Deepwater Horizon Incident Investigation

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Interlink Systems Cameron Automatic Mode Function Battery Performance		
Note to File		

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Introduction:

This Note to File is to identify the results of a test performed by Interlink Systems on the characteristics of the AMF batteries used in the Cameron MUX pods. The tests were conducted to understand the discharge characteristics of the SAFT suplied battery packs. The report adresses how the voltage and current relate to eachother through the life of the battery. See attached report.

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Cameron Automatic Mode Function
Battery Performance

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TABLE OF CONTENTS

1. INTRODUCTION

The Cameron Mark I and Mark II BOP control pods can be supplied with an Automatic Mode Function (AMF). The purpose of the AMF is to execute an emergency well shut in the absence of hydraulic pressure and electrical power to the BOP. In order to accomplish this, the AMF has its own hydraulic accumulators and batteries.

The Horizon BOP was fitted with an AMF system at the time of the incident. There are independent AMF systems in the Blue and Yellow Pods and it appears that neither of them functioned properly. The condition of the batteries in the Blue Pod has been a subject of much attention, since the voltages measured after the incident were low. There was also a question about battery voltage in the Yellow pod, and a number of conclusions about the functioning of the AMF system have been made in other studies based on the measured battery voltages.

Low battery voltage implies batteries near the end of their life. The battery manufacturer does not specify the performance of the batteries near the end of their life since equipment is not normally designed to operate with batteries that are nearly "dead". The purpose of this series of tests is to examine how the AMF batteries actually perform as they are discharged and to examine the relationship between the measured battery voltage and its ability to supply a useful amount of power when in a deeply discharged state.

2. SUMMARY

2.1 AMF Battery Construction and Requirements

The AMF battery is built from 9 volt packs (nominal voltage), each composed of 12 "D"-sized $LiMnO_2$ cells similar to the M20 cell manufactured by Saft. They are primary cells (non-rechargable), each rated at about 12 Ah and about 3 volts. The 12 cells are arranged in 4 stacks. Each stack consists of 3 cells and a Schottky diode in series, for a terminal voltage of about 9V. The four stacks are connected in parallel to form a battery pack of about 48 Ah rated capacity. An AMF system has 5 of these packs: two used alone to supply 9V power to SEM's A and B via the AMF circuits, and three more connected in series to supply 27V to the AMF relays, solenoid drivers, solenoids, and pressure transducers.

The diagram in Appendix 3 shows the basic circuit of the battery pack and Appendices 3 and 4 show pictures of the battery internal construction. The pack includes thermal cutouts and solid state, self resetting electrical fuses to protect the pack against short circuits.

The 9V batteries supply power to the AMF circuit and the SEM itself. For the Mark II SEM in the Horizon pod, this battery has to supply a minimum of 6.5 volts to the AMF circuit at a current of 6 to 7 amperes. The 27V battery supplies the solenoid driver circuits, two pressure transducers, relays on the AMF circuit board, and the solenoid valve coils. For proper operation it must supply at least 18V at a current of up to about 3 amperes.

2.2 Available Energy

All of the cells tested for this report were about 5 years old. They had been used in AMF systems and then removed as part of the normal BOP maintenance procedures. All of the cells still had enough charge to operate a simulated AMF sequence over 100 times.

2.3 Open Circuit Voltage

The open circuit voltage of a battery is the voltage that you measure at its terminals when no significant current is being drawn from the battery and it has been a "long time" since any current was drawn from the battery. When you measure the voltage of an isolated battery that has been without a load for hours or days, using a modern digital voltmeter, you are measuring the open circuit voltage. This is the way all battery tests were done on the Horizon pods following the incident.

The open circuit voltage of a cell is determined primarily by the chemistry of the cell, rather than its state of charge. Especially in the case of the $LiMnO_2$ cells, the open circuit voltage will remain very high until almost all of the chemicals in the battery have been depleted. After drawing power from the battery, it may take minutes, hours, or days for the open circuit voltage to stop increasing. The open circuit voltage of the battery is, therefore, a very poor indicator of its ability to supply energy at a useful voltage.

