Idaho State University

Component Flooding Evaluation Laboratory

Alison Wells, PhD Candidate
Emerald D. Ryan, PhD
Chad L. Pope, PhD, PE

ROAR

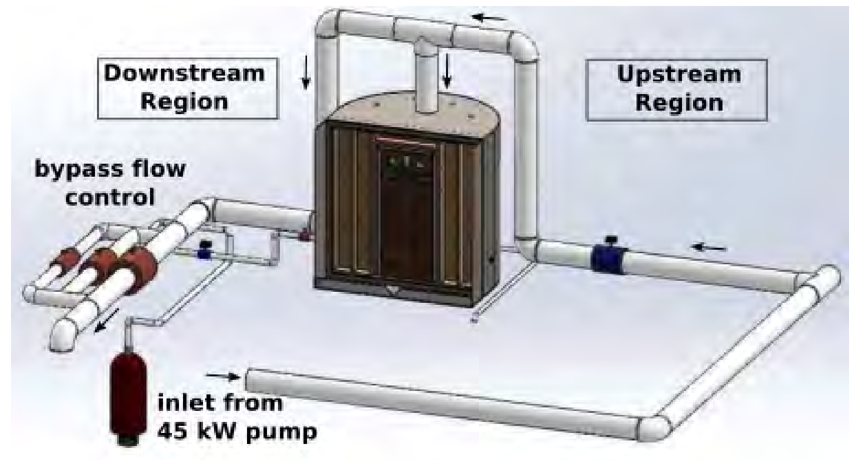
Objective

Support development of deeper comprehension of nuclear power plant flooding risks through three pathways:

1. Execution of component flooding experiments
2. Comprehensive data analysis and component fragility curve development
3. Integration of component fragility into flooding simulation

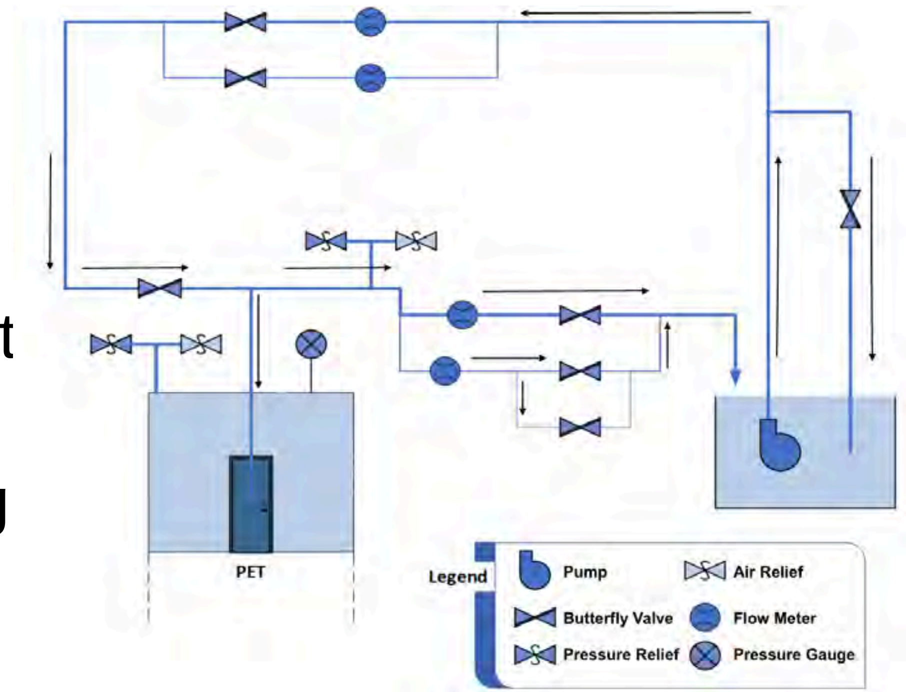
Portal Evaluation Tank

- 2,000-gal tank
- 8,000-gal reservoir
- 4500 gpm pump
- 8 ft x 8 ft opening for components



Instrumentation

- 2 inlet flowmeters
- 2 outlet flowmeters
- 2 pressure based depth measurement
- Small leakage measurement using V-notch weir



