Modeling Total Plant Response to Flooding Events

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Idaho National Laboratory

Contents

I. Background

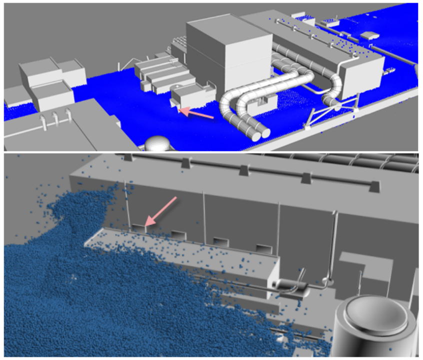
- External Flood hazard could interrupt offsite power, threaten safety important SSCs and limit plant access
- They have often been qualitatively assessed as risk insignificant and screened out from detailed evaluation in the past
- Total plant response should be evaluated to ensure that flood protection features and mitigation measures are adequate

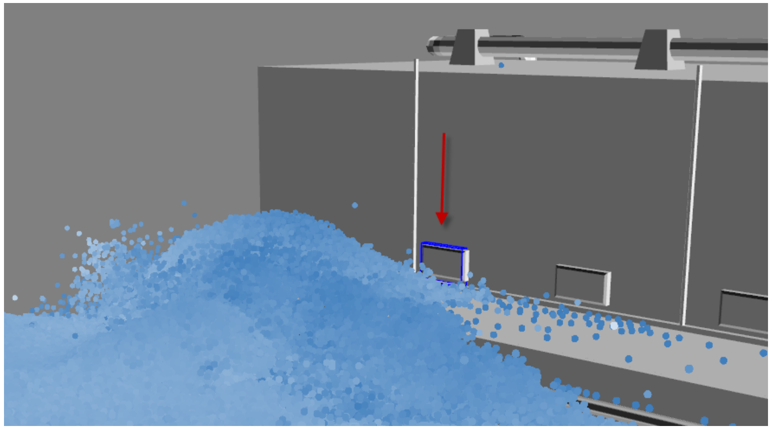
I. Background (Cont.)

- Unique challenges exist for a comprehensive external flooding analysis:
  - Flood protection may be a function of flooding levels (spatial)
  - Degree of flooding may influence the rate of stochastic or common cause failures (dynamic)
  - Response relies heavily on procedures and manual actions
  - Feasibility and reliability of actions can be impacted by the flooding (dynamic and spatial)
  - Duration of the flooding event can be quite long and onsite conditions may change throughout the event
- Might be difficult to capture in static models

I. Background (Cont.)

- This project explores dynamic analysis approaches that depict scenarios through simulation methods
  - an alternative for representing highly time- and location-dependent nature of flooding response
- Proof-of-concept project
- Local Intense Precipitation (LIP) as the case study
- Focus on total plant response to external flooding, not details of hazard or fragility analysis



