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THE USE OF FLOODING FRAGILITY CURVES IN NUCLEAR POWER PLANT RISK ANALYSIS

by

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Committee Approval

To the Graduate Faculty:

The members of the committee appointed to examine the thesis of David Kamerman find it satisfactory and recommend that it be accepted.

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Dedication

This Thesis is dedicated to my mentor Frank Goldner, who first encouraged me to pursue an advanced degree and has been a constant source of encouragement and support for me throughout.

Acknowledgments

I would like to acknowledge and thank everyone on the CEFL research team at Idaho State University as the work has truly been a team effort: Sneha Suresh, Alison Wells, Emerald Ryan, Bishwo Bhandari, Gregory Roberts, and Cody Muchmore. I would also like to acknowledge and thank my advisor Dr. Chad Pope for guiding me through this thesis process and leading our research team.

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Abstract

The topic of this thesis is the use of flooding fragility curves in nuclear power plant risk analysis. The thesis presents an overview of safety analysis in the nuclear power industry and movement of that analysis to more risk based models which incorporate probability concepts such as fragility curves. Some small scale experiments were conducted to observe how components fail in flooding scenarios. The data from those experiments was used to derive flooding fragility curves which were used to analyze an example problem. The lessons learned from the research, experimentation and data analysis are used to develop a roadmap for a research program at Idaho State University that will be capable of furthering the development of flooding fragility curves which can be used to further the understanding of flooding risk to the nuclear power industry.

1 Introduction

The topic of this thesis is an investigation into the development of flooding fragility curves for use in the risk analysis of nuclear power plants. Fragility curves are simply the concept of treating a component's failure point as a probability distribution rather than a discrete point [1]. Safety analysis in the nuclear industry has evolved a great deal starting with basic mechanistic simulations of bounding accident scenarios, to probabilistic risk assessments, and presently to risk informed safety margin characterization studies. Analyzing the safety margin of a nuclear power plant in flooding scenarios presents numerous computational and analytical challenges. This thesis contributes to the field of nuclear power plant risk analysis by exploring the concept of flooding fragility curves, and determining if they can be a useful tool in these risk analyses by better characterizing safety margin in flooding scenarios. After showing that flooding fragility curves have significant potential in analyzing these safety margins, an integrated roadmap is presented that shows how a research program at Idaho State University will accomplish the goal of developing these curves.

The thesis begins with a look at the history of safety analysis in the nuclear power industry including an examination of the inherent strengths and weaknesses in historical safety analysis. The concept of fragility curves is then investigated. The most common use of component level fragility curves in the nuclear industry is in the area of seismic probabilistic risk assessments. A significant amount of rigor and experience has gone into the methodology development of these seismic fragility curves and their use in corresponding seismic probabilistic risk assessments. Flooding probabilistic risk assessments are then researched to gain an understanding of how fragility concepts could be incorporated into those analyses and to help narrow the scope of the research. Flooding fragility concepts in other industries are also examined.

Using the knowledge gained through a literature search, small scale experiments on two components were conducted in an attempt to develop flooding fragility curves that describe their failure in flooding scenario. The two components investigated are a small scale door and a self-powered radio, which were used to simulate the failure of structural and electrical components. The fragility curves that were developed were then used to analyze a simple example problem. The problem was analyzed in two ways, first without the fragility data, and second with it. The results show that even in this simplistic example problem a much deeper understanding of the risk informed safety margin is gained through the use of the fragility curves.

The last part of the thesis focuses on the Component Flooding Evaluation Laboratory (CFEL) program that is underway at Idaho State University. This program is being set up for research and development in the area of flooding risk analysis, particularly the generation of flooding fragility curves for nuclear power plant components. Lessons learned from the initial research will be used to drive the design requirements of the laboratory as well as the research and development strategy of the program. The planned evolutions of the facility and the research program are presented with more detail being provided for near term activities. The integrated roadmap discusses both the conceptual design requirements of the laboratory, and an installation schedule. The integrated schedule focuses on building up the experimental "know how" such that fragility data is generated as early as possible in the program and the rigor of the testing is steadily increased to the point where actual nuclear power plant components will be able to be tested and flooding fragility curves for those components actually generated.

2 Safety Analysis at Commercial Nuclear Power Plants

The existing fleet of nuclear power plants is in the process of extending its lifetime and increasing the power generated from these plants via power upgrades [2]. Safety is central to the design, licensing, operation, and economics of nuclear power plants (NPPs) and a central consideration to plant stakeholders in making decisions about extending the life and power of NPP. The ability to better characterize and quantify safety margin is important to improved decision making about Light Water Reactor (LWR) design, operation, and plant life extension. A systematic approach to characterizing safety margins and the subsequent risk informed management options represents a vital input to the licensee and regulatory analysis and decision making that will be involved [2].

2.1 Deterministic / Mechanistic Safety Analysis

Traditional safety analysis follows a logical, mechanistic approach by considering a series of what may be considered “bounding” accidents called Design Basis Accidents (DBA). The theory behind this approach is that the DBA’s represent a bounding set of the worst case scenarios to challenge the plants design basis and are likely to occur at the plant in its lifetime [3]. The goal of such analysis is to show that even under these scenarios the safety of the public is maintained. Events are studied in a deterministic fashion using a series of conservative assumptions about the performance of plant systems predicting unmitigated release to nearest members of the public. The dose to the nearest member of the public is considered the Evaluation Guideline (EG). Regulators will specify that the EG is required to be below a certain limit. Systems, Structures, and Components (SSC) that are necessary to prevent the EG being challenged in a DBA are considered “Important to Safety SSCs” and limits to their operation are specified in associated technical specifications. Other SSCs are delegated a Defense in Depth function as it is assumed their successful operation will lower the risk of exposure to both plant workers and members of the public in accident scenarios. Numerous regulations spell out the steps required in conducting traditional safety analysis. While DOE-STD-3009 is principally aimed at DOE owned Nuclear Facilities and not Commercial Nuclear Power Plants (NPP), it is a good reference for showing the logical structure that is indicative of most all deterministic safety analysis [3].

Nuclear Regulatory Comission (NUREG) 2150 documents the regulatory framework used by the Nuclear Regulatory Commission (NRC) for evaluating these kinds of safety analysis for commercial nuclear facilities including Nuclear Power Plants (NPP). The report is the result of work by the Risk Management Task Force at the NRC. One of the principal findings of this report is that there is little guidance on the concept of Defense in Depth SSCs. While some Defense in Depth SSCs may contribute greatly to the safety posture of the plant, others may provide little to no benefit [4]. The report concluded that more informed risk assessments can provide valuable and realistic insights to inform decisions about which Defense in Depth measures are most appropriate.

As indicated by the findings of NUREG 2150, there are many advantages to performing a mechanistic safety analysis. However, there are also some significant drawbacks. A traditional safety analysis will derive a simple set of controls in the technical specifications that are simple for both plant safety personal, and outside regulators to monitor (e.g. reactor power cannot increase beyond 3000 MWth, back-up generators must be tested monthly). By monitoring these controls, the plant is said to be operating within its “Safety Envelope”. However, as a drawback the scenarios that are modeled are finite in nature and may not accurately capture the risk posture of the plant. This kind of analysis does not provide plant stakeholders with any indication of the plants safety margin, the plant is either operating within its safety margin or not. As such planning scenario responses become difficult as it is not always clear how the loss of a specific SSC or the exceedance of a technical specification actually affect the plants safety posture. Overly conservative reactions to such events can cause limits on plant operation without an actual understanding of the risk associated with such events.

Traditional safety analysis also hinges on the fact that the DBAs that were analyzed are in fact representative of the most limiting kind of accident the plant will experience and are focused on assessment of dose release to the environment and public. In short these kinds of assessments make it difficult to quantify the risk from unknowns and uncertainties. To compensate for these unknowns a significant level of conservatism is often built into both the analysis and allowable operating limits. In addition to plant resources, analysis resources are focused on understanding a set of DBAs that may never actually occur while events that are more likely to occur will receive little analytical attention. For example, a significant amount of resources are spent analyzing a Double Guillotine Large Break Loss of Coolant Accident (LB-LOCA). However, in the history of the commercial nuclear power industry no such event has occurred. In contrast little attention was given to the problem of Irradiation Assisted Stress Corrosion Cracking, until this crack allowed boric acid to leak through erroding the pressure vessel of the Davis

Besse reactor head [5]. Figure 1 shows a graphic visual of just how large the corroded volume became.

Figure 1) Davis Besse Reactor Head 17 inch Cut Out [5].

While the resulting damage to the plant would likely have been bounded by one of the DBAs in the plants safety basis, the event shows the limits of traditional safety analysis when it comes to understanding a NPP's risk posture. The event also illustrates that safety analysis in this fashion tends to be reactionary rather than pro-active. While these kinds of Deterministic Analysis are still useful, a more informed approach is needed to advance the understanding a of safety margin and risk posture in the commercial nuclear industry.

2.2 Probabilistic Risk Assessments

As early as the mid-1970s, there was a push to consider more carefully safety analysis at NPPs. The push came from a desire to consider the risk of living near a NPP compared to the risk of other activities. The Wash-1400 report published in 1975 began

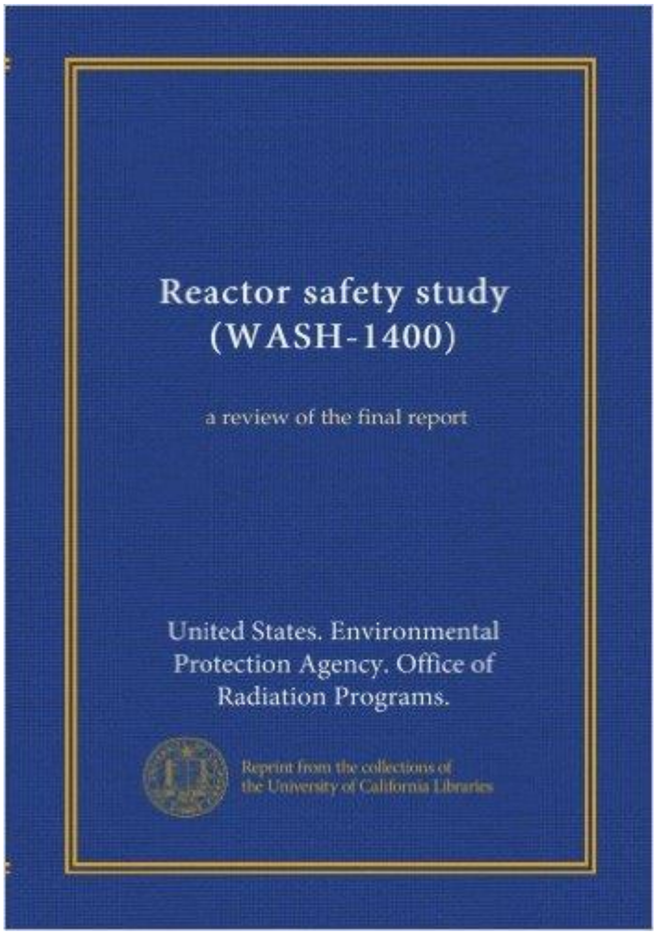

Figure 2) WASH-1400 Cover

by estimating the risk to the public from a NPP accident in terms of fatality probability per year [6]. The analysis deviated from the traditional mechanistic safety analysis of the past in that it used probabilistic failure models to assess the likelihood or frequency of plant failure. The benefit of such a report was that it allowed NPP risk to be compared easily with other kinds of risk such as that of fighting a forest fire or driving a car. The report used a fault tree / event tree type methodology which would become standard for Probabilistic Risk Assessments (PRAs) over the next several decades [6]. While the study was a breakthrough in the methodology used to understand accidents at a NPP it was only a first step and contained many of the inherent flaws with deterministic approaches such as the propagation of conservative assumptions. This is especially true at the component level where components are conservatively given a high probability of failure early in the accident progression. Follow on studies such as NUREG-1150 [7] which was published in 1990, and the State of the Art Consequence Analyses (SOARCA) which is currently under development (a draft was released in 2012 as NUREG-1935) by the NRC seek to improve upon the conservative estimates made in Wash-1400 [8].

One conclusion that came out of Wash-1400 that has been the subject of much controversy and follow on research is the estimate of Core Damage Frequency (CDF) which was determined to be one Core Damage in 20,000 reactor years or a CDF of 5E-5 [6]. The benefits of reporting a CDF is that it provides a simple straightforward way of communicating the safety posture of the plant to a large number of plant stakeholders. Drawbacks are that the CDF can easily be taken out of context. In the same way that deviations of technical specifications can lead decision makers to faulty conclusions about a plants safety posture, the reporting of a CDF out of context can also cause misunderstandings of a plants safety posture to stakeholders.

Numerous follow on analysis by the commercial nuclear industry have sought to show that the CDF is in actuality much smaller because of the conservatively high failure probabilities used in the study [7] [8]. These studies have examined the risk of core damage from a large variety of internal and external initiating events seeking to improve upon these conservative assumptions with more realistic treatment of events. These kinds of PRAs that look exclusively at the probability of core damage and do not consider the accident progression beyond such point are considered level 1 PRAs [7]. The general methodology that is employed is that the frequency of the event is multiplied by the probability that such an event will lead to core damage. The higher level of detail of resolution included in the event trees, the more realistic the result becomes and a higher understanding of the uncertainty in the point estimate of the CDF is available.