Hollow-core Door Experiments

- Inexpensive
- Rapid
- Learning to build
- Learning to operate
- Learning to collect data

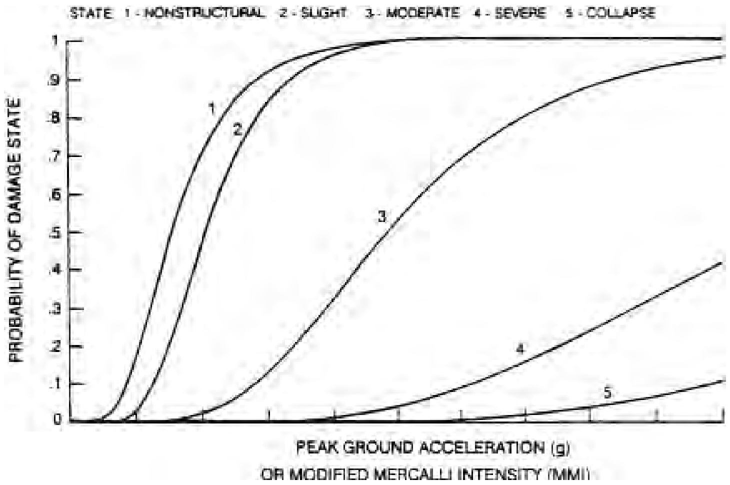
Steel Door Experiments

- Representative of industrial setting
- Required strengthened construction
- Outward swinging
- Inward swinging
- With and without dead-bolt