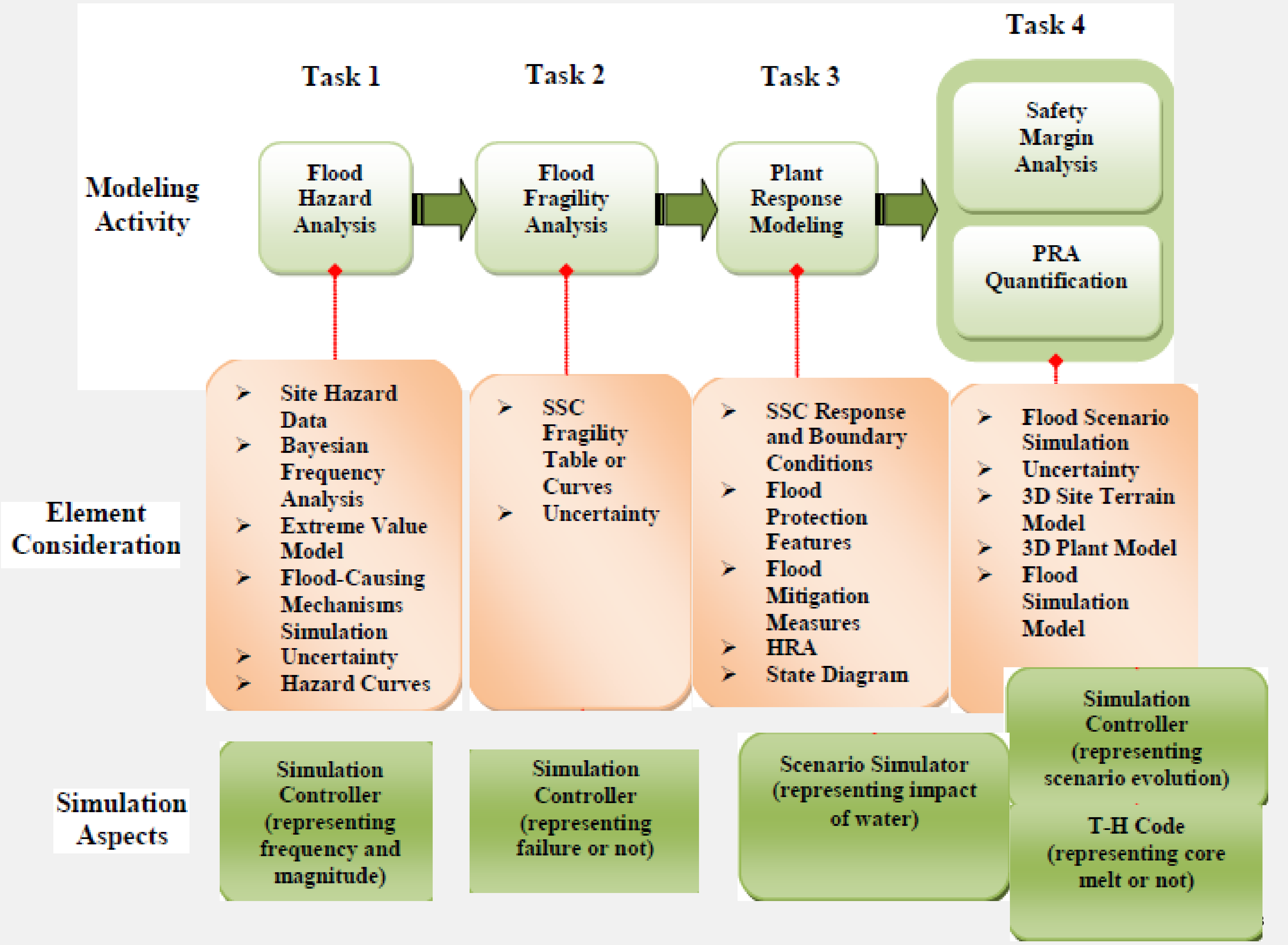


I. Background (Cont.)

- The project started September 2014
  - NRC COR is Dr. Joseph Kanney
  - INL PI is Dr. Curtis Smith
- The project has four specific tasks
  - Task 1 - Work Plan Development
    - Completed in March 2015
  - Task 2 - Margins Assessment Approach for Local Intense Precipitation External Flooding Events
    - Completed in September 2015
  - Task 3 - PRA Approach for Local Intense Precipitation External Flooding Events
    - Completed in September 2016
  - Task 4 - Knowledge Transfer
    - Seminar – completed in October 2016
    - PFHA Research Workshop – January 2017
    - NUREG/CR Report – April 2017

II. Simulation Based Dynamic Flooding Analysis Framework

- External Flood Hazard Analysis
  - Evaluates the frequency that parameters representing flood magnitude (e.g., flood elevation) will be exceeded at a site based on site-specific probabilistic evaluation
- External Flood Fragility Analysis
  - Identify plant SSCs that are susceptible to the effects of external floods
  - Determine their plant-specific failure probabilities as a function of the magnitude of the external flood
- External Flood Plant Response Analysis
  - Develop plant response model to address the initiating events and other failures resulting from the effects of external flood that can lead to core damage or large early release
- External Flood 3D Simulations and PRA Quantification
  - Develop 3D flood scenario simulations that represent component or system behavior, as well as human actions
  - Interact with plant response model by providing flood-induced failures
  - Quantify plant response model


Task 1
Task 2
Task 3
Task 4
Modeling Activity
Flood Hazard Analysis
Flood Fragility Analysis
Plant Response Modeling
Safety Margin Analysis
PRA Quantification
Element Consideration
Site Hazard Data
Bayesian Frequency Analysis
Extreme Value Model
Flood-Causing Mechanisms Simulation
Uncertainty
Hazard Curves
SSC Fragility Table or Curves
Uncertainty
SSC Response and Boundary Conditions
Flood Protection Features
Flood Mitigation Measures
HRA
State Diagram
Flood Scenario Simulation
Uncertainty
3D Site Terrain Model
3D Plant Model
Flood Simulation Model
Simulation Aspects
Simulation Controller (representing frequency and magnitude)
Simulation Controller (representing failure or not)
Scenario Simulator (representing impact of water)
Simulation Controller (representing scenario evolution)
T-H Code (representing core melt or not)

