MHK Technology Development Risk Management Framework—DRAFT

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List of Acronyms

AAR	after action review
ABS	American Bureau of Shipping
ALARA	as low as reasonably achievable
API	American Petroleum Institute
CBS	cost breakdown structure
CEC	current energy converter
DNV	Det Norske Veritas
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EMEC	European Marine Energy Centre
ESBI	Electricity Supply Board International (Ireland)
EWTEC	European Wave and Tidal Energy Conference
FMEA	failure mode effects analysis
FOA	funding opportunity announcement
FRQ	frequency of risk
GL	Germanischer Lloyd
HSE	Health & Safety Executive
ICOE	International Conference on Ocean Energy
IEC	International Electrotechnical Commission
IMCA	International Marine Contractors Association
ITTC	International Towing Tank Conference
LCOE	levelized cost of energy
MEC	marine energy converters
MFOP	maintenance free operating periods
MHK	marine and hydrokinetic
MRP	maintenance recovery period
MTBF	mean time between failures
MTTR	mean time to repair
NASA	National Aeronautics and Space Administration
NREL	National Renewable Energy Laboratory
OES	Ocean Energy Systems
OREDA	Offshore REliability DAta
PMBOK	Project Management Body of Knowledge
PMI	Project Management Institute
PTO	power take-off
RBS	risk breakdown structure
RPN	risk priority number
SOP	safe operating procedure
SEV	severity of risk
TEC	tidal energy converter
TPL	technology performance level
TRL	technology readiness level
TYP	risk type
WEC	wave energy converter

MHK Technology Development Risk Management Framework

Over the years, the global marine and hydrokinetic (MHK) industry has suffered a number of technological and commercial setbacks, including some that resulted in bankruptcy. To help reduce the risks of industry failures and advance the development of new technologies, the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) developed an MHK technology reliability and survivability risk assessment framework.

The purpose of this risk management framework is to increase the likelihood of successful development of a MHK technology by addressing negative and positive uncertainties. It is designed to be applicable to all MHK projects of any Technical Readiness Level (TRL) or Technical Performance Level (TPL) and all risk types (e.g. technological risk, regulatory risk, commercial risk, etc.) over the entire scope of the development project. This framework is intended for use with development and deployment of a single MHK technology—not for multiple device deployments within a farm.

Developers of MHK technologies should use this risk framework to guide proposals and meet risk management expectations for the DOE's MHK funding awards (see Appendix A). It also serves as an overview of other relevant risk management tools and documentation.

This framework emphasizes design and risk reviews as formal gates to ensure risks are managed throughout the technology development cycle. Section 1 presents the recommended technology development cycle. Sections 2 and 3 present tools to assess the TRL and TPL of the project, respectively. Section 4 presents a risk management process with design and risk reviews for actively managing risk within the project, while Section 5 presents a detailed description of a risk registry to collect the risk management information into one living document. Section 6 presents recommendations for collecting and using lessons learned throughout the development process.

Hyperlinks to external websites are embedded throughout this document via underlined text. These hyperlinks are for the convenience of the user, to aid in the quick viewing of external references. The long-term integrity of these external links cannot be ensured. If hyperlinks are not functioning because of changes at the external source, consult the References section of this framework for search criteria.

1 Technology Development Flowchart

Figure 1 contains a flowchart that describes the cycle of MHK system- and component-level development, followed by definitions of individual processes and decision gates. If the user is developing individual components in parallel to a full-system development, then the processes in Figure 1 should be applied separately for each component in addition to the full system.

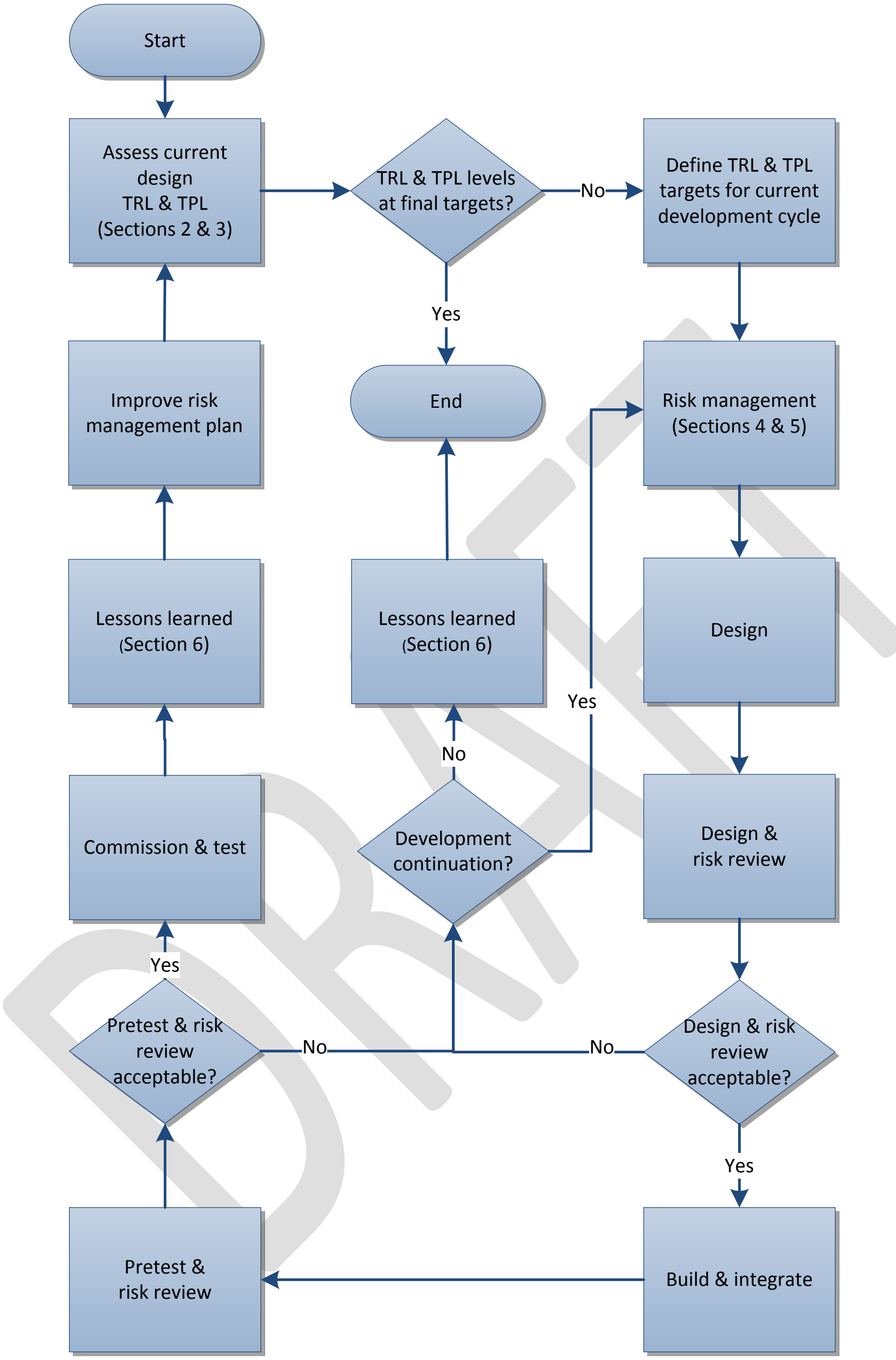

Figure 1. MHK technology development flowchart

1.1 Flowchart Processes and Decision Gates

Assess current design TRL & TPL— The process of categorizing the current state of TRL and TPL for the system and/or its constituent components. See Sections 2 and 3 for details on assessment criteria.

TRL & TPL levels at final targets?—The decision gate to check if the existing TRL and TPL values for the system and/or its constituent components have reached the final targets.

Define TRL & TPL targets for current development cycle—The process of choosing a TRL and TPL for the next development cycle. (e.g., repeat at current TRL, advance TPL but not TRL, advance TRL and maintain TPL, etc.).

Risk management—The process of developing and executing the risk management plan (Section 4.1). The specific risk management requirements at each TRL are detailed in Table 3. The risk management plan may be this risk framework document, or it may be based on equivalent processes within an organization. The process of identifying, analyzing, monitoring, and controlling risks continues throughout the Figure 1 development cycle.

Design—The process of designing the system and/or its constituent components.

Design & risk review—The process of reviewing the design and risks for the current development cycle. All of the pertinent Table 3 items should be reviewed during this process.

Design & risk review acceptable?—The decision gate that determines if the design and risks are acceptable. This review can be a go/no-go gate for DOE or others to monitor the technology development. Approval at this point should be based on: 1) design with documentation, 2) risk management completion, per Table 3, and 3) acceptable risk management results. The general risk management process of identifying, analyzing, monitoring, and controlling risks continues after an acceptable outcome at this gate.