Inward Swing Steel Door

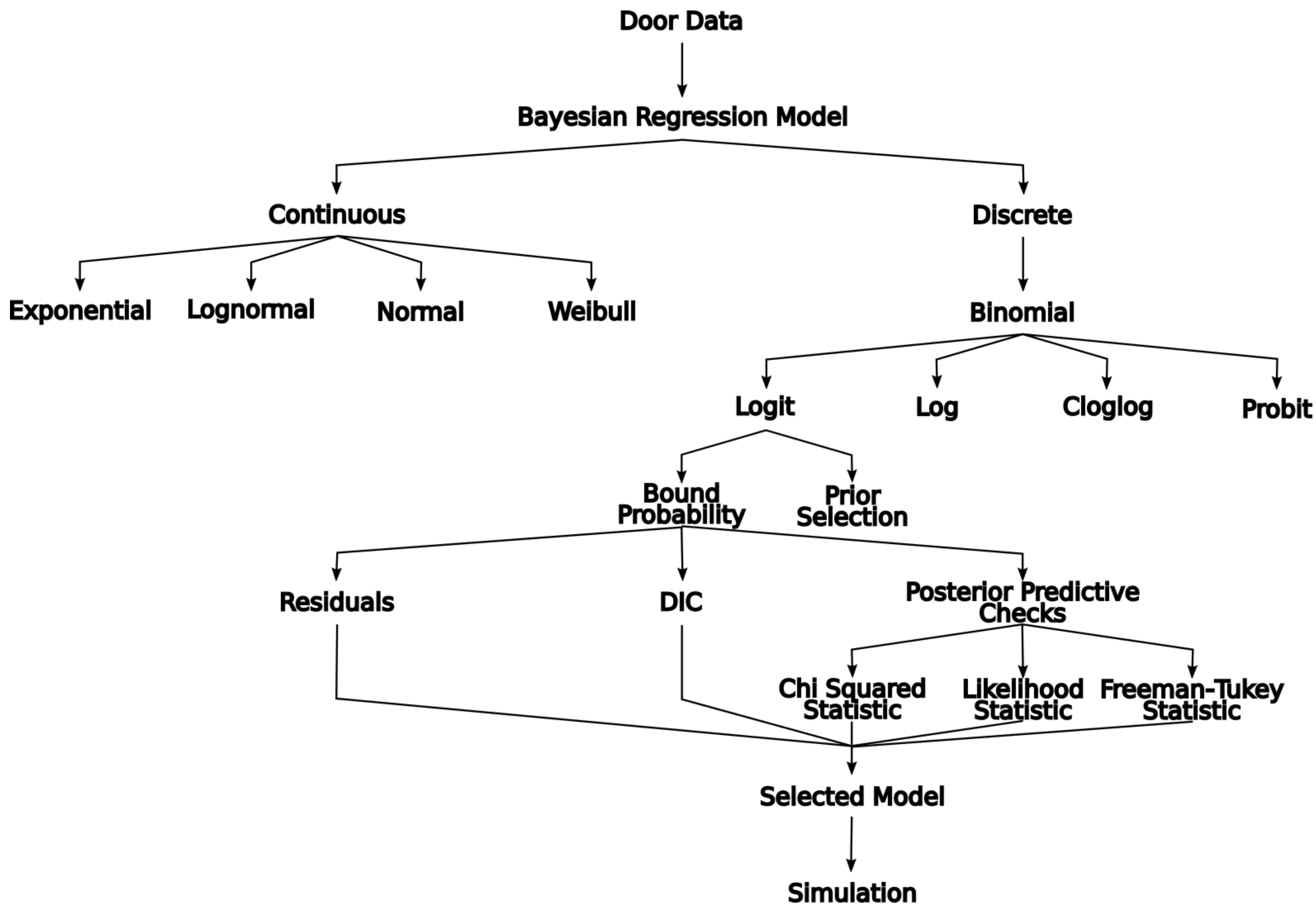
Fragility Modeling Approach

- Most fragility modeling has focused on seismic component fragility determination
- Additional observables may be better indicators for the potential of failures
  - X, Y, and Z parts of the ground motion
  - Frequency of the wave
  - Age of component
  - Anchorages of the component
  - Specifics of the component type



- Limitations can be avoided by moving to a more flexible, data-informed approach
  - Bayesian fragility modeling through experiment-driven regression modeling

Model Development



Bayesian Inference

- Need a model that represents the failure of a component during a flooding event
  - Binomial model
  - Key variable is probability of failure, *p*
- Determine what observable phenomena drive failure
  - Turn the parameter *p* into its own regression model
  - *p* is possibly a function of the water depth, flow rate, and even temperature

Model

```
model    {
    for(i in 1:tests){
            failure[i] ~ dbin(p.bound[i], numtested)
            logit(p[i]) <- a + b*Depth[i]
            }
```

Prior Distributions

```
        #Prior Distributions
        a ~ dnorm(0, .000001)
        b ~ dnorm(0, .000001)
        }
```

Data

```
data
list(
tests= 19,
numtested= 1,
failure= c(1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1),
Depth= c(46.1, 39.0, 37.1, 37.8, 37.5, 37.6, 37.7, 37.1, 44.5, 25.7, 17.0, 27.4, 30.9, 32.3, 24.3, 34.8, 37.5, 38.0, 41.4)
)

inits
list(a= 0, b= 0)
```

