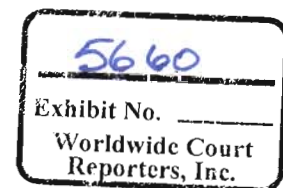


## Appendix N AMF Testing



The Automatic Mode Function (AMF) is an optional feature of the subsea control system designed to automatically close the blind shear rams (BSRs) in the blowout preventer (BOP) stack in the event of an unplanned separation of the drilling riser from the BOP. The AMF option was offered by Cameron and purchased by Transocean for the *Deepwater Horizon* BOP stack.<sup>1</sup> The AMF monitors the connectivity to the BOP stack from the surface control system and initiates a sequence of functions if electrical power, electronic communication between pods, and hydraulic supply from surface are lost.

### BOP Control System Components<sup>2</sup>

The following components are associated with BOP control and AMF functionality:

- **Surface Control Panels:** Driller's control panel located on the drill floor and toolpusher's control panel located in the central control room<sup>3</sup>
- **Central Control Unit (CCU):** Main electronic hub and interface point to both surface and subsea controls<sup>4</sup>
- **Hydraulic Unit:** High-pressure pumps and surface accumulators to maintain a supply of operating fluid at the pressures and volumes necessary to function the BOPs<sup>5</sup>
- **Yellow and Blue Pods:** The yellow and blue pods house subsea controls on the BOP stack, including the subsea electronic modules (SEMs), subsea transducer modules (STMs), hydraulic pressure regulators, solenoid pilot valves, hydraulic accumulators and hydraulic valves. The yellow and blue pods operate functions on the BOP stack in response to commands from the surface control system with the exception of the AMF system.<sup>6</sup>
- **Subsea Electronic Modules:** Two subsea electronic modules (SEM A and SEM B) are located in each pod for a total of four SEMs on the BOP stack.<sup>7</sup> The SEMs consist of programmable logic controllers (PLC), power supply units, AMF controllers, batteries, fuse boards and communication boards. When functions are activated from the surface controls, a signal is sent to the SEMs to energize the respective solenoid valves, which then route the pressurized hydraulic fluid to a particular BOP function. Each solenoid valve has two operating coils — one coil is connected to SEM A and the other coil is connected to SEM B — allowing either or both SEMs to operate the valve. In normal subsea operation, both SEM A and SEM B in each pod receive a signal from the surface control system and activate their respective coil in the solenoid simultaneously.
- **Automatic Mode Function:** The AMF is designed to secure the wellbore during a loss of electrical power, electronic communication between pods and hydraulic supply from surface. The system consists of electrical circuitry housed in the SEMs and uses existing hardware (including solenoids, valves and pressurized hydraulic fluid) to function the BOP.<sup>8</sup> Each AMF card works independently, and any or all of them can initiate the function of the high-pressure shear circuit.<sup>9</sup>

Components of the AMF system include:

- AMF processor board (one per SEM, two per pod and four in the BOP system).<sup>10</sup>
- Dedicated 9-volt (V) DC battery pack per AMF card (one per SEM, two per pod and four in the BOP system).<sup>11</sup>
- 27V DC battery pack shared for both SEM A and B (one per pod and two in BOP system).<sup>12</sup>
- Dedicated subsea hydraulic accumulators to operate the functions commanded by the AMF system.<sup>13</sup>
- A custom software file added to the PLC in each of the SEMs that defines the hydraulic activation sequence and timing instructions.<sup>14</sup>
- A bi-stable "latching" relay in each AMF card. Once the relay is latched in either the arm or disarm mode, it will remain in that mode whether it is powered or not.

