Lessons Learned from 3 Years of Failure: Validating an FMEA with Historical Failure Data

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***Abstract*—Device reliability is often considered essential to the performance of a wave energy converter. Developers may undertake a Failure Mode and Effects Analysis (FMEA) as a design process to evaluate the high priority failure modes of a prototype to approximate device reliability. However, failures identified by this process are typically predicted, and often lack validation from actual marine operations history. In view of this, an FMEA undertaken for the Albatern Squid 6 Series Wave Energy Converter (WEC) has been validated using historical failure rate and marine operations data. Results indicate that a high volume of major structural and hydraulic failures occurred in the initial stages of deployment, whilst minor electrical and instrumentation failures occurred towards the latter. A notable observation is that human driven failures constituted a much larger portion of failure occurrences than the FMEA predicted. As a general observation, the retrospective analysis of failure rate requires consistent data recording procedures, especially given the introduction of new innovations, which may cause a resurgence of early-stage faults. Lessons learned in the operation of a redundant, modular and accessible array are discussed in the view of designing devices that are not immune, but resilient to failure.**

***Index Terms*—Lessons Learned, Failure Mode and Effects Analysis, Failure Log, Deployment History, Wave Energy Array**

I. Introduction

A. Failure and Reliability of Wave Energy Converters

The reliability of Wave Energy Converters (WEC) has long been identified as a key development metric, and has retained its place of priority amongst wave energy research across the last decade [1] to current state of the art [2]. In the most recent UK Energy Research Centre (UKERC) report, reliability has consistently been identified as an Energy Technologies Institute (ETI) priority activity.

Device developers are often required to demonstrate careful consideration of device reliability, availability and maintainability. Technology-specific funding bodies such as Wave Energy Scotland (WES) and the National Renewable Energy Laboratory (NREL) address these principles as an integral part of the funding application [3] or technical appraisal process [4]. In NREL's Structured Innovation system, being reliable, durable and survivable are counted amongst the functions required for a successful Wave Energy Farm.

In lieu of historical failure rate data, design processes such as a Failure Mode and Effects Analysis (FMEA) may be used to provide estimates for device reliability. Simply stated, an FMEA is undertaken to identify the likely failure modes of a functional system, once identified, risks are attributed a probability, consequence and detection ranking to determine their overall risk priority level. FMEAs have been conducted for a number of wave energy converters, including two examples of attenuators; hemi-spherical buoys attached to a hinged mechanical arm [5], [6], and a point absorber; a floating buoy connected to a linear rack and pinion mechanism [7].

The application of these FMEAs typically involve a feedback to the design process of the WEC in question. Ambuehl uses the Wavestar FMEA to design for structural reliability [5], whilst Chandrasekan is prompted to revise a Power Take Off (PTO) configuration to remove high-failure rate components and improve overall reliability [7]. Okoros FMEA differs in approach by using weighted parameters to reduce subjectivity in attributing risk rankings, this allows for the prioritisation of components for inspection, repair and maintenance [6].

One notable aspect of Okoros FMEA is that the parameters contain information regarding operating conditions; the current and projected status of each component is taken into account in the risk ranking calculation, hence the model can be updated from inspection findings. This prompts the idea of validating perceived failure probability and consequence rankings with actual marine operations data. By following this principle, the FMEA is revised and is able to reflect more realistic operating conditions of the device.

B. Lessons Learned Approach

Prior to this study, an FMEA has been conducted for Albatern's Squid 6S WEC [8], this investigation led to the identification of 271 independent failure modes for 112 unique components and sub-assemblies. In particular, the high and