Idaho State University

Steel Door Results

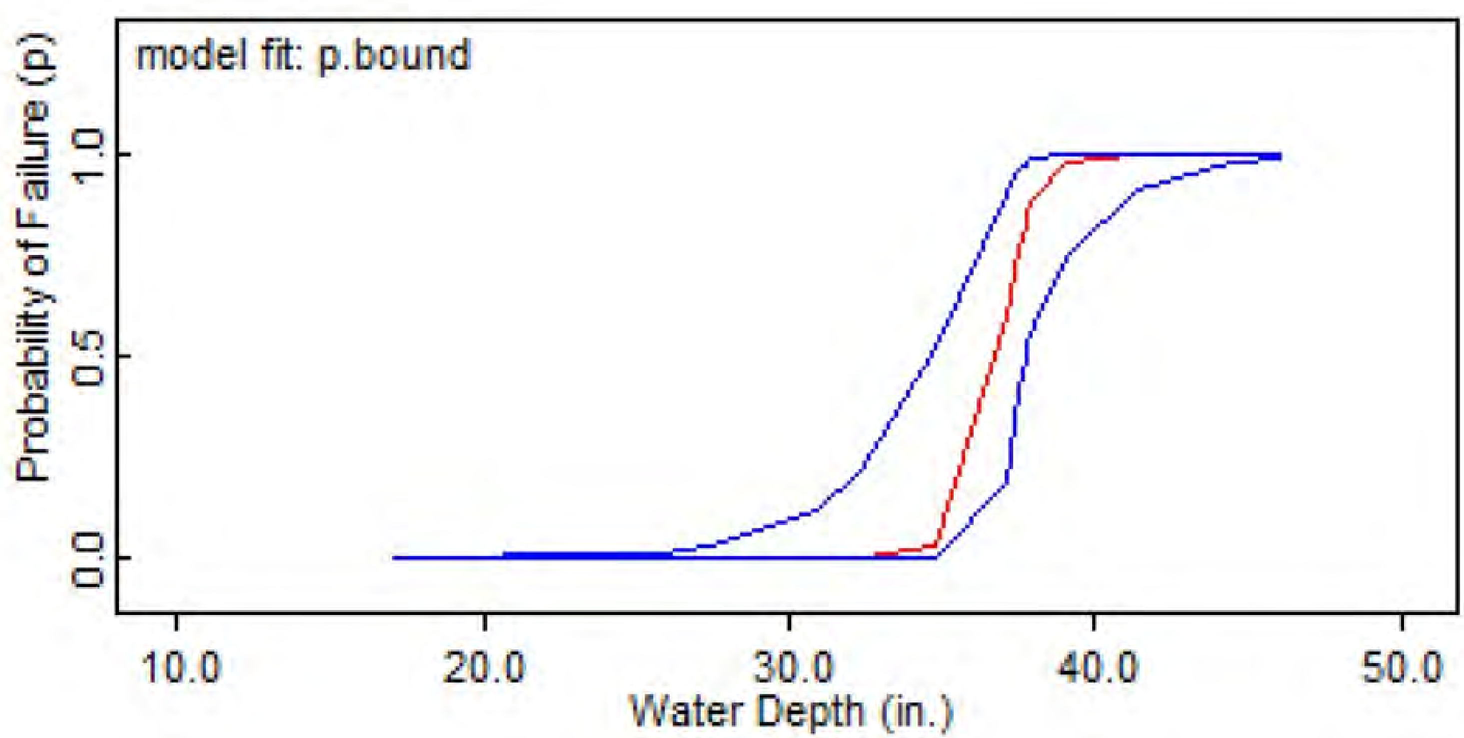
Parameter	Depth	Flow Rate	Depth & Flow Rate
a (intercept)	-75.68	-8.51	-72.5
b (depth coeff.)	2.05	na	1.83
c (flow rate coeff.)	na	0.01	0.007
sat. deviance	12.88 (10.65, 17.43)	14.29 (12.07, 18.92)	13.31 (10.1, 18.82)
Chi-square p-value	0.19	0.26	0.14
Likelihood ratio p-value	0.38	0.36	0.29
Freeman-Tukey P-value	0.33	0.23	0.21
DIC	14.42	16.01	15.66

- Posterior estimates can be used with the fragility model to calculate the failure probability for a steel door:

$$p = \frac{1}{e^{-(-75.68+2.05D)}+1}$$

ROAR

Steel Door Fragility Curve



Smoothed Particle Hydrodynamics

- Theory
  - Particle based, Lagrangian, method
  - Interpolation method
  - A particle's property depends on the particles surrounding it
  - Equations of motion
    - Momentum

$$\frac{d\boldsymbol{v}_i}{dt} = -\sum_j m_j \left(\frac{P_j}{\rho_j^2} + \frac{P_i}{\rho_i^2} + \Pi_{ij} \right) \nabla_i W_{ij} + \boldsymbol{g}$$

    - Continuity

$$\frac{d\rho_i}{dt} = \sum_j m_j \boldsymbol{v}_{ij} \cdot \nabla_i W_{ij}$$

    - Moving particles

$$\frac{d\boldsymbol{r}_i}{dt} = \boldsymbol{v}_i + \frac{1}{2} \sum_j \frac{m_j}{\rho_{ij}} \boldsymbol{v}_{ij} W_{ij}$$