2.4 Response to a Load

The cells have an internal resistance that causes the terminal voltage to drop when a load is placed on the battery. This resistance is very small in new batteries resulting in a fairly small change in voltage as a load is applied. But, as the chemicals are depleted, the internal resistance and, consequently, the voltage drop increases. Eventually the voltage drop becomes great enough that the equipment being powered cannot function properly; the battery is "dead".

When a load is applied to a cell, the voltage is a function both of the load current and of the time it has been applied. There is an immediate drop followed by a more gradual drop that continues as long as the load is present. Even though this voltage changes with time and current, measuring the

voltage under a load is the only reliable way to know the ability of the battery to successfully power the AMF.

2.5 Information contained in the Open Circuit Voltage

While the open circuit voltage is not a reliable indication of what the battery can do, it can be used as a rough indication of what the battery cannot do. Stated another way, a good open circuit voltage does not necessarily mean a good battery, but a bad open circuit voltage is a pretty good indicator of a bad battery.

By discharging the cells in a consistent way, and waiting a relatively consistent time for the voltage to recover, these tests showed a fairly reliable relationship between cell open circuit voltage and remaining charge, as shown in the following table[1].

Table 1

Remaining Charge (Ah)	Open Circuit Voltage 9V / 27V (volt)	9V battery under 6A load (volt)	9V will operate the SEM	27V battery under 3A load (volt)	27V battery will operate the AMF
5	8.88 / 26.6	7.63	Probably	24.0	Probably
4	8.79 / 26.4	7.42	Probably	23.1	Probably
3	8.61 / 25.8	6.94	Probably	22.2	Probably
2	8.46 / 25.4	6.37	Maybe	20.7	Probably
1	8.13 / 24.4	4.42	No	17.9	Maybe
0	7.65 / 23.0	2.32	No	11.0	No

There are two important observations about the use of Table 1. The first is that it cannot be used to tell you that the AMF "will" work. It can only tell you that the AMF "may" work or that the AMF "will not" work. A battery will never be any better than the table indicates, but it might be much worse. That is because the table is built from voltages measured after a no-load rest period of 8 to 12 hours. The open circuit voltage was, in all test cases, still slowly rising at that point.

The second important observation is that the difference between the open circuit voltage of a battery that will work and one that will not is very small. So, small errors or small random differences can make a big difference in one's judgment of the apparent state of the battery.

[1] This table is not meant to be highly accurate since the data it is based on has a large variance and there may be variations with batches of cells and temperature. Note also the definition of 0 remaining capacity, explained later in this report.

It cannot be emphasized enough that the only way to be sure that the battery will properly power a certain load is to run a test at a similar load current.

2.6 Comments on Voltage Observed in the Field

Several open circuit voltage measurements were reported or inferred from field tests in the weeks after the incident. They will be commented on here.

2.6.1 Yellow Pod 27V Battery = 18.41 volts, with example

A 27V battery with an open circuit voltage of 18.41 cannot operate the AMF solenoids. But we know that it operated the AMF sequence more than once, and the rig crew reported later that the measurement was in error and they measured it again at near 27 volts. Measuring the voltage between a healthy 9V and a healthy 27V battery could easily yield 18.41 volts, so that is the most likely scenario.

Example: 18.41 volts in more than enough to operate most solenoids (see sections 5.1.1 and 5.1.2), so why can it not operate the AMF solenoids? At 18.47V open circuit, the average cell voltage is 2.05 volts. Referring to the plot in Appendix 8 for Stack 2, that implies a charge state of -1 Ah or less. At -1 Ah, if you try to draw 0.25A from the cell (the mid curve), the voltage of the cell will drop to less than 1 volt. Counting 9 cells in series with 3 Schottkey diodes, the total load voltage for a 0.25A load is less than 8 volts. This is not enough to operate a solenoid.

2.6.2 Blue Pod 27V Battery = 7.61 volts

A 27V battery with an open circuit voltage of 7.61 is essentially dead and has no chance of operating an AMF. The open circuit voltage is already too low to operate most devices in the AMF, it is unlikely to sustain even a couple of volts across even the AMF transducers.

2.6.3 Blue Pod 27V Battery = 16.39 volts

A 27V battery with an open circuit voltage of 16.39 will not operate the AMF. See section 2.6.1 above. This voltage is inferred from a measurement mistake scenario (see section 5.1.3).

