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Use of Flooding Probabilistic Risk Assessment

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Changing the World's Energy Future

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Idaho National Laboratory

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Outline of my talk today

- **SDP related to flooding in US**
- **Door integrity tests at Idaho State University**
- **Smoothed Particle Hydrodynamics for external flooding**
- **NRC-INL Flood Barrier project**

SDP related to flooding in US

SDP related to flooding in US NRC

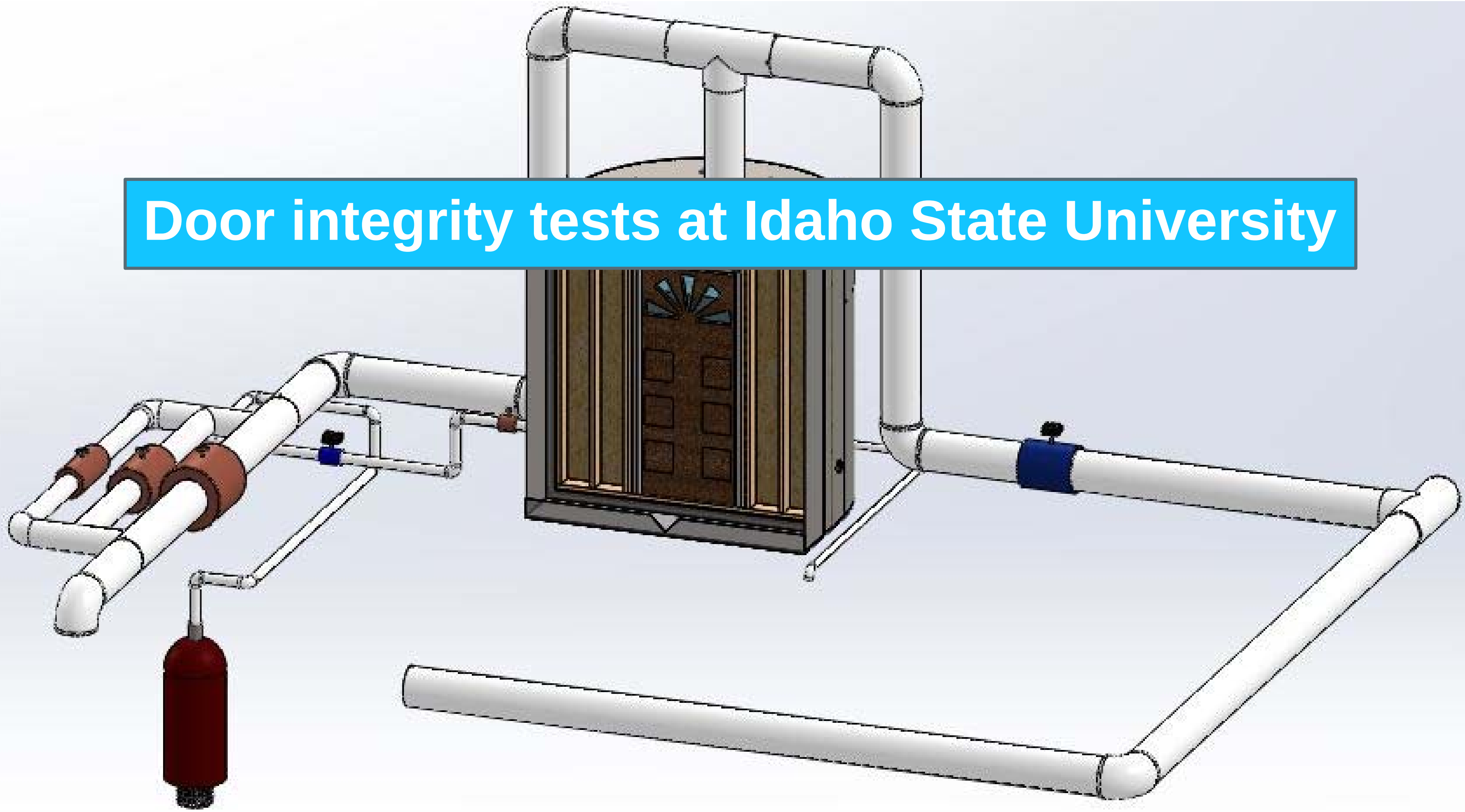
- **Collected information from public NRC documents related to SDP for flooding**
- **NRC ROP includes determining safety significance of inspection findings through SDP**
  - Specific hazards are evaluated → external flooding a challenge
    - Site-specific hazard that depends on geographical, meteorological, hydrological, and hydraulic information needed to characterize potential events relevant to the site
    - Limited data available to characterize PRA tools
- **NRC technical guidance does exist**
  - IMC 0609 Appendix A, Risk Assessment Standardization Project (RASP) handbooks
- **Several events have been evaluated**
- https://www.nrc.gov/docs/ML1515/ML15152A315.pdf
- **Items that correlate back to application of PRA**
  - Modeling of flooding sequences
  - Quantification of SSCs and flood protection that are credited in specific scenarios
  - Evaluation of operator manual actions outside the control room involving flood mitigation

NPP Site	Significance Determination	Reference
St. Lucie[†]	White	ML14294A466
Ginna	White	ML14107A080
Point Beach	White	ML13221A187
Monticello[†]	Yellow	ML13240A435
Dresden	White	ML13213A073
Three Mile Island	White	ML13042A277
Watts Bar[*]	White	ML13155A572
Watts Bar[*]	Yellow	ML13155A572
Sequoyah[*]	White	ML13155A560
Sequoyah[*]	White	ML13155A560

Examples of flood SDP

- **Oconee Standby Shutdown Facility (ML14058A051)**
  - Open penetration into SSF for two years
  - Opening below maximum flood height identified by licensee (5 feet)
  - Susceptible to up-stream dam failure
    - Independent analysis indicated 12 feet flood possible
  - Analysis indicated possible WHITE finding
- **Fort Calhoun Flooding Strategy (ML15152A315)**
  - January 2010, NRC identified inadequacies of buildings protection against floods
    - Site flood protection strategy may not be fully effective during scenarios
    - NRC determined that a “Yellow” finding was appropriate
  - Specific challenges associated with flooding after Fukushima were highlighted
    - Credit for hardening a facility prior to flood waters affecting the site
    - Assessing credit for limited available actions during a flood scenario based on timing availability (e.g., procuring additional equipment during or after the flood)
  - Consideration of information provided by licensee via qualitative IMC 0609 Appendix M approach in SDP was also evaluated and the finding was reaffirmed as “Yellow”