- Time stepping scheme

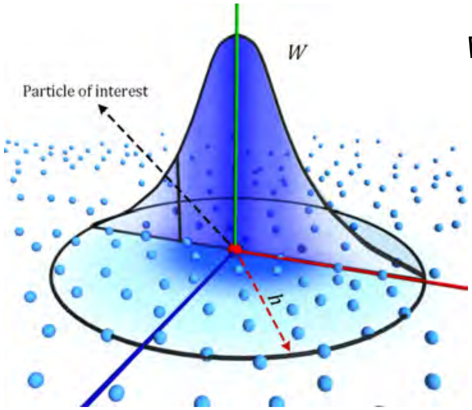
$$\boldsymbol{v}_{t+\Delta t} = \boldsymbol{v}_t + \Delta t \boldsymbol{a}_t$$
$$\boldsymbol{r}_{t+\Delta t} = \boldsymbol{r}_t + \Delta t \boldsymbol{v}_{t+\Delta t}$$

- Compressibility model

$$\boldsymbol{v}_i^* = \boldsymbol{v}_i(t) + \Delta t(-\sum_j m_j \Pi_{ij} \nabla W_{ij}(t) + \boldsymbol{g})$$

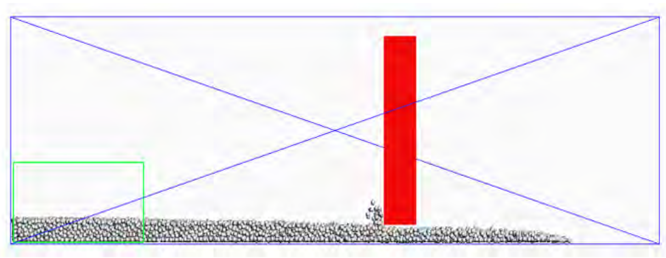
$$\rho_i^* = \rho_i(t) + \Delta t \sum_j m_j (\boldsymbol{v}_i^* - \boldsymbol{v}_j^*) \cdot \nabla W_{ij}(t)$$