2.6.4 Blue and Yellow Pod 9V Battery = 8.78 to 8.92 volts

Batteries were actually measured as 8.78 and 8.85 volts, while the 8.92 is inferred from a measurement mistake scenario (see section 5.1.3). A 9V battery with an open circuit voltage of 8.78 or more has a good chance of operating a SEM, though that cannot be said with certainty.

2.6.5 Blue Pod 9V Battery = 7.47 to 7.61 volts

This voltage is inferred from a measurement mistake scenario (see section 5.1.3). A 9V battery with an open circuit voltage of 7.61 or less will not operate a SEM. It corresponds to cells with about 2.53 volts open circuit, which ate at 0 Ah remaining charge and cannot sustain more than 1 volt per cell, or about 2.65 volts with the SEM connected. This will not properly operate anything.

2.7 Suggested Battery Tests

The tests suggest that the average loaded voltage of a single cell should remain above 2.75 volts when the cell is in the first 50-65% of its life. Using that cell voltage and the 0.34 to 0.36 volt drop in the Schottky diode, the following tests are proposed as a rigorous way to qualify AMF batteries for service. These are unproven, proposed tests to augment existing procedures. They should be subjected to cross checking and possible alterations before use and are not meant to be used in place of the maintenance procedures recommended by the equipment manufacturer.

2.7.1 Primary Test method

A primary test method is to connect a chart recorder or data acquisition system to the pie-slice battery monitor connections and run an AMF sequence. In addition to making sure that the sequence completes as expected, make sure that the 9V batteries never fall below 7.9 volts and the 27 volt battery never falls below 23.7 volts. Batteries that do not meet the criteria should be replaced.

2.7.2 Alternate Test Method

An alternate test method is to connect a chart recorder or data acquisition system to the pie-slice battery monitor connections. Connect a 6 ampere load to each battery for one minute. Make sure that the 9V batteries never fall below 7.9 volts and the 27 volt battery never falls below 23.7 volts. Batteries that do not meet the criteria should be replaced.

2.8 Cross-check of Recommended Maintenance

The rated capacity of the cells is about 12 Ah discharging to 2 volts under a load of 1 to 2 amperes. The cells reach 2V under load at about 1.5 Ah remaining charge (see Appendix 9). Since this report recommends not going less than 3 Ah, the battery should be rated at about 1.5 Ah less than the point that it reaches 2V. Therefore, 10.5 is a more conservative rating for the cells. This gives the pack a safely conservative rating of 42 Ah.

The AMF circuit draws about 1.75 ma when armed. In a year, it will probably spend less than 10 months armed, for a total draw of 12.6 Ah, leaving 29.4 Ah left.

Assume an extreme self discharge rate for the year of 30%. That consumes 12.6 Ah, leaving 16.8 Ah in the battery.

Assuming a 6.5 amp discharge for 2 minutes, an AMF sequence test will draw 0.22 Ah from the battery. At 16.8Ah remaining, this allows for 75 tests and one real AMF cycle.

This calculation and the condition of the batteries tested imply that the maintenance specifications for the AMF of 1 year or 33 operation is conservative.

3. TEST DETAILS

3.1 Test Setup

3.1.1 Hardware

Appendix 1 includes a diagram and description of the hardware used to control the battery test and to collect data. The test took so long and demanded such a repeatable cycle that it was impractical to do by hand.

Appendix 2 shows pictures of the apparatus itself including the laptop running the data acquisition software, and the microcontroller that controlled the load on the battery.

3.1.2 Load Cycle

The load cycle consists of a sequence of load pulses designed to roughly simulate a repeating AMF sequence and to include low and high current data point. A load pulse starts with the application of a load of about 1.6 amp for one minute. This then drops to about 225 ma for another minute. Finally the load drops to about 8 ma for 10 minutes. This pulse is repeated 33 times and then the load is dropped to zero. At this point the battery is allowed to rest for 8-12 hours to allow the open circuit voltage to rise. In all cases, the open circuit voltage was still slowly rising at the end of 12 hours. The whole cycle drains about 1 Ah from the stack of cells.