Door integrity tests at Idaho State University

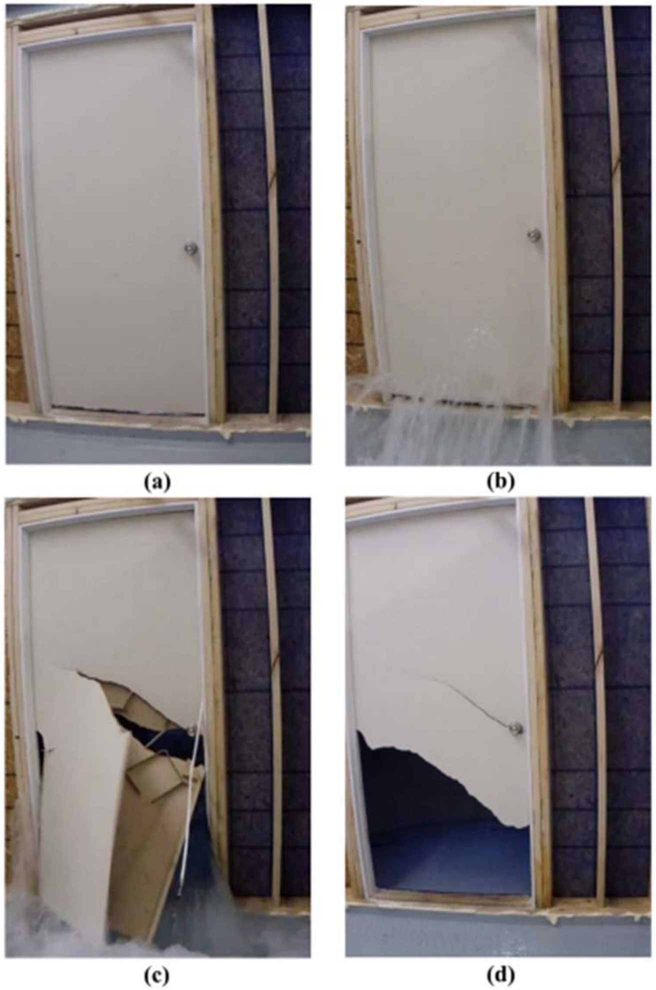


The Portal Evaluation Tank (PET)

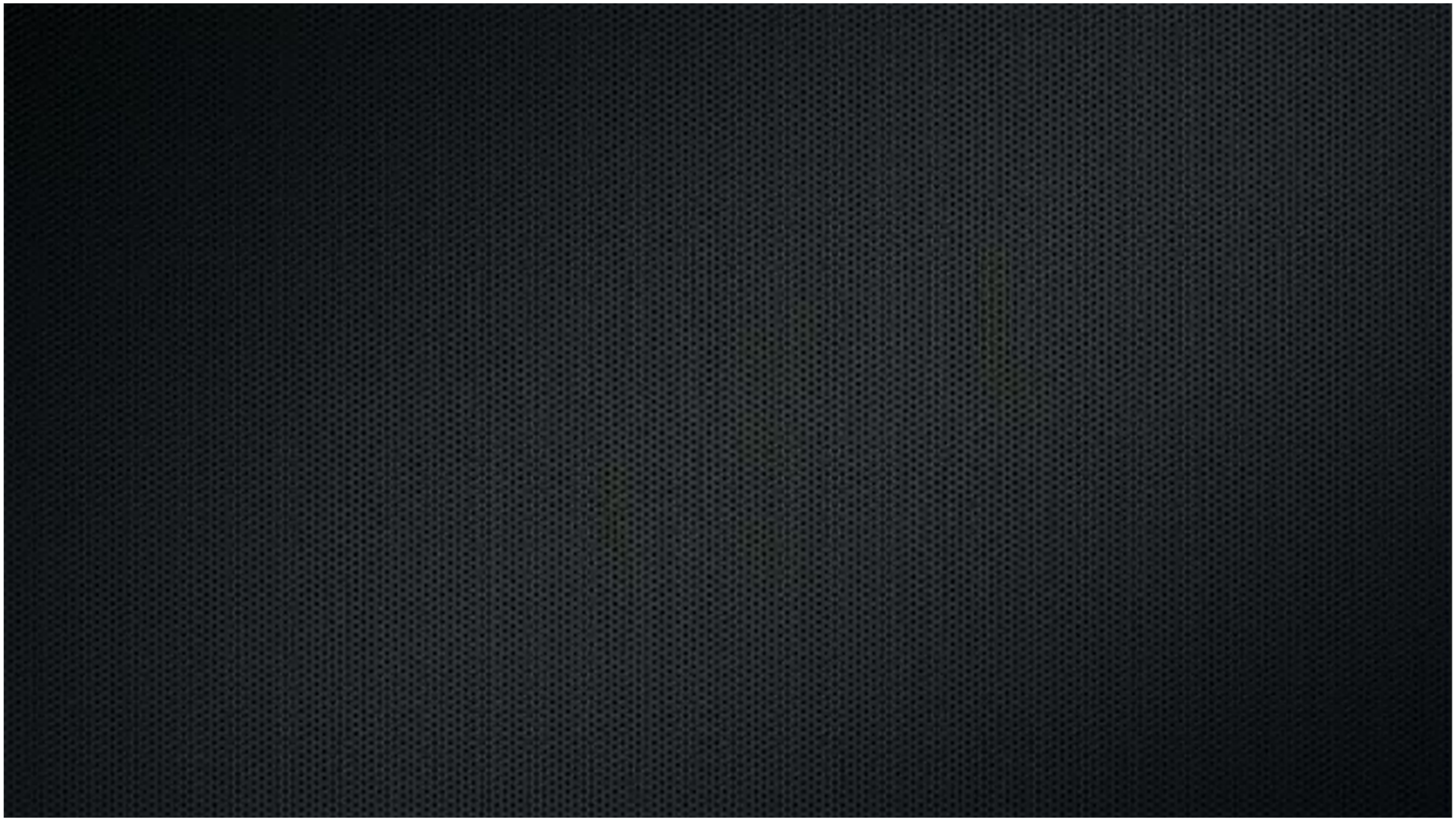
- **PET is a semi-cylindrical 7,500 liter capacity steel tank**
- **An opening environment of 2.4 x 2.4 m for installation**
- **PET is connected through 3 in. PVC pipe to a 5 Hp. submersible pump**
  - Located inside a 30,000 liter water reservoir
- **Instrumentation**
  - Electronic flow meter
  - Ultrasonic sensor
  - Pressure transducer
  - Pressure Gauge

Flooding Fragility Experiments

- **A door frame was constructed using building code and decreased stud spacing**
- **Initial tests used hollow core doors and involved water rise until catastrophic failure occurred or leak rate equalization**

