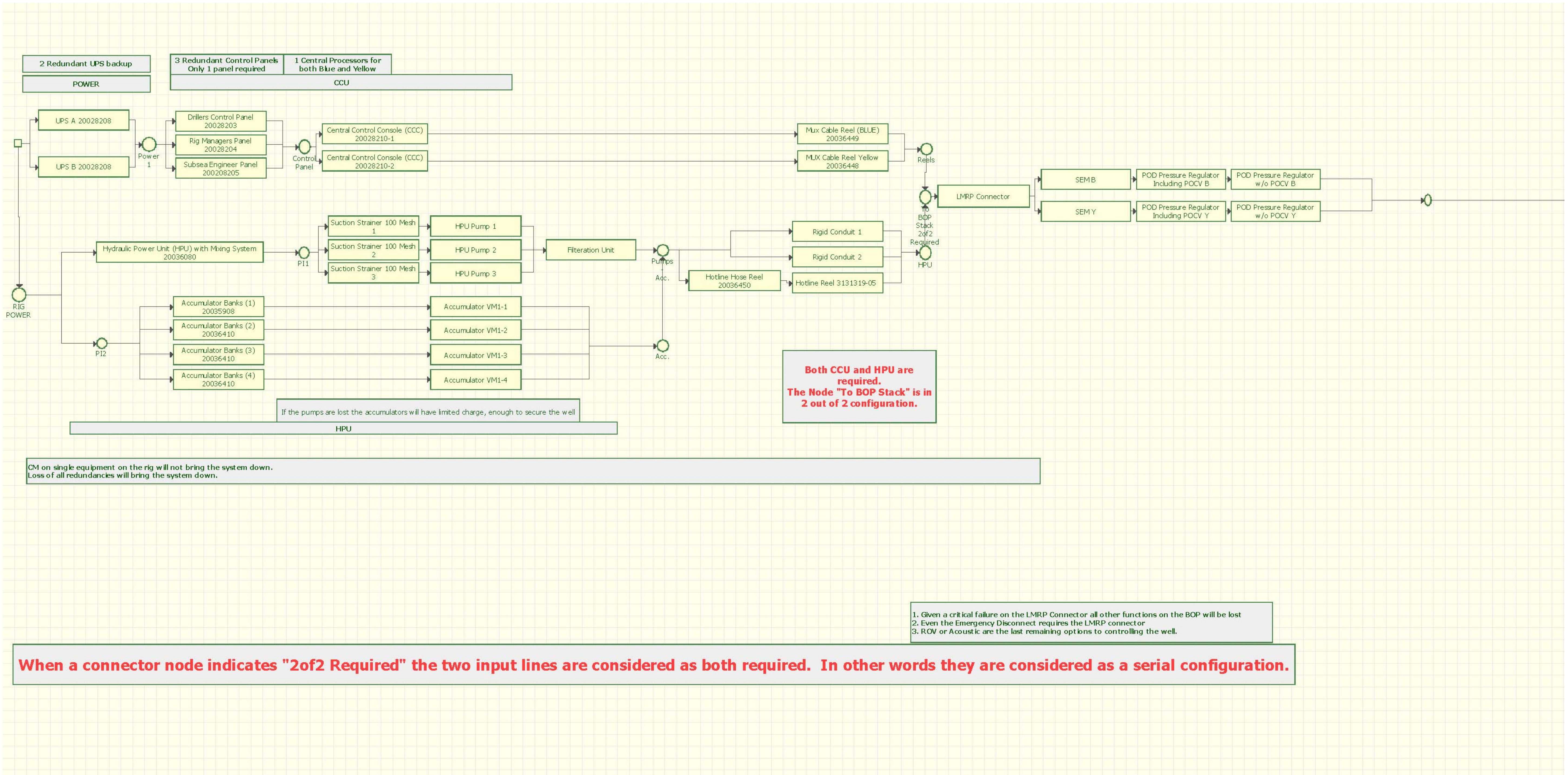

Figure D-3 LMRP Annular Only Reliability Block Diagram (2 of 3)

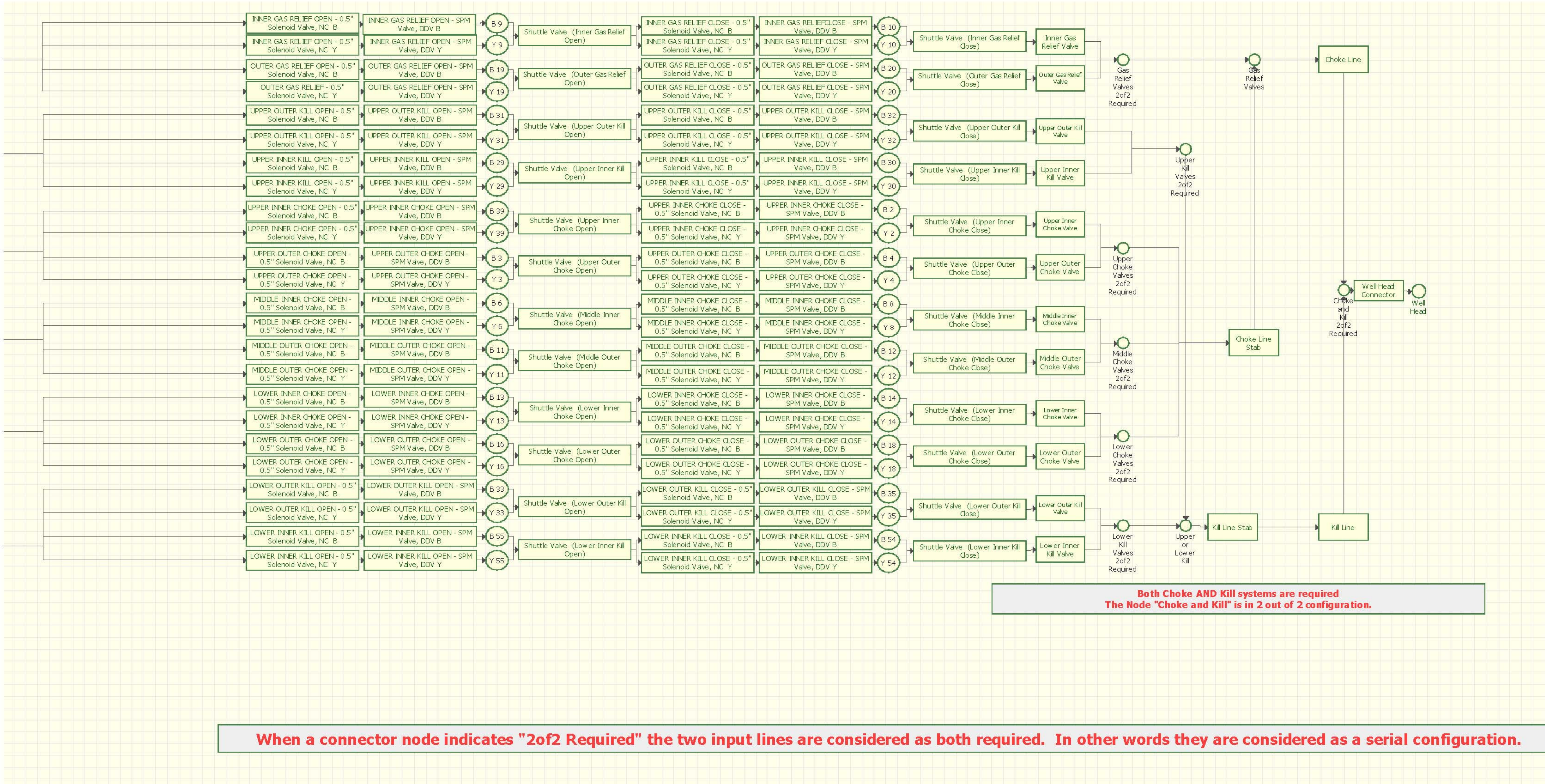

Figure D-3 LMRP Annular Only Reliability Block Diagram (3 of 3)

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SUMMARY OF BLOWOUT PREVENTER (BOP) RELIABILITY, AVAILABILITY, AND MAINTAINABILITY (RAM) ANALYSES FOR THE BUREAU OF SAFETY AND ENVIRONMENTAL ENFORCEMENT

2650788-RAM-SR-F3	2	Final Report for Issue to BSEE	6/27/13
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This work was performed by American Bureau of Shipping and ABSG Consulting Inc. for the Bureau of Safety and Environmental Enforcement (BSEE) under the terms of BSEE contract number M11PC00027

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LIST OF CONTRIBUTORS:

ABS Consulting
David Montague
Kamran Nouri
Kamyar Nouri

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SUMMARY

As part of the Blowout Preventer (BOP) Maintenance and Inspection for Deepwater Operations study (BSEE Contract Number M11PC00027), the American Bureau of Shipping (ABS) and ABSG Consulting Inc. (ABS Consulting) performed a Reliability, Availability, and Maintainability (RAM) analysis of a typical BOP used in industry. Using a Reliability Block Diagram portraying the various combinations of component/subsystems required for successful BOP operation, failure data for the BOP system components, and maintenance, inspection and test data for a typical system, the analysis team estimated the availability of the BOP system. Availability, as used in this study, is the probability the BOP system functions properly on demand. This summary report presents the results for two RAM analysis performed on two of the Industry Participant's BOP designs.