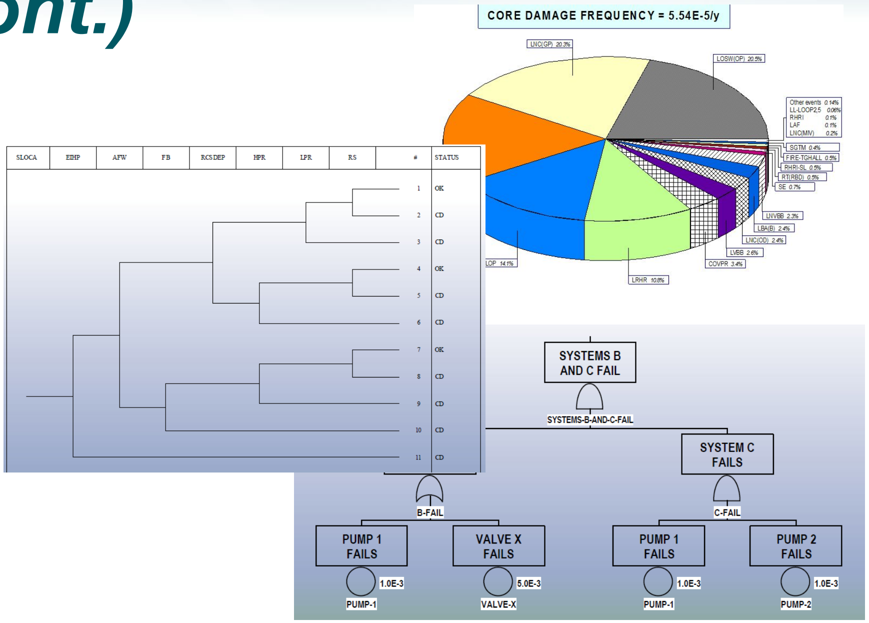
II. SBDFA Framework (Cont.)

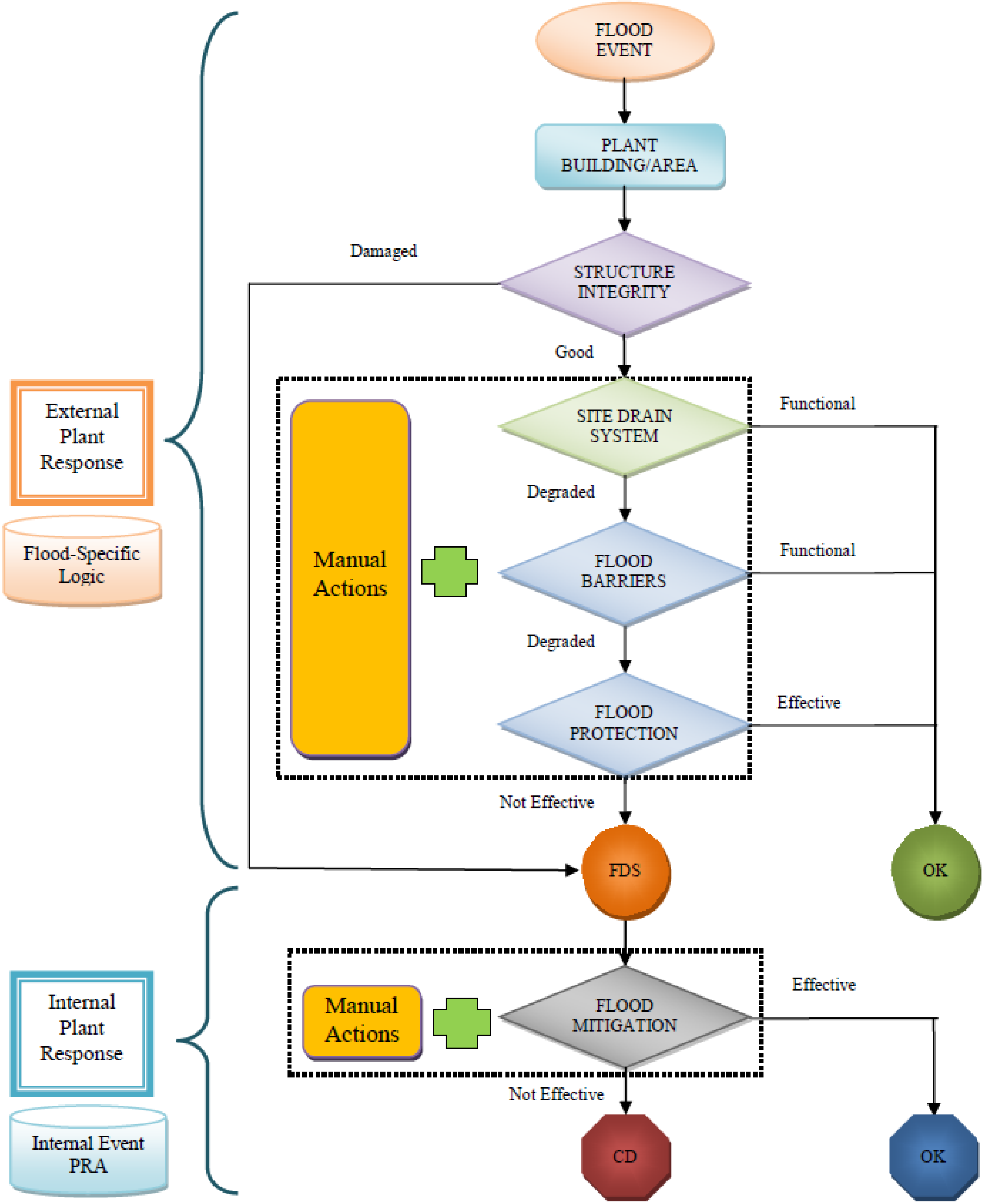
- Develop plant response model that includes
  - External flood-caused initiating events
  - External flood-induced SSC failures
  - Unavailabilities and failures not induced by external flood
  - Human errors
- Two-stage response model
  - External plant response – flood protection features
    - As-designed features (site drain system, water-tight doors and penetration seals, etc.)
    - Temporary features (portable pumps, sandbag barriers, etc.)
  - Internal plant response
    - Plant mitigation measures and manual actions to maintain key safety functions and prevent core damage and large early release