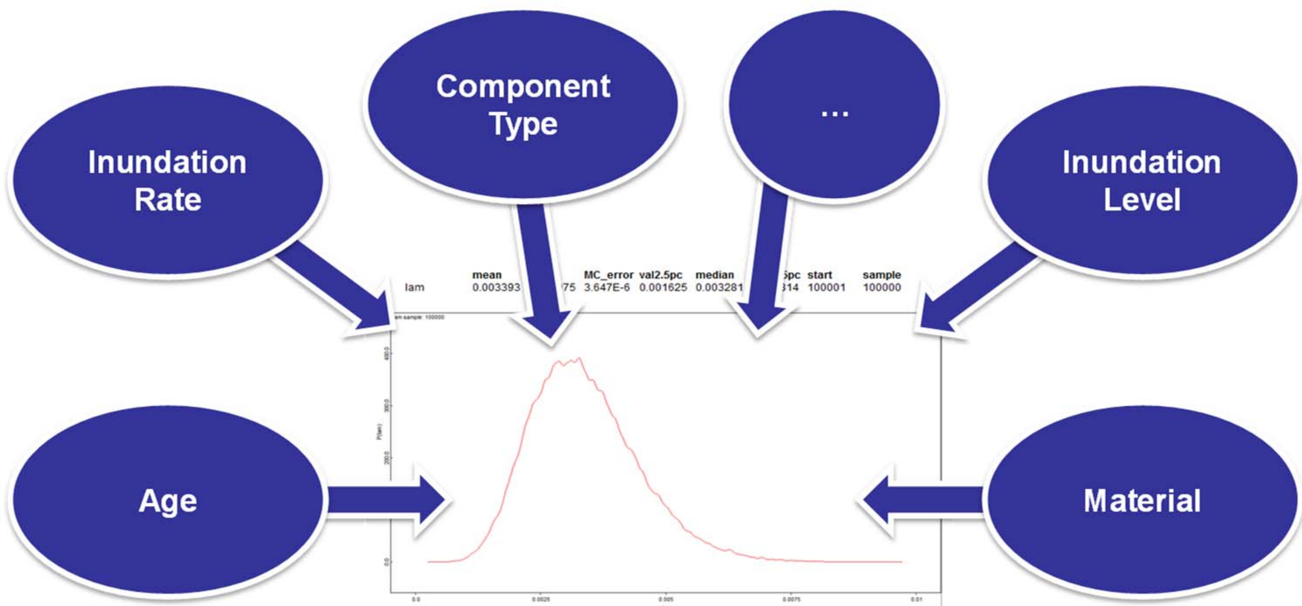


PET Video Demonstration



Flooding Bayesian Analysis

- **One of the complications for the flooding fragility modeling is the variety of observable phenomena related to the flood itself**
  - Some thought should be given to which factors might be the most important
- **An advantage of the Bayesian quantification approach is parameters in the regression model associated with unimportant factors should be found to be negligible**



Work Using PET Data

- **Eight complete sets of data**
  - Depth at failure or greatest depth achieved
  - Average flow rate
  - Average temperature
- **Door failure when damage is permanent & leakage increases in a short time (1)**
- **Success when an equilibrium state is reached between the flow and leakage rate (0)**
- **Also moved on to testing metal doors**

Depth (in)	Flow Rate (gal/min)	Temp (°F.)	Failure
23.23	291.5	65.98	0
20.75	292.5	67.04	0
42.3	292.5	66.02	1
21.05	297	67.67	0
24.22	294.5	66.6	0
35.41	292.5	66.87	1
40.76	291	68.33	1
38.85	294	68.14	1

INL-EXT-18-45247 - Nuclear Power Plant Component Flooding Fragility Research

Example of Flooding Model

- **The fragility model for this case looks at seven possibilities:**

1. $logit(p) = int + aD + bF + cT$
2. $logit(p) = int + aD$
3. $logit(p) = int + bF$
4. $logit(p) = int + cT$
5. $logit(p) = int + aD + bF$
6. $logit(p) = int + aD + cT$
7. $logit(p) = int + bF + cT$

```
#Flow Rate (F), Depth (D), and Temperature (T) Model
model    {
for(i in 1:tests) {
        failure[i] ~ dbern(p[i])
        # Regression model
        logit(p[i]) <- int + a*flow[i] + b*depth[i] + c*temp[i]
        # failure.rep[i] ~ dbin(p[i], num.tested)        # Replicate values for model validation
        # diff.obs[i] <- pow(failure[i] - num.tested*p[i], 2)/(num.tested*p[i]*(1-p[i]))
        # diff.rep[i] <- pow(failure.rep[i] - num.tested*p[i], 2)/(num.tested*p[i]*(1-p[i]))
        }
#chisq.obs <- sum(diff.obs[])
#chisq.rep <- sum(diff.rep[])
#p.value <- step(chisq.rep - chisq.obs)
# Prior distributions
int ~ dnorm(0, 0.0001)
a ~ dnorm(0, 0.001)
}
data
list(tests=8,
        flow = c(291.5,292.5,292.5,297,294.5,292.5,291,294) ,
        depth = c(23.23,20.75,42.3,21.05,24.22,35.41,40.76,38.85),
        temp = c(65.98,67.04,66.02,67.67,66.6,66.87,68.33,68.14),
        failure = c(0,0,1,0,0,1,1,1))
inits
list(int=0, a=0)
```

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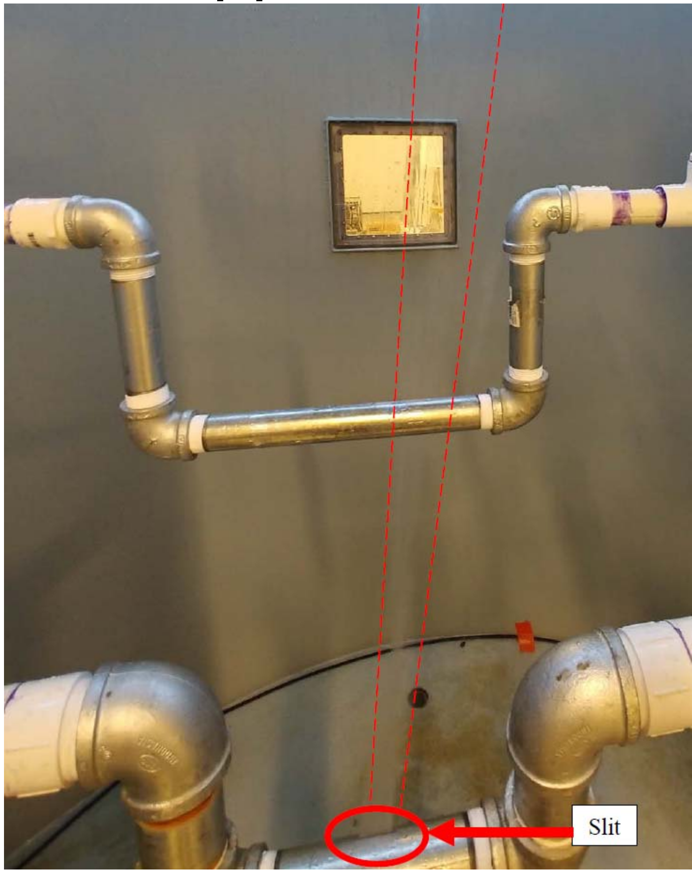
Results for the Cloglog equations