The open circuit voltage was measured one to three times manually while resting and just before starting the next load cycle. The total rest time was normally 8 to 15 hours.

The currents mentioned above are for testing one stack of 3 cells. Since an AMF battery is built up of 4 stacks in parallel, the equivalent currents for the complete battery pack would be about 6.5 amp, 1 amp, and 32 ma, for a total drain of 4 to 4.5 Ah per load cycle.

3.1.3 Definition of Zero Capacity

Zero capacity does not mean the battery can no longer supply any current at all. That point is too difficult to define and is not very useful anyway. Saft defines zero capacity to be the point when a cell drops to 2 volts under a specified load. Since much of the area of interest to this report is actually beyond that point, the definition of zero capacity was changed for this report.

Zero capacity for this report is defined to be the point when, with the high load, the voltage of a cell falls below 1.000 volts. This represents a stack voltage (including the Schottky diode) of about 2.6 volts, which is completely useless for the AMF. Therefore, most of the area of interest has a positive remaining capacity.

Even so, these tests draw the batteries to a negative remaining capacity by this definition. A negative capacity may look a little strange, but, since the zero point is arbitrary, this should not be a cause for concern.

3.2 Battery Disassembly

3.2.1 Battery Components

Appendices 3 and 4 detail the internal diagram and the physical components in the 9V battery pack. It was disassembled by splitting and removing the black shrink wrap, and then cutting through the hot glue with a knife. All parts were marked identifying the particular battery and the position in the battery occupied by that component.

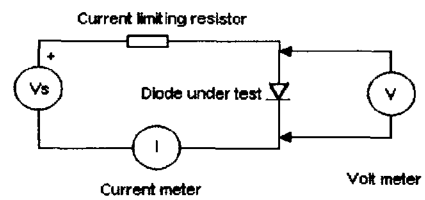
3.2.2 Safety Circuit

The safety circuits introduce an additional resistance in series with the battery pack. The series combination of a PTC fuse with a thermal cutoff is about 0.023 ohm. There are two in parallel, so the total resistance for a battery pack is about 0.012 ohm. This adds a small voltage drop (10-20 mv) in series with a loaded battery and is completely negligible for open circuit conditions. The values in Table 1 include the drop in the safety circuits.

3.2.3 Schottky Diodes

The Schottky diodes influence the interpretation of battery tests because they introduce a significant voltage drop in series with the cells in the complete pack. The following table shows the measurement circuit and measured voltage drop in one of the diodes. The others should be similar.

Measured Current (ma)	Measured Voltage (mv)
9.8	212
18	229
39	250
100	276
200	295
470	319
700	332
835	336
1110	346
1710	361



The measured voltage follows the following relation to within 2 mv.

$$V = iR + \frac{T}{11609}\ln\left(\frac{i}{Io} + 1\right)$$

where
- i = current through the diode
- V = the voltage across the diode
- T = 300°K
- R = 0.01 ohm
- Io = 2.6 x 10^{-6} amp

The Schottky diode introduces a voltage drop of about 0.34 to 0.36 volts in the range of currents that are of interest for normal operation. For open circuit conditions, the voltage drop is much less being around 6-8 mv for a voltmeter with an input impedance of 10 megohms. The Schottky diode was ignored when considering open circuit voltage but was included for all loaded voltage calculations in Table 1.

3.3 Description of the Batteries Tested

A total of 9 cells were tested, consisting of three stacks taken from two different 9V battery packs. Neither the Schottky diodes nor the safety components were part of the test.

One of the packs (stacks 2 and 3) was from the disposal bin at Cameron, so nothing is known of how it was used. It had about 40% of its rated capacity left. The other was from a Pride rig (stack E1). It had about 75% of its rated capacity left.

The cells have a date code on them that indicates where and when they were made. They were all made at the Saft facility in South Fields England and were made August 1, 17, and 20 of 2005. So, all of the cells are about 5 years old. I have no information on when they were put into AMF service, or when they were removed from service.