II. SBDFA Framework (Cont.)

- Internal plant response modeling could use existing at-power, internal event (including internal flooding) PRA model as the basis and modify as necessary

- External plant response modeling may need new, flood mechanism-specific analysis for the site

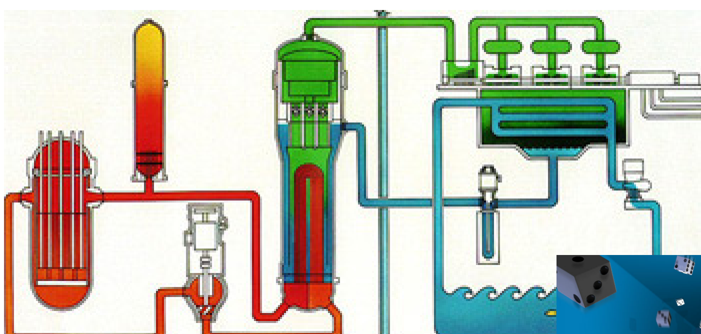


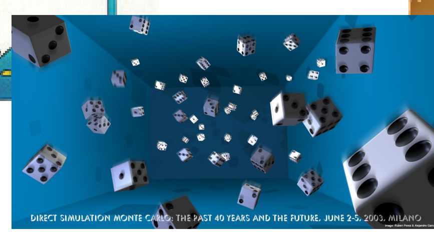


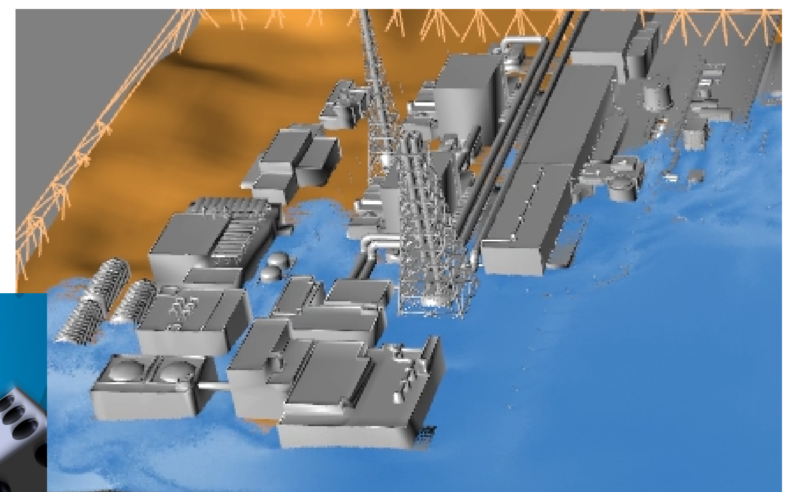
- Two-stage response model
  - External plant response – flood protection features
  - Internal plant response - flood protection and/or mitigation measures

II. SBDFA Framework (Cont.)

- It may be challenge for static models to represent highly time- and spatial-dependent flooding events
- Simulation-based dynamic analysis can be helpful
  - Integrates simulation and time elements into the logic models
  - Advanced 3D modeling and simulations
  - Monte Carlo simulations, 3D physical simulations, and mechanistic analysis are coupled together