This report represents a portion of Deliverable F for the studies associated with Tasks 6.2.3, 6.2.3.1, and 6.2.3.2, as outlined in the above referenced contract. This report presents the summary of objective and scope of the RAM study, analysis process, analysis assumptions, comparison of the results of two RAM analysis, and conclusions/observations.

The objective of RAM analysis is to determine the impact of Maintenance, Inspection and Testing (MIT) activities on the overall availability of BOP system manufactured by the Original Equipment Manufacturers (OEMs) participating in the MIT project. This was accomplished by (1) developing an Reliability Block Diagram (RBD) model representing the BOP system; (2) analyzing the model using a simulation method in order to estimate the availability of the BOP system during operations (drilling and MIT periods); (3) modeling three different operating scenarios, and (4) developing and analyzing two design variances and two "what-if" scenarios (regarding changes to MIT intervals and improved reliability of a few BOP system components) to assess the impact of these selected changes on BOP availability for each operating scenario.

The analysis team estimated BOP system availability by developing an RBD for each of the BOP designs (base case) and performing a Monte Carlo simulation using the RBDs and industry failure data for the components in the model. In addition, alternative designs and two what-if models were developed.

Table S-1 presents the comparison of the availability results for two BOP designs. Depending on the operating scenario and specific design alternative, the key point of these results are the estimated availability of the BOP system during the drilling operation period (on well or without Preventive Maintenance [PM] and Inspection). The mean availability for BOP 1 ranged from (1) 0.9937 to 0.9995 for Operating Scenario A, (2) 0.9871 to 0.9912 for Operating Scenario B, and (3) 0.9835 to 0.99 for Operating Scenario C. The mean availability for BOP 2 ranged from (1) 0.9928 to 0.9994 for Operating Scenario A, (2)0.9863 to 0.9913 for Operating Scenario B, and (3) 0.9822 to 0.9882 for Operating Scenario C.

The results presented here consider BOP surface and subsea controls and the stack equipment. While detected failures on the BOP stack may result in the BOP to be pulled, the subsystems located on the rig will be repaired without having to pull the BOP stack.

Table S-1: Comparison of BOP Availability Results Summary

BOP Analysis Cases	**Operating Scenario A**		**Operating Scenario B**		**Operating Scenario C**	
	Mean Availability for Drilling Operation Period (On Well) With At Least One Well Control Function Remaining to Control a Well Kick		Mean Availability for Drilling Operation Period (On Well) While Maintaining **All** BOP Well Control Functions Assuming Corrective Maintenance (CM) Performed Without Pulling of the Stack		Mean Availability for Drilling Operation Period (On Well) While Maintaining **All** BOP Well Control Functions Assuming Any Subsea CM Performed Requires Securing of the Well and Pulling of the Stack	
	BOP 1	**BOP 2**	**BOP 1**	**BOP 2**	**BOP 1**	**BOP 2**
Base Case: All Well-Control Functions	.9991	.9991	.9902	.9875	.9835	.9843
Design Change 1 (LMRP Annular(s) & Pipe Rams Only)	.9946	.9943	.9881	.9875	.9882	.9869
Design Change 2 (LMRP Annular(s) Only)	.9937	.9928	.9876	.9873	.9878	.9867
What-If Case 1 (4 week test interval)	.9995	.9991	.9871	.9863	.984	.9822
What If Case 2 (Improved reliability of select components)	.9993	.9994	.9912	.9913	.99	.9882

Based on the analysis results, the team made the following observations:

- Operating Scenario A results represent the BOP availability to control a well kick by at least one well control function, which is a better measure of the BOP system availability relative to overall safe operation.

- Operating Scenarios B and C represent the BOP availability relative to maintaining all BOP well control functions while on the well (i.e., it models the regulatory requirement relative to maintaining all BOP functions at all times while on the well). These results measure the availability for two differing corrective maintenance responses to subsea component failures: (1) on-the-well repair and (2) pulling-of-the-stack repair. While actual operations likely result in a combination of these two responses, these models provide upper and lower bounds for actual operation relative to maintaining all BOP functions.

- While the BOP system is constructed with many subsystems that internally have multiple layers of redundancy, the BOP also has single component failure points in its design. These single failures are the dominant contributors to the estimated BOP probability of failure on demand. Based on these RAM results, the dominant contributors to the estimated BOP failure on demand probability are the two single failure points: LMRP connector failure, and Well Head Connector failure. Combined, these two component failures contribute over 99% to the estimated unavailability of the BOP system during "on well." In the calculations, these two components have an equal contribution to the estimated unavailability of the BOP system.

(Note: These dominant contributors were identified based on the total failure rate data for these devices for all failure modes without any differentiation to unsafe and safe failure fraction of the respective failure modes.)

- For Operating Scenarios B and C, the estimated availability of BOP 2 is somewhat lower than the estimated availability of BOP 1 for several of the operating scenarios and analysis cases. These lower estimates are attributed to (1) the higher failure frequency of selected BOP 2 system components (relative to the BOP 1 system counterparts), (2) the additional subsystems/components associated with the second annular ring in the BOP 2 design, and (3) the associated corrective maintenance time to address these failures.

- To demonstrate the contribution of the component failures associated with non-shearing control measures (i.e., pipe rams and annulars), BOP system availability considering pipe rams and annular(s), and annular(s) only operating were evaluated (i.e., design changes 1 and 2). While these results indicate that the removal of the shear rams and pipe rams (design change 2 only) had little impact on the BOP system availability, this is because the remaining component failures, especially the two single point of failure items, have a more significant impact on the BOP system availability than the impact of the removed items on the system availability. However, readers are cautioned to not draw the conclusion that these results indicate the redundancy provided by the removed well control items are not important. The shear and pipe rams are considered important part of the BOP system and provide the required redundancy and essential functions for controlling the well.

- What-If Case 1 analysis indicate the system availability is not significantly changed by the extending of the test interval for all operating scenarios and results in an average availability reduction of 0.2% for Operating Scenarios B and C. Specifically, the no change in Operating Scenario A availability was expected since this scenario is based on allowing the BOP functionality to degrade until the BOP can't sufficiently function to control a kick (i.e., no inspection and test are performed for this scenario). As for the Operating Scenarios B and C, the BOP availability is reduced for three of the four cases. (Note: The fourth case may indicate no change or drop in availability, but due to model rounding of the results, it is not possible to determine the significance between the results, 0.9835 and 0.984.)

- What-If Case 2 analysis shows that improving the reliability performance of a few selected components in the BOP 1 and 2 systems caused a slight improvement in the estimated BOP availability for all three operating scenarios. The four components selected for improvement were identified in the BSEE Data Analysis Study (ref. 1) as less reliable BOP components. However, the BOP system design includes redundant features for these particular components and thus their failures were small contributors to the BOP system failure probability.

- Improving the reliability of, or gaining better understanding of unsafe and safe failure fractions for, the single point of failure components and other components, which were the major contributors to the BOP estimated unavailability, should cause a significant improvement in BOP availability. Improvements might be achieved through better construction/quality assurance of these items, better item design, and/or reducing detection/repair time of the items.

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LIST OF ACRONYMS

ABS	–	American Bureau of Shipping
ABS Consulting	–	ABSG Consulting Inc.
BOP	–	Blowout Preventer
BSEE	–	Bureau of Safety and Environmental Enforcement
CM	–	Corrective Maintenance
FMECA	–	Failure Mode Effect and Criticality Analysis
HPU	–	Hydraulic Power Unit
IP	–	Industry Participant
LMRP	–	Lower Marine Riser Package
MIT	–	Maintenance, Inspection and Test
MUX	–	Multiplex
PM	–	Preventive Maintenance
OEM	–	Original Equipment Manufacturer
RAM	–	Reliability, Availability, and Maintainability
RBD	–	Reliability Block Diagram
SPM	–	Sub Plate Mounted (Valve)

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1.0 INTRODUCTION

As part of the Blowout Preventer (BOP) Maintenance and Inspection for Deepwater Operations study (BSEE Contract Number M11PC00027), the American Bureau of Shipping (ABS) and ABSG Consulting Inc. (ABS Consulting) performed a Reliability, Availability, and Maintainability (RAM) study of a typical BOP system used in industry. The analysis team developed a Reliability Block Diagram (RBD) model and used BOP system failure events data and maintenance, inspection, and test (MIT) data to estimate BOP system availability. This report represents a portion of Deliverable F for the studies associated with Tasks 6.2.3, 6.2.3.1, and 6.2.3.2, as outlined in the contract.