Parameter	Equ. 1	Equ. 2	Equ. 3	Equ. 4	Equ. 5	Equ. 6	Equ. 7
Intercept	10.84	-107.5	4.832	5.301	5.847	1.222	1.88
a *(depth coeff)*	47.88	3.705	–	–	45.31	35.61	–
b *(flow rate coeff)*	-10.84	–	-0.01814	–	-4.648	–	0.02401
c *(temp coeff)*	25.86	–	–	-0.08646	–	-15.89	-0.141
DIC	0.01568	0.2372	12.68	13.25	0.0174	0.0203	13.51

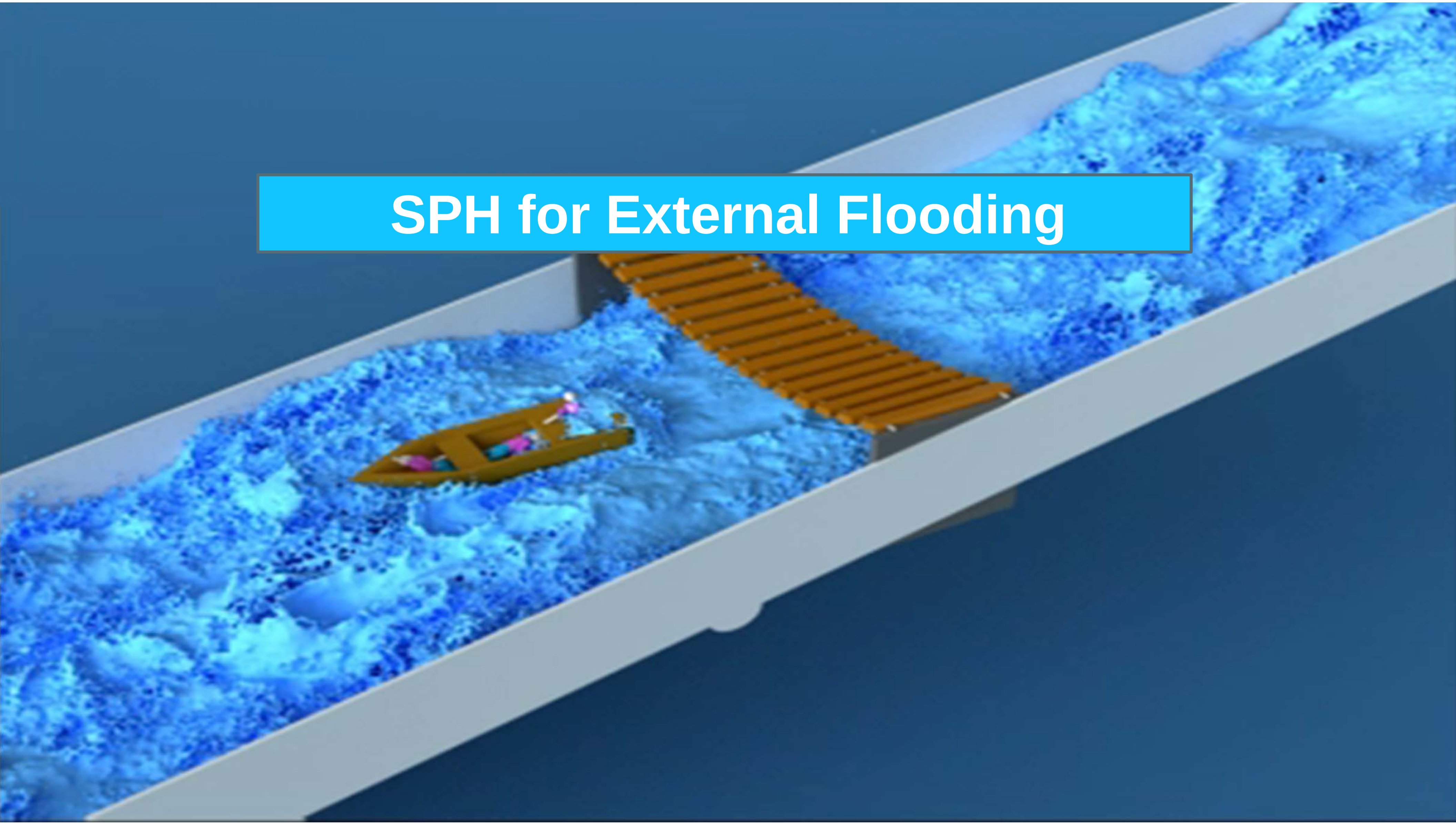
- **Deviance Information Criterion (DIC) can be used to examine the relative fit of a model**
  - Measure of relative goodness of fit
  - Smallest DIC indicates the best fitting model

Pipe break tests

- **ISU also performed tests to better understand water spray for breaks in pipes**

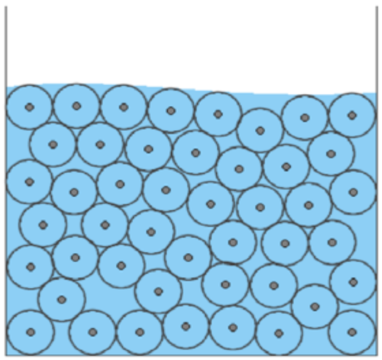


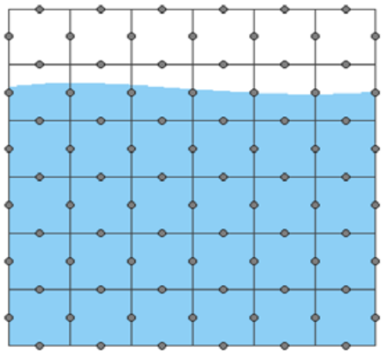
SPH for External Flooding



Smoothed Particle Hydrodynamics

- **A way to simulate flooding scenarios is needed**
- **Smoothed Particle Hydrodynamics (SPH)**
  - Particle based method
  - Originally developed for astrophysics applications in 1977
  - Later extended for fluid dynamic applications
- **SPH allows for flooding scenarios to be simulated**
  - Does not confine fluid to meshes
  - Allows for a natural flow to be modeled
- **A reliable SPH code is needed**
  - Compare to experimental results





