Deepwater Horizon RBS 8D BOP MUX Control System Report

To the U. S. Chemical Safety and Hazard Investigation Board

<u>CSB-FINAL REPORT-MUX(06-02-2014)</u>

The Deepwater Horizon BOP stack at NASA-Michoud (with the upper LMRP portion on left)

This analysis considered the BOP examinations that were conducted by Det Norske Veritas (DNV) at the NASA Michoud facility near New Orleans, Louisiana. The examinations were in two phases, the first conducted for the Joint Investigation Team and a Phase 2 funded by BP. CSB and Engineering Services were excluded from Phase 2, but subsequently obtained examination information from that period.

MUX Control System Investigation Index

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1 Executive Summary

The control system for the Deepwater Horizon blowout preventer (BOP) supported manual functioning of the BOP for normal drilling operations as well as automatic and manually-initiated emergency functions to seal the well. The completely automatic emergency shut-in functions were the AMF/deadman and autoshear. The Emergency Disconnect System (EDS) was a manual shutdown system, requiring human initiation. Each of these emergency shut-in systems were designed to activate an emergency closure of the BOP by using high pressure hydraulic fluid to close the BOP blind shear ram (BSR), a device intended to shear drill pipe passing through the BOP and then shut in the well, stopping any further flow of fluids from leaving the well. At various instances during and following the blowout of the Macondo well on April 20, 2010, each of these systems were called upon to seal the well.[1]

The main focus of this control system investigation has been on whether and when the AMF/deadman activated. The control systems were reviewed from the subsystem down to a component level, where sufficient evidence and testing were available for evaluation.

A Joint Investigation Team (JIT) was formed by the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) and the United States Coast Guard (USCG). BOEMRE contracted Det Norske Veritas (DNV) to conduct a *Forensic Examination* of the BOP, which had been recovered and brought to a USCG base at the NASA Michoud Booster Assembly facility, near New Orleans, Louisiana. The objectives of conducting tests on the recovered BOP included determining the "performance of the BOP system during the well control event, any failures that may have occurred, and the sequence of events leading to failure(s) of the BOP."[2]

After a testing plan was approved by the participants,[3] the physical testing started November 15, 2010 at the NASA Michoud Booster Assembly Facility, outside of New Orleans. The site work, which was later referred to as Phase 1 BOP testing, was declared over by DNV and BOEMRE representatives on March 4, 2011.

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[1] Engineering Services supports the finding determined by BP and others that when the EDS was manually initiated from the Deepwater Horizon, communication with the BOP had already been lost due to the explosions and fire on the rig. As a result, the EDS could not activate the BSR. The autoshear function was activated 33 hours after the explosions using a remotely operated vehicle at the BOP, but flow from the well was not stopped. See Engineering Services separate report, *Deepwater Horizon Blowout Preventer Failure Analysis*, for further discussing and documentation.

[2] Bureau of Ocean Energy Management Regulation and Enforcement (BOEMRE), March 11, 2011. Forensic Examination of Deepwater Horizon Blowout Preventer, Report No. EP030842 (hereinafter "DNV Report"), http://www.uscg.mil/hq/cg5/cg545/dw/exhib/DNV%20Report%20EP030842%20for%20BOEMRE%20Volume%20I.pdf. Accessed March 12, 2012, and *Addenda*, May 2, 2011, page 1.

[3] Five other parties were organized along with the U.S. Chemical Safety Board (CSB) into a Technical Working Group (TWG): BP, Transocean, Cameron, U.S. Department of Justice, and the Multi-District Litigation group (MDL). The TWG served to review and approve protocols and to approve/disapprove any deviations in the test procedures as the need arose. The TWG members had a closer level of access than other party representatives in witnessing the actual testing. In addition, USCG, FBI, NASA, and EPA had various responsibilities at the test site. CSB contracted Engineering Services LP (ES) to assist in the BOP examination and analysis. An ES engineer usually served as the CSB TWG representative, although CSB staff also served in this role at times.

There was a Phase 2 of the BOP examination that excluded CSB and ES, but Phase 2 documents, photos, and videos were subsequently made available and considered in this report. During Phase 2 additional tests were conducted and some components further disassembled. While much of the test results used for the analysis presented in this report were developed in concert with other investigatory entities, new key findings presented here are also the result of independent Chemical Safety Board (CSB)-initiated testing.

Specifically, the analysis in this report aims to answer the following questions:

1. Were the AMF/deadman emergency shut-in system components in place and operable?
2. For any failed AMF/deadman subsystems and components, were the pre-accident testing procedures capable of revealing the failed components, and were those procedures utilized?
3. What lessons learned can be developed to minimize the effect of any control component failures in the future?

1.1 Key Findings

1. *The BOP emergency shut-in systems were not fully operable prior to the incident. Despite failures to multiple redundant systems, the AMF/deadman activated when communications, electric power and hydraulic power were severed between the Deepwater Horizon and the BOP immediately following the explosions and fire on the rig.*

    a. *Internal SEM miswiring drained the blue control pod 27 volt battery pack, preventing the blue control pod from activating the emergency AMF/deadman sequence.* Wiring nonconformances were discovered at Michoud during Phase 2 testing.[4] This miswiring caused premature connection of the emergency 27 volt battery to two AMF/deadman pressure transducers, which were already powered by the SEM 24vdc power supply. The premature connection drained the 27 volt batteries, preventing the emergency AMF/deadman sequence from activating the blind shear ram from the blue control pod. Phase 2 testing further confirmed that the 9 volt battery packs in the blue pod were not drained as asserted in other theories for the failure of the blue pod.[5]

    b. *The batteries for the blue control pod were used beyond their recommended useful life, but the blue pod 27 volt battery pack failed prematurely due to miswiring in the SEM A signal wiring*. The date codes on the batteries of the control pod in the blue position on the BOP suggest they were manufactured in 2005 and 2006.[6] The Transocean Report implied that the batteries for the pod in the blue position were

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[4] Phase 2 Test Preparation Sheet, DNV2011061904: BOP-033.

[5] This finding is contrary to the *Transocean Report*, which suggested that the 27 volt battery failed after successfully carrying out the AMF/deadman sequence. *Transocean Report*: *Macondo Well Incident – Transocean Investigation Report*, June 2011, page 31 and Appendix N, page 27.

[6] Phase 2 Test Preparation Sheets, DNV2011061602:BOP-028 and DNV20110603:BOP-027.

newly installed in 2009.[7] However, testimony indicates pod #3 (typically referred to as the white or 'spare' pod) was in the blue position at the time of the incident.[8] The batteries for pod 3 were last replaced in November of 2007,[9] a date which is consistent with the battery manufacturer's date codes observed during post-incident inspection. Pod 3 had been installed on the BOP stack in December 2008.[10] Cameron recommends replacing the batteries after one year of on-time operation, or 33 actuations, or within five years of shelf life,[11] therefore the batteries in pod 3 were beyond the manufacturer's recommended life. However, the ultimate failure was found in the seldom-used 27 volt battery instead of the 9 volt batteries which should have sustained the more significant depletion during the multiple drilling cycles during which the 9 volt batteries would provide 24/7 power to the AMF/deadman card. The fact that these batteries still proved viable in Phase 2 testing implies that the recommended operational limits of the 9 volt battery's actual life cycle were not exceeded. Under normal circumstances, we would also not expect the 27 volt battery to reach its end of life before the 9 volt battery packs. The specific cause and effect of the unexpected depletion of the 27 volt battery pack, the miswiring in the SEM, is discussed in detail later in this report.

c. *The yellow pod contained two solenoid valves which were miswired such that reverse polarity existed on one coil of the dual-coil solenoids*. One of these solenoid valves, SV 103Y (Y = yellow pod), was intended to activate the high pressure (HP) close function of the BSR, an essential part of the yellow pod AMF/deadman sequence. However, a serendipitous failure of the yellow pod SEM B 9 volt battery allowed the solenoid valve to function on just the SEM A coil, and thus it successfully actuated the blind shear ram during execution of the AMF/deadman sequence immediately following the explosions and fires on April 20, 2010. If the SEM B battery had not failed, the opposite polarity of the two coils in SV 103Y most likely would have prevented the AMF/deadman operation of the blind shear ram from working as designed.

   Yellow pod solenoid valve 3A was also miswired in the same manner. When the associated control panel push button is pressed, this valve passes hydraulic fluid used to increase the closing pressure on

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[7] Transocean, *Macondo Well Incident: Transocean Investigation Report Volume II* (hereinafter "Transocean Report"), June 2011, https://www.deepwater.com/_filelib/FileCabinet/pdfs/12_TRANSOCEAN_Vol_2.pdf, Appendix N, pg. 4., accessed 12/9/2013.

[8] Testimony given in the U.S. District Court for the Eastern District of Louisiana under the Multi-District Litigation docket MDL No. 2179 was conflicting, see McWhorter Designations Vol 1, p, 78-79 where he describes that pod #3 was in the blue stack and pod #2 was in the yellow stack at the time of the incident. Also refer to Exhibit #3792, publicly accessible at http://www.mdl2179trialdocs.com/releases/release201302281700004/McWhorter_Jim-Depo_Bundle.zip. In Hay Designations Vol 1, p, 74, he states that pod #1 was in the blue stack and that pod #3 was the spare pod, publicly accessible at http://www.mdl2179trialdocs.com/releases/release201302281700004/Hay_Mark-Depo_Bundle.zip.

[9] Exhibit #3792,Feburary 24, 2010 Email, Subject: Batteries [TRN-MDL-00310821], publicly accessible at http://www.mdl2179trialdocs.com/releases/release201302281700004/McWhorter_Jim-Depo_Bundle.zip; Transocean subsea work book [TRN-INV-02932167].

[10] DAR Consolidation Report, entry, December 29, 2008 indicates the 'blue pod' was changed out [TRN-INV-03259688]; Cameron Daily Report Sheet December 29, 2008 notes "[…] OIM decided that they need to put the old POD back on the stack and go with it for now because the SEM that came from Cameron has a possible problem with a modem so they changed the POD […]" [CAM-CSB 000007498]; and Subsea work book indicates SEM # 1 was overhauled in April 2009 [TRN-INV-0293227] which could only happen it if was not installed on the BOP.

[11] Cameron Engineering Bulletin EB 891 D, *AMF/Deadman Battery* Replacement, September 2004.

the BOP upper annular preventer. ES does not have any evidence that the miswired SV 3A prevented setting of the upper annular regulator pressure set point during normal operations. Testing of an exemplar solenoid valve suggests that rig operators could possibly have succeeded in using the miswired 3A by persistently pressing the associated control system push button rather than just holding it down. Post-incident testing of the yellow pod at the surface reported that operation of the 3A solenoid was "sluggish," and took a "long time to fire."[12]

2. *Pre-accident testing procedures using the rig-based BOP control system were not capable of revealing all of the failed components of the BOP emergency shut-in system.*

   a. *The design of the BOP control system did not allow independent functional testing of its redundant AMF/deadman subsystems either while the BOP was on the rig or while it was in subsea service*. There were four separate emergency subsystems which could activate the AMF/deadman; there were two control pods, each with its own 27 volt battery pack, and each of these two pods had two independent subsea electronics modules (SEMs), each with its own programmable logic controller (PLC), AMF/deadman card and 9 volt battery pack. However, the four subsystems could not be independently tested using the BOP control system. Without independent functional testing for each of these four subsystems, latent failures which disable as many as three of these redundant systems could still result in a successful overall AMF/deadman test result. A successful test even with no working redundant backups would fail to reveal that the reliability of the AMF/deadman emergency safety was severely compromised.

3. *Other items relating to the control system.*

   a. *The emergency AMF/deadman system was not tested either before deployment to the wellhead nor while the BOP was in service subsea*. ES found no evidence in the form of deck test function results or testimony to suggest that testing of critical AMF/deadman system components (e.g., electronics, batteries and high pressure shear circuits) was performed prior to deploying the BOP at Macondo. The control system had no capability for reporting the condition of the batteries after being deployed subsea.

   b. *Regular subsea testing of the blind shear ram did not include the high pressure emergency circuit that included the miswired solenoid SV 103Y.* The blind shear ram was function tested regularly (closed and reopened) while the BOP was in service. This function test can be done with either a low-pressure (1,500 psig) manifold regulator circuit used for normal drilling operations, or with a high-pressure circuit (4,000 psig) that is shared with the AMF/deadman. These two hydraulic circuits are

[12] Handwritten note by Cameron representative on Deck Test Procedure for Mark-II Control Pod, for solenoid (3A), "sluggish—activate & takes a long time to fire, skips." [BP-HZN-BLY00060717].

independent, using different electronic controls and solenoids. The high-pressure AMF/deadman circuit containing the miswired SV 103Y solenoid was not tested.[13]

1.2 BOP Control System Architecture

The BOP control system (Figure 1) included multiple rig-mounted control panels and two subsea control pods (designated as blue and yellow), containing control computers sealed in subsea electronics modules (SEMs).[14] Data was sent between the rig and the control pods via multiplexed (MUX) communication, a method which is capable of sending multiple simultaneous signals over a single communications cable. In this case, modems transmitted and received commands and inputs to and from the subsea BOP on copper wire MUX cables. The cables were supported by attachment to the drilling riser, the connection pipe between the rig and the BOP through which the drill pipe, drilling tools and drilling fluid were passed. Electrical power for the MUX system was provided from the surface to the pods by the Deepwater Horizon's normal power system and its battery-based backup power system, called the uninterruptible power supply (UPS). Hydraulic power was used for normal operation of the BOP functions, and this was also provided from the rig via hydraulic lines.

The subsea control system included redundancy. The complete subsea BOP control system contained the blue pod and the yellow pod, both attached to the lower marine riser package (LMRP).[15] Each pod had its own 27 volt battery for emergency power supply independent of surface-supplied power. Each control pod also had two redundant SEM computer systems (SEM A & SEM B), each with a dedicated AMF/deadman CPU card powered by a dedicated 9 volt battery.

[13] API RP 53, 3rd Ed., the MMS-referenced standard, states "All operational components of the BOP equipment systems should be functioned at least once a week to verify the component's intended operations." The definition of component is commonly interpreted to be the various preventers (e.g., upper annular, blind shear ram). Thus, a test using the LP BSR would be in compliance in the API recommendation and MMS requirements.

[14] RBS8D Multiplex BOP Control System – Volumes 1-8, CAM-CSB 000004070.

[15] For a description of the BOP stack components, see Appendix B of the separate Engineering Services report *Deepwater Horizon Blowout Preventer Failure Analysis*.

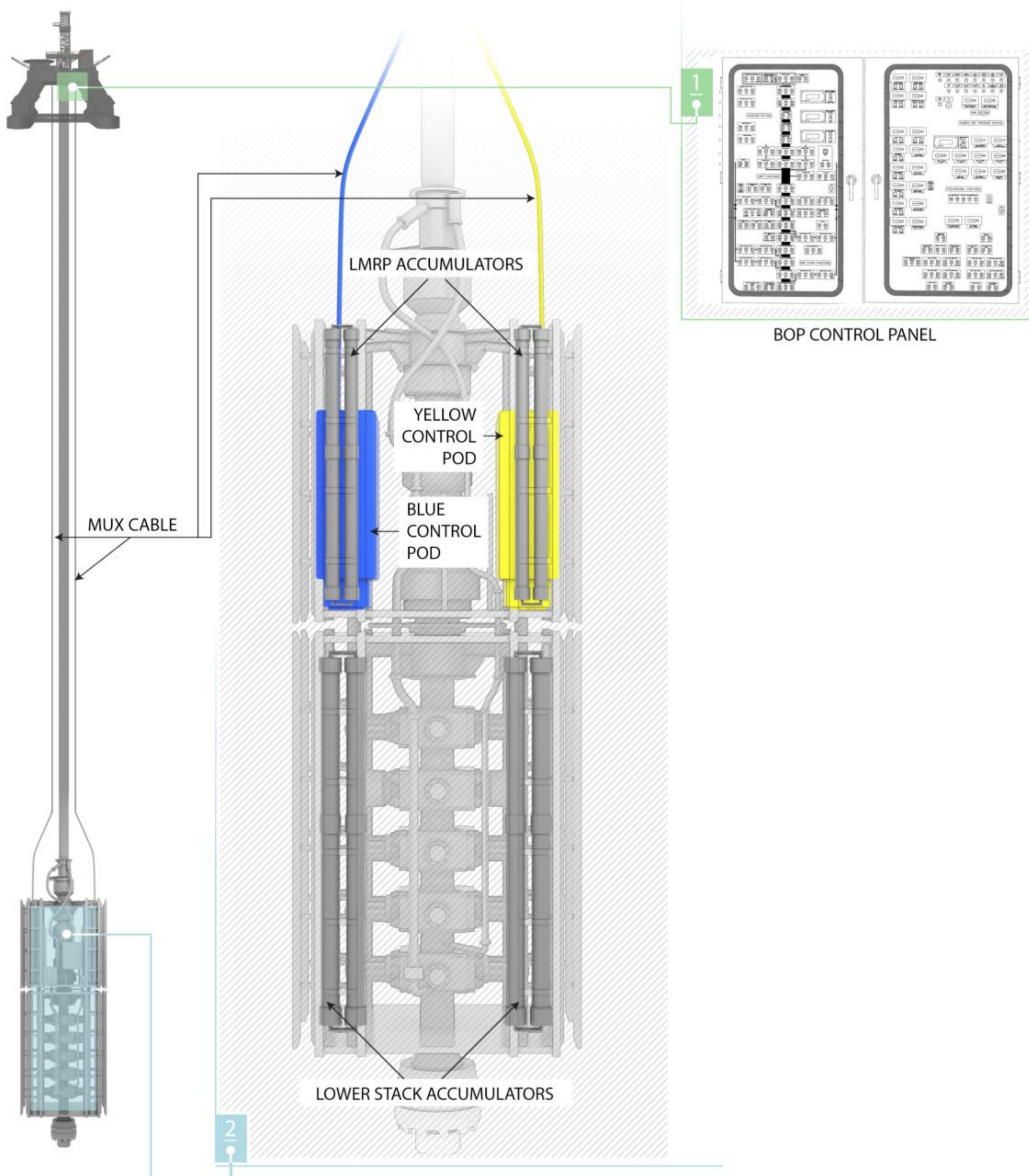

Figure 1. The BOP control system included multiple rig-mounted control panels and two subsea control pods (designated as blue and yellow). Data was sent between the rig and the control pods via multiplexed (MUX) communication cables supported by attachment to the drilling riser. During normal operations, electrical and hydraulic power for the MUX system was provided from the rig, but during emergency situations could be provided from subsea batteries contained in the yellow and blue pods and hydraulic reservoirs called accumulators.

The Emergency Disconnect System (EDS) was one of the BOP emergency systems. The EDS required human initiation. It was designed to activate the high pressure blind shear ram (HP BSR) close circuit, shearing drillpipe in the BOP and sealing in the well. It would then disconnect the LMRP, the top portion of the BOP located above the BSR and other rams and preventers. The Deepwater Horizon could then leave the area with the riser and LMRP hanging below the rig. A typical scenario that might have necessitated the use of EDS would be if the Deepwater Horizon had begun to drift off station and outside an allowable operating distance. Increasing offset could have pulled the riser apart, and/or potentially bent the wellhead. The crew could have activated the EDS while still within safe limits, sealing the well and disconnecting the riser before excessive loads developed.

The Automatic Mode Function, or Deadman, emergency shut-in system (AMF/deadman) was designed to close the HP BSR without human intervention and without electrical or hydraulic power from the rig by using subsea batteries and hydraulic reservoirs called accumulators. The AMF/deadman should activate on the simultaneous loss of electrical power, communications, and hydraulic pressure from the rig to the BOP. Both the blue and yellow pods should respond in parallel to provide the logic and battery power for initiating a sequence of solenoids intended to hydraulically close the HP BSR and some other connected functions. A typical scenario might be the accidental severing of the riser, examples being over-tension from excessive vessel offset (telescoping joint becoming fully extended), connector fatigue/corrosion damage, or a severe explosion and fire such as what occurred on the Deepwater Horizon.

The autoshear emergency shut-in system could also activate the HP BSR close function. When armed, this system was designed to function upon an unintended separation of the LMRP from the lower portion of the BOP, e.g., an accidental disconnect due to human error or controls malfunction.

1.3 AMF/deadman Activated in Response to Incident

The ES analysis concludes that when utilities and communication were lost between the Deepwater Horizon and the BOP during the incident on April 20, 2010, neither the blue or yellow pod executed a normal AMF/deadman sequence. However, through a combination of redundancy and serendipity, the AMF/deadman did activate.

The blue pod failed to execute the AMF/deadman upon loss of surface utilities and communication from the Deepwater Horizon because of an aging drained 27 volt battery which was further aggravated by SEM internal wiring deficiencies. The 27 volt battery in the blue pod failed to energize the programmed sequence of solenoids, including the HP blind shear ram close solenoid (SV 103 – blue) because the voltage on the battery pack was too low.[16]

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[16]BP Deepwater Horizon accident investigation report, September 8, 2010, p. 154 (hereinafter "BP Report"), http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cts=1331666404195&ved=0CCkQFjAA&url=http%3A%2F%2Fwww.bp.com%2Fliveassets%2Fbp_internet%2Fglobalbp%2Fglobalbp_uk_english%2Fincident_response%2FSTAGING%2Flocal_assets%2Fdownloads_pdfs%2FDeepwater_Horizon_Accident_Investigation_Report.pdf&ei=x55fT7qYJunIsQKFqPSMCA&usg=AFQjCNE4cEa7fTYS0DYjDfGY60zekb6cqw. Accessed March 12, 2012;
DNV Report, p. 60, Accessed August 14, 2013.

The redundant yellow pod also had an unknown condition which might have caused the yellow pod to fail. Its safety-critical HP blind shear ram close solenoid (SV #103 Y) was miswired. The pod solenoids each have two redundant coils (A and B), each independently energized by one of the two redundant SEMs in the pod. Normally, the 2-coil solenoid can be successfully energized by either SEM A or SEM B or by both. But in the case where one coil is miswired, the reverse polarity of that coil will fight the forward polarity of the other coil when energized at the same time. Simultaneously energizing opposing coils will cause the solenoid not to actuate. In the AMF/deadman scenario, this miswiring of the SV 103 Y means if both SEMs worked as designed, the blind shear ram would not be closed by the yellow pod. As it turned out, the SEM B 9 volt battery had been prematurely drained due to some unknown external condition or internal battery defect. It did not even have enough capacity to complete the first step of the AMF/deadman sequence, that of rebooting the SEM B PLC. ES concludes that the premature failure of the SEM B 9 volt battery allowed only the SEM A coil to energize and thus SV 103Y successfully actuated attempting to seal the well. However, at the time of actuation, off-center drill pipe in the BOP prevented the BSR from closing and sealing the well.[17]

1.4 Miswired Solenoid Testing

AMF/deadman system testing and solenoid component tests accomplished during Phase 1 testing provided inconsistent results. ES discusses the test results in this report. Part of the ES research to clear up the Michoud test results includes CSB-sponsored testing of an exemplar solenoid valve (SV) to determine the effect of having one coil reverse-wired. We determined that a miswired solenoid should work satisfactorily when only one coil is energized at a time. When both coils are energized simultaneously, neither coil succeeds in actuating the valve as designed.

When a SEM actuates a solenoid, it does not send a simple constant voltage DC electrical signal. Instead, it uses a 30-second long complex signal called a pulse-width-modulated (PWM) DC voltage.[18] The response of energizing forward-wired and reverse-wired solenoid coils with the type of PWM signal used by the SEMs is difficult to predict. Differences in timing between activating the signals of less than a second could make a difference. Using an exemplar solenoid, ES designed testing to determine whether a non-simultaneous or out-of-sync energizing by SEM A and SEM B could actuate the solenoid valve. Pulse-width-modulated (PWM) DC voltages were programmed similarly to the pulse sequences used in the SEMs. Our testing reveals that the valve could actuate in brief, intermittent pulses if the 103 solenoid valve was energized for 30 seconds with SEM A and SEM B PWM cycles out-of-sync by more than 250 milliseconds.[19] ES, therefore, hypothesized two possible scenarios for the AMF/deadman sequence concerning the yellow pod during the incident, both relating to the critical health of the SEM B 9 volt battery.

Scenario 1 for yellow pod AMF/deadman—assuming both yellow pod SEM A & B 9 volt battery packs are viable—SEM A and SEM B are out of sync by more than 250 milliseconds.

[17] See separate Engineering Services report, *Deepwater Horizon Blowout Preventer Failure Analysis* for off-center drill pipe discussion.

[18] Phase 2 Test Preparation Sheet, DNV2011060643: BOP-015-2, PETU Solenoid Drive Characterization testing, p. 4-5.

[19] See Appendix F: CSB Exemplar Solenoid Testing in this report

After loss of surface power and communications, the SV 103Y possibly could have been moved enough to transmit a series of hydraulic pulses during the 30 seconds that 103 would have been energized. But those pulses would have been of limited duration. SV 103Y passes hydraulic fluid at pilot pressure (3,000 psi) to actuate the HP shear valve, which, in turn, provides hydraulic fluid at high pressure (4,000 psi) to close the BSR. We did not simulate or otherwise evaluate the high-pressure circuit to the BSR pistons; therefore, we cannot reach a conclusion about the extent to which SV 103 pulses would have provided useful shearing in the HP circuit. It is not possible to quantify from our test how much hydraulic pressure and fluid volume would have been available to act on the blind shear rams. However, even in this scenario, we believe some useful work would have been produced to compress or dent the drill pipe.[20] Of the two, we conclude that this is not the more probable scenario unless it were shown that the Yellow pod SEM B battery had not failed under subsea conditions at the time of the incident.

Scenario 2 for Yellow Pod AMF/deadman—Assuming SEM B 9 volt Battery Pack Was Prematurely Drained

This scenario is based on the SEM B battery pack in the yellow pod being in a drained condition at the time of the AMF/deadman actuation. As a result, the yellow pod initiated the AMF/deadman sequence only on SEM A. With only one coil of the miswired SV 103Y being fired, the solenoid actuated correctly and attempted to close the blind shear rams. The yellow pod AMF/deadman tests during Phase 1 testing occurred at ambient temperatures was near 21ºC. Subsea temperatures would have been closer to 2ºC. While SEM internal temperatures would have been higher than 2ºC, the cooler subsea environment would have decreased the ability of the 9 volt battery to power the SEM. In addition, when compared to the SEM A 9 volt battery, the SEM B battery was in a defective condition totally unrelated to normal electrical loads imposed. When applying non-linear capacity re-rating factors for subsea thermal conditions and battery resting recovery and then comparing the Michoud results to those non-linear conditions, ES concludes that the defective 9 volt battery would not have successfully powered the SEM B PLC through the AMF/deadman sequence at the time of the incident, and that the sequence was completed successfully by the SEM A PLC alone. Of the two, we conclude that this scenario is more probable. (See Appendix Sections C1.2 and C1.3 for additional details of the failing battery capacity.)

A third possibility is that the 9v SEM B battery had enough power sub-sea to complete the SEM B AMF/deadman sequence. ES considered this possibility. Given that possibility, Scenario 1 then becomes the more likely. However, the fact remains that the SEM B 9 volt battery dramatically failed all battery load testing at Michoud by quickly drawing down the battery voltage. Our research on the 5 volt Linear Technology regulator on the AMF card revealed that it required approximately 6.0 volts from the AMF 9v battery to carry the load for the SEM PLC. This factor in combination with the thermal and resting recovery factors mentioned above, led us to assign a low probability to the viability of this battery. In any case, we believe that the evidence has shown that some useful hydraulic pressure to the blind shear rams acted on the off-center drill pipe.

[20] For additional discussion of the initial hydrostatic/wellbore differential pressure acting to close the Blind Shear Rams, see Engineering Services' BOP Failure Analysis Report, Section 11.

2 Definitions and Acronyms

Automatic Mode Function (AMF/deadman) – A pre-programmed emergency shut-in mode for closing the blind shear ram in the BOP using batteries for control power and high-pressure hydraulic energy stored in accumulators on the BOP stack. The term 'deadman' implies that this sequence is initiated without human intervention when all other electrical power, data communications and hydraulic pressure from the rig have been lost.

AMF/deadman Shutdown Sequence Definition File – An ASCII file with a programmed sequence and timing executed by the PLC in the SEM when triggered by the AMF/deadman printed circuit board's CPU.

Autoshear – A mechanical spring-loaded pin tied to a pilot valve that actuates a low-pressure hydraulic signal when the LMRP accidentally separates from the BOP. The low-pressure hydraulic circuit energizes the pilot-operated HP shear valve, which sends high pressure to the blind shear ram and closes the ST locks on any closed ram.

Blind Shear Rams (BSR) – A two-piece heavy duty BOP valve designed to close the annular space and shear drill pipe, if necessary, and to seal the entire area. The blind shear ram could be closed under LP (low operating pressure) by human initiation to use the BSR without drill pipe across the BSR. The HP BSR could also be closed by human initiation or by the AMF/deadman or autoshear sequences without human intervention and with or without drill pipe inside the BOP. The HP BSR hydraulic circuit was separate from the LP BSR circuit.

Emergency Disconnect System (EDS) – A manually initiated system which closes the blind shear ram and then unlatches the LMRP and riser from the BOP. This system is intended for an incident in which the dynamically-positioned rig unexpectedly or intentionally is to move off location.

Emergency shut-in Device (ESD) – A generic term for a BOP emergency control that closes the BSR, specifically the Emergency Disconnect System, the AMF/deadman, and the autoshear. API Specification 16D identifies the latter two as backup control systems. [21]

Factory acceptance testing (FAT) – A FAT procedure is typically developed by the equipment manufacturer. It is usually performed after original manufacture and following any modification by the manufacturer. A FAT procedure can be used in the field as well. In this case, the equipment may be connected to the customer's process, requiring adjustments in the test procedure. This test procedure is sometimes referred to as a Site Acceptance Test. Regardless, the purpose is the same; to fully test the equipment functionality against its specifications.

Multiplex Control System (MUX) – A system which uses modems (modulator/demodulator) for sending and receiving signals through copper wiring to and from control computers. The subsea MUX cables are attached to the riser. These multi-conductor cables carry the multiplexed signals in both directions. Some conductors in the

[21] *API Specification 16D, Specification for Control Systems for Drilling Well Control Equipment and Control Systems for Diverter Equipment*, Second Edition 2004, p. 37.

MUX cable also carry 230 VAC power from the UPS systems on the rig to power the subsea MUX system under normal conditions.

MUX Control Pod – An electro-hydraulic valve control on the Lower Marine Riser Package (LMRP) of the BOP stack. The Deepwater Horizon included three control pods designated Pod #1, Pod #2, and Pod #3. The pods were interchangeable and any one of them could be installed in the yellow or blue position on the BOP stack.[22] Operators select one pod as the primary pod to control hydraulic functions BOP. Both pods receive MUX controller commands to initiate solenoid valve actions in parallel with the selected pod. But without hydraulic pressure, the actuation of the unselected solenoid valve has no hydraulic effect.

Programmable Logic Controller (PLC) – An industrial computer which accepts commands from the rig deck control panels and continually cycles through programmed inputs. The subsea MUX PLCs normally communicate with other computers on the rig and subsea, but they can operate individually in an emergency on battery power during the AMF/deadman sequence. All MUX control computers on the entire system (subsea and rig-based) respond to the communications bus and react as prompted.

Relay – An electrical switch which is electrically initiated by the control system and can have multiple outputs for small power activation or control inputs to other logical devices.

Solenoid Valve (SV) – A hydraulic valve which is initiated electrically by the control system and which produces a pressure output by opening an internal valve. The DWH Cameron Mark IIsubsea SV had two redundant coils within their core. The design of the solenoid permits actuation of the hydraulic valve by either coil or both when the coils are energized by the 24/27vdc power supplies.

ST Locks –Wedge-shaped devices which are used to automatically lock the BOP rams in the closed position after an emergency closure, such as the AMF/deadman or autoshear. They may also be activated by a surface panel push button command.

Subsea Electronic Module (SEM) – A sealed pressure vessel used to protect the subsea electronics and batteries from the subsea environment pressures and moisture. One SEM module/vessel is included with each MUX control pod. Each SEM has internal redundancy including two PLCs, two 9 volt battery packs, and two AMF/deadman cards. These duplicate systems are referred to as SEM A and SEM B.

Subsea Transducer Modules (STM) – Vessels on each pod which facilitate the electronics and wiring to the pressure and temperature transmitters used for MUX control system inputs. There were two STMs at Macondo.

Technical Working Group (TWG) – During Phase 1 of the BOP testing, five other parties were organized along with the U.S. Chemical Safety Board (CSB) into a Technical Working Group: BP, Transocean, Cameron, U.S. Department of Justice, and the Multi-District Litigation group (MDL). The TWG served to review and approve

[22] Testimony given in the U.S. District Court for the Eastern District of Louisiana under the Multi-District Litigation docket MDL No. 2179, see McWhorter Designations Vol 1, p, 67-68.

protocols and to approve/disapprove any deviations in the test procedures, as the need arose. The TWG members had a closer level of access (than other party representatives) in witnessing the actual testing.

3 Overview of BOP Subsea Control System

This section provides a general description of the components of the Deepwater Horizon blowout preventer which are associated with the control system for emergency shut-in functions. The details provided here include those necessary to understand the ES analysis. For a more detailed review of the control system, the reader is referred to other previously published reports on the Macondo incident that describe the BOP control system.[23]

3.1 BOP System Overview

See Appendix B of the separate Engineering Services report, *Deepwater Horizon Blowout Preventer Failure Analysis* for description of the BOP stack components.

3.2 MUX Control System Component Description

The Deepwater Horizon BOP was controlled by a Cameron Mark II electro-hydraulic MUX[24] control system.[25] Electro-hydraulic means that portions of the system were controlled by electrical signals and portions by manipulating hydraulic fluid. Electrical power for was provided to the BOP system from the Deepwater Horizon's Power and Communication Cabinets (A & B). Each cabinet also had a dedicated UPS (uninterruptible power supply) that supplied 230 VAC electrical power to the BOP system for a minimum of two hours if main power from the rig were interrupted or removed.[26] Hydraulic power was also provided from the rig via hydraulic lines. A series of hydraulic fluid storage vessels, called accumulators, were located on the rig to provide fluid pressure in the event that pumps supplying hydraulic power were interrupted. Two additional sets of accumulators (one for the BOP stack and one for the LMRP) were located on the BOP stack for use by emergency systems in the event that hydraulic pressure from the rig was lost. The Mark II control system, commands and sensor signals were transmitted and received between the BOP system and the rig using modems transmitting over copper MUX cables.

The Deepwater Horizon MUX control system was housed in the LMRP. The fluid connection for hydraulic controls between the LMRP and the BOP stack were made using devices called stingers. The stingers were located at the bottom of the LMRP. To connect, they were extended into corresponding receptacles in the top of the BOP stack. Seals on the stingers were then activated to prevent leaks.

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[23] Appendix H of the BP Report Sections 1 and 2.

[24] MUX is an abbreviation for "multiplexed communications," a method which is capable of sending multiple simultaneous signals over a single communications cable.