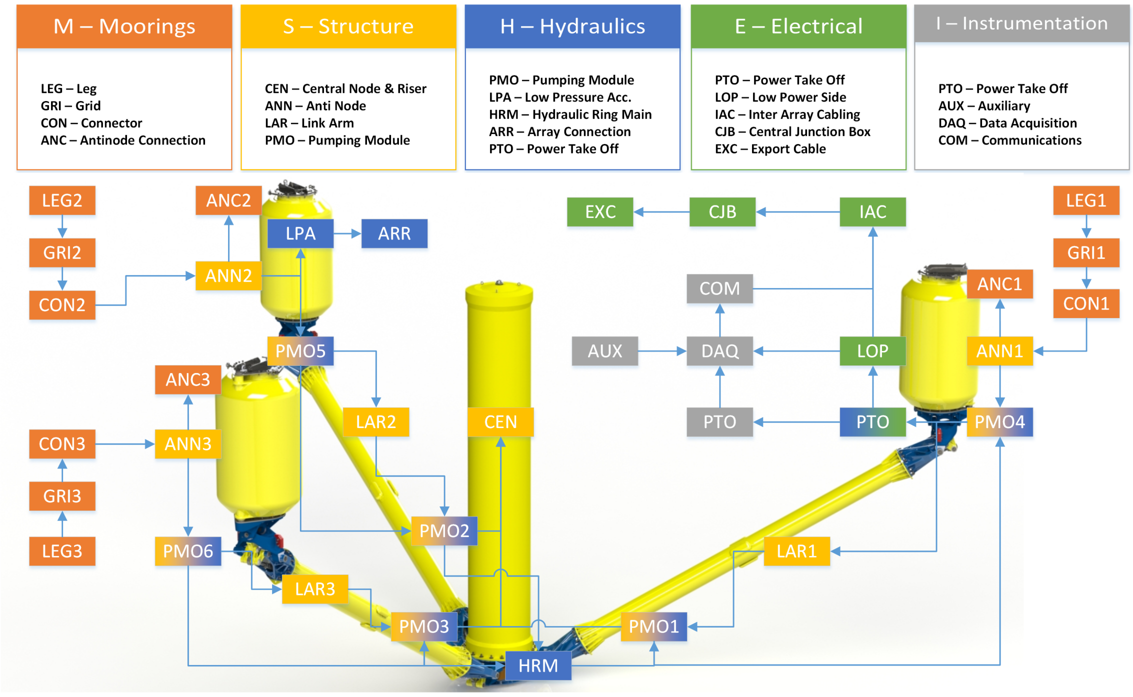

Fig. 1. Squid 6 Series WEC System Block Model - Division into Sub-Assemblies

medium priority failure modes identified were used to inform sensor selection for a Condition Monitoring System (CMS). Additional useful outputs included recommended design alterations, a set of Risk Based Inspection (RBI) protocols and a list of critical sub-systems and priority components.

However, this predicted list of failure events has not been validated with real prototype data. In the interest of capturing the lessons learned from 3 years of marine operations history, a historical failure log has been diligently compiled using the relevant information available.

From a project management perspective, experience in the industry has demonstrated a significant opportunity to learn from the installation, operations and maintenance of a wave energy array [9], where the evaluation of success and failure throughout the project lifecycle can enable an improved development trajectory. From a reliability-centered perspective, learning from the common modes of failure over the course of various wave energy prototype deployments allows for a more refined approach in component reliability testing [10]. With a 'lessons learned' approach in mind, this paper attempts to draw more general observations and learnings from 3 years of failure, with the ultimate goal of improved reliability and technology robustness.

II. Methodology

A. Failure Mode and Effects Analysis

An FMEA was set up under the guidance document DNV-RP-2013 Qualification of a New Technology [11], this is described fully in [8]. In accordance with the DNV risk categories, Probability and Consequence rankings were given a value of 1-5, whilst a Detection ranking of 1-4 was added. This gave a maximum Risk Priority Number (RPN) of 100. Due to the small-size of the Squid 6S, the risk matrix required adjustment to maintain appropriateness for the scale of the technology. A design life of 20 years was chosen with an average project size of 6 devices; corresponding to the existing Mingary Bay wave array.

The FMEA was undertaken for a 7.5kW Squid 6 Series device, an articulated wave energy converter that employs a hydraulic PTO to convert the motion of its buoyant arms into electricity. As waves pass over the device, pumping modules convert rotational motion into a reciprocating linear motion by a series of mechanical linkages connected to a hydraulic cylinder, this pumping action sends pressurised hydraulic fluid to a high pressure accumulator and hydraulic motor, located in one of the outer buoyancy floats (Antinodes). A full breakdown of a Squid 6 Series unit is depicted in Figure 1, where the device is categorised into its constituent assemblies.

A single Squid 6S device may be divided into its Moorings, Structure, Hydraulic, Electrical and Instrumentation sub-assemblies. In doing so, the components of each sub-assembly may be systematically addressed for each possible failure mechanism. The System Block Model further shows the interdependencies of each sub-system, and illustrates where sub-assemblies may be critical to the production of electricity. As described in Section I-B, a total of 271 risks have been ranked for the device.