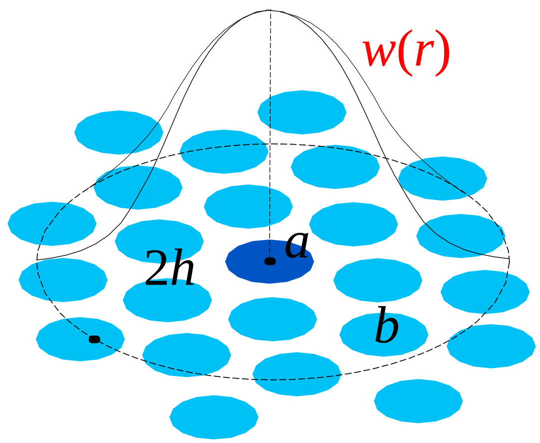
Introduction: SPH

- **Particles**
  - A particle is a minute fragment or quantity of matter’
- **Usual meanings in science**
  - Smallest constituents of matter (Standard Model)
  - Nanoparticles, colloidal particles
  - Dust, powder, ashes
  - Sediment grains, water droplets
- **The duality of ’particles’ in SPH**
  - They are material points
  - They have volume, mass, pressure, density, etc.

Introduction: SPH Interpolation

- Particle *a* has position $\mathbf{r}_a$, mass m_a, volume V_a, etc.
- Particle Interactions are computed using the '**kernel**' $w(r)$
- The support of w has size $2h$, h = **smoothing length,** w is normalized

$$w(r)d\mathbf{r} = 1$$

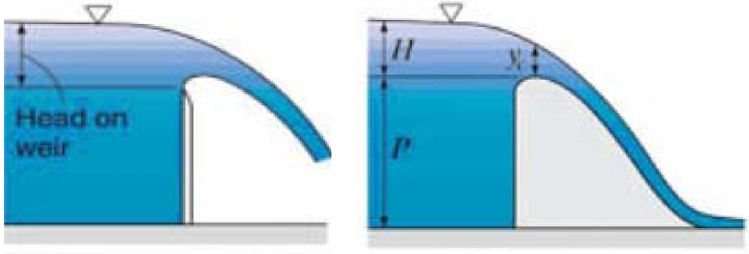


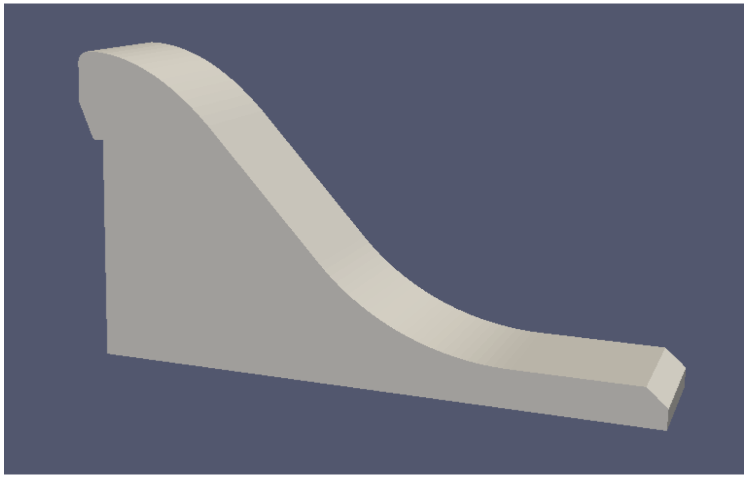
Lucy, L.B. (1977), Astron. J. **82**:1013–1024

Gingold, R.A., Monaghan, J.J. (1977), Mon. Not. R. Astron. Soc. **181**:375–389

Ogee Spillway Comparison

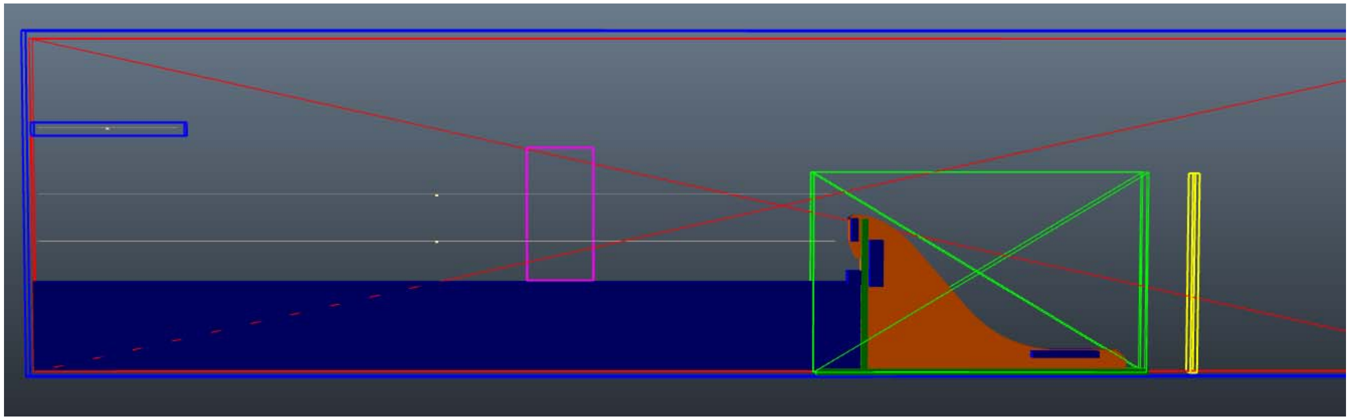
- **Comparison Model**
  - Ogee spillway with horizontal apron
  - Details of experiment provided in Flow over Ogee Spillway: Physical and Numerical Model Case Study by Bruce M. Savage and Michael C. Johnson
  - Experiment details (scaled model):
    - Measurements taken 2 m upstream
      - Flow Rate
      - Total Head
    - Ten different runs conducted
  - Prototype scale was used for the SPH comparison which required scaling the model scale up 30 times