In the history of the U.S. Commercial Nuclear Power Industry only a single core damage event has taken place, and that was the partial melt down of the Three Mile Island (TMI) reactor near Middletown, PA on March 28, 1979. In this event a relief valve became stuck open, and due to faulty instrumentation the plant operators were unaware that coolant from the primary system was being released to the reactor containment building. The plant experienced what is described as a Small Break Loss of Coolant Accident (SB-LOCA), which ended with nearly half of the core melting as illustrated in Figure 3 [9]. By the time plant operators knew what was going on, core damage had already occurred. A more accurate risk informed understanding of safety margin at the plant could have resulted in plant personal having a much better understanding of the risk of core damage in the time period leading up to the accident.

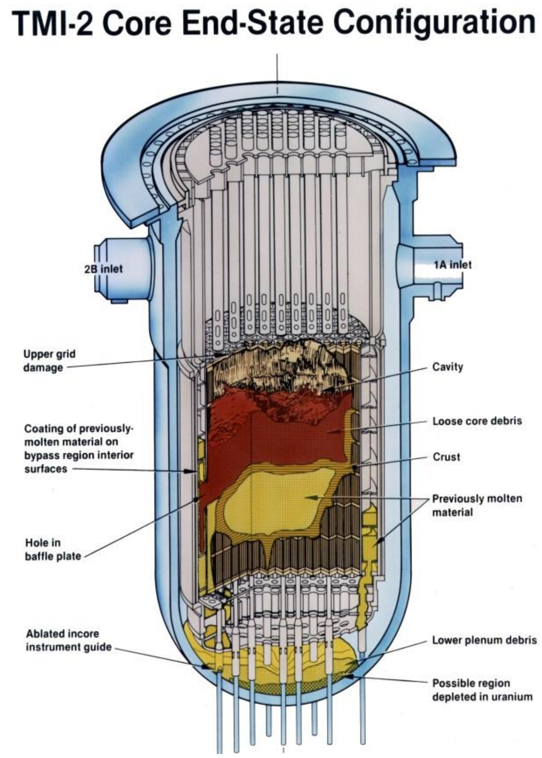

Figure 3) Illustration of Core Damage at Three Mile Island [9]

Given the limited number of operating reactor years, this single data point would seem to indicate a larger CDF then that predicted by WASH-1400. However, important safety information is neglected in only reporting a CDF. The (TMI) accident caused little to no release of radioactive material and next to zero health effects to the workers or members of the public [9]. A major finding from the event was that the plant operators had little information on just how close the core was to melting in the hours and minutes preceding the core damage event [9]. While PRA studies provide valuable information as the probability and frequency of core damage events, they fall short in that they do not provide a quantifiable measurement of safety margin. Safety margin can be described as a measurement of the risk of negative safety consequences at a given plant operating condition. A more adequate understanding of safety margin at the TMI power plant may have provided plant operators with the additional information needed to respond in a more active way and could have prevented or mitigated the consequences in the TMI accident.

2.3 Risk-Informed Safety Margin Characterization

The Department of Energy's (DOE) Light Water Reactor Sustainability (LWRS) program has launched a research and development pathway focused on taking a new approach to safety analysis called Risk-Informed Safety Margin Characterization (RISMC). When evaluating the safety margin of a NPP, RISMC seeks to describe not just the frequency of an event like core damage, but how close (or not) to key safety-related events the plant may be. RISMC also seeks to understand how safety margin may be increased through proper application of Risk Informed Margin Management (RIMM) [2]. These studies rely on both probabilistic and mechanistic approaches. Safety margin and uncertainty quantification rely on plant physics (e.g., thermal-hydraulics and reactor kinetics) coupled with probabilistic risk simulation. The coupling takes place through the interchange of physical parameters (e.g., pressures and temperatures) and operational or accident scenarios. The logic and event trees that are used in traditional PRA analysis are replaced with real physical simulations. These kinds of analysis are particularly useful in seeking to understand plant risk under highly dynamic and inherently uncertain events such as a Station Blackout (SBO) Event initiated by an external flood. Figure 4 Illustrates the RISMC approach to analyzing these kinds of events. [2]

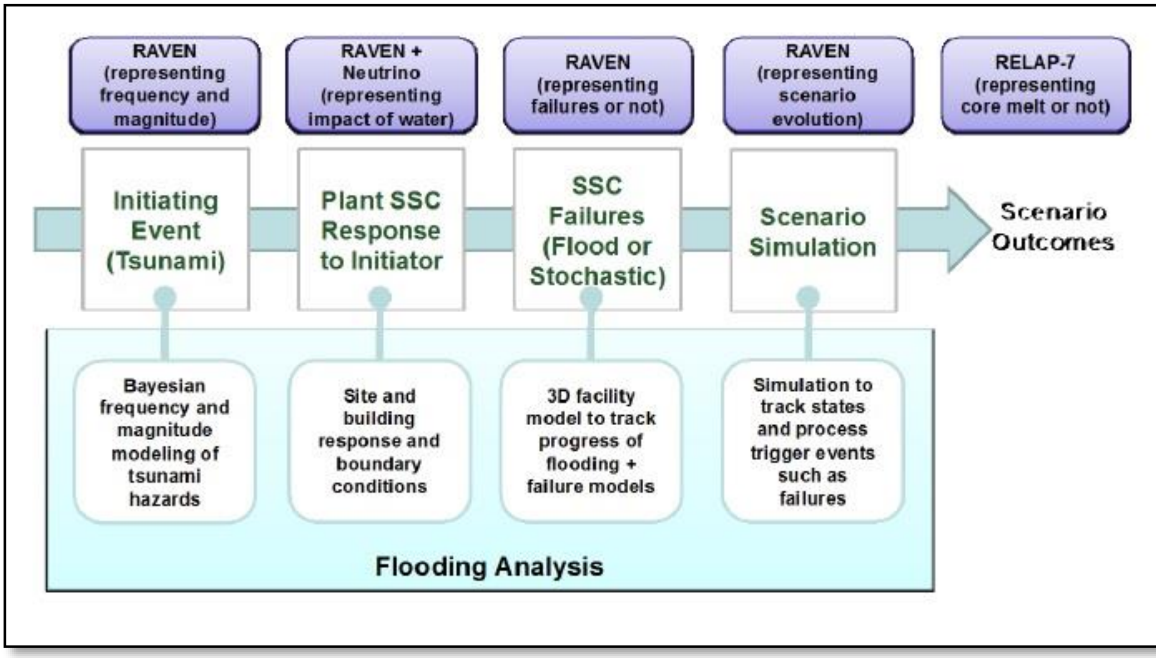

Figure 4) The RISMC Approach to SBO Flooding Event [2]

The RISMC approach uses Monte Carlo sampling to determine the probability that initiating events lead to core damage as well as other outcomes. Key steps to the RISMC approach are (1) Initiating event modeling, (2) Plant response modeling, (3) Components failure modeling, (4) Scenario simulation, (5) Analysis of statistical information to determine probability of various outcomes [2]. Given an initiating event, the plant has the probability of responding in a variety of different ways. Random sampling of probability distributions will generate the defined plant response for a given simulation. Then a statistically significant number of simulations will be run to determine the likelihood of a given outcome given the initiating event. Studies of the probabilities of the space of initiating events will then provide plant stakeholders with an accurate picture of the plants overall safety posture. The probability distributions that are sampled to determine the plants response play a critical role in the outcome of the analysis. As with the PRAs described in Section 2.2, a finer resolution in the scenario analysis increases the understanding of the risk informed safety margin. If information is available that describes the statistical likelihood of component failure, a highly resolved scenario evolution can be run increasing the confidence in the overall result. The research described in this thesis shows how such data could be generated for components in flooding events at NPPs that can be used to support the RISMC effort.

While the task of developing the data required to have reasonably certain fragility curves for all the components in a NPP seems like a daunting task, techniques such as Bayesian Inference allows for curves to be developed with only limited data sets [10]. These techniques work by developing “prior” failure distributions based on best available knowledge; perhaps from industry practice, vendor data, etc. The credibility of the “prior” distribution is subject to much uncertainty. Bayesian Inference uses Monte Carlo techniques to update these prior distributions with actual failure data. Often a surprisingly small sample of failure data can either confirm the hypothesis posed by a prior distribution or discredit it. Today’s computing resources allow the information contained in the developed random variables to be propagated through many complex algebraic and differential equations. This unique ability allows the benefits of deterministic safety analysis to be combined with the benefits of Probabilistic Risk

Assessments. Rather than relying on conservative estimates, uncertain variables can be passed through the system in a meaningful and reliable way to give NPP owners, regulators, and the public a more refined understanding of risk [10].

3 Fragility Curves in Safety Analysis

The notion of distributing a components failure point according to an underlying probability distribution is referred to as the component's fragility curve. The limits of many materials and engineering systems can be accurately described in this fashion. The challenge is in developing a probabilistic model of the failure that can be accurately relied upon in engineering analysis. The desire to probabilistically describe NPP component failure in flooding events using fragility curves is a broad and challenging undertaking. The effort begins by looking at how the concepts of fragility curves and flooding risk analysis are already employed in the nuclear industry as well as branching out and identifying if other industries have used fragilities in their analysis of flooding risk. In Section 4 of this thesis, flooding fragility curves for 2 components will be developed. In Section 5 these curves will then be used to analyze the safety margin in a given flooding scenario. Section 6 will constitute a roadmap for a research and development effort focused on scaling up these studies to provide meaningful flooding fragility data to the RISMC effort.

3.1 Seismic Fragility Curves

Seismically initiated events and specifically the loss of offsite power that comes with the seismic event have received a good deal of study in the nuclear industry. This kind of risk assessments are known as Seismic Probabilistic Risk Assessments (SPRAs) and they make use of component level seismic fragility curves to realistically describe the probability of a components failure in various severities of seismic events. Seismic fragilities are a distribution of the peak ground acceleration at which the component will fail [1]. The probability of a component failing (or reaching a specified damage state) is described as a random variable governed by an underlying probability distribution.

The Electric Power Research Institute report Methodology for Developing Seismic Fragilities [1] documents the methodology employed in developing seismic fragility curves that can be used in conducting SPRAs. These curves represent a unique and insightful idea that helps to capture much of the inherent uncertainty associated with external events. Critical components are identified early in the SPRA development and data on those components is used to develop the probability of reaching various damage states. Seismic fragility analysis estimates the conditional probabilities of structural or equipment failure for a given level of seismic ground motion. Seismic fragility defines the probability of a certain failure mode as:

$$P_f(A) = \Phi\left(\frac{\ln\left(\frac{A}{A_m}\right)}{\beta_R}\right) \tag{1}$$

Where A is the peak ground acceleration, A_m is the median ground acceleration, Φ is the standard Gaussian cumulative distribution function, and β_R is the log standard deviation of randomness. For a given failure state a curve can then be generated where the probability of failure is a function of the peak ground acceleration [1].

Failure due to seismic loading is in fact more complex than a correlation to peak ground acceleration. For example an earthquake may have small peak ground acceleration, but may continue for some time with numerous aftershocks. However, in the case of SPRAs it has been shown that failure probability correlates reasonably well to peak ground acceleration. Other phenomena such as the duration of the earthquake and number of aftershocks have been shown to be relatively weak variables in comparison and their impact is accounted for in the uncertainty of the distributed random variable [1]. For some components, failure needs to be expressed as different degrees of failure or damage states. For example, a pipe may suffer varying severities of ruptures ranging from numerous pin-hole leaks up to a complete guillotine break. The effect of these components in various damage states can then be propagated through the plant via the event trees that are established as part of the PRA effort, uncertainties are also meaningfully propagated in this way.

3.2 Fragility Concepts in Flooding Analysis

Flooding events tend to be much more complicated to model than seismic events and have the potential to add serious complications to NPP operations. However, as discussed above, the inherently unpredictable nature of flooding scenarios lends itself well to the linking of probabilistic data with deterministic models using RISMC tools. The following Figure 5 is a photo of an electrical room in the Fukushima Daiichi NPP following the earthquake and subsequent tsunami [11]. It is easy to see from the photo that the electrical components are likely to have suffered critical damage from this severe of a flood. Uncertainty still exists however in understanding at what point in the flooding scenario these electrical components began to fail. Simulations have shown that even minutes of additional cooling time early in a SBO event can add hours of grace time later in the event as the decay heat generated in the plant's core is dropping off exponentially [2]. Also while the Fukushima flood happened very rapidly, questions remain as to the risk of electrical components in similarly designed reactors that are unlikely to experience tsunami like floods, but may be at risk for slower developing floods. Developing fragility curves for these components may be able to help answer these questions.

Figure 5) March 17, 2011 Photo of Fukushima Daiichi 6 Electrical Room [11]

Starting at a high level, the flood risk of a particular NPP can be expressed the same way as seismic risk, that is the frequency of the flood times the probability that the flood will lead to core damage. Similarly then to seismic events there is potentially great value to component level "fragility data" to determine the risk of various critical components reaching certain damage states. What makes this kind of analysis more difficult for flooding scenarios is that the damage mechanism may be different depending on the nature of the flood and response of other plant components to the flood. While failure probabilities in seismic events correlate quite well to a single variable "peak ground acceleration", it is unlikely that a single such variable will be found for flooding risk. In addition, while seismic events are likely to cause damage at a discrete point in time, the failure of plant components from flooding are likely to evolve over time as components will come into contact with water at various times depending on the nature of how the flood progresses. Components may be exposed to damage from relatively static water loading under water rise flooding events, or more dynamic loads in the case of water spray and wave impact events. Relative to SPRAs, little attention has been given to developing flooding PRAs at the same level of rigor. However, the events at Fukushima Diiachi have showed that flooding risk cannot be ignored [11].