Two RAM models were developed for BOP systems from two different original equipment manufacturer (OEM) designs. This summary report presents the objective and scope of the RAM study and analysis process and discusses the analysis assumptions, comparison of two analyses results and analysis details, and conclusions.

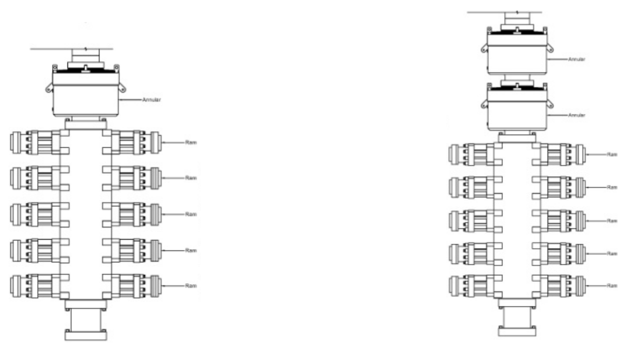
1.1 OBJECTIVES

The objective of this summary RAM analysis report are to (1) provide comparison between the two BOP configurations used for this analysis, and (2) provide a discussion about the base design, two design variations, and two what-if scenarios and compare the results.

1.2 ANALYSIS SCOPE

The physical scope of the RAM analysis was limited to a selected BOP system and associated equipment designed by two OEMs and used by two drilling contractor and operators participating in the study. The selected BOP systems design met the following criteria:

- Operation Location – Gulf of Mexico (majority of the operation and maintenance to be from the Gulf of Mexico)
- Operating Depth – 5,000 Feet and Deeper
- BOP Configurations:
  - **Class VI BOP,** five ram configuration and single annular
  - **Class VII BOP,** five ram configuration and dual annular



Class VI BOP **Class VII BOP**

Figure 1-1. BOP Configurations

Each analysis involved compiling information provided by the industry participants (IPs), followed by discussions with the OEMs and the drilling contractors on BOP operation, inspection and maintenance.. Table 1-1 presents the subsystem for each model and compares their associated OEM.

Table 1-1: Comparison of BOP System and Associated Control Systems

Model	Surface Control System	Subsea Control System	BOP Stack
RBD 1, 5 Rams, 1 Annular	OEM A	OEM A	OEM A
RBD 2, 5 Rams, 2 Annulars	OEM B	OEM B	OEM B

Each BOP included the above 3 major BOP subsystems and their associated components. Table 1-2 provide a comparison of the subsystems and components used in each RBD model.

Table 1-2: Comparison of Subsystem and Component

Subsystem/Component	Quantity	
	BOP 1	BOP 2
POWER Subsystem		
UPS	2	2
POWER DIST PANEL	2	
SUBSEA XFMR	2	2
CCU – Elect. Controls		
Remote Driller Panel	2	
Driller's Panel	1	
Remote Control Panel	1	
Processor & Equipment Cabinets (CCU)	2	
Power Isolation J-Box	1	
Drillers Control Panel		2
Rig Managers Panel		1
Subsea Engineer Panel		1
Central Control Console (CCC) with redundant ICs		2
Multiplex (MUX) System		
J-Box MUX Umbilical	2	
Cable Reel	2	2
Hydraulic Power Unit (HPU) - Hydraulic Controls		
HPU I/F Control Panel	1	
Reservoir / Mixing Unit	1	
HPU with Mixing System		1
Accumulator 180 GAL 16 Station 5K	1	
Accumulator 285 GAL 20 Station 5K	2	
Accumulator Banks		4
Accumulator VM1	3	4
100 HP Pump	3	3
Suction Strainer 100 Mesh	3	3

Table 1-2: Comparison of Subsystem and Component (cont'd)

Subsystem/Component	Quantity	
	BOP 1	BOP 2
Filtration Unit	1	1
Hydraulic Hotline & Rigid Conduits		
Hotline Reel	2	2
Rigid Conduit	1	2
Stack		
Lower Marine Riser Package (LMRP) Connector	1	1
Stack Accumulators (16 * 80 Gal)	1	1
Valve, 3WNC, SSUB X SSUB, Sub Plate Mounted (SPM)	32	42
Shear Seal Valve, Solenoid, 3WNC (6)	36	40
VALVE 3W DOUBLE PILOT (38)	2	2
Shuttle Valve	16	30
LMRP Annular	1	
Upper Annular		1
Lower Annular		1
Upper Shear Rams	1	
Lower Shear Rams	1	
Casing Shear Rams		1
Shear Rams		1
Upper Pipe Rams (Pipe Ram 1)	1	1
Middle Pipe Rams (Pipe Ram 2)	1	1
Lower Pipe Rams (Pipe Ram 3)	1	1
SSTV Rams (Test Ram)	1	1
Auto Shear ARM Valve T4	1	
Hydraulic Autoshear Valve	1	
Well Head Connector	1	1
Subsea Electronic Module	2	2
POD Pressure Regulator w/o POCV Y	2	2
POD Pressure Regulator Including POCV B	2	2
Choke & Kill System		
Choke Line	1	1
Kill Line	1	1
Upper Inner Choke Valve	1	1
Lower Inner Choke Valve	1	1
Lower Inner Kill Valve	1	1
Upper Inner Kill Valve	1	1
Lower Outer Choke Valve	1	1
Upper Outer Choke Valve	1	1
Lower Outer Kill Valve	1	1
Upper Outer Kill Valve	1	1
Inner Bleed Valve	1	

Table 1-2: Comparison of Subsystem and Component (cont'd)

Subsystem/Component	Quantity	
	BOP 1	BOP 2
Outer Bleed Valve	1	
Inner Gas Relief Valve		1
Outer Gas Relief Valve		1
Choke STAB	1	1
Kill STAB	1	1
Choke Test Valve	1	1
Kill Test Valve	1	1
Shuttle Valve	20	24
SPM VALVE	40	48
Shear Seal Valve, Solenoid, 3WNC (6)	40	48

The BOP system functions incorporated in the RBDs were defined in the related Failure Mode Effect and Criticality Analysis (FMECA) studies. Given the fact that the BOP system availability depends on multiple subsystem functions at any time and any failure could lead to stoppage of drilling operation, each RBD base case model was developed to be inclusive of all BOP system functions.

Ultimately, the results from this assessment are intended to provide a relative measure of the BOP system availability with respect to the existing maintenance, inspection, and test policies.

1.3 RAM ANALYSIS AND MEETING SCHEDULE

The analysis team for each study included personnel from two IPs, the American Bureau of Shipping (ABS), and ABSG Consulting Inc. (ABS Consulting). The IPs participating included one or more representatives from an OEM and a drilling contractor. These individuals provided knowledge of the design, engineering, operation, and maintenance of the BOP system being evaluated. Table 1-3 lists the functional positions for the IP personnel who participated in each study.

Table 1-3: IP RAM Team Members

<table>
<tr><th rowspan="2">IP Organization</th><th colspan="2">Position/Expertise</th></tr>
<tr><th>BOP 1</th><th>BOP 2</th></tr>
<tr><td rowspan="4">BOP OEM</td><td>Engineering Manager, Drilling Products</td><td>Engineering Director</td></tr>
<tr><td>Manager, Reliability Engineering/Drilling and Production</td><td>Project Manager</td></tr>
<tr><td>Electrical Engineering Manager, Drilling and Production</td><td></td></tr>
<tr><td>Sub Section Manager, Stacks, Mechanical Controls and Risers</td><td></td></tr>
<tr><td rowspan="3">Drilling Contractor</td><td>Corporate Subsea Operation Manager</td><td>Subsea Operation Manager</td></tr>
<tr><td>Subsea Superintendent</td><td></td></tr>
<tr><td>Subsea MUX System SME</td><td></td></tr>
<tr><td>Operator</td><td>Engineer Operations, Drilling and Completions</td><td>Manager Deepwater Wells</td></tr>
</table>

In addition to the IP representatives, personnel from ABS and ABS Consulting participated in the several RAM meetings. Specifically, ABS personnel provided knowledge of the overall BOP operations and class society and regulatory requirements applicable to BOP design and operation. ABS Consulting personnel developed the RBD models, facilitated teleconferences and meetings with

IPs to refine the RBD model and component failure data, performed the analyses, and documented the RAM studies. Table 1-4 lists the ABS and ABS Consulting personnel participating in each study.

Table 1-4: ABS and ABS Consulting RAM Team Members

Name	Organization	Title	Study Role
David Cherbonnier	ABS	Staff Consultant, Corporate Offshore Technology	Subsea Engineer
Bibek Das	ABS	Senior Engineer II, Corporate Shared Technology	Senior Engineer II (Risk and Reliability), Corporate Technology
Randy Montgomery	ABS Consulting	Senior Director, Integrity Management	Project Technical Lead
Kamyar Nouri	ABS Consulting	Senior Risk and Reliability Engineer	Risk and Reliability Analyst (model & logic development)
Kamran Nouri	ABS Consulting	Senior Risk and Reliability Engineer	Risk and Reliability Analyst (review and documentation)

To prepare for the RAM studies, ABS and ABS Consulting held a kickoff meeting with the IPs on August 14 and 15, 2012. The purposes of the kickoff meeting were to discuss the FMECA and RAM analysis approaches and the analyses scope to help ensure that all participants have the same level of understanding of the FMECA & RAM procedures.