[25] Drawing SK-122100-21-04 *General Arrangement of MUX Control System*, CAM-CSB000004214.

[26] Drawing SK-122100-21-04 sheet 1 of 4, *Interconnection Diagram*. TRN-HCEC-00016703.

3.2.1 MUX Control Panels

There were two redundant control panels for sending commands to the BOP system. On the Deepwater Horizon, the driller's control panel (DCP) was located in the driller's shack on the rig drilling floor. This panel contained pushbuttons for controlling the various BOP functions (see Figure 2 and Figure 3). A redundant pushbutton control panel, alternately referred to as the toolpusher's (TCP) or offshore installation manager's control panel was located on the bridge of the Deepwater Horizon.

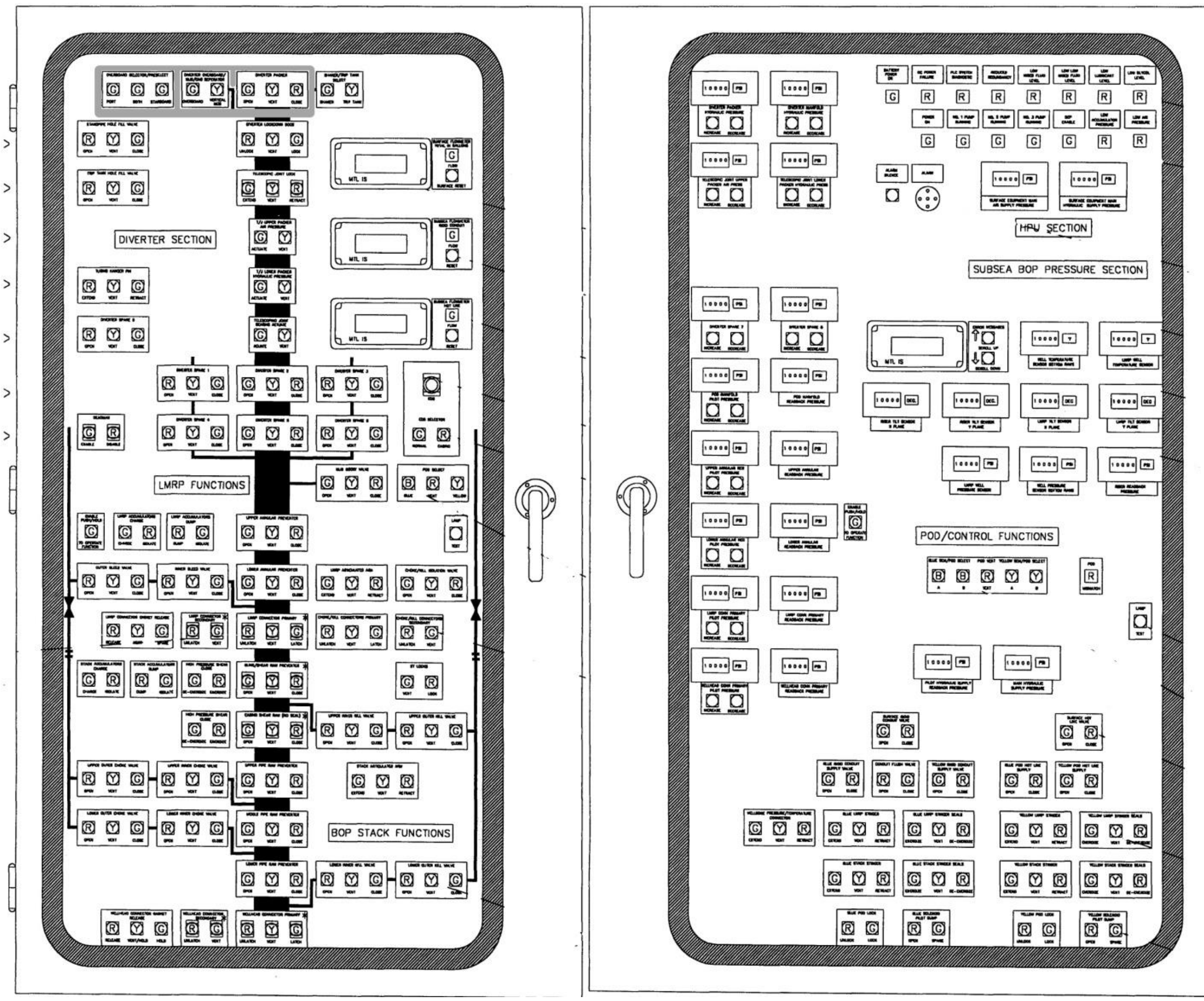

Figure 2. Deepwater Horizon Driller's Control Panel[27]

The photograph in Figure 3 shows the pushbuttons for the BSR and the casing shear ram (CSR). The pushbuttons shown on a graphic depicting the BOP stack (black vertical stripe, also seen in Figure 2) are for the lower pressure BSR and CSR functions. The HP BSR and HP CSR buttons can be seen to the left of the lower pressure pushbuttons. There are also control panel pushbuttons for manually extending and sealing the stingers

[27] Constructed from CAM-CSB-000005284 and CAM-CSB-000005286.

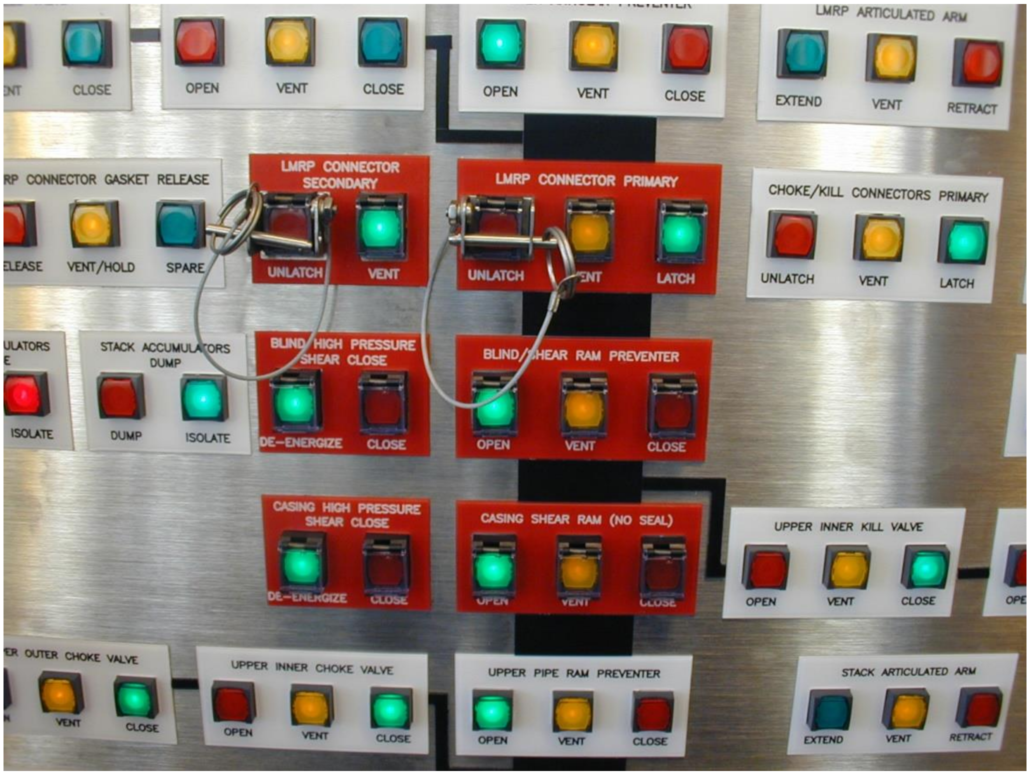

Figure 3. Portion of the control pushbutton panel for the BOP.[28]

3.2.2 BOP Control Pods

At the BOP stack, the electrical power, hydraulic power and control signals are received by devices located in two redundant, sealed containers mounted to the LMRP. These containers were called pods, one the yellow pod, and the other the blue pod. The pods contain the subsea electronic modules (SEMs), subsea transducer modules (STMs), hydraulic pressure regulators, solenoid pilot valves, hydraulic accumulators and hydraulic valves.[29]

Each pod contains two redundant subsea electronic modules (SEM A and SEM B) located in a SEM housing. See Figure 4. Each SEM includes a programmable logic controller (PLC), an AMF/deadman controller card, and a 9 volt battery pack for booting and operating the AMF/deadman card. There is one 27 volt battery pack per SEM housing, providing power for sensors and solenoids needed by both SEMs only during an emergency event.

[28] BP-HZN-BLY00056468
[29] Transocean Report, Appendix N, AMF Testing, p.1.

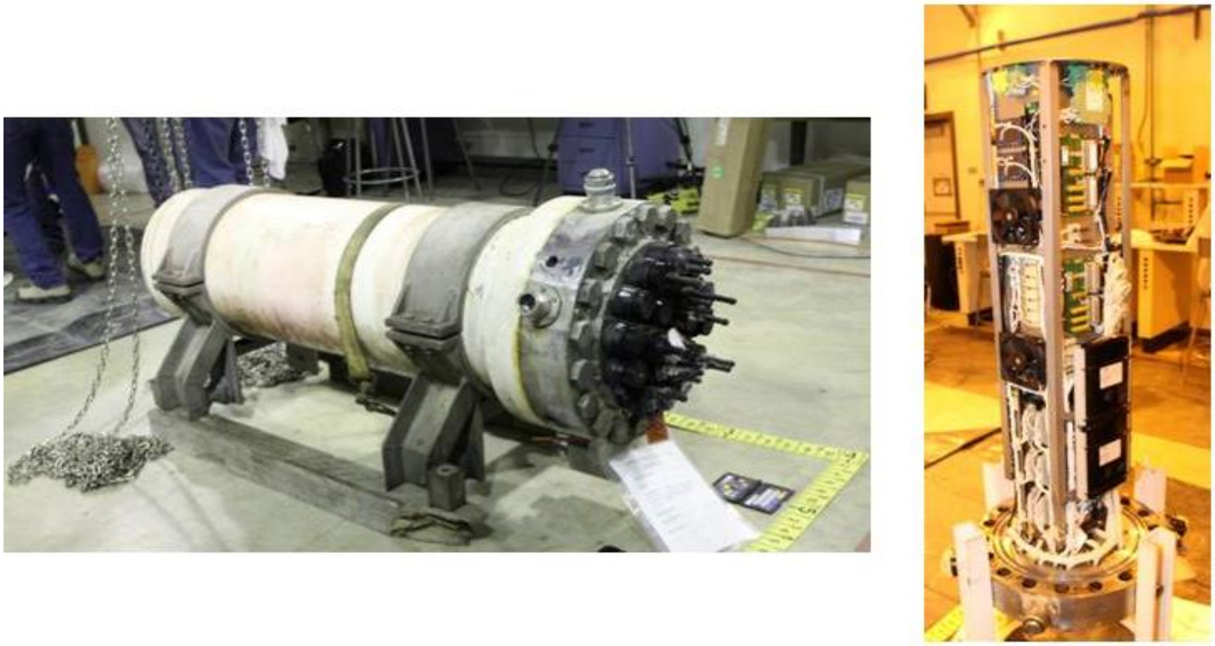

Figure 4. SEM from the Deepwater Horizon (left) with its protective housing removed (right) as observed during Phase 1 testing.

3.2.3 BOP Solenoid Valves

The SEMs convert the MUX control commands from the rig (or autonomous commands generated within the SEMs) to various actions, hydraulically operating the BOP system devices (rams, preventers and valves). The SEM electrical outputs are converted by hydraulic fluid actions using electrically-powered devices called solenoid valves. A solenoid is a device which uses a magnetic field to cause a mechanical action. In this case the magnetic field is caused by a SEM electrical signal passing through a coil of wire, and the mechanical action is to open and close a solenoid valve to start and stop hydraulic fluid to a BOP system device. The solenoid valves had to operate under pressures of 3000 to 5000 psi, and at cold subsea temperatures on the order of 35°F. As a result, they were enclosed in a heavy stainless steel housing which protected the solenoid and valve parts, and they included a cable assemblies that allowed them to be plug-connected to the control system. See Figure 5.

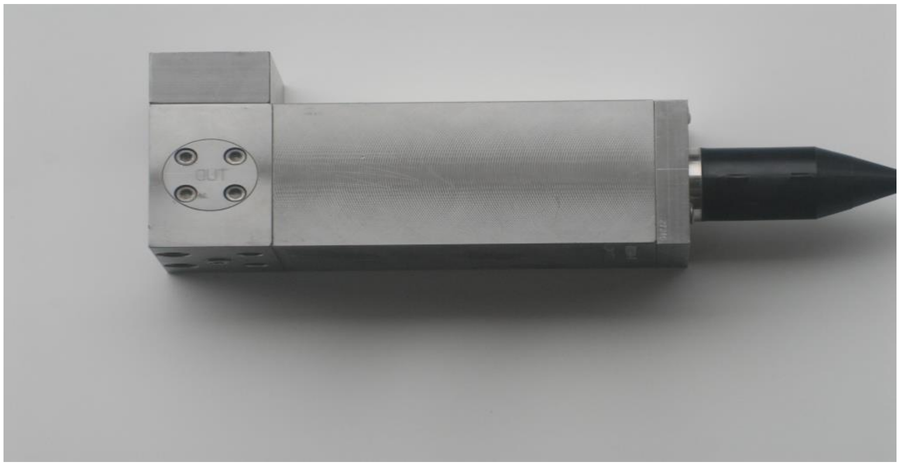

Figure 5. Typical BOP solenoid valve (Photo—Engineering Services)

Each BOP control system solenoid valve has two operating coils, one is connected to SEM A and the other coil is connected to SEM B. While this dual coil design was meant to provide redundancy, it was the basis for failure of solenoid valves on the Deepwater Horizon.

When a solenoid is electrically energized, the magnetic forces in the coil[30] pull the armature of the solenoid into the space within the coil and open the valve. When the coil is deenergized, a spring pushes the armature back outside of the coils, closing the valve. With redundant dual coils, energizing either coil is sufficient to actuate the solenoid. However, the polarity of the coils is critical. If one of the coils is wired with opposite polarity, the magnetic effect will be canceled. One coil creates an electromagnet with a North-South orientation. The other creates a South-North orientation. The net magnetic force is zero. In this condition, the valve would not open, even though both coils were energized. A solenoid key to the operation of the AMF/deadman on the Deepwater Horizon BOP, the #103 solenoid valve operated by the yellow pod (SV 103Y) was erroneously wired with reverse polarity coils.

3.2.4 BOP Pod Batteries

Each SEM housing has two types of battery packs. Each SEM has a 9 volt battery pack which provides power to the AMF/deadman card. The second is a 27 volt battery pack common to both SEMs which provides power to the 24 volt-rated relays on the AMF/deadman card, to the hydraulic fluid pressure sensors and to the output modules from the SEM programmable logic controllers.

The batteries in use at the time of the accident were manufactured by SAFT.[31] The battery packs in the pods consisted of multiple 3 volt lithium manganese dioxide cells (Li-MnO_2) cells. The arrangement of the individual

[30] Passing an electrical current through a coil of wire creates a magnetic field, an electromagnet, with a North and South pole, just like a permanent magnet.

[31] See Appendix A in this report for catalog cuts and additional battery details.

batteries (two in series, and three sets of two in parallel) formed the 9 volt battery packs, and three 9 volt packs were connected in series to form the 27 volt battery pack.[32]

Using the manufacturer's information, we calculated that each of the 9 volt and 27 volt battery packs were derated by Cameron from the manufacturer's amp-hour ratings by 12.5%. After derating, each battery had a rating of 42 amp-hours, which was published by Cameron in its quality test procedures.[33]

3.2.5 BOP Pod Selection

The Deepwater Horizon control panels contained two sets of section pushbuttons which determined how control signals were handled by the pods. The primary pod selection pushbuttons allowed the rig crew to select either the blue pod or yellow pod as the active control pod. The active control pod would be connected to the rig hydraulic supply through the conduit valve package (CVP). If, for example, a hydraulic fluid leak developed in one pod, the other pod could be selected as the active pod from the surface control panel. The transfer of control between pods was handled by remote control valves in the CVP.

While only the selected pod received normal rig-sourced hydraulic fluid supply, both pods received simultaneous commands from the rig and both energized their respective solenoid valves. The difference was that only the selected pod solenoid valves, connected to the CVP, did useful work since it did had hydraulic pressure available.

In a situation such as activation of the AMF/Autoshear system, hydraulic power came from the BOP system-mounted accumulators, not the rig-based hydraulic system. In this case, hydraulic fluid was made available to both pods, and both blue and yellow solenoids would act in parallel to actually do work to complete the command.

3.3 Emergency Operating Modes

The control system can enter an emergency operating mode in three situations:

- rig personnel are aware of an impending problem prompting them to initiate the emergency disconnect system to disconnect riser and LMRP from the well;
- the rig unexpectedly moves off location causing the autoshear system to initiate, closing the blind shear ram and releasing the LMRP;
- when deck utilities are lost and the crew has no other way to communicate with and operate the subsea BOP the AMF/deadman will trigger.

The emergency shut-in modes are discussed next.

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[32] Additional battery information appears in the *BP Report*, Appendix X, p. 1.

[33] Cameron Factory Acceptance Test Procedures for Subsea Electron Module (Horizon AMF/Deadman In Current Situation) ,Document No. X-065449-05-03, Rev 2, CAM-CSB000008040.

Emergency Disconnect System – The emergency disconnect system (EDS) is managed by the surface MUX and is manually initiated. A single-button activation initiates a pre-defined sequence of functions on the BOP stack to secure the well and disconnect the LMRP and riser. The EDS is most frequently used to avoid damage to the BOP and wellhead if a dynamically positioned rig unexpectedly moves off location. The emergency disconnect sequence can be activated from either the toolpusher's or driller's control panels (TCP or DCP). The sequence is designed to close the high-pressure blind shear ram, close the choke and kill valves and unlatch the LMRP connector (along with choke/kill connectors).

Witness accounts indicated that the crew attempted to activate the EDS approximately seven minutes after the initial explosion.[34] The LMRP did not disconnect and hydrocarbons continued to flow, indicating that the BSR did not function or seal, most likely due to lost communications and electrical power to the MUX cables caused by the explosions on the rig.

Autoshear Function System – The autoshear mechanically activates the high-pressure shear circuit to close the blind shear rams and ST Locks if the LMRP is unexpectedly disconnected from the BOP stack. A trigger valve between the LMRP and Stack plates will activate the Blind Shear Ram and Blind Shear ST Lock functions. The Autoshear function must be "Armed" via the function on the DCP or TCP (Auto Shear, ARM). The hydraulic power to close the Blind Shear Ram will be from the stack mounted accumulators.

AMF/deadman – Once the AMF/deadman has been armed from the surface, three conditions are necessary to initiate the deadman sequence:

1. Loss of electrical power and communication from the MUX umbilical
2. Loss of communication from the other pod's SEM
3. Loss of conduit pressure relative to hydrostatic (subsea ambient) pressure

A pushbutton on the control panels was used to arm and disarm the AMF/deadman. When AMF/deadman was armed, the pod's 9 volt battery packs would be connected to power the AMF/deadman card for each SEM. When condition 1 occurred, loss of electrical power and communications, the 27 volt battery pack would be connected to power the two pressure transducers used to check condition 3.

Conditions 1 through 3 would occur during a disaster such as parting of the riser, or major explosion and fire on the rig which could damage the MUX cables causing loss of surface utilities and leaving the subsea BOP control system to self-initiate the closure of the blind shear ram.

The stored hydraulic power to perform the AMF/deadman sequence was supplied from the stack mounted accumulators.

[34] *BP Report*, p. 47.

4 Analysis: AMF/deadman Activation April 20, 2010

The first set of findings to be analyzed center around our conclusion that the AMF/deadman sequence activated on April 20, 2010 when communications, electric power and hydraulic power were severed between the Deepwater Horizon and the BOP immediately following the explosions and fire on the rig.

As described in detail is in this section, and summarized in Figure 6, the two SEMs in the blue pod were miswired, which caused the emergency 27 volt battery to prematurely connect the two AMF/deadman pressure transducers. The premature connection drained the 27 volt battery, preventing the AMF/deadman sequence from activating from the blue pod. The yellow pod contained two miswired solenoid valves such that a reverse polarity existed between the dual coils. One of these solenoids (103 Y) was for the yellow pod AMF/deadman system to actuate the BSR. However, a premature depletion of the yellow pod SEM B 9 volt battery caused the solenoid valve to be functioned by the SEM A coil alone, thus actuating the BSR closure. Drill pipe buckled off-center in the BOP prohibited the BSR from fully closing and sealing the well.[35]

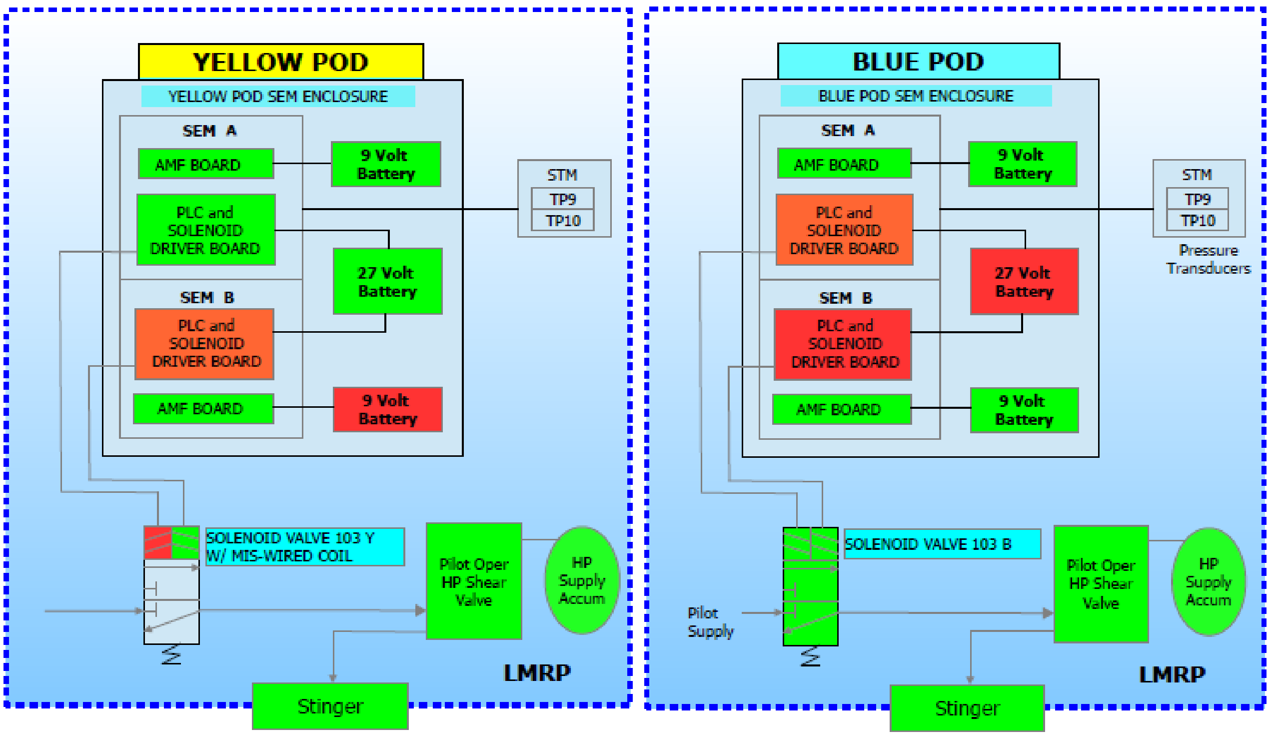

Figure 6. Summary of battery conditions and solenoid 103 wiring within the yellow (left) and blue (right) pods at the time of the incident.

[35] See separate Engineering Services separate report, *Deepwater Horizon Blowout Preventer Failure Analysis*, for description of buckling phenomena.

The analysis of Deepwater Horizon BOP was completed in a three-part process that began during intervention efforts to halt the flow of hydrocarbon from the well, and then continued through two phases of analysis, referred to as Phase 1 and Phase 2. Intervention efforts included re-establishing electrical and hydraulic communications with the BOP stack.[36] To do this, the yellow and blue pods, were individually brought to the surface of the Q4000 and Discoverer Enterprise, intervention vessels used to assist with intervention efforts, May 4, 2010[37] and July 4, 2010[38] respectively. When raised to the surface, the solenoids of each pod were function tested and the integrity of pipe, tubing, hoses and hydraulic lines were verified as well as execution of the AMF/deadman system.[39] During testing, neither the yellow pod nor the blue pod completed the AMF/Deadman sequence correctly. After repairs and modifications had been made to the pods, they were re-deployed to the BOP stack subsea.[40]

The Deepwater Horizon's blowout preventer, including the yellow and blue pods, was recovered from the well head on September 4, 2010 and transferred to the NASA-Michoud facility in New Orleans, LA for Phase 1 testing. Det Norske Veritas (DNV) was contracted by The Joint Investigation awarded to complete Phase 1 testing.[41] Phase 1 testing was declared over by DNV and BOEMRE representatives on March 4, 2011. ES and CSB were present for this testing.

Phase 2 testing of the BOP began after BP filed a Motion for Access to the Deepwater Horizon Blowout Preventer for Further Forensic Inspection.[42] ES and CSB were excluded from this phase of testing, but documents, photos, and videos were subsequently made available and considered in this analysis. During Phase 2 additional tests were conducted and some components further disassembled. Phase 2 testing commenced on April 18, 2011 and then concluded on June 22, 2011. [43]

What follows in Section Analysis: AMF/deadman Activation April 20, 2010 is the analysis which provides the basis for AMF/deadman activation findings. The first section describes the location of the available control pods on the BOP stack at the time of the incident. The next three sections contain analysis which documents portions of the AMF/deadman control system which were found not to be causal:

- Location of the Control Pods on the BOP Stack at the Time of the Incident

The Deepwater Horizon had three pods for its BOP, referred to as pod #1, #2, and #3. Any of these three pods could be installed in the yellow or blue position on the BOP stack. A review of various Transocean documents

[36] Re-run & Function Test Yellow Pod, Document Number 2200-T2-DO-PR-4039, 10 May 2010, Document Revision C BP-HZN-bLY00060764.
[37] Cameron Controls Daily Report Sheet. Publicly accessed at http://www.mdl2179trialdocs.com/releases/release201304041200022/TREX-03602.pdf; CAM_CIV_0046703.
[38] Internal BP Recovery Logs [BP-HZN-BLY00061061].
[39] Yellow Pod: Cameron Controls Daily Report Sheet. Publicly accessed at http://www.mdl2179trialdocs.com/releases/release201304041200022/TREX-03602.pdf; CAM_CIV_0046705.
Blue Pod: Cameron Factory Acceptance Test Procedures for Subsea Electron Module (Horizon AMF/Deadman In Current Situation) [BP-HZN-BLY00061082 - BP-HZN-BLY00061093].
[40] Blue Pod Deployment [OSC-OWH BOEM-GOMR-B04-00003-0156]; Top Kill Procedures Manual for MC252-1 Re-run & Function Test Yellow Pod [BP-HZN-BLY00060869 - BP-HZN-BLY000060905].
[41] DNV report p.10.
[42] 2011-04-19 Court Order Approving DNV-BP BOP TESTING CONTRACT.
[43] Lab notebook from Phase 2 testing.

indicates the pods were not clearly differentiated by pod number or color. For example, the Rig Maintenance System (RMS) refers to the pods simply by their position (blue or yellow), but does not indicate if the work being completed is on pod 1, 2, or 3. A review of work orders for the various pods appear to correlate the pod numbers to colors, blue (pod 1), yellow (pod 2), and white (pod 3), While witness testimony asserted that the color designations were consistently correlated to the numbers, we have found one Cameron equipment repair quote that refers to the 'blue pod' as the 'third pod'.

In a 'subsea workbook' that summarizes daily logs and the RMS, the pods are referred to by numbers, but *Transocean's Daily Activity Report (DAR) consolidation reports which summarize daily activities refer to the* pods either by color (or 'spare' when referring to the white pod) or number. Sometimes the DAR specifies the location of a pod on the BOP stack, for instance on January 23, 2006 the following entry is made "Installed #1 pod in the yellow position on LMRP […]," but not always. Witness testimony indicates that pod 3 (white or 'spare') was in the blue position and pod 2 (yellow) was placed in the yellow position before the Deepwater Horizon BOP was deployed at Macondo. The same witness testimony further indicates the SEM of pod 1 had been transferred into pod 2. While the DAR documents the SEM transfer, it does so by referring to pod 1 (blue pod) as the 'spare pod', "Removing SEM from yellow pod and installing SEM from spare pod into yellow." The DAR does not explicitly document that pod 1 (blue) was in the spare position or that pod 3 (white) was in the blue position, but other documents support that to be the case.

For the remainder of the report, 'blue pod' or 'blue control pod' will be used to refer to the control pod found in the blue position and 'yellow pod' or 'yellow control pod' for the control pod found in the yellow position.

- The AMF/deadman was Armed at the Time of the Incident
- Pie Connectors
- PLC Executable Files

The final four sections provide the analysis of the portions of the system where faults were found:

- Premature Draining of the Blue Pod 27 volt Battery
- SV 103Y Solenoid Valve Miswired
- How a Miswired Solenoid Valve Operates
- BOP Batteries

4.1 Location of the Control Pods on the BOP Stack at the Time of the Incident

The Deepwater Horizon had three pods for its BOP, referred to as pod #1, #2, and #3. Any of these three pods could be installed in the yellow or blue position on the BOP stack. A review of various Transocean documents indicates the pods were not clearly differentiated by pod number or color. For example, the Rig Maintenance System (RMS) refers to the pods simply by their position (blue or yellow), but does not indicate if the work being

completed is on pod 1, 2, or 3.[44] A review of work orders for the various pods appear to correlate the pod numbers to colors, blue (pod 1), yellow (pod 2), and white (pod 3),[45] While witness testimony asserted that the color designations were consistently correlated to the numbers,[46] we have found one Cameron equipment repair quote that refers to the 'blue pod' as the 'third pod'.

In a 'subsea workbook' that summarizes daily logs and the RMS, the pods are referred to by numbers,[47] but Transocean's Daily Activity Report (DAR) consolidation reports which summarize daily activities refer to the pods either by color (or 'spare' when referring to the white pod) or number.[48] Sometimes the DAR specifies the location of a pod on the BOP stack, for instance on January 23, 2006 the following entry is made "Installed #1 pod in the yellow position on LMRP […],"[49] but not always. Witness testimony indicates that pod 3 (white or 'spare') was in the blue position and pod 2 (yellow) was placed in the yellow position before the Deepwater Horizon BOP was deployed at Macondo.[50] The same witness testimony further indicates the SEM of pod 1 had been transferred into pod 2. While the DAR documents the SEM transfer,[51] it does so by referring to pod 1 (blue pod) as the 'spare pod', "Removing SEM from yellow pod and installing SEM from spare pod into yellow." The DAR does not explicitly document that pod 1 (blue) was in the spare position or that pod 3 (white) was in the blue position, but other documents support that to be the case. [52]

For the remainder of the report, 'blue pod' or 'blue control pod' will be used to refer to the control pod found in the blue position and 'yellow pod' or 'yellow control pod' for the control pod found in the yellow position.

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[44] RMS II Equipment History [TRN-INV-03235829], publically available at http://www.mdl2179trialdocs.com/releases/release201305171200030/TREX-052683.pdf.

[45] Yellow pod work orders [TRN-INV-00031471], Blue pod work orders [TRN-INV-00031384], and White pod work orders [TRN-INV-00031441].

[46] Testimony given in the U.S. District Court for the Eastern District of Louisiana under the Multi-District Litigation docket MDL No. 2179, see Hay Designations Vol 1, p, 74, publically available at http://www.mdl2179trialdocs.com/releases/release201302281700004/Hay_Mark-Depo_Bundle.zip.

[47] Transocean subsea work book [TRN-INV-02932167].

[48] DAR Consolidation Report for subsea personnel activities printed June 2, 2010 covering the time period from April 24, 2002 to February 17, 2010 [TRN-INV-03259497].

[49] *Ibid* [TRN-INV-03259590].

[50] Testimony given in the U.S. District Court for the Eastern District of Louisiana under the Multi-District Litigation docket MDL No. 2179 was conflicting, see McWhorter Designations Vol 1, p, 78-79 where he describes that pod #3 was in the blue stack and pod #2 was in the yellow stack at the time of the incident, publicly accessible at http://www.mdl2179trialdocs.com/releases/release201302281700004/McWhorter_Jim-Depo_Bundle.zip.

[51] DAR Consolidation Report, entry September 8, 2009, [TRN-INV-03259710].

[52] DAR Consolidation Report, entry, December 29, 2008 indicates the 'blue pod' was changed out [TRN-INV-03259688]; Cameron Daily Report Sheet December 29, 2008 notes "[…] OIM decided that they need to put the old POD back on the stack and go with it for now because the SEM that came from Cameron has a possible problem with a modem so they changed the POD […]" [CAM-CSB 000007498]; Subsea work book indicates SEM # 1 was overhauled in April 2009 [TRN-INV-0293227] which could only happen it if was not installed on the BOP; DAR Consolidation Report, entry, April 15, 2009 indicates "SEM from spare pod to be sent in to Cameron" [TRN-INV-03259697].

4.2 The AMF/deadman was Armed at the Time of the Incident

Two items suggest that the AMF/deadman was armed on April 20, 2010. First, Transocean claims a photo taken during a routine ModuSpec survey on April 10, 2010[53] shows that the system was armed. It should be noted that neither the CSB nor ES have been able to independently verify Transocean's photographic evidence. Second, screenshots of each pod's SEMs after retrieval show three of the SEMs were in a disarmed (blue SEM A, yellow SEM A, and yellow SEM B) while one of the SEMs was in an armed state (blue SEM B).[54] The residual state of arming for the blue SEM B indicates that it had been armed at some point prior, but for some reason did not dis-arm.

ES has not reached a conclusion on why the blue pod SEM B still exhibited an "armed" status when retrieved, [55] but one possibility for the lack of disarming lies with the depleted condition the blue pod 27 volt battery was found in after the incident (see Appendix A). When the AMF/deadman system is armed from the rig, the system sends a 12 volt pulse (using SEM power) to a 12 volt bi-stable relay.[56] This implies that when rig personnel disarm the AMF/deadman intentionally, the necessary pulse voltage is available on the 24 volt SEM bus. In the case of an AMF/deadman actuation, at the end of the sequence the PLC directs the 27 volt battery, which was used to energize the solenoids, to fire the 12 volt pulse to unlatch the bi-stable relay which then disconnects the batteries and disarms the AMF/deadman. An expert retained by BP to investigate the DWH BOP control system conducted testing of an exemplar bi-stable relay. BP's expert concluded that a depleted 27 volt battery could operate the 12 volt relay even though it might be unable to operate the solenoids in the pod. [57]

4.3 Pie Connectors

Pie connections, Figure 7, were used to interface the SEM electronics pressure-rated vessel with wiring to other parts of the pod. The wedge-shaped plug contacts used to make this interface connection were subject to long-term corrosion. The pie connections were inspected during Phase 2 testing of the BOP. There is no evidence that the pie connection or the solenoid cable interface to the pie connectors played any negative role in the MUX control system or AMF/deadman sequence. Faults on the system due to bad pie connections would have been noted on the deck by system diagnostics before the accident as well as during Phase 1 testing at Michoud. No

[53] *Transocean Report*, Appendix N, reference 16.