Development continuation?—The decision gate that determines if the technology development will continue. This decision immediately follows the identification of an unacceptable risk from the previous stage of the development cycle. Decisions at this gate incorporate evaluating the identified negative risks (threats) and costs of the project against the positive risks (opportunities) and benefits of the project. A decision to not continue development moves to cataloguing lessons learned and termination of the project short of the TRL or TPL goal, while a decision to continue returns the cycle to the risk management planning stage.

Build & integrate—The process of building and integrating the items approved in the previous design and risk review.

Pretest & risk review—The process of reviewing the built and integrated system and/or constituent components before they are tested. This process should include a risk review with particular emphasis on the technology qualification plan. All of the pertinent Table 3 items should be reviewed during this meeting

Pretest & risk review acceptable?—The decision gate that determines if the system or constituent components are ready for testing. This review can be a go/no-go gate. Approval at this point should be based on: 1) verification showing built equipment is the approved design, 2) risk management completion, per Table 3, and 3) acceptable risk management results. The general risk management process of identifying, analyzing, monitoring and controlling risks continues after an acceptable outcome at this gate.

Commission & test—The process of executing the test plan; this may be a system- and/or component-level test.

Lessons learned—The process of gathering lessons learned from the team to formalize institutional learning. The lessons learned process identifies specific problems and recommendations to avoid reoccurrence, as well as project successes that can be promoted in the future. The lessons learned may lead to risk management plan improvements. Section 6 provides additional details for collecting lessons learned.

Improve risk management plan—The process of improving the risk management plan (Section 4.1) based on information documented during the lessons learned process. The risk management plan is modified to ensure it continues to be a valuable tool for the team.

2 Assess TRL Process

The TRL definitions by DOE are used to assess and guide the technology development cycle through the Section 4 risk management requirements. The TRL metric is associated with the maturity of a technology under development and quantifies its commercial readiness. Table 1 contains the verbatim TRL definitions from the DOE guideline [1]. For further reading, Westwave publishes alternate TRL definition for marine energy conversion (MEC) devices [2].

Table 1. DOE TRL Guideline [1]

Relative Level of Technology Development	Technology Readiness Level (TRL)	TRL Definition	Description
System Operations	TRL 9	Actual system operated over the full range of expected mission conditions.	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.
System Commissioning	TRL 8	Actual system completed and qualified through test and demonstration.	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review has been successfully completed prior to the start of hot testing.

Relative Level of Technology Development	Technology Readiness Level (TRL)	TRL Definition	Description
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment.	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning.[1] Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
Technology Demonstration	TRL 6	Engineering/pi-lot-scale, similar (prototypical) system validation in relevant environment.	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants.[1] Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
Technology Development	TRL 5	Laboratory scale, similar system validation in relevant environment.	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants[1] and actual waste.[2] Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
Technology Development	TRL 4	Component and/or system validation in laboratory environment.	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small scale tests on actual waste.[2] Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.

<table>
<tr><th>Relative Level of Technology Development</th><th>Technology Readiness Level (TRL)</th><th>TRL Definition</th><th>Description</th></tr>
<tr><td rowspan="2">Research to Prove Feasibility</td><td>TRL 3</td><td>Analytical and experimental critical function and/or characteristic proof of concept.</td><td>Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants.[1] Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.</td></tr>
<tr><td rowspan="2">TRL 2</td><td rowspan="2">Technology concept and/or application formulated.</td><td>Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.</td></tr>
<tr><td rowspan="2">Basic Technology Research</td><td>Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.</td></tr>
<tr><td>TRL 1</td><td>Basic principles observed and reported.</td><td>This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.</td></tr>
</table>

[1]Simulants should match relevant chemical and physical properties.

[2]Testing with as wide a range of actual waste as practicable and consistent with waste availability, safety, ALARA, cost and project risk is highly desirable.

3 Assess TPL Process

The TPL metric is a complementary assessment metric to the TRL metric. In conjunction with the TRL metric, it is used to assess and guide technology development progress and to quantify the value of technology under development. The TPL metric is directly associated with the techno-economic performance capability of a technology under development and quantifies the economic performance potential of the technology [3]. Thus, the TPL metric is not an alternative to TRL metric. The TPL metric expresses the techno-economic performance as opposed to the TRL metric that express the commercial readiness. Development steps targeting the improvement of technology performance may be quantified by TPL or other more detailed techno-economic performance metric — this is a choice of the user of the risk management framework.

Table 2 contains the verbatim TPL definitions from Weber's, "WEC Technology Readiness and Performance Matrix - finding the best research technology development trajectory" [4].

Table 2. Technology Performance Levels – Categories and Characteristics [4]

TPL	Category		TPL Characteristics
		Characteristic	
9	high	Technology is economically viable and competitive as a renewable energy form.	Competitive with other energy sources without special support mechanism.
8			Competitive with other energy sources given sustainable support mechanism.
7			Competitive with other renewable energy sources given favorable support mechanism.
6	medium	Technology features some characteristics for potential economic viability under distinctive market and operational conditions. Technological or conceptual improvements may be required.	Majority of key performance characteristics & cost drivers satisfy potential economic viability under distinctive and favorable market and operational conditions.
5			To achieve economic viability under distinctive and favorable market and operational conditions, some key technology implementation improvements are required.
4			To achieve economic viability under distinctive and favorable market and operational conditions, some key technology implementation and fundamental conceptual improvements are required.
3	low	Technology is not economically viable.	Minority of key performance characteristics & cost drivers do not satisfy potential economic viability.
2			Some key performance characteristics & cost drivers do not satisfy potential economic viability.
1			Majority of key performance characteristics & cost drivers do not satisfy and present a barrier to potential economic viability.

4 Risk Management Process

Table 3 contains the TRL-specific risk management activities that should be completed at each technology development cycle. Each of the items within this table is described in the subsections following the table. The order of the Table 3 activities is approximately the flow of activities within a Figure 1 development cycle.

Table 3. Risk Management Activity as Function of TRL

Activity required at TRL level									Risk Management Activity	Section
1	2	3	4	5	6	7	8	9		
x	x	x	x	x	x	x	x	x	Risk management plan	4.1
x	x	x	x	x	x	x	x	x	Project plan	4.2
x	x	x	x	x	x	x	x	x	Risk register	4.3
x	x	x	x	x	x	x	x	x	Design basis – requirements	4.4
			x	x	x	x	x	x	Design basis – loads	4.5
			x	x	x	x	x	x	Design description	4.6
			x	x	x	x	x	x	Design analysis	4.7
x	x	x	x	x	x	x	x	x	Define survivability targets & strategies	4.8
				x	x	x	x	x	Define reliability & maintainability targets & strategies	4.9
			x	x	x	x	x	x	Failure mode effects analysis (FMEA)	4.10
x	x	x	x	x	x	x	x	x	Technology qualification plan	4.11
x	x	x	x	x	x	x	x	x	Lessons learned	4.12

4.1 Risk Management Plan

The risk management plan activity creates the overall plan for how risk management will be conducted throughout the development cycle. This MHK Risk Management Framework may provide the foundation for this risk management plan. However, this plan should be improved after each development cycle based on lessons learned (see Section 4.12). The continuous improvement of this plan ensures it is a useful tool for the development team.

4.2 Project Plan

The project plan describes how the project will be managed during the development cycle. This plan reduces negative risk impacts to the project by considering and managing all the dynamic elements influencing the project. The level of detail for the project plan is commensurate with project complexity. The plan should consider all Project Management Institute's (PMI's) Project Management Body of Knowledge (PMBOK) areas (i.e., integration, scope, time, cost, quality, human resources, communication, risk, procurement, and stakeholder) [5].

4.3 Risk Register

The risk register is a list of all uncertain events that could have a positive or negative impact on the MHK technology development. The risk register contains prioritized risks along with a response plan for each risk. A risk register should contain: risk categories, owners, severity assessments, frequency assessments, priorities and response plans. Additional risk register details are contained in Section 5.

4.4 Design Basis—Requirements

The purpose of the design basis—requirements activity is to state the conditions that will be taken into account while designing the MHK technology. These requirements may include environmental conditions, design standards, controllability, and others. The design basis document should include relevant standard(s), requirements at the current TRL development cycle, and design requirements (as available) for subsequent TRL development cycles.

The design basis should comply with the requirements within IEC 62600—Part 2 (currently in committee draft format as of May 2014) [6]. Also, the design basis document should consider the recommendations within European Marine Energy Centre's (EMEC's) design basis guideline [7] and the Det Norske Veritas (DNV) WEC design guideline [8]. The Electricity Supply Board International's (ESBI's) verification checklist may be helpful when developing TRL-specific requirements [2].