In addition to the kickoff meeting, the analysis team held several teleconferences and meetings with the IPs from December 2012 to March of 2013. During these sessions, the RAM team members were provided an introduction to RBD methodology and collaborated on the RBD model logic for the base case, the two design alternatives, and the two "what–if" cases. BOP functions were defined in a related FMECA study and were incorporated into the model. All BOP system functions were considered during the development of various analysis cases.

1.4 REPORT ORGANIZATION

Section 2 of this report provides an overview of the methodology used to analyze the BOP's availability models for the base case, alternate design cases, and what-if cases. Section 3 discusses the analysis assumptions. Section 4 provides a comparison of the RAM analysis results. Section 5 discusses the analysis conclusions and observations. Appendices A, B and C contain lists of references, BOP system drawings and BOP reliability block diagrams for the two designs, respectively.

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2.0 RELIABILITY AND AVAILABILITY ANALYSIS PROCESS

To estimate the availability of the BOP system, the analysis team developed a Reliability Block Diagram (RBD) model. The RBD shows the logical interaction of BOP subsystems and equipment required for successful system operation. The RBD model consists of series and parallel trains of components and subsystems required for successful BOP system operation.

The analysis team identified a baseline BOP system (base case) according to one OEM design and one configuration used by one of the drilling contractors participating in the MIT project. The base-case model was used to estimate the reliability and availability of the BOP system. In addition to the base-case model, several alternative designs and what-if scenarios were evaluated based on input from the Industry Participants (IP).

For the BOP system analysis, the team used BOP component/subsystem failure and maintenance data provided by the IPs. The team developed the RBD model and performed the availability calculations as described in Section 2.1.The BOP system RAM characteristics estimated are:

- Mean BOP Availability for Drilling Operation Period (on well)

2.1 ANALYSIS APPROACH

The basic fundamentals of RBD modeling are to logically show the interaction of subsystems and components required for successful operation of the system. Or conversely, to show combinations of component/subsystem failures that lead to system failure (unavailability or probability of failure on demand).

Figure 2-1 depicts a sample RBD made up of two subsystems, each containing three components. Subsystem 1 contains three series blocks and subsystem 2 contains a combination of parallel and series blocks. In subsystem 1, any component failure will translate to system failure. Subsystem 2, however, has redundant components D and E and thus can withstand a single failure of D or E without suffering system failure. In subsystem 2, component F is in series with all other components and it is a single point of failure for the system.

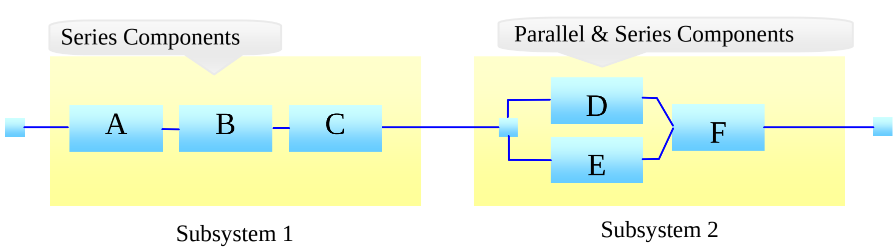

Figure 2-1 RBD Example 1

More complex relationships like ‘K’ out of ‘N’ components and cross relationships can exist and are modeled, if necessary (Figure 2-2).

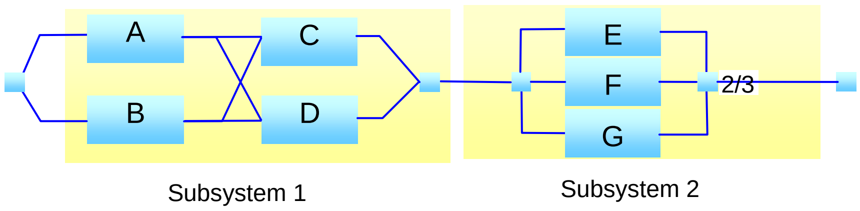

Figure 2-2 RBD Example 2

In both examples, each component is analyzed with respect to failure characteristics and its functional relationship to other components. The component’s failure characteristics are used to determine the component’s time of failure. This information is then passed on to the subsystem and subsequently to the system level, using the RBD as a roadmap for determining how to mathematically combine this information and arrive at system level failure characteristics

After the logic model development, component failure and maintenance data are required for logic model quantification. The analysis team collected equipment/component failure, inspection, test and maintenance data based on available industry data and this project’s data analysis study (BSEE Data Analysis). The reliability data included time-based or “running” failure rates and associated repair and restoration times for identified failure modes.

Monte Carlo simulation using a preset number of iterations was used to estimate system-level results. In this simulation, each component’s failure distribution is sampled each iteration for input into the system calculation until such time that the simulation results converge to a steady state result for the system.

Utilizing this approach, the analysis team developed an RBD model for each base case BOP system and two alternate BOP design cases. They performed an availability analysis using these models. The team then performed two what-if analyses on the base case BOP system, modifying the testing interval and the failure characteristics of a few select BOP components. Results for all five cases were documented and analyzed for “lessons learned.”

2.2 Operating Scenarios

In order to evaluate the BOP performance and evaluate the impact of BOP MIT, the RAM study involved the evaluation of the three operating scenarios. The first operating scenario was designed to estimate the BOP availability to control a well kick via at least one well control measure (e.g., pipe ram and associated choke and kill valves, annular and associated choke and kill valves). This operating scenario was evaluated by allowing system redundancies to degrade when component failures occur until last well control measure is no longer functional. This approach models the loss of all system redundancies until the BOP is no longer available to sufficiently function and control a well kick. Operating Scenario A evaluates this operating state.

The other two operating scenarios were designed to evaluate the BOP availability for all BOP well control functions relative to two corrective maintenance responses. The two corrective maintenance responses evaluate the regulatory requirement to perform corrective maintenance whenever a BOP component failure is detected to help ensure all BOP well control functions are maintained while on the well. The two specific responses evalauted were (1) corrective maintenance of subsea failures being performed without pulling of the stack (i.e., on-the-well repair) and (2) corrective maintenance of subsea failures always requiring the securing of the well and the pulling of the stack (i.e., pulling-of-the-stack repair). While it is recognized that actual operations likely result in a combination of these two responses, these models provide bounds for the actual operation.

2.3 BASE-CASE MODEL, ALTERNATE DESIGNS AND WHAT-IF CASES

Each base-case RBD model developed reflects successful operation of the BOP system design per the drawings listed in Appendix B. The base-case RBD model is used to estimate the availability of the BOP system as it is designed and operated at the time of this project. This model includes control and stack subsystems that are involved in sealing, shearing, and balancing the well.

After developing and analyzing the each base-case model, the analysis team developed two design variation cases and two what-if cases for further analyses. The identified test cases, developed in collaboration with the IPs, were used to evaluate the impact of system design changes, test/inspection frequency changes, and selected component improvement changes on the BOP system's availability. In each test case, only a single design change or specified parameter was modified; all other parameters stayed the same as the base-case RBD model. Section 4, Table 4-1 provides a detailed description of each case.

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3.0 ANALYSIS ASSUMPTION

In performing the RBD simulation to estimate BOP system availability characteristics, the analysis team made the following assumptions for RBD 1 and RBD 2.

3.1 GENERAL ASSUMPTIONS

- All spare parts are available at the rig; the average repair time for components does not include any time for obtaining spare parts from onshore suppliers
- All specialized crews needed to make necessary BOP repairs are available at the rig
- Human errors introducing failures into the BOP system during test, inspection and/or maintenance are not included model; however, they were indirectly considered via improving the reliability of selected components in What-If case 2.
- Common cause failures of BOP subsystems with redundant components were not included in the analysis due to insufficient data.

The system availability results presented in this report are only based on the estimated time that is required to perform the preventive maintenance (PM) and CM tasks, assuming that the spare parts and the specialized crew are available to perform the necessary tasks. However, the absence of the required spare parts and specialized maintenance crew could result in additional time to perform the maintenance tasks, hence reducing the estimated system availability.