B. Failure Log

In order to facilitate the collection and analysis of reliability data, the US Department of Defense provides guidance for the use of the Failure Reporting, Analysis and Corrective

Action System (FRACAS) [12]. The purpose of FRACAS is to provide information on what component has failed, how and why it failed and what may be done to eliminate future failures.

In the interest of comparing historical failure records to the FMEA, a failure recording template identical to the FMEA was used in the recording of marine operations failures. This ensured a coherent and comprehensive format for collected data for comparison to the FMEA. As this method was not in place during the marine operations, data from marine operations reports, operations change logs and internal consultation was used to populate the failure log template retrospectively. Example failure log entries are displayed on Figure 2.

C. Deployment History

In conjunction with the compilation of the Failure Log, the entirety of Albatern's marine operations history has been consolidated into a single document. The deployment history may be found on Figure 4, which displays the site of deployment and device status of each Squid 6S unit. Over the course of 3 years, Albatern has undertaken 3 major deployments on the West Coast of Scotland:

1) Isle of Muck Aquaculture Project, 2014
2) Loch Kishorn WaveNET Expansion, 2015
3) Mingary Bay Pathfinder Project, 2016 until present

In 2014, marine operation activity was focused in the North-West Highland region, in a sheltered sea-loch, where the first batch of Squid 6 Series units were deployed for initial trials. Following this, a total of 3 devices were deployed near the Isle of Muck in a triangular mooring pattern. These devices were subsequently retrieved, undergoing a period of maintenance until a total of 6 devices were deployed in an expanded grid layout in Loch Kishorn, 2015. Finally, the Squids were transported to Glenmore Bay (Figure 3, on the West Coast of Scotland, in preparation for a grid-connected deployment in Mingary Bay beginning August 2016.

Fig. 3. Squid 6S at Glenmore Bay

Using the information available, the Deployment History was used in conjunction with the failure log to derive:

1) Time to Failure - Number of days until failure occurence
2) Time to Detect - Number of days until failure detected
3) Time to Repair - Total active repair time