3.4 Calculation of Remaining Capacity

The whole point of these tests was to characterize the battery behavior in the last Ah of its life because that is where a depressed open circuit voltage will occur. To do this, the stacks were discharged following the test cycle described in 3.1.2 Load Cycle until all three cells dipped below 1 volt during the high current load. Current and voltage data were recorded every 10 seconds and transferred to an Excel spreadsheet. Each file contains data for one load cycle.

A column was created in the spreadsheet for calculating total time. The reference time for this column is 0hr, 4 September 2010. The plots in Appendices 5, 6, and 7 use that time scale.

Remaining capacity for each cell is calculated in other columns by a Simpson's rule integration of current*time for each sample. The calculation formula looks like this:

Capacity now = Previous capacity – 0.5*(Previous current + Current now) * Time Increment

Each row in the remaining capacity column, except for the top row, has that formula in it. The top row has the constant of integration for the column and is set manually so that the bottom values in one file match the top values in the next file. In the file where the cell voltage first goes under 1 volt (usually the last file), the capacity at the top of the column is set to a value that results in zero remaining capacity at the point where the cell dips below 1 volt.

3.5 Total Test Plots

Appendices 5, 6, and 7 show plots covering the entire test period. Each plot is composed of data from several files covering the various load cycles performed. The black traces are the cell voltage, with the broad band showing the 33 load pulses in each load cycle. The bottom of the bands are the minimum voltage reached during the 1 minute high current load, and the top of the bands show the maximum voltage reached at the end of the 10 minute low current load.

It can be seen in the plots that the battery performance is relatively constant until the last 3-5 Ah of battery life, when the voltage begins to drop more rapidly, especially in the last 3 Ah. Clearly, in a safety system such as the AMF, one should avoid any intentional operation in the last 3 Ah of battery life.

3.5.1 Stack 3 Total Test

The test of stack 3 is shown in Appendix 6. This test was uninterrupted and complete for the several days that the test lasted and consists of 8 load cycles.

3.5.2 Stack 2 Total Test

The last part of the test of stack 2 is shown in Appendix 5. This test suffered from a computer malfunction that destroyed the data record for the 4th load cycle and made it difficult to determine how much of the cycle it had completed. Due to this, the plots for stack 2 are not projected back to the beginning of the test. But 3 load cycles of about 1 Ah each were definitely completed before the malfunction plus a partial cycle. So, the complete remaining capacity of stack 2 at the start of the test would have been 7 to 8 Ah, similar to the capacity of stack 3.

3.5.3 Stack E1 Total Test Cycle

The test of stack E1 is shown in Appendix 7. This test suffered from a computer malfunction due to bad weather that damaged the data for the third load cycle, recording only 30 of the 33 load pulses. In this case, the microcontroller preserved a record showing that it had completed the load cycle and removed the load from the cells. Stack E1 data was accurately reconstructed by estimating the capacity loss in the missing 3 load pulses.

Stack E1 also suffered a malfunction that lost all of the data for the second to last load cycle. Again, the microcontroller confirmed that the load cycle was completed and that the stack was left with an open circuit. This made it easy to make an accurate estimate of the capacity decrease during the lost load cycle, so the complete test for stack E1 was plotted.

3.6 Voltage vs. Remaining Charge

Four different voltages were considered of special interest for these tests: voltage at high, mid, and low loads, and open circuit voltage. In order to plot these, I wrote software to examine the raw test data for each load pulse and extract the voltage at the end of the high current time, at the end of the mid current time, and at the end of the low current time. In addition, the first data sample and the last 1-3 samples[2] of each load cycle file represents open circuit voltage, which the software also extracted. This created 4 files from which voltage could be plotted as a function of remaining capacity for the four different load conditions.

The results are shown in Appendices 8 and 9. Appendix 8 shows individual plots for each stack. These plots show clearly the increasing voltage drop resulting from increasing load and decreased remaining capacity. You can also see "saw tooth" shaped discontinuities at the boundaries between load cycles that are due to the rise in voltage while a cell is resting with an open circuit.

Appendix 9 shows the same data, but with the data for all cells superimposed at one load. This shows the consistency of the data from cell to cell. It also shows clearly the desirability of not operating into the last 3 Ah of battery life, since that is the region where the voltage is rapidly dropping.