3.2.1 Internal Flooding Probabilistic Risk Assessments at Nuclear Power Plants

Some NPP have performed internal flooding PRAs that document the water height at which critical components fail. The structure in these analyses provides a good basis to explore the use of flooding fragilities. However, these PRAs do not account for the random or uncertain nature of component failure when exposed to water. The height at failure is a discrete number and is not distributed in a fragility curve. The Prairie Island NPP has performed such an analysis [12].

The Prairie Island PRA considers the connection of components relative to each other using the standard fault and event tree structure. As an example the PRA considers a pump which receives power from an electrical junction box; the pump could function for a flood height of up to three feet, but the junction box may fail at a flood height of one foot. The pump will therefore fail at one foot of water since it is powered by the junction box. The flood height at which components fail is known as that components critical height. The PRA lists equipment in lower levels of buildings where submergence is most likely to occur [12]. It does not mention how the critical flood height was determined. The random nature of the failures is not taken into account and components are simply assumed to fail at a certain water height level. The analysis does show that there is a logical basis for assuming that failure for many components in certain flooding scenarios can be reasonably estimated by the hydrostatic head of the water. Later development of flooding fragility curves can consider distributing water height in a fragility curve as a logical starting place.

The flooding PRA also takes spray events into consideration when it comes to failure. It considers the flowrate to be the driving cause of the failure. The analysis assumes that spray less than 20 gpm to 50 gpm will not cause equipment failure. It then states that 20 gpm is assumed to be the failure threshold for small areas, and 50 gpm for large areas [12]. This is directly analogous to the example above of critical water height. The PRA justifies these flowrates using engineering judgement to consider it reasonable. As with the example of critical water heights, these flowrates could be modeled as random variables, the engineering judgement used above could serve as the basis for developing a prior distribution which could be updated with the results from experimentation. While these analyses do not directly employ the concept of flooding fragility curves they provide insight into what variables may be the driving factors of failure in flooding events.

3.2.2 Probabilistic Flooding Analysis in Other Industries

It is worthwhile to look at what is done by other industries and agencies concerned with flooding events, to determine if additional insight can be gained in the area of component level flooding fragility modeling. The Federal Emergency Management Agency (FEMA) has a software package that is used for the modeling of towns and cities in the event of a natural disaster called Hazus® [13]. It is capable of modeling four types of hazards: earthquakes, hurricanes, coastal surges, and floods. The earthquake modeling includes the development and application of seismic fragility curves. Hazus® uses the same methods as those discussed above and referenced in the EPRI report to develop these curves. A standard normal distribution is used to describe the probability of a failure state, and the peak ground acceleration being the driving variable for the shape of the distribution curve. As the purpose of the tool is to assess macroscopic impacts to cities and regions, the "components" investigated are not highly resolved (i.e. building failure vs beam or foundation failure).

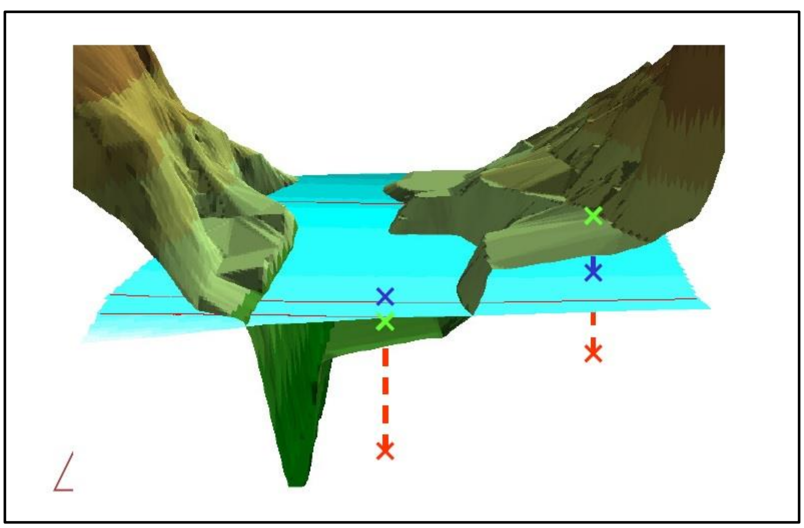

Figure 6) Modeling Flood Plain Heights in HAZUS® [14]

The flooding module is capable of calculating flood plain heights in various geographical regions as shown in Figure 6. The heights in regions are compared to distributed damage heights of structures in the analysis. The program is similar to the earthquake module in that it models events mostly on the building level scale, which is not to the degree of resolution required for NPP analysis[14]. It is able to create depth-damage curves, but they are dependent on the type of building, and the user defined inputs of the worth of material on each floor. Additionally, it does not have the capabilities of modeling single buildings, using census blocks as its smallest resolution of measurements. Single buildings are done by taking an average for the same type of building across a census block.

Even though Hazus® models on a scale that is not applicable to NPP applications, it helps provide a broad sense to model flood hazards. It helps confirm the notion that there is value to developing component level flooding fragility data and in breaking the flooding problem down using fragilities using similar methodology employed in SPRAs, albeit modified to account for the dynamic nature of the flooding hazard.

3.3 Flooding Fragility Curves Path Forward

The research indicates that the development of component level flooding fragility models would provide a useful and meaningful impact in the understanding of flood based risk to NPP. The models would build off the experience learned from applying seismic fragilities as they could be applied in the same way to Flooding PRAs as seismic fragilities are applied to SPRAs. Additionally they can be a valuable tool to the RISMC effort in aiding to better quantify the safety margin of NPP in these kind flooding events.

In the proceeding sections of this thesis report, small scale experiments will be conducted to determine if the data from such an exercise can be used to develop meaningful flooding fragility curves. Then these curves will be applied to simplistic flooding analysis to determine if they in fact aid in understanding the flooding risk. Finally, plans will be discussed for the Component Flooding Evaluation Laboratory (CFEL) at Idaho State University (ISU) which will be capable of scaling up these experiments to testing actual NPP components in prototypic flooding scenarios. A roadmap will be discussed for the laboratory which focuses on maximizing the value of the effort as early as possible and building off of lessons learned as testing becomes more advanced.

4 Experimental Development of Flooding Fragility Curves

Small scale testing was conducted to determine if data generated from experiments on components could be used in the development of component level flooding fragility models that would have a meaningful impact on enhancing the understanding of plant safety. Testing was conducted on a small 1/12th scale door and a portable radio (which is used to simulate an electrical component like an electrical junction box). It is acknowledged that these small scale components will not actually behave in the same quantitative way that a real door or electrical component will, but the purpose of the activity is to see if data from these experiments can be used to develop flooding fragility curves and if these curves can deepen the level of understanding of flood risk in the analysis of a flooding event.

4.1 Small Scale Door Experiment and Data Analysis

The small scale door was set into a piece of thin plastic using waterproof caulking. The door was 18 cm tall and 7.5 cm wide. The plastic was then set into the middle of a tank that was approximately 38 cm tall using the same caulking, as shown in Figure 7. The caulking was leak tested to ensure that water would only flow from one side of the tank to the other through the door.

Figure 7) Small Scale Door Testing Apparatus

Testing was performed by applying a steady volumetric flow rate to one side of the tank. The side of the tank that was receiving the steady flow rate of water was designated to be the “Flooding Side” and the side that was receiving water through the leaking door was designated to be the “Leaking Side”. Notches on either side of the tank indicated the height of the water on both the Flooding Side and Leaking Side. The time at which the water level on each side of the door reached a given height was recorded. Testing ended once the water on the Flooding Side of the tank reached 30 centimeters, as that is near the top of the tank. Seven tests were run with different flow rates and similar qualitative behavior was observed regardless of the flow rate. A plot of the water height on the Flooding Side of the door for the fifth test is provided below in Figure 8. The rate of water rise on the flooding side of the door indicates how much water is leaking through the door.

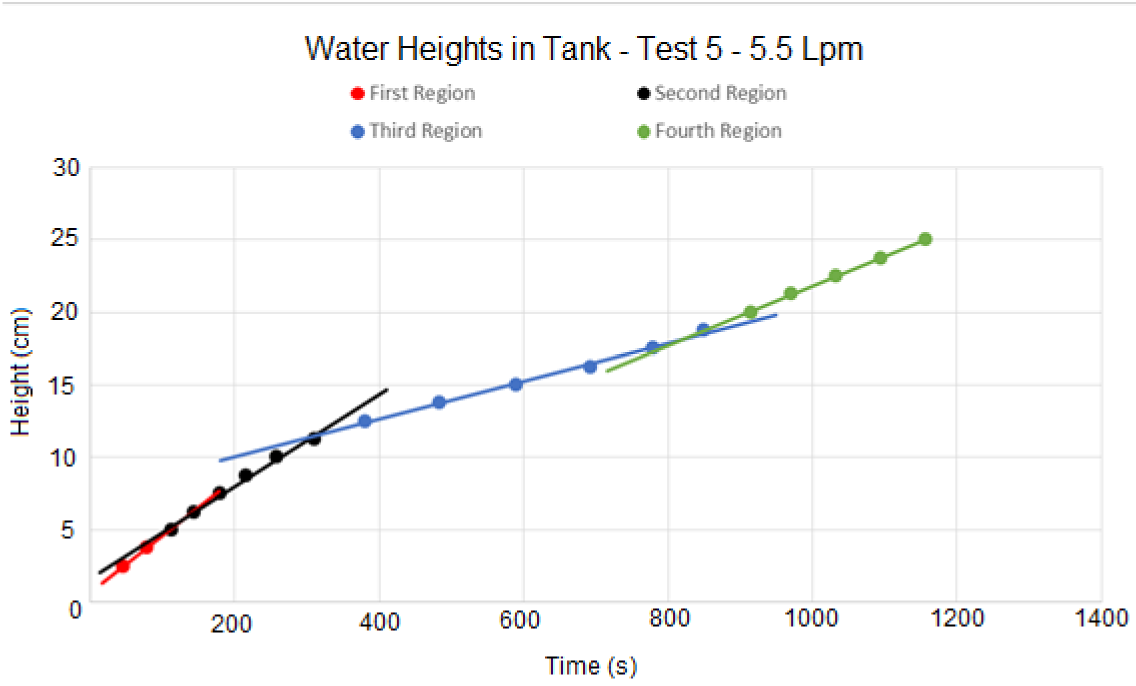

Figure 8) 5.5 Liters per Minute Small Scale Door Test Results

It is assumed that the velocity of the water leaking through the door is constant throughout the experiment. This is likely valid for this small scale experiment as the hydrostatic head does not change much and there are little to no hydrodynamic forces at play in the experiment. It is hypothesized that the transition between these linear regions corresponds to a condition when the leak rate changes as the water height on the flooding side should increase linearly when the leak rate is constant. Provided this assumption holds, a change in leak rate would correspond to a change in the area of the doorway that the water is leaking through. This is theorized as a progression in damage state of the door (i.e. as the door is damaged, it projects a greater cross sectional area that water can pass through). To determine the location when the slope has changed significantly enough to imply that a new linear function is starting to dominate, the standard error in the linear regression was plotted sequentially across the data set. When the standard error became greater than 0.1 it was assumed that an evolution in damage state had occurred and that the leak rate had changed. A new linear regression was then started and again plotted sequentially until the standard error became greater than 0.1. The 0.1 threshold in the standard error provided a good linear fit of the data without breaking the curve up into too many regions with too few data points. This resulted in 4 linear regions in all seven tests, with three transition points (indicating three damage states) on each test. Table 1 shows the linear regression calculations for the fourth test. The transition points are highlighted in yellow. The plot in Figure 8 also shows these regions with a different color for each leak rate region.

Table 1) Data from Fifth Door Failure Test

Water Height (cm)	Time when Height is reached on Flooding Side (s)	Standard Error in Linear Regression	
0	0		First Linear Region
2.5	46		
4	78	0.093709336	
5	113		Second Linear Region
6.5	144	0.024727188	
7.5	180	0.02174678	
9	216	0.023647381	
10	258	0.047420366	
11.5	310	0.097698184	
12.5	380		Third Linear region
14	483	0.077405949	
15	589	0.071950566	
16.5	692	0.064695142	
17.5	779	0.056775706	
19	850	0.070994622	
20	915		Fourth Linear Region
21.5	970	0.033981383	
22.5	1032	0.024029131	
24	1095	0.021421462	
25	1156	0.018969949	

Table 2 presents the height at which the leak rate changed in each test and summary statistics from all seven tests. The height at which the leak rate changed (indicating evolution of damage state) is herein referred to as critical heights, consistent with the terminology used in the Prairie Island Internal Flooding PRA. The results were scaled to represent a 2 meter high door and the mean and standard deviation for each critical height were used to derive μ and σ parameters for a lognormal distribution. The basis for assuming the critical heights are lognormally distributed is somewhat arbitrary but these distributions are frequently used to represent failure points in statistical modeling and are the distribution is used to predict failure in seismic fragilities [1]. Developing failure curves in this way is referred to as a frequentist approach and assumes that the data set is large enough to represent the population of doors in general. This is in contrast to Bayesian techniques which were mentioned earlier which use prior knowledge about a component and update that knowledge base with the data set. No prior data for the small scale doors is available, nor would it be relevant even if it were available as there is no engineering basis for translating data on small scale doors to actual doors found in NPP. As such, Bayesian approaches to analyzing the data were not pursued as part of this illustrative study. Plots of the lognormal distribution for the second critical height is shown in Figure 9, the plots for the other critical heights follow a similar shape only with parameters specific to the different height.