3.2 SPECIFIC ASSUMPTIONS

- The lifetime of the BOP is 5 years (for analysis purposes).
- Failures of any BOP components located in the stack forces the model to switch to maintenance phase and counts against the on-well availability (availability without PM and inspection).
- Failures of any BOP components located on the rig will not count against the on-well availability (availability without PM and inspection) unless all redundancies have been exhausted.
- Failures of any BOP components located on the rig are assumed to be correctable without the introducing any downtime. In other words corrective maintenance of equipment located on the rig does not require the system to be down. The only exception to this is simultaneous failures of redundant components.
- All subsea subsystems can only be repaired once the BOP brought up to the rig.
- All BOP preventive maintenance takes place on the rig.
- Choke and kill systems are both required for BOP successful operation.
- The use of shear rams is considered as an emergency action in which the well will be abandoned. In reality, there are two other situations where the shear rams may be activated but these events are not considered in the model:
    - Accidental shear by the operator
    - Shear due to rig loss of position control

- A failure in one of the SPM valve "open" circuits effectively disable the corresponding SPM valve closure circuit, eliminating this circuit ram closure signal.
- Hydraulic accumulators provide redundant backup to the hydraulic pumps.
- Average time the BOP is on well (i.e., not on the rig for MIT) is 8 weeks.
- Pressure tests occur at 2-week intervals.
- Duration of each test is 10 hours which is based on an average of the test durations reported by the IPs. The BOP is available for operation if needed, during testing.
- Once a failure occurs, the failed BOP component will undergo CM and PM.
- For the purpose of this RAM study, the time duration for pressure and function testing were combined. The test time includes actual test time and any preparation before testing begins.

3.3 BLOCKSIM 7 ANALYSIS PARAMETERS

In performing the RBD simulation of the BOP system, the analysis team specified the following parameters for the analysis:

- Simulation Factors:
  Simulation End Time: 43,825 Hours or 5 Years
  Number of Simulations: 100
- Corrective maintenance takes place upon a failure for Operating Scenarios B and C.
- Preventive maintenance occurs only when the BOP is on the RIG.
- BlockSim's inspection facility is used to emulate the 14-day tests.

4.0 LIST OF ANALYSIS CASES

Using two separate component failure datasets and considering several design alternatives and what-if scenarios, fifteen separate analyses of the BOP system were performed. These fifteen separate analyses included the analysis of the following three operating scenarios and the five analysis cases outlined in Table 4-1:

- Operating Scenario A – Considers the on-well operation of the BOP until a system failure occurs (i.e., all redundancies failure so that the BOP is no longer available to control a well kick) and prevents the BOP from being capable of controlling a well kick via at least one well control function (e.g., annular, pipe ram, shear ram).

- Operating Scenario B – Considers the on-well operation of the BOP relative to maintaining **all** BOP functions assuming the ability to perform corrective maintenance of surface and subsea components without the securing the well and the pulling of the BOP stack. This scenario models the regulatory requirement to perform corrective maintenance when a BOP failure is detected in order to help ensure all BOP well control functions. Specifically, this scenario models corrective maintenance using the mean-time-to-repair for the failed component without pulling of the stack.

- Operating Scenario C – Considers the on-well operation of the BOP relative to maintaining **all** BOP functions with the requirement that the well must be secured and the BOP stack pulled to the surface in order to perform corrective maintenance on all subsea system components. (Note: This scenario does not require securing of the well and pulling the BOP stack to perform corrective maintenance on surface BOP components). As with Operating Scenario B, this scenario models the regulatory requirement to perform corrective maintenance when a BOP failure is detected in order to help ensure all BOP well control functions. Specifically, this scenario models corrective maintenance based the unavailable time being based on (1) the average time to secure the well when subsea component fails and (2) the mean-time-to-repair for the failed surface components. (Note: Based on input from the industry participants, the average time to secure well was set at 96 hours.)

In each analysis case, the input mean time to failure values are obtained from the BSEE Data Analysis Report, supplemented with data from industrial data references (IEEE STD 497, OREDA 2009) where gaps existed.

Table 4-1: List of Analysis Cases

Analysis Case	Description
Base Case – All functions; IP Data	This configuration considers all BOP well control system capabilities, including annular, pipe rams, shear rams, auto shear and emergency disconnect systems and associated controls and choke and kill components.
Design Change 1 LMRP Annular & Pipe Rams Only; IP Data	This configuration considers BOP well control system capabilities, associated with annular, pipe rams, and their associated controls, and choke and kill components.
Design Change 2 – LMRP Annular Only; IP Data	This configuration considers BOP well control system capabilities associated with annular only and its associated controls and choke and kill components.
What If Case 1; Test Interval 4 weeks; IP Data	This What-If case evaluates the impact of increasing the inspections interval form 2 weeks to 4 weeks. The base-case BOP configuration is used for this What-If case.
What If Case 2; Improved Reliability of Select Components; IP data	This What-If case evaluates the impact of improving the reliability of more frequently failing BOP components, based on the data analysis results. Specifically, this What-If case includes reliability improvement of the (1) blue and yellow subsea control system, choke and kill valves and lines, MUX control system, pipe and test rams. The base-case BOP configuration is used for this What-If case.

5.0 CONCLUSIONS AND OBSERVATIONS

The simulation calculated two system availability figures of merit, one for the BOP system without PM and inspection activity (i.e., while in service "on well"). Since the BOP is a safety critical system the availability result without the PM and inspection is of interest.

Table 5-1 presents the BOP analysis cases and compares the estimated availability of the BOP system during the three operating scenarios.

Table 5-1: Comparison of BOP Availability Results Summary

BOP Analysis Cases	**Operating Scenario A**		**Operating Scenario B**		**Operating Scenario C**	
	Mean Availability for Drilling Operation Period (On Well) With At Least One Well Control Function Remaining to Control a Well Kick		Mean Availability for Drilling Operation Period (On Well) While Maintaining **All** BOP Well Control Functions Assuming CM Performed Without Pulling of the Stack		Mean Availability for drilling Operation Period (On Well) While Maintaining **All** BOP Well Control Functions Assuming Any Subsea CM Performed Requires Securing of the Well and Pulling of the Stack	
	BOP 1	**BOP 2**	**BOP 1**	**BOP 2**	**BOP 1**	**BOP 2**
Base Case: All Functions	.9991	.9991	.9902	.9875	.9835	.9843
Design Change 1 (LMRP Annular(s) & Pipe Rams Only)	.9946	.9943	.9881	.9875	.9882	.9869
Design Change 2 (LMRP Annular(s) Only)	.9937	.9928	.9876	.9873	.9878	.9867
What-If Case 1 (4 week test interval)	.9995	.9991	.9871	.9863	.984	.9822
What If Case 2 (Improved reliability of select components)	.9993	.9994	.9912	.9913	.99	.9882

The estimated availability of the BOP systems for Operating Scenario A ranges from 0.9928 to 0.9995. (Note: Results from Operating Scenario A represent the BOP availability to control a well kick by at least one well control function, which is a better measure of the BOP performance relative to overall safe operation.) For Operating Scenarios B and C, the estimated availability for the BOP systems ranges from 0.9863 to 0.9902 and from 0.9822 to 0.99, respectively. A comparison of the results of Operating Scenario A to the results of Operating Scenarios B and C indicate the expected outcome that the BOP availability for at least one well control function operating would be significantly higher (i.e., approximately one order of magnitude improvement) than the BOP availability for all well control functions.. In addition, the study indicates the availability for BOP 1 and BOP 2 systems are essentially the same for Operating Scenario A and are slightly different for Scenarios B and C. The differences in the results for Operating Scenarios B and C can be attributed to (1) the higher failure frequency of selected BOP 2 system components (relative to the BOP 1 system counterparts), (2) the additional subsystems/components associated with the second annular ring in the BOP 2 design, and (3) the associated corrective maintenance time to address these failures.

In addition to the above observations, the team made the following observations:

- While the BOP system is constructed with many subsystems that internally have multiple layers of redundancy, the BOP also has single component failure points in its design. These single failures are the dominant contributors to the estimated BOP probability of failure on demand. Based on these RAM results, the dominant contributors to the estimated BOP failure on demand probability are the two single failure points: LMRP connector failure, and Well Head Connector failure. Combined, these two component failures contribute over 99% to the estimated unavailability of the BOP system during "on well." In the calculations, these two components have an equal contribution to the estimated unavailability of the BOP system.

  (Note: These dominant contributors were identified based on the total failure rate data for these devices for all failure modes without any differentiation to unsafe and safe failure fraction of the respective failure modes.)

- To demonstrate the contribution of the component failures associated with non-shearing control measures (i.e., pipe rams and annulars), BOP system availability considering pipe rams and annular(s), and annular(s) only operating were evaluated (i.e., design changes 1 and 2). While these results indicate that the removal of the shear rams and pipe rams (design change 2 only) had little impact on the BOP system availability, this is because the remaining component failures, especially the two single point of failure items, have a more significant impact on the BOP system availability than the impact of the removed items on the system availability. However, readers are cautioned not to draw the conclusion that these results indicate the redundancy provided by the removed well control items are not important. The shear and pipe rams are considered important part of the BOP system and provide the required redundancy and essential functions for controlling the well.