## AMF System Activation

During normal drilling operations, when the BOP stack is latched on the wellhead, the AMF system is armed and will remain in the armed state.<sup>15</sup> The following conditions must be met before the AMF will activate:

- **The AMF must be armed.** The AMF is armed at surface by a single-button activation from the surface control panel. All four AMF processor cards are armed by this signal. A photo taken during a ModuSpec survey on April 10, 2010, shows that the AMF system was in the armed mode.<sup>16</sup> When the AMF is armed, the voltage reading at the control system event logger is approximately 0V.<sup>17</sup>
- **Communication and electrical power loss from the surface control system.** If one pod loses power from the surface, the two AMF cards in that pod are powered from two 9V battery packs, one dedicated to each card. Each AMF card monitors the condition of the other pod to verify that it is still operating normally and has power from the CCU. In the event of a power loss from the surface control system, the AMF processor will send a signal to pressure transducers in the pod to check the status. The pressure transducers are powered by the 27V battery pack.
- **Surface hydraulic supply pressure loss.** Each AMF card checks the status of the pressure transducers in the subsea transducer module. The pressures monitored are the seawater hydrostatic and surface hydraulic fluid pressures from the rigid conduit supply manifold. When the pressure reading from the rigid conduit manifold drops to 400 psi or less above the hydrostatic pressure reading, the AMF processor will initiate and verify the status of the other requirements. If power and communications loss signals are present, the AMF processor card will activate the sequence.

Once the AMF conditions are confirmed by the processor, the AMF card provides power to the SEM PLC using the 9V battery pack. The AMF controller indicates to the PLC that the AMF card is in an active state. Immediately after startup, the SEM PLC detects the AMF active state and initiates the AMF sequence by firing the solenoids in the pre-programmed sequence.<sup>18</sup>

The AMF sequence of functions for the *Deepwater Horizon* pods was custom-programmed into the SEMs. The Cameron recommendation for any AMF sequence is that no more than six solenoids be activated at any one time to reduce power consumption.<sup>19</sup>

The following was the sequence for the *Deepwater Horizon*:

- 0-second LMRP stinger extend
- 0-second stack stinger extend
- 5-second LMRP stinger seals energize
- 5-second stack stinger seals energize
- 7-second deactivate LMRP stinger extend
- 7-second deactivate stack stinger extend
- 7-second high-pressure shear ram close
- 37-second deactivate high-pressure shear ram close

## AMF Batteries

Each Cameron AMF system uses non-rechargeable battery packs that power the SEM PLC, solenoid driver card, solenoids, AMF card and STM for the AMF sequence.<sup>20</sup> The battery type used by Cameron for this application has a flat discharge curve, which means that the battery supplies constant output voltage until it reaches the end of life. See *Figure 1*. Due to this characteristic there is no practical way to predict the battery life simply by measuring the voltage.<sup>21</sup>