Table 2) Linear Transition Heights for Small Scale Tests

	First Transition Height (cm)	Second Transition Height (cm)	Third Transition Height (cm)
Test1 (2.33 gpm)	7.5	14	25.5
Test2 (1.89 gpm)	7.5	14	24
Test3 (4.57 gpm)	7.5	16.5	25.5
Test4 (2.80 gpm)	9	15	28
Test 5 (1.46 gpm)	5	12.5	20
Test6 (2.43 gpm)	7.5	14	24
Test7 (6.13 gpm)	6.5	16.5	24
Mean	7.25	14.75	24.5
Standard Deviation	1.25	1.5	2.25

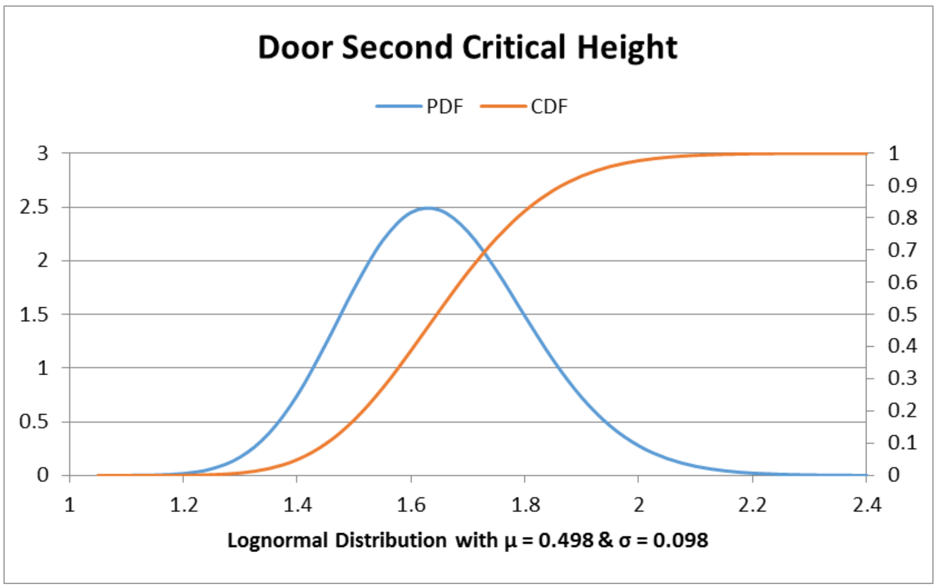

Figure 9) Second Door Critical Height

4.2 Small Scale Radio Experiment and Data Analysis

Radios were tested in water rise flooding events in the same glass tank as the door, which was filled with a constant flow rate. The tank was 44.5 cm. wide by 89 cm. long and 38 cm. deep. Battery powered radios were tested using a stand to hold the radio upright in the tank. An amp meter connected to a computer was used to measure and record the current that was being drawn by the radio throughout the flooding simulation. The batteries for the radios were wired to be kept out of the water while connected to the amp meter for the duration of the tests. The radio was tuned to a station that supplied a fairly constant current measurement as shown on the ammeter, and was then placed on the stand. The amperage recorded by the ammeter was not constant because the current required increased or decreased based on the volume and the type of sound that was coming from the radio. To normalize the error due to the different volumes between radios, all of the radios were tested with their volume at the maximum setting. The stand was secured to the bottom of the tank to prevent floatation with water addition. The setup used in all the rising water tests can be seen in Figure 10.

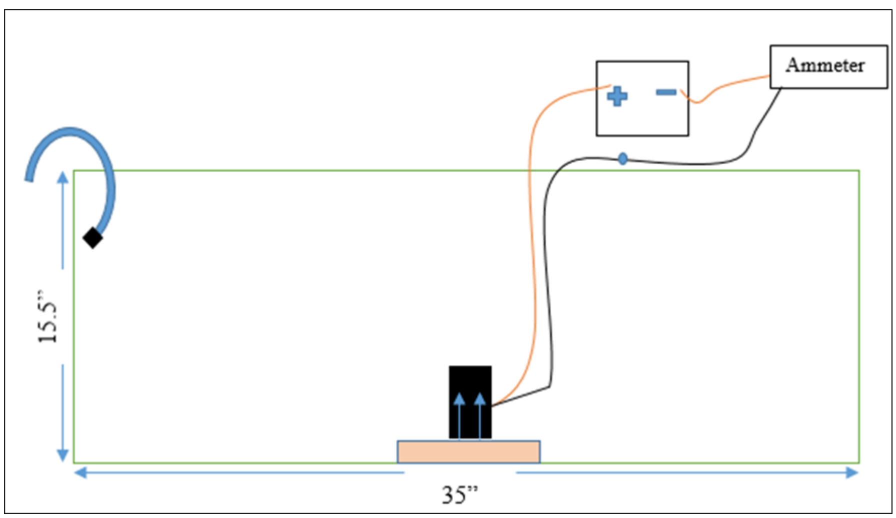

Figure 10) Small Scale Radio Test Setup

Data was obtained from multiple rising water tests with the same flow rate of 3.33 Liters per minute. The amperage fluctuated at the beginning of each of the tests. During this time, the radios continued to output sound and the tuning lights remained lit. The tuning proceeded to change with the addition of water, and different stations were picked up by the radios. At approximately the 40% water coverage point, the amperage started to fluctuate greatly before complete failure was reached at slightly below 60% water coverage of the radio. Complete failure was defined by full loss of sound, and a current drop to 18 mA. A total of nine different tests were performed and the percentage of the radio covered in water was recorded for each test. That percentage was then scaled to represent a 1 meter high electrical junction box, 1 meter off of the ground and parameters for a lognormal distribution were obtained using the same frequency statistics as was used with the door. That is, the mean and standard deviation of the sample data were assumed to be the mean and standard deviation of the underlying lognormal distribution. Table 3 shows the failure data for the radio and Figure 11 shows the lognormal pdf and CDF for the modeled lognormal distribution.

Table 3) Failure Data for Radio

Test Number	Fail Time (s)	Percent Covered at Failure	Scaled to Electric Box (m)
1	237	42.66	1.4266
2	239	43.02	1.4302
3	265	47.7	1.477
4	267	48.06	1.4806
5	272	48.96	1.4896
6	279	50.22	1.5022
7	284	51.12	1.5112
8	304	54.72	1.5472
9	319	57.42	1.5742
		Mean	Mean
		49.32	1.4932
		Standard Deviation	Standard Deviation
		4.837447674	0.0484

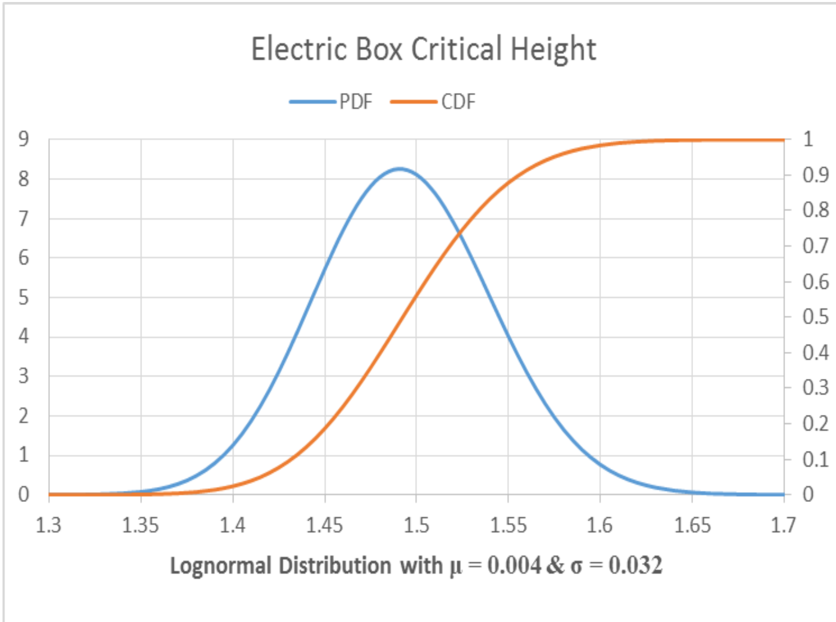

Figure 11) Electric Box Critical Height

5 Analysis of a Flooding Event Using Derived Flooding Fragility Curves

An example analysis shows the benefit of component flooding fragilities, and how the data obtained above can be used to aid in the risk based understanding of an actual flooding analysis. Consider the risk posed to an electrical panel with flooding occurring in the adjacent room as illustrated in Figure 12 below.

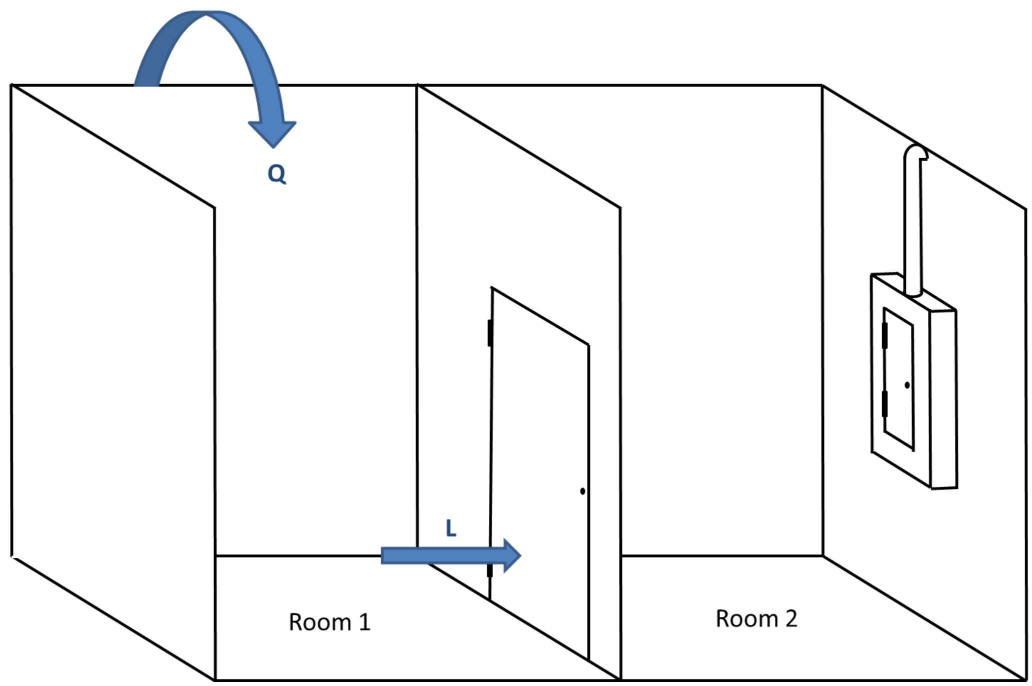

Figure 12) Diagram of 2 Room Flooding Scenario (NTS)

The information of interest in this problem is the electrical panel's failure time for a given flow rate Q. A better way of stating the problem may be that the analysis seeks to describe the risk of the electrical panel failing for a given flooding event. It will be assumed that the door is 2 meters high and that the electrical panel is 1 meter off of the ground, and 1 meter high. It will also be assumed that the area of room 1 is 15 meters squared and the area of room 2 is slightly larger at 20 meters squared. It will also be assumed that there are no other leak pathways for the water into either room 1 or room 2. The failure time of the electrical panel depends on how vulnerable the panel is to water and how long it takes water to reach the panel. How long it takes water to reach the panel is dependent on how much water is leaking through the door, which is in turn a function of how vulnerable the door is to leaking. The water levels in the two rooms can be described by the differential equations presented below which are derived from a conservation of mass standpoint.

$$A_1 \frac{dz_1}{dt} = Q(t) - L(t) \tag{2}$$

$$A_2 \frac{dz_2}{dt} = L(t) \tag{3}$$

The flooding rate (Q(t)) for the computational effort illustrated here it will be assumed constant. The leak rate (L(t)) will be dependent on the differential water heights in Room 1 and Room 2 (which establishes the hydrostatic head) and the effective open area provided around the door. Simply using the Bernoulli equation an expression for L(t) can be written as shown below.

$$L(t) = A_{door} * \sqrt{2g(z_1(t) - z_2(t)} \tag{4}$$

It is recognized that this simplification may not be entirely accurate as dynamic forces may also be in play such as water jets impinging on the door. Also leaks in the door may be above the height of the water in room 2 resulting in less static head than what equation (4) represents, in addition any contraction coefficients are left off.

5.1 Mechanistic Analysis of the Flooding Scenario

Equations (2) and (3) can be rewritten by substituting L(t) from equation (4) above creating two coupled differential equations. When the problem is approached from a traditional conservative standpoint, 2 additional assumptions will be made. The first is that the door will fail after such point that the differential heights provide a pressure on the door past the design limit of the door's hinges reduced by some safety factor. That is (A_{door}) in equation (3) will discontinuously increase from some small value determined by the area under the door, to a much larger value determined the area of the entire doorway. The water level at which this occurs will be called the door's critical height (z_{1cr}) and it is assumed for the purpose of this analysis that this height is 1 meter. Assuming that the door is 0.75 meters wide with a quarter centimeter gap between the bottom of the door and the floor, the initial (A_{door}) value would be about 0.002 meters squared. The failed (A_{door})' value would be 0.75 meters squared. The rapid increase in area will quickly result in the water heights in each room equalizing. The MATLAB® script used to solve the problem experienced bugs associated with this discontinuity when the value of (A_{door})' was too large so the value was set to 0.1 meters squared. As will be shown below this value is large enough to result in a quick equalization of the water heights.