$$\nabla^2 p_i(t) = \frac{\rho_0 - \rho_i^*}{\Delta t^2}$$

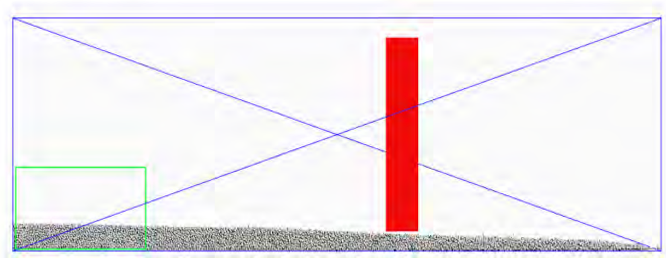


Particle Spacing Selection

- 0.0625 m particle spacing



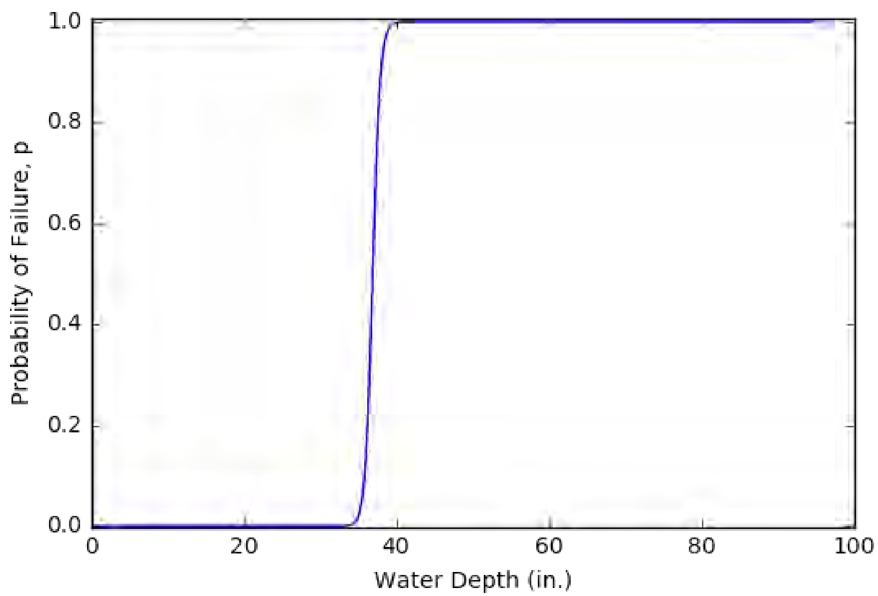
- 0.03125 m particle spacing

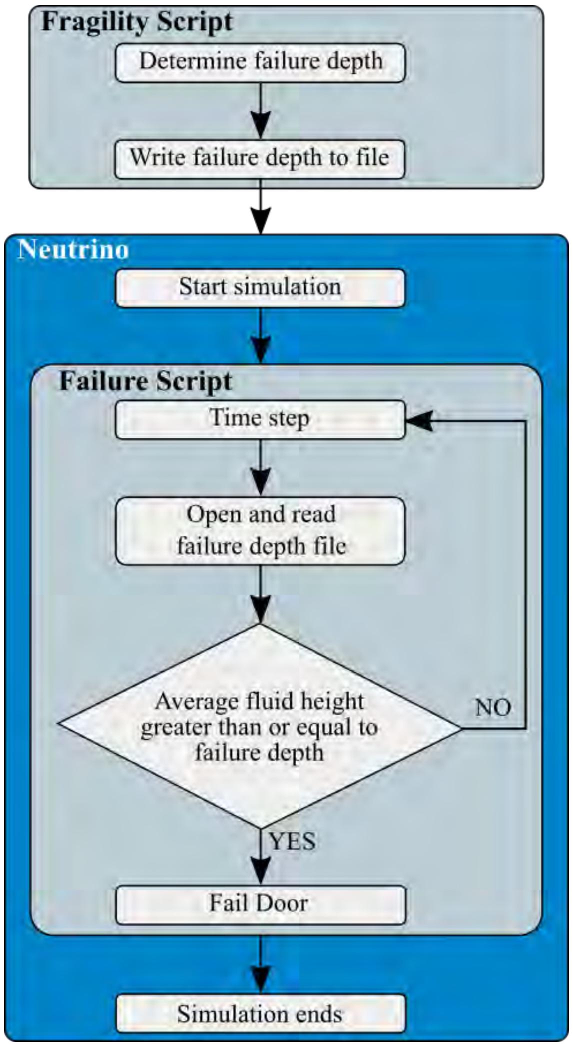


Simulation Overlay

Fragility Integration

- Flooding fragility can improve simulation to realistically model component behavior
- Couple fragility model to Neutrino via Python dynamic expression scripts





Simulation with Fragility

Conclusion

- Significant progress has been made in all three pathways
  - Walk-then-run approach for experiment activities
  - Detailed research on SPH validation and particle spacing selection
  - Detailed research on fragility model development
  - Coupling of fragility models and flooding simulation

Idaho State University

References

PUBLICATIONS

- E. D. Ryan, C. L. Pope, Coupling of the Smoothed Particle Hydrodynamic Code Neutrino and the Risk Analysis Virtual Environment for Particle Spacing Optimization, *Nuclear Technology*, DOI: 10.1020/00295450.2019.1704576.
- A. Wells, E. Ryan, B. Savage, A. Tahhan, S. Suresh, C. Muchmore, C. L. Smith, and C. L. Pope, "Non-watertight Door Performance Experiments and Analysis Under Flooding Scenarios," *Results in Engineering*, **3** (2019)
- E. D. Ryan, B. M. Savage, C. L. Smith, C. L. Pope, "Comparison of Free Surface Flow Measurements and Smoothed Particle Hydrodynamic Simulation for Potential Nuclear Power Plant Flooding Simulation," *Annals of Nuclear Energy* **126** (2019).
- A. Tahhan, C. Muchmore, L. Nichols, A. Wells, G. Roberts, E. Ryan, S. Suresh, B. Bhandari, C. L. Pope, "Development of Experimental and Computational Procedures for Nuclear Power Plant Components Under Flooding Conditions, *Proceedings of the 2017 25th International Conference on Nuclear Engineering* (2017).