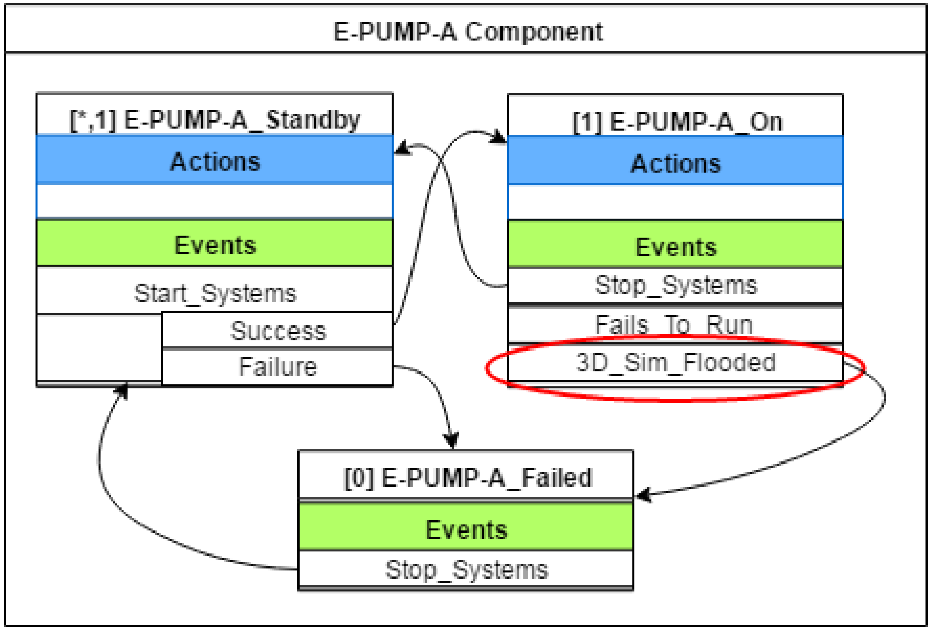
II. SBDFA Framework (Cont.)

- EMRALD – Event Model Risk Assessment using Linked Diagrams
- Uses “states” to represent and track the conditions of the SSCs in the model
- A set of states is represented at any given moment within the mission time
- The set of current states could change over the time until a terminal state is reached
- The model can represent the flooding event dynamically and determine
  - Which components fail?
  - When components fail?
  - What caused their failure?
  - What impact these failures have on the systems?
  - What impact system failure have on the overall plant?

II. SBDFA Framework (Cont.)

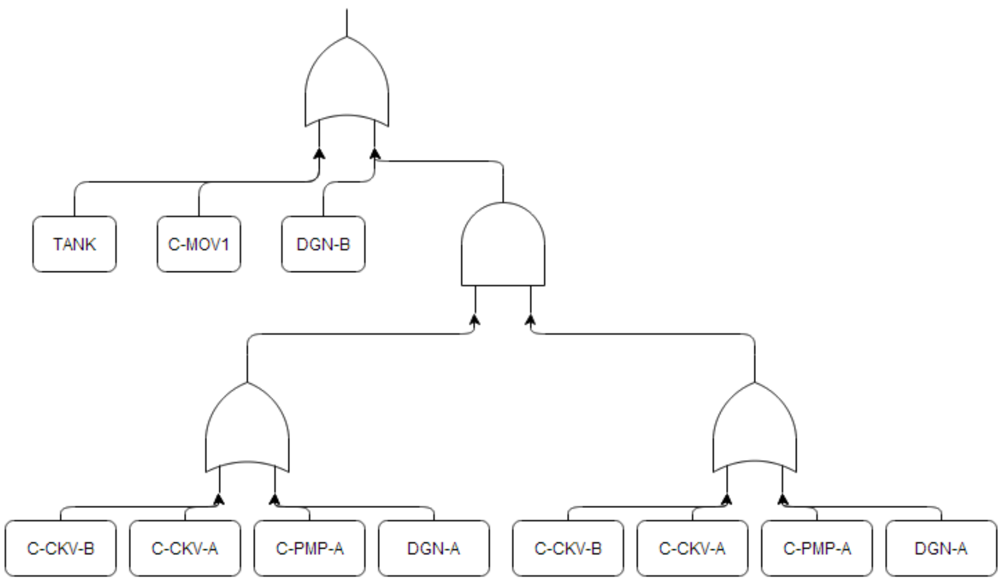
- State-Based Component Modeling

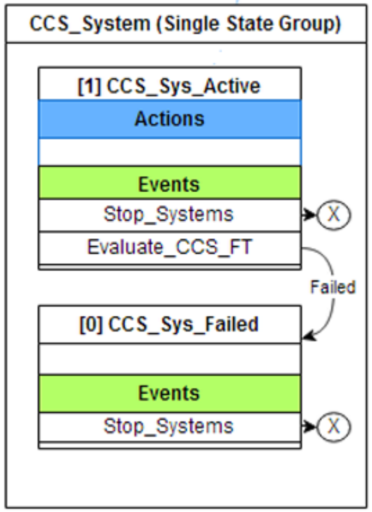
- Standby, On, Failed states
- Designation [1] for success
  [0] for failure
- Monte Carlo Sampling
  - Fail-to-start probability
  - Fail-to-run probability
    - Timer for mission time
- 3D flood simulation failure feedback



II. SBDFA Framework (Cont.)

- State-Based System Modeling
- Active, Failed states
- Evaluate system logic diagram
  - Component-specific basic events in EMRALD:
    C-PMP-A, …
  - Failure mode-specific basic events in SAPHIRE:
    C-PMP-A-FS, C-PMP-A-FR, ...