The second assumption will be that the electrical panel will have no resistance to the water and that as soon as it comes into contact with water it will fail. The water heights at which the electrical panel fails will be referred to as the electrical panel's critical height (z_{2cr}) and as it is 1 meter above the floor, it will be assumed to be 1 meter. The equations below illustrate how this problem will be solved using the concept of critical heights for the door (z_{1cr}) and electrical panel (z_{2cr}) respectively.

$$A_1 \frac{dz_1}{dt} = Q(t) - A_{door} * \sqrt{2g(z_1(t) - z_2(t)} \tag{5}$$

$$A_2 \frac{dz_2}{dt} = A_{door} * \sqrt{2g(z_1(t) - z_2(t)} \tag{6}$$

Equations (5) and (6) are applicable with the initial conditions and domain specified in (7).

$$z_1(0) = z_2(0) = 0;\ t \in (0, t_{cr1} \rightarrow\ z_1(t) = z_{1r}) \tag{7}$$

At the time when the door critical height is reached the equations will change because (A_{door}) will change to (A_{door})' discontinuously. The time at which this occurs will be considered t_{cr1} and will be the upper bound of the time domain for equations (5) and (6). Initial conditions will be set up such that the height functions $z_1(t)$ and $z_2(t)$ are continuous (Although their time derivatives may not be as the problem experiences an instantaneous change). The next set of equations (very similar to the first set) will be valid over the domain from z_{1cr} to z_{2cr}, the time when the electric box fails (t_{cr2}) will be the failure time.

$$A_1 \frac{dz_1}{dt} = Q(t) - (A_{door})' * \sqrt{2g(z_1(t) - z_2(t)} \tag{8}$$

$$A_2 \frac{dz_2}{dt} = (A_{door})' * \sqrt{2g(z_1(t) - z_2(t)} \tag{9}$$

Equations (8) and (9) are applicable with the initial conditions and domain specified in (10).

$$z_1(t_{cr1}) = z_1(t);\ z_2(t_{cr1}) = z_2(t);\ t \in (t_{cr1}, t_{cr2} \rightarrow z_2(t) = z_{2r}) \tag{10}$$

A MATLAB® script was developed to calculate the above for a scenario with the variables defined as shown in Table 4, consistent with the problem description above. The calculation first solves with (A_{door}) set to a minimum value and at the first critical point, updates the initial conditions for t, z_1(t,) and z_2(t) and solves the set again with (A_{door})' set to a larger value until the second critical point when the electric panel fails. The time when the Electric Box fails is determined to be the failure time. Figure 13 shows a trace of the water heights in rooms 1 and 2 as the scenario evolves. It is noted that the water level in the rooms increase in linear fashion while (A_{door}) is constant. This validates the assumption made in the small scale testing experiments that the velocity of the water through the doorway is relatively constant and that changes in leak rate must correspond to changes in the area of the doorway. As shown in the plot the failure time for the electrical panel is 701 seconds after the flooding began.

Table 4) Parameters for Deterministic Simulation

Parameter	**Value**
Flow Rate in (Q(t))	50L/s (0.1m^3/s)
Area Room 1 (A1)	15m^2
Area Room 2 (A2)	20m^2
Initial Area of Doorway (A_{door})	0.002m^2
Area of Doorway after failure (A_{door})'	0.1m^2
Door Failure Height (z_{1cr})	1m
Electric Box Failure Height (z_{2cr})	1m

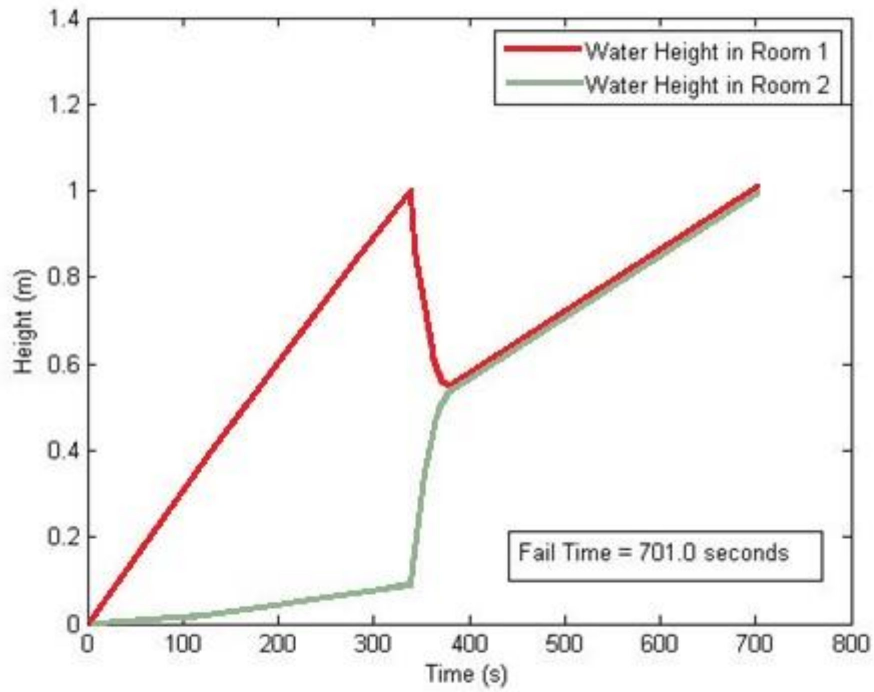

Figure 13) Trace of Water Heights in Mechanistic Simulation

5.2 Incorporation of Flooding Fragility Curves

Using the component level flooding fragility curves developed in the small scale testing experiment, the analysis can be re-run with the knowledge that the area of the doorway will increase over time in a random or probabilistic way as the door stochastically advances to different damage states. Likewise the panel will fail in a stochastic way. While equations presented in the earlier analysis can still be used as a basis for approaching the problem it is now understood that the critical heights are actually random variables which are distributed according the distributions described by the fragility curves. While propagating random variables through even simple differential equations once presented an enormous computational challenge, modern computational tools using Monte Carlo techniques allow these calculations to be done to high degrees of accuracy in reasonable periods of time.

A modification to the MATLAB® code used for the deterministic simulation was made to include lognormal random variables for 3 critical heights on the door (each with a correspondingly larger doorway area) and electric panel, the parameters of which are shown in Table 5 and Table 6. The parameters for the lognormal distributions are those from the flooding fragility curves developed in Sections 4.1 & 4.2. The simulation began by choosing the 4 critical heights (3 for door, 1 for electrical panel) by randomly sampling these distributions. The water height in each room is calculated in the same as it is done in Section 5.1. When the door's first critical height is reached the model updates the leaking area, indicating a damage state progression. The simulation runs until the water height in the second room reaches the critical height of the electrical box. The time when this occurs is the failure time which is stored in an array. New critical heights are then sampled and the simulation repeats itself and calculates a new failure time. The simulation calculated 10,000 failure times which took approximately 3 hours on a standard desktop computer. The MATLAB® script used for these calculations is provided in Appendix A.

Table 5) Random Variables in Probabilistic Simulation

Parameter	(μ)	(σ)	Corresponding Door Area before Critical Height Reached
First Door Critical Height	-0.217	0.165	$0.002m^2$
Second Door Critical Height	0.498	0.098	$0.008m^2$
Third Door Critical Height	1.01	0.093	$0.032m^2$
Electric Box Critical Height	0.004	0.032	NA

Table 6) Static Values in Probabilistic Simulation

Parameter	Value
Flow Rate in (Q(t))	50L/s ($0.1m^3/s$)
Area Room 1 (A1)	$15m^2$
Area Room 2 (A2)	$20m^2$
Area of Doorway follow failure (A_{door})'	$0.1m^2$

The results of the simulation show a Mean Time to Failure (MTTF) for the Electrical Box of 863.8 seconds with a standard deviation of 52.4 seconds. The pdf and CDF for the simulation are presented in Figure 14. The results show that the conservative deterministic prediction of electrical box failure at 701 seconds is highly unlikely. In fact there is less than a 0.07% chance that the box will fail before 701 seconds. Using a 95% confidence interval it can be claimed that there is high confidence that the box will still be functioning after 767 seconds, which is a 10% increase in safety margin over what the deterministic simulation predicts. Comparing the two simulations illustrates that component level failure data can lead to increases in safety margin and a more informed understanding of accident progression.

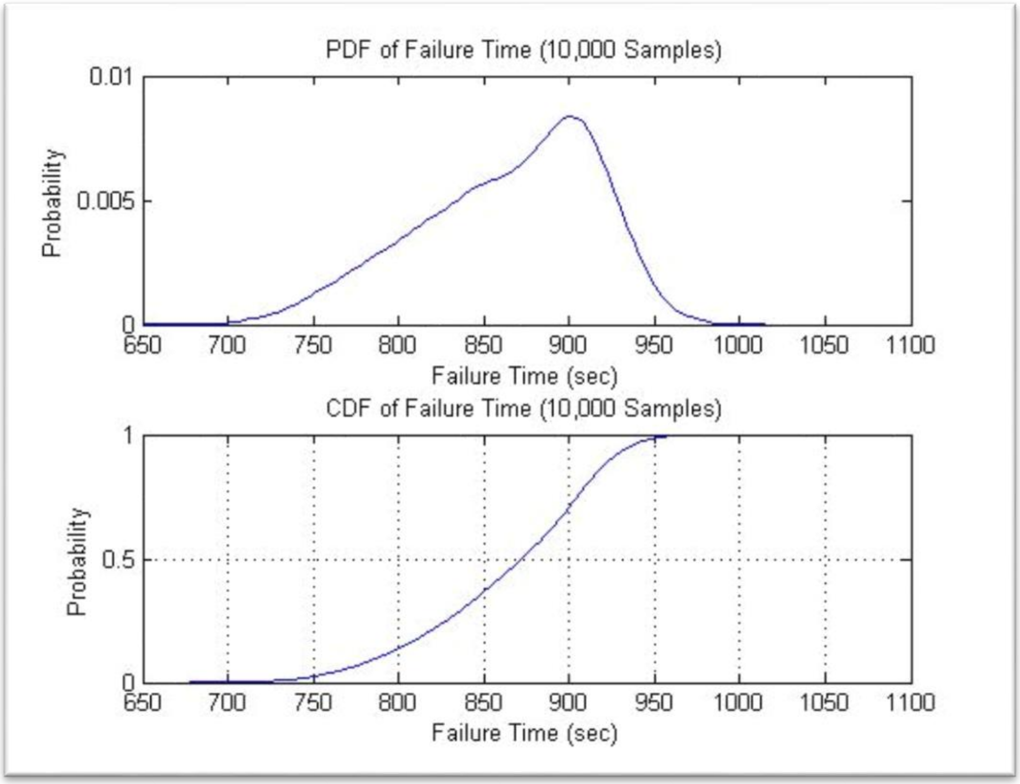

Figure 14) PDF and CDF of Electric Box Failure Time

Simulations were also completed with a 100 samples and 1,000 samples to compare how running more iterations would affect the results. While the MTTF and the uncertainty changed relatively little, the lower bound on the 95% confidence interval increased from ~740 seconds to ~760 seconds to 767 seconds as the number of samples increased from 100, to 1,000 to 10,000. This likely indicates that there are some low probability scenarios with early failure times that are biasing the results low until a large enough sample size is taken. A sensitivity analysis could take place to further investigate these affects.

The above sample problem has illustrated several important facts. The first is that a study of component level failure in flooding scenarios using modern probabilistic techniques has the potential to increase understanding of NPP safety margin in flooding scenarios. The second is that much more work is required to refine these techniques, and develop higher quality data on actual components. The analysis above first relied on a greatly simplified model with only two rooms and 2 connected components (door and electric box). This simplification allowed the use of the Bernoulli equation to solve for the water heights in each room as a function of time. Work should be conducted in the area of open channel flow using more advanced deterministic methods like CFD (Computational Fluid Dynamics) or SPH (Smoothed Particle Hydrodynamics) and coupling these calculations to a Monte Carlo code that can stochastically update components and structures in these codes based on their probabilistically assessed failure points. This coupling should follow the framework of what is currently under development as part of the RISMC effort.

Second, work should be conducted to better understand exactly how components fail in flooding scenarios and what factors influence the likelihood of failure. For example, the door was assumed to progress along three discrete damage states, likely the door fails in a continuous fashion, degrading over time. More refined modeling tools should be explored to more accurately account for these types of failures. In developing the fragility curves the above example took a simplistic approach of looking at a single variable (water height) and distributing it lognormally. Due to the dynamic nature of flooding events more complex models may be required that consider multiple variables such as rate of water rise, time, likelihood of debris impact, etc. In order to develop the understanding required to construct these more complex models testing of actual components in simulated flooding scenarios will be required.

It is for this reason that the Component Flooding Evaluation Laboratory (CFEL) program is being initiated at Idaho State University. Here actual components will be tested, starting initially with simple components and eventually more complex components. These tests will not only provide insight to the mathematical modelling effort, but will also provide a database of failure data for components which can be used to verify the models that are developed. The remainder of this thesis will present a roadmap for the standing up this program and evolving it from work with simple models, basic components, and elementary flooding scenarios to complex models, larger components, and more dynamic flooding scenarios.