- What-If Case 1 analyses indicate the system availability is not significantly changed by the extending of the test interval for all operating scenarios and with an average availability reduction of 0.2% for Operating Scenarios B and C. Specifically, no change in Operating Scenario A availability was expected since this scenario is based on allowing the BOP functionality to degrade until the BOP can't sufficiently function to control a kick (i.e., no inspection and test are performed). As for the Operating Scenarios B and C, the BOP availability is reduced for three of the four cases. (Note: The fourth case may indicate no change or drop in availability, but due to model rounding of the results it is not possible to determine the significance between the results, 0.9835 and 0.984.)

- What-If Case 2 analysis shows that improving the reliability performance of a few selected components in the BOP 1 and 2 systems caused a slight improvement in the estimated BOP availability in all three operating scenarios. The four components selected for improvement were identified in the BSEE Data Analysis Study (ref. 1) as less reliable BOP components. However, the BOP system design includes redundant features for these particular components and thus their failures were small contributors to the BOP system failure probability.

- Improving the reliability of, or gaining a better understanding of unsafe and safe failure fractions for, the single point of failure components and other components, which were the major contributors to the BOP estimated unavailability, should cause a significant improvement in BOP availability. Improvements might be achieved through better construction/quality assurance of these items, better item design, and/or reducing detection/repair time of the items.

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APPENDIX A – LIST OF REFERENCES

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This appendix provides a list of relevant industry data sources used during the RAM analysis.

1. BSEE Data Analysis, BOP Failure Event and Maintenance, Inspection and Test (MIT) Data Analysis for BSEE (project related analysis), ABS Consulting Inc., 2013.
2. IEEE Std 493™, Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems, Institute of Electrical and Electronics Engineering, Inc., 2007.
3. OREDA 2009, Offshore Reliability Data 5th Edition, Volume 1 &2, SINTEF, 2009.
4. SINTEF Report 2012, Reliability of Deepwater Subsea BOP Systems and Well Kicks, SINTEF, 2012.

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APPENDIX B – LIST OF DRAWINGS

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This appendix provides a list of drawings used during the RAM analysis.

Drawings related to BOP 1:
S/D, SCOPE OF SUPPLY
S/D, HYDRAULIC, LMRP
S/D, HYDRAULIC, STACK
S/D, HYDRAULIC, MUX POD
S/D, BLOCK DIAGRAM HYDRAULIC INTERCONNECT
S/D, HYDRAULIC POWER UNIT
S/D, FAMILY OF FUNCTIONS
S/D, SYSTEM CABLING BLOCK DIAGRAM

Drawings related to BOP 2:
SYSTEM BLOCK DIAGRAM
SCHEMATIC BOP STACK
SCHEMATIC MUX POD
SCHEMATIC ACOUSTIC POD
SCHEMATIC HYDRAULIC/PNEUMATIC, HYDRAULIC POWER UNIT

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APPENDIX C – RELIABILITY BLOCK DIAGRAM

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BOP 1, BASE CASE – ALL FUNCTIONS RELIABILITY BLOCK DIAGRAM

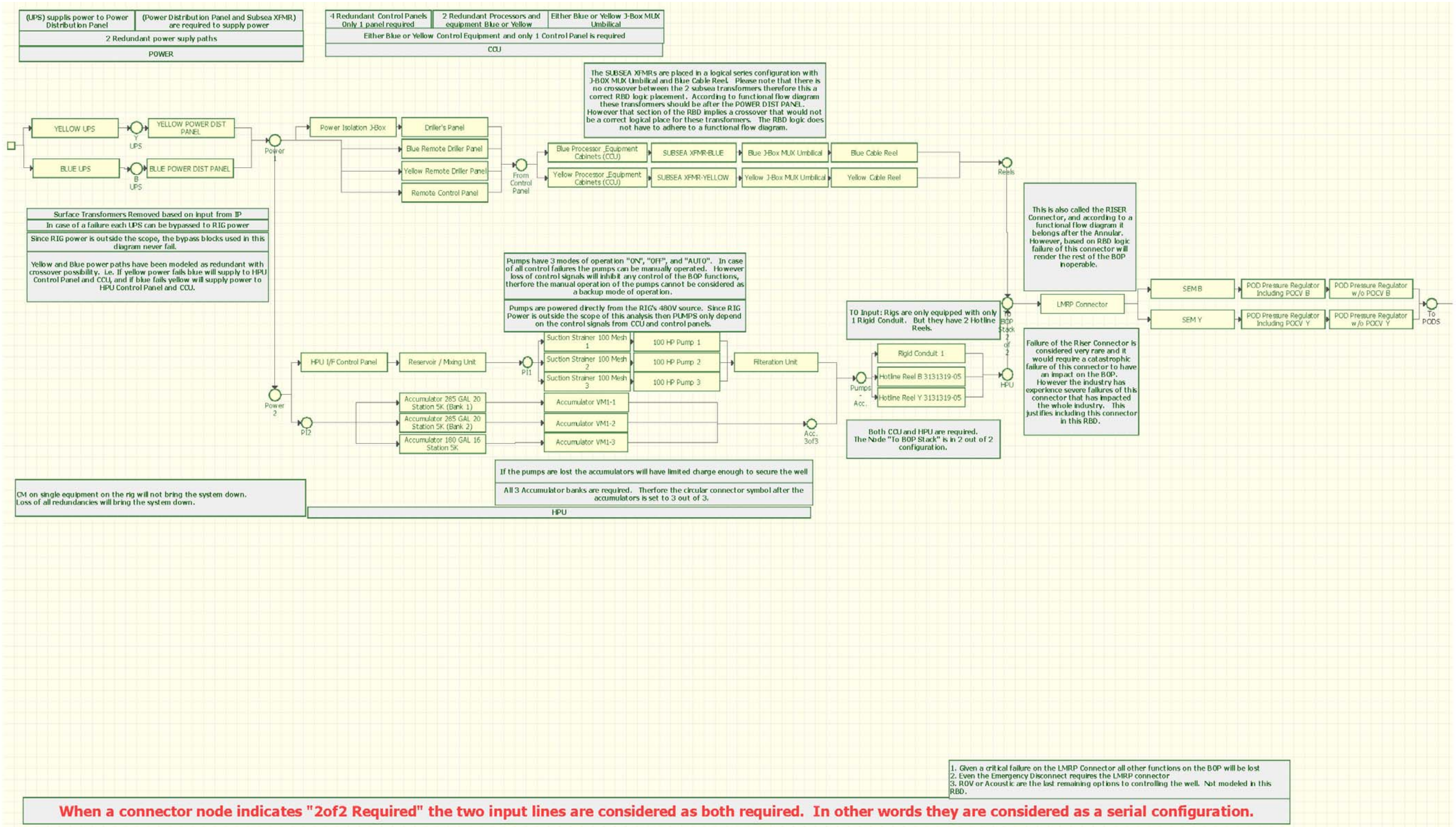

Figure C-1 BOP 1, All Functions Reliability Block Diagram (1 of 3)