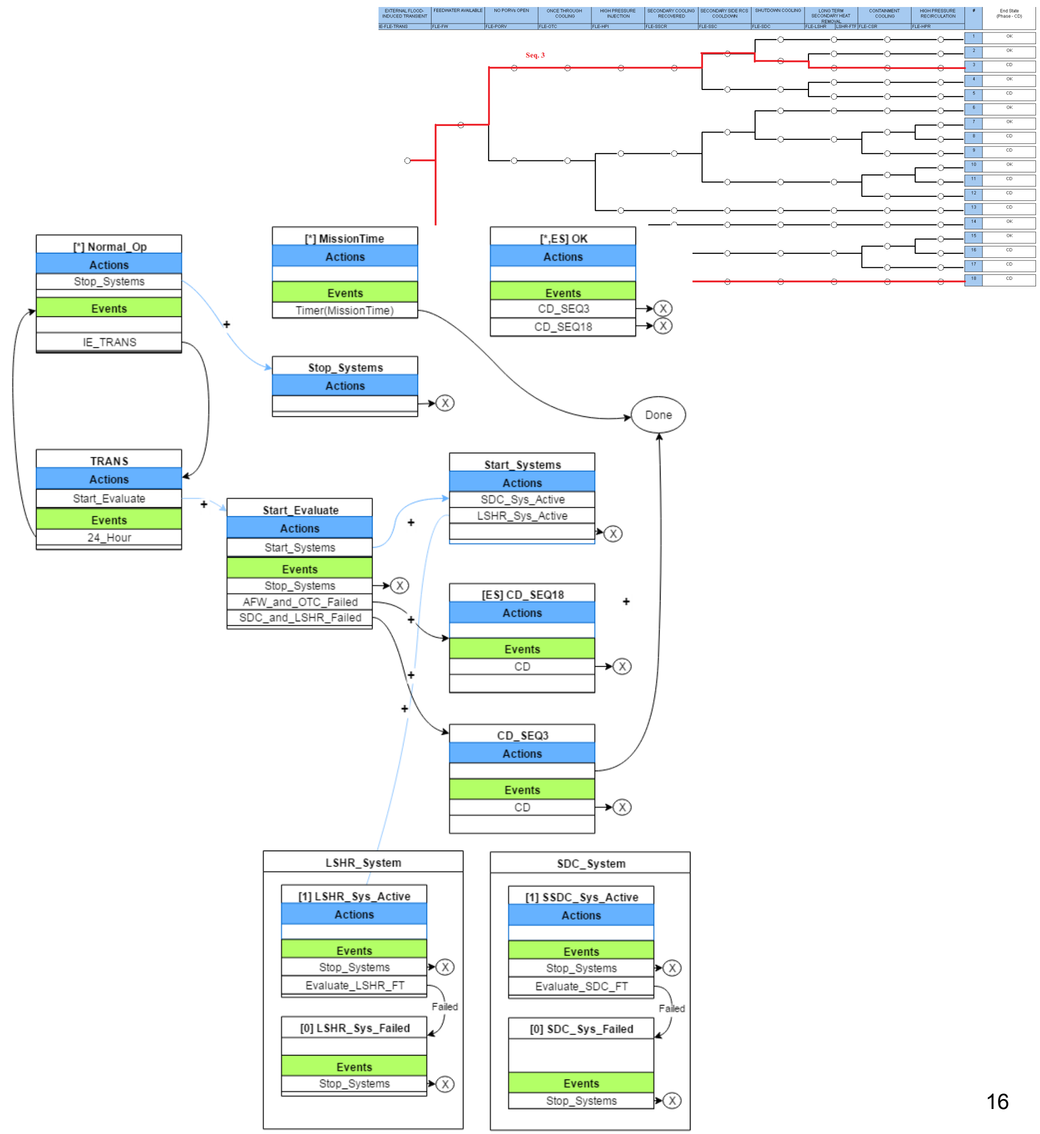


II. SBDFA Framework (Cont.)

- State-Based Accident Sequence Modeling

- No explicit accident sequence modeling such as event tree in EMRALD

- Implicitly represented in the plant state diagram with the flow paths between the initiating event states, system or component states, and key/end states