[54] BP-HZN-BLY00404955 and BP-HZN-BLY00329472.

[55] There is an open question as to whether the blue pod may have actually initiated the suspended AMF/deadman sequence when power from the PETU was first connected to the retrieved pod. No visible stinger actions would have been noted since no hydraulic power was connected to the pod at that point in time. During the Michoud AMF/testing, the blue pod immediately responded and began the AMF solenoid sequence once PETU power was restored following an unsuccessful AMF/deadman test. The "Deadman" analog values following that Michoud test also showed a disparity between the SEM A (active) and SEM B (not active) after the AMF/deadman sequence had completed.

[56] The 12 volts is generated by cutting the 24 volt SEM bus in half using a RC (resistor capacitor) circuit. Expert Report of Author Zatarain, *Transocean Deepwater Horizon Blowout Preventer Subsea Control System*, p 43, publically accessible http://www.mdl2179trialdocs.com/releases/release201305171200030/TREX-040009.pdf.

[57] Expert Report of Author Zatarain, *Transocean Deepwater Horizon Blowout Preventer Subsea Control System*, p 45, publically accessible http://www.mdl2179trialdocs.com/releases/release201305171200030/TREX-040009.pdf.

faults were noted on solenoid valves in the AMF/deadman sequence. For additional analysis of the pie connectors and their oxide coating, see Appendix H.

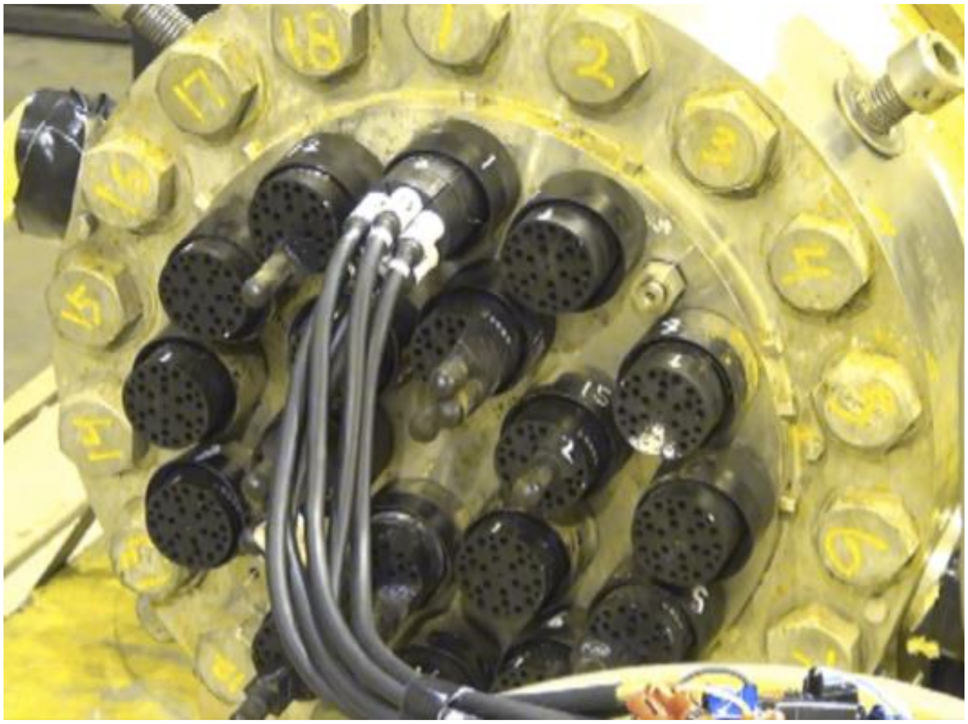

Figure 7. Pie connectors as observed in Phase 2.

4.4 PLC Executable Files

Technicians downloaded the programmable logic controller executable files from the SEMs of the blue and yellow pods.[58] The checklist contained in the test document indicates that the executable files were identical across all four SEMs.

4.5 Premature Draining of the Blue Pod 27 volt Battery

The blue pod was initially retrieved on July 4, 2010 as part of the intervention efforts by BP and Transocean to stop the continuing blowout.[59] Tests that simulated the conditions necessary to trigger the AMF/deadman system on SEM A and SEM B showed that the AMF/deadman sequence would not initiate until power was reapplied using a portable electronic test unit (PETU). [60] A PETU allows simulation of signals to the SEMs so that various SEM functions can be tested. Subsequent testing of the batteries on the Q4000 and during Phase 1 and Phase 2 testing showed that the 27 volt battery pack was depleted (See Appendix A for more details).

[58]Phase 2 Test Preparation Sheet DNV2011062110: BOP-038.
[59] Internal BP Recovery Logs [BP-HZN-BLY00061061].
[60] Internal BP Recovery Logs [BP-HZN-BLY00061076]; Cameron Factory Acceptance Test Procedures for Subsea Electron Module (Horizon AMF/Deadman In Current Situation) [BP-HZN-BLY00061082 - BP-HZN-BLY00061093].

Integrity testing of the connections for both SEM A and SEM B in the blue pod revealed nonconformances with the wiring diagrams provided by Cameron. The data were collected during Phase 2 testing at Michoud, and by charter, only published test measurements. The scope did not include investigation beyond the test measurements. The technicians performing the tests did not draw any conclusions as to the cause or effect of any nonconformances found. The conclusions reached below are the result of analysis by ES.

4.5.1 Blue Pod SEM A and SEM B Miswiring

During the Phase 2 observations and tests on the SEM electronics, the technicians traced the wiring from both AMF/deadman card connectors using continuity test methods to verify the point-to-point wiring.[61] Several of the point-to-point tests on the blue pod resulted in "Open Lead" notations, which means that no electrical connection existed between two points which the wiring diagram showed were supposed to be connected by a wire.[62] This result was unexpected

4.5.2 The Effect of Blue Pod SEM Miswiring

Engineering Services reviewed the *Subsea Electronic Module Wiring Diagrams*[63] to determine the potential impact of the missing or disconnected wires on the integrity of the AMF/deadman system. The AMF/deadman system was designed to minimize the need to use battery power. Active monitoring of the hydraulic pressure transducers using power from the 27 volt battery pack was not supposed to begin until an AMF/deadman card detected that both power and communication had been lost to itself and to the other three AMF/deadman cards. This is what we believe would have resulted from the miswiring condition. The open leads would have caused the blue SEM A AMF/deadman card to act as if all power and communications been lost. This card then triggered monitoring of hydraulic pressure using the 27 volt battery pack, draining it over time, beginning with BOP deployment on February 8, 2010 until, at some point prior to the incident on April 20, it no longer had the capability to complete the AMF/deadman sequence. A detailed explanation of the miswiring appears in Appendix D4: Review of Blue Pod SEM Wiring Defects.

The resulting effect of this additional drain on the blue pod 27 volt battery must be considered in conjunction with our finding that all of the blue pod batteries were beyond their "recommended" useful life cycle expectancy based on Cameron's recommendations for battery replacement.

4.5.3 Testing Which Should Reveal Wiring Defects

Evidence exists that Cameron conducted a point-to-point wiring check of what we believe was the pod 1 SEM on June 22, 2009.[64] We arrived at this conclusion based on notations on the purchase orders and other FAT test documents from that same period. The records indicate that all sheets were fully highlighted for any external wiring (non-pc board circuits) between the various components and terminal strips within the SEM. This is the SEM that was transferred into pod 2 in the yellow position on the BOP. If these wiring checks had been

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[61] Phase 2 Test Preparation Sheet DNV2011061904: BOP-033.
[62] *Ibid*, p. 31.
[63] Subsea Electronic module Wiring Diagrams, Drawing No. SK-122178-21-06, sheets 2-45 [CAM-CSB000013924].
[64] There is a handwritten note on the drawing that states "Point to point 6/22/09" and then it is signed, Subsea Electronic module Wiring Diagrams, Drawing No. SK-122178-21-06, sheets 2-45 [CAM-CSB000013924].

accomplished on pod 3when it was last refurbished at the beginning of 2007,[65] we believe that the same discrepancies found during Phase 2 would have been found during point-to-point checks. We have not found any documentation to indicate the wiring checks were completed on pod 3.

A deck test, configured like those written for the yellow and blue pods when they were raised to the surface during intervention, should have detected the wiring deficiencies in the blue pod had they been implemented prior to splashing the BOP. For example, consider three possible scenarios of the AMF deck test procedure:[66]

1. The deck test called for sequentially cutting off power and communications and then reducing hydraulic pressure (or simulated pressure). In this case the AMF test would have worked correctly.

2. The deck test called for first reducing hydraulic pressure (or simulated pressure), and then removing power by turning off the PETU. This test would have immediately and prematurely activated the AMF sequence after the reduction in hydraulic pressure.

3. If FAT or deck tests were not accomplished on this level of detail, then the miswiring would not have been found.

There is a FAT procedure that has been filed with other documents concerning the 2007 repair on pod 3, but it should be noted that while the steps of the procedure have been initialed, there is not accompanying Cameron employee signature like we have observed with most other FAT procedures we have reviewed.[67] ES cannot explain why pod 3 appears to have passed the AMF/deadman FAT procedure.

4.6 SV 103Y Solenoid Valve Miswired

The yellow pod was also retrieved as part of BP and Transocean's intervention efforts and initially tested between May 6 and May 8, 2010.[68] During this testing, solenoid valves were functioned from SEM A and SEM B and SV 103Y was recorded as failed for both SEMs. The AMF/deadman test conducted on the Q4000 with the yellow pod also failed to complete. As a result, SV 103Y was replaced with a different solenoid, referred to as SV 103 Replacement, or SV 103R. With the replacement solenoid in place, the yellow pod passed the on-deck AMF/deadman tests and was redeployed subsea. Later, Phase 2 testing revealed that one of the coils of SV 103 Y was wired with reverse-polarity.

The Upper Annular Preventer "increase pressure" solenoid valve for the Yellow pod, SV 3AY, also failed for both SEM A and SEM B on the Q4000 and was found to be miswired during Phase 2 testing. One of the tests said 3A

[65] Transocean subsea work book [TRN-INV-02932227]; Horizon WCS BOP-BOP Control Pods [BP-HZN-BLY00055866]; Operation Control Ticket MARK 2, MUX SECTION. CONTROL POD [CAM-CSB-000013542]; White pod work orders [TRN-INV-00031448].

[66] Cameron Factory Acceptance Test Procedures for Subsea Electron Module (Horizon AMF/Deadman In Current Situation) ,Document No. X-065449-05-03, Rev 2, [CAM-CSB 000008037].

[67] Operation Control Ticket MARK 2, MUX SECTION. CONTROL POD [CAM-CSB-000013542].

[68] Deck Test Procedure for Mark-II Control Pod Cameron, P/N 2020708-21 DWH, 4 May 2010, CAM-CSB000008013. All non-regulator pod solenoid valves were pressure tested. The result columns on test pages 8 to 10 for SEM A and SEM B are initialed and timed separately; Cameron Controls Daily Report Sheet. Publicly accessed at http://www.mdl2179trialdocs.com/releases/release201304041200022/TREX-03602.pdf; [CAM_CIV_0046703].

was “sluggish—activate & takes a long time to fire, skips.”[69] Our testing of an exemplar solenoid valve, Section How a Miswired Solenoid Valve Operates, provides a potential explanation of this test result.

4.6.1 Solenoid Testing: PETU Characterization

Technicians used four different PETUs during testing at various times on the Q4000 and during Phase 1 and 2 of the BOP testing. Visual inspection of the PETUs revealed they all had a switch that could be toggled between “A” or “B”. Some of the PETUs had another switch that could toggle between “Single” and “A+B”. This switch is apparent on the PETU shown in Figure 8, but missing from the PETU shown in Figure 9.

At the time of Phase 1 testing, during individual solenoid valve testing DNV believed that the PETU with the “A+B/single” switch could simultaneously energize both coils in the SV and that the other type of PETU would only energize a single coil as selected by the “A/B” toggle switch.[70] Characterization tests of the PETUs completed by DNV during Phase 2 testing determined this not to be the case. As clarified during Phase 2, the PETU with the “A+B/single” switch only activates a single coil (as determined by the setting of A/B toggle switch) while the PETU lacking the “A+B/single” switch always activated both coils.[71] For further information on the PETU testing see Appendix C2 – PETU Characterization Analysis.

Table 4-1: Summery of PETU capabilities as determined from Phase 2 BOP testing.

	PETU with “A+B/single” switch (Figure 8)	**PETU lacking A+B/single switch (Figure 9)**
Coils activated	Only activates one coil at a time as determined by the “A/B” toggle switch	Always activates both coils

[69] Handwritten note by Cameron representative on Deck Test Procedure for Mark-II Control Pod, for solenoid (3A), “sluggish—activate & takes a long time to fire, skips.” [BP-HZN-BLY00060717].

[70] *DNV Report* page 50

[71] Phase 2 Test Preparation Sheet DNV2011060643: BOP-015-2 Summary PETU Solenoid Drive Characterization and DNV2011060743 :BOP-015-3 Summary PETU Solenoid Drive Characterization.

Figure 8. PETU: Note the A/B switch and the Single/A+B switch - Photo Phase 2 testing

Figure 9. PETU: This one has no Single/A+B switch - Photo from Q4000 Intervention”

When testing of the pods was first conducted on the Q4000, serial numbers of the PETUs used were not recorded, but a technician conducting the test recalled that a PETU without the "A+B/single" (Figure 8) was used;[72] test results from the miswired SV 103Y support this recollection.[73] To fail during deck testing, both coils in SV 103Y would have to be energized simultaneously. If only one coil were energized, SV 103Y should have opened (See Section 4.7 for details).

The effect of this PETU misunderstanding also created the perception of inconclusive test results at Michoud during Phase 1 testing. During Phase 1, DNV conducted several tests on 103 Y using the two (2) PETUs to select the target SEMs and so determine how a particular solenoid activated using SEM A, SEM B, or both. During the tests, SV 103Y exhibited inconsistent actuations which could not be explained at the time.

During Phase 2, protocols were developed to characterize each PETU with all of the variable SEM A and SEM B settings available on the front panel of each device. The results proved valuable in understanding the idiosyncrasies of each PETU. Once testing revealed that the solenoid valve was reverse wired on one coil, and once the functioning of the switch positions on the PETUs were understood, all but one of the SV component tests exhibited predictable results. ES determined that simultaneous energizing of both coils of a solenoid valve using a PETU when one coil has reversed polarity prevents the solenoid valve from actuating. Energizing either coil individually, whether reverse wired or not, will actuate the solenoid properly. Further analysis of these characterization tests is included in Appendix C of this report.

This insight into the operation of the PETUs clarified the AMF/deadman and component tests at Michoud during Phase .[74] An analysis of the five AMF/deadman tests[75] now reveals the following findings, all of which will be discussed in detail shortly:

1. Tests 1 and 2 both revealed a possible 6-second, out-of-sync delay between SEM A and B on both pods (yellow pod with SV 103R and blue pod with PETU power).
2. Test 2 confirmed that the AMF/deadman sequence could not be initiated due to the dead 27 volt battery in the blue pod.
3. Test 3, yellow pod, exhibited a 7-second pressure duration resulting from a dying 9 volt battery (using original SV 103Y).
4. Tests 4 and 5, yellow pod, actuated the AMF/deadman properly because by this time the SEM B 9 volt battery had died and SV103Y could be energized from only one coil.

[72] Testimony given in the U.S. District Court for the Eastern District of Louisiana under the Multi-District Litigation docket MDL No. 2179, see LeNormand Designations Vol 1, p, 83, publicly accessible at http://www.mdl2179trialdocs.com/releases/release201302281700004/LeNormand_William-Depo_Bundle.zip.

[73] Yellow Pod: Cameron Factory Acceptance Test Procedures for Subsea Electron Module (Horizon AMF/Deadman In Current Situation), [BP-HZN-BLY00060717].

[74] *DNV Report*, *p.* 43-51

[75] See Appendix E for a review of the Michoud AMF/deadman testing.

4.6.2 Solenoids Laboratory Bench Testing

During the Phase 1 testing, the bench testing of the solenoids did not include simultaneous energizing of both coils. Instead, individual coils were energized to determine pick-up and drop-out voltages. The tests were performed under laboratory conditions, ambient temperature, and without pressure applied to the inlet.[76]

During Phase 2, additional tests were performed on the solenoid valves to determine how they operated at deep sea temperatures (approximately 32-34ºF). These tests were accomplished first without pressure, and then with 3,000 psig pressure.[77] Solenoids from the yellow pod, SV 3AY, SV 103Y, and SV 103R, and from the blue pod, SV 103B, were tested in the laboratory setup. A microphone was mounted inside the cold test chamber to pick up valve actuation. The protocol called for energizing coils A and B separately, then A and B simultaneously using a laboratory 24vdc power supply. SV 3AY and SV 103Y both failed to actuate when both A and B coils were energized.[78] Since the test facility was noisy, additional tests were accomplished with 3,000 psig hydraulic pressure. Again, solenoids SV 3AY and SV 103Y failed only on the simultaneous A and B tests.[79]

The results of these simultaneous coil tests indicated that the polarity of the two coils in SV 3AY and SV 103Y were opposing, therefore negating each other's magnetic effect under constant 24vdc power, which caused the solenoid valve to not actuate.

4.6.3 Solenoids Disassembly: Verification of Miswiring

During Phase 2 testing, technicians disassembled and compared four solenoids to Cameron specifications, SV 3AY, SV 103Y, SV 103R and SV 103B.[80] As indicated in the photograph of one of the disassembled solenoids (Figure 10),

[76] *DNV Report*, p. 41-42.
[77] Phase 2 Test Preparation Sheet DNV2011051601:TPS BOP-009 and DNV2011051801 :TPS BOP-010.
[78] Phase 2 Test Preparation Sheet DNV2011051601 : TPS BOP-009, p. 2-3.
[79] Phase 2 Test Preparation Sheet DNV2011051801 : TPS BOP-010 p. 2-3.
[80] Disassembly and verification of wiring connections appear as follows: Phase 2 Test Preparation Sheet DNV2011052708, May 27, 2011, for original solenoid valve 103 yellow; Phase 2 Test Preparation Sheet DNV2011052603, May 26, 2011, for solenoid valve 3A yellow; Phase 2 Test Preparation Sheet DNV2011052602, May 26, 2011, for solenoid valve 103 blue; and Phase 2 Test Preparation Sheet DNV2011052513, May 25, 2011, for solenoid valve 103 replacement.

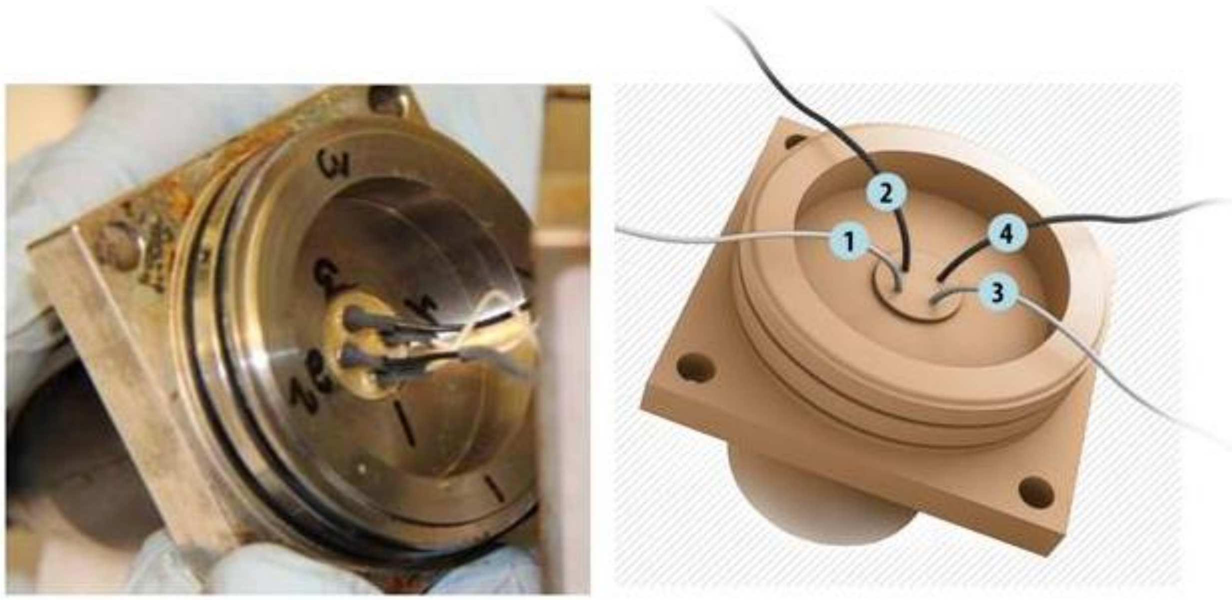

Figure 10. (Left) Photograph of Y103 wire arrangement from Phase 2 testing with pins 1 and 4 connected to white wires and 2 and 3 connected to black wires. (Right) Schematic of correct arrangement of wires, with pins 1 and 3 connected to white wires and 2 and 4 connected to black wires.

one coil end was terminated with a white insulated wire and the other end was terminated with a black insulated wire. Pin assignments inside the housing were consistent with the cable outside the housing which connected each solenoid valve to its SEM. Pins 1 and 2 were for coil #1, and Pins 3 and 4 were for coil #2.

SV 103R was found to be connected as follows: white to Pin 1, black to Pin 2, white to Pin 3, and black to Pin 4. This solenoid valve appeared to be correctly wired. SV 103B had the same wiring arrangement. SV 3A and SV 103Y, both had reversed colors (black-white rather than white-black) on one coil. The reversed colors verified that one coil had been miswired in each of the solenoid valves.

4.7 How a Miswired Solenoid Valve Operates

Bench testing of SV 3A and SV 103Y during Phase 2 indicated that simultaneously energizing both coils (with one coil reverse-wired) resulted in no actuation of the solenoid. This bench testing used constant 24 volt DC power. However, the SEMs do not use constant voltage DC power to energize the solenoids. They use a cycling pulse-width-modulated (PWM) voltage that peaks at 24 volts. Due to the properties of this SEM-generated PWM, the effective voltage, measured with a multimeter during Phase 1 solenoid testing, cycled from an initial high of 24-26 volts to a subsequent low of 13-15 volts.[81] See Figure 11 below. This is a common technique used to minimize power to a solenoid. The high voltage (long pulse) “pulls in” the solenoid, and then the lower voltage (short pulses) are sufficient to “hold it in.” The PWM power supply thus minimized battery drain during AMF/deadman sequencing and reduced heat buildup in the solenoids.

[81] The multimeter measures a type of average voltage called the root-mean-squared (RMS) voltage.

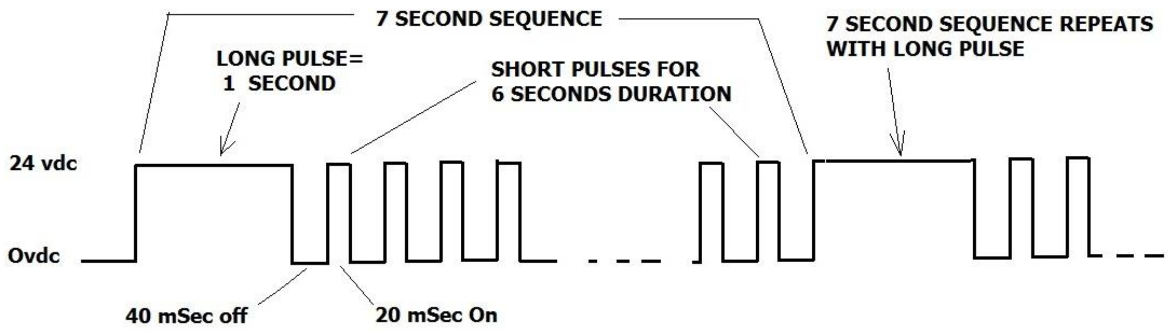

Figure 11. Pulse Width Voltage Sequence (Engineering Services)

Since the PWM-applied voltages are not constant, we considered the possibility that the two opposing coils in a miswired solenoid might not fully cancel each other all of the time. The PWM cycle for each coil could be out of sync, permitting periods when one coil was at an effective voltage peak while the other was at an effective voltage minimum. These periods of non-zero net voltage might allow operation of the solenoid for short periods of the total 7 second cycle sequence.

To test this hypothesis, the CSB sponsored testing of an exemplar solenoid valve to determine whether any out-of-sync energizing of the two opposite polarity solenoid valve coils would permit the valve to open.[82] (More details of this testing are presented in Appendix E.)

Out-of-sync operation between the two AMF/deadman cards in the yellow pod could result from differences in SEM A and B PLC reboot timing, differences in electronic component tolerances, and different response times to the interpretation of the loss of hydraulic pressure. Cameron's QA testing documents for AMF/deadman FAT procedures[83] contained the following note: "The AMF/deadman card in the PLC rack has a delay of 12-15 seconds once all conditions are met." The timing tolerance between the two AMF/deadman cards, therefore, appeared to be as much as 3 seconds different based on this situation anticipated by this note alone. An Engineering Services analysis of the AMF/deadman tests from Michoud concludes that the SEMs can be out of sync by as much as 6 seconds.[84] ES testing showed that the SEMs can experience a short cycle differential delay that can allow one coil to actuate before the other miswired coil is able to oppose its magnetic effect. This minor offsetting of effective voltage can cause the solenoid to open briefly. Our tests of a 30-second duration solenoid valve open signal (matching the programming of the AMF/deadman sequence) could have produced as much as 13 seconds of opening time for SV 103Y, based on the SEMs being out of sync by at least 3 seconds.

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[82] The test took place in a lab of Koester Corporation, Napoleon, Ohio on September 18-20, 2012. Additional follow-up testing was accomplished in Kingwood, Texas on November 12, 2012.

[83] Factor Acceptance Test Procedure for Subsea Electronic Module, Document No. X-065449-02, June 1999, p. 34 [CAM-CSB000013890].

[84] See the spreadsheet analysis of SV 103 timing for five AMF/deadman Tests at Michoud in Appendix E. CSB testing included a series of out-of-sync tests, and ES developed a graphics program to analyze the test results.

Evidence suggests that this type of limited, partial operation of a miswired solenoid was possible. The Upper Annular Preventer "increase pressure" solenoid valve for the yellow pod, SV 3AY, was also found to be miswired during Phase 2 testing. During testing on the Q4000, test results noted that it was "sluggish—activate & takes a long time to fire, skips."[85,86] Normally, in order to increase the pressure of the upper annular preventer, the appropriate button on the rig was simply depressed. However, if the yellow pod was selected from the rig, this would not have been the case. At best, assuming the valve stayed open while the button was pressed, the limited, partial movement caused by the miswired solenoid would be manifest as a slow-operating, or "sluggish" valve. Even if the miswired SV 3AY would only stay open for a short period of time and then close, rig operators could possibly have succeeded in using it by persistently pressing the control system push button rather than just holding it down.

A handheld electrostatic field detector in the form of a "light pen" had been used during initial functional testing of SV 103Y on the Q4000, so ES also tested the electrostatic field around the exemplar solenoid while it was being operated in opposing polarity mode as well as in correct polarity mode. Our electrostatic tests aimed to determine the effectiveness of the handheld detector tests by observing whether the magnetic and electrostatic fields outside the stainless steel solenoid casing would permit the observer to differentiate between electromagnetic fields of coils that were of the same polarity and those that were of opposing polarity. We determined that the sensitivity of the light pen used in the Q4000 testing of SV 103 could possibly detect the fields, but it would register only the net electrostatic effect of the opposing coils (i.e., no solenoid actuation).

In summary, we reached the following conclusions from our exemplar testing:

1. The minimum offset between coils which produced any valve actuation was 250 mSec.
2. Delays of more than 250 mSec due to out-of-sync PWM voltage sources and short-cycle effects, similar to that which we saw during component testing at Michoud, could cause the solenoid valve to be open in a series of periodic pulses.
3. Delays of more than 3 seconds could cause the valve to open for as much as 40% of the duration of the PWM sequence (for 12 seconds of a complete 30 second cycle in this case).[87]

4.8 BOP Batteries

The AMF/deadman emergency shut-in procedure was totally dependent on the viability of at least one 9 volt battery pack and the 27 volt battery pack in the same control pod. AMF/deadman was the only emergency shut-in system that relied on batteries for initiating the sequence. Normal operations, manual initiation of EDS, and autoshear modes did not rely on the BOP batteries. Lithium manganese dioxide batteries which evidence an extremely low voltage can be obviously identified as a failed battery. However, open circuit voltage tests on severely drained batteries can show near-normal voltages which cannot indicate available battery life unless load tested. This type of battery has a very flat discharge curve over its life cycle. The voltage will remain in range

[85] The test was intended to activate the solenoid on just one coil, but as explained earlier, ES believes the PETU being used was actually actuating both SEM A and SEM B simultaneously rather than one at a time.

[86] Handwritten note by Cameron representative on Deck Test Procedure for Mark-II Control Pod, for solenoid (3A), "sluggish—activate & takes a long time to fire, skips." [BP-HZN-BLY00060717].

[87] The test protocol, further analysis, and data appear in Appendix E: CSB Exemplar Solenoid Testing.

when not under load and can recover some voltage and power after load has been imposed and removed. The batteries used in the BOP were not rechargeable.

4.8.1 Age of BOP Batteries

Our investigation of the age of the batteries in the blue and yellow pods at the time of the accident differ from the findings in the *Transocean Report*.

The *Transocean Report* states:

> Cameron recommends replacing the batteries after one year of operation or 33 AMF/deadman actuations, or within five years of shelf life. The Deepwater Horizon pod batteries were last changed on the following dates:
>
> - Pod No. 1 (Blue pod) on April 25, 2009
> - Pod No. 2 (Yellow pod) on Oct. 13, 2009
> - Pod No. 3 (spare pod) on Nov. 4, 2007
>
> During a routine rig condition assessment on the Deepwater Horizon in April 2010, ModuSpec confirmed that all batteries in the SEMs were new.[88]

However, testimony given the U.S. District Court for the Eastern District of Louisiana case revealed that the batteries for the pod in the blue position were last replaced in November of 2007,[89] a date which is more consistent with the battery manufacturer's date codes observed during post-incident inspection.

The following table shows the battery date codes as inspected by technicians during the SEM observations during Phase 2: [90]

Table 4-2: 27 volt Battery Inspection History

Pod	**27 VOLT BATTERY PACKS**			**9v SEM A**	**9v SEM B**	**Date Installed**
Blue	01/2006	01/2006	01/2006	10/2005	10/2005	2007
Yellow	05/2009	04/2009	04/2009	04/2009	04/2009	2009

Engineering Services

[88] Battery dates are from the *Transocean Report*, Appendix N, p. 4.

[89] Testimony given in the U.S. District Court for the Eastern District of Louisiana under the Multi-District Litigation docket MDL No. 2179, see McWhorter Designations Vol 1, p, 78-79 where he describes that pod #3 was in the blue stack and pod #2 was in the yellow stack at the time of the incident. Also refer to Exhibit #3792, publicly accessible at http://www.mdl2179trialdocs.com/releases/release201302281700004/McWhorter_Jim-Depo_Bundle.zip.

[90] Phase 2 Test Preparation Sheet Test Protocol Sheets DNV2011061603: TPS BOP-027 and DNV2011061602: PS BOP-028.

4.8.2 Overview of Battery Expectations and Engineering Services Investigation of the DWH BOP Batteries

Engineering Services investigated the operation of the BOP batteries including their intended and actual function during the AMF/deadman arming duration, emergency initiation of the solenoid firing sequence and conclusion of that sequence. This research resulted in the development of a typical profile of battery pack capacity drain in both the 9 volt and 27 volt batteries.

4.8.2.1 The 9 volt Battery Pack Loads

Our calculations of the theoretical loads showed that the long term arming activity, while drilling, imposed a greater load on a 9 volt battery while powering only the AMF card than did the loads imposed by an actual AMF/deadman firing sequence. While the AMF firing sequence imposes a heavy 5.5-7.0 amp load on the 9 volt battery, it does so for only 37 seconds.[91] This is defined as one (1) actuation. In contrast, the AMF arming duration imposed less than 2 milliamperes of load to run the AMF CPU,[92] but for a much longer time. In our case it had to do so from February 8, 2010 to April 20, 2010 (71 days). This amounts to some 6.13 million seconds. Simply multiplying current times the time duration tells us that the arming cycle consumed 48.5-60.2 times as much battery capacity than it needed during the 37 seconds of heavier loading while the AMF/deadman was rebooting and running the SEM programmable logic controller (PLC) CPU. This is important because it shows that the small continuing drain on a 9 volt battery can lead to more serious depletion of that battery leading up to the all-important emergency event, when it needs to then provide a much heavier load to also power the SEM through its solenoid control sequence. If the 9 volt battery is aging, or has some internal defect, it may provide sufficient power for the arming phase, but then fail just when it is required to produce the heavier load imposed by the initiation of the emergency AMF sequence.

Load testing evidence indicates there was an internal battery deficiency in the 9 volt SEM B battery pack in the yellow pod on April 20, 2010 not experienced by the SEM A battery. During load testing of both batteries during Phase 2, the SEM A battery tested much better than the SEM B battery. Since both batteries had the same date codes and were being used in the same pod, there is no known reason for the two battery packs to have such different results in the load testing. Ultimately, this likely failure of the SEM B battery subsea would have permitted the AMF/deadman sequence to successfully initiate to close the Blind Shear Rams.

4.8.2.2 The 27 volt Battery Pack Loads

The 27 volt battery packs in the Cameron design are not intended to be utilized in any way until they are connected to the subsea ambient pressure and hydraulic conduit supply pressure sensors (transducers and one AMF card relay coil) once the AMF card senses a complete loss of deck power/communications. Once the AMF card senses the additional critical condition that hydraulic supply pressure is lost, the AMF/deadman will begin its reboot of the SEM PLC and signal the need for it to execute the AMF/deadman sequence. Only during that phase,

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[91] "FAT Procedure for SEM" CAM-CSB 000014282

[92] *Ibid* - page 000014277 and "Battery Pack Longevity Tests" TREX 5153 dated 03/22/04, pg. 3

will the 27 volt battery pack provide the power necessary to fire the solenoids in the programmed sequence controlled by the SEM PLC. Based on this understanding of how the 27 volt battery is delivering power over the course of a drilling cycle, we found that this battery should see no drain on its capacity until an emergency event occurs or when being tested in an AMF/deadman FAT or deck test.