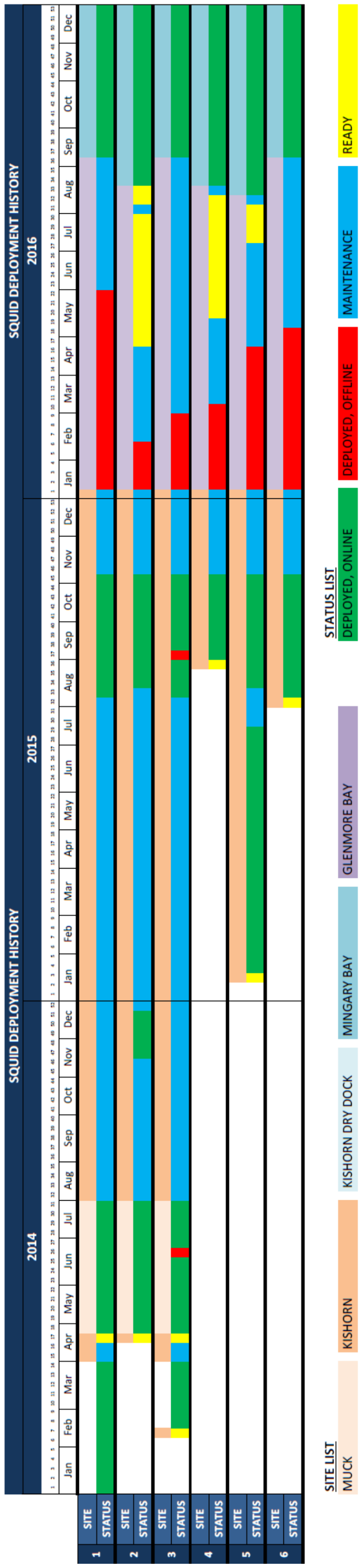

Fig. 4. Squid 6S Deployment History

ID	Sub Assembly	Component	Failure Mode	Root Cause	Probability	Failure Effect (Consequence)	Consequence	Current Controls, Prevention	Current Controls, Detection	Detection	Risk: RPN	Risk: Risk	Recommended Actions (reduce risk)	Actions Taken (mitigation)	Risk Based Inspection
14	PTO Instrumentation	Cabling and Terminations	Cable caught during instrumentation module removal	Maintenance fault	4	Electrical connectors tugged out of place	2	Cable adequately sized for instrumentation module maintenance	Detection during event occurrence.	1	8	Low	Move towards single point connection, remove cable harness entirely	Design of robust IP67 protected system with B&R X67 remote	PTO Instrumentation
15	Auxiliary Instrumentation	Load Cell	Incorrect wiring of load cell in PTO	Fabrication / Assembly error	4	Inability to install load cell, requiring intervention	1	Quality check on fabrication and instrumentation commissioning	Detection upon load cell installation attempt	1	4	V.Low	Point to point terminations as opposed to cable harness connections	Unable to connect	PTO Instrumentation
17	Communications	FO Media Converter and Switch (CJB and Shore)	2 fibre optic connections to fibre optic media converter bent 330 degrees, 6 spare FO connections also bent 180	Design fault	2	Communications failure, loss of fibre optic connection	3	CJB Adequately sized to house communications components [Needs revision]	Loss of communications line	4	24	High	Design and refit of new cable harness and cable aggregation system	Expansion of central junction box with circular lid. Testing of working connections - last	Communications
16	Data Acquisition	LabJack	Incorrect address on LabJack	Software design fault	2	Unable to establish connection to device	2	Quality check on instrumentation system commissioning	Require programming of C&I system to ensure lack of comms recognised	4	16	Med	More stringent procedures during commissioning	In situ repair using laptop offshore	Communications
16	Data Acquisition	Ethernet Switch	Strain gauge Ethernet switch wired incorrectly	Poor installation	2	Unable to establish connection to Strain Gauge DAQ unit	2	Quality check on instrumentation system commissioning	Module availability via HMI	1	4	V.Low	Require pre-deployment commissioning check. Use of keyed connectors to prevent operations staff from	In situ repair offshore	Communications
15	Auxiliary Instrumentation	Load Cell	Failure of load cell electrical connectors	Electrical short	4	Short circuit causes significaint issues with PTO connection	1	Adequate sealing on load cell connectors	During installation of PTO	1	4	V.Low	Improve selection of electrical connectors for load cell	In situ repair	Connector check
16	Data Acquisition	LabJack	Power supply unplugged	Poor installation	3	Loss of communications	2	Quality check on instrumentation system commissioning	Module status on HMI	4	24	High	Consider UPS module for power management and safe shutdown in event of	in situ repair	Communications
1	Moorings	Connecting Strap	Strap failure	Unexpected service loads	4	Antinode pairing displaced	1	Connecting strap rated for service loads	Visual inspection during deployment	1	4	V.Low	Long term solution requires new chain arrangement	Require: Use of higher rated lifting strap	Moorings
10	Low Power Side	DC/DC Converter	Soldering failure	Fabrication / Assembly error	4	Components displaced from circuit board	2	Circuit board suspended by hexagonal standoffs	Visual inspection, communication failure	1	8	Low	Elimination of prototype circuit board, potted circuitry, use of protected enclosure	In situ repair offshore; pushed components back into place	PTO Instrumentation
14	PTO Instrumentation	Electrical Connectors	Connector male pin displaced during mating	Fabrication / Assembly error	4	Sensor malfunction	2	Connectors epoxied during fabrication to avoid displacement	Detection during event occurrence	1	8	Low	Use of standardised M12 connector blocks	Repair on male connector on spot	PTO Instrumentation

Fig. 2. Failure Log - A Sample of Squid 6 Series Failure Occurrences Recorded in Retrospect

III. Results

A. FMEA Vs. Failure Log

1) Common Failure Modes: Table I denotes the common failure modes as observed in the FMEA [8], and displays failures experienced in the field emboldened. Fortunately, no significant mooring failures were experienced, however, major failures occurred within the structural and hydraulic assemblies, whilst minor failures were experienced by the electrical and instrumentation sub-systems. The occurence of minor failures associated with the electrical and instrumentation sub-systems persisted in Mingary Bay after the installation of the V3 Power Take Off module.

TABLE I
COMMON FAILURE MODES (ACTUAL OCCURRENCES EMBOLDENED

Moorings	Structural
Loss of pretension	**Loss of watertight integrity**
Entanglement	Hull breach
Drags from position	**Structural failure**
Structural failure	**Deformation / yielding**
Incorrect orientation	**Disconnection**
Hydraulic	Electrical
Seal failure	**Electrical short**
Hose burst	**Connector fault**
Water ingress	Generator failure
Oil leakage	Electrical overload
Valve jams shut/open	**Battery failure**
Instrumentation	
Calibration error	
False alarm	
Software fault	
Intermittent output	
Communications failure	

2) Root Causes of Failure: Table II lists the number of instances a root cause appears in the FMEA, in comparison to the number of instances the root cause has been attributed to failure in the Failure Log. The sub-totals have been normalised against the total number of failures, whilst the difference between the predicted (FMEA) and actual (Failure Log) root causes is taken. This difference is ranked, leading to Figures 5 and 6, which essentially show the discrepancy between the number of predicted and actual failures.