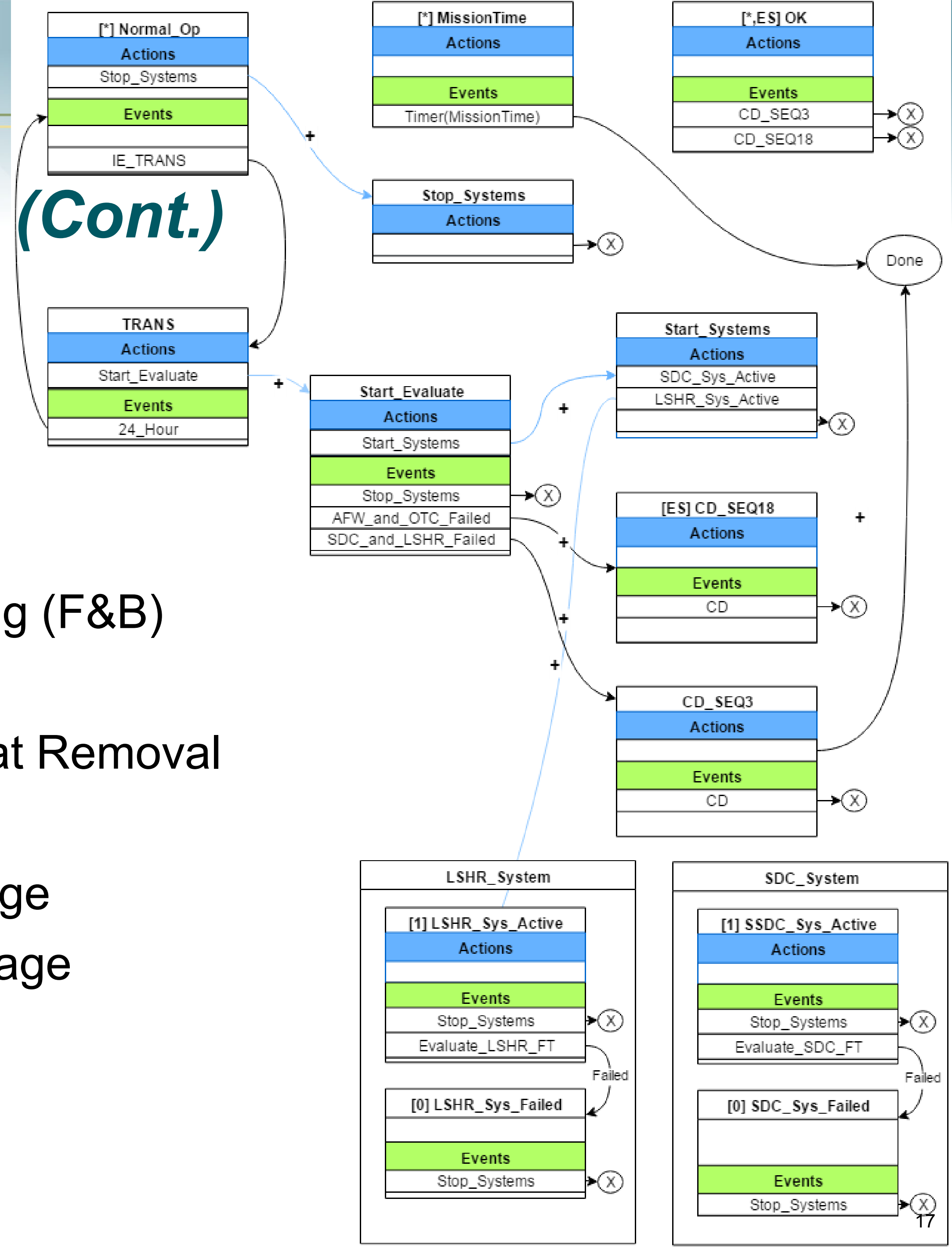


II. SBDFA Framework (Cont.)

- Plant State Diagram

  (Without 3D flooding IE)
- General Transient event
- AFW – Auxiliary Feedwater
- OTC – Once Through Cooling (F&B)
- SDC – Shutdown Cooling
- LSHR – Late Secondary Heat Removal