If rig power and communications are lost before hydraulic pressure is lost, the 27 volt battery will be connected to power the pressure transducers in order to verify the subsequent loss of hydraulic pressure. In a catastrophic emergency situation similar to that which occurred on the Deepwater Horizon, the 27 volt battery might only have to power the sensors for a few seconds at most. The load imposed by these pressure sensors was calculated to be only 30.53 milliamperes (based on actual pressure transducer ratings, conditions at the time plus 8mA for the relay coil). This is a minimal load considering the short time frame in which it is usually imposed. When the SEM has started its solenoid control sequence, the 27 volt battery load increases dramatically as it fires the programmed solenoids ending with solenoid valve 103 which should close the BSRs and set the ST Locks. The SEM PLC finalizes its 37 second sequence by causing the 27 volt battery to power a final 12 volt pulse which shifts the bi-stable relay on the AMF card back to the dis-armed position and causes both the 9 volt and 27 volt battery packs to be disconnected.

Engineering Services calculated that one completed AMF/deadman sequence should only consume 0.64 amp-hrs or 1.5% of the initial design capacity of 42 amp-hrs for the 27 volt battery pack. Assuming that the 27 volt battery was utilized for 33 AMF/deadman actuation sequences, a simplistic calculation would imply that the 27 volt battery pack could easily handle that number of actuations with 50% capacity remaining. These calculations and the discussion above regarding the 9 volt battery typical discharge profile, led us to consider the important question of why the blue pod 27 volt battery failed rather that the 9 volt batteries in that pod. Load testing of the 9 volt blue pod batteries at Michoud proved that they were still viable, even after being utilized beyond Cameron's recommended limitations of 1 year of service or 33 AMF actuations. One possible answer as to why the 27 volt battery was depleted was that the blue pod had been subjected to numerous AMF/deadman tests and emergency activations. If this were the case and the ratio of AMF tests relative to the length of total AMF arming duration was high, then we might consider that as a factor which could explain the depletion of the 27 volt battery much more quickly than the 9 volt batteries in the blue pod.

The question of why the blue pod 27 volt battery was so depleted compared to the 9 volt batteries was answered in that it had been subjected to a premature connection to pressure sensors as soon as the AMF was armed subsea. This was caused by the miswiring in the blue pod SEM documented by technicians during phase 2 testing. The effect of this miswiring was to cause the logic in the AMF card to immediately connect the 27 volt batteries to long-term transducer loads at the start of each drilling cycle. Our calculations show that the pressure transducers and relay coil loads on the 27 volt battery could have consumed as much as 80% of its useful capacity on the Macondo well.[93]

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[93] These calculations are based on the interpolated ratio of the (4-20 mA) pressure transducer actual pressures to the rated pressure of each transducer. The hydraulic conduit P/T rating was 12,000 psi; actual pressure was 5500; and the interpolated (4-20mA) result was 11.33 mA. The ambient subsea pressure P/T rating was 5000 psi; actual pressure was

4.8.3 Battery Testing Results

The yellow and blue pod batteries were initially tested, not under load, on the Q4000 and Enterprise with the following results.

Table 4-3. Battery Testing on the Q4000 – Yellow pod[94]

Battery	Test 1 Volts
SEM A (9V)	8.85
SEM B (9V)	8.85
Solenoid/Transducer (27V)	18.41 *

The reading for the 27 volt battery is suspect because later readings during Phase 1 indicated that this 27 volt battery had good voltage of 28.2 volts. The technician might have tested the incorrect terminals for the 27 volt battery and effectively tested the differential between 27 volt and 9 volt batteries (28.2v – 8.85v = 19.35v).

Table 4-4. Battery Testing on the Enterprise – Blue pod[95]

Battery	Test 1 Volts	Test 2 Volts
SEM A (9V)	8.78	8.77
SEM B (9V)	0.142*	0.142*
Solenoid/Transducer (27V)	7.61	7.61

These readings for the SEM B battery are suspect because later readings at Michoud indicated that this 9 volt battery had good voltage and passed the load tests. The technician might have tested the incorrect terminals, measuring the differential between the failed 27 volt battery and the good 9 volt battery.

During the Phase 1 testing, technicians measured battery voltages externally at the pie connections. Table 4-5 indicates the as-received voltages measured at Michoud for the control pod batteries. The blue pod 27 volt battery failed, showing minimal residual voltage.

2250; and the interpolated (4-20mA) result was 11.20 mA. Adding these results to the 8 mA load for the relay coil = 30.53 mA.

94 Cameron Daily Report Sheet – 5 May 2010 [CAM-CSB 000015435].

95 Blue Pod Recovery Log – 5 July 2010; BP-HZN-BLY00061 076

Table 4-5. As-received blue and yellow pod battery testing at Michoud[96]

Battery	Blue Pod Test 1 Volts	Blue Pod Test 2 Volts	Yellow Pod Test 1 Volts	Yellow Pod Test 2 Volts
SEM A (9V)	8.9	8.9	8.7	8.7
SEM B (9V)	8.7	8.7	8.4	8.4
Solenoid/Transducer (27V)	1.1	1.0	28.2	28.2

Table 4-6 shows the results of load testing, first using a 100 ohm resistor, and then using a 20 ohm resistor. The yellow pod SEM B 9 volt battery dipped below 8.0 volts in the 20 ohm load test, indicating that it was the most susceptible to failure of any of the 9 volt batteries.

Table 4-6. Battery load test results from Phase 1.[97]

	Blue Pod				Yellow Pod			
	Load Resistor				Load Resistor			
	100 Ohm		20 Ohm		100 Ohm		20 Ohm	
	Voltage				Voltage			
Battery Description	**Initial**	**After 2 Min.**	**Initial**	**After 2 Min.**	**Initial**	**After 2 Min.**	**Initial**	**After 2 Min.**
SEM A (9V)	8.6	8.6	8.3	8.2	8.3	8.3	8.0	8.0
SEM B (9V)	8.4	8.4	8.1	8.0	8.1	8.1	7.7	7.6
Sol. & P/T (27V)	N/A	N/A	N/A	N/A	27.1	26.9	26	25.4

Table 4-7. Battery Test Voltages following the AMF/deadman tests (not under load) from Phase 1.[98]

Battery Description	Blue Pod (Volts)	Yellow Pod (Volts)
SEM A (9V)	8.9	8.6
SEM B (9V)	8.6	8.4
Solenoid/Transducer (27V)	0.7	27.7

The load tests are a better measure of the battery's health and possible remaining life than a voltage test. The 9 volt battery packs had to maintain a minimum of 5vdc during load testing to assure that the battery could reboot

[96] *DNV Report*, p. 42.

[97] *DNV Report*, p. 43.

[98] *DNV Report*, p. 46.

the PLC in the SEM. During Phase 1 testing, The SEM B 9 volt battery for the yellow pod exhibited a voltage dip to 7.6 volts when tested with a 20 ohm resistor. The 20 ohm load was not sufficient though to stress the 9 volt battery to its routine limits. During Phase 2 testing, additional tests that more closely emulated the AMF/deadman load scenario revealed that the 9 volt SEM B battery in the yellow pod had failed (see Appendix A for analysis on the appropriate load testing).

Figure 12 and Figure 13 show that only the SEM B 9 volt battery in the yellow pod failed both ambient and cold load tests during Phase 2 testing.

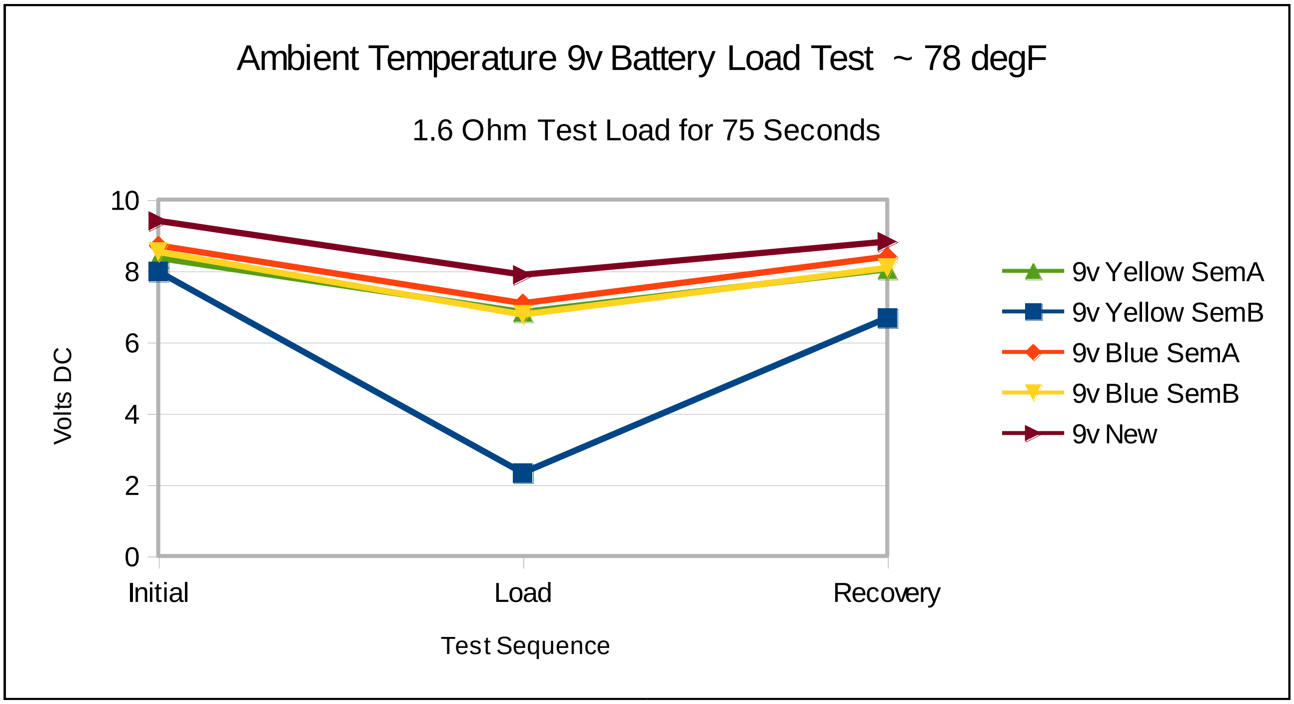


Figure 12. Ambient load testing of the 9 volt batteries during Phase 2.

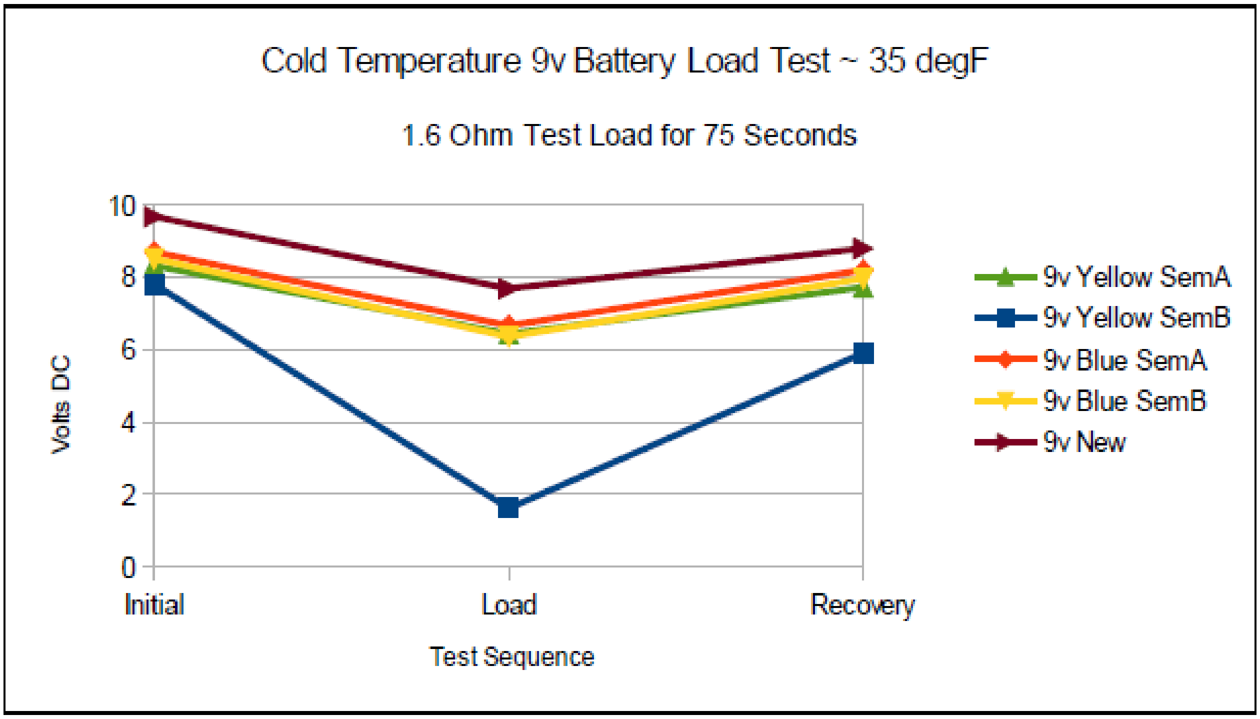


Figure 13. Cold temperature load testing of the 9 volt batteries during Phase 2.

4.9 AMF/deadman testing at Michoud

ES believes that the 9 volt SEM B battery in the yellow pod failed during AMF/deadman testing at Michoud on March 3, 2011, otherwise the partial success of the AMF/deadman tests using the miswired 103 Y original solenoid could not have occurred. The failure of this battery while rebooting and operating the AMF/deadman card and PLC in SEM B caused the solenoid valve 103 original to work correctly on only the SEM A solenoid coil for the last seven seconds of the sequence (See Appendix E for more details).

The load testing of the yellow SEM B battery in both Phase 1 and Phase 2 indicated that the battery capacity had deteriorated between March 4, 2011 and June 18, 2011. This deterioration might have been due to a combination of unexplained internal cell failure, AMF/deadman testing load and/or battery load testing. After considering the fact that the 9 volt SEM B battery experienced failure during AMF/deadman testing, we then attempted to analyze the battery's condition subsea on April 20, 2010. ES estimates that the Yellow pod SEM B 9 volt battery should have had 91% of useful life remaining even after the AMF/deadman tests during Phase 1 and load testing in Phase 2 (See Appendix A). Since this battery failed load testing and the SEM A 9 volt battery was still viable, we conclude that this battery pack (manufacturer date codes indicate April 2009) suffered a premature failure and depletion of its amp-hour capacity. The failure may be due to a latent internal defect, though external defects cannot be dismissed.[99]

4.10 Actuation of the AMF/deadman Sequence on April 20, 2010

Since the yellow pod SEM B battery failed to successfully execute AMF/deadman at Michoud where the ambient temperature was between 60 and 70ºF, the possibility exists that the battery had failed in subsea service during the incident due to lower temperatures and subsequent decreased capacity. This would be important because the failure of one SEM in the yellow pod during the AMF/deadman sequence would cause the miswired SV 103 to actuate successfully on one coil. The ES review of the SAFT temperature derating tables for these cells indicates that the decrease in battery capacity could be as much as 12-15 percent given a 20ºC temperature difference (20ºC - 0ºC) between Michoud ambient and subsea operation, making it likely the battery would not have had sufficient power to energize the SEM B coil on the day of the incident (See Appendix A). Despite actuation of the blind shear ram as part of the AMF/deadman sequence, drill pipe buckled off-center in the BOP prohibited the BSR from fully closing and sealing the well

5 Conclusion

The main focus of the ES MUX control system investigation has been on the events that occurred after the release of hydrocarbons on the rig caused catastrophic explosions which damaged the ability of the surface control system to shut in the well with human intervention. Once the surface controls were rendered inoperable, the only remaining system that could detect the damage and attempt to prevent additional hydrocarbons from being released was the subsea blowout preventer and its electro-hydraulic control system. The autoshear was not triggered during the incident, but was initiated during the ROV intervention in the days following the disaster. The only other emergency shut-in system that required no human intervention and that was left to respond was the AMF/deadman. That system eventually became the focus of the CSB's controls investigation.

The Mark II MUX control system emergency shut-in procedure (AMF/deadman) was vulnerable to failure due to its dependence on battery power to complete the required sequence of solenoids to close the blind shear ram. Battery capacity was limited. AMF/deadman testing was discouraged because of the resulting drain on the batteries. Without periodic testing, however, component failures within the AMF/deadman system such as miswired components or failed batteries could not be detected. Battery life concerns were at odds with the need to verify the availability of the AMF/deadman components.

Cameron's advice to users of the Mark II batteries covers parameters for predicting the useful life of these emergency batteries including maximum shelf life, number of actuations and time in service. All of these requirements depend on human observations and maintenance programs to predict the time of replacement. There was no real-time method to analyze remaining life of the 9 volt or 27 volt battery packs.

[99] See Appendix A: Yellow Pod Battery Drain Analysis.

The Mark II MUX control system redundancy relies, in part, on the application of dual-coil solenoids to improve the availability of the solenoid and to initiate the function from either of the two SEM control PLCs. The dual-coil concept is valid unless one coil is miswired, which causes it to work in opposition to the correctly wired coil. Coil polarity must be verified after any refurbishment and after its placement on the pod, to realize the true redundancy.

The reverse polarity of one coil of a dual-coil solenoid is a fault condition that could have been monitored by programming the system diagnostics, which would analyze the functioning of each solenoid coil separately and together and analyzing the results. However, the Mark II system did not have this type of system diagnostic; rather, to catch solenoid defects, it relied on procedures to verify proper refurbishment and testing procedures. This made the solenoids vulnerable to human error by maintenance technicians.

The more troublesome defect in the MUX control system was the miswiring of the blue pod SEM. Wire tracing efforts during Phase 2 testing revealed that the AMF/deadman circuits were not wired consistent with the available drawings. Without unfettered access to the Phase 2 testing details or to the proprietary design of the AMF/deadman card and SEM, ES can only hypothesize the impact of those wiring nonconformances on the AMF/deadman system. The fact remains that the blue pod and yellow pod SEMs were wired differently.

Appendices

Appendix A: Control Pod System Battery Information, Testing, and Analysis

The batteries in service on the Deepwater Horizon BOP were manufactured by SAFT. The 9 volt and 27 volt battery packs were assembled by using multiple cells to achieve the required voltage and amp-hour capacity. The following are catalog cuts from the battery cell manufacturer's website.[100]

Primary lithium battery
LM 33550

3 V Primary lithium-manganese dioxide
High power
D-size spiral cell

For applications requesting excellent voltage response and operating life in -40°C/+70°C environments.

Benefits

- High voltage response, stable during most of the lifetime of the application
- High drain/pulse capability
- Minimum voltage delay after long dormant periods
- Competitive capacity at high current and low temperature
- Easy integration into compact systems
- Low self-discharge rate *(less than 3 % after 1 year of storage at +20°C)*

Key features

- Steel container
- Hermetic glass-to-metal sealing
- Built-in safety vent
- Non-corrosive electrolyte
- Restricted for transport *(Class 9)*
- Made in the USA

Main applications

- Radiocommunication
- Measuring equipment
- Marine equipment
- ELTS, EPIRBS, etc...

Cell size reference		**R20 – D**
Electrical characteristics		
(typical values relative to cells stored for one year or less at +30°C max.)		
Nominal capacity *(at 250 mA +20°C 2.0 V cut-off. The capacity restored by the cell varies according to current drain, temperature and cut-off)*		12 Ah
Open Circuit Voltage	(at +20°C)	3.2 V
Nominal voltage	(under 1 mA at +20°C)	3.0 V
Pulse capability : Typically up to 8 A *(The voltage readings may vary according to the pulse characteristics, the temperature, and the cell's previous history. Fitting the cell with a capacitor may be recommended in severe conditions. Consult Saft)*		
Maximum recommended continuous current *(to maintain cell heating within safe limits)*		4 A
Storage	(recommended) (for more severe conditions, consult Saft)	+30°C (+86°F) max
Operating temperature range *(Operation below ambient T may lead to reduced capacity and lower voltage readings)*		-40°C/+70°C (-40°F/+158°F)
Physical characteristics (with sleeve)		
Diameter (max)		34.2 mm (1.35 in)
Height (max, without tabs)		61.4 mm (2.42 in)
Typical weight		120 g (4.23 oz)
Li metal content		approx. 3.7 g
Standard cell comes with vent washer at the bottom and two radial 0.15 mm thick nickel tabs Other configurations available on request.		

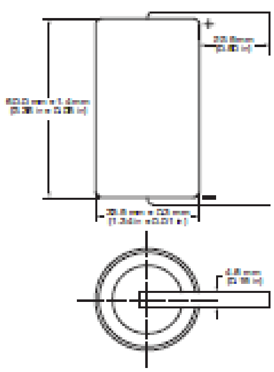
saft

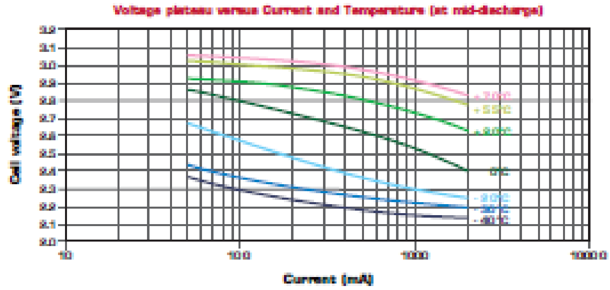
July 2009

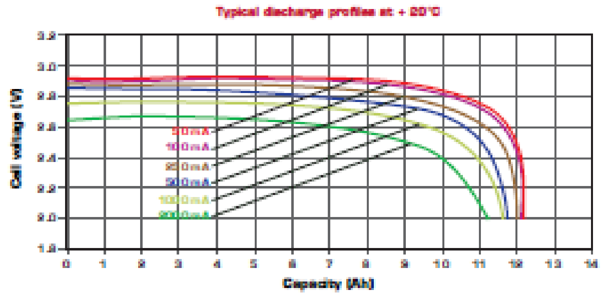
Figure 14. Catalog cuts from the battery cell manufacturer's website.

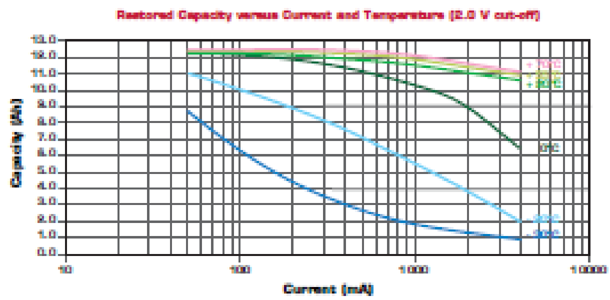
[100] www.saftbatteries.com/force_download/LM_33550.pdf

LM 33550









Storage

- The storage area should be clean, cool, dry and ventilated.

Warning

- Fire, explosion and burn hazard.
- Do not recharge, short circuit, crush, disassemble, heat above 70°C (158°F), incinerate, or expose contents to water.
- Do not solder directly to the cell *(use tabbed cell versions instead).*

Saft
Specialty Battery Group
12, rue Sadi Carnot
93170 Bagnolet - France
Tel.: +33 (0)1 49 93 19 18
Fax: +33 (0)1 49 93 19 69

313 Crescent Street
Valdese, NC 28690 - USA
Tel.: +1 (828) 874 4111
Fax: +1 (828) 879 3981

www.saftbatteries.com

Doc. N° 31094-2-0708

Information in this document is subject to change without notice and becomes contractual only after written confirmation by Saft.

For more details on primary lithium technologies please refer to Primary Lithium Batteries Selector Guide Doc N° 31048-2.

Published by the Communications Department.

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Société anonyme au capital de 31 944 000 €
RCS Bobigny B 383 703 873

Produced by Arthur Associates Limited.

saft

Figure 15. Catalog cuts from the battery cell manufacturer’s website.

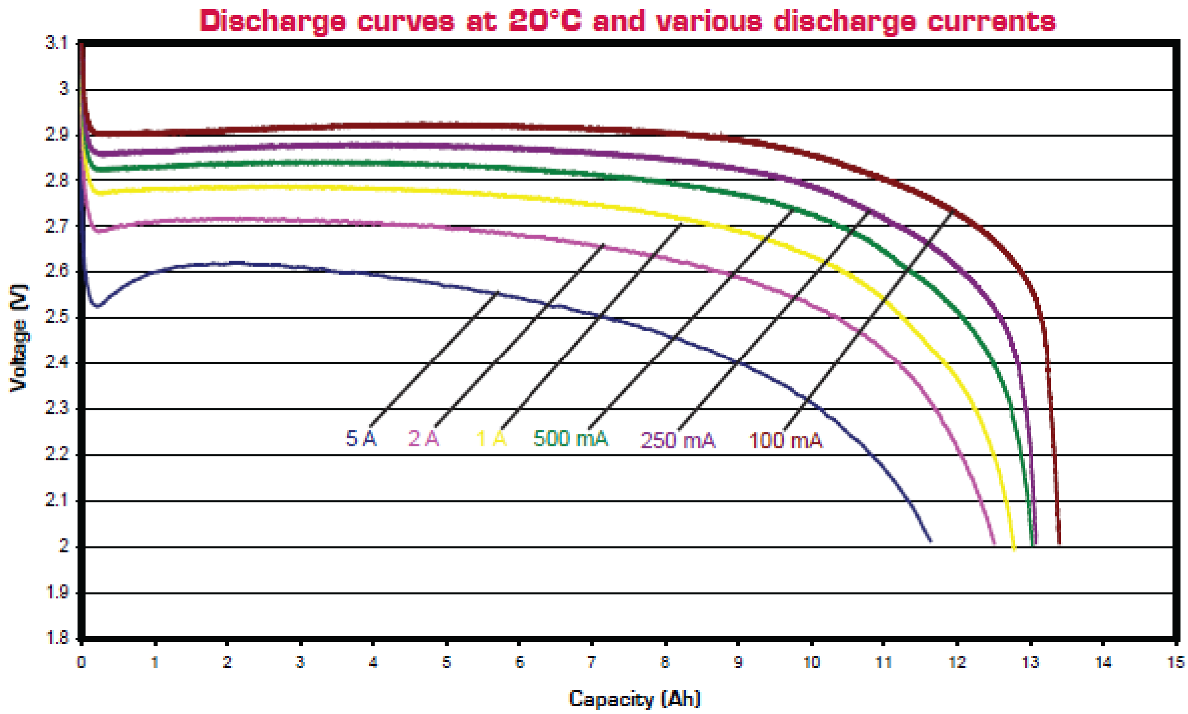


Figure 16. Catalog cuts from the battery cell manufacturer's website.

A.1 Battery Parts Documentation

The following data from the Phase 2 inspections document the date codes of the SEM batteries as found in each pod. Date codes are coded as follows: Four digit number followed by a single letter. The first two digits indicate MONTH, following 2 digits indicate YEAR, and the letter corresponds to the Week of Month of manufacture.[101]

[101] Testimony given in the U.S. District Court for the Eastern District of Louisiana under the Multi-District Litigation docket MDL No. 2179, see Gaude Designations, p 36, publicly accessible at http://www.mdl2179trialdocs.com/releases/release201302281700004/Gaude_Ed-Depo_Bundle.zip.

A.1.1 Blue Pod Batteries[102]

Battery Pack Blue Pod - SEM A

Cameron Part No. 2232368-01
Contract No. 4500604090
Date Code: **1005-C**
S/N: 000269 Connector: -X78
Location: Top from flange – Side of 2 batteries

Battery Pack Blue Pod - SEM B

Cameron Part No. 2232368-01
Contract No. 4500604090
Date Code: **1005-C**
S/N: 000267 Connector: -X79 Note: gash on battery
Location: Bottom side from flange – Side of 2 batteries

Battery Pack Blue Pod – 27VDC

Cameron Part No. 2232368-01
Contract No. 4500633612
Date Code: **0106-B**
S/N: 000353 Connector: -X80 (Positive term)
Location: Top from flange – 3 batt side

Battery Pack Blue Pod - 27VDC

Cameron Part No. 2232368-01
Contract No. 4500633612
Date Code: **0106-B**
S/N: 000435 Connector: -X76 Note: scratch on battery cover
Location: Middle battery on 3 batt side

[102] Phase 2 Test Preparation Sheet, DNV2011061603: BOP-027.

Battery Pack Blue Pod - 27VDC

Cameron Part No. 2232368-01
Contract No. 4500633612
Date Code: **0106-B**
S/N: 000333 Connector: -X77
Location: Bottom battery on 3 batt side (+27VDC)

A.1.2 Yellow Pod[103]

Battery Pack Yellow Pod - SEM B

Cameron Part No. 2232368-01
Contract No. 4501923014 (45019230140)
Date Code: **0409A**
S/N: 000706 Connector: -X79
Location: Top from flange – 2 batt side

Battery Pack Yellow Pod - SEM A

Cameron Part No. 2232368-01
Contract No. 4501923014
Date Code: **0409A**
S/N: 000705 Connector: -X78
Location: Top from flange – 2 batt side

Battery Pack Yellow Pod – 27VDC

Cameron Part No. 2232368-01
Contract No. 4501923014
Date Code: **0509D**
S/N: 000743 Connector: -X77 (Negative term)
Location: Top from flange – 3 batt side

[103] Phase 2 Test Preparation Sheet, DNV2011061602: BOP-028.

Battery Pack Yellow Pod - 27VDC

Cameron Part No. 2232368-01
Contract No. 4501923014
Date Code: **0409A**
S/N: 000703 Connector: -X76
Location: Middle from flange – 3 batt side

Battery Pack Yellow Pod - 27VDC

Cameron Part No. 2232368-01
Contract No. 4501923014
Date Code: **0409A**
S/N: 000704 Connector: -X80 (Positive term)
Location: Bottom from flange – +27 volt batt side

A.2 Battery Testing, Phase 2[104]

The following data is included from the Phase 2 load testing of the pod batteries and exemplar batteries with date codes of October 2010. These load tests were accomplished in warm ambient (77+ºF) and cold subsea (35-39ºF) temperatures.

[104] Phase 2 Test Preparation Sheets, DNV2011061701: BOP-029 (6/17/11), exemplar (new) 9 volt and 27 volt battery load tests (20 ohms - ambient); DNV2011061702: BOP-030, exemplar (new) batteries cold load tests (1.5 ohm, 10 ohm –35ºF); DNV2011061802: BOP-032 (6/18/11), exemplar (new) and pod batteries cold load tests (1.5 and 10 ohm); DNV2011061903: BOP-030 (6/19/11), exemplar (new) and pod batteries ambient load tests (1.5 and 10 ohm).