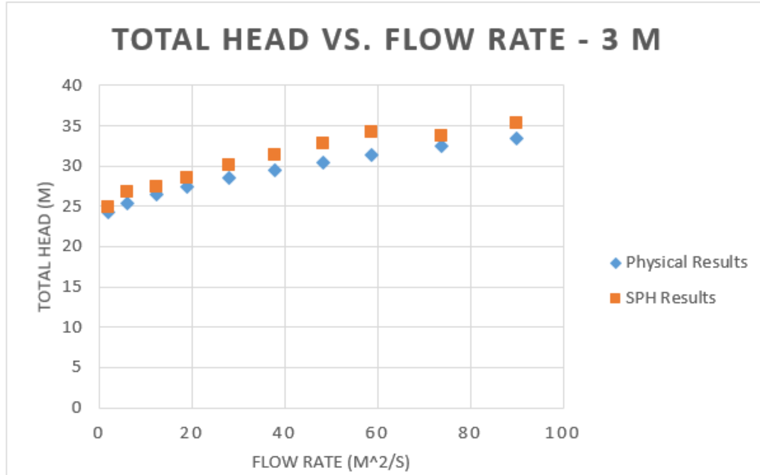
Neutrino Model

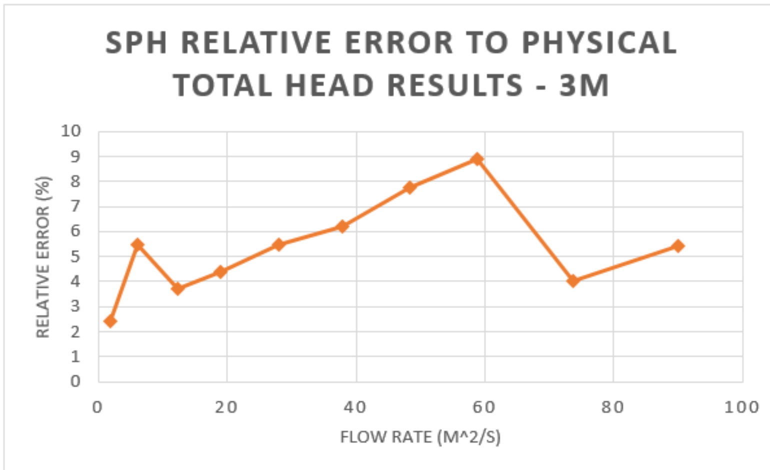
- **Developmental SPH code Neutrino was used to conduct the comparison**
- **Model construction process:**
  - Determine how to fill particles behind the spillway
  - Reduce leakage
  - Determine particle emitter location to set total head
  - Determine particle emitter location to set flow rate instead
  - Conduct parametric studies on model width and particle size
  - Reduce leakage again
  - Change particle emitter types



Comparison Results

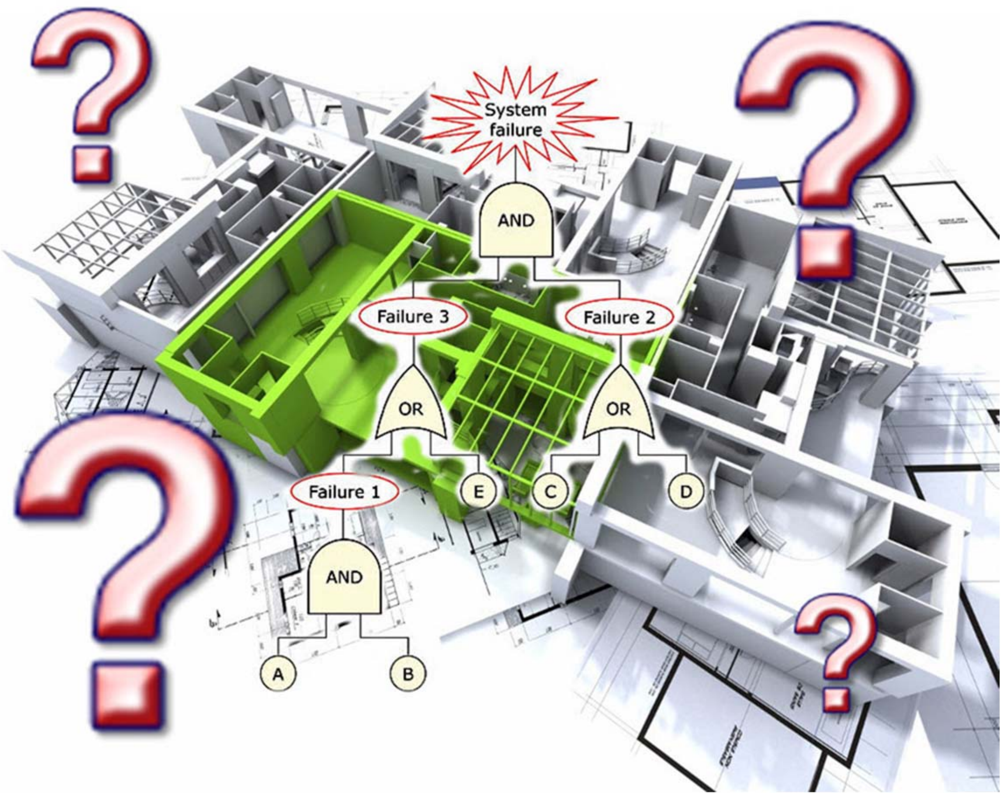
Run	Flow Rate	Physical Total Head Result	SPH Total Head Result	Relative Error
1	1.9 m^2/s ± 0.25%	24.3 m	24.9 m	2.4 %
2	6.0 m^2/s ± 0.25%	25.3 m	26.7 m	5.5 %
3	12.3 m^2/s ± 0.25%	26.5 m	27.5 m	3.7 %
4	19.0 m^2/s ± 0.25%	27.4 m	28.6 m	4.4 %
5	27.9 m^2/s ± 0.25%	28.5 m	30.0 m	5.5 %
6	37.8 m^2/s ± 0.25%	29.5 m	31.3 m	6.2 %
7	48.2 m^2/s ± 0.25%	30.4 m	32.8 m	7.7 %
8	58.9 m^2/s ± 0.25%	31.4 m	34.1 m	8.9 %
9	73.8 m^2/s ± 0.5%	32.4 m	33.7 m	4.0 %
10	89.9 m^2/s ± 0.5%	33.5 m	35.3 m	5.4 %