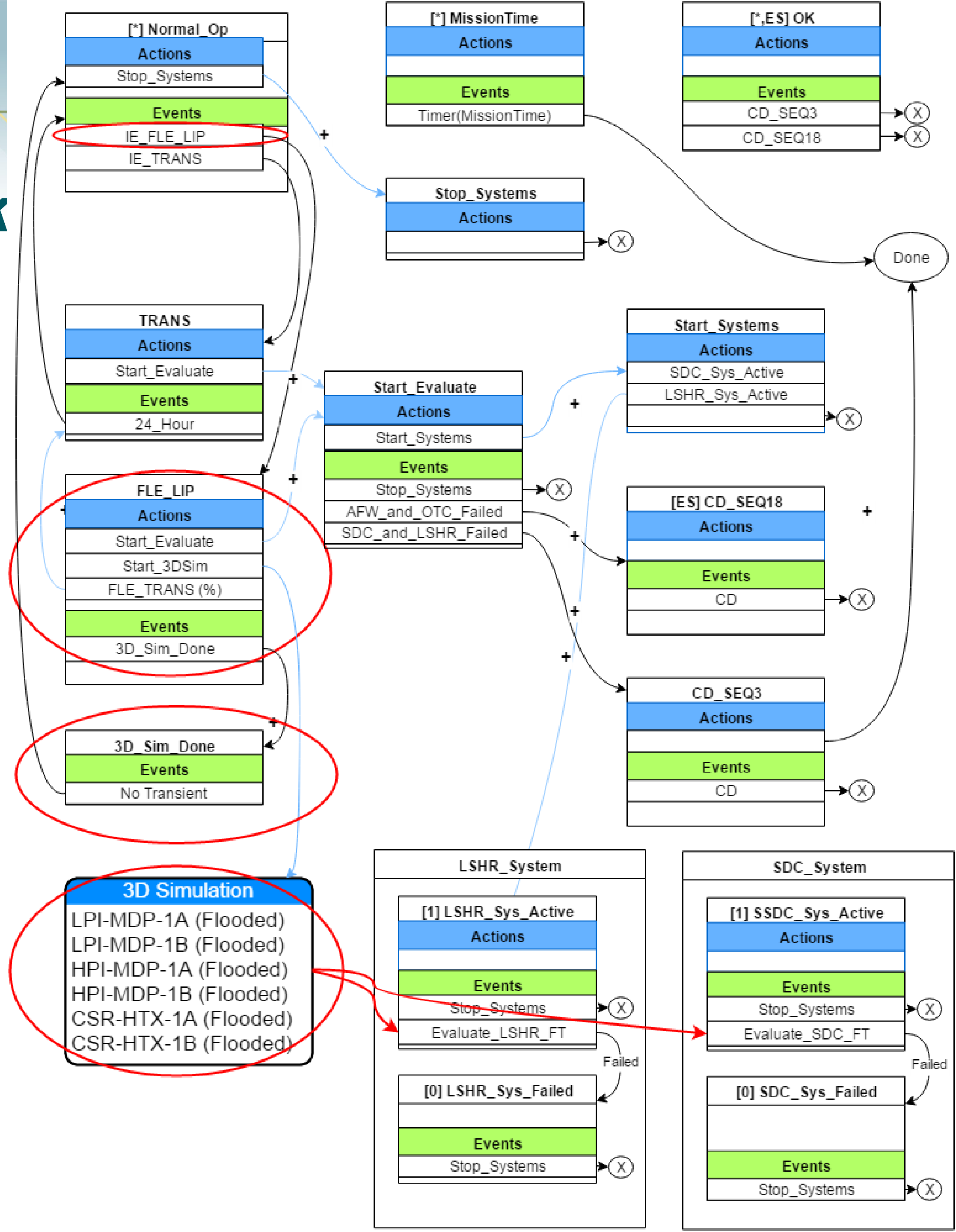
- IE*AFW*OTC -> Core Damage
- IE*SDC*LSHR -> Core Damage



II. SBDFA Framework

- Plant State Diagram

  (With 3D flooding IE)
- External Flood (LIP) IE added
- Flood-caused failures added
- New human actions added
- System logic revised
- 3D simulation results added

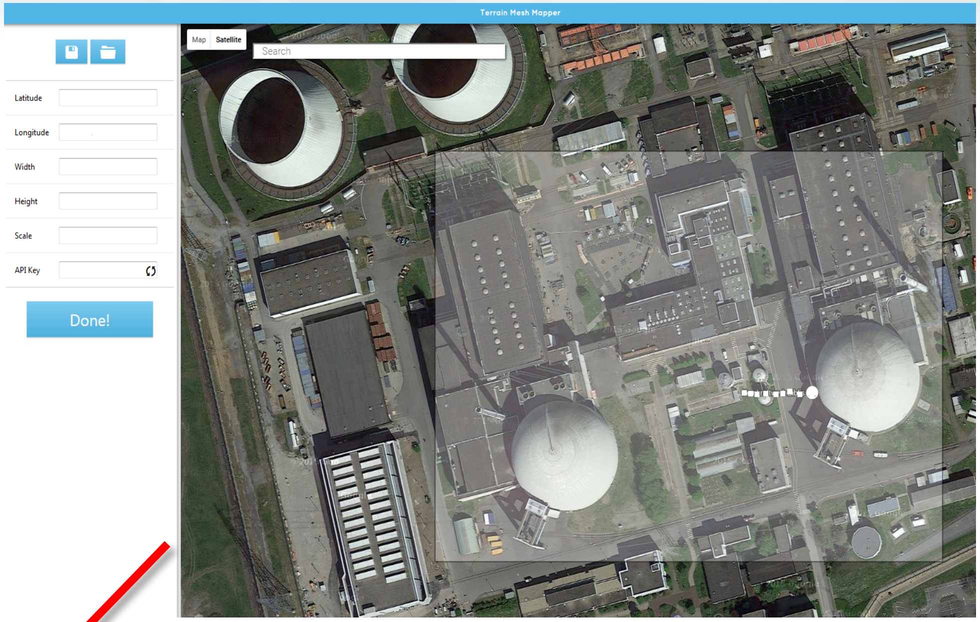