In Figure 5 corrosion, fatigue and wear are amongst the most over predicted failures. However, these failure mechanisms typically come into effect during the latter stages of a components service life, hence suggesting why they have not occurred in such volumes as the FMEA would suggest. On the other hand, Figure 6 displays the most under predicted failures, three of which may be attributed to human error; design faults and assembly errors. Overall, human error accounts for 17.7% of FMEA failures, and 27% of failures recorded in the Failure Log, indicating a propensity for unpredictable, yet inevitable mistakes in the design, commissioning and operations and maintenance processes. It is also worth noting the difficulty in predicting design faults.

The number of failures driven by unexpected service loads greatly skews Figure 6, this is a result of an ambitious hose burst protection system used in the Isle of Muck deployment. Due to a series of anti-burst measures, hydraulic lock ups occurred, causing extreme loading on the structural members of the Pumping Module sub-assembly. As a result, several breakages and deformations of components were experienced. However, with the retrofit of the V2 and V3 manifold blocks in subsequent deployments, major structural failures have been mitigated.

TABLE II
ROOT CAUSES OF FAILURE: FMEA VS. FAILURE LOG

Root Cause of Failure	FMEA	%	Log	%	change
Corrosion	25	9.2%	3	3.4%	-5.9%
Wear	30	11.1%	8	9.0%	-2.1%
Service Limit State SLS	16	5.9%	4	4.5%	-1.4%
Fatigue Limit State FLS	10	3.7%	1	1.1%	-2.6%
Ultimate Limit State ULS	6	2.2%	2	2.2%	0.0%
Accident Limit State ALS	1	0.4%	0	0.0%	-0.4%
Insufficient lubrication	1	0.4%	0	0.0%	-0.4%
Overheating	1	0.4%	0	0.0%	-0.4%
Bolt loosening	11	4.1%	0	0.0%	-4.1%
Malicious damage	4	1.5%	0	0.0%	-1.5%
Vibration fatigue	2	0.7%	0	0.0%	-0.7%
Calibration error	1	0.4%	0	0.0%	-0.4%
Connector failure	4	1.5%	2	2.2%	0.8%
Electrical short	12	4.4%	4	4.5%	0.1%
Insulation failure	4	1.5%	0	0.0%	-1.5%
Lightning strike	2	0.7%	0	0.0%	-0.7%
Loss of power	8	3.0%	2	2.2%	-0.7%
Loss of communications	0	0.0%	1	1.1%	1.1%
Conducting debris	3	1.1%	0	0.0%	-1.1%
Software design fault	2	0.7%	3	3.4%	2.6%
Overcurrent	8	3.0%	0	0.0%	-3.0%
Moisture ingress	12	4.4%	4	4.5%	0.1%
Design fault	6	2.2%	6	6.7%	4.5%
Unexpected service loads	17	6.3%	20	22.5%	16.2%
Poor installation	18	6.6%	6	6.7%	0.1%
Maintenance fault	3	1.1%	2	2.2%	1.1%
Manufacturing defect	5	1.8%	2	2.2%	0.4%
Fabrication / Assembly error	2	0.7%	4	4.5%	3.8%
Material degradation	20	7.4%	5	5.6%	-1.8%
Contamination - debris	6	2.2%	1	1.1%	-1.1%
Contamination - moisture	3	1.1%	3	3.4%	2.3%
Contamination - air	2	0.7%	0	0.0%	-0.7%
Underpressure	0	0.0%	2	2.2%	2.2%
Overpressure	7	2.6%	2	2.2%	-0.3%
Miscibility	0	0.0%	0	0.0%	0.0%
Entanglement	2	0.7%	0	0.0%	-0.7%
Biofouling - airbourne	1	0.4%	0	0.0%	-0.4%
Marine growth - subsea	5	1.8%	1	1.1%	-0.7%
Ship impacts	7	2.6%	1	1.1%	-1.5%
Foreign body impacts	4	1.5%	0	0.0%	-1.5%
	271		89		