How to Join Physics Model & System Model

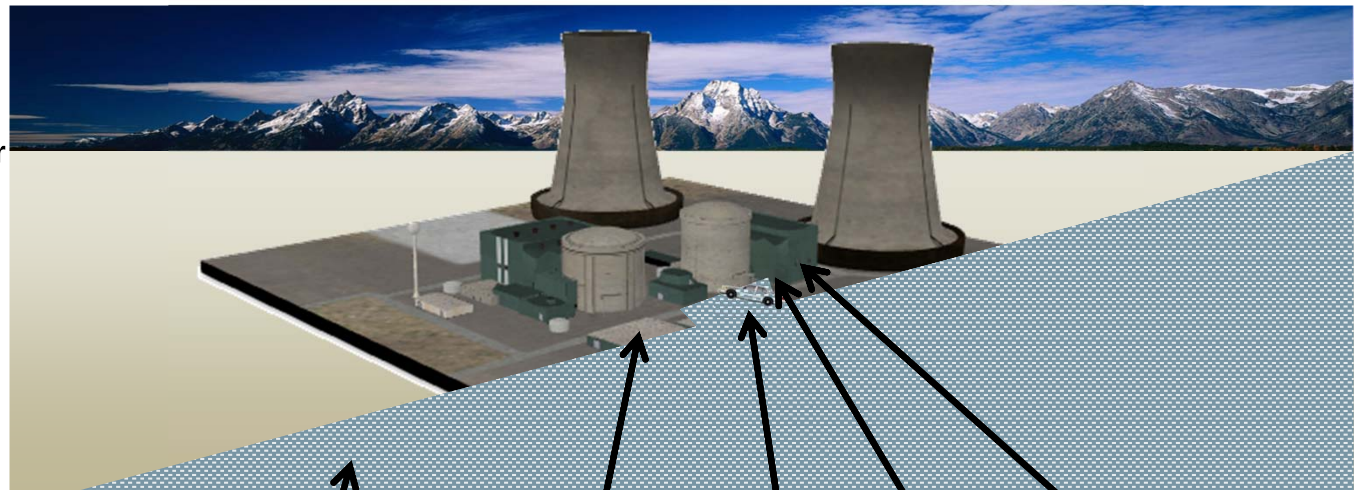
- **Good - Run repeated simulations and add the failure information into the existing static models**
- **Best – Dynamic PRA model that can interact with the simulation**
  - No corrections needed for time dependent calculations
  - Determine average or mean time of particular outcomes
  - Analyze time order of failures to determine early protection methods



Risk Analysis Steps for Scenario Generation

Enabling Conditions → Flood → Plant SSC Response to Initiator → SSC Failures & Successes → Scenario Simulation

3D Models for the Facility including Systems, Structures, & Component (SSC)



Computational Layers Used for the Analysis

Probabilistic events

Seismic

Flooding: Hazard Freq. | Static/Dynamic Loads | Debris | Water Migration | Fragilities

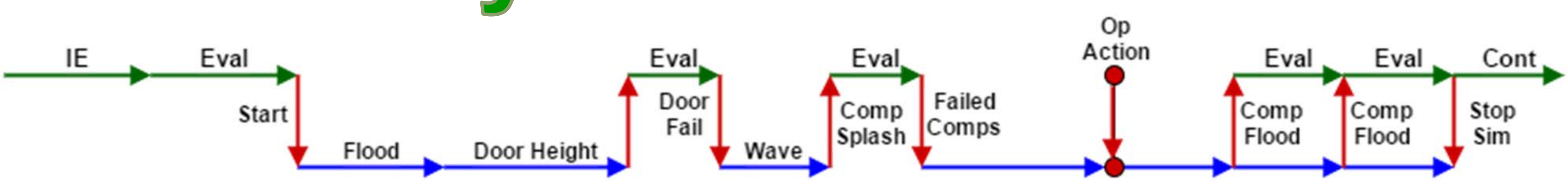
. . .

Thermal-hydraulics

Timing is Everything

- **Physics simulation are dynamic and time dependent**
- **Control logic is not always available in simulations**
- **Need to modify the behavior of the simulation at during execution.**

System Model



Simulation

Modeling Options

- **Time Steps**
- **Next event in time (EMRALD)**

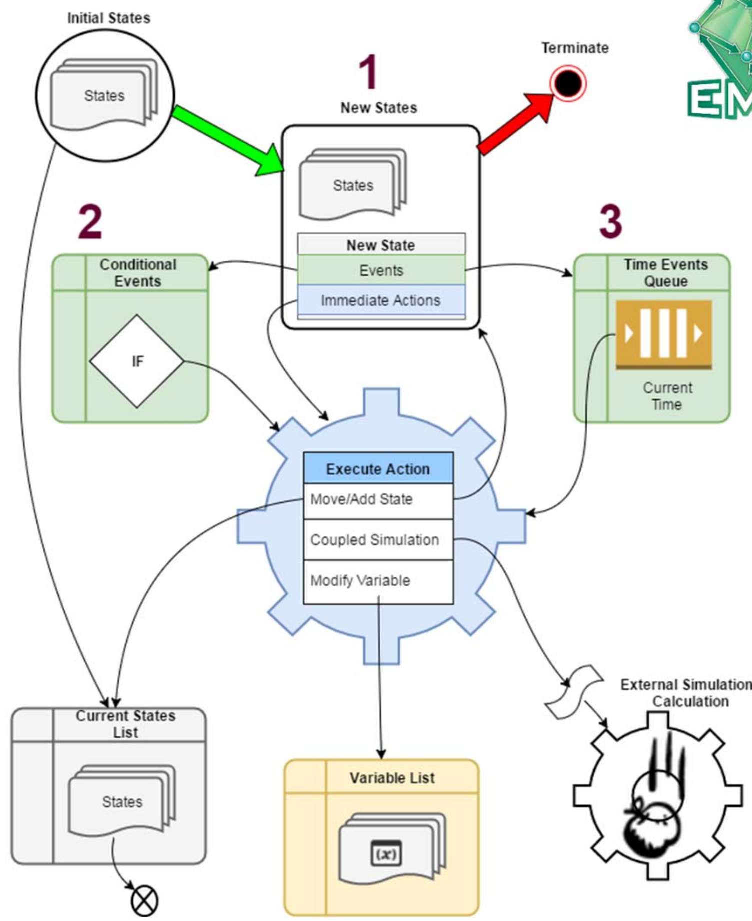
Dynamic probabilistic risk assessment (PRA) model based on a three-phased discrete event simulation

To begin, add initial start states to Current and New States List

1. While there are States in the New Sates list, For each State :
   - Add the Events to the Time Queue or Conditional List.
   - Execute any Immediate Actions