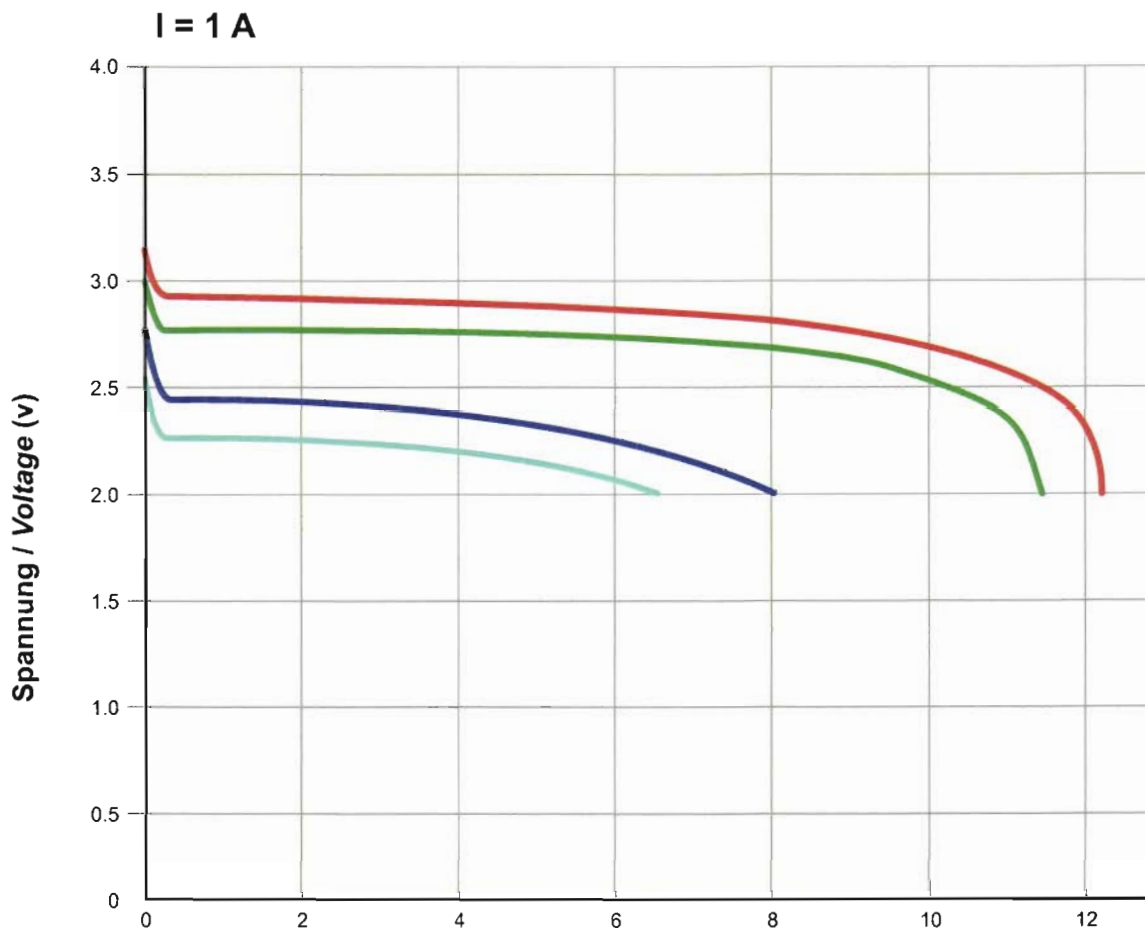


Figure 1 Representative Discharge Curve of SAFT Li MgO<sub>2</sub> Type AMF Battery<sup>22</sup>

Cameron recommends replacing the batteries after one year of operation or 33 AMF actuations, or within five years of shelf life.<sup>23</sup> The *Deepwater Horizon* pod batteries were last changed on the following dates:<sup>24</sup>

- 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

Cameron completed the overhaul of the *Deepwater Horizon* spare pod SEM in 2010, and it arrived on the rig after the BOP stack was lowered to the wellhead in February 2010. The AMF system in the SEM had new batteries installed and was factory-acceptance tested prior to shipment.

During a routine rig condition assessment on the *Deepwater Horizon* in April 2010, ModuSpec confirmed that all batteries in the SEMs were new.<sup>25</sup>

### Software and AMF Function Testing

Tests using AMF cards and an SEM from a functionally identical Cameron BOP stack were performed to check various fault conditions and how these may relate to the Macondo incident. During the pod interventions, battery readings were taken showing that the yellow pod batteries were at an acceptable voltage level. However, the blue pod battery readings recorded during the intervention indicated that two out of the three batteries had low readings. The batteries that supply the AMF system have four potential failure modes. These conditions are:

**Condition 1**

<i>Battery</i>	<i>Condition</i>
9V (2)	Both have low voltage and insufficient power to operate the AMF cards.
27V	Sufficient power to (1) operate the solenoids and STM, and (2) disarm AMF card.
Result	The AMF will not activate and power the PLCs. The 27V battery will not be connected to power the STM or operate the solenoids. Inspection will show two low 9V batteries and one good 27V battery.

**Condition 2**

<i>Battery</i>	<i>Condition</i>
9V (2)	Both have sufficient voltage and power to operate the AMF cards.
27V	Insufficient power or low charge to (1) operate the solenoids and STM, or (2) disarm AMF card.
Result	The PLC drains the 9V batteries until they are depleted, as the AMF card cannot receive a 24V signal to disarm from the 27V battery. Inspection will show two low 9V batteries and one good 27V battery.