4.5 Design Basis—Loads

The design basis—loads activity is a subset of the design basis document describing the load conditions that guide the design development. These load conditions should consider dead, live, and accidental load conditions during all relevant life phases (manufacturing, transportation, assembly, deployment, commissioning, normal operation, extreme events, faults, maintenance, and decommissioning). The same references stated in Section 4.4 apply to this loads document.

4.6 Design Description

The design description is a document describing the design at the current TRL & TPL levels. The design description is based on the design basis document (Section 4.4 & 4.5). The design description is adequately detailed to build, integrate and test the design at the current development cycle. The design documentation may include: model code, descriptive text, schematics, build prints, and/or an assembly design in the form of solid models or CAD models.

4.7 Design Analysis

The design analysis document presents analysis results of the design at the current TRL & TPL levels. These analyses are based upon the requirements and loads from the design basis document (Section 4.4 & 4.5). These analyses consider structural response and material resistance as appropriate. The analysis fidelity should be commensurate with failure risk.

4.8 Define Survivability Targets & Strategies

The survivability targets describe the conditions the MHK technology is expected to survive. These conditions may be a combination of environmental, operating, control, and fault conditions. The survivability strategy is the plan to achieve the survivability targets. These targets and strategies may be stated for the current and/or future TRL & TPL development cycle(s).

These targets and strategies should comply with the requirements within IEC 62600—Part 2 (currently in committee draft format as of May 2014) [6]. Sections 6 and 8 from the EMEC reliability, maintainability and survivability guideline may be a useful reference when developing these targets and strategies [9].

4.9 Define Reliability & Maintainability Targets & Strategies

The reliability and maintainability targets define the expected level of reliability and maintainability for the MHK technology during a stated period. The reliability target may be defined in terms of mean time between failures (MTBF) or mean time to repair (MTTR), and the maintainability targets may be defined in terms of maintenance free operating periods (MFOP) or maintenance recovery period (MRP) [9]. The reliability and maintainability strategy is the plan to achieve these targets. The same references stated in Section 4.8 apply to this section.

4.10 FMEA

A failure mode effects analysis (FMEA) is a method of analyzing a system or component to obtain possible failure modes, effects, and causes [10]. Recommendations developed through the process of creating an FMEA may reduce failure risk to the system or component. FMEA results will contain a prioritized list of failure modes based on expected frequency and severity.

Appendix C contains references for FMEAs and other failure management tools. NREL anticipates releasing in 2015 an FMEA framework for MHK technology development projects [11].

4.11 Technology Qualification Plan

The technology qualification plan outlines the steps to verify the technology has met the design requirements and targets. A wide range of tasks and activities, including tests, may be required to complete the technology qualification plan. Section 9 of DNV-RP-A203 provides recommendations for a technology qualification plan [12].

A test plan is a subset of this technology qualification plan and should be created before beginning the test, if applicable to the development cycle. A test plan should describe the procedure for obtaining data to satisfy the technology qualification plan. The Equimar Protocols for assessing marine energy converters should be utilized when developing a test plan [13]. Also, a WEC test plan should consider the recommendations outlined in the International Towing Tank Conference (ITTC) Guideline for model test experiments [14] and the Ocean Energy Systems (OES) Guideline for testing systems [15].

4.12 Lessons Learned

Lessons learned should be captured throughout the development cycle and at a formal debrief meeting following each TRL & TPL development cycle, per Figure 1. Section 6 contains details for collecting lessons learned.

5 Risk Register

The purpose of the risk register is to contain a current list of prioritized risks that could influence project success. Risk registers are used as a repository for current risk information. The risk register contains information described in the following subsections. Each risk identified within the risk register is analyzed in terms of the severity of its implications to the project and the expected frequency of its occurrence, along with a unique response plan describing how the risk will be managed. Monitoring and controlling risks involves detecting new risks and changes to existing risks. The ongoing process to monitor and control each risk should continuously occur throughout each technology development cycle displayed in Figure 1.

Figure 2 shows how the risk register processes interact, along with the document subsections describing these processes in further detail. A risk register template is provided in the referenced spreadsheet [16], which uses consistent terminology with this framework document.

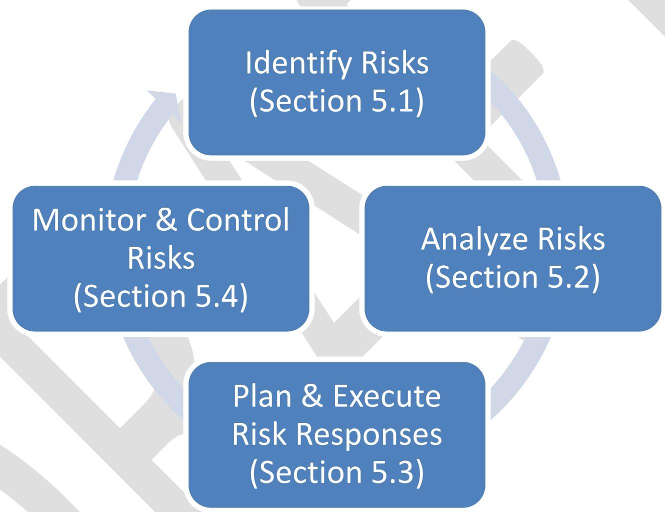

Figure 2. Risk register development processes

5.1 Identify Risks

The purpose of risk identification is to identify uncertainties that may impact the MHK technology development. These uncertainties may be from the particular application of a common design or from the pursuit of unproven design concepts. International standards may be used with or without adaptation to help identify risks. Risk identification facilitates the FMEA process by identifying inputs not contained within applicable standards. It is important to consider risks from other projects and industries that may be relevant to the MHK technology development.

Risk identification involves categorically listing risks with associated risk owners. All uncertain project elements are possible inputs to the risk identification process. The process output is the creation and maintenance of a comprehensive risk registry. This registry will be continuously updated throughout the technology development project as new risks are identified or changes occur to existing risks. The following subsections describe the risk identification process.

5.1.1 Risk Breakdown Structure

The purpose of a risk breakdown structure (RBS) is to categorize project risks into common categories. The RBS is a hierarchical breakdown of all project risks into common categories. A RBS outline can help the user consider a diverse set of risk categories when identifying new risks. The cost breakdown structure (CBS) for the MHK project may be a useful way to decompose the overall system for risk assessment.

The example RBS in Table 4 may be a helpful starting point when identifying project risks. Alternate RBS-level definitions and sublevels may be used as appropriate for a project. The Table 4 material was copied or adapted from the specified references [17] [18]. Table 5 contains example MHK risks mapped to RBS levels in Table 4—these risks were copied from the DNV WEC design guideline [8]. The Appendix B from DNV-RP-A203 contains a cause-of-failure checklist that may be used when considering possible project risks [12].

Table 4. Example RBS [17] [18]

RBS Level 0	RBS Level 1	RBS Level 2
All sources of project risk	1. Technical Risk	1.1 Scope definition
		1.2 Requirements definition
		1.3 Estimates, assumptions, constraints
		1.4 Technical processes
		1.5 Technology
		1.6 Technical interfaces
		1.7 System reliability
		1.8 Performance
		1.9 Safety
		1.10 Security
		Etc.

RBS Level 0	RBS Level 1	RBS Level 2
	2. Management Risk	2.1 Project management
		2.2 Program/Portfolio management
		2.3 Operations management
		2.4 Organization
		2.5 Human resourcing
		2.6 Funding
		2.7 Communication
		2.8 Information
		2.9 Quality
		2.10 Reputation
		Etc.
	3. Commercial Risk	3.1 Contractual terms and conditions
		3.2 Internal procurement
		3.3 Suppliers and vendors
		3.4 Subcontracts
		3.5 Client/customer stability
		3.6 Partnerships and joint ventures
		3.7 LCOE
		Etc.
	4. External Risk	4.1 Legislation
		4.2 Exchange rates
		4.3 Site/facilities
		4.4 Environmental/weather
		4.5 Competition
		4.6 Regulatory
		4.7 Political
		4.8 Force majeure
		4.9 External stakeholder
		Etc.