6 The Component Flooding Evaluation Laboratory Program Roadmap

The research and small scale experimentation have shown the value of conducting experiments that can be used to develop flooding fragility curves. The Component Flooding Evaluation Laboratory (CFEL) at Idaho State University (ISU) is being designed for that purpose and will be capable of testing a variety of full scale Nuclear Power Plant (NPP) components to failure under spray, water rise, and eventually wave impact flooding events. The mission of CFEL is a relatively large undertaking. As such, the work scope has been divided into four parallel paths as illustrated in Figure 15 below. The first two paths focus on the installation of testing equipment to physically develop CFEL. The second two paths are research tasks that will begin immediately in parallel with the laboratory installation and mature as the laboratory becomes available.

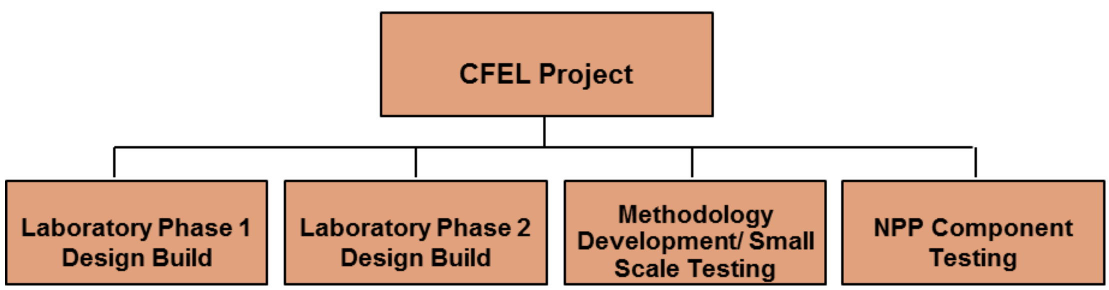

Figure 15) CFEL Work Break Down

The laboratory installation has been divided into 2 Phases with the goal of being able to naturally evolve the project from testing of simple components and scenarios to more complicated events with more prototypic components. The first phase focuses on the initial installation of CFEL in the Idaho State University (ISU) Engineering Research Center (ERC) and includes installation of major systems required for laboratory operation including modifications to the facility structure, HVAC, and electrical systems. In addition, it involves the installation of a crane, a below grade flooding chamber, and the expansion of an existing water reservoir. Everything required to conduct water rise and spray scenario testing will be installed as part of Phase 1. The second phase will focus on the modification of the facility to support wave impact testing, through the installation of a wave generation machine. While the first phase is underway, research will be conducted into how wave impact events can be simulated. Given the increased difficulty of simulating tsunami like waves, a longer more methodical design approach will need to be taken, to ensure that the system installed delivers prototypic results.

Likewise the program research will also be divided into 2 phases which will take place in parallel and will continue after the facility installations are complete. The "Methodology Development & Small Scale Testing" task will provide valuable insight into the direction of more complex tests, by evolving the methodology described in Section 4 of this report. The program strategy for CFEL will be to begin conducting a large number of simple tests using simple components utilizing existing or easy to procure and install testing infrastructure. The goal of these lower rigor tests will be to develop a qualitative understanding of how different kinds of components such as structural, mechanical, and electrical components behave in various flooding scenarios. The testing in this task will be similar to the testing described in Section 4 above except at an increasing scale. The concept of damage states corresponding to different cross sectional areas of the doorway is an example of a qualitative conclusion which was observed while watching the doors fail. This task will seek to discover similar observations and apply new and creative stochastic models that describe the failure of components based on the results of actual testing.

As the CFEL infrastructure is upgraded, the testing methodology and sophistication will increase building on the experience gained in early testing. Testing with actual NPP components will be expensive and the testing protocol must be highly refined prior to conducting these tests to ensure the quality of the data is sufficient for use in making safety decisions at NPP. The program will solicit participation from Industry and Regulatory stakeholders and procure more expensive and more prototypic NPP components. The first step in the NPP Component Testing task will be the development of a CFEL Users Guide. The CFEL Users Guide will document the capabilities developed to date from Phase 1 and Phase 2 installation projects as well as the lessons learned and methodologies developed under the "Methodology Development & Small Scale Testing" task. The Guide will serve as an important asset to communicating the CFEL capabilities to stakeholders, as well as guiding the planning, preparation, and execution of larger scale experiments. Testing on actual components will require a high degree of rigor, quality assurance and planning in the experiment planning and execution.

Figure 16 shows the integrated roadmap for the CFEL research program over the next three years. The following sections for this thesis report describe the four work breakdown areas of the CFEL effort in more detail. A greater level of detail is provided for those activities taking place in the near term while the goals for longer term research are also identified as it is recognized that the roadmap for CFEL will need to evolve as the laboratory is installed, data is collected, and stakeholder input is obtained. This strategy provides a roadmap with defined goals and a logical approach while also remaining adaptable to evolving as lessons are learned over time.

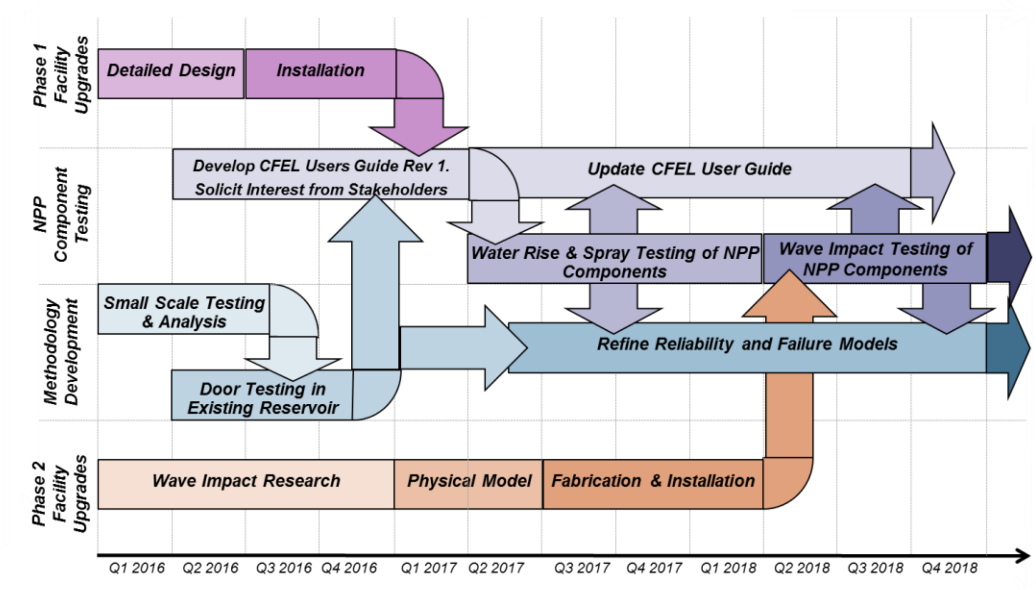

Figure 16) Integrated CEFL Research Program Roadmap

6.1 Laboratory Phase 1 Additions

CFEL will be located within the ISU ERC building located at 1030 S 2nd Avenue in Pocatello, Idaho. Appendix B shows the main floor plan of the ERC facility with the space set aside for CFEL identified. While the current facility is limited in its ability to function as a testing facility for NPP components, much of the preliminary investigations can take place in some of the adjacent laboratories located at the facility. For example the small scale testing that was discussed in Section 4 of this report took place at ERC. Further and more sophisticated small scale tests will help in developing fragility models early on as well as guiding the requirements of installed CFEL additions. An effort is also underway to test full scale doors in an existing water reservoir at ERC.

CFEL will occupy the northeast side of the ERC building utilizing a currently unused space that is 24 feet in width and 70 feet long. A large roll-up door that is already installed at the location adds to the appeal, as it will support easy receipt of components. If more space is required the electrical panels currently in the back of the existing space can be relocated and a temporary wall separating the proposed CFEL space from a thermal fluids lab can be moved several feet to the southwest. The space allocated for the CFEL formerly was used as a storage area and while most of the materials have been removed some the large metal shelfing remains and will need to be displaced before installation of CFEL can begin. Figure 17 shows the space where the CFEL laboratory will be located in the ERC, the large roll up door can be seen in the background.

Figure 17) CEFL Space in ERC (excess materials have been removed)

The desired features of the facility modifications are described below. The project to install CFEL Phase 1 will be managed by the Department of Public Works (DPW) as this is the standard for University owned buildings. The Myers-Anderson architectural firm was hired to begin the initial design and cost estimate for the facility modifications. After a design and cost estimate is completed, bids will be solicited from construction firms to begin the construction.

6.1.1 Installation of Below Grade Flooding Chamber

While the exact dimensions of the below grade flooding chamber is an open design issue, some proposed dimensions are a fifteen foot wide, fifteen foot long, and fifteen foot deep installation. This allows for approximately 25,000 gallons of water in the flooding chamber and will be able to accommodate a variety of components of various geometrical dimensions. The flooding chamber will require additional space for stairs or a ladder to allow researchers into the chamber in order to set up the experiment. A safety circuit will be required to ensure that the flooding system does not activate and begin flooding while researchers are present in the chamber.

A fifteen foot deep chamber is a significant depth and the cost of an undertaking may vary greatly on the size of rocks that are present beneath the buildings foundation. The space available in ERC that will host the CFEL is long and can be made longer with the facility modifications described above. Boreholes will be drilled in several locations along the corridor to determine if there are any obstacles to having a fifteen foot excavation and how those obstacles can be avoided. If due to the presence of large obstacles along the length of the corridor a fifteen foot deep excavation is deemed unfeasible, it may be required to have the chamber extend above grade for a couple feet.

Flood testing in CFEL will take on a variety of different forms. The water rise rates in the tank are likely to be a critical variable in understanding how the components fail. As such it may be desirable to be able to segment the flooding chamber into smaller sections to accommodate a higher rate of water rise for a given flowrate. For the spray testing and later wave impact testing, large volumes of high velocity water will impact the sides of the flooding chamber. As such the chamber will be required to have walls that are capable of bearing these heavy loads and be resistant to erosion from the high velocity water jets.

6.1.2 Hoisting and Rigging / Structural Modifications / Utilities

In order to house the variety of components desired for experimentation at CFEL an overhead crane will need to be installed into the CFEL portion of the ERC. Components for testing will enter the laboratory via the rollup door on the north corner of the building. The components will then likely need to be moved to a staging area and eventually loaded into the testing bay. Following the destruction of the component in the testing chamber it will again need to be removed for examination and eventual removal from the facility. Some initial scoping has indicated that a 5 ton crane would be ideal for most components that would be tested, and 5 ton crane does not add significant financial burden to the project. Further trade off studies may be required to determine the value or larger or smaller cranes. If an overhead crane is installed in the facility some structural modifications will likely be required as it is unlikely that the current wooden structure is capable of bearing a crane and the anticipated 5 ton capacity. Regardless of the crane option chosen some structural refurbishment will likely be required. Figure 18 shows some of the current damage in the facility that will need to be repaired as part of phase 1 of the CFEL project. The walls and support beams of the building also have a dated appearance; as such additional work will likely include a refurbishment of the interior walls and perhaps the inclusion of shelving units or bins in a material staging area.

Figure 18) Current Damage in ERC Structure

The current concrete floor is rough and will require a refinishing to accommodate efficient movement of material as well as to provide an aesthetically pleasing lab space. Additionally, depending on the location of the flood chamber and anticipated location of the future wave generation machine the wall that borders the CFEL lab and the thermal fluids lab may need to be moved. Currently a unisex bathroom exists in the back of the laboratory which may require either a refurbishment or removal depending on impacts of the other required facility systems.

Currently the facility space where CFEL will be located does not contain a sufficient HVAC system. An evaluation will need to take place to determine the appropriate system. The evaluation will need to include an assessment of the likely higher humidity levels in the laboratory given the large amount of water that will be present. In addition to the HVAC requirement, the CFEL portion of the facility is also very dimly lit and will require a number of new lighting fixtures to be installed, as video recording of the experiments will be desired. Any desired communication lines for communicating sensor information to computers or data collection terminals in other parts of the building will also need to be thought of in the desired electrical upgrades.

One of the main types of components that are desired for testing is electrical components. As these components will be tested live, it will be necessary for them to be isolated from the balance of the building electrical supply such that when the components fail they do not cause facility wide outages. A separate gas powered generator to supply power to components that are being tested is one idea for accomplishing this isolation. This simple, near term solution will allow for collecting of data early while more sophisticated systems are installed later. As mentioned above, several electrical panels are currently located along the northeast wall of the facility and it may be necessary to move these if they become at risk of water damage due to the location of the flooding test chamber.

6.1.3 Water Storage and Supply System

An existing below grade 8,000 gallon water reservoir currently exists within the facility and is located within the flume laboratory in the southeast part of the facility. The reservoir has a maximum depth of 8 feet below grade. This reservoir will need to be expanded by an additional 25,000 gallons to accommodate both the Phase 1 and Phase 2 modifications to the facility. It may not be feasible for the reservoir to be a single integral unit due to space limitations in the flume laboratory where the reservoir is located. A separate reservoir will likely be required to gain the desired capacity. It will be required that the two reservoirs be connected in such a way that water can be accessed from both. The location of the additional reservoir capacity is an open design issue.

A water supply and return system will be required to transfer water to and from the flood chamber and the reservoir. Currently a high power pump exists in the 8,000 gallon reservoir, if the new reservoir is deeper than 8 feet, the pump will be moved. The addition of a smaller pump could be added to allow for flexibility in providing different flow rates to the flooding chamber. A pump will also be required in the flooding chamber to transfer water back to the reservoirs after the testing is complete. The size of the feed and return lines will be dependent of the range of flowrates that are desired.