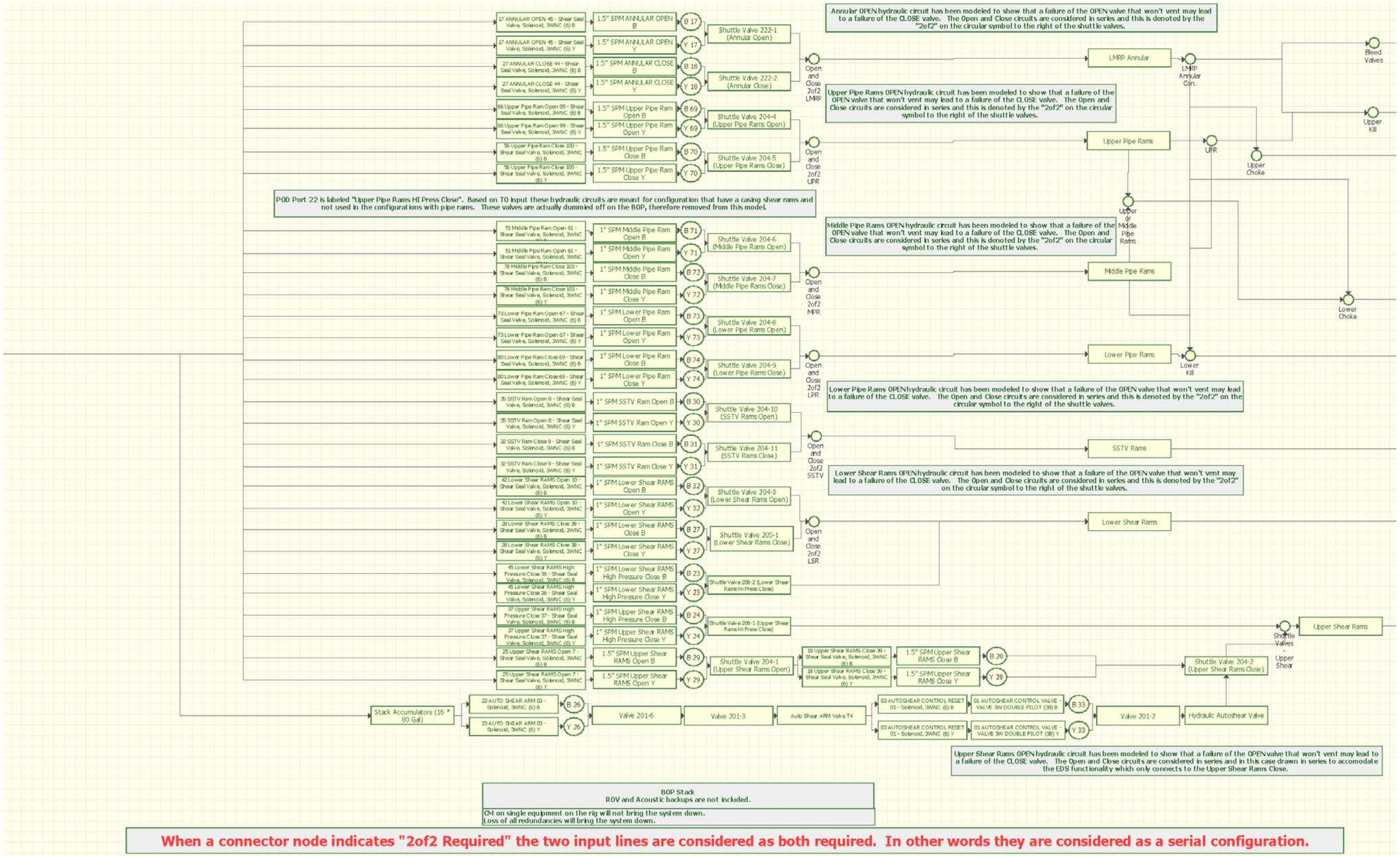

Figure C-1 BOP 1, All Functions Reliability Block Diagram (2 of 3)

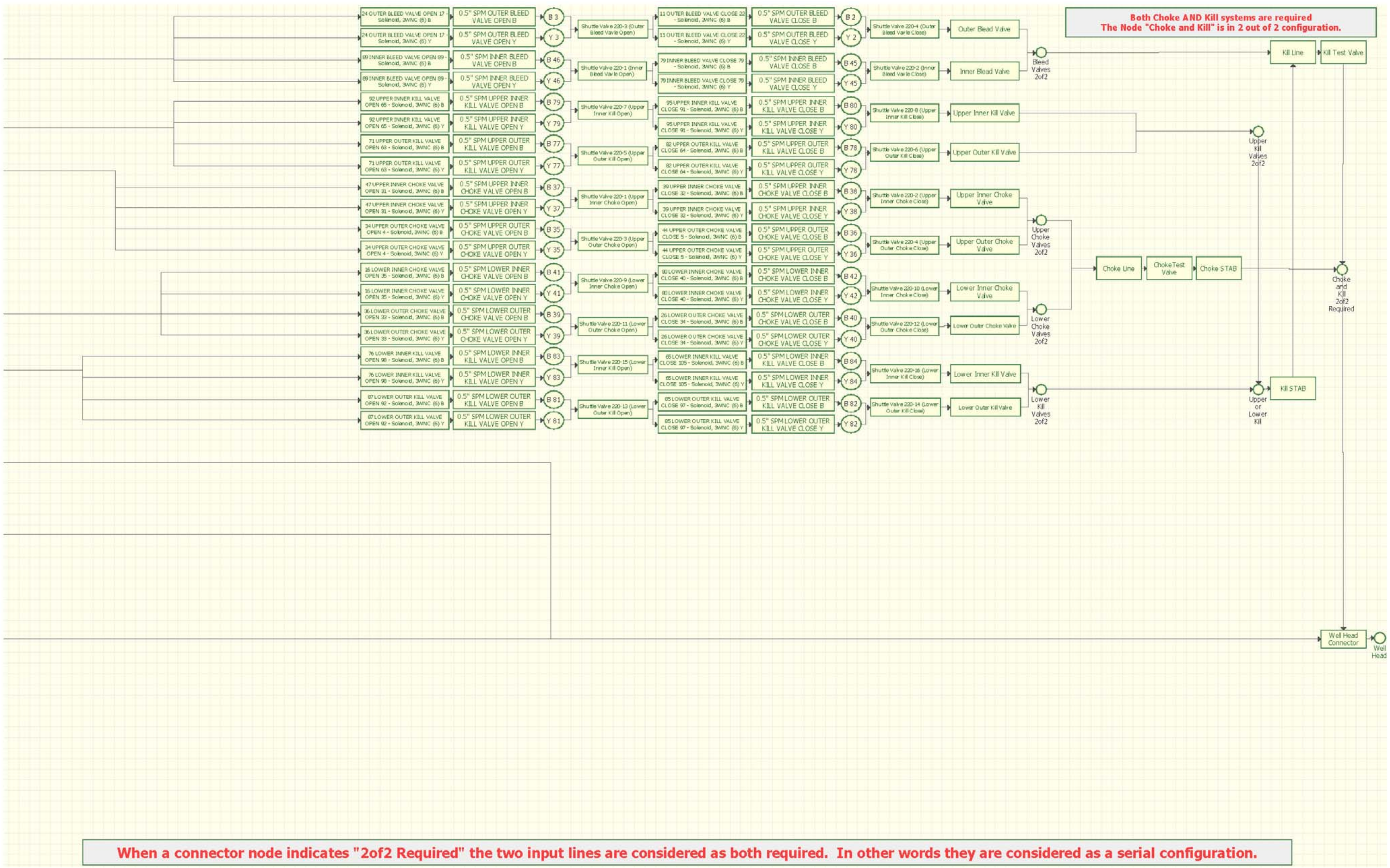

Figure C-1 BOP 1, All Functions Reliability Block Diagram (3 of 3)

BOP 2, BASE CASE – All FUNCTIONS RELIABILITY BLOCK DIAGRAM

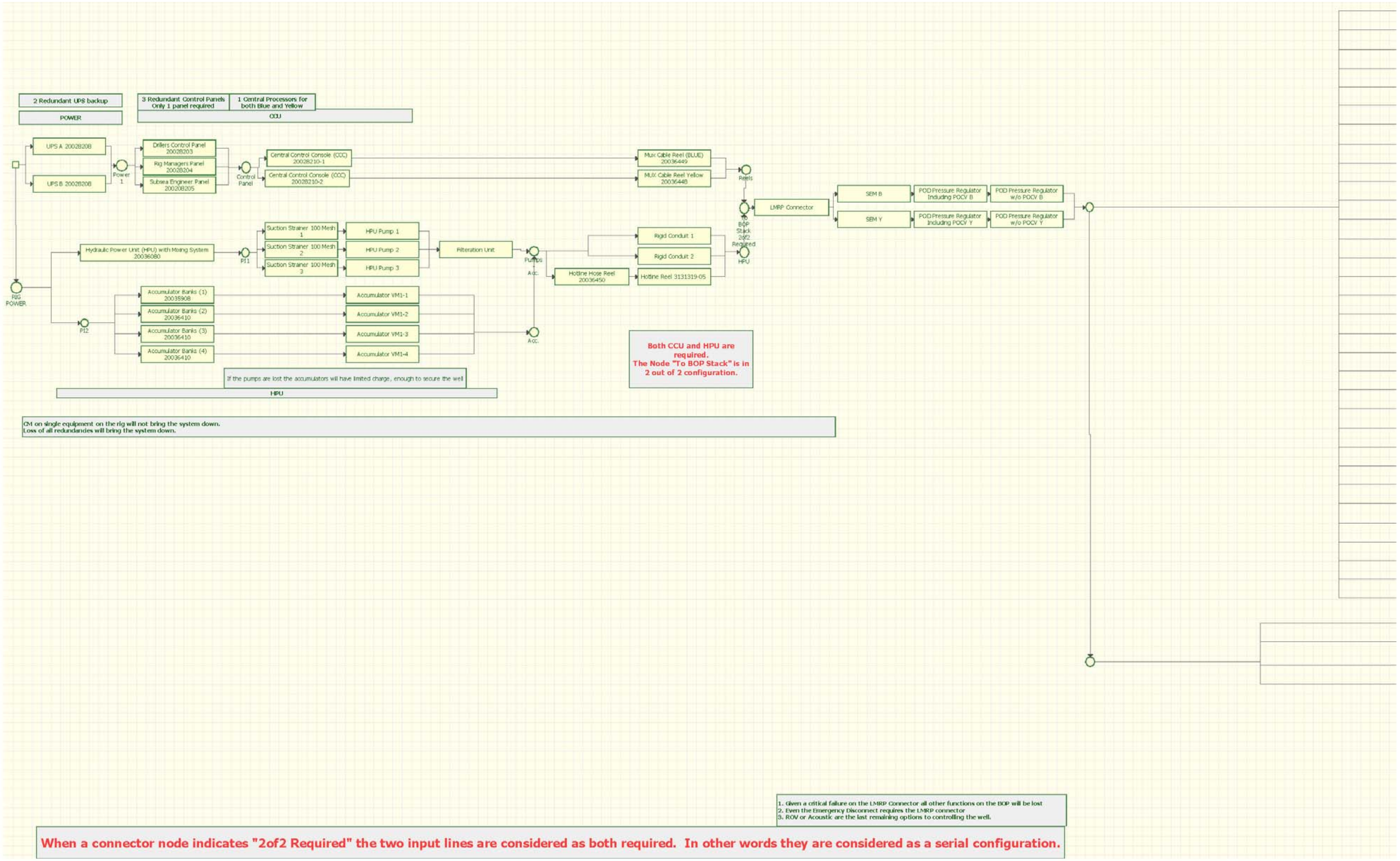

Figure C-2 BOP 2, All Functions Reliability Block Diagram (1 of 3)