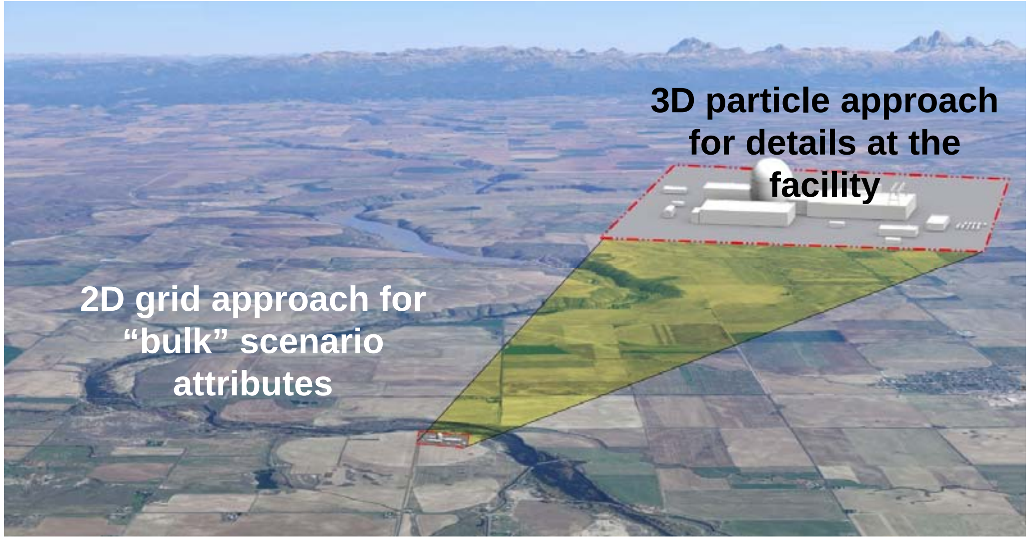
2. If any Conditional Events criteria is met.
   - Execute that events action/s.
   - (Go to Step 1)

3. Jump to the next chronological event.
   - Process that event's actions.
   - (Go to Step 1)



River flood modeling

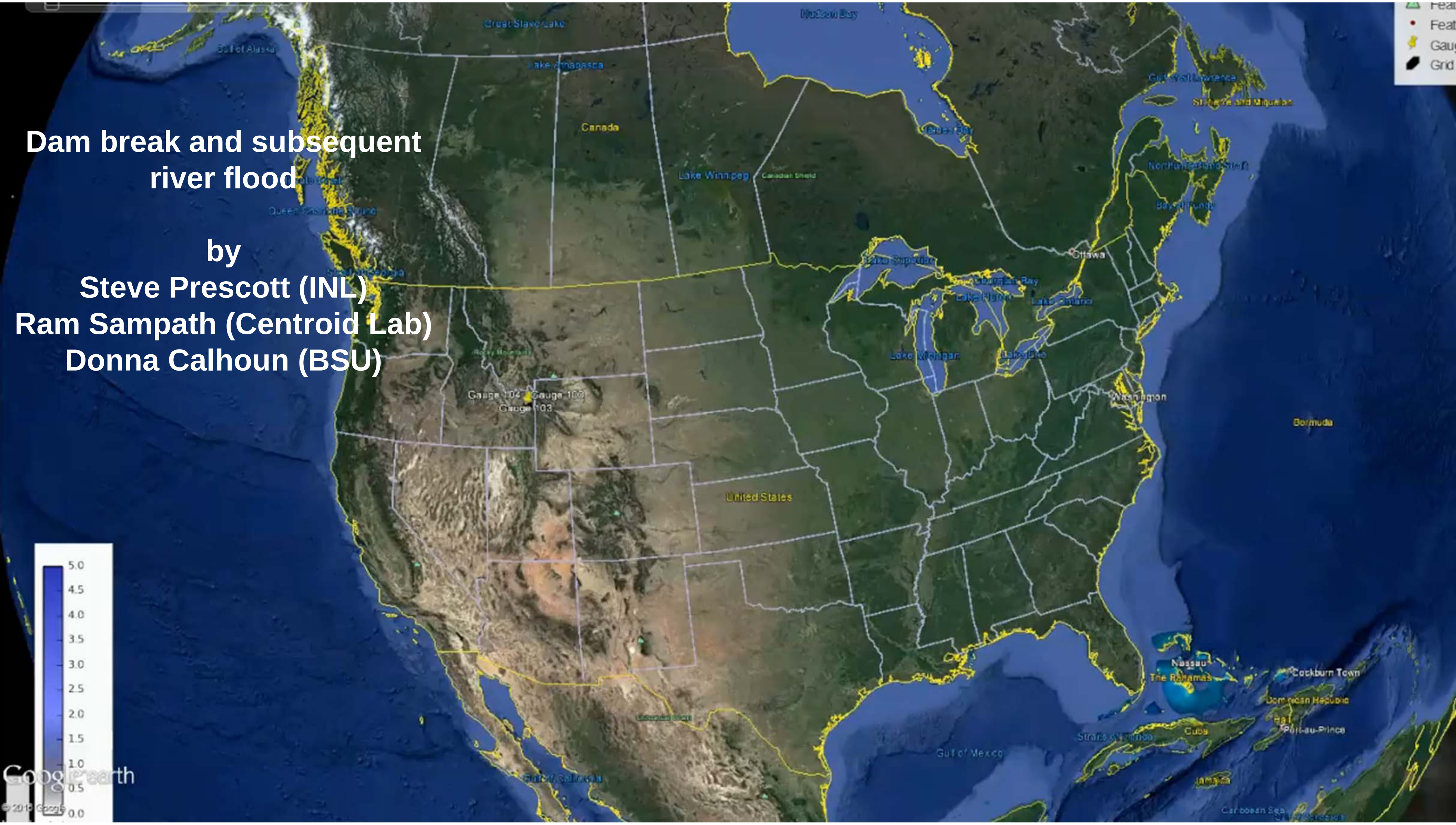
- **INL/EXT-15-37091, Flooding Capability for River-based Scenarios**
- **Evaluated two different types of potential river-based flooding tools**
  - 1D/2D grid based (GeoClaw, EPA's SWMM code, and Army Corps HEC)
  - 3D particle based
  - Both the 2D and 3D methods have positives and negatives
- **Combination of both seems to be best approach moving forward**



Dam break and subsequent river flood

by

Steve Prescott (INL)
Ram Sampath (Centroid Lab)
Donna Calhoun (BSU)



NRC-INL Flood Barrier Project

Project overview

- **Project will identify and assess options and develop strategies for testing nuclear power plant (NPP) flood barriers**
  - Including permanent components such as flood penetration seals, water tight doors as well as temporary flood protection features
  - Flood barriers external to the plant (e.g., earthen berms, aqua berms, sandbags) are not a focus of the review
  - Will look for information that may be useful when developing strategies for testing (e.g. prospects for harvesting, in-situ non-destructive testing or enhanced inspection, in-situ destructive testing)
- **Project is part of NRC's Probabilistic Flood Hazard Assessment (PFHA) Research Program**
- **Looking at decommissioning plants for likely source for harvesting**
  - Visited Oyster Creek during December 2019
- **Recently completed draft report → Goal to publish NUREG**
- **Will be supporting flood barrier testing workshop during the week of the NRC Regulatory Information Conference**
  - Thursday and Friday (March 12-13)

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Thank you!