For water spray events, a bank of pressurized nozzles will be required. The number, flowrates, and pressure of these nozzles are also open design issues. On the return line, a filtration system may be required as some of the components that may be tested to destruction may fragment and cause silt and debris to get mixed in with the water. It is desirable to maintain the water in a potable state so that it can be disposed of easily in the cities storm drain. Part of the design effort will be working with the city to determine if any direct connections to the cities storm drain are needed to dispose of these high volumes of water when the system requires maintenance.

6.1.4 CFEL Phase 1 Organization and Schedule

The installation activities for accomplishing the modifications described above will be accomplished through a Design/Build project. The management and reporting for the effort is represented in Figure 19. The Idaho State University Nuclear Engineering Program Director will be the Principal Investigator for the CFEL Program and he will be supported by the other ISU faculty working on the project as well as the students conducting the research. The director will be responsible for guiding the activity as well as providing the budget, and functional and operational requirements for the Phase 1 installations (many of which were described in the above sections).

The director will provide the final acceptance of design documents and will approve the start of installation activities. The Department of Public Works (DPW) will supply the project manager for the effort. The project manager will be responsible for the day to day oversight and execution of the overall effort. DPW will solicit bids for a general contractor, who will be responsible for the work execution. The Myers Anderson architectural firm has already been selected to lead the design effort. The design effort will be responsible for defining the scope of the effort sufficiently such that the Program Director can secure the funding for the effort and that the Project Manager can solicit bids for a general contractor which will be responsible for the installation of the laboratory.

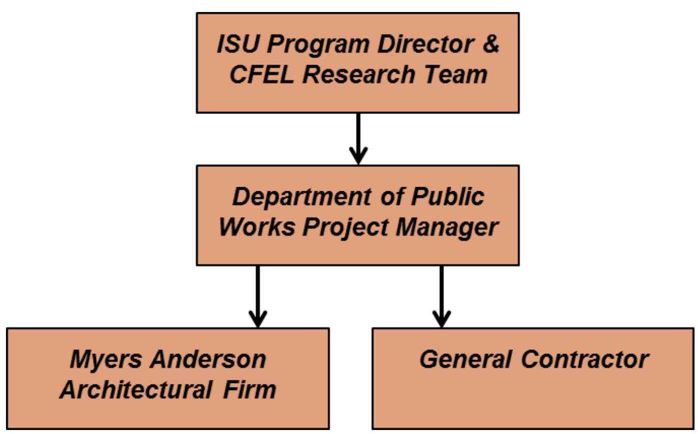

Figure19) CEFL Phase 1 Reporting Structure

The schedule for the installation activities of CFEL is very aggressive as testing on full scale components needs to begin in earnest and is an important critical path item in the overall CFEL program. The design activities are estimated to take between 45 and 60 days to develop a design that is sufficiently mature to have a cost estimate that can be relied upon. The cost estimate is required to secure funds from the program sponsor (LWRS) as well as put together a bid package for general contractors. Table 7 depicts the schedule for Phase 1. The overall goal is to be able to begin testing of full sized components in January / February of 2017. To support that goal and an anticipated minimum 4 month time to complete the installation activities, the design will need to be completed by the end of August 2016. Following that time a 30 day response time for the contractors to respond to the bid will be required. A major milestone for the effort will be to have the general contract for CFEL installation signed in the September 2016 timeframe. While an aggressive schedule is desired, it is important that the laboratory be a quality product. As information is developed in the design phase a higher fidelity schedule for the installation activities will also be developed and milestones for testing may need to be adjusted.

Table 7) CFEL Phase 1 Schedule

Task	Start	End
Initial Scoping Review	February 23, 2016	March 09, 2016
Contract Negotiations	March 09, 2016	March 28, 2016
Design Development	March 28, 2016	May 16, 2016
Review	May 16, 2016	May 30, 2016
Develop Construction Documents	May 30, 2016	August 01, 2016
Review	August 01, 2016	August 22, 2016
Bidding	August 22, 2016	September 19, 2016
Construction Contract Award	September 19, 2016	October 10, 2016
Construction Duration	October 10, 2016	February 21, 2017

6.2 Laboratory Phase 2 Additions (Wave Generation Machine)

Phase 2 of the laboratory installation is the development of a capability to simulate the hydraulic loads from high velocity waves. The goal of this effort is to have the capability of simulating the loads from a 20 foot wave. There is a considerable increase in the difficulty of the design of such a system which will require a much more timely and concerted effort. Most open channel wave impact machines utilize a ram and even large facilities are only capable of simulating waves in the 5 foot range. Initially research will be done to determine appropriate ways to simulate these larger waves. An effort funded by the CFEL program is underway using numerical models to determine if water transients can be developed in a closed channel system that simulates the hydrodynamic loading of a 10 foot by 10 foot section of the 20 foot tsunami wave. The effort is currently using a CFD code to map pressure forces to rigid bodies interacting with waves.

The results of the numerical simulation will need to be compiled and they will be used as the input to the design effort of the wave generation machine. A small scale prototype of this machine will need to be built and tested to verify its functionality. As stated above, wave generation machine is somewhat of a misnomer as the goal of the machine will actually be to simulate the forces of a section of a large high velocity wave. Space will be allocated in the Phase 1 effort as being set aside for the Phase 2 additions. The wave impact machine will need to be linked with the water storage and supply system as well as with the flooding chamber. Components will be placed in the flood chamber as in water rise and spray events. In these more advanced tests the wave impact machine will supply a short duration, high pressure slug of water which may be capable of failing the component. An instrumentation and control system for this machine will be required as it will be desirable to monitor and vary the conditions of the wave impact tests. The installation of Phase 2 additions will follow the same framework as the Phase 1 additions in that it will be executed in a Design / Build fashion.

The current roadmap as depicted in includes a 12 month numerical modeling research effort to aid in the development of design concepts. Once the design concept is chosen, a prototype will be constructed to verify the design concept. Nine months are allocated to the fabrication and installation of the machine, although this part of the schedule is highly uncertain and will depend greatly on the design concept chosen. These efforts can take place in parallel with the Phase 1 installation activities as well as the initial methodology development, and initial NPP component testing.

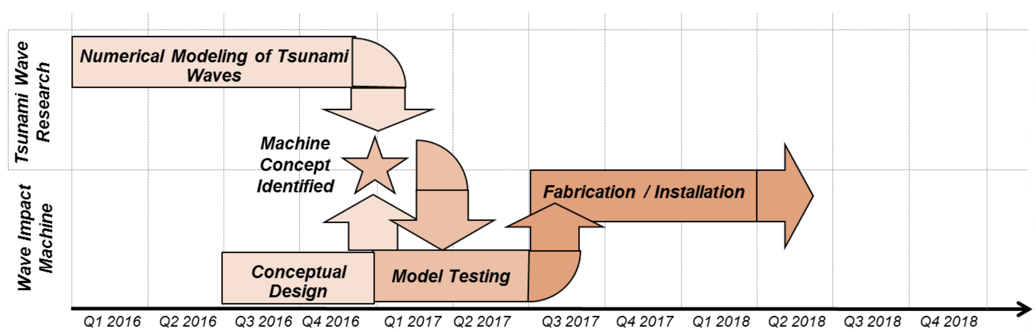

Figure 20) CFEL Phase 2 Schedule

6.3 Methodology Development & Small Scale Testing

In parallel to the design and installation of the facility, research is needed into how components should be prioritized for testing and what the testing protocol should be for various components. A larger base of experience with developing flooding fragility knowledge on common commercial and industrial components will add experience and credibility to the research. Experiments in this task will be lower rigor and larger in number. The goal of this task is to answer the questions of how mechanistically components fail and what data will be generated and how that data will be used to better describe the safety margin of the NPP. Using the capabilities that are currently available at CFEL testing will be done simply to observe the ways in which components fail under flooding scenarios. Structural components such as doors are a logical starting point as they are a common component in NPP. Small scale testing has shown there to be significant value in understanding how they fail, and testing is relatively simple in comparison to more complicated components. Testing of doors also provides a good platform to explore the use of instrumentation. Using the existing reservoir at the ERC, full scale doors can be tested in water rise scenarios. The doors used in these initial tests can be a standard commercial grade construction item which will enable good statistical information to be generated as a large number can be tested with relative ease in comparison to industrial or nuclear grade doors. Later a portable generator can be brought in to test low load electrical and mechanical components without the complications of tying into the ERC facility's electrical systems.

6.3.1 Understanding the Qualitative Behavior of Components in Floods

The initial testing, like the small scale testing described in Sections 4.1 and 4.2 can be very open ended as the principal goal is to learn qualitatively how various structural, mechanical, and electrical components behave in flooding scenarios. The small scale testing showed that doors progress through various damage states, while the radios had a more simple failure. More testing is needed to refine these understandings. Testing also needs to take place with a variety of instrumentation to identify the resolution available on critical parameters of the tests such as fill rate, water height, and potentially other parameters of interest that are observed in early tests. Test reports should be written for each failure test with as much control over the testing parameters as possible. The goal should be to conduct a sufficient number of repeatable tests such that a statistically relevant sample size can be generated.

In the small scale tests, the radios began working again once they dried out. In addition to testing the failure of components, it will also be of interest to understand how quickly components can be restored in later stages of the flooding event. This phase of the effort will be focused on conducting a variety of experiments both small scale, and at larger scales, using a variety of components and a variety of flooding scenarios and drawing qualitative conclusions on the nature of failure as the outcome. These qualitative descriptions of component behavior will be important inputs to the next phase of the methodology development task which is beginning to describe quantitatively the probabilities of component failure.

6.3.2 Developing Flooding Fragility Curves for NPP Components

After the qualitative understanding of component failure is developed, fragility curves can begin to be developed that quantitatively describe the failure. A key part of this task is to identify the flooding variable which drives the failure and ought to be distributed in the fragility curve. In the analysis presented in Section 4 that variable was determined to be the water's height relative to the component. The reason this was chosen was that it is consistent with the approach used in the internal flooding PRA referenced in Section 3.2.1 [12]. Also the water height at which failure occurred was a relatively easy to derive number from the small scale experiments that were conducted. The water height is also the likely to be the strongest contributing factor to the hydrostatic loading of the components. Especially for structural components, water height is a logical place to start. However, depending on the component and nature of flood, water height may not always be the strongest variable to consider. Research should be conducted looking at how other factors play a role in failure. Again research into the internal flooding PRA suggests that flow rate may be an important variable to consider and distribute in a fragility curve. Other variables that may be important factors are the hydrodynamic (impulse) loading, and time of submergence. As indicated above, determining when a component will come back online after the water has receded may also be an important factor to consider. The factors that influence return to operation may be as diverse as the factors that lead to failure.

Once the main variable(s) of interest are identified, the appropriate probability distribution will also need to be determined. Lognormal distributions were chosen in this thesis as a logical starting point because they are the distribution used in seismic fragility curves [1]. However, it should not be assumed that distributing these fail points lognormally is necessarily the best case for the flooding application. For example if time of submergence is the key variable of interest an exponential distribution may be more appropriate as failure times are most often distributed in this manner. Also if multiple variables are desired to be modeled, other more complex schemes such as Weibull distributions may be more applicable [10].

Finally, the example in this thesis directly applyied the summary statistics of the mean and standard deviation of a sample set to the parameters of the fragility curves. It is highly unlikely that CFEL, even when fully operational, will be able to conduct a sufficient number of failure tests on components for this approach to be utilized. The most logical course of action will be to apply the Bayesian Inference technique and develop informed prior distributions based on the engineering data available for the components, combined with the qualitative knowledge generated from generic testing. A key part of this task will be to research components of interest in flooding analysis and come up with ways to develop these prior distributions based on the design specifications of those components.

As a good starting place, the diesel generators were shown to be especially vulnerable to flooding in the Fukushima Daiichi accident. It is unlikely that a full scale diesel generator will be tested in CFEL, however that does not mean that the CFEL research program will be unable to develop a flooding fragility curve for diesel generators. Research into the operation of these generators at nuclear power plants and testing of smaller generators at CFEL can provide valuable insight into how generators at NPPs fail in floods. Once the failure mechanisms are identified experimentation on that mechanism can help provide a basis to distribute the failure points in a fragility curve. A list should be developed of components that are of interest in NPP flooding scenarios, and then research on the design specifications of those components will provide a basis for developing a prior distribution. After an informed prior distribution is generated a few focused tests at CFEL can be used to validate or minimize the uncertainty in those distributions through Bayesian updating, or confirm that these distributions are off base and require a new approach to describing failure.

6.3.3 Incorporating Fragility Curves into Safety Analysis Codes

Once the fragility curves for critical components in the NPP have been developed they can be used to help inform plant stakeholders about the risk posture of the plant to various flooding scenarios. In order to be of use however, this data will need to be tied in with the codes that are currently used by the RISMC effort (as well as potentially new codes) to model risk informed safety margin. As an example, most of the codes used to model open channel flow during the flooding scenario model structural components as rigid bodies. The open channel fluid transport code (likely an SPH code) will need to be coupled to a Monte Carlo simulator. The simulator will sample the fragility curve for the component(s) of interest to determine its failure point. When the fail point is reached the SPH code will need to be updated by advancing the rigid body to the next damage state which will likely influence where water particles in the simulation will move next. In addition to updating structural components in open channel flow codes, mechanical and electrical components that are built into plant system codes such as thermal hydraulic codes will need to be coupled in a similar fashion.