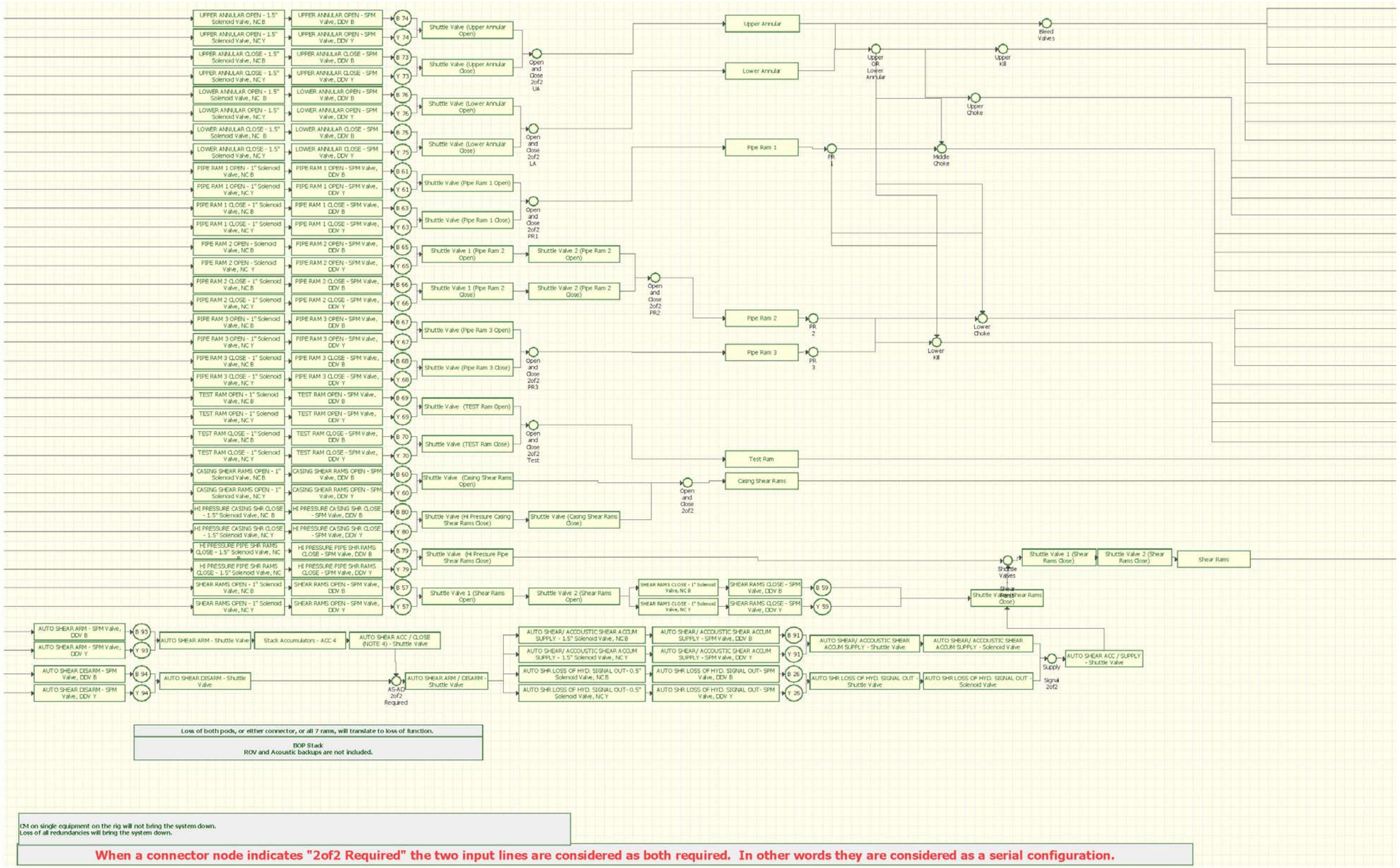

Figure C-2 BOP 2, All Functions Reliability Block Diagram (2 of 3)

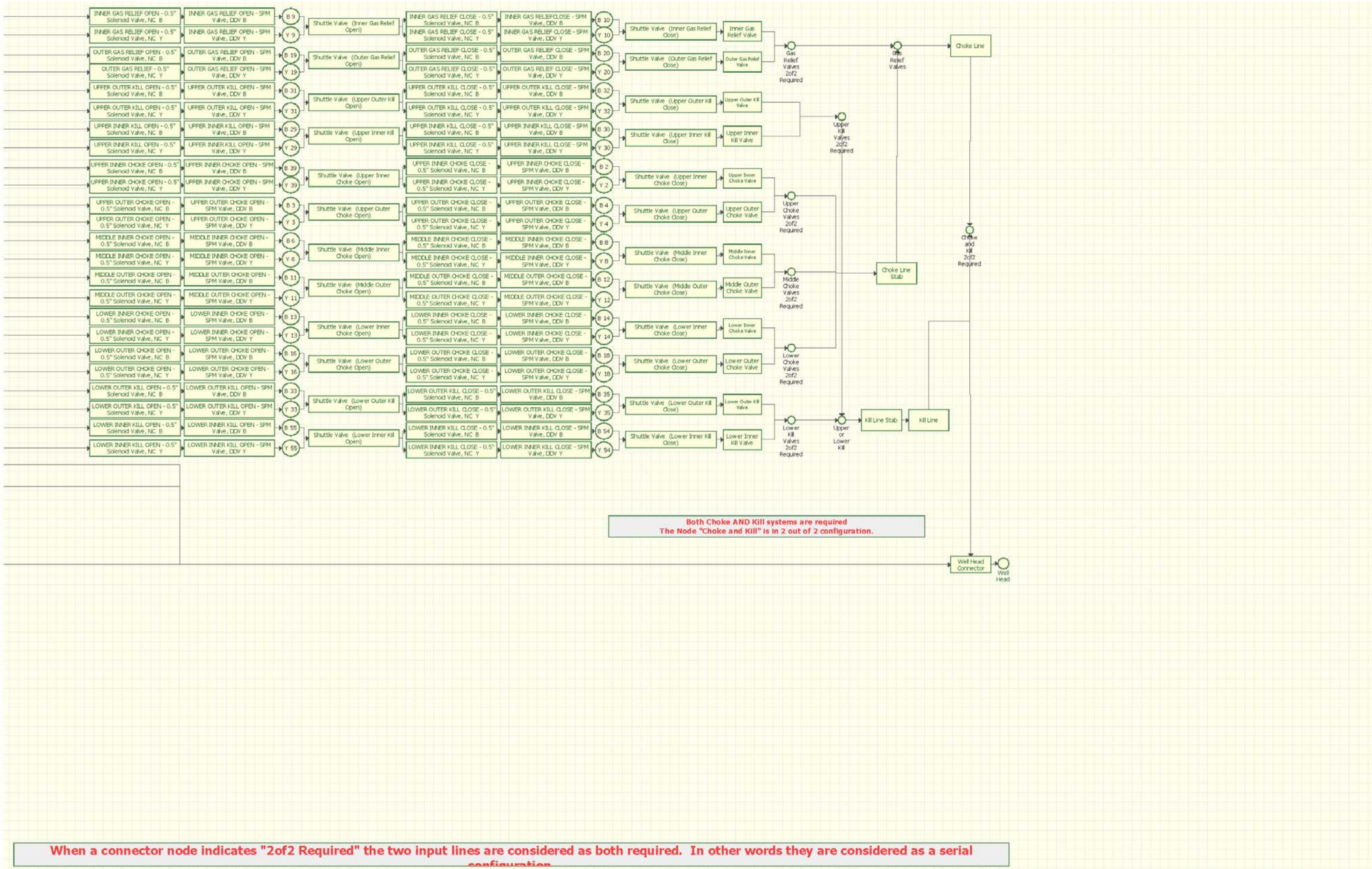

Figure C-2 BOP 2, All Functions Reliability Block Diagram (3 of 3)