Exemplar (new) battery load test. (20 ohm load only)

Battery: New 9V Part No.: 2232368-01 Rev 02
Date Code: 1010-A S/N: 0001124
Initial Battery Voltage: 9.66 vdc – No load
Battery Voltage after 3 minutes at load: 9.13 vdc
Battery Voltage recovered: 9.36 vdc (after some unknown time)

Exemplar (new) battery load test: (20 ohm load only)

Battery: New 27V Part No.: 2232368-01 Rev 02
Date Code: 1010-A (All- top, middle and bottom)
S/N: 0001122 – top, 0001119 – middle, 0001123 – bottom
Initial Battery Voltage: 28.76 vdc – No load
Battery Voltage after 3 minutes at load:26.00 vdc
Battery Voltage recovered: 27.01 and climbing (after some unknown time)

Exemplar (new) batteries – at Deep Sea cold temperature

Battery load resistance: 1.5 ohms
Battery Temperature: 35 DegF at start of test
Initial Battery Voltage: 9.66 vdc
Battery Voltage after 75 seconds: 7.63 vdc, 4.8 amps
Battery Voltage recovered: 8.72 climbing
Battery Temperature: 34.9 degF at end of test

Battery load resistance: 10 ohms
Battery Temperature – “ambient” ? (Temperatures not recorded for this test; assumed near 34 degF)
Initial Battery Voltage: 27.55 vdc
Battery Voltage after 75 seconds: 25.43 vdc, 2.55 amps (2.48 near end of test)
Battery Voltage recovered: 26.73 vdc

Full Load Battery Tests at Deep Sea (Cold) Temperature

New Exemplar 27 v Battery – Lot date codes; 1010A, 1010A, 0710A
Serial Numbers: 0001118, 0001117, 0001022
Part No.: All (3ea) 2232368-01 Rev2
Start Test Battery Temperature; 40.2 degF
Initial Battery Voltage = 28.88 VDC
Load resistor = 10 ohms
Battery Voltage at 75 seconds = 24.82 vdc, 2.454 amps
Recovery Voltage = 26.87 vdc

Yellow Pod 27 v Battery Pack

Start Test Battery Temperature: 39.8 degF
Initial Batt. Voltage = 27.27 vdc
Load resistor = 10 ohms
Battery Voltage at 75 seconds = 23.98 vdc, 2.413-2.374 amps
Recovery Voltage = 26.22 vdc

Blue Pod 27 v Battery Pack (not tested due to drained condition)

Full Load Battery Test (Cold) – New Exemplar 9 vdc battery

Part No.: 2232368-01 Rev2
Date Code: 0710B
Serial Number: 0001021
Start Test Battery Temperature: 39.6º F
Initial Battery Voltage = 9.67 vdc
Load resistor = 1.5 + 0.1 ohms
Battery Voltage at 75 seconds = 7.68 vdc, 4.8 - 4.63 amps
Recovery Voltage = 8.79 vdc

Full Load Battery Test (Cold) – 9 vdc Battery Yellow Pod SEM B

Start Test Battery Temperature: 39.0 degF
Initial Battery Voltage = 7.81 vdc
Load resistor = 1.5 + 0.1 ohms
Battery Voltage at 75 seconds = 1.61 vdc, 1.24 - 0.98 amps
Recovery Voltage = 5.9 vdc (climbing very fast)

Full Load Battery Test (Cold) – 9 vdc Battery Yellow Pod SEM A

Start Test Battery Temperature: 39.6 degF
Initial Batt. Voltage = 8.32 vdc
Load resistor = 1.5 + 0.1 ohms
Battery Voltage at 75 seconds = 6.43 vdc, 3.83 amps
Recovery Voltage = 7.72 vdc (climbing)

Full Load Battery Test (Cold) – 9 vdc Battery Blue Pod SEM A

Start Test Battery Temperature: 38.6 degF
Initial Batt. Voltage = 8.69 vdc
Load resistor = 1.5 + 0.1 ohms
Battery Voltage at 75 seconds = 6.66 vdc, 4.023 amps
Recovery Voltage = 8.19 vdc

Full Load Battery Test (Cold) – 9 vdc Battery Blue Pod SEM B

Start Test Battery Temperature: 38.9 degF
Initial Battery Voltage = 8.51 vdc
Load resistor = 1.5 + 0.1 ohms
Batt. Voltage at 75 seconds = 6.35 vdc, 3.84 amps
Recovery Voltage = 7.96 vdc

Full Load Battery Test (Ambient) – New Exemplar 27 vdc battery

Part No.: 2232368-01 Rev02
Date Code: 1010A, 1010A, 0710A
Serial Numbers: 0001118, 0001117, 0001022
Start Test Battery Temperature: 77.6 degF
Initial Battery Voltage = 28.24 vdc
Load resistor = 10 ohms
Batt. Voltage immediately on application of load = 26.45v 2.602 amps
Batt. Voltage at 75 seconds = 25.34 vdc, 2.508 amps
Recovery Voltage = 26.76 vdc (climbing)

Full Load Battery Test (Ambient) – New Exemplar 9 volt battery

Part No.: 2232368-01 Rev2
Date Code: 0710B
Serial Number: 0001021
Start Test Battery Temperature: 77.7 degF
Initial Battery Voltage = 9.40 vdc
Load resistor = 1.5 (+ 0.1?) ohms
Batt. Voltage immediately on application of load = 8.34 vdc, 5.01 amps
Batt. Voltage at 75 seconds = 7.89 vdc, 4.77 amps
Recovery Voltage = 8.82 vdc

Full Load Battery Test (Ambient) - Yellow Pod 27 v Battery Pack

Start Test Battery Temperature: 77.5 degF
Initial Batt. Voltage = 27.03 vdc
Load resistor = 10 ohms
Battery Voltage immediately on application of load = 25.54 vdc, 2.526 amps
Battery Voltage at 75 seconds = 24.92 vdc, 2.467 amps
Recovery Voltage = 26.31 vdc (climbing)

Full Load Battery Test (Ambient) – 9 vdc Battery Yellow Pod SEM A

Date Code: 0409A   S/N: 0000705
Start Test Battery Temperature: 78.0 degF
Initial Battery Voltage = 8.36 vdc
Load resistor = 1.5 (+ 0.1?) ohms
Batt. Voltage immediately on application of load = 6.98 vdc, 4.20 amps
Batt. Voltage at 75 seconds = 6.84 vdc, 4.13 amps
Recovery Voltage = 8.04 vdc (climbing very fast)

Full Load Battery Test (Ambient) – 9 vdc Battery Yellow Pod SEM B

Date Code: 0409A   S/N: 0000706
Start Test Battery Temperature: 78.1 degF
Initial Battery Voltage = 7.98 vdc
Load resistor = 1.5 (+ 0.1?) ohms
Battery Voltage immediately on application of load = 2.8 vdc, 1.64 amps
Battery Voltage at 75 seconds = 2.330 vdc, 1.404 amps
Recovery Voltage = 6.68 vdc (climbing)

Full Load Battery Test (Ambient) – 9 vdc Battery Blue Pod SEM A

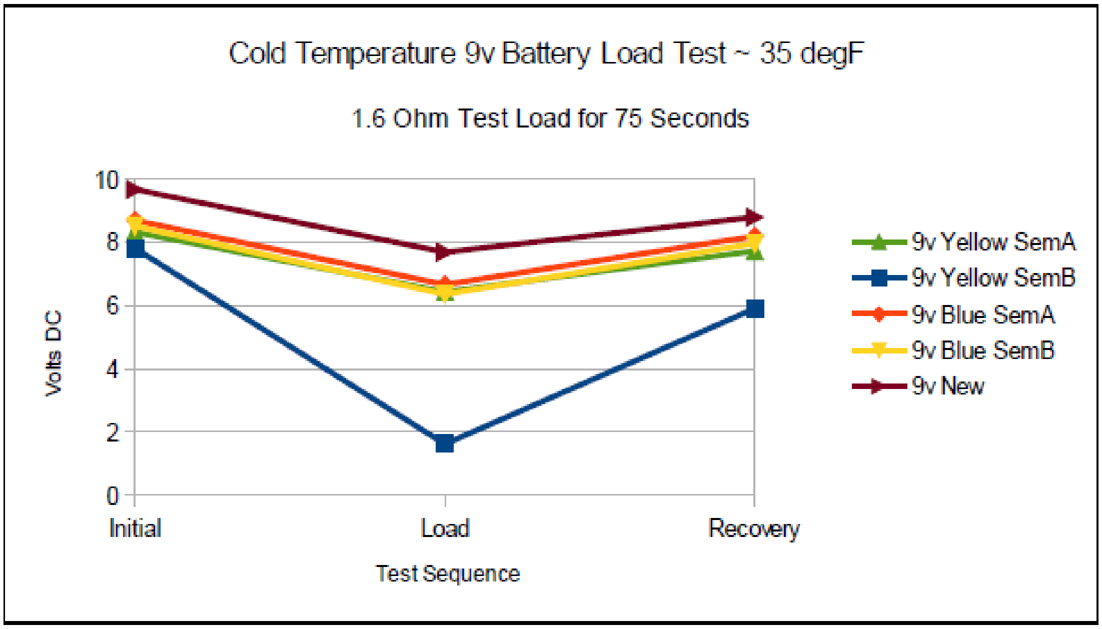
Date Code: 1005C   S/N: 0000269
Start Test Battery Temperature: 78.1 degF
Initial Battery Voltage = 8.71 vdc
Load resistor = 1.5 (+ 0.1?) ohms
Batt. Voltage immediately on application of load = 7.32 vdc, 4.36 amps
Batt. Voltage at 75 seconds = 7.09 vdc, 4.28 amps
Recovery Voltage = 8.40 vdc (rising)

Full Load Battery Test (Ambient) – 9 vdc Battery Blue Pod SEM B

Date Code: 1005C   S/N: 000267
Start Test Battery Temperature: 78.2 degF
Initial Battery Voltage = 8.53 vdc
Load resistor = 1.5 (+ 0.1?) ohms
Batt. Voltage immediately on application of load = 6.93 vdc, 4.17 amps
Batt. Voltage at 75 seconds = 6.77 vdc, 4.09 amps
Recovery Voltage = 8.08 vdc (rising quickly)

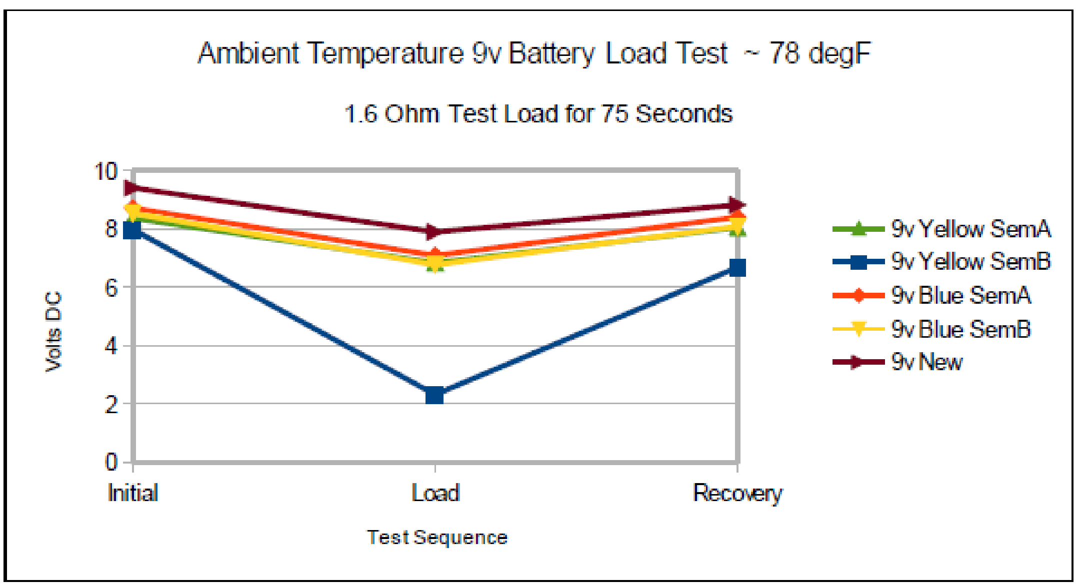
A.3 Battery Load Testing Results and Analysis

A graphical analysis of the load testing data in the prior section appears in the following charts.



Engineering Services

Figure A3-1: 9 volt Battery Cold Test Results
The yellow pod SEM B 9 volt battery failed the load test.



Engineering Services

Figure A3-2: 9 volt Battery Ambient Test Results
The yellow pod SEM B 9 volt battery also failed the ambient temperature load test.

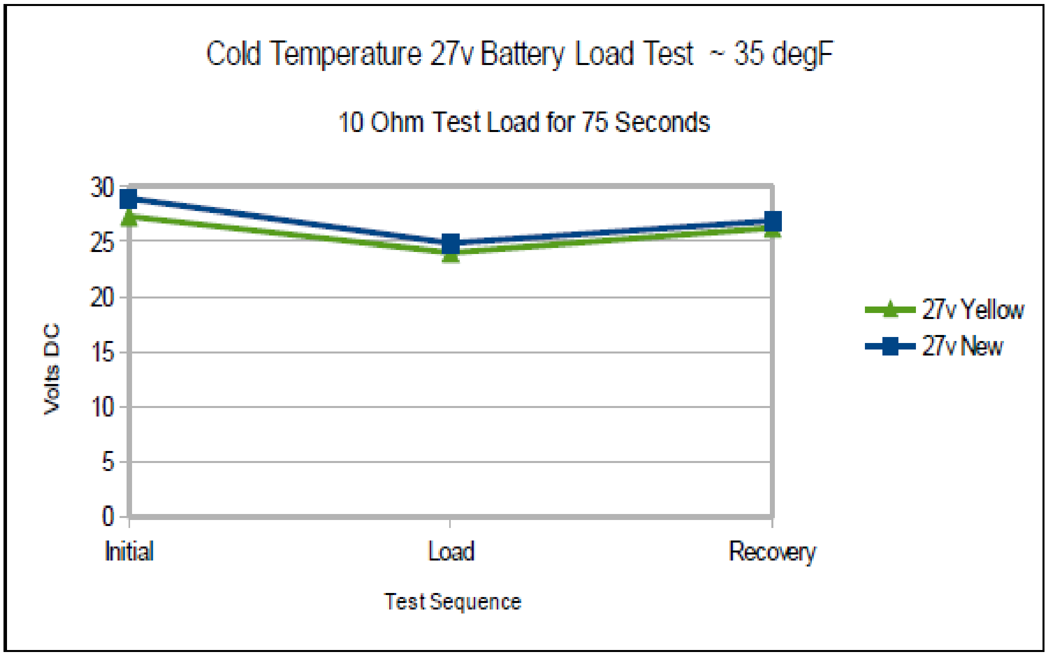


Figure A2-3: 27 volt Cold Battery Load Test Results
The yellow pod 27 volt battery closely follows the new battery cold load test.
The blue pod 27 volt battery was drained and could not be tested.

Engineering Services

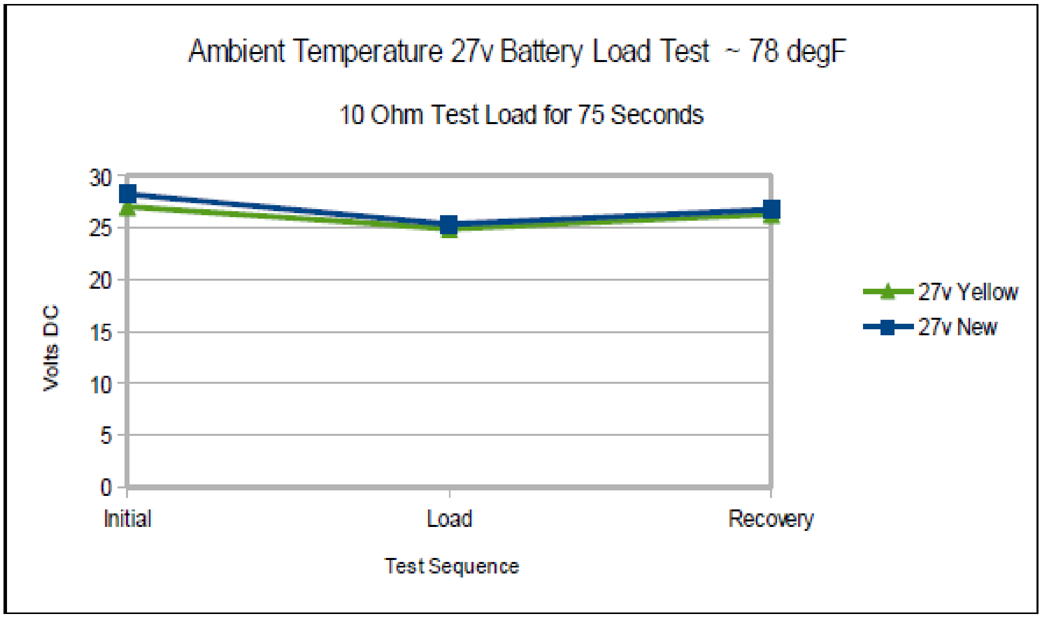


Figure A3-4: 27 volt Ambient Load Test Results
The yellow pod 27 volt battery closely follows the new battery ambient load test
The blue pod 27 volt battery was drained and could not be tested

A Cameron Factory Acceptance Test Procedure for the subsea electronic module,[105] indicates that the 9 volt battery load during AMF/deadman is 4-7 amp (with a note: "Each SEM A & B, depends on SEM electronics") and < 3 amps for the 27 volt battery.[106] AMF/deadman duration is described as less than 1.5 minutes.

Assuming a 9 volt battery must produce 4-7 amps, it should be tested at a conservative level of approximately 7 amps or more. The predicted resistor size to achieve 7 amps would be 1.29 ohms.[107] Assuming the addition of a shunt resistor of 0.1 ohms in the circuit, the additional resistor size should have been 1.2 ohms. The test was accomplished using 1.5 ohms, which was in the proper range given the specific unknown current draw for the PLC reboot cycle.

Assuming a 27 volt battery must produce 3 amps, it should be tested at 3 amps or more. The calculated resistor size to achieve that 3 amps would be 9 ohms.[108] Assuming the addition of a 0.1 ohm shunt resistor, the additional resistor should have been 8.9 ohms, but was tested with 10 ohms. This is within an adequate range. An analysis of the AMF/deadman solenoid firing sequence indicates that no more than four solenoids are energized at one time in one pod during AMF/deadman. Since the total load imposed by one solenoid is approximately 0.6 amps (assume 24v / 40 ohm coil resistance = 0.6), then the total load for four solenoids would be 2.4 amps. This was within the range of the load testing.

One of the functions of the 9 volt AMF/deadman battery is to reboot the PLC so that it can execute the AMF/deadman sequence in the shutdown.asc file. The PLC requires 5 vdc to operate, and this voltage is designed to be provided through the AMF/deadman card and its onboard 9v-to-5v DC regulator. This Linear Technology regulator (LT11083CP-5) requires a minimum 6.5v on the input to produce an output of 5 volts at the rated load of 7.5 amps. Assuming that we only needed 2.7 amps to reboot the PLC, the regulator would need 5 volts to accomplish the reboot according to the manufacturer's documentation.

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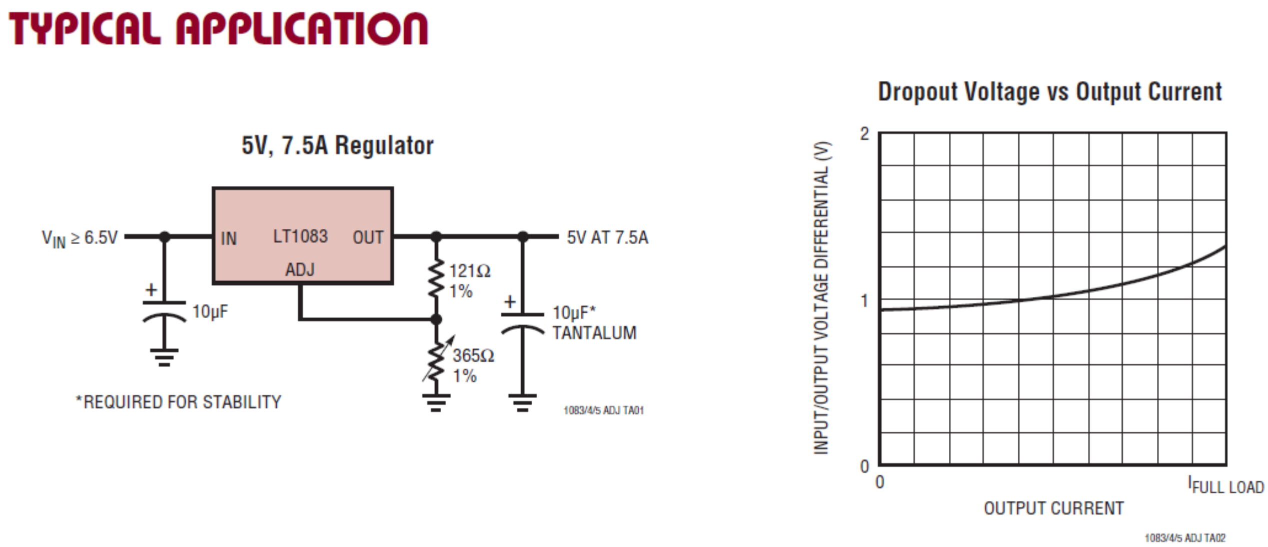
[105] Factor Acceptance Test Procedure for Subsea Electronic Module, Document No. X-065449-05-03, May 11, 2010, [CAM-CSB000008040].

[106] Note, test documentation from Phase 2 (DNV2011061903 - BOP-030 Full Load Battery Test with SEM batteries) indicates that the load on the 9 volt battery during the AMF/deadman sequence was 2.3 to 2.6 amps which does not agree with the Cameron FAT procedure cited in the previous footnote.

[107] R=V/I, → 9 volts/7 amps

[108] R=V/I, → 27 volts/3 amps



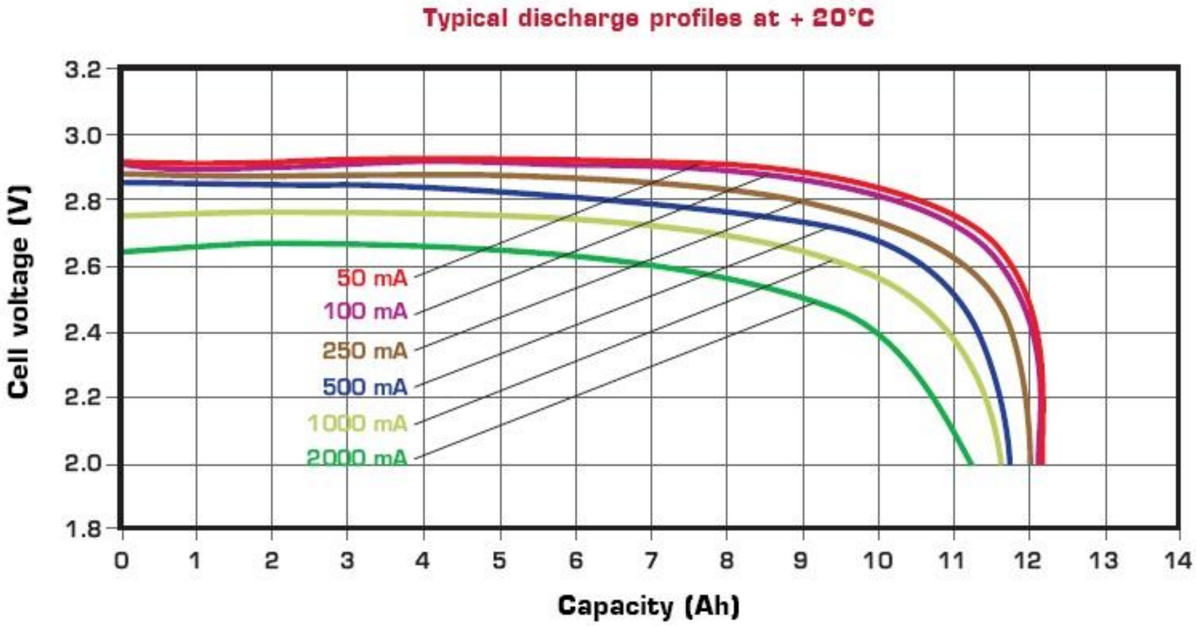
Linear Technology

Figure A3-5: Typical Application for the LT1083 Regulator

Anything less than 5 volts would severely limit the ability of the regulator to produce enough power for the reboot cycle (5 Vin → 5 Vout, 1.0 input/output ratio on the graph above).

A.4 Battery Discharge Curve and Derating

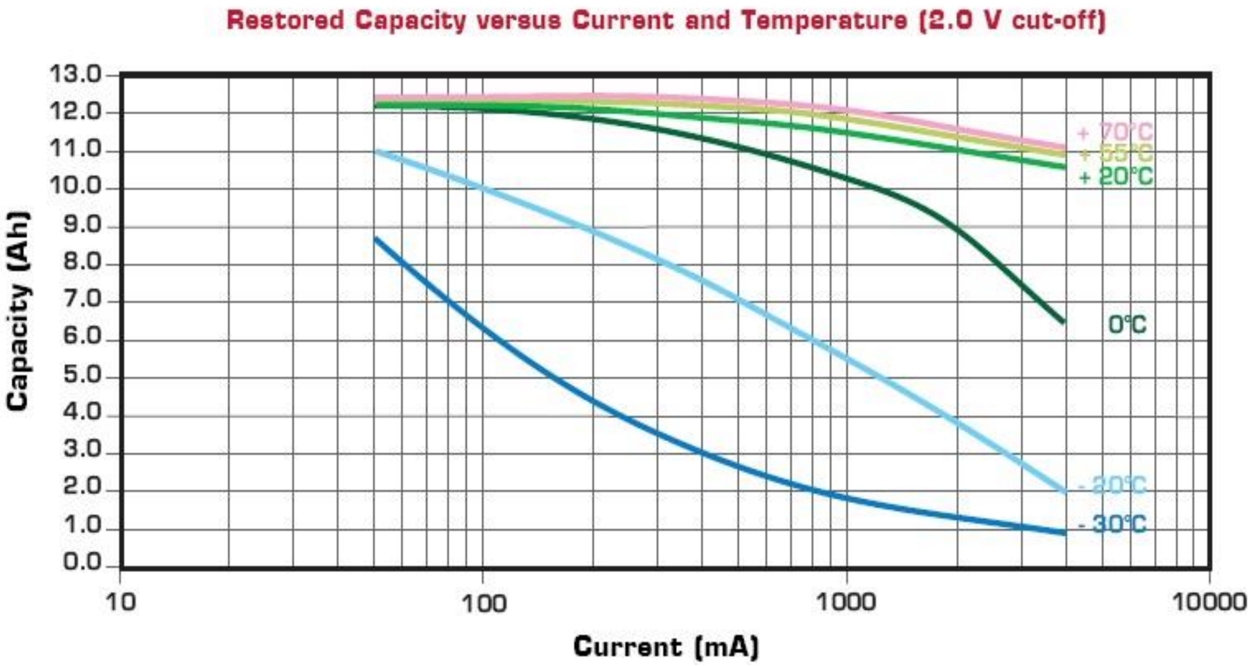
The following discharge profile (for 20ºC) for the SAFT LM33550 battery cell indicates that the knee of the curve, where useful life ends, is at approximately 2.6 volts per cell.



SAFT

Figure A3-6: Battery Discharge Profiles at +20ºC

For three cells in a series, the critical voltage is approximately 7.8 to 8.0 volts. Battery pack (3-Cell) voltage measurements under 7.5 volts with some significant loading would indicate a failing battery near the end of its amp-hour limits.



SAFT

Figure A3-7: Capacity vs. Current and Temperature

A.4.1 SAFT LM 33550 Battery Capacity Chart as Function of Temperature and Current

For a 12-cell battery pack consisting of three cells in series and four strings in parallel, the amp-hour rating would be 4 x 12 AH = 48 (@ 20ºC), but Cameron documents indicate 42 AH for this complete package. Their calculated derating was therefore 6/48 = 12.5%. The capacity curve from SAFT (above) confirms that these cells should be derated by approximately 12.5% for subsea temperatures (21ºC vs. 0ºC curves).

A.4.2 Estimated Battery Drain on 9 volt Yellow Pod Battery

ES estimated all of the known battery drains on the failed yellow pod battery leading up to the suspected point of failure in the second yellow pod AMF/deadman test at Michoud Phase 1. These calculations were accomplished to determine whether the known battery usage and testing could have used a significant portion of the derated amp hours for this battery. The resulting calculations (1.03% of derated capacity) show that the testing before the point of suspected battery failure on March 3, 2011 did not reveal any significant loading on the battery.

That 1.03%, is shown in the right column in the spreadsheet of Figure A3-8. This minimal depletion of the battery suggests that its condition was not much changed from its original condition subsea. Adding that 1.03% capacity back into the battery would give us an indication of its subsea condition at the time of the incident. There are other factors that must also be considered which we will address below.

Battery Test Description	Date	Reference	Comments	9v Battery Load Amps	Time Seconds	Amp-Hrs Used	Amp-Hrs * Remaining	% AH * Remaining	Amp-Hrs ** Surface	
Original Installation	10/13/09	T.O. Report App N, Pg 4					**42.00**	100.00%		
Deck/FAT Test of AMF	Oct '09 – Feb '10 ?	No documented AMF test prior to deployment	Assuming 1 AMF test on this pod prior to deployment.	**7**	**37**	**0.0719**	**41.93**	99.83%		
Arm AMF	02/08/10	T.O. Report App N, pg 7	"Armed" current for 71 days	**0.002**	**6,134,400**	**3.4080**	**38.52**	91.71%		
AMF Actual	04/20/10		Incident Fired AMF	**7**	**37**	**0.0719**	**38.45**	91.54%		**Failure**
AMF Simulation	05/06/10		Using original 103 SV	**7**	**37**	**0.0719**	**38.38**	91.37%	**0.43**	**1.03%**
AMF Simulation	05/06/10		Using original 103 SV	**7**	**37**	**0.0719**	**38.30**	91.20%	**0.36**	**0.86%**
AMF Simulation	05/12/10		Using replacement 103 SV	**7**	**37**	**0.0719**	**38.23**	91.03%	**0.29**	**0.69%**
AMF Simulation	05/12/10		Using replacement 103 SV	**7**	**37**	**0.0719**	**38.16**	90.86%	**0.22**	**0.52%**
Battery Load Testing – Michoud	Phase 1	DNV pg 43	Using 100 ohm resistor	**0.081**	**120**	**0.0027**	**38.16**	90.85%	**0.15**	**0.35%**
Battery Load Testing – Michoud	Phase 1	DNV pg 43	Using 20 ohm resistor load	**0.385**	**120**	**0.0128**	**38.15**	90.83%	**0.14**	**0.34%**
AMF Simulation	03/03/11	DNV pg 46	Using replacement 103 SV	**7**	**37**	**0.0719**	**38.08**	90.66%	**0.13**	**0.31%**
AMF Simulation	03/03/11	DNV pg 47	Orig 103 SV, **battery fails during testing**	**7**	**30**	**0.0583**	**38.02**	90.52%	**0.06**	**0.14%**
AMF Simulation	03/03/11	DNV pg 47	Orig 103 SV, **battery failed**	**7**	**37**	**0.0719**	**37.95**	90.35%	**0.00**	**0.00**
AMF Simulation	03/03/11	DNV pg 49	Orig 103 SV, **battery failed**	**7**	**37**	**0.0719**	**37.87**	90.17%	**-0.07**	
Battery Load Testing	06/18/11		Cold load testing	**3.83**	**75**	**0.0798**	**37.79**	89.98%	**-0.15**	
Battery Load Testing	06/19/11		Ambient load test	**1.4**	**75**	**0.0292**	**37.76**	89.92%	**-0.18**	

*** De-rated AmpHrs for new battery. See De-Rating sheet.**

**** Calculations of Amp-Hrs used on surface since incident and prior to battery failure at Michoud in reverse order, as battery capacity drains to the point where it was unable to reboot/power the PLC**

Figure C1-8: Yellow Pod SEM B Battery Drain History

We assumed only 2 mA of current draw on the 9 volt battery pack for the AMF/deadman card during AMF/deadman arming period of 71 days while the BOP was in service before the April 20, 2010 incident. The assumed 2 mA has not been confirmed other than as referenced in the *Transocean Report.*[109]

ES calculations indicated that only about 10% of the yellow pod SEM B 9 volt battery amp hours had been used from February 8, 2010 to the start of AMF/deadman testing at Phase 1. These calculations are very sensitive to the current draw of the AMF/deadman card during arming. ES assumed 100% of the derated capacity of 42 amp-hrs at the start of Macondo drilling.

Even though the calculations do not imply significant battery drain on the Macondo well and subsequent testing, ES believes that this battery experienced premature failure during the second AMF/deadman test of the yellow pod (using original SV 103). This opinion is based in part on the significant disparity between the two identical 9 volt batteries in the yellow pod with the same date codes. The failure of this battery while rebooting and operating the AMF/deadman card and PLC in SEM B while the sequence was energizing SV 103 (AMF/deadman Testing at Michoud) caused the solenoid valve 103 original to work correctly on only the SEM A solenoid coil for the last seven seconds of the sequence.

Since the battery failed to successfully execute AMF/deadman at Michoud where the ambient temperature was between 60 and 70ºF, the possibility existed that the battery had failed in subsea service during the incident due to lower temperatures and subsequent decreased capacity. This would be important because the failure of one SEM in the yellow pod during the AMF/deadman sequence would cause the miswired SV 103 to actuate successfully on one coil. The ES review of the SAFT temperature derating tables for these cells indicates that the decrease in battery capacity could be as much as 12-15 percent given a 20ºC temperature difference (20ºC - 0ºC) between Michoud ambient and subsea operation (at a current draw of 7 amps).

Testimony given in the case by a Cameron representative indicated that subsea internal SEM operating temperatures could be in the range of 60-70ºF.[110] Neither Cameron nor BP was able to provide any more specific information concerning the subsea SEM internal operating temperatures.[111]

Regardless of the absolute temperature differential between subsea and Michoud, it would be expected that there would be some relative delta T (temperature). The 9 volt battery would need to have only 1.03% less capacity subsea than at Michoud for it to be at the same point of failure as it was at during Michoud testing.

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[109] *Transocean Report*, Appendix N, p. 7.

[110] When asked to provide the operating temperature range within the SEM vessel, the response was, “I don’t remember any specific number. I do remember a range being, just from , you know, discussion with some of the service personnel […] 60 degrees Fahrenheit to 70 degrees Fahrenheit. That’s just a rough estimate.” Testimony given in the U.S. District Court for the Eastern District of Louisiana under the Multi-District Litigation docket MDL No. 2179, see Coronado Designations Vol 1, p, 45, publically available at http://www.mdl2179trialdocs.com/releases/release201304041200022/Coronado_Richard-Depo_Bundle.zip.

[111] Communications with CSB.

There are, in fact, two factors that could have caused the failing 9 volt battery to have slightly increased capacity at Michoud. The first, as we have mentioned, is the increased delta T thermal effect on capacity from subsea to Michoud. Also, there is another known effect in all batteries which is the recovery in capacity due to "resting". This is an effect based on the chemistry of the battery which restores some minimal capacity after a period of loading. In order to quantify the relative capacity of the battery subsea we must "add back" the amp hours used by that battery in surface testing since the accident and then subtract the effects of the increase due to delta T thermal increase and resting recovery capacity. If the increased capacity due to thermal increase and resting recovery was greater than 1.03%, then we can conclude that the yellow pod SEM B 9 volt battery capacity was below the failure capacity level at the time of the incident.

Photographs taken on the Q4000 indicate that internal operating temperatures of the SEM when on the surface could be 81 to 94ºF (27 to 34.5ºC).[112] If we assume a subsea internal operating temperature of 60ºF (15.5ºC), we could have a delta T as much as (34.5-15.5ºC) 19ºC differential increase at Michoud.[113] Next, we take a zoomed look at the SAFT capacity chart in Figure A3-7.

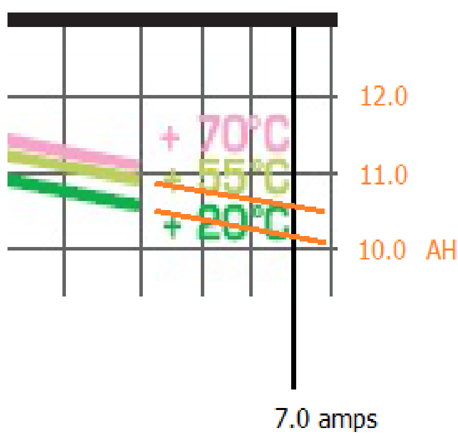

Figure A3-8: Zoomed View of SAFT Capacity chart vs. current and temperature – modified by Engineering Services

From this chart we cannot interpolate the capacity difference (increase) based on an increase in temperature from 15.5 to 34.5ºC at 7.0 amps. We can however, get some indication that an increase of 0.1 to 0.2 AH capacity might be entirely possible. This would amount to 1 to 2% recovered capacity based on temperature rise from subsea to Michoud.

112 Photographs BP-HZN-BLY00061060 and BP-HZN-BLY00061073

113 MDL Exhibit TREX-3628 is an email in which the Blue pod SEM internal temperature is noted at "88.02 degrees" on Feb. 19, 2010. We do not know if this temperature is normal or abnormal and we have seen no records regarding the internal temperature of the Yellow pod SEM during the Macondo drilling activities.

In addition to the thermal capacity increase effect, we addressed the resting capacity increase which would have occurred after the 9 volt and 27 volt batteries in the yellow pod would have been disconnected after the AMF/deadman sequence concluded on April 20, 2010. Engineering Services accomplished load testing on exemplar SAFT batteries. (Battery Cells - SAFT Model LM22150, 3v nominal, 3.2 volts (no load), 900mAH rated capacity) These cells were similar in chemistry and construction to the SAFT batteries used in the DWH BOP, but smaller capacity. Our testing included simulating a multi-cell battery pack (4 cells, 2 series and 2 parallel strings) which included one previously depleted cell. This setup was intended to simulate a battery pack with a single defective cell. First, we drained this nominal 6 volt battery pack to 1.3 volts using 18.1 ohms of resistance. This test duration was slightly less than 6 hours. The test was accomplished at 70^0F. After 3 days of resting (no load), we again tested the battery pack at 70^0F and found a 0.28% increase in resting capacity (based on full rated capacity of 1.8 AH). If we were to base this resting recovery as a percentage based on a “dis-abled” capacity rating due to the defective cell, the resting recovery would be something closer to 0.46%.

If we consider the thermal increase in battery capacity to be at least 1%-2% and the resting recovery capacity increase to be on the order of 0.28 to 0.46%, we find that the battery had gained enough capacity to provide the 1.03% capacity utilized on the surface. Any additional increase in delta T or resting recovery gains would serve to increase confidence in these results.

As a result of our investigation, we conclude that the 9 volt SEM B yellow pod battery functioned to some extent at Michoud in early testing due to the thermal increase and resting recovery increase in capacity when compared to its subsea condition on April 20, 2010.

Based on these calculations and estimates, it appears possible that the battery had already failed on April 20, 2010. The yellow pod SEM B battery may not have been able to support the 5-7 amp load required to power the SEM PLC and therefore the AMF/deadman would have worked on the redundant SEM A, with only one coil of the miswired 103 being energized. If the SEM B 9v battery was viable during the incident, then the alternative scenario becomes the effective case in which the mis-wired 103 solenoid valve can partially fire the AMF/deadman sequence based on the out-of-sync timing plus the cumulative pulsation durations.

The battery date code for the battery pack was April 2009. The failure of this battery so soon after manufacture indicates that it experienced either an internal defect, loose inter-cell connection, or some other unexplained external drain of its capacity.

Appendix B: Blue Pod SEM B D17 Diode Discoloration

On June 19 and June 20, 2011, as part of Phase 2 testing, technicians removed the AMF/deadman cards from the yellow and blue pod SEMs and traced the circuitry that was attached to the four AMF/deadman cards. The technicians photographed both sides of each card and annotated the photos with notes regarding the quality of the protective conformal coating on the printed circuit boards and other observations of potential quality concerns.[114] Most of the notes were relatively innocuous, but a notable exception from June 20 concerned "some discoloration at the solder joints" of diode[115] D17 on the blue pod SEM B AMF/deadman card. The discoloration, seen in Figure B-1, on diode D17 suggests heat stress, most likely due to overcurrent.