3.7 Voltage vs. Time

The cells show a complex relationship of voltage to time of discharge and time at open circuit. After a rest the cells show an ability to temporarily supply a higher voltage. It is tempting to say that this would help to start and run an AMF routine since the AMF routine is short, but this is not justified.

3.7.1 Speed of voltage drop when applying a load

Appendix 10 shows a plot of a modified load pulse taken at the end of the test of stack 2 when the cells are almost "dead". The pulse starts with an open circuit for 30 seconds, followed by a 1K ohm load for 30 seconds, followed by a 2 ohm load for 1 minute, followed by an open circuit. The cells do not react badly to the 6.2 ma load, but drop quickly when the 2 ohm load is applied. Most of the drop takes place within the first 0.1 seconds or less.

A tenth of a second may not be long enough to operate a solenoid valve and is certainly not long enough to boot the SEM. Therefore, it is not advisable to count on this recovery of voltage to be useful in completing an AMF sequence.

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[2] The last 1 to 3 samples in a file were open circuit voltages measured by hand and added manually to the end of the data files.

3.7.2 Recovery of open circuit voltage with time

Most of the open circuit voltage measurements in this report were taken 8 to 12 hours after the last load pulse. But at the end of the test of stack 2, an additional open circuit data is included for a time about 48 hours later (about 60 hours after the last load pulse). This can be seen in the top plot of Appendix 8, the black traces for cells 22 and 23 at a remaining charge of about -1 Ah. You can see a rather large 0.3 volt increase in the open circuit voltage of these very seriously depleted cells. This emphasizes the difficulty of using open circuit voltage to assess the health of the battery.

4. SELF DISCHARGE

The self discharge rate of these cells at elevated temperatures is unknown. Saft has presumably done tests but did not reveal the results or discuss the subject. Saft eventually provided cells that could be tested, but too late to be used for this report and testing for self discharge would take a very long time and was beyond the scope of the study.

5. REFERENCES

5.1 Other Related Reports

5.1.1 Solenoid valve energisation test result – in air – BP, CF3-NTF-18

5.1.2 *Solenoid valve* energisation *test result – with hydraulic pressure* – BP, CF3-NTF-19

5.1.3 *AMF card electrical characteristic test result* – BP, CF3-NTF-20

5.2 Glossary

AMF — Automatic Mode Function – a system to detect that the BOP is completely isolated from surface control and to supply electrical and hydraulic power to operate a predefined sequence of valve operations designed to close the BOP and disconnect the riser.

Boot — The sequence of steps that a computer goes through to load its program or operating system when it is initially turned on. The term originated as a reference to pulling one's self up by one's own bootstraps.

BOP Blowout preventer

DAQ Data acquisition system, a means of recording voltages and currents from several different sources at a selectable number of samples per second.

Horizon The Transocean, Deepwater Horizon drilling rig

Load Pulse In the test sequence, a load pulse is a high load for one minute, followed by a medium load for 1 minute, and then a low load for 10 minutes.

Load Cycle In the test sequence a "load cycle" is a sequence of 33 load pulses, followed by 8 to 12 hours of open circuit "resting" of the battery under test.

Pack A battery pack is a 9V battery consisting of 12 cells in a series-parallel arrangement including isolation diodes and safety components.

Pie conn. The solenoids connect to the SEM via a set of circular connectors on the bottom. Each circular connector receives 6 wedge-shaped plugs resembling pie slices. Each plug has 4 pins and goes to one dual-coil solenoid valve.

PTC Positive Temperature Coefficient – A PTC fuse is a device that acts like an electrical fuse, going into a high resistance state in the presence of high current. When the current is removed, it cools down and goes back to a low resistance and conducts properly again.

Resting A stack or cell is resting when no current is being drawn from it.

SEM Subsea Electronic Module – AC operated power supplies, a computer, solenoid driver circuits, and analog transducer circuits that are used to control and monitor the BOP. Used alone, "SEM" refers to the whole electronics module contained in the Blue or Yellow pod. Used with a letter as "SEM A" or "SEM B", it refers to each of the redundant controllers that are contained within one electronics pressure vessel.

Stack A column of 3 cells connected in series. An AMF battery has 4 of these connected in parallel.