Table 5. Example Risks Mapped to RBS [8]

Risk Name	Table 4 RBS Level
Anchor/foundation failure	1.7
Mooring failure	1.7
Breach of water integrity of compartments or equipment	1.6

Risk Name	Table 4 RBS Level
Stability failure	1.7
Collision risks	4.8 or 4.9
Interference with commercial and recreational marine activities	4.9
Structural failure	1.7
Fishing gear impact	1.3
Personnel risks to operators and to the general public	1.9
Pressure containment failure from hydraulic or pneumatic systems	1.7
Electrical failures and shore connector failures	1.7
Seismic events	4.4 or 4.8
Fires	4.8
Interference floating debris with device	1.7

5.1.2 Technology Life Phases

Technology life phases are the unique phases the technology will proceed through from beginning its life to the end of life. Each TRL and TPL development cycle will have a set of technology life phases. Life phases are an important consideration within risk management when risks are different within each life phase.

If possible, the user should determine the appropriate technology life phases within the current and future TRL and TPL development cycles. The user may assign risk to one, multiple, or all life phases, as appropriate. The overall life phases within each TRL and TPL cycle may include, but are not limited to the following:

- Specification
- Design
- Manufacturing
- Transportation
- Assembly and commissioning
- Operation:
    - Normal power production
    - Extreme events
    - Faults
    - Maintenance
    - Repair
- Decommissioning

- All life phases

5.1.3 Risk Owner

The purpose of assigning an owner to each risk is to maintain clear risk management responsibility. A risk owner is listed for each risk within the risk registry. The risk owner is responsible for managing their assigned risk(s) throughout the project development cycle(s), which includes monitoring and controlling the risk and implementing the risk response strategy. Monitoring risks includes noting any changes that may warrant an update to the risk registry.

5.2 Analyze Risks

The purpose of analyzing risks is to enable risk prioritization based on quantifiable impacts. Prioritized risks allow the team to focus efforts on the most important risks. The quantified risk impacts may guide the team when making technology development decisions.

The IEC/ISO 31010 standard describes many different tools and techniques to analyze risks, including: consequence/probability matrix, fault tree analysis, scenario analysis, cost/benefit analysis, root cause analysis and many others [19]. The PMI's PMBOK describes multiple risk analysis methods [5]; their risk management standard provides even greater details on risk analysis tools and techniques [17].

A probability and impact matrix [5] is the tool described in Section 5.2 (same as a consequence/probability matrix [19]). This tool was chosen based on its ease of use and its application to a diverse set of project risk scenarios. A weakness of this tool is the subjective nature of assigning risk frequency and severity levels [19]. The user is encouraged to utilize additional risk management tools that may be more appropriate for each unique situation.

5.2.1 Risk Types and Severity (TYP & SEV)

The purpose of assigning a risk severity value (SEV) is to quantify the severity of risk occurrence. This severity quantification combined with its frequency will enable risk prioritization. Risk types (TYP) allow risk categorization with respect to the areas primarily impacted by risk occurrence.

Table 6 contains a risk severity and risk type matrix. The risk increases in severity from 0, no severity level, to 5, lethal. The risk categories include: safety, cost, time, scope, quality, environment, and regulation. A given risk could be assessed at every risk type or at the perceived most important one(s), provided the impacts to the other risk types are maintained at acceptable levels when controlling the risk. For example, a given risk could be analyzed in terms of its impacts on safety and/or cost and/or time, etc.

Positive risks can be tracked with a negative severity parameter and opposite definitions of those in Table 6 (i.e. a "-2 time risk" would advance—versus delay—the schedule by 1 week to 1 month).

Table 6. Risk Types and Severity Definitions [8]

Consequence to persons, project, environment and regulatory compliance								
Severity (SEV)	**Severity Level**	**Risk Type (TYP)**						
		Safety (S)	**Cost (C)**	**Time (T)**	**Scope (P)**	**Quality (Q)**	**Environment (E)**	**Regulation (R)**
0	None	No injury	$0K	No delay	No scope impact	No quality impact	No pollution	Full compliance
1	Insigni-ficant	Nuisance	$1K	Less than one week delay	Insignificant scope impact	Insignificant quality impact	Insignificant pollution	Insignificant regulatory infraction with no consequences
2	Marginal	Minor injuries	$10K	1 week to 1 month delay	Moderate scope impact	Moderate quality impact	Minor pollution	Moderate regulatory infraction with inconvenient but reversible consequences
3	Critical	Signifi-cant injuries and/or health effects	$100K	1 month to 6 months delay	Major scope impact (rescoping required to some of the project)	Critical quality impact (possibly irreversible)	Limited levels of pollution, manageable	Major regulatory infraction causing system shutdown until compliance is reassured
4	Catastro-phic	Life threaten-ing injuries and/or health effects	$1M	6 months to 1 year delay	Serious scope impact (rescope most of project)	Catastrophic quality impact (likely irreversible)	Moderate pollution, with some clean-up costs	Serious regulatory infraction likely causing irreversible system shutdown and substantial fines
5	Lethal	Fatality	$10M	1 year or more delay	Complete scope impact (rescope entire project)	Devastating and irreversible quality impact	Major pollution event, with significant clean-up costs	Very serious regulatory infraction causing project shutdown, major fines and/or bankruptcy, lengthy legal proceedings

[8]

5.2.2 Risk Frequency (FRQ)

The purpose of assigning a risk frequency (FRQ) value to each risk is to quantify the probability of it occurring during a given period. The risk frequency combined with the risk severity will enable risk prioritization. Table 7 contains suggested definitions for a relative frequency scale from zero to five, with an analyzed period of one year. Typically, the assigned frequency will be based on the expert judgment of the user, however historical data should be used when available. Also, published reliability data from similar industries such as offshore oil and gas may be used, as appropriate [20].

Table 7. Risk Frequency Definitions

Frequency (FRQ)	Estimated Probability (p) of Occurrence During One Year (% per year)
0	p < 0.01%
1	0.01% < p < 0.1%
2	0.1% < p < 1%
3	1% < p < 10%
4	10% < p < 50%
5	p > 50%

5.2.3 Risk Priority Number (RPN)

The purpose of the risk priority number (RPN) from a probability and impact matrix is to provide a method for risk prioritization. The RPN is the product of the risk frequency and severity values. The RPN is segregated into low, medium, and high risk zones, as shown in Figure 3. Generally, a low RPN should be targeted for all risks, a medium RPN may be acceptable under certain circumstances, and a high RPN is unacceptable. It is up to the user to define acceptability thresholds for their project. It is important to establish the basis for risk acceptability before analyzing risks.

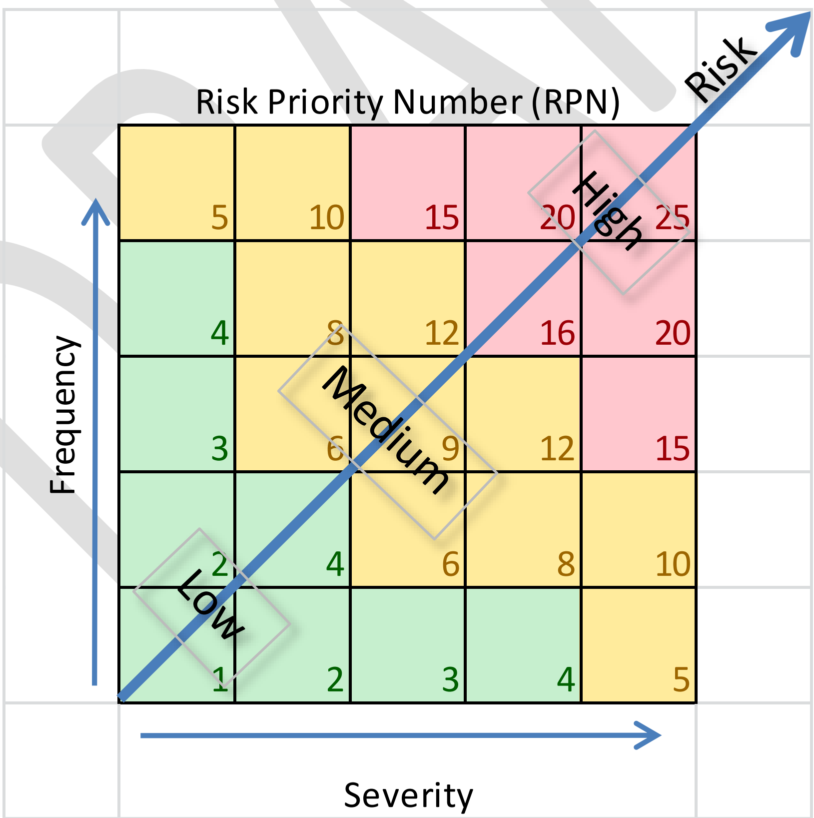

Figure 3. Risk priority number [8]

5.3 Plan and Execute Risk Responses

A risk response plan describes how each risk will be uniquely managed. A risk response plan is important because each risk may have interdependencies with other project functions. The implications of each risk occurring is considered when developing the response plan. The risk register is structured to contain information described in the following subsections for each identified risk.