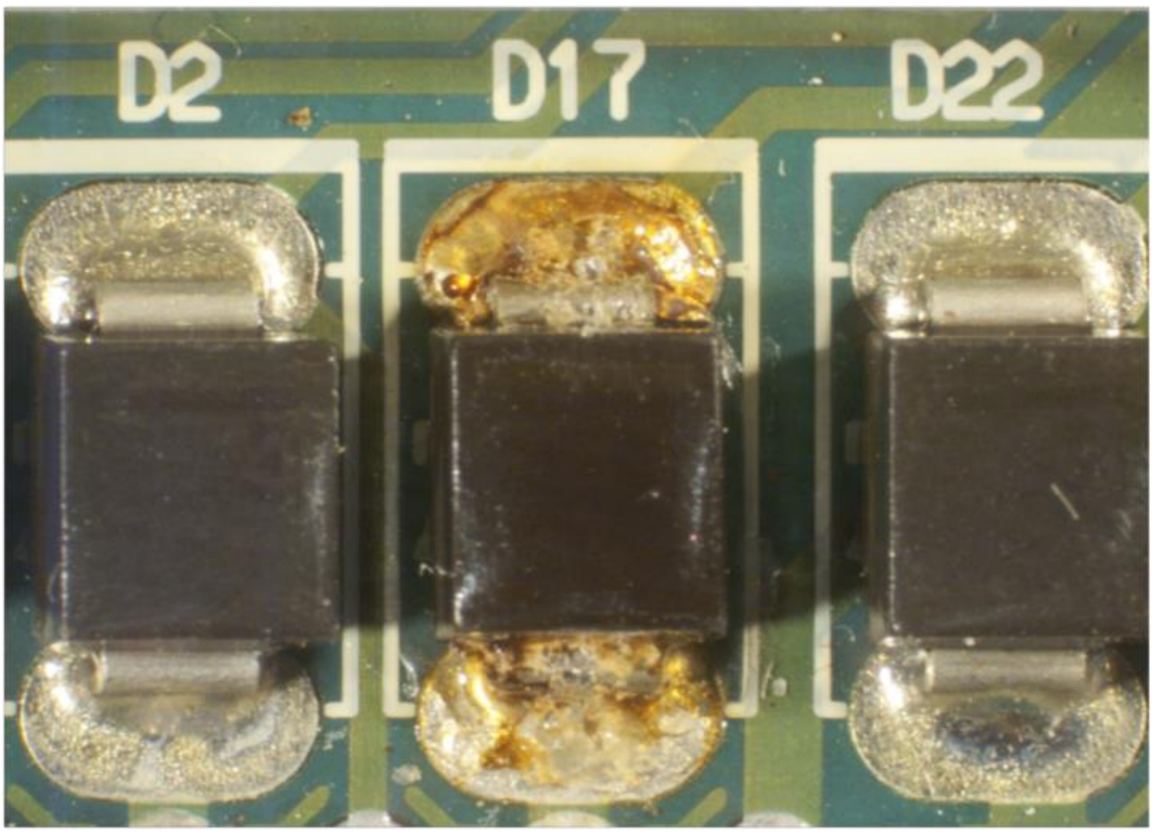

Figure B-1. Discolored Diode D17 on blue pod SEM B AMF/deadman card as observed during Phase 2 testing.

Diode D17 on the AMF/deadman cards is the first board-mounted component connected to the external 9 volt AMF/deadman battery pack. This battery, while connected to the AMF card through diode D17, does not power the AMF card until a 12 volt latching relay on the card is energized by an external command from the SEM. This command is referred to as "arming" the AMF/deadman and is initiated by deck personnel during normal drilling

[114] Technician notes on the AMF/deadman card appear in DNV2011061904 Test Preparation Sheet BOP-033.
[115] A diode is like a one-way valve for electrical current. Current can flow in one direction, but not in the reverse direction.

operations. Once armed, the latching relay connects the 9 volt battery power to the AMF card and its CPU. When in the armed state, the AMF card can sense the input requirements for a healthy BOP and will remain powered from the 9 volt battery until dis-armed manually from surface control panels or after a completed emergency shut-in via the AMF Deadman sequence.

If diode D17 had failed prior to the incident, then the blue pod SEM B AMF card could never have gotten the battery power it needed to operate. In this case, however, MUX diagnostics should have alerted the operator of the

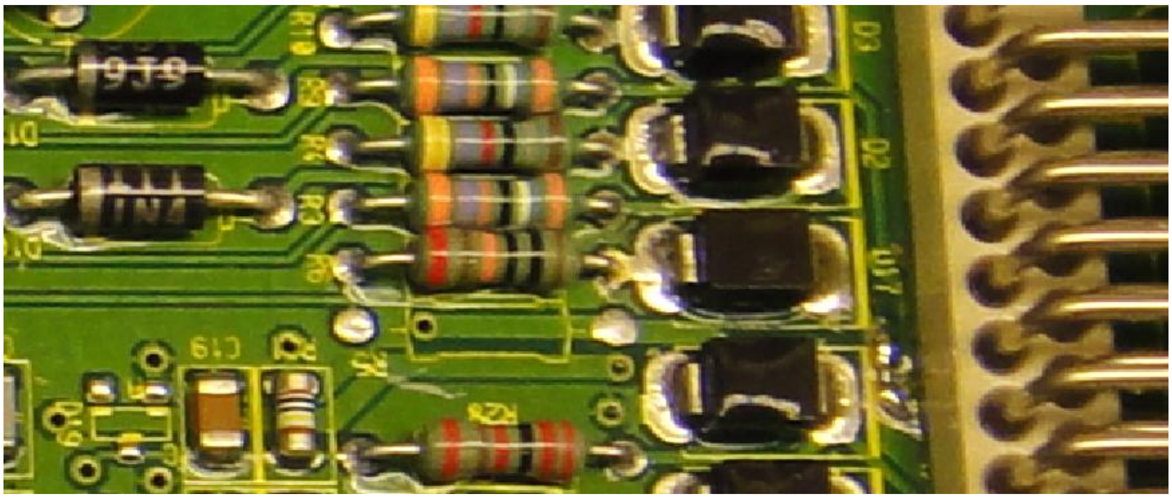

Figure B-2. Photograph of diode D17 connected to resistor R6.

defect.[116] Regardless, one would expect that the redundant blue pod SEM A AMF/deadman system would have still been available and the blue pod could have still activated the AMF/deadman sequence.

Using a volt-ohm meter, a technician tested both the forward and backward resistance of diode D17.[117] The forward resistance was recorded at 4.5 meg-ohm, and the reverse resistance was recorded at 1.0 meg-ohm. These tests indicate that there would be no current flow through the diode in either direction. The forward resistance check should have been less than 1 ohm. Another test was accomplished to test the board end of diode D17 and it was found to be grounded (to pin 15 or 17) at 0.2 ohms.

An open question about D17 is whether the technician actually broke through the conformal coating when taking the measurements, but we were able to make use of other measurements to verify the failed condition of the diode. The most significant of the technician's measurements was the grounded connection on the in-board side of D17. The photograph in of D17 in Figure B-2 reveals that it is connected in series to a resistor (R6) mounted on

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116 ES cannot verify whether a single (1 out of 4) AMF/deadman card fault would generate a "not armed" signal. Since each AMF/deadman card had an armed output signal, the assumption is that the control system would require all four AMF/deadman cards to report arming success to display an armed status.

117 Page 26 of the datasheet.

the board. At the very least, the circuit then has the following configuration from the external battery to the resistor – Figure B-3.

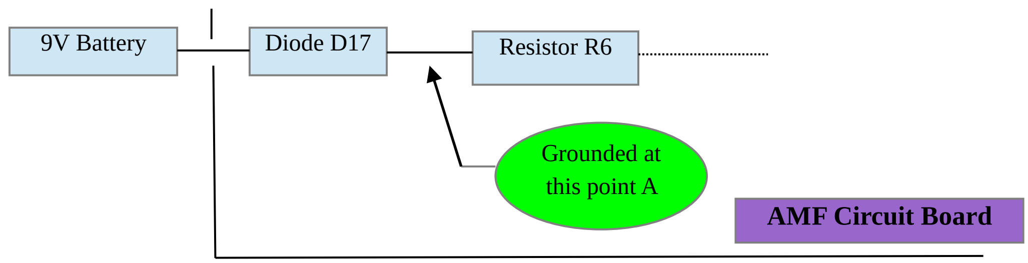

Figure B-3. Circuit configuration from the 9 volt battery to resistor R6.

It is obvious that one of the technician's measurements pierced the conformal coating in order to get such a low reading of 0.2 ohm to ground. If diode D17 were grounded at point A and the diode was still working, then the SEM B 9 volt battery would have been completely drained over a short period of time due to the short to ground. Since the Blue SEM B 9 volt battery passed all load tests imposed on it late in the Phase 2 testing, we conclude that the diode was not conducting forward current to the AMF card.

The next question is when did the D17 diode fail? When an AMF/deadman sequence is activated, there is an analog signal called "AMF/deadman Arm" which changes value once the AMF/deadman is set and then when it has concluded. When AMF/deadman sequence is activated, the raw analog value is around 15. When the AMF/deadman sequence has been deactivated, the signal is greater than 900.

During Phase 1 testing, the initial analog values for Blue pod SEM B indicated that AMF/deadman sequence was not active for either SEM. Then, after activating the AMF/deadman system, both SEMs in the blue pod displayed active signals:

Table B-1. Analog Channel Values

Action	Yellow Pod		Blue Pod	
	SEM A (mA)	**SEM B (mA)**	**SEM A (mA)**	**SEM B (mA)**
Baseline	913	916	919	915
Deactivate AMF/deadman	917	915	918	915
Activate AMF/deadman	18	16	14	16

DNV Report Table 7[118]

Because the AMF/deadman system could be armed prior to AMF/testing, ES suspects that diode D17 likely failed during the AMF/deadman test, but that it was operable before the AMF/deadman began on March 3, 2012 and was not a factor at the time of the incident.

118 *DNV Report*, Table 7, p. 45.

Appendix C: Portable Electronic Test Units (PETU) Characterization Analysis

This section documents the use of PETUs in the Phase 1 and Phase 2 testing and explains the apparent idiosyncrasies in PETU operation and inconsistencies in actuating solenoid valve 103Y original.

SEM Designation	**PETU-1**	**PETU-2**	**PETU-1 Original***	**PETU-2 Original****
Manufacturer	Cameron	Cameron	Cameron	Cameron
Assembly #	222650-78	222650-78	223180-49	223180-38
Serial #	300082255		4286 B0004	11780713-01
A/B/ Switch Capability	Yes	Yes	Yes	Yes
Single/A+B Switch Capable	No	Yes	No	Yes
Test Procedure Reference	BOP-015-2	BOP-015-1	BOP-015-3	BOP-015-3
Problems – PETUs did not work as per SEM A/B switch indications	A/B switch (A or B) actuates both A and B. Neutral position actuates both also.	A/B switch is OK But A+B switch setting does not fire both SEMs	Incorrectly actuates both coils regardless of A/B switch setting.	Does not operate the A+B when set. Only fires A or B depending on A/B switch setting.

Engineering Services

Table C-1 PETUs Used in Phase 1 and 2 Testing And Characterization of the Results and Idiosyncrasies

*** Original – indicates PETUs used in testing in March 2011 – Phase 1**

****PETU 1 original was used in Phase 1 until on March 4, 2011, Cameron also provided PETU 2 original because TWG wanted to test with A+B switch capabilities assuming we could fire both coils simultaneously. This PETU-2 original did not energize A+B coils. The *DNV Report* also refers to PETU-1 original as PETU-Y. PETU-2 original is referred to as PETU-B in the *DNV Report* (p. 50).**

C.1 Solenoid Driver Characterization

Solenoid valve 103 replacement (yellow) was tested with PETU 2 A+B/single switch in the single position. PETU 2 worked as set up, but 103R failed on coil A due to a shorted internal lead wire (pinched in prior re-assembly, or the result of an impressed test overvoltage of 35 vdc for 1µsec.[119]

Solenoid valve 103 Blue was tested with PETU 1 and PETU 2.[120] PETU 2 worked as expected in both SEM A and SEM B single positions. However, when set on A+B, PETU 2 did not fire both coils, instead, firing only the single A or B coil. PETU 1 actuated both coils A and B when set in the A position. PETU 1 also actuated both coils A and B when set in the B position. Technicians found that both coils also fired when the A/B switch was set in a neutral position.

Solenoid valve 103 blue was tested with PETU 1 original and PETU 2 original.[121] PETU 2 original worked correctly in both SEM A and SEM B single switch settings. When set on the A+B settings, PETU 2 original did not operate as expected and energized only one coil A or B in the respective SEM settings.

PETU 1 original actuated both A and B coils in all switch positions (SEM A, SEM B, and neutral positions). SEM A and SEM B appeared to have the same length of the initial pulse (6.4 div * 200 mSec = 1.28 seconds for initial long pulse).

C.2 Background On the PETUs and Miswired Solenoids

Several details of the solenoids and PETUs are noteworthy as background information relating to the PETU characterization study.

When solenoids 3A and 103 original from the Yellow pod were bench tested in February 2011, we did not know that these two solenoids were miswired. When they were tested in the lab using proper +/- voltage connections on pins 1-2 and 3-4, these solenoids actuated even on the miswired coils. Coil pickup and dropout voltages were measured and recorded. The takeaway is that a single miswired coil can actuate the solenoid even though the coil would see reversed voltage. This is simply a function of how a coil acts on a free-floating armature core or plunger. The action of the magnetic circuit is such that the plunger wants to minimize the air gap regardless of how voltage is applied to the coil.[122]

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[119] Phase 2 Test Preparation Sheet, DNV2011060642: BOP-015-1, p 4.

[120] Phase 2 Test Preparation Sheet, DNV2011060643: BOP-015-2.

[121] Phase 2 Test Preparation Sheet, DNV2011060743: BOP-015-3.

[122] *DNV Report*, sections 6.1.10 and 6.1.11, p. 41.

However, we now know that when the two coils are energized simultaneously with steady DC voltage, the solenoid will not actuate because the coils are opposing each other with identical and offsetting forces with the net result that the armature does not move.[123]

When a PETU is used to actuate a solenoid, the PETU does not provide power to the solenoid. Instead, it only sends a control signal to one or both SEMs, which power the solenoid through the SEM 24 vdc power supply and the solenoid driver board. The PETU control signal is instantaneous in actuating one or both of the A and B solenoid coils through the SEMs. In this respect, the PETUs differ from the potential out-of-sync manner that SEM A and SEM B would fire both solenoid 103 coils during a reboot and initiation of the AMF/deadman sequence.

C.3 Review of PETU Idiosyncrasies Acting on Solenoid Component and AMF/deadman Tests

During the Phase 1 component testing of the pod solenoids and AMF/deadman sequences, there appeared to be inconsistencies in whether the solenoids activated. As it turned out, most of the inconsistencies were due either to the idiosyncrasies in the internal A/B or A+B switch wiring of the PETUs or to solenoid 103Y original having one coil reverse wired. Table C2-2 itemizes the DNV component test results when using PETUs to actuate the solenoid valve and resolve the inconsistencies. The “Expected” column data is based on what we now know about the PETUs

[123]Phase 2 Test preparation Sheet, DNV2011051801: TPS BOP-010.

Test #	PETU*	Attempted Action SEM A, B or A+B	Actuation	Expected**	*DVN* Page Reference
1	1 Original	103B - Blue A	Yes	Yes	44
2	1 Original	103B – Blue B	Yes	Yes	44
3	1 Original	103Y orig – Yellow A	No	No	44
4	1 Original	103Y orig – Yellow B	No	No	44
5	1 Original	103Y replace – Yellow A	Yes	Yes	44
6	1 Original	103Y replace – Yellow B	Yes	Yes	44
7	1 Original	103Y orig – Yellow A	No	No	47
8	1 Original	103Y orig – Yellow B	No	No	47
9	1 Original	103Y orig – Yellow A	No	No	49
10	1 Original	103Y orig – Yellow B	No	No	49
11	2 Original	103Y orig – Yellow A+B	Yes	Yes	50
12	2 Original	103Y orig – Yellow A	Yes	Yes	50
13	2 Original	103Y orig – Yellow B	Yes	Yes	50
14	1 Original	103Y orig – Yellow A	Yes	No – aberration	50
15	1 Original	103Y orig – Yellow B	No	No	50
16	1 Original	103Y orig – Yellow A	No	No	50
17	2 Original	103Y – Yellow A	Yes	Yes	50
18	2 Original	103Y – Yellow B	Yes	Yes	50
19	2 Original	103Y – Yellow A	Yes	Yes	51
20	2 Original	103Y – Yellow B	Yes	Yes	51
21	2 Original	103Y – Yellow A+B	Yes	Yes	51

Engineering Services – based on DNV Report, March 2011.
Note: See also handwritten notes DNV-CSB 000228

Table C-2 – Solenoid Component Testing Using PETUs, March 3, 2011
The table omits multiple tests with the same results.

***PETU 1 original is also referred to as PETU-Y; PETU 2 original is also referred to as PETU B.**

****Expected column based on the characterization results of Phase 2 testing, which determined how each PETU acted as described above If Expected column = Actuation column, then results were consistent with identified PETU operation.**

Based on the characterization testing of the PETUs in Phase 2, the solenoid component testing in Phase 1 is sound (with the one aberration noted above in test 14). During the Phase 1 AMF/deadman and solenoid component testing, it seemed that solenoid 103Y original was exhibiting inconsistent actuations. The inconsistencies were likely due to the internal miswiring of the PETUs, which were used to actuate the miswired 103Y original solenoid. Once it was clear that the solenoid valve was reverse wired on one coil and that the labeling of the switch positions on PETU 1 and PETU 2 was presenting incorrect expectations, all of the SV component tests, except one, exhibited predictable results.

The removal of apparent inconsistencies in the operations of the PETUs and 103Y solenoid provides a better understanding of the test results from the Phase 1 solenoid component and AMF/deadman testing. Armed with this insight, we proceeded with pulse-width-modulation testing, both in-sync and out-of-sync, on an exemplar solenoid valve to determine the probabilities that a miswired solenoid could accomplish the AMF/deadman actuation of the blind shear rams.[124]

[124] Referenced diagrams and procedures: PETU Circuit Diagram, SK-122126-21-06, CAM-CSB000005589; PETU Interconnection, Cable Circuit Diagram, SK-066201-55-04, CAM-CSB000005595; PETU Inteconnection. Distribution Cab. Circuit Diagram, SK-066200-85-04, CAM-CSB000005593; FAT Procedure PETU, Doc. X-065396-38, CAM-CSB000010937.

Appendix D: Review of Blue Pod SEM Wiring Defects

Figure D-1 and this discussion outline the effect of the miswiring in the blue pod SEM. The illustration shows the results of the technicians' point-to-point wiring verification of the blue pod SEM A and SEM B AMF card connections to the rest of the pod during Phase 2 testing. [125] The technicians found that several connections required by the drawings were not connected and were referred to in the technicians' notes as an "open lead." The test measurement cannot determine if the wire was missing entirely, routed to another unknown location, or simply disconnected at one end or the other. The technicians testing scope did not include investigation beyond the initial conductivity test.

The open lead/missing connections were identified as:

Blue SEM A (-X47 is the edge connector for the SEM A AMF card)

-X47 pin 14 to -X10, pin 11

-X47 pin 14 to -K4, pin 14

-X47 pin 16 to -X10, pin 11

Additional tests were made to connector -X11 which proved that terminals 14 and 16 were connected instead to pins 7 & 8 on connector -X11. Since there was no connection of terminals 14 & 16 to -X10, it is implied that pins 7 & 8 of connector -X11 were also not connected to -X10. Wiring diagram sheet 2 of 47 requires pins 7 & 8 of -X11 to be connected to -X10 pin 11. These pins have to do with an AMF trigger in or out from the second pod.

D.1 Blue SEM B (-X75 is the edge connector for the SEM B AMF card)

On page 34 of the TPS, two (2) wiring tests were noted as being "Open Lead > 20M" [20 megOhm].

-X75 pin 14 to -X10, pin 11

-X75 pin 16 to -X10, pin 11

It should be noted that the test from -X75 pin14 to -K6, pin 14 showed normal continuity of 0.3 ohm. Also, the technicians apparently did not test SEM B terminals 14 & 16 connections to -X11. If these wires were connected to -X11, then they would not conform to sheet 2 of 47.

Instead of pin 11 on Connector -X10, additional tests proved that Blue SEM A terminals 14 and 16 were mistakenly connected to pins 7 and 8 on Connector -X11. No test results could be located to determine if analogous mistaken connections existed from blue SEM B terminals 14 and 16 to pins 7 and 8 on Connector –

[125] Test Preparation Sheet DNV2011061904 BOP-033, pp. 30, 31, 33, and 34.

X11. If these SEM B wires were connected to -X11, then, like SEM A, they would not conform to the wiring diagram.

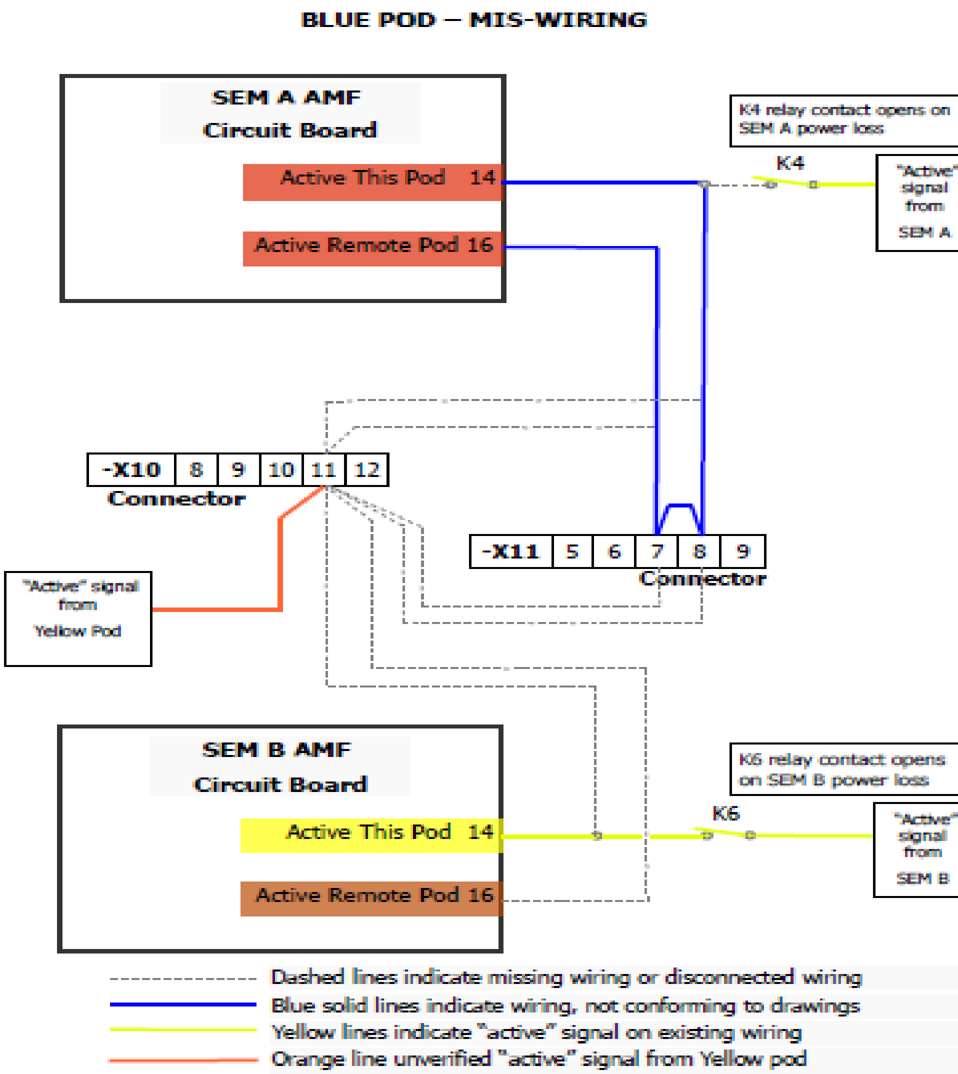

Figure D-1: Blue Pod Miswiring (Source: Engineering Services)

At the time of their testing, the pod SEMs had been removed from each pod with no physical wiring connection between pods. Figure D-1 shows the simulated orange connection point from the yellow to connector -X10 terminal 11. Since wires were not connected from -X10:11 to the AMF card, terminals 14 or 16, the blue pod could not sense that the yellow pod was active.

All of the open lead connections in the blue pod SEM concerned terminals 14 and 16 on the AMF card, which are labeled on Figure D-1 as “Active this Pod” and “Active Remote Pod,” respectively. No open leads were found in the yellow pod. [126]

Since the AMF board is required to check for certain signal conditions before executing the AMF/deadman sequence, these two terminations are essential to determining the healthy state of the power and communications within the current pod and within the other remote pod. Some call this the “heartbeat” signal.

This appendix focuses on the effect of these missing and miswired connections, beginning with what the SEM B card and the SEM A card sense after the AMF is armed.

D.2 SEM B Card

In the SEM B card, terminal 14 is not connected to connector -X10, terminal 11 as required, but it is connected to the closed K6 relay, which is closed when the SEM power supply and communications signals are present. This connection communicates to the SEM B card that there is still some health (power and communications active) in this pod, confirming that it is not yet time to connect the 27 volt battery pack to power and measure the two pressure transducers for the hydrostatic and riser conduit hydraulic pressure.

There is no signal to terminal 16 because of missing wiring, implying that the remote pod may not be active. However, if this pod is still active through terminal 14, the AMF card logic would not proceed with the AMF emergency sequence. The conclusion is that the SEM B card determines that the system is still partially active and healthy.

D.3 SEM A Card

The short answer to what the SEM A card senses is nothing. There is no active signal connected to either terminal 14 or 16. The SEM A card terminals 14 and 16 are not connected to connector -X10 or to the K4 relay contact. This presents a false condition caused by the missing wiring to connector -X10 and miswiring instead to connector -X11. If the missing wires from -X11 to -X10 had been in place, the signal from the yellow pod would have been present to the SEM A card. Since there are no active signals to either the “Active this Pod” or “Active Remote Pod” terminals, the armed SEM A card must initiate the next step in the logic sequence, which is to turn on the relay connecting the blue pod 27 volt battery pack to power the two pressure transducers.

The conditions that resulted from the wiring nonconformances would be detected immediately upon the initial arming of the blue pod AMF from the surface, on February 8, 2010. When arming was initiated, the pressure transducers would have reported that both pressure conditions were normal, in effect communicating to the AMF card that there was no need to proceed with the emergency AMF/Deadman sequence.

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[126] Other open lead exceptions were noted for the battery connections in both the yellow and blue pods, but they were corrected with updated drawings.

The blue pod SEM A card would have then remained for some time following arming until the 27 volt battery was drained to the point that it had a lower voltage than the SEM 24vdc power supply. Because of the missing wiring and false signal to the AMF card, the SEM 24v power supply was still available and connected to power the two pressure transducers. Once the 27 volt battery voltage dropped below 24 volts, the 24v SEM power supply would automatically power the supply for the two AMF pressure transducers. The 27 volt battery and the SEM power supply were prevented from reverse power flow by blocking diodes. The battery likely drained to lower than 24 volts because of a continuing relay load of 8 mA during the 71 days that the AMF was armed prior to the accident on April 20, 2010.

ES concludes that the missing wires and miswiring in the blue pod caused the premature battery drain on the 27 volt battery pack so that it could not support the required AMF functions of rebooting the PLC and energizing the solenoid sequence once the final AMF condition, surface hydraulic pressure, was lost in the disaster.

D.4 Detailed Review of the Blue Pod Defects

In CAM-CSB 000005174, SEM A wiring starts on Sheet 2 and ends on Sheet 23 with the SEM A AMF card interface. SEM B wiring starts on Sheet 24 and ends on Sheet 45 with the SEM B AMF card interface. Sheets 46 and 47 are apparently not used. Sheet 1 of 47 contains legend information regarding the nomenclature used to identify wiring device designations, terminations, and locations within the various sheets. For example, nomenclature on the end of a wire shown on the drawing might be: *-X10:11* and *2.2*, meaning the wire shown will be routed from the termination point shown on that drawing to termination on device -X10, terminal 11 – to be found on sheet 2, at approximately column 2 of that sheet.

Following the open wires found in blue pod SEM A would lead to Sheet 23, which is included in the Phase 2 Test *Preparation Sheet* BOP-033 page 30. The first open wire originated from the AMF Card (-A31) termination point (-X47) terminal 14. This terminal is identified as “Active this Pod.” This is one of the critical signal inputs indicating that this pod is alive and functioning. Terminal 14 should be wired to -X10:11 on Sheet 2 column 2. On Sheet 2, -X10 is the subsea J-Box connection point, which connects the blue pod SEM (A&B) to the exterior of the SEM. Numerous wires are connected to terminal 11 of -X10. The wiring from the SEM A AMF terminal 14 to this multiple-junction point terminal 11 was missing or disconnected.

Following the second open lead (page 31 of BOP-033) again from terminal 14 on the AMF card leads to -K4 pin 14 on Sheet 17 column 6. This is the same Active this Pod terminal and should be wired to Sheet 17, device -K4. K4 is a relay and -K4:14 is a normally open (N.O.) relay contact.

Following the line from -K4.A1 (column 6, below terminals 11 and 14) to the left side of the drawing leads to -X3:37, which is connected to the 24vdc bus for SEM A. This implies that the coil of relay K4, terminals A1 and A2, is energized whenever 24vdc exists on the bus. The N.O. contact, terminals 11 and 14, will close whenever there is power from the deck to the SEM via the riser electrical cables. This connection to terminal 14 of the AMF card and its subsequent indirect connection to -X10 appear to form part of the necessary conditions, which if absent, could elect to initiate the AMF/Deadman sequence.

A third wire was "open lead" on page 31 of BOP-033. This wire extends from terminal 16 of the AMF card. That termination point is identified as "Active Remote Pod." Terminal 16 should also have been connected to -X10:11 Sheet 2 column 2. This is the same termination point for terminal 14. Therefore, were the wires connected properly, terminals 14, 16, and -K4:14 were essentially all to be tied together at the same common multiple-termination point on Sheet 2. But testing showed that these wires were not connected as shown on the drawings for some unknown reason. Additional testing by NASA indicates that the technicians found continuity from terminals 14 and 16 from the AMF card to connection point -X11.[127] Since there was no conductivity to -X10, there were additional missing wires between -X10 and -X11.[128]

The purpose of "capped" receptacle -X11 is unclear. Some quality tests refer to both X10 and X11, but we cannot reverse engineer the purpose for connector X11. Perhaps it was used only for testing purposes on the surface.

There were also missing wires in SEM B AMF card of the blue pod (Sheet 45). [129] Again, the same terminals 14 and 16 on the AMF card are found not connected as shown on the drawings. These two terminals should have been connected to the same multiple-termination point as shown on Sheet 2. In NASA's point-to-point testing, terminal 14, which also connects to -K6 pin 14, was in fact connected to that K6 relay shown on Sheet 40 column 6. Relay K6 functions identically to relay K4 in that it provides a healthy condition signal that power and control are "normal." The wire from AMF terminal 16, Active Remote Pod, however, was not connected to the common termination point on Sheet 2.

By the fact that the K6 relay contacts, terminal 14, was found connected to terminal 14 of the AMF card, the Active This Pod was getting an external signal that "this pod" was alive and had power available from the deck under normal operating conditions, even though terminal 16 was not getting an indication of health from the remote pod. The result is the false indication that the AMF is armed and ready to read such signals.

Assuming that AMF is armed the wiring defects were present before April 20, 2010, the SEM B AMF card would be getting a signal that the remote pod (yellow) was alive and healthy, which indicated that power and control

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127 See the handwritten note of Phase 2 Test Preparation Sheet, DNV2011061904 BOP-033 at the bottom of page 31.

128 ES researched the possibility that a "heartbeat" signal might have been available to the SEMs from external connections at connector –X11 to the Riser Control Box (RCB). Per the drawings, there was only one external cable to the "Sub-sea J-Box" which was then connected to the RCB. That cable connected only to the connector at –X10. The following drawings confirm that the only external connection for the "heartbeat" signal is a single cable to –X10. SK-122178-21-06 Sht. 2 of 47 TREX-5157 (-X11 connection is shown as "Not Used – 20k PSI Cap", SK-122178-21 Sht. 1 of 1 (CAMCG-00000334) indicates that there are four (4) external connectors around the periphery of the SEM vessel; These are "Sub-sea J-Box, STM I, STM II,… the fourth indicates "CAP". SK-122100-21-04 Sht. 1 of 4 (TRN-HCEC 00016703) is a complete interconnection diagram for the MUX. It clearly shows no direct connection between the RCB and the "SEM Assy." other than the one through the Sub-sea J-Box. This is consistent with Sht. 1 of 1 above that the SEM is connected only to the Sub-sea J-Box, STM I and STM II and shows 1 external blank connection. The sub-sea J-box is connected to the RCB and there is a "heart beat" signal in that cable from the RCB through the Sub-sea J-box to the SEM connector –X10. There is no external connection to –X11 shown on these drawings.

129 See Phase 2 Test Preparation Sheet, DNV2011061904 BOP-033, page 34.

were still available to the remote pod even if this blue pod was not healthy. But the result of the wiring defects on the SEM A AMF card losing both Active this Pod and Active Remote Pod signals would result in communicating to this one SEM A AMF card that all power and control/communications signals had been lost.

This miscommunication signaled that the only remaining condition for activation of the AMF/Deadman sequence would be the loss of hydraulic pressure, which did not happen in the 71 days of drilling activity and normal operations leading up to the incident.

It appears that the control system logic requires the 27 volt battery pack to be connected only after a loss of power, control, and communications signals, with the exception that it holds one 24v relay coil to permit the AMF control of other 24v relays. The *BP Report* confirms this logic step.[130]

This precondition for connecting the 27 volt battery is somewhat contrary to the *Transocean Report*, which advised that the 27 volt battery was connected whenever the AMF was armed. It is connected only to one relay coil, but not to the two pressure transducers. Connection to the pressure transducers requires loss of SEM power and control. Transocean's battery load calculations were then based on maximum loading (20 mA) of the 4-20 mA transducers, allowing only the 27 volt battery pack to have 43.75 days of useful life. This calculation is erroneous, as it would require changing the battery pack after a month of drilling service. Transocean's estimated short life cycle also excludes any use of the 27 volt battery to fire solenoids. ES concurs with BP's understanding of the 27 volt battery getting connected to the transducers only after the AMF card senses a loss of power to the SEM. In addition, Transocean's calculations reveal that the 27 volt battery should have completely drained by March 22, a full month before the accident. This 9 volt battery failure scenario is not credible, because the 9 volt blue pod batteries passed all load tests at Michoud.