ROAR

Idaho State University

References

TECHNICAL REPORTS

- *Nuclear Power Plant Component Flooding Fragility Research,* C. L. Pope, B. Savage, S. Jash, B. Johnson, C. Muchmore, L. Nichols, E. Ryan, S. Suresh, A. Tahhan, R. Tuladhar, A. Wells, C. L. Smith, INL/EXT-18-45247, Idaho National Laboratory, Research Report (2018).
- *Nuclear Power Plant Mechanical Component Flooding Fragility Experiments FY-2017 Report*, C. L. Pope., B. Savage, B. Johnson, C. Muchmore, L. Nichols, G. Roberts, E. Ryan, S. Suresh, A. Tahhan, R. Tuladhar, A. Wells, C. Smith, INL/EXT-17-43439, Idaho National Laboratory, Research Report (2017).
- *Nuclear Power Plant Mechanical Component Flooding Fragility Experiments Status*, C. L. *Pope*, B. Savage, B. Johnson, C. Muchmore, L. Nichols, G. Roberts, E. Ryan, S. Suresh, A. Tahhan, R. Tuladhar, A. Wells, C. Smith, INL/EXT-17-42728, Idaho National Laboratory, Research Report (2017).
- *Flooding Fragility Experiments and Prediction,* C. Smith, B. Bhandari, C. Muchmore, A. *Tahhan*, A. Wells, L. Nichols, C. L. Pope, INL/EXT-16-39963, Idaho National Laboratory, Research Report (2016).
- *Status of the Flooding Fragility Testing Development,* C. L. Pope, B. Savage, A. Sorensen, B. *Bhandari*, D. A. Kamerman, A. Tahhan, C. Muchmore, G. Roberts, E. Ryan, S. Suresh, A. Wells, C. Smith, INL/EXT-16-39115, Idaho National Laboratory, Research Report (2016).
- *Progress on the Industry Application External Hazard Analyses Early Demonstration*, C. L. Smith, S. Prescott, J. Coleman, E. Ryan, B. Bhandari, S. Sludern, C. L. Pope, R. Sampath, INL/EXT-15-36749, Idaho National Laboratory, Research Report (2015).
- *Industry Application External Hazard Analyses Problem Statement*, R. H. Szilard, J. Coleman, C. L. Smith, S. Prescott, A. Kammerer, R. Youngblood, C. L. Pope, INL/EXT-15-36101, Idaho National Laboratory, Research Report (2015).

ROAR

Idaho State University

References

PHD STUDENTS

- Alison Wells, PhD, *Assessing Nuclear Power Plant Component Fragility in Flooding Events using Bayesian Regression Modeling with Explanatory Variables* (defense scheduled for April 3, 2020)
- Emerald Ryan, PhD, *Determination, Development, and Validation of a Fluid Height Analysis Method and Particle Spacing Protocol for the Smoothed Particle Hydrodynamic Code Neutrino* (2019)

MS STUDENTS

- Cody Muchmore, MS, *Categorization and Evaluation of Spray Patterns from Pipe Leaks,* (2018)
- Antonio Tahhan, MS, *Performance Improvements to the Portal Evaluation Tank, Characterization Analysis of Nuclear Power Plant Component Flooding Tests* (2018)
- Soumadipta Jash, MS, *Instrumentation for Measuring Velocity of Wave Produced by Wave Impact Simulation Device for the Idaho State University Component Flooding Evaluation Laboratory* (2018)
- Sneha Suresh, MS, *Development of an Interior Component Flooding Fragility Model and Design of Component Evaluation Flooding Laboratory Safety Circuit* (2017)
- Emerald Ryan, MS, *Construction of a Smoothed Particle Hydrodynamic Model for Flow Over an Ogee Spillway Comparison to Determine Viability in Modeling Flooding Scenarios* (2016)
- Bishwo Bhandarai, MS, *Full Scale Door Testing Under Flooding Conditions to Develop Testing Protocol* (2016)
- David Kamerman, MS, *The Use of Flooding Fragility Curves in Nuclear Power Plant Risk Analysis* (2016)

ROAR