3) Risk Priority Number Distribution: Figures 7 and 8 depict the risk ranking of failure instances for each sub-assembly, according to the FMEA and the Failure Log. Again, the structural failures experienced in the Isle of Muck skew the data; where there is typically a greater proportion of very low and low risks, in the failure log an equal number of high risk failures are recorded. The total number of high

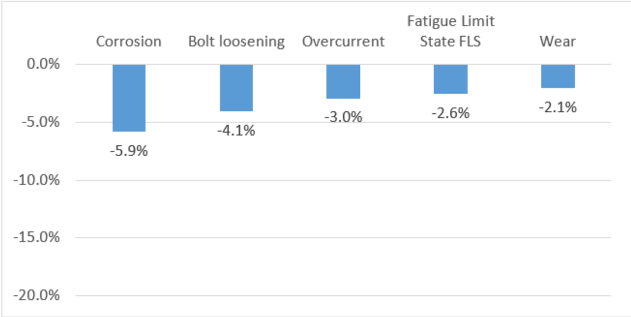

Fig. 5. Overpredicted Failure Mechanisms by Percentage of Total

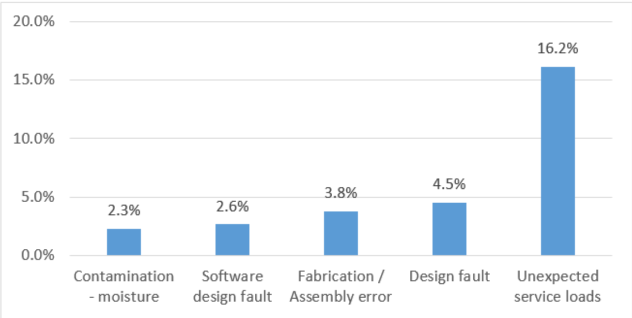

Fig. 6. Underpredicted Failure Mechanisms by Percentage of Total

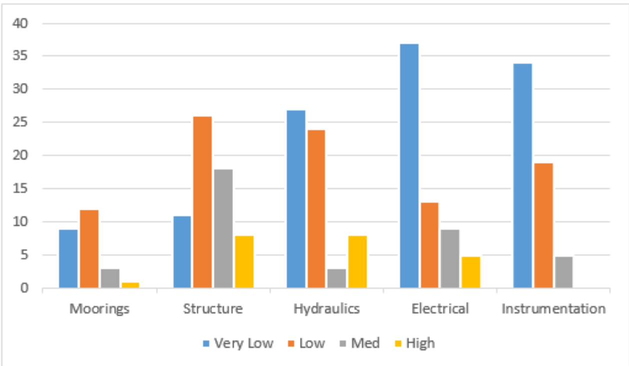

Fig. 7. FMEA Risk Rankings by Sub-Assembly

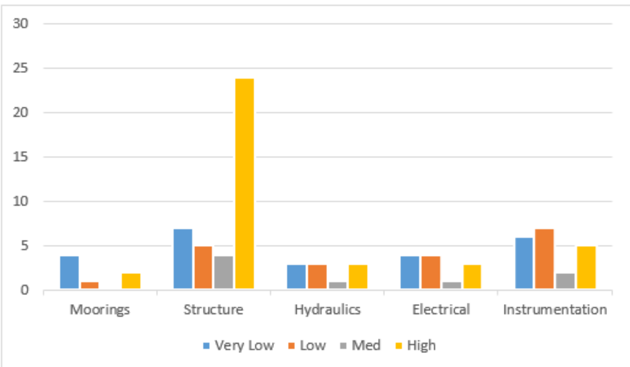

Fig. 8. Failure Log Risk Rankings by Sub-Assembly

risks may be exaggerated by the Detection ranking; failures detected beyond one week receive a ranking of 4, resulting in a significant amount of high risks. Furthermore, as higher priority failures occur, attention and resources may be drawn towards diagnosing and fixing them, hence explaining a lack of very low and low risks failures recorded in the earlier stages of the failure log.

B. High and Medium Priority Failure

Based upon the high and medium priority failures identified in the Albatern Squid 6 Series FMEA, an array of sensor configurations were suggested for the purpose of condition monitoring [8]. In Tables III and IV the high and medium priority failures are compared to actual occurrences recorded in the failure log.