When the 27 volt battery gets connected, then the wiring defect in the blue pod SEM A (and not the wiring defects in SEM B) would have signaled the SEM A AMF card to connect the 27 volt battery using an AMF card relay to energize the two pressure transducers, TP9 and TP10. These pressure transducers were necessary to detect the loss of hydraulic pressure relative to the ambient subsea hydrostatic pressure. They are normally powered by the SEM's 24vdc bus until that bus loses power. The premature connection of the 27 volt battery would occur immediately whenever AMF was put into the armed state. This would cause the 27 volt battery of the blue pod to be loaded prematurely even though it was designed to be connected only after loss of power and communications. In turn, this premature connection of the blue pod battery caused the early failure of the 27 volt battery before the incident. ES battery drain calculations appear below.

130 *BP Report*, Appendix X, AMF Sensor Relay, p.4,

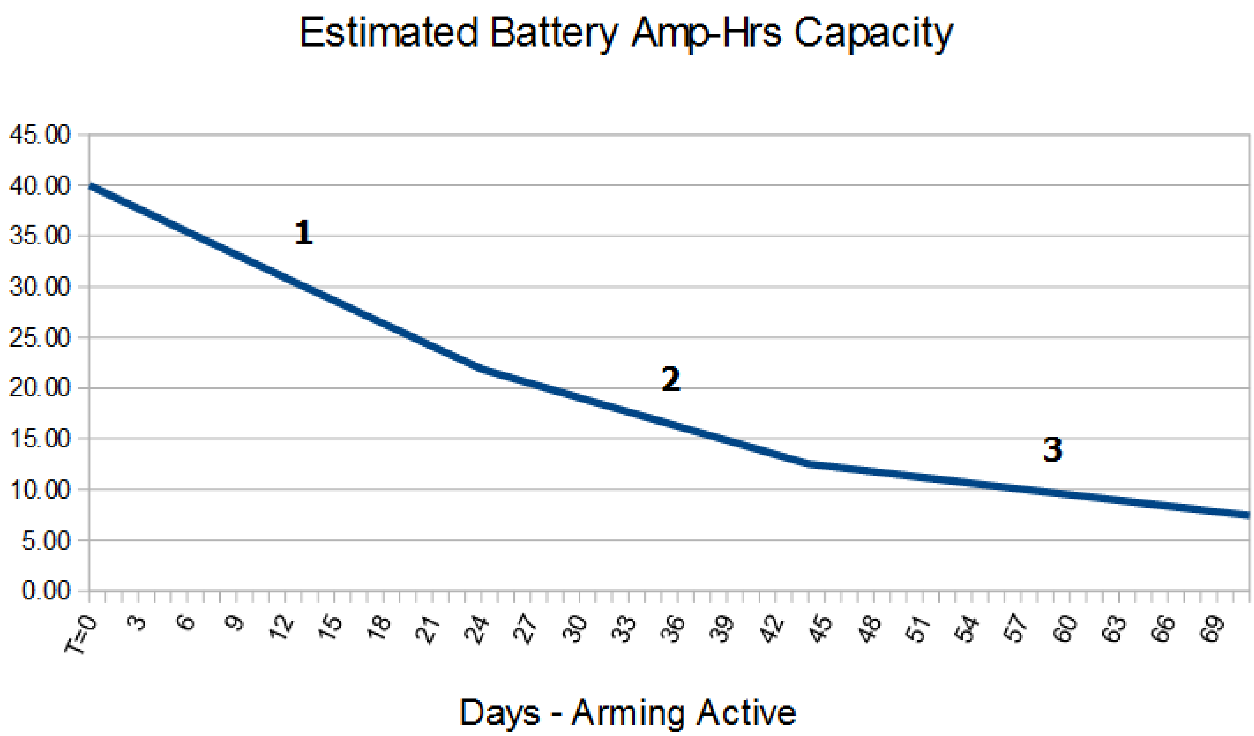

Figure D-2: Blue Pod 27 volt Battery Loading Time Segments (Source: Engineering Services)

Figure D-2 contains three distinct blue pod 27 volt battery loading time segments:

1. Load for relay 1 coil and two pressure transducers from initial arming

2. Load for relay 1 coil and shared load on two pressure transducers with SEM

3. Load for relay 1 coil only

Assuming that arming started on February. 8, 2010 and continued until the loss of rig power on April 20, 2010, we have produced estimated calculations based on the expected load current of the pressure transducers and relay 1 coil current on the 27 volt battery for these 71 days. This is accomplished by first extrapolating the actual pressures for each transducer across the 4-20 mA range of the transducers. Each transducer had a different maximum pressure rating. The hydraulic/conduit rating was 12,000 psi, and the hydrostatic/ambient rating was 5,000 psi. The actual total milli-amp load for the transducers was estimated to be 22.53 mA. The current load of the relay 1 coil varied from a high of 9.6 mA down to 7.6 mA as the battery voltage declined. We also considered the additional factor of the active SEM 24v power supply contributing some power to the transducers as the battery voltage dropped below 24 volts.

The resulting amp-hour load calculated for the arming period turns out to be more than 80% of the battery capacity starting condition of 40 AH (40 → 7.5 AH). We chose 40 AH for the initial condition of the battery, which was derated from 48 AH for subsea temperature conditions by 12.5%, and we then further assumed some shelf life (2006 to 2010) and prior testing losses of 2 AH).

We concluded that the premature connection of the blue pod 27 volt battery, caused by miswiring in the SEM, led to a premature, unintended, and critical drain of the battery through the two pressure transducers, thereby preventing the 27 volt battery from energizing the emergency AMF solenoids.

Appendix E: CSB Exemplar Solenoid Testing

The test protocol included programming two PLCs (programmable logic controllers) to simulate the pulse-width-modulated DC voltage sequence similar to the sequence used in the SEM's solenoid driver module. This appendix describes the programmed test sequence;

The 24 vdc was programmed as a fixed pulse-width sequence similar to the original PLC solenoid drivers in the SEMs. The repeating pulse widths were used to simulate the solenoid driver sequence observed during solenoid testing at Michoud. The sequence was programmed to be 30 seconds long for each PLC to match the SV 103 duration in the AMF/deadman sequence.

Both PLCs were programmed with the same 30 second sequence; however, PLC-1 was programmed to start the PLC-2 sequence with a delay, which could be varied for each test. The minimum increment of delay was 1 mSec. A four-channel digital storage oscilloscope[131] was used to review and save the test data. Once the sequence was initiated by pressing a start button for PLC-1, the oscilloscope would capture the voltages for each coil, the current for coil A, and the output of the solenoid outlet pressure transducer, and the data saved for further evaluation.

Air pressure (~ 100-125 psig) was applied to the SV inlet. The outlet of the SV was deadheaded in a pressure gauge and the pressure transducer. The vent was open to atmosphere. The solenoid valve was placed in an ice water bath during testing to prevent overheating of the coils.

[131] Agilent Technologies, oscilloscope model DSOX2004A, 4-channel, 70 MHz, S/N MY521411068. Certificate of calibration: April 8, 2012.

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Figure E-2: Exemplar Solenoid Valve with Fabricated Header and Piping

A manifold header connection block was fabricated to compress the inlet, vent, and outlet o-rings with the aim of forming a sealed interface with the valve and providing threaded ports for the manifold piping.[132]

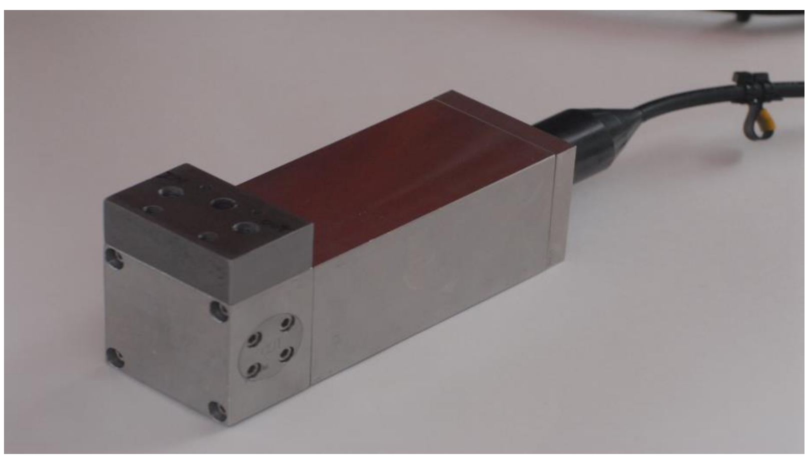

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Figure E-3: Exemplar Solenoid Valve with Attached Cable

[132] Exemplar solenoid information: Assembly PN 223290-63 Rev 04, Assembly SN 110744510-88 5009. Other ID: 400276664-01, 200070974.

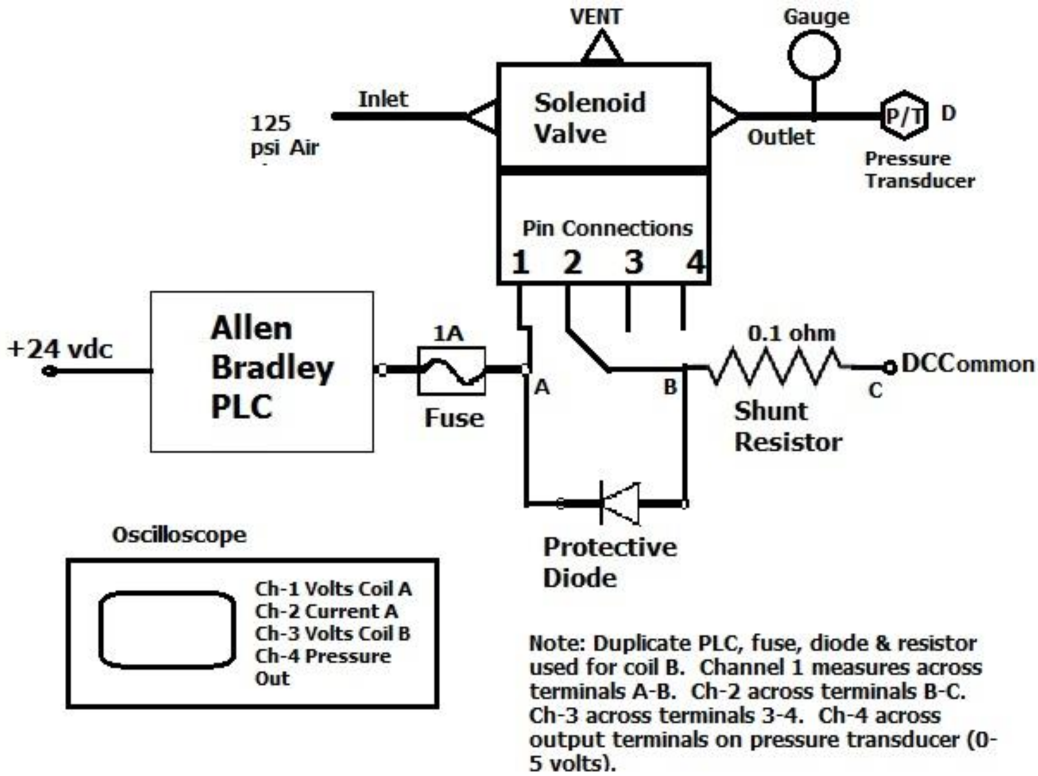

Figure E-3: Exemplar Solenoid Control (Source: Engineering Services)

Figure E-3 shows the layout and connections for the solenoid test protocol. There were two PLCs operating the test. For simplification, only one is shown in this diagram representing SEM A / coil A.

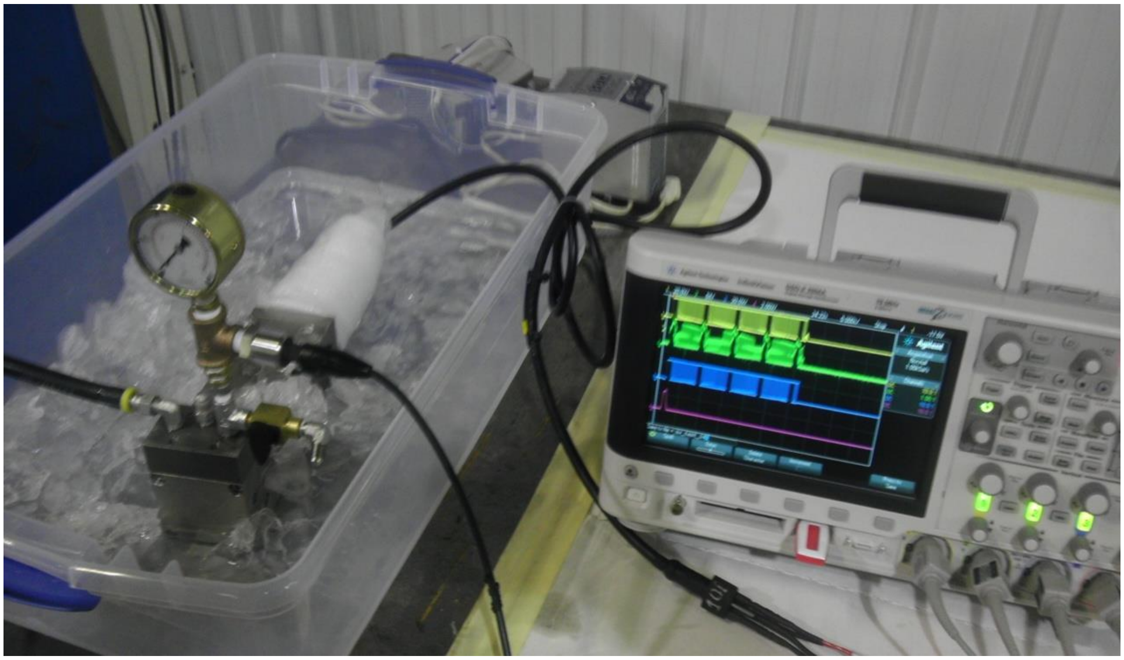

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Figure E-4. Ice bath with exemplar solenoid and oscilloscope

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Figure E-6. Allen Bradley PLCs with power supply, pushbuttons, and I/O wiring

E.1 Exemplar Solenoid Testing Results and Graphics

A minimum of 200 mSec delay in PLC-2 was necessary to open the SV briefly. Out-of-sync delays greater than 200 mSec caused increases in opening time. Since the opening pulse was one second long, the series of tests revealed that delays beyond the length of the opening pulse did not produce any additional number of valve openings. (See Figure E-.) Increasing the delay between PLCs, however, did increase the duration of total valve opening time for the programmed 30 second sequence. (See Figure E-7.)

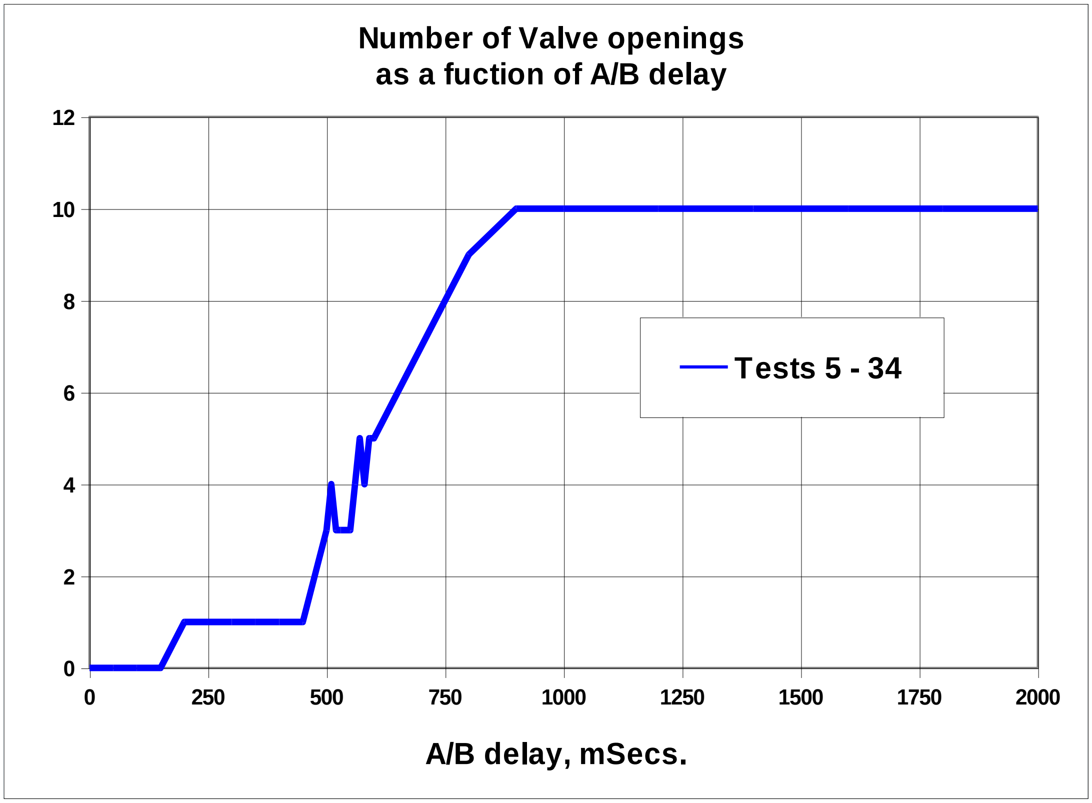

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Figure E-6. Number of Valve Openings as a Function of Delay

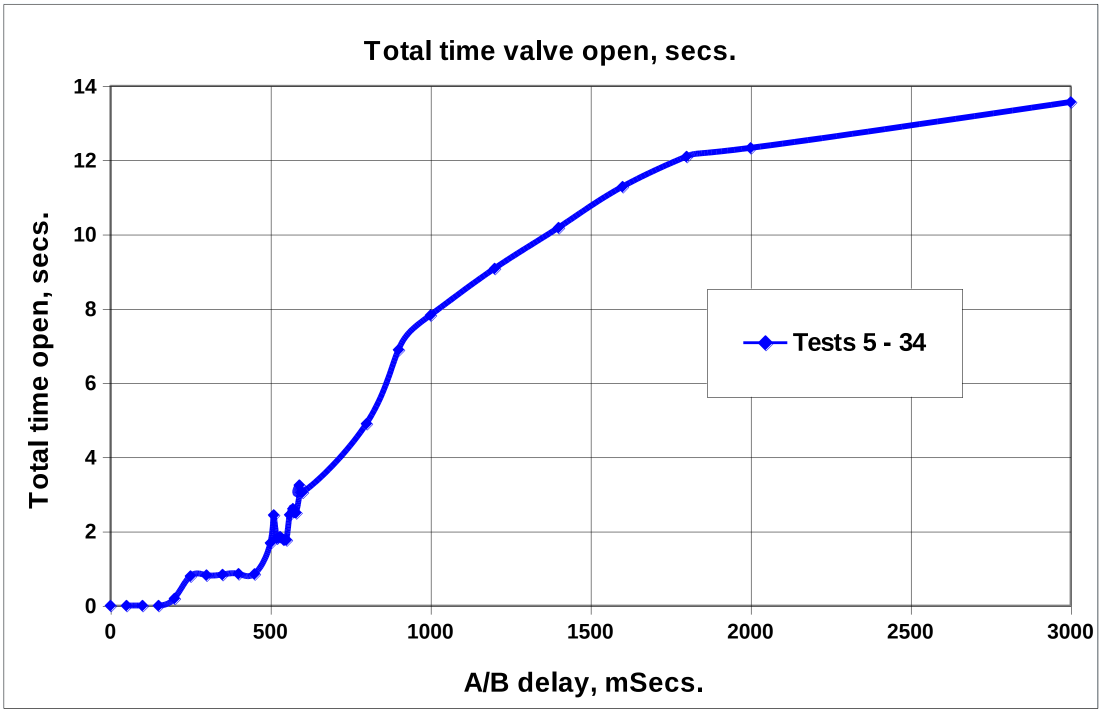

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Figure E-7. Total Valve Open Time for the SV as a Function of Delay between the two PLCs, 30-second Sequence

The following is a snapshot of the oscilloscope trace for Test #34, which consisted of a 33-second duration using a 3-second delay in PLC-2. There were 10 solenoid pulses during this test period, which totaled 13.6 seconds of opening time.

Traces #1 & 3 are solenoid coil voltages (A&B) on a PWM pulse sequence with offset delay. Trace #2 is coil A current. Trace #4 is voltage related to air pressure output of the valve on a pressure transducer (0-5v). Valve is open when voltage goes high.

The traces above and graphic plot below indicate 10 pulses for a total opening time of 13.6 seconds for a test duration of 33 seconds (30-second sequence + 3-second delay).

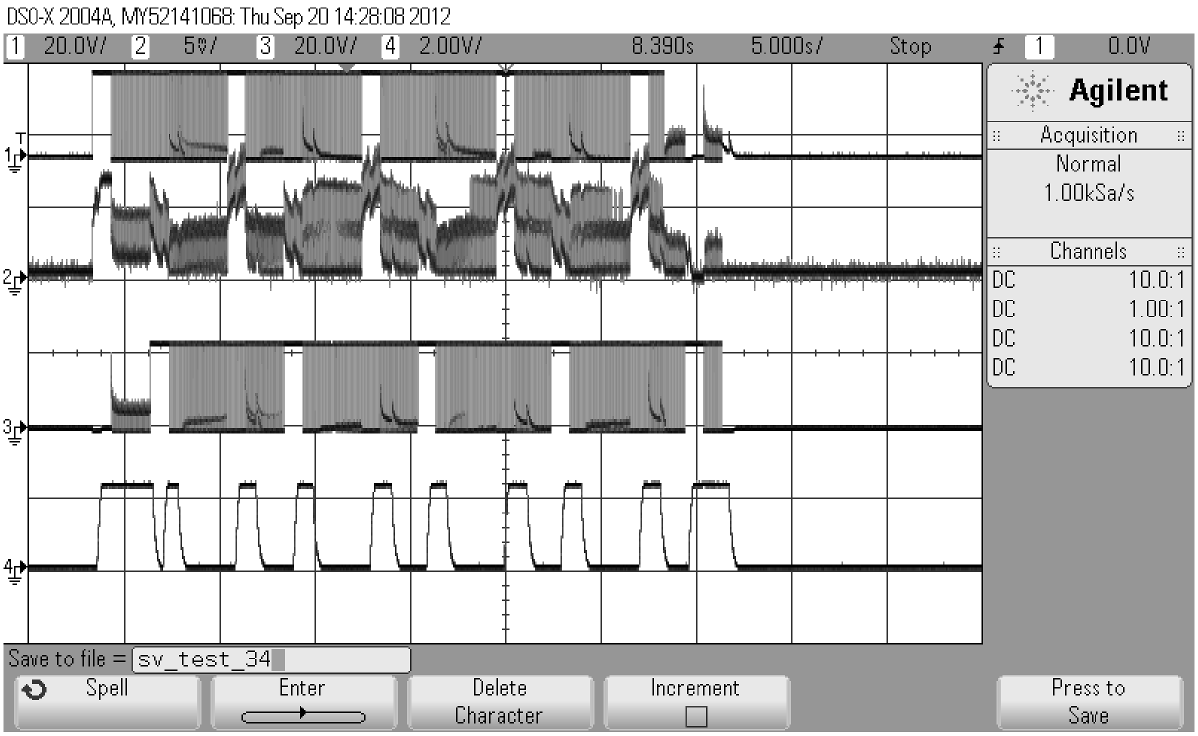

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Figure E-9: Oscilloscope Trace - Test #34

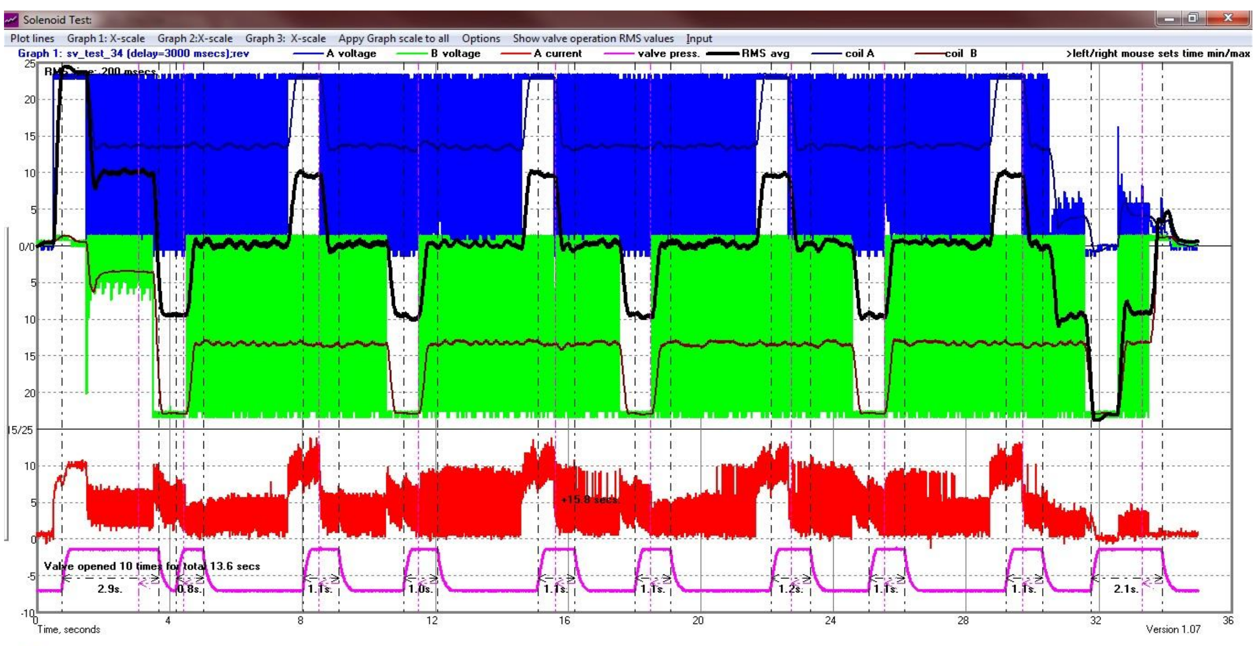

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Figure E-10: Graphical Plot of Valve Pulses 3-Second Out-of-Sync Condition

Figure E-10 plots Test #34, showing the PLC-A voltage plot in blue, the PLC-B plot in green (shown as negative pulses to indicate reversed coil wiring), the PLC-A current in red and the pressure transducer opening in purple. The dark lines over the voltage plots are calculated RMS (root mean squared) voltage values, as a proportional representation of the effective value of voltage contributing to the magnetic effect. The RMS values were calculated for each coil and then added together to show the net effect of the applied voltage in producing an electromotive force to move the solenoid core (heavy black line).

E.2 Effect of Out-of-Sync and Short-Cycle Testing

Cameron documents advised that there would be a 12- to 15-second delay in starting the AMF/deadman sequence after meeting all conditions.[133] AMF/deadman testing at Michoud during Phase 1 also confirmed the delays after PETU power was removed from the SEM. Given this variable timing in responding to an emergency, energizing coil A and coil B could be out of sync by as much as 3 seconds and permit the solenoid valve to fire in pulses on the pilot pressure side of the blind shear rams. Our analysis of actual Michoud AMF/deadman testing indicates that the out-of-sync delay could be as much as 6 seconds. (See Figure E-13, AMF%20Timing%20SpreadsheetTiming Analysis of SV103.)

We also found that one of the solenoid component tests at Michoud revealed a short-cycle of the initial sequence in SEM A while being initiated by a PETU. This shortened cycle was approximately 6.2 seconds, as opposed to 7.2 seconds seen in the SEM B sequence. The Michoud test data appears in Figure E-11.[134]

The initial short cycle of approximately 6 seconds in SEM A is seen in the test (1.00 S/division) captured in Figure E-11. The out-of-sync condition continued throughout the test even though the short-cycle did not continue, as seen in Figure E-12.

[133] CAM-CSB000013890, Document X-200261-62-18, p. 20.
[134] DNV2011060643, TPS BOP-015-2, *PETU Solenoid Driver Characterization*.

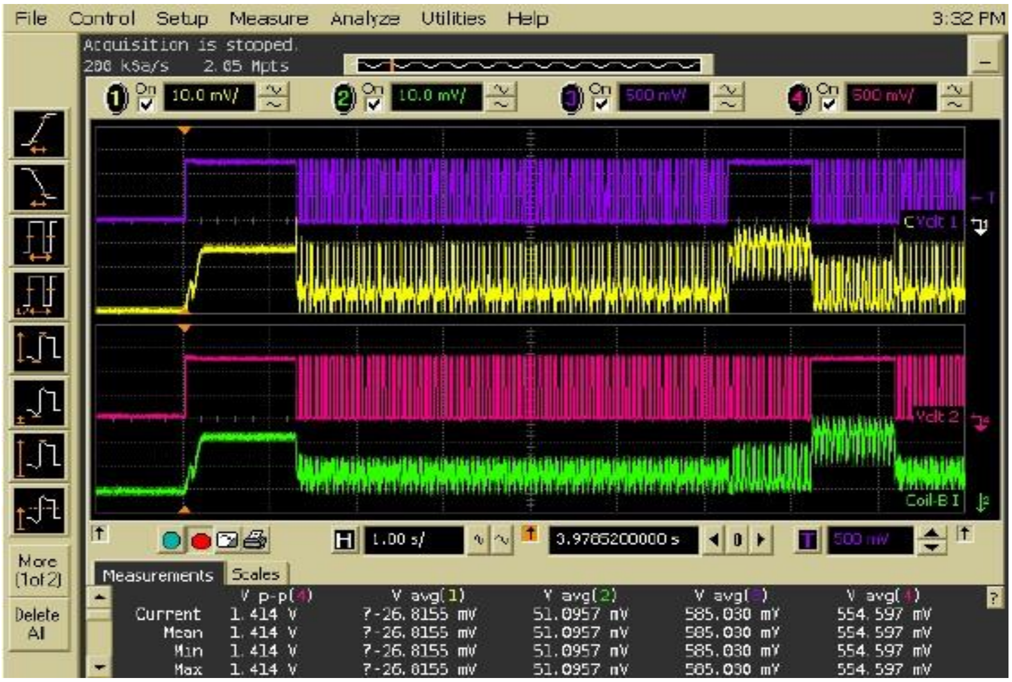


Figure E-11: Short-cycle Seen in PETU Characterization Tests during Phase 2 testing.

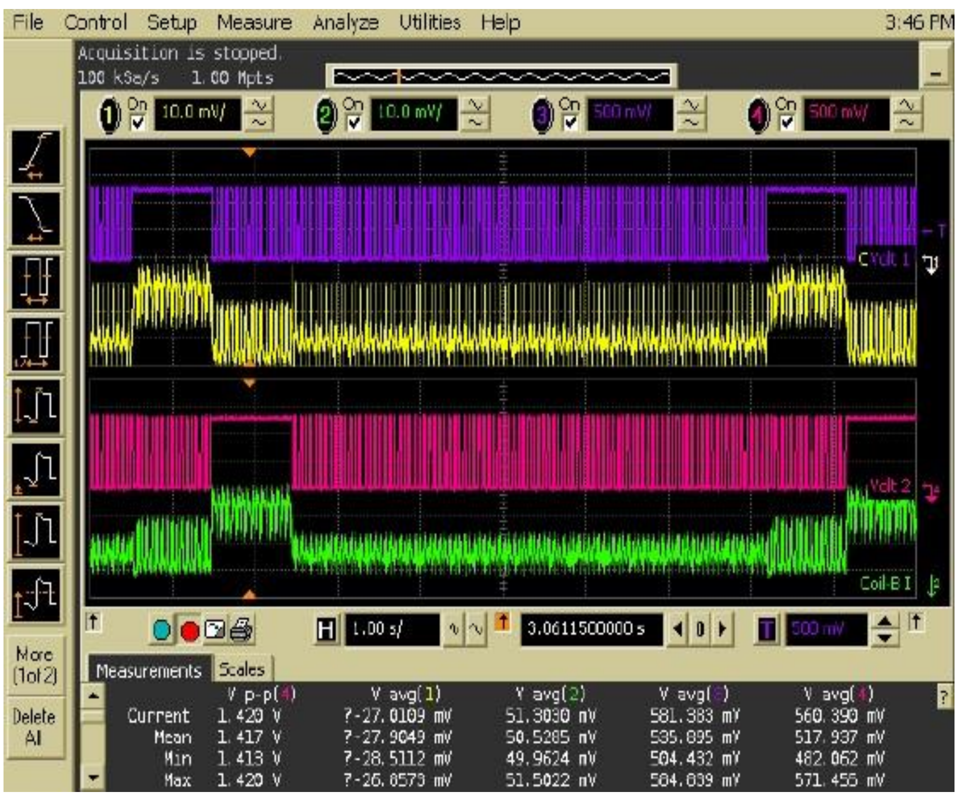


Figure E-12: Out-of-Sync Condition Remains after Short Cycle Ends as observed during Phase 2 testing.

The SEM A trace in Figure C5-12 reveals that the 7.2-second sequence resumed after the initial short cycle of 6.2 seconds. However, the out-of-sync condition remained between the two SEM A and B coils. ES believes that the SEM solenoid driver module, not the PETU, caused this condition.

This short cycle produced an out-of-sync condition of approximately 1 second. We tested this condition in Tests 58 – 61 by setting the second PLC for a 1-second delay and then making the electrical connections to the valve (using an auxiliary DPDT switch) after the initial long pulses from both PLCs had fired. Thus, we prevented any possible residual magnetic effect or valve operation from an initial long pulse in PLC-1. The result of Test 58 was eight brief pulses within the 30 second test for a total valve opening time of 8.6 seconds.

When the RBS 8D BOP was manufactured in 2000, the AMF/deadman sequence was programmed to include a 56-second sequence in which the actuation of the 103 BSR solenoid was set for 18 seconds. Prior to being deployed at Macondo, the AMF/deadman sequence was revised. Evidence taken during the inspection of the pod SEMs (ref – DNV2011062110 TPS BOP-038) on June 21, 2011 indicate that all four SEMs had identical shutdown.asc files. These files were used during the AMF/deadman reboot of the PLCs to interrupt the normal PLC cycle to execute the AMF/deadman solenoid valve sequence.

The programmed sequence calls for a 30-second activation duration for the 103 HP BSR solenoid valve. Based on our 30-second exemplar test duration, and a 3-second delay between PLCs, we saw 10 pulse operations of the solenoid valve and a total opening time of 13.6 seconds for the solenoid valve (Test 34 as shown earlier).

While we cannot precisely define the out-of-sync conditions at the time of the incident, we do know from our exemplar testing that a minimum of 200 mSec differential was required to actuate the valve in miswired condition (for 0.2 seconds). Much more than 200 mSec of delay would be required to do significant work through the pilot-operated high pressure shear valve to send sufficient high-pressure hydraulic fluid to the blind shear ram pistons.

E.3 Additional Analysis of Out-Of-Sync Conditions

Figure E-13 shows the results of our graphic analysis of the five AMF/deadman tests during Phase 1 Michoud testing. The green bars on the timing analysis indicate the duration in which the 103 solenoid valve was open for each test. Table E-1 summarizes the opening times for the 103 close BSR valve.