5.3.1 Risk Response Strategies

The risk response strategy describes the type of response to each risk and how this will be implemented. A unique response strategy is important because it describes the authorized response plan for each risk. The response strategy for each risk is structured using the Table 8 strategy types combined with a unique description. The response may address the root cause and/or the effect of the risk. An effective response strategy requires budget and schedule authorization to implement the response. Risk responses consider input from—and are communicated to—all relevant project stakeholders [17].

The four strategy types for negative risk responses in Table 8 include: avoid, transfer, mitigate, and accept. The avoid strategy is usually preferred because the risk will not have any impact on the project. The transfer strategy may be used if an important risk cannot be avoided or mitigated, and there is a third party willing to accept the risk. The mitigate strategy may be the most common strategy where efforts are made to reduce the probability and/or impact of the risk. An accept strategy may be chosen because the risk impacts are negligible. Alternatively, the accept strategy may be conditional if a process is started under controlled conditions to verify risk assumptions, or it may be temporary if data is obtained under controlled conditions for future risk reassessment.

The positive risk response strategies from Table 8 are complementary to the associated negative strategies. Positive risk response strategies are planned to maximize impact from uncertain opportunities.

Table 8. Risk Response Strategies [17]

Negative Risk (Threats) Responses		**Positive Risk (Opportunity) Responses**	
Strategy Type	**Strategy Description**	**Strategy Type**	**Strategy Description**
Avoid	Ensuring the risk cannot occur or will have no impact on the project (e.g., removing high-risk equipment from the system)	Exploit	Ensuring the opportunity will occur and the project will benefit from it
Transfer	Transferring the risk to a third party (e.g., insurance company)	Share	Sharing the opportunity with another party
Mitigate	Reducing the probability and/or consequence of a risk	Enhance	Increasing the probability and/or consequence of an opportunity

Negative Risk (Threats) Responses		Positive Risk (Opportunity) Responses	
Strategy Type	**Strategy Description**	**Strategy Type**	**Strategy Description**
Accept	Accepting the risk without pursuing any of the other strategies—contingency plans may be developed if the risk occurs	Accept	Accepting the opportunity without pursuing any of the other strategies

5.3.2 Risk Response Timing and Triggers

The timing and trigger conditions clearly identify *when* a risk response is commenced. This is important because the risk response initiation may depend on external conditions. The timing may simply be the schedule for implementing the risk response (e.g., risk response strategy will be implemented on June 24). Risk-response triggers are conditions—other than the risk becoming reality—that will cause the risk response to occur (e.g., begin risk response if project is over budget by more than 10% at any quarterly review).

5.3.3 Residual Risk after Risk Response

The residual risk quantifies the expected results from the risk response, which includes the residual risk RPN and a description of the anticipated results. The residual risk RPN is calculated using the same methods as the baseline risk (see Section 5.2). The residual risk description includes the expected primary outcome from the risk response (i.e., the expected results by implementing the response strategy).

From Table 8, if using an avoid strategy, then the residual risk severity and frequency is zero. If using a transfer strategy, then the residual risk severity may be less because a third party is sharing responsibility, but the frequency will remain unchanged. If using a mitigate strategy, then the residual risk severity and/or frequency will be less. If using an accept strategy, then the residual risk severity and frequency will be the same as the baseline risk condition.

5.3.4 Secondary Risks Resulting from Risk Response

Secondary risks are those risks caused by implementing a risk response strategy to the primary risk. It is important to identify and analyze secondary risks to ensure the risk response is worth pursuing. The risk register includes a field identifying secondary risks within each primary risk; each secondary risk is analyzed as a separate risk item within the risk register using the Section 5.2 methods.

5.3.5 Contingency Plan

The contingency plan describes the actions to take if a risk event occurs. The purpose of a contingency plan is to prepare for the situation where the risk response strategy was not successful in preventing the negative risk event from occurring (or conversely, it was successful in realizing the positive risk event). Each risk within the risk register contains a unique contingency plan.

For example, there may be an estimated 5% probability that a critical regulatory permit will not be issued for a project. The *contingency plan* is the plan if this permit is not issued. In contrast, the *risk response strategy* may be the plan to minimize the impact or frequency of this risk event from occurring.

5.4 Monitor and Control Risks

Monitoring risks includes detecting any differences between the current project conditions and the risk register information—it also includes the identification of new risks not contained within the risk register. Controlling risks includes the execution of risk responses by the risk owner according to the risk response timing and trigger conditions. The risk register is updated with new information according to the cycle in Figure 2. Monitoring and controlling risks is a process that occurs continuously throughout each technology development cycle (Figure 1).

6 Lessons Learned

This section describes a process to collect and utilize lessons learned from the development team. Collecting lessons learned is an important part of a comprehensive risk management plan because it promotes organizational learning that may reduce the frequency and/or severity of future negative risks. Also, this organizational learning may help foster future successes in areas where positive outcomes were realized.

Lessons learned may be documented using separate tables; one for issues (problems) and one for successes. The issue table should describe each issue along with its impact and contain recommendations for improvement. The success table should describe each success, factors supporting the success, and its impact. Action items are assigned to implement changes based on each lesson learned.

Lessons learned are best captured when they are noted by a team member. Also, a formal debrief meeting with all team members should conclude each technology development cycle. The debrief meeting allows the team to stop and examine what occurred during the previous development cycle. The risk register is updated, as appropriate, from lessons-learned information. The lessons learned will provide input to improve the risk management plan (Section 4.1) as shown in Figure 1.

The following are suggested templates for documenting lessons learned during or after each development cycle. Table 9 is a suggested template to document issues and Table 10 is a suggested template to document successes. Mock data are shown in these tables to demonstrate its potential use; red font is used to highlight action items. The Vanderbilt Guide contains additional recommendations for collecting lessons learned [21].

The following are some possible questions to consider when conducting a project debrief:

- What worked well—or didn't work well—during this development cycle?
- What worked well—or didn't work well—for the project team?
- What needs to be done differently?
- What project circumstances were not anticipated?

- How can we improve our technology development process?

Table 9. Template for Lessons-Learned Issues (Mock Data Shown)

Date	Project Cycle	Issue category	Issue name	Issue description (possible cause)	Impact	Recommendation for improvement (action items)	Action item initials	Follow-up actions completed
140712	TRL 5, TPL 7	Scope	Bolt torque	It was uncertain if bolts on generator were torqued according to the specification	Potential damage to generator if operated without proper torque; required potentially unnecessary retorque operation	Develop a checklist for technician to initial when torque operation completed	MD	Checklist developed for next test phase
140712	TRL 5, TPL 7	Quality	Missing test records	During testing, notes were not regularly taken by test personnel	Unable to reconstruct the actual test events	Develop a dedicated logbook for each test campaign; develop process for capturing test events in logbook	RB	Logbooks available for each test; procedure developed for logbook usage
140712	TRL 5, TPL 7	Human resource	Staff availability	Staff availability was unknown in advance of absence	Testing was delayed due to key staff being unavailable	Develop a staff calendar indicating upcoming staff vacations and other out of office events	DS	TBD

Table 10. Template for Lessons-Learned Successes (Mock Data Shown)

Date	Project Cycle	Success category	Success name	Success description	Impact	Factors supporting success (action items)	Action item initials	Follow-up actions completed
140712	TRL 5, TPL 7	Integration	Good test setup	All test setup components functioned as expected	No mid-test rework	Good test set-up planning; develop test plan template from existing test phase	TJ	TBD
140712	TRL 5, TPL 7	Safety	No injuries	No injuries occurred during test project	Healthy team; satisfied management expectations	Team's commitment to safety; safe operating procedures; check if any gaps may exist between existing safe operating procedures and scope of next test phase	JJ	Existing SOP adequately covers scope of next project phase
140712	TRL 5, TPL 7	Quality	Test setup maintenance	Thorough daily test maintenance during test phase addressed issues before major problems developed	Potential major problems avoided	Diligent technicians & relevant checklists; add maintenance checklist requirement for next pre-test review	BE	Maintenance checklist added to requirements for next pre-test review

6.1 Definitions for Terms Used Within the Fields from Table 9 and Table 10:

Date—the date when the problem/success was documented.

Project Cycle—the current project cycle based on TRL and TPL designations from Figure 1.

Issue/Success Category—the category assigned for each problem/success. A suggested categorization scheme is to use safety and the 10 PMBOK knowledge areas [5]. Alternatively, the 7 risk type categories from Table 6 may be used to categorize the lessons learned. Although each issue/success may fit within more than one category, choose one category with the greatest impact.