The example problem that was modeled in Section 5 indicated that completing Monte Carlo analysis in this fashion could be accomplished with today's computing resources. A NPP safety analysis is however much more complex than the simple example used in this thesis. In order for the analysis to be successful, dedicated computer architecture may be required. Monte Carlo codes work well in parallel processing environments with multiple computer cores solving various simulations at once. Open channel flow codes such as SPH are sometimes designed to run best on GPU architecture. As such the algorithms and corresponding hardware that will be required to take full advantage of flooding fragility data is an area that requires much additional research. As with many of the other tasks identified in Section 6 of this thesis, this work can take place in parallel with many of the others and can proceed with an increasing level of rigor and sophistication consistent with the rigor and sophistication of the fragility data generated.

6.3.4 Methodology Development Schedule

The task will begin by building off of what has already been shown in small scale testing, while the Phase 1 of the facility is being installed. Figure 21, below shows the integrated roadmap for this task.

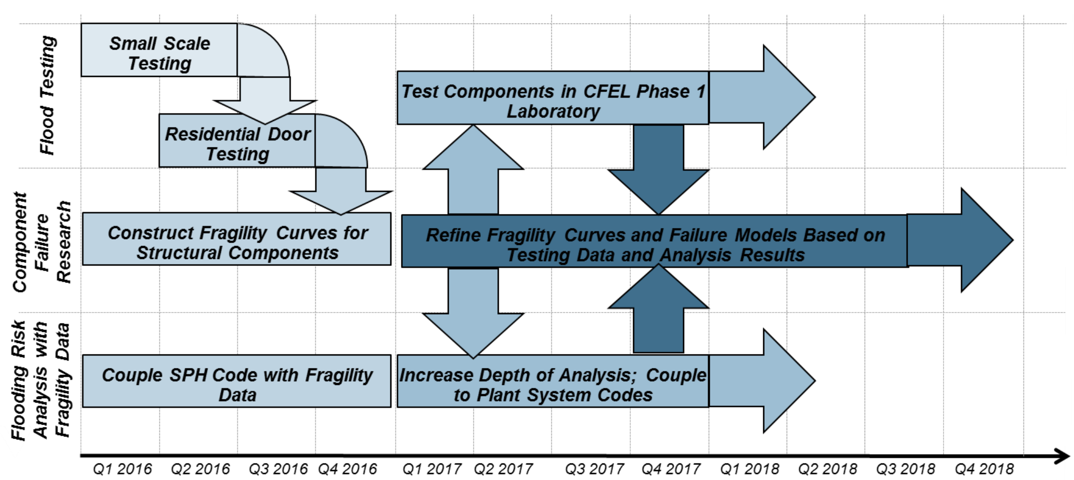

Figure 21) Methodology Development Schedule

Small scale testing will continue and a test is also being designed to fail full scale residential grade doors. Feedthroughs may also be able to be tested in existing facilities prior to CFEL Phase 1 installation. While testing is taking place on these structural components, research will take place to determine what the most likely failure mechanism is for these components in flooding scenarios and an appropriate way to distribute that failure point across an applicable probability distribution. In parallel with these efforts the fragility curves that are being developed will need to be coupled with the SPH codes used to simulate the movement of water through the facilities. This can likely be accomplished with a Monte Carlo job handler such as Raven which is used in most of the RISMC efforts already [2]. Raven will sample from the fragility curves the failure points of the structural components in the SPH simulation. When a failure point is reached the SPH simulation will stop, update its rigid body network, and Raven will select the next set of failure points. After CFEL Phase 1 is installed this same kind of coupling can be explored with more complex plant analysis models eventually also coupling the SPH and fragility modules with a plant system code such as RELAP 7. It is unlikely that all of the components in a NPP safety analysis will be able to have fragility data associated with them in the analysis models as the computational resources to run those simulations may become enormous. Comparisons can take place to determine which components have the strongest effect on improving plant safety margin. Those components can then be prioritized for testing. The flood testing data, fragility curve development, and plant safety analysis tasks will need to be continually updating their research focus based on the results in the other tasks.

6.4 Nuclear Power Plant Component Testing

The ultimate goal of the CFEL program is the testing to failure of actual NPP components. The first task in this phase will be publishing a first revision of a CFEL Users Guide. The Guide will be a compilation of the work that has taken place in the other tasks and will consist of two main sections. In the first section, it will describe the current status of the facility and its capabilities as well as include a section on near term modifications such as the wave impact machine that will likely still be under development when this Guide is first published. The second section of the guide will be a discussion on how the data from component testing can be used in safety analysis studies including mechanistic models, PRAs, and in the type of advanced RISMC models. This section of the guide will discuss the results from small scale testing as well as the progress made in incorporating fragility curves into analysis. This section of the report can take the same form as was used in Sections 4 and 5 of this thesis only the curves will be developed from a more extensive base of equipment testing and deeper knowledge of the failure statistics. Additionally more complex scenarios than the simple 2 room example can be discussed and the results of a simulation which couples fragility curves to an SPH code and Thermal Hydraulics code can be presented.

In parallel to the development of the Guide, the CFEL program will reach out to nuclear utilities to determine if any spare or excess components are available. To date it has proven difficult to arrange these connections given the sensitive nature of most utilities to discuss what their vulnerable components are in flood scenarios and limited supply of excess equipment. However, with the development of the User's Guide the credibility of the CFEL program will increase tremendously. Papers on the CFEL testing capability can be submitted at American Nuclear Society Annual and Winter Meetings, as well as at topical meetings relevant to the LWR industry. In addition, using the contacts in the LWRS program which is the principal supporter of the CFEL effort, presentations can be given to NRC Research, the EPRI Nuclear Power Council, and other industry groups which hold meetings and are involved in the nuclear regulatory business.

Once industry input has been secured a steering committee can be set up which will be principally in charge of prioritizing components for testing. Once the components are selected, work will need to take place with vendors of those components and in consultation with the User's Guide an appropriately scoped series of failure experiments will need to be conducted. Unlike the experiments discussed in Section 6.3 which were low rigor and large in number, the cost of these experiments will result in only a few highly rigorous tests taking place. Predicted fragility curves should be developed for the component prior to the test, using knowledge gained from the experience of testing similar components at CFEL, data from the vendor, as well as expert consultant knowledge. The goal of the actual NPP components tests should be to confirm the hypothesis that the fragility curve is correct or to disprove this hypothesis. Bayesian updating techniques can also be applied to use the limited number of tests on the NPP component. The schedule for establishing NPP component testing is presented in Figure 22 below.

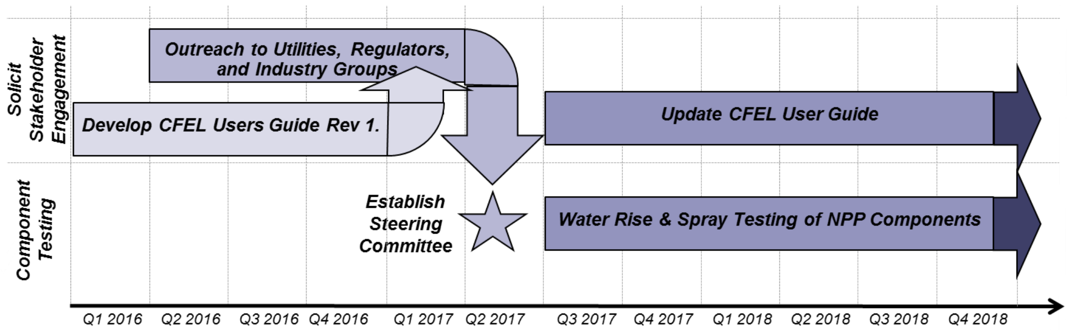

Figure 22) Schedule for NPP Component Testing

7 Conclusion

The safety analysis of NPPs is clearly moving towards more quantitative risk based models. The recent events at the Fukushima Daiichi plant have shown that flooding risks at NPPs need to be given a greater level of attention. The value of developing flooding fragility curves for critical components is clear. There is already precedent for including fragility curves in risk analysis of NPP mostly as they relate to seismic risk. The lessons learned from those risk analyses combined with the work being performed in the RISMC pathway of the LWRS program provide a solid scientific basis to explore the use of fragility curves in flooding risk analysis. Some of the key challenges for developing and incorporating flooding fragility curves into the risk analysis of NPP were identified both in the literature research and through the small scale testing of components in flooding scenarios. The small scale testing and analysis of the subsequent example problem confirmed that a more quantifiable understanding of safety margin can be achieved by including flooding fragility curves in risk analysis.

The positive indications from the research, experimentation and analysis have provided the basis for the development of a research program at Idaho State University in the area of flooding risk analysis with the goal of developing flooding fragility curves that can be used in risk analysis of NPP. A comprehensive roadmap was presented that outlines a path toward achieving that goal. The design envelope for the facility was described and a methodical approach for the initial research was presented. Opportunities to expand into wave impact testing and a description of how NPP components would be tested was also described at a higher level. The central theme of the roadmap is to have clear objectives with a defined pathway toward achievement of those objectives, while also remaining flexible to adapt as results from the initial testing is developed. The program will be required to think creatively and explore new ways of including fragility concepts in risk analysis given the complex and very dynamic nature of flood scenarios. The Component Flooding Evaluation Laboratory Program at Idaho State University is well suited for this task and can provide meaningful progress in the area of safety margin quantification for nuclear power plants in flood scenarios.

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Appendix A

MATLAB® Code Used in Example Problem in Section 5

```
clear all

% Set All Physical Static Variables
qdot = 0.05;
A1 = 15;
A2 = 20;
Doorwayarea = 0.1;
A1a = 0.002;
A1b = 0.008;
A1c = 0.032;
DoorA1 = [A1a, A1b, A1c];

%Set simulation variables
samples = 1000;
s = 1;
timestep = 0.1;
failtime = 0;

% Set Physical Probabilistic Variables
while s < samples + 1

tinit = 0 + timestep;
z1init = 0;
z2init = 0;
n = 1;
Tfull = 0;
Zfull = [0,0];
DCa = lognrnd(-0.217,0.165);
DCb = lognrnd(0.498,0.098);
DCc = lognrnd(1.01,0.093);

DoorCrit = [DCa, DCb, DCc];

EBCrit = lognrnd(0.004,0.032);


%While loop solves the Bernoulli Equation for each damage state
while n < length(DoorA1)+1
```

```
t = tinit:timestep:(A1+A2)*DCc/qdot; %Ten minutes is used as a conservative allocation
for t

ode1 = @(t,z) tworoom(qdot,A1,A2,DoorA1(n),t,z);
[t, z] = ode45(ode1,t,[z1init,z2init]); %Solves for the heights in the rooms
z = real(z);

maxindex = find((z(1:end,1)-DoorCrit(n))<0, 1, 'last' ); %Finds the time when door
damage state advances

t = t(1:maxindex);
z = z(1:maxindex,1:2); %Trims t and z vectors to the index of critical time

Tfull = vertcat(Tfull,t);
Zfull = vertcat(Zfull,z); %Builds the reportable vectors as t,z are rewritten in each loop.

if Zfull(end,2) - EBCrit > -0.1; % Checks that the EB is still functioning before re-itterating

maxindex = find((Zfull(1:end,2)-EBCrit)<0, 1, 'last' ); %If EB has failed finds time of failuire

Tfull = Tfull(1:maxindex);
Zfull = Zfull(1:maxindex,1:2);

n = length(DoorA1)+2; % Advances n so while loop will terminate
end

if Zfull(end,2) - EBCrit < -0.1; %When EB is opporating the initial conditions are updated
to be ready for next iteration

tinit = Tfull(end) + timestep;
z1init = Zfull(end,1);
z2init = Zfull(end,2);

n = n+1;

end

end


if Zfull(end,2) - EBCrit < -0.1; %If door is completely failed and EB still operating this code
advances simulation

t = tinit:timestep:(A1+A2)*DCc/qdot; %Agagin conservatively going to 100 minutes
```

```
ode2 = @(t,z) tworoom(qdot,A1,A2,Doorwayarea,t,z); %Solves z vector
[t, z] = ode45(ode2,t,[z1init,z2init]);
z = real(z);

maxindex = find((z(1:end,2)-EBCrit)<0, 1, 'last' ); %finds EB fail time

t = t(1:maxindex);
z = z(1:maxindex,1:2);

Tfull = vertcat(Tfull,t); %final update of reportable vectors
Zfull = vertcat(Zfull,z);

end

failtime = vertcat(failtime,Tfull(end));  %Gets the failure time before next probabilistic
iteration.

s = s + 1;

end

failtime = failtime(2:end);
MTTF = mean(failtime);
MTTF_uncertainty = std(failtime);

subplot(2,1,1)
ksdensity(failtime)
axis([650 1100 0 0.01])
ylabel('Probability')
xlabel('Failure Time (sec)')
title('PDF of Failure Time (1000 Samples)')

subplot(2,1,2)
cdfplot(failtime)
grid on
axis([650 1100 0 1])
ylabel('Probability')
xlabel('Failure Time (sec)')
title('CDF of Failure Time (1000 Samples)')

//

function f = tworoom( Qdot,A1,A2,DoorA1,t,z )
```

```
f(1,1) = Qdot/A1 - (DoorA1/A1)*(18.6*(z(1)-z(2)))^(1/2);
f(2,1) = (DoorA1/A2)*(18.6*(z(1)-z(2)))^(1/2);
end
```

Appendix B

Engineering Research Center Floor Plan