	Programmed Sequence		Yellow – Using Replace. 103 SV	Blue – on PETU Power	Yellow – Using Orig. 103 SV	Yellow – Using Orig. 103 SV	Yellow- Using Orig. 103 SV
			Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**
	For SV 103		**DNV Table 8**	**DNV Table 9**	**DNV Table 11**	**DNV Table 12**	**DNV Table 13**
SV 103 Total Opening Time	30 sec.		36 sec.	36 sec.	7 sec. *	31 sec. **	30 sec. **
Differential SEM Timing	0		+ 6 sec.	+ 6 sec.	SEM B Battery Failed in Test	1 sec.	0 sec.

Engineering Services

Table E-1: Phase 1 AMF/deadman Tests - Timing for SV 103 (Source: Engineering Services)
*** 9 volt SEM B Battery fails during test sequence**
**** 9 volt Battery fails and is unable to reboot SEM B**

The PLCs in the pods were programmed only for 30 seconds of operation of the 103 solenoid valve. Actual testing at Michoud revealed in the above table, Tests 1 and 2, show that the SEMs can be out of sync by as much as 6 seconds in actual AMF/deadman since the total opening time was 36 seconds. The 36 seconds cannot be taken to mean some random variable in the PLC timing, but rather in the timing of the AMF card to start the sequence in one SEM prior to the start of the sequence in the other SEM. The 36 seconds in Test 1 says nothing about the viability of the SEM B 9v battery. That battery appears to have failed in Tests 3, 4 and 5. It is quite possible that this same battery failed to support SEM B (and the 103 solenoid valve) for a full 30 seconds in Test 1. It is possible that SEM B was "leading" SEM A in the initiation of the sequence, but failed during the final seconds of Test 1 when SEM A was carrying the second coil of the replacement 103 solenoid.

The 6 second differential timing is significant to the theory and exemplar testing in that it would permit a mis-wired solenoid valve to 6 seconds of initial operating time plus the cumulative duration of the open pulses while both SEMs are acting on the solenoid valve.

Table E-1. Timing Analysis of SV 103 for Five AMF/deadman Tests at Michoud.

		Event /Func			Yellow Pod – 103 Replacement		Blue Pod – AMF on Re-power		Yellow Pod – 103 Original		Yellow Pod – 103 Original		Yellow Pod – 103 Original	
					Test 1		Test 2		Test 3		Test 4		Test 5	
Timing secs.	**AMF Testing Sequence**	**ID**	**Programmed Sequence**	**ID**	**DNV pg 46 Table 8**	**ID**	**DNV pg 46 Table 9**	**ID**	**DNV pg 47 Table 11**	**ID**	**DNV pg 47 Table 12**	**ID**	**DNV pg 49 Table 13**	**ID**
-16	Disconnect PETU Power to Pod	**X**			Disconnect PETU Power to pod	**X**				**X**		**X**		**X**
-15														
-14	This delay, prior to starting the PLC													
-13	reboot likely caused by power													
-12	supply capacitanc e.													
-11	Laptop Comms to PETU- Off and PLC Starts Reboot	**Y**	Loss of Power, Comms & Hydraulic	**Y**	Laptop Comms off – PLC starts reboot cycle	**Y**	AMF signal to PLC starts reboot when power was re-established by PETU	**Y**		**?**				**Y**
0	PLC Rebooted, Starts AMF sequence,	**33/43**	PLC Rebooted, Starts AMF sequence,	**33/43**		**33/43**				**?**		**33/43**		**33/43**
1	Stack & LMRP Stingers Extend		Stack & LMRP Stingers Extend											

		Event /Func			Yellow Pod – 103 Replacement		Blue Pod – AMF on Re-power		Yellow Pod – 103 Original		Yellow Pod – 103 Original		Yellow Pod – 103 Original	
					Test 1		Test 2		Test 3		Test 4		Test 5	
Timing secs.	**AMF Testing Sequence**	**ID**	**Programmed Sequence**	**ID**	**DNV pg 46 Table 8**	**ID**	**DNV pg 46 Table 9**	**ID**	**DNV pg 47 Table 11**	**ID**	**DNV pg 47 Table 12**	**ID**	**DNV pg 49 Table 13**	**ID**
2					Early by 3 sec	**35/45**								
3					possible timing measurement							**35/45**		**35/45**
4					error									
5	Energized Stack & LMRP Stingers	**35/45**	Energized Stack & LMRP Stingers	**35/45**						**?**	This activation of 103 works	**47**	This activation of 103 works	**47**
6					One second early	**47**					because SEM B 9v battery		because SEM B 9v battery	
7	De-activate Stingers Extend &	**47**	De-activate Stingers Extend &	**47**	possible timing measurement						has failed and cannot		has failed and cannot	
8	Energize 103 Blind Shear Ram Close		Energize 103 Blind Shear Ram Close		**error**			**47**			reboot SEM B PLC		reboot SEM B PLC	
9														
10				**P**										
11				**R**										
12				**O**										
13				**G**										
14				**R**										
15				**A**										
16				**M**										
17				**M**										
18				**E**										
19				**D**										

		Event /Func			Yellow Pod – 103 Replacement		Blue Pod – AMF on Re-power		Yellow Pod – 103 Original		Yellow Pod – 103 Original		Yellow Pod – 103 Original	
					Test 1		Test 2		Test 3		Test 4		Test 5	
Timing secs.	AMF Testing Sequence	ID	Programmed Sequence	ID	DNV pg 46 Table 8	ID	DNV pg 46 Table 9	ID	DNV pg 47 Table 11	ID	DNV pg 47 Table 12	ID	DNV pg 49 Table 13	ID
20														
21				S										
22				E										
23				Q										
24				U										
25				E										
26				N										
27				C					Delay in activation of 103	47				
28				E					due to opposing wired coils					
29									9V SEM B battery fails					
30				30					and PLC-B goes off-line.					
31														
32				S										
33				E										
34				C										
35				.					Short cycle of 7 sec. Due	Off			Pressure is off after 30 sec	Off
36									to mis-wired 103 and the		Pressure off after 31 sec.	Off	Timing is exactly as	
37	De-activate BSR Close	Off	De-activate BSR Close	O F F					failure of SEM B 9v batt.		Difference of 1 second		programme d. One 9v	

		Event /Func			Yellow Pod – 103 Replacement		Blue Pod – AMF on Re-power		Yellow Pod – 103 Original		Yellow Pod – 103 Original		Yellow Pod – 103 Original	
					Test 1		Test 2		Test 3		Test 4		Test 5	
Timing secs.	**AMF Testing Sequence**	**ID**	**Programmed Sequence**	**ID**	**DNV pg 46 Table 8**	**ID**	**DNV pg 46 Table 9**	**ID**	**DNV pg 47 Table 11**	**ID**	**DNV pg 47 Table 12**	**ID**	**DNV pg 49 Table 13**	**ID**
38											may be measuring error.		battery has failed to	
39											One 9v battery has failed		reboot SEM B.	
40											to reboot SEM B.			
41														
42					Pressure is Off after 36 sec.	**Off**								
43					Extended duration could									
44					have been due to A&B		Pressure is Off 36 sec.	**Off**						
45					**sync delay of 6 sec.**		Extended duration could							
46							have been due to A&B							
47							**sync delay of 6 sec.**							

E.4 Electrostatic Detector Measurements on the Reverse-wired Solenoid Valve

ES conducted a test using a non-contact voltage tester with sensitivity control (Extech DVA30) in an attempt to get an external indication that the solenoid was being energized. We wired coil B backwards and set PLC-B for the minimum 1 mSec delay. Essentially, PLC-A and PLC-B were synchronized with coil B being miswired. We knew from prior tests that this wiring arrangement would not permit the valve to actuate.

Figure E-14: Extech DVA30 Non-contact Voltage Detector

The detector was placed on the exterior of the solenoid, and the sensitivity was adjusted to not light or beep when there was no electrical power to the SV. The test was started with both coils energized at the same time. The detector sensed the voltage, but the solenoid valve did not actuate.

Our testing revealed that the sensitivity of such devices can cause erroneous results. Any external attempt at checking solenoid actuation, may verify electrification, but it cannot confirm actuation of the valve in the case that one coil of the dual-coil solenoid is reverse-wired.

Appendix F: Review of Cameron FAT Test Procedures

ES reviewed several FAT and AMF/deadman testing procedures for DWH MUX control pods or individual SEMs to assess their ability in detecting problems in the emergency control systems. These procedures provided vital input to understand what Cameron considered necessary for quality assurance functioning of the MUX control pods and SEMS. The sections that follow document our comments on each procedure. Comments were made where deviations to the written procedure were made during testing or where test equipment or methods appeared to be changed over time. In most cases, we make no attempt here to analyze the "color" identity or position of these pods/SEM relative to their location on the date of the accident. If a color of the pod is indicated, it is because the FAT procedure indicated it as such.

F.1 Cameron FAT Test for Subsea Electronic Module.[135]

This procedure was used during the upgrade of the yellow pod SEM with new pie connectors and batteries from August to December 2006. ES has the following comments on this procedure:

1. Section 2, page 22 of 43 of this procedure states: "Remove PETU connection from X10 and install on X11. Leave the PETU switch in the A position." The pulse generator is to be connected to X11 pins 9 & 12 (SEM B).
2. The procedure was signed off,[136] but no AMF/deadman test result steps (pages 20-28) were initialed.
3. In an email to Cameron, Transocean apparently was dissatisfied with the quality of the work.
4. Another FAT AMF/deadman Procedure was accomplished – X-065449-05 (CAM-CSB000013591) for this work.
5. The bottom of page 6, AMF should have been initiated, but there are no initials or checkmarks.
6. This procedure uses external power supplies in lieu of 9 volt and 27 volt batteries.

Summary – A" pulse generator" is used in this test to simulate part of the AMF/deadman conditions. The AMF/deadman test used external power supplies. The AMF/deadman batteries were not used.

F.2 Cameron FAT Test for Blue Pod SEM, November 2007[137]

1. This test setup description used two PETUs and two pods and -X10 and -X11 connections.
2. The results columns[138] show only check marks in columns Ba and Bb, implying that only one pod was used. Perhaps the other pod was simulated by the second PETU.

[135] Document X-200751-21-03, December 6, 2006, [CAM-CSB000013545].
[136] *Ibid.*, p. 29 of 43.

[137] AMF/deadman procedure X-065449-05, November 7, 2001 [CAM-CSB000013742].
[138] *Ibid.*, pp. 4-7 of 9.

3. The final condition to complete the AMF/deadman trigger is downward adjustment of the TP9 pressure transducer (simulated pressure).[139] This action triggered the AMF/deadman sequence correctly.

Summary – This test would not have caught the wiring nonconformance found by technicians in the Blue pod since the simulated removal of power and communications was not the last conditional trigger.

F.3 Cameron FAT Test for Subsea Electronic Module (Extended Version)[140]

This FAT procedure was accomplished on the blue pod in June 2009. ES has the following comments on this procedure:

1. The solenoid test does not specify how to set up the PETU switches (A/B, Single/A+B).[141]
2. It is not clear that the solenoid test separately test coils A and B. The test does not include both separate tests and simultaneous tests.
3. Analog tests for SEM A and B seem to imply nonconformances (NCR) on the analog values.[142] These non-conformances were simply accepted by Transocean and Cameron. The Deadman active and deactivate values were not documented and might have been part of the nonconformances which were deemed acceptable.
4. The analog values for AMF/deadman active/de-active are not documented in the AMF/deadman sequence test for SEM A. [143] Test 1 proves that loss of hydraulic pressure can trigger AMF/deadman sequence.[144]
5. Handwritten changes appear on the testing pages relating to -X10, -X11, pins 7, 8, 9, and 12,[145] and regarding how the PETU was connected to -X10 or -X11 and its switch (A/B) settings.
6. In this test procedure, the PETU was to be connected to -X10 (SEM A), but the pulse generator was to be attached to -X11 (SEM B) pins 9 and 12 (handwritten pins 7, 8). This procedure may be the wrong one for this pod SEM. See note at grid F:5 "AMF/deadman Trigger In … Not Used," regarding pins 7, 8.[146]
7. This test was a SEM-only test, which did not involve the actual solenoids on the Blue pod. It used test solenoids that were connected temporarily.[147] In this procedure, only one coil is energized at a time. No polarity testing of SV coils is accomplished because this test does not apply to a test of the actual pod solenoid valves.

[139] *Ibid.*, p. 6,
[140] CAM-CSB000013890, Document X-065449-02, June 22, 1999.
[141] *Ibid.*, p. 10.
[142] *Ibid*, pp. 14-15.
[143]NEED TO FIX CITATION: Form X200261-62-18, April 4, 2007, p. 20.
[144] Test 1, p. 21.
[145] *Ibid.*, pp. 20, 22, 23.
[146] CAM-CSB000005175, SEM Wiring Diagram, SK-122178-21-06, Sheet 2 of 47.
[147]*Ibid.*, pp. 20 and 22.

8. Page 20 notations include: "Redline AMF/deadman Functions."

Summary – Technicians were modifying the written procedures during the tests. Either the procedures were incorrect for this type of test or the tests were conducted out of compliance with design requirements. This test has limitations since actual solenoids were not in place. Nonconformances were noted on the AMF/deadman functions.

F.4 Cameron Refurbishment of Yellow Pod SEM

Cameron refurbished and tested the apparently defective yellow pod SEM in February 2010, while drilling was underway at Macondo. Given our hindsight that miswired solenoids and defective wiring were in the subsea pods, this review of test procedures for a pod that was not in use on the DWH aimed to assess the state of the quality of FAT testing in early 2010.[148] ES has the following comments on this procedure:

1. There are differences between this procedure and X200261-62-18 in C6.3. In this case, the PETU connections are being made to SEM A, but the pulse generator is connected directly to pins 14 and 16 on the AMF/deadman card instead of to -X10 or -X11. If the wires from pins 14 and 16 were misconnected as they were in the blue pod, then this procedure would not pick up the wiring deficiencies external to the AMF/deadman card that technicians observed.
2. Solenoids being tested here are test solenoids, not actual pod solenoids. In this procedure, only one coil is energized at a time. No polarity testing of SV coils is accomplished because this test does not apply to the actual pod solenoid valves.
3. The test technician appears not to have complied with the SEM B test (Section 2) instruction to remove the "PETU connection from SEM A and move to SEM B" and instead, simply switched the PETU to SEM B (handwritten) instead of leaving the switch in the SEM A position and moving the connection to SEM B. Alternately, the test technician might have assumed a typographic error in the procedure. In either case, he did not follow the procedure as written.
4. This SEM is shipped to the DWH rig and becomes the spare SEM on the white pod.

Summary – The test technician is adapting the procedure to the equipment under test. The procedure does not exactly fit the equipment. Cameron's procedure has now changed for using of the pulse generator. The procedure calls for the pulse generator to be connected in a way that places it at the AMF/deadman card, which assumes that the SEM is open and those terminals are accessible. Access to these terminals would not be available when the SEM is closed, unless these terminals are wired to external connector -X10 or -X11.

[148] The FAT procedure was CAM-CSB000014274, X-065449-05, "Factory Acceptance Test Procedure for Subsea Electronic Module (AMF)," July 24, 2009, revision 01.

F.5 Cameron Deck Test Procedure for Mark II Control Pod[149]

This procedure was used for the retrieved pod retrieved from the yellow position. ES has the following comments on this procedure:

1. This is the only deck test procedure that we have seen for the Cameron Mark II control pods. It is unnumbered and there were no recommended deck test procedures for the MUX BOP control system found in the RBS 8D Data Books or Operations Manual.
2. PETU to SEM cable has only four conductors/pins. This arrangement is not compatible with the connection described in the PETU-SEM cable circuit diagram.[150] No mention of PETU A/B switch settings. No mention is made of separate SEM A and SEM B connection points.
3. Upper annular pressure increase (3A) solenoid fails to operate. PETU operating mode must energize both coils due to the fact that this miswired SV failed its test.[151]
4. The solenoid valve of the upper annular regulator is noted to have failed (3A),[152] but there are separate tests for SEM A and SEM B. Apparently, the test setup or the PETU was not able to test only one coil separately from the other. If it had, both tests would have passed since miswired 3A would have failed only on simultaneous energizing of both coils.
5. There is no advice on switching PETU A/B switch or moving PETU-SEM cable for the pilot and function circuit.[153] Both SEM A and B columns were verified and initialed. The miswired SV 103 appears to have passed this test,[154] while the SV 103 is identified as failing the test.[155]

Summary – Michoud evidence from PETU characterization is that the A/B switch energizes both coils even though set to one or the other. This deck test procedure, if used on the deck prior to BOP deployment, needs clarification relative to polarity of the coils. Testing verification of coil A and B apparently cannot be made by a PETU that tests both coils at the same time.

F.6 Cameron FAT Procedure for SEM Horizon AMF/deadman[156]

This procedure was used for the retrieved Yellow pod. ES has the following comments on this procedure:

1. Page 4 of the procedure states, “All connectors designations and channel references left blank should be filled out by referencing the schematics.” Previous AMF/deadman procedures specified X10 and X11 connection points, but here referred only to SEM A and SEM B connections. This may

[149] Cameron P/N 2020708-21 May 4, 2010 (used during intervention only).
[150] CAM-CSB000005595, SK-066201-55-04, p. 5
[151] *Ibid., p.* 11.
[152] *Ibid.,* 13.
[153] *Ibid.,* p. 19.
[154] CAM-CSB000008033, p. 21.
[155] CAM-CSB000008036, p. 10.
[156] CAM-CSB000008037, Applicable in current situation – Form X-065449-05-03, May 11, 2010 (Used in intervention only).

imply that Cameron's internal wiring of the SEM (to X10 and X11) has been changed from the version of the drawings that technicians were using in their wiring point-to-point checks.

2. Page 5 notes that solenoid and battery connections were left "as is" from subsea.

3. Page 6, Test SEM B, Section 2 calls for removing "the PETU connection from SEM A and connect to SEM B. Select SEM B modem with the PETU modem switch." This instruction is verified with initials.

4. On page 9, the AMF/deadman sequence is signed off for Tests 1 and 2. The test sequence is 74 seconds long instead of 37 seconds as programmed into the SEM.

Summary – We question the results that show the 74-second duration of the AMF/deadman test.

F.7 FAT for AMF/deadman In Current Situation[157]

ES has the following comments on this procedure:

1. Test 1 relates to the simulation of loss of hydraulic pressure to the pod, and Test 2 relates to the loss of power and communications. These tests now have only two conditional triggers for AMF/deadman to start instead of the three conditional triggers. The difference is that this test assumes that the other pod is not pulsing the digital line and has lost its power and communications.

2. Testing was accomplished with pressure on the hydraulic and hydrostatic pressure transducers.

Summary – None of the four AMF/deadman tests on the blue pod was successful. The AMF/deadman fired only after PETU power was reconnected to the SEM because the 27 volt battery was nearly completely drained.

F.8 Integrity of AMF/deadman Functional QA Testing on DWH in 2010

The FAT testing procedures for the MUX control pods and the AMF/deadman function depend on whether the test includes both pods, a single pod, or a single SEM. The procedures appear to be dependent on the technician's knowledge of the equipment. In some cases, the procedures are modified. Section F6 shows that Cameron's AMF/deadman procedure for a single pod leaves the technician to determine which connector and channel are to be used based on the schematic drawings. This lack of specificity causes concern that the test requirements are dependent on the current state of the drawings. Perhaps changes to the pods have been made over the years which cannot be tracked, or they have not been tracked by the manufacturer, but they should have been documented by red-lined drawings. If the manufacturer cannot be specific on how to test a pod or SEM which was manufactured in 1999-2000, then the integrity of the testing falls to the owner to prepare deck and functional tests based on the owner's knowledge and modifications over the years and its own as-built drawing modifications.

The post-accident deck test procedures were apparently generated post-accident, suggesting that there was no procedure in place for testing the AMF/deadman functionality on the rig.

[157] Intervention Testing on Enterprise, July 2010 Blue pod. Document X-065449-05-03 form, May 11, 2010. (BP-HZN-BLY00061082)

Appendix G: Analysis of Pie Connector Evidence

External observations during Phase 2 testing indicate some of the pie connectors exhibited white oxidation at the male/female plug interface on the SEM housing external connections. The exterior portions of these plugs were exposed to seawater and subsea pressures. The presence of oxidation around the male plugs indicates some galvanic action occurred to form the oxide deposits.

Phase 1 protocols did not permit the TWG to review the PETU diagnostic analysis of the control pods to determine if there were any faults on any of the solenoid circuits. Any fault on a solenoid coil might have been due, in part, to abnormally high pie connection resistances caused by oxide buildup.

The male/female connection interfaces were cleaned of the oxide deposits during Phase 2 on June 13 and 15, 2011. Resistance measurements were then taken external to the SEM at the plug (female connection) interface. These measurements were essentially open-circuit measurements in the range of 40 to 60 k-ohms and did not address the in-circuit resistances with the oxide in place.[158]

[158] Test Documents DNV2011061012 and DNV20110615

G.1 Review of Oxidation on Control Pod SEM Pie Connectors

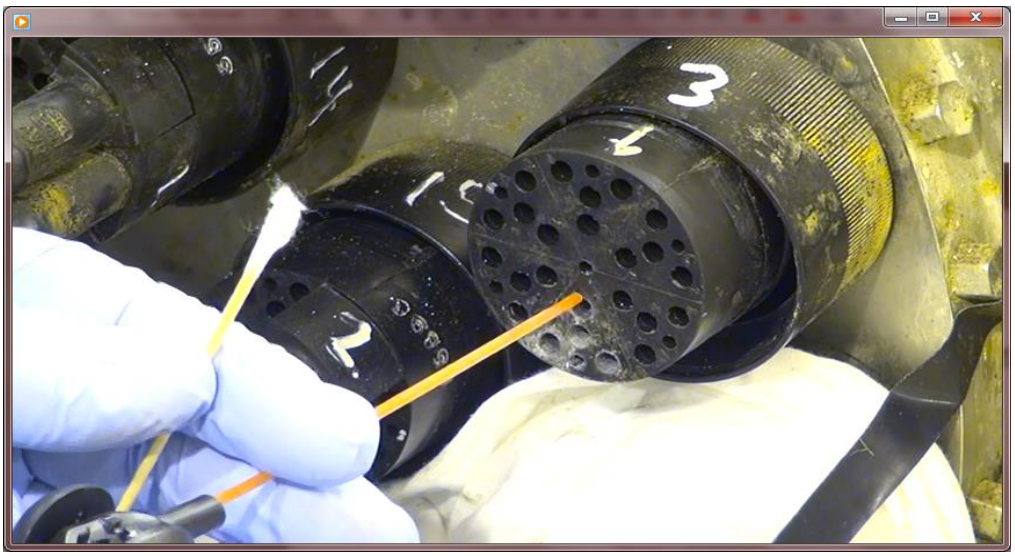
The following snapshots were taken from Phase 2 videos. These views show oxidation created on certain pie connectors.[159]

Figure C7-1: Blue Pod SEM
Pie Connector 3 appears to be the only connection which has severe oxide exposure. In particular, pie connection 3E is the only connection that exhibits these corrosion products. (function 3E = Blue Pod Hotline Supply)

[159] Documentation of the pie connector numbering system is found in CAMCG 00000334 and CAM-CSB000005171on drawing SK-122178-21-04 sheet 1 of 3.

Figure C7-2: Title Pre-test Oxide Cleaning

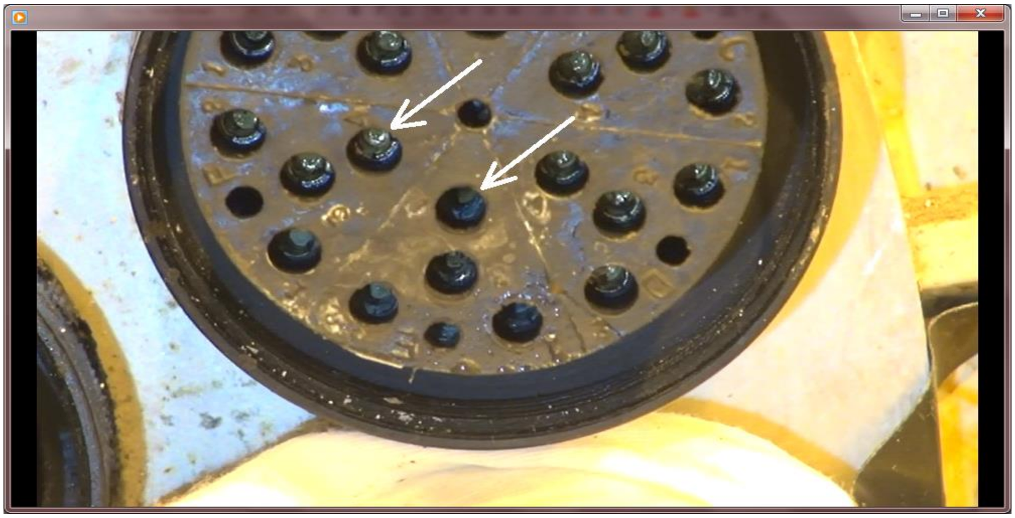
Close-up of Blue pod SEM connection 3E as technician begins to clean the oxide before testing resistance in connections. Dummy plugs are used to seal unused connections as in connectors #14 and #15.



Phase 2 Testing

Figure C7-3: Oxide Cleaning Process

Technician uses swab and compressed air to clean oxide out of connection. After cleaning, 3E pie connection interior contacts are not bright and shiny like other connections.



Phase 2 Testing

Figure C7-4: Contact Comparison
This image from Video 20120614084748 at 1:17:00 shows dull gray contacts in 3E and brighter contacts in 3F.

G.2 Functional Analysis of Blue Pod SEM Oxides on Pie Connectors

Pie Connector Number = Solenoid Number & SV Action.

The following solenoid had significant oxide buildup on the Blue pod pie connectors:

3E = SV15 – Blue/Yellow[160] Pod Hotline Supply – OPEN

In general, there was more oxidation on the yellow pod SEM than on the blue pod. The yellow pod anodes were almost completely consumed while the Blue pod anodes were still in relatively good shape. The visual difference between the condition of each pod's anodes is dramatic.

The blue and yellow pod anodes were documented with photographs during Phase 2 testing.[161] We found no written summary or quantitative analysis by DNV on their anode findings.

Our review of the Phase 2 photos and videos visually determined which pie connections looked to have the most oxide buildup before they were cleaned. Some pie connections were spare and had dummy plugs inserted into the female connection point.

[160] Note: drawings are not clear regarding the correct Blue/Yellow notations on both pod's 3E solenoid valves
[161] DNV Test Documentation DNV2011042002 and DNV2011042003

The next photograph shows corrosion on the yellow pod pie connections.

Figure C7-5: Corrosive Oxides on Yellow Pod SEM as seen during Phase 2 testing.
The yellow pod SEM has several areas of corrosion from oxides (Video 20110614174414).

Figure C7-6: Yellow Pod SEM Connections, Alternative View as seen during Phase 2 testing.
This view of yellow pod SEM connections is just before cleaning (Video June 15, 2011, BD C14 411 20110615095114).

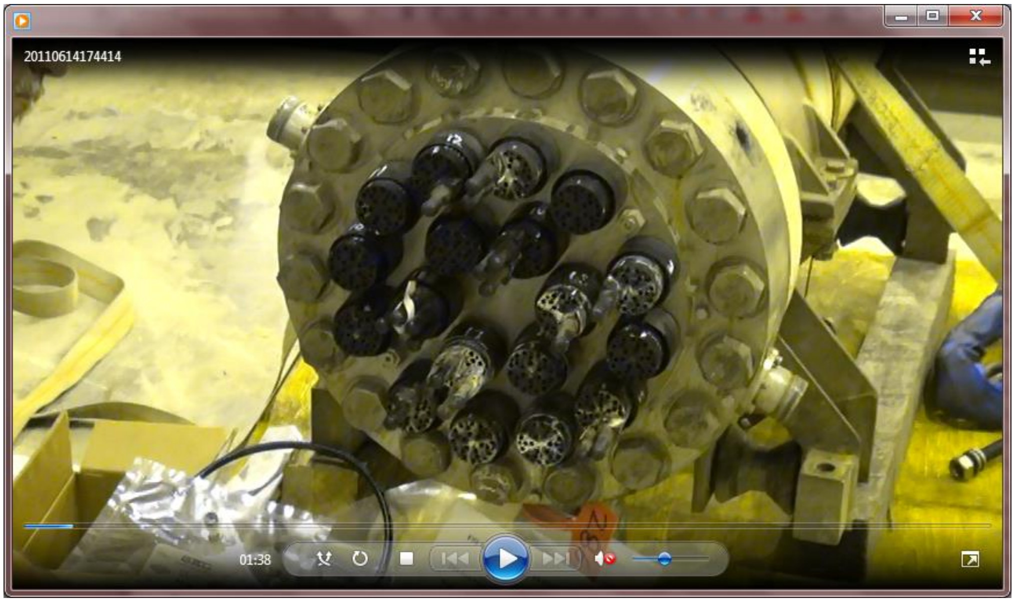


Figure C7-7: Yellow Pod - 20110614174414 video snapshot as seen during Phase 2 testing.

Figure C7-8: Close-up of yellow Pod Pie Connections as seen during Phase 2 testing.

G.3 Functional Analysis of Yellow Pod SEM Oxides on Pie Connectors

Pie Connector Number = Solenoid Number & SV Action **-**

The following solenoids were observed to have significant oxide buildup on the Yellow pod pie connectors:

3E = Solenoid Valve (SV) 15 – Yellow/Blue* pod Hotline Supply – OPEN

5B = SV36 – Mud Boost Valve – CLOSE

5C = SV39 – Quick Start Accumulator Pilot – (action not specified)

6B = SV48 – Wellbore P/T Connector – RETRACT

6E = SV52 – (Internal Direct) LMRP Stinger Seal Cylinders – ENERGIZE

7A = SV111 – Wellhead Connector Gasket Release – HOLD

7C = SV19 – Choke/Kill Connector Primary – UNLATCH

8E = SV103 – H.P. Shear Ram – CLOSE

15D = SV28 – Outer Bleed Valve – CLOSE

17C = SV58 – (Blue/Yellow) Solenoid Pilot Supply Dump – OPEN

17E = SV116 – Tubing Hangar Pin – RETRACT

The testing during the Michoud Phase 2 testing did not adequately address the potential for these oxides to add resistance to solenoid valve electrical circuits, which might have affected the ability of the BOP to function as intended.

The male/female connection interfaces were cleaned of the oxides deposits on June 13 and June 15, 2011. Resistance measurements were then taken external to the SEM at the plug (female connection) interface. As essentially open-circuit measurements in the range of 40 to 60 k-ohms, they did not address the in-circuit resistances with the oxide still in place.

The formation of the oxides could have been caused by a galvanic interaction between the sacrificial anodes on the pod when the solenoid was energized with a 24-volt DC voltage during periodic actuation. There may also be some oxidation due to dissimilar metal corrosion in the connections where the plug did not adequately seal to keep seawater from getting to the male/female interface.

The quality of the forensic evaluation was also affected when solenoids 3A and 103 of the Yellow pod were removed during intervention on the Q4000. These solenoids were suspected of not working and were replaced. Removal and reinsertion of the plug might have improved the connection by reducing any oxide resistance.

Samples of the oxide were obtained during Phase 2 examination, but were not tested.

The SEM diagnostics use minimal voltages and currents to test the integrity of the solenoid coil circuits. The oxide coatings at the interface might not have interfered with the SEM diagnostics, but theoretically could have minimized the actuation voltage at the solenoid coils.

Appendix H: Historical Changes to AMF/deadman Sequence

The original SEM software and AMF/deadman shutdown sequence (circa 2000) was different and more complex than the one in place at the time of the incident in 2010. The original AMF/deadman sequence took 56 seconds and included several functions which had been removed from sequence by 2010. The original sequence[162] appears in Table H1 below.

From the earliest days of manufacture of this BOP control system, Cameron recommended against testing the AMF/deadman sequence using the internal batteries, [163] mounted at that time in the subsea transducer module (STM). Instead, Cameron tested the AMF/deadman sequence at the factory using an external STM battery simulator which used external 9 volt and 27 volt power supplies.[164]

Over time, Cameron modified the pods, AMF/deadman batteries, and the AMF/deadman sequence.

When the executable programs were downloaded from the blue and yellow pod SEMs,[165] the AMF/deadman original sequence was found to be modified to eliminate all of the non-bold functions in Table H-1, those which follow "De-energize HP Blind Shear Ram Close (#103)." The duration for the HP BSR Close function was also increased from 18 seconds to 30 seconds, providing additional assurance that the BSR would close completely. Explicit setting of the ST locks was removed from the sequence programming, but the ST locks were still set by control system changes to automatically set them as part of the HP BSR Close function

[162]See pg 440, [CSB2010-10-I-OS-042101] [CAM-CSB 000009325]
[163] A guidance note from Cameron sates, "Cameron Controls does not recommend operation of this test due to battery life." Cameron also advised that only five solenoid valves can be energized at one time.
[164] [CAM-CSB 000009838], p 514.
[165] Phase 2 Test Preparation Sheet TPS BOP-038, June 21, 2011

Table H-1: Original (Pre-Macondo) SEM software and AMF/deadman shutdown sequence
Non-bold functions were later deleted from the sequence

Elapsed Time (seconds)	Activity
:00	**Energize LMRP Stinger, Extend** **Energize Stack Stinger, Extend**
:05	**Energize LMRP Stinger Seals, Energize** **Energize Stack Stinger Seals, Energize**
:07	**De-energize (Vent) LMRP Stinger, Extend** **De-energize (Vent) Stack Stinger, Extend** **Energize LMRP Accumulator, Charge Pilot (#21)** **Energize LMRP Accumulator, Charge (#23)** **Energize High Pressure Blind/Shear Ram Close (#103)**
:25	**De-energize (Vent) High-Pressure Blind/Shear Ram Close (#103)** Energize ST Locks, Lock (#70)
:29	De-energize (Vent) ST Locks, Lock (#70) Energize Stack Accumulators, Dump (#101)
:34	De-energize (Vent) Stack Accumulators, Dump (#101) De-energize (Vent) Stack Stinger Seals, Energize Energize Stack Stinger Seals, De-energize
:36	Energize Stack Stinger Retract De-energize (Vent) Stack Stinger Seals, De-energize Energize Mud Boost Valve, Open (#35)
:41	De-energize (Vent) Mud Boost Valve, Open Energize Stack Stinger Seals, Energize
:43	De-energize (Vent) Stack Stinger, Retract De-energize (Vent) Stack Stinger Seals, Energize Energize Dead Man System Activate (#22)
:51	De-energize (Vent) Dead Man System, Activate (#22) Retract, Wellbore Pressure/Temperature Connectors Unlatch, Choke/Kill Connector Primary Unlatch, Choke/Kill Connector Secondary Unlatch, LMRP Connector Primary Unlatch, LMRP Connector Secondary Energize LMRP Accumulators, Dump (#57)
:56	De-energize (Vent) LMRP Accumulators, Dump (#57) De-energize (Vent) LMRP Accumulators, Charge Pilot (#21) De-energize (Vent) LMRP Accumulators, Charge (#23)