Issue/Success Name—the unique name given to the identified issue/success.

Issue Description (Possible Cause)—the description of the issue along with any possible causes.

Success Description—the description of the success.

Impact—the impact on the project or team as a result of the specific issue/success.

Recommendation for Improvement (Action Items)— recommendations that may reduce the frequency of reoccurrence or severity of the issue. Action items should be listed to implement these changes. Action items are shown in red font within Table 9 to highlight items requiring follow-up.

Factors Supporting Success (Action Items)—the positive factors that contributed toward the successful outcome. Action items should be listed if activities can be implemented that promote these factors to reoccur in the future. Action items are shown in red font within Table 10 to highlight items requiring follow-up.

Action Item Initials—the person responsible for executing the action item.

Follow-up Actions Completed—the follow-up actions taken based on the assigned action items.

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Appendix A—Risk Management Checklist for DOE FOA Applications

Effective risk management is an important precursor to a successful project. Demonstrating risk management according to the MHK Risk Management Framework may be required of all DOE FOA awardees. All FOA applicants should review and understand this framework. The FOA awardee may use their existing risk management procedures if they meet or exceed the basic requirements outlined in the MHK Risk Management Framework. As part of the FOA application, the following items should be addressed within the FOA proposal:

- ✓ Provide a brief description of the system and/or constituent components to be developed within this FOA project
- ✓ Describe your risk management strategy with reference to each of the following subsystems and project metrics:
    - Loss of functionality to:
        - PTO or rotor assembly
        - electrical systems
        - mechanical systems
        - wear items (seals, bearings, etc.)
        - structure (break, fatigue, etc.)
        - mooring or foundation
        - control system
        - data/monitoring system
    - Loss of device
    - Reduced power production compared to expectations/predictions
    - Low availability
    - Incomplete data amount collected during period
    - Delay in deployment or commissioning
    - Breach of safety requirements
- ✓ Will you use the MHK Risk Management Framework or other risk management plan? If other, then provide adequate documentation of this plan that includes detail equivalent to the MHK Risk Management Framework (i.e., it must contain structured reviews [design, pretest and risk] and activities described in Table 3).
- ✓ Currently, what is the technology TRL & TPL (pre-FOA)?
- ✓ What are expected TRL & TPL at funding conclusion?
- ✓ What are proposed TRL & TPL steps to take during FOA period of performance? (e.g., starting at TRL-1 & TPL-1, then TRL-3 & TPL-3, etc.)
- ✓ What components or subsystems, if any, will be developed and tested in parallel with the overall system? How does this de-risk the overall system test?
- ✓ Describe the preliminary survivability targets and the strategy to obtain these targets, per Section 4.8 of this framework.

- ✓ If the TRL is 5 or more at FOA conclusion, then describe the preliminary targets for reliability and maintainability—and the strategy to obtain these targets—at the project conclusion, per Section 4.9 of this framework.
- ✓ List the planned risk management deliverables during the FOA period of performance, i.e., as stated in Table 3 of the MHK Risk Management Framework (or equivalent), that apply to this project.
- ✓ List the relevant standards to be used during the technology development under this FOA.
- ✓ List the top 10 expected project risks. Then, analyze and provide risk responses for these 10 preliminary risks according to Section 5 of this framework; complete the MHK Risk Register Template spreadsheet [16], or equivalent for these 10 preliminary risks.

Appendix B—Failure Mode Trend Analysis

This appendix describes a framework for tracking and trending failure modes during an MHK deployment. For consistency, the same failure modes and severity level definitions should be used when quantifying failure occurrence (see Table 11). Any modifications to the failure mode and severity level definitions should be completed before data is collected.

This framework can track trends over a single project, or it can be applied to aggregated data from multiple projects. Trends should be tracked separately for each failure mode. The time period should be consistent within a single project and across multiple projects. The occurrence of each failure mode and severity should be tabulated during each period. Some failure modes may occur multiple times at various severity levels during a period (e.g. loss of functionality), while other failure modes will only have one occurrence during a given period (e.g. availability).

A hypothetical example of data during three periods is shown in Table 12 through Table 14. All failure modes during a given period can be displayed in a graph such as Figure 4. Trends across all periods for a single failure mode can be displayed in a graph such as Figure 5.

Failure Modes and Severity Definitions

Table 11. Failure Mode Severity Definitions for Trend Analysis

ID	Failure mode	Severity Level Definitions					
		0	1	2	3	4	5
1	Loss of functionality definitions [8]	None	Minimal effect, easily repairable or redundant system	Loss of redundant function, reduced capacity	Loss of parts of main function, with significant repairs required	Subsystem failure; system requires retrieval	Complete failure
1.1	Loss of functionality—PTO or rotor assembly	See: *Loss of functionality definitions*					
1.2	Loss of functionality—electrical systems	See: *Loss of functionality definitions*					
1.3	Loss of functionality—mechanical systems	See: *Loss of functionality definitions*					
1.4	Loss of functionality—wear items (seals, bearings, etc.)	See: *Loss of functionality definitions*					
1.5	Loss of functionality—structure (break, fatigue, etc.)	See: *Loss of functionality definitions*					
1.6	Loss of functionality—mooring or foundation	See: *Loss of functionality definitions*					

ID	Failure mode	Severity Level Definitions					
		0	**1**	**2**	**3**	**4**	**5**
1.7	Loss of functionality—control system	See: *Loss of functionality definitions*					
1.8	Loss of functionality—data/monitoring system	See: *Loss of functionality definitions*					
1.9	Loss of functionality—other	See: *Loss of functionality definitions*					
2	Loss of device (% loss)	None	Temporary	Light Damage (25%)	Damage (50%)	Severe Damage (75%)	Total Loss (100%)
3	Reduced power production compared to expectations/predictions	>90%	80-90%	50-80%	20-50%	10-20%	<10%
4	Low availability	>90%	80-90%	50-80%	20-50%	10-20%	<10%
5	Incomplete data amount collected during period	>90%	80-90%	50-80%	20-50%	10-20%	<10%
6	Delay in deployment or commissioning	None	Less than one week delay	1 week to 1 month delay	1 month to 6 months delay	6 months to 1 year delay	never
7	Breach of safety requirements	None	Nuisance	Minor injuries	Significant injuries and/or health effects	Life threatening injuries and/or health effects	Fatality
8	Other	TBD	TBD	TBD	TBD	TBD	TBD

Failure Mode Trend Analysis Hypothetical Example #1

The following subsection contains a hypothetical application of the failure trend analysis described in Table 11. This example shows data from three consecutive periods (Table 12 through Table 14). The numbers within each table are the quantity of occurrence of each failure mode at the stated severity level during the period.

Table 12. Hypothetical Example #1—Failure Trend Analysis Period 1

ID	Failure mode	Failure Occurrence During Period for each Severity Level					
		0	1	2	3	4	5
1.1	Loss of functionality—PTO or rotor assembly	1					
1.2	Loss of functionality—electrical systems		2		3		
1.3	Loss of functionality—mechanical systems		1				
1.4	Loss of functionality—wear items (seals, bearings, etc.)	1					
1.5	Loss of functionality—structure (break, fatigue, etc.)	1		2			
1.6	Loss of functionality—mooring or foundation	1					
1.7	Loss of functionality—control system			1			
1.8	Loss of functionality—data/monitoring system		1				
2	Loss of device (% loss)		1				
3	Reduced power production compared to expectations/predictions	1					
4	Low availability	1					
5	Incomplete data amount collected during period		1				
6	Delay in deployment or commissioning	1					
7	Breach of safety requirements			3			

Table 13 contains hypothetical failure-mode-occurrence data during the second analyzed period. The increase in safety incidents from the first period may indicate a growing need to manage safety risks.

Table 13. Hypothetical Example #1—Failure Trend Analysis Period 2

ID	Failure mode	Failure Occurrence During Period for each Severity Level					
		0	1	2	3	4	5
1.1	Loss of functionality—PTO or rotor assembly	1					
1.2	Loss of functionality—electrical systems		2			1	
1.3	Loss of functionality—mechanical systems	1					
1.4	Loss of functionality—wear items (seals, bearings, etc.)	1					
1.5	Loss of functionality—structure (break, fatigue, etc.)	1					
1.6	Loss of functionality—mooring or foundation	1					
1.7	Loss of functionality—control system		1				
1.8	Loss of functionality—data/monitoring system	1					
2	Loss of device (% loss)	1					
3	Reduced power production compared to expectations/predictions	1					
4	Low availability	1					
5	Incomplete data amount collected during period			1			
6	Delay in deployment or commissioning	1					
7	Breach of safety requirements			5			

Table 14 contains hypothetical failure-mode-occurrence data during the third analyzed period. The increase in severity for the safety incidents indicates a higher priority is necessary for managing safety risks, even though no other failure modes occurred during this period.