With regards to the high priority failures displayed in Table III, the actual occurrence of significant failures is varied. For example, major hydrualic failures were predicted in the Low Pressure Antinode and PTO module, however in reality only minor and isolated leakage incidents occurred. Although significant mooring failures were anticipated, no significant change to the mooring pattern was experienced, however the minor failure of connecting straps occurred very often. The high priority electrical failures predicted were as a result of their probability, although connector issues were widespread, their occurrence did not cause severe consequences.

However, due to the structural failures experienced in the Isle of Muck, a significant amount of structural failures occured in the pumping module assembly due to unexpected service loads. Although fastener damage was anticipated, the extent of the damage to the structural components of the pumping modules was not predicted. Once more, Table IV illustrates that several hydraulic failures were anticipated amongst the PTO module, however in reality, only isolated contamination incidents have been experienced. This however does not preclude the occurrence of hydraulic failures later in the service life of the device.

IV. Discussion

A. Data Incompleteness

A few sources of discrepancy may account for the completeness of the data. This may primarily be attributed to the lack of disciplined marine operations reporting during the 2014 Isle of Muck deployment. Although the 2015 Loch Kishorn operations saw an improvement in the consistency of data collection, reports were still done on a weekly basis. The 2016 Mingary Bay deployment showed a considerably consistent report with device specific repair information on a daily basis, however the data still suffers from periodic gaps.

Due to the critical structural failures that occurred throughout the 2014 Isle of Muck deployment, it appears that there has been a tendency to overlook minor failures regarding the electrical and instrumentation systems during this period. This further points towards the need of having more stringent failure recording measures.

TABLE III
HIGH PRIORITY FAILURE MODES: FMEA VS. FAILURE LOG

Sub-System	Sub-Assembly	FMEA Failure Mode	Failure Log
Moorings	Connector	Loss of station keeping	Mooring pin intact, connecting strap failure
Structural	Antinode	Loss of watertight integrity	No significant leakage incident, lid leakage only
Hydraulic	PTO module	System overpressure, oil leakage	Minor leakage incidents
	PTO module	Water ingress	Contamination experienced in hydrualic cylinders
	Low pressure antinode	Oil leakage (gradual)	Minor leakage incidents
	Low pressure antinode	Oil leakage (sudden)	1 LP gas vessel explosion due to poor handling
Electrical	Low power side	Battery failure	Loss of power most common
	Low power side	Connector failure	Widespread connector issues
	PTO module	Generator failure	Require automation of start-up procedure
	PTO module	Generator failure	No significant generator failures experienced
Instrumentation	PTO module	Intermittent output	Re-calibration of sensor and software

TABLE IV
MEDIUM PRIORITY FAILURE MODES: FMEA VS. FAILURE LOG

Sub-System	Sub-Assembly	Failure mode	Measured parameter
Moorings	Grid	Loss of pretension	No significant disturbance to mooring pattern
	Connector	Ship or foreign body impacts	Minor ship impacts, no significant damage
Structure	Pumping Module	Bolt disconnection, structural failure	Failure of pumping module fasteners
	Pumping module	Deformation, structural failure	Structural failure of pumping modules
	Connection bolt	Deformation, yielding	Significant deformation and bolt shearing
Hydraulic	PTO Module	Choking	Yet to occur
	PTO Module	Contamination, water ingress	Isolated contamination incident
	PTO Module	Failure of filter	Difficult to verify without measurement
	Pumping Module	Hose burst from pressure spike	Single isolated hose burst incident
Electrical	PTO Module	Bearing failure	Generator bearings exhibiting wear
	PTO Module	Motor-generator shaft misalignment	Difficult to verify without measurement

B. Increased Early Failures

Due to the constant innovation of the Squid 6 Series prototype, both electrical and instrumentation issues were experienced in Kishorn in 2015 and subsequently in Mingary in 2016. Rather than indicate a constant high failure rate, it appears a new innovation effect is taking place with the introduction of a new upgrade. Similar to the upgrade of Software, the introduction of untested components may result in an extended infant mortality period, as illustrated on Figure 9, this effect may account for the disproportionate number of minor failures experienced with the version 2 manifold blocks and instrumentation installed in Kishorn in 2015, and version 3 Power Take Off modules and fibre optic communications link installed in Mingary in 2016.