**Condition 3**

<i>Battery</i>	<i>Condition</i>
9V (2)	One with insufficient energy to boot and power the PLC. The other has sufficient energy to boot and power the PLC.
27V	Sufficient power to (1) operate the solenoids and STM, and (2) disarm AMF card.
Result	Both PLCs will start up, but only the SEM with the good 9V battery will fully complete the AMF sequence and disarm that AMF card. The SEM powered by the insufficient 9V battery will not be able to complete its sequence, and will try continually to boot up the PLC, draining both the 27V and remaining 9V battery of energy.

**Condition 4**

<i>Battery</i>	<i>Condition</i>
9V (2)	Both with insufficient energy to boot and power the PLC.
27V	Sufficient power to (1) operate the solenoids and STM, and (2) disarm AMF card.
Result	The SEMs powered by the insufficient 9V battery will not be able to complete their sequence, and will try continually to boot up the PLC, draining the 27V and both remaining 9V batteries of energy.

During the tests it was noted that the condition of the 9V battery packs is important to a successful completion of the AMF cycle. In the event that the 9V battery pack has insufficient power, the PLC will not successfully complete its startup. The 9V battery pack will be drained by continuous startup attempts of the PLC. In this condition the PLC will not supply a 24V disarm signal to the AMF card, leaving the 27V batteries draining while connected to and powering the STM.

During testing it was also found that AMF cards will start their activation sequence again, if not disarmed. The time to restarting the sequence is 3 minutes 43 seconds for the *Deepwater Horizon* AMF.

Based on the battery voltages found in the pods during the intervention process and the subsequent testing at



Michoud, the investigation team concluded that the yellow pod AMF cards both fired and completed the AMF sequence. The investigation team concluded that the low voltage on the blue pod SEM B 9V battery pack is caused by the scenario described above as Condition 3. One AMF card correctly fired the AMF sequence, and the second AMF card could not boot and power its associated PLC, therefore continually cycling and draining one 9V and the common 27V battery in the pod.

### Post-Incident Investigation

#### Pod Intervention – Yellow Pod Condition

The yellow pod was pulled to the surface for the first time 15 days after the incident. The yellow pod functions were tested by Cameron using a Portable Electronic Test Unit (PETU). The pod functioned as designed with the following notations:<sup>26</sup>

- No indication of Solenoid No. 103 firing on SEM A or B. This valve was replaced during the rig move in February 2010.<sup>27</sup>
- Upper annular regulator increase, Solenoid 3A would not function on SEM A or B.<sup>28</sup>
- Lower outer choke close on SEM B would not function.<sup>29</sup>
- The yellow pod batteries were tested and found to be at acceptable voltage levels.<sup>30</sup>

#### Battery readings:

- 9V SEM A Battery: 8.85V<sup>31</sup>
- 9V SEM B Battery: 8.85V<sup>32</sup>
- 27V Pod Battery: 26V<sup>33</sup>
- Solenoid 103 was replaced with a spare.
- The yellow pod AMF system was tested and functioned as expected following the Cameron AMF test procedure.

When the yellow pod was pulled the second time on July 23, 2010, the following conditions were noted:

- Extend stack stinger – observed leak from 1/4-in. pod valve.<sup>34</sup>
- Replaced lower annular close valve due to slide not going into vent, 1 1/2-in. pod valve.<sup>35</sup>

The yellow pod AMF system was tested by DNV at Michoud.

- *Test No. 1:* AMF system test with the spare solenoid 103 installed in the pod. The AMF functioned as expected.
- *Test No. 2:* The original solenoid 103 was then re-installed on the yellow pod. The AMF system in the pod was tested with SEM A and SEM B active (normal operation). The AMF functioned, and solenoid 103 functioned (at 43 seconds) after a 22-second delay from the expected activation time.<sup>36</sup>
- *Tests Nos. 3 and 4:* The AMF system in the yellow pod was tested two additional times with SEM A and SEM B active. Solenoid 103 functioned (at 21 seconds) as expected at the correct activation time.<sup>37</sup>

#### Pod Intervention – Blue Pod Condition

During the post-incident intervention on the BOP stack, the blue pod was pulled to surface 74 days after the incident and the following items were noted:<sup>38</sup>

- BOP manifold regulator was leaking.
- Using a PETU, it was noted the blue pod AMF did not activate on the AMF battery power when functioned. Once the external power was re-supplied via the PETU, the PLC completed the AMF sequence.