Table 14. Hypothetical Example #1—Failure Trend Analysis Period 3

ID	Failure mode	Failure Occurrence During Period for each Severity Level					
		0	1	2	3	4	5
1.1	Loss of functionality—PTO or rotor assembly	1					
1.2	Loss of functionality—electrical systems	1					
1.3	Loss of functionality—mechanical systems	1					
1.4	Loss of functionality—wear items (seals, bearings, etc.)	1					
1.5	Loss of functionality—structure (break, fatigue, etc.)	1					
1.6	Loss of functionality—mooring or foundation	1					
1.7	Loss of functionality—control system	1					
1.8	Loss of functionality—data/monitoring system	1					
2	Loss of device (% loss)	1					
3	Reduced power production compared to expectations/predictions	1					
4	Low availability	1					
5	Incomplete data amount collected during period	1					
6	Delay in deployment or commissioning	1					
7	Breach of safety requirements				1	2	

Figure 4 is a graph of all the failure mode data from Period 1. This figure provides a method for viewing data from Table 12.

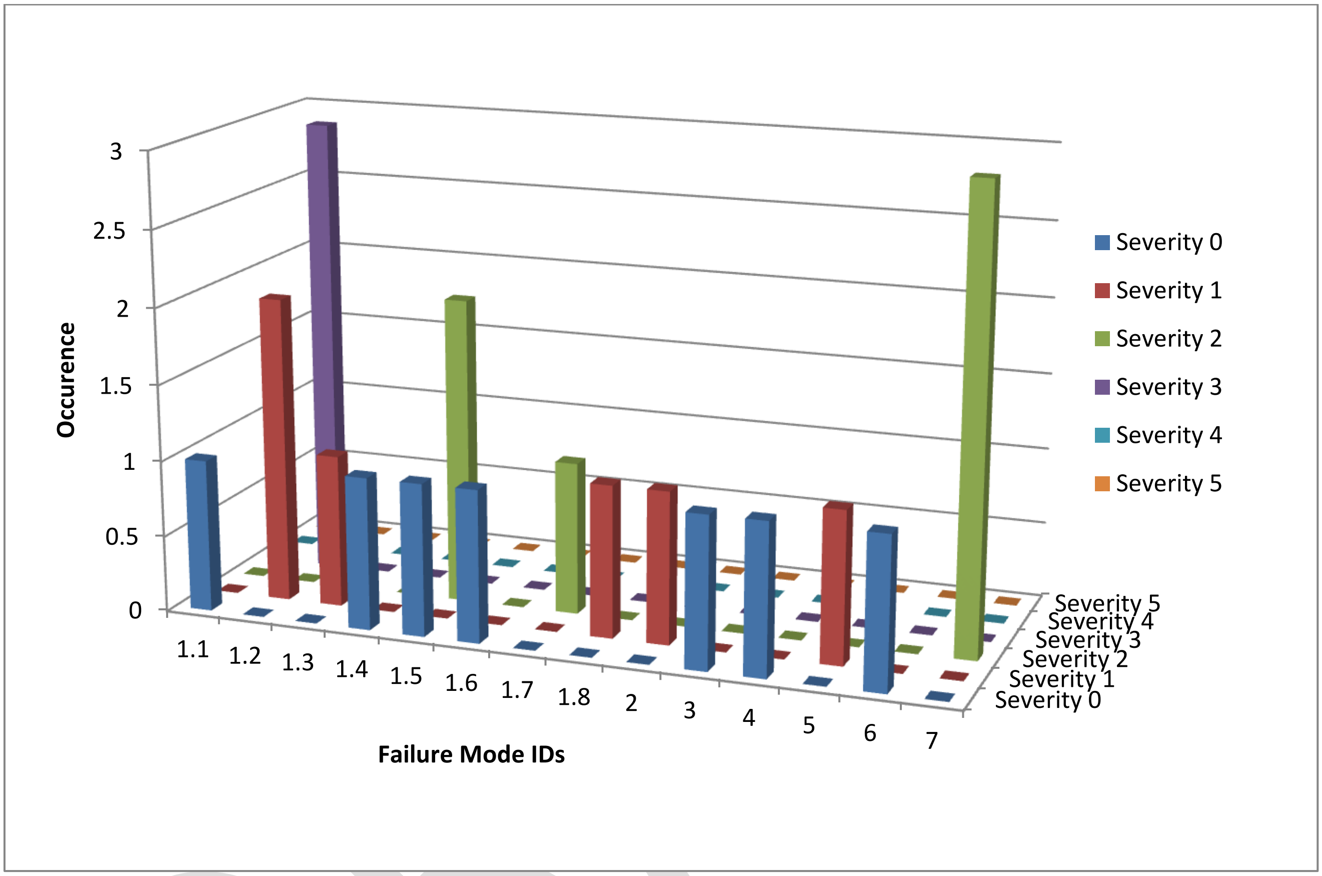

Figure 4. Hypothetical analysis #1—failure mode occurrences during Period 1

Figure 5 shows the failure trends across three time periods for Failure Mode 7 (safety incidents). As shown, there is a trend of increased severity from period 2 to period 3. This type of figure shows how failure mode trends can be tracked through time for a range of severities.

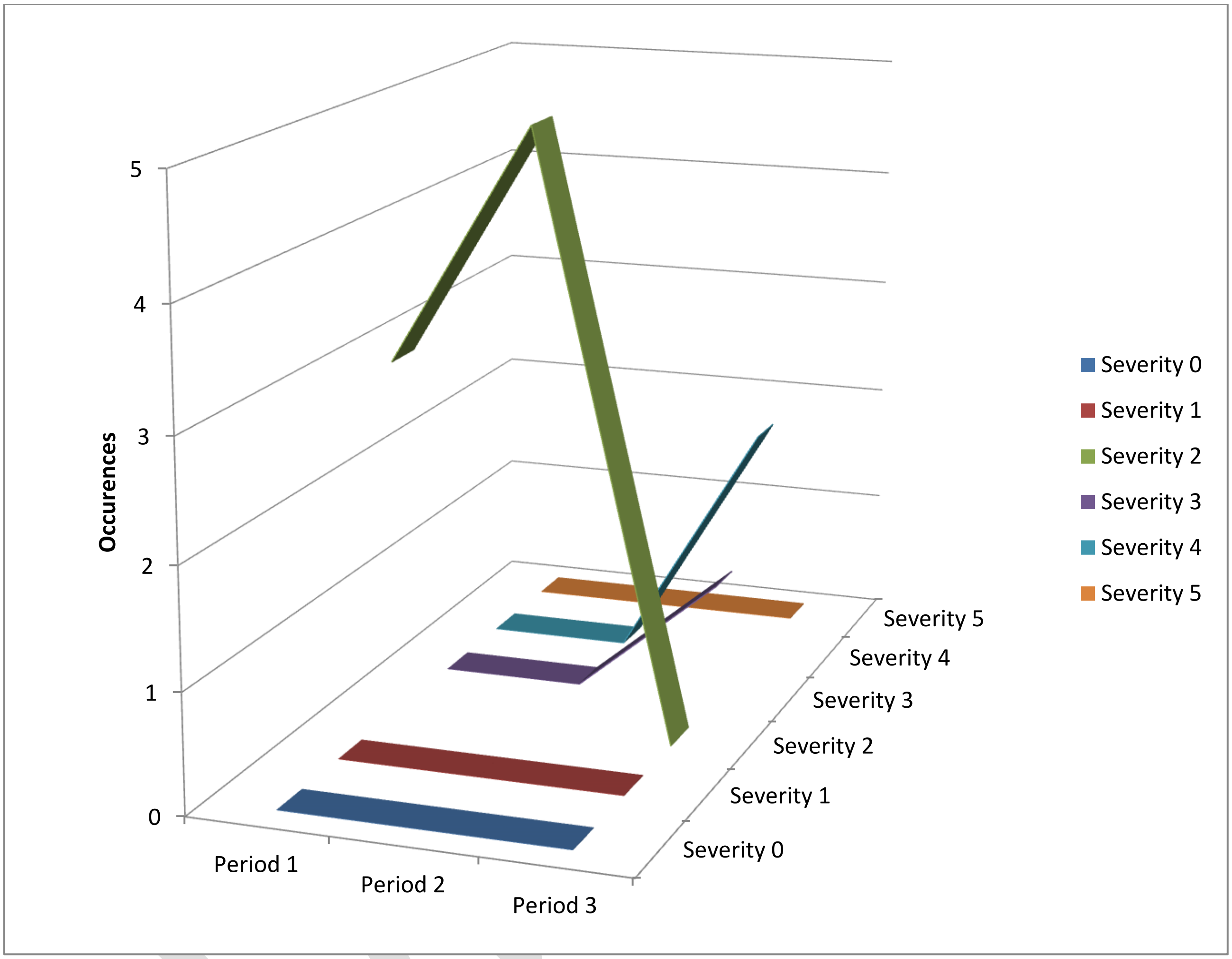

Figure 5. Hypothetical analysis #1—failure trends over three periods for Failure Mode 7

Appendix C—Risk Management Outlined Bibliography (Standards, Guides & Reports)

The following is an outlined bibliography for further reading on topics related to MHK risk management. The underlined text contains external links to the source document; the non-underlined references must be purchased to view. There is no particular order to the information presented here.