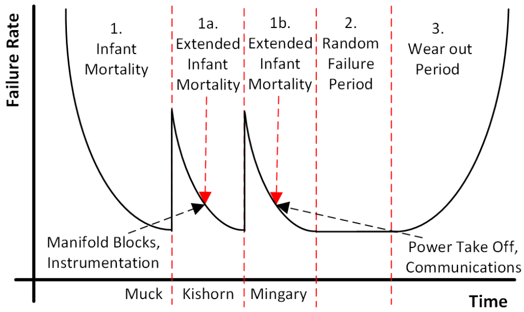

Fig. 9. Illustrative Bathtub Curve with New Innovations

C. Mean Time To Failure

Preliminary work has been undertaken to observe the field failures occurred in relation to predicted failures. Due to the poor resolution of data, it was not possible to accurately predict Mean Time To Failure values for further analysis. In time, given diligent data collection and recording, more significant failure rate prediction models will be able to be developed from the field data gathered.

V. Lessons Learned

In the effort to build on the learning gained from undertaking this study, lessons learned are briefly discussed.

A. Data Recording Procedure

In order to facilitate reliability analysis and optimisation in the future, tools must be laid down in the present in order to slowly work towards developing commercial scale industrial reliability databases. A diligent approach to collecting data must be taken. These measures should be in place through the life cycle of the device, from the beginning of deployment, throughout operations and during retrieval and decommissioning. By maintaining the consistency and centralisation of data collection, the ease of data analysis in hindsight becomes much less time consuming and demanding of effort.

In addition, where possible, data recording should be undertaken with a minimal precision of 24 hours. By enforcing stricter document control and operations procedures, operators are capable of ensuring a higher quality of data gathered. These measures for recording failure, root cause, consequence and intervention should be in place for the entire deployment phase, and will save significant time and effort in the future.

B. Design Principles and Outlook on Marine Operations

1) Redundancy: An advantage of having multiple sub-assemblies to provide the same function, i.e. transfer energy to the power take off, allows flexibility during the operations phase in the number of sub-assemblies that may be permitted to fail before intervention is required. A favourable aspect of the Squid WaveNET technology is the redundancy available on multiple levels; redundancy per device is achieved through multiple pumping modules, whilst redundancy throughout the array is achieved by multiple devices.

2) Modularity: Deploying a plurality of devices, rather than a single prototype, has enabled the acceleration of the learning process by increasing the probability of component failure by the number of devices. In view of the failure log, a range of varied failures has taken place, facilitating learning. However, a great drawback for modularity is the requirement to implement a design modification across the entire fleet, should an adjustment be necessary.

3) Accessibility: Encouraging the accessibility of devices, and ease of access to critical sub-assemblies for in-situ repair, has allowed for rapid response to minor failures during the commissioning and operations phases. In the event of a more serious repair, 'plug-and-play' modules that can be hotswapped with spares have proven useful over a series of deployments. Due to the high rate of failure of prototype devices, the ease of quick interventions and 'fire-fighting' is extremely important.

C. Failure Resilience Vs. Failure Immunity

Failures in the marine environment are an intrinsic part of the marine operations process. It is of significant importance to understand a device's high priority failure modes and prepare for them. However, oftentimes device failure may be perceived negatively as poor engineering, on the contrary, it would seem natural that the focus of prototype development should shift from building systems that are immune to failure towards building systems that are resilient to failure. As such, rather than avoiding failure altogether, device developers should prepare for the inevitable, and embrace this learning process. Furthermore, it should be noted that the reliability of prototypes will naturally improve as teething issues and design faults are addressed, thus it is not possible to directly extrapolate the reliability of a prototype to predict that of a commercial device.

VI. Conclusion

This study has examined an existing FMEA in contrast with a Failure Log retrospectively generated from marine operations reports. Due to the complexity of the Squid 6 Series WEC system, it is difficult to deduce all possible failure modes in an accurate manner. However, the FMEA has provided a valuable approximation of device reliability in lieu of failure rate data.

Now equipped with marine operations experience over the span of 3 years, it has been possible to validate the FMEA with actual failure rate data. Though initial unprecedented failures and teething issues were high, by capturing the knowledge learned from failure, it is possible to design systems with improved reliability and robustness to failure.

In view of this, particular attention should be given to the human drivers of marine operations and device design, especially in the event of the installation of a new component or sub-assembly. By implementing simple design processes such as an FMEA or Fault Tree Analysis, in addition to thorough documentation and a quality management checklist, costly and avoidable mistakes can be prevented.

It is hoped that the learnings gained from the Albatern marine operations history will be beneficial to other device developers, with the aim of capturing the lessons learned from failure and designing the next generation of failure resilient devices.

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