**Battery readings:**<sup>39</sup>

- 9V SEM A battery: 8.78V
- 9V SEM B battery: 0.142V
- 27V pod battery: 7.61V

During the DNV investigation at Michoud, NASA engineers measured the following for the blue pod batteries:

- 9V SEM A battery: 8.91V
- 9V SEM B battery: 8.68V
- 27V pod battery: 1.04V

The investigation team concluded that the NASA engineers recorded the correct voltage readings. The low voltage readings taken while the POD was on the *Discoverer Enterprise* for the 9V SEM B battery pack likely reflect an error in measuring the voltage difference across the wrong pins in the PIE connector, and reading the difference in voltage between the 9V SEM A battery pack and the 9V SEM B battery pack. After the AMF test of the blue pod by DNV, the blue pod SEM B AMF card did not reset after power was re-applied with the PETU. In addition, after power was re-applied with the PETU, the blue pod completed the AMF sequence, indicating that SEM B had a weak 9V battery.

The investigation team concluded that the 27V and the SEM B 9V battery packs were drained due to continual cycling of the AMF, trying to boot the PLC in the SEM, as evidenced by the dead 27V battery and SEM B not resetting upon testing at Michoud. The Cameron technician verified that solenoid 103 fired after external power was reapplied to the SEMs during surface testing after the incident. The intervention tests on surface showed that the AMF electrical circuitry and components were functional and that the solenoids did not function initially during the intervention tests on surface because the 27V and SEM B 9V battery had insufficient battery capacity. This conclusion is based on the battery voltages and subsequent testing on a similar Cameron AMF system.

The SEM B 9V battery did not have sufficient power to boot the AMF processor, resulting in a continuing "re-boot" cycle approximately every three minutes. In addition, it has been determined the AMF cards have a "low voltage drop out" feature that prevents the 9V battery from powering the PLC when voltage is less than 5V. The 27V battery powers the STM on and off as the AMF "re-boot" cycle continues. This allows the 9V battery to rest and regenerate; however, the higher voltage reading is not indicative of the remaining power. The investigation team has demonstrated this phenomenon in the lab where a 9V battery was drained to 0V at 32°F (approximate temperature at operating water depth), and voltage increased dramatically when returned to room temperature only to go back down to near 0V when tested under load. This indicates voltage alone is not a valid indicator of the battery condition.

When the AMF card is armed, the 27V battery powers the STM. While the SEM B 9V battery did not have sufficient power to boot the SEM PLC, the 27V battery would power the STM during the "re-boot" cycle of approximately 3 minutes. This continued until the 9V battery voltage dropped to less than 5V. During the period that the SEM B 9V battery remained at a voltage less than 5V, the 27V battery would continue to power the STM for several seconds while the AMF card determined whether the AMF conditions were met. The resulting condition would have drained the remaining power in the 27V battery until the blue pod was retrieved 74 days after the incident and tested.

Table 1 shows the relative difference of the in-service time for two new batteries powering the AMF card and two STM transducers. Cameron rates both the 27V battery and the SEM 9V battery for 42 amp-hr. The AMF card requires 2 mA of power while in the armed state. Each STM transducer provides a current output proportional to the pressure reading of 4 mA to 20 mA. At these current drain rates, a full 42 amp-hr. battery will provide 875 days of service life powering the AMF card, but only 43 days of service life powering two STM transducers.

	Amp-hr.	Rate of Discharge – Amps	Hours of Service	Days of Service
27V B powering 2 sensors	42	0.040	1,050	43.75
9V B powering AMF card	42	0.002	21,000	875.00

Table 1

## Appendix N AMF Testing

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