Terminology

IEC 62600-1, MHK Terminology [22]

ISO 73, Risk Vocabulary [23]

Certification & Qualification Guidelines

DNV-RP-A203, Technology Qualification [12]

DNV-OSS-312, MHK Certification Standard [24]

General & Marine Risk Management

PMBOK, 5th edition [5]

Practice Standard for Project Risk Management [17]

ISO 31000 Risk Management Guideline [25]

IEC ISO 31010 Risk Management Techniques [19]

DNV-RP-H101 Risk Management in Marine Operations [26]

ABS Offshore Oil Risk Assessment [27]

API 17N Subsea Risk Management [28]

ATOM Risk website contains several risk management templates and examples [18]

Marine risk assessment, Offshore Technology Report, DNV—2001/063 [29]

Failure Management

IEC 60812, FMEA Analysis Techniques [10]

DNV-RP-D102, FMEA of Redundant Systems [30]

IMCA M166, Guidance on FMEA [31]

DOD MIL-STD-1629RevA FMEA Procedure [32]

IEC 61025, Fault Tree Analysis [33]

IEC 61078, Reliability Block Diagram [34]

IEC 62502, Event Tree Analysis Techniques [35]

Design & Testing Guidelines

DNV WEC design guideline [8]

EMEC design basis guideline [7]

EMEC reliability, maintainability, and survivability guideline [9]
- Annex F defines risk in terms of equipment maturity and organizational capability

OES Guideline by Holmes, for testing wave energy systems [15]
-provides a test validation outline based on technology TRL.

EquiMar Protocols for assessing marine energy converters [13]

DNV-OS-C501 Composite Components [36]

ITTC Guideline for model test experiments [14]

IEC 62600-10 Mooring systems [37]

ABS Offshore Fatigue Assessment Guide [38]

GL Offshore Structural Design Guide [39]

Safety Management

ISO 12100 Safety of Machinery [40]

TRL & TPL Definitions

DOE TRL assessment guide, see Table 1 [1]

NASA TRL definitions [41]

Appendix 2 Technology Readiness Levels for Supply Chain Study for WestWave, provides TRL functional definitions for wave power devices & a verification checklist [2].

Weber TPL papers from ICOE and EWTEC conferences [3] [4]

Miscellaneous

DNV-OS-D201 *Offshore Electrical Installations*, DNV, October 2013 [42]

Review of the risk assessment of buoyancy loss (RABL) project, by R.G. Standing from BMT Fluid Mechanics Limited, 2003; this document exemplifies the importance of risk management [43]

Tidal Turbine That Survive, presentation from University of Southampton [44]

Reliability-Based Fatigue Design of Marine Current Turbine Rotor Blades, Master thesis by Shaun Hurley [45]

Tidal Current Turbine Fatigue Loading Sensitivity to Waves and Turbulence – a Parametric Study, GL Paper [46]

Evaluation of the Durability of Composite Tidal Turbine Blades, by Peter Davies, et al. Provides framework for rotor blade qualification [47]

DNV-RP-C205, *Environmental Conditions and Environmental Loads*, DNV, October 2010 [48]

Appendix D—MHK Lessons Learned (Publically Available Information):

The following contains publicly available articles or reports on MHK lessons learned, collected for the express purpose of managing negative risk in future projects. All articles were drawn from websites accessible in November 2014, and, as such, only include information in the public domain. No endorsement or repudiation of the designs or companies mentioned in the articles is implied by their inclusion in this list; nor does this report make any claims regarding the veracity of the information present therein.

The following are some common themes from this information:

- Rotor blade failures
- Operational loads and tidal/wave resources have not always been well understood
- Transporting/installing the system may have unanticipated loads/complexities
- Buoyant components have sinking risk
- Small failures may cascade to system failures

Breach of Water Integrity of Compartments or Equipment:

http://www.publications.parliament.uk/pa/cm200001/cmselect/cmsctech/291/1031409.htm

Electrical Failures and Shore Connector Failures / Pressure Containment Failure from Hydraulic or Pneumatic Systems:

http://www.aquamarinepower.com/news/oyster-800-back-in-operation/

Structural Failure:

http://www.oceanrenewable.com/2011/09/12/atlantis-resources-corporation-connects-1mw-tidal-turbine-to-the-national-grid/
http://www.bbc.co.uk/news/uk-scotland-highlands-islands-11492829

Breach of Water Integrity of Compartments or Equipment:

http://www.renewableenergyworld.com/rea/news/article/2007/11/while-finaveras-buoy-sinks-hopes-of-harnessing-ocean-energy-survive-50510

Electrical Failures and Shore Connector Failures / Structural Failure:

http://www.marineturbines.com/3/news/article/11/delay_in_commissioning_one_of_seagen_s_rotors
http://en.wikipedia.org/wiki/Marine_Current_Turbines

Mooring Failure / Breach of Water Integrity of Compartments or Equipment:

http://cleantechnica.com/2010/05/22/massive-offshore-waves-sink-australias-oceanlinx-wavepower-pilot/

Breach of Water Integrity of Compartments or Equipment / Bankruptcy:

http://www.adelaidenow.com.au/news/south-australia/oceanlinx-forced-to-tow-wave-energy-converter-out-of-troubled-waters-off-the-fleurieu-peninsula/story-fni6uo1m-1226844686996
http://www.abc.net.au/news/2014-04-01/oceanlinx-wave-energy-generatorjpg/5359456
http://www.abc.net.au/news/2014-04-02/support-aired-for-oceanlinx-project-as-creditors/5361898
http://www.businessspectator.com.au/news/2014/4/2/renewable-energy/oceanlinx-goes-bankrupt-owing-10m
http://www.offshorewind.biz/2014/04/15/video-oceanlinx-wave-energy-generator-stuck-off-carrickalinga/

Structural Failure:

http://www.greentechmedia.com/articles/read/a-big-setback-for-tidal-power
http://www.cbc.ca/news/canada/nova-scotia/failed-tidal-turbine-explained-at-symposium-1.1075510
http://www.renewableenergyfocus.com/view/14766/openhydro-tidal-turbine-recovered-blades-missing/

Structural Failure / Breach of Water Integrity of Compartments or Equipment / Regulatory:

http://www.adelaidenow.com.au/news/south-australia/oceanlinx-forced-to-tow-wave-energy-converter-out-of-troubled-waters-off-the-fleurieu-peninsula/story-fni6uo1m-1226844686996
http://www.oregonlive.com/environment/index.ssf/2013/08/oregon_wave_energy_stalls_off.html

Electrical Failures and Shore Connector Failures:

https://bangordailynews.com/2013/04/10/news/down-east/year-one-of-eastport-tidal-turbine-research-presents-challenges/

Breach of Water Integrity of Compartments or Equipment / Bankruptcy:

http://www.treehugger.com/renewable-energy/portugals-pelamis-wave-power-project-dead-in-the-water.html
http://www.rechargenews.com/news/wave_tidal_hydro/article1282035.ece
http://www.pelamiswave.com/news/news/173/Pelamis-Wave-Power-Limited-Pelamis-to-be-put-into-administration

Structural Failure:

http://dnr.alaska.gov/mlw/wslca/appendix_g/verdant_power_marine_renewables.pdf

Breach of Water Integrity of Compartments or Equipment

http://www.modec.com/up_pdf/20141218_pr_skwid_en.pdf

[Summary Report by Manufacturer]:

http://www.jupiterhydro.com/SiteAssets/industry/IcfMarbek%20Tidal%20Energy%20Report_20%2009%2012_Final.pdf
http://www.osti.gov/scitech/servlets/purl/1115743
http://www.osti.gov/scitech/servlets/purl/1124124
http://www.osti.gov/scitech/servlets/purl/1111482
http://www.osti.gov/scitech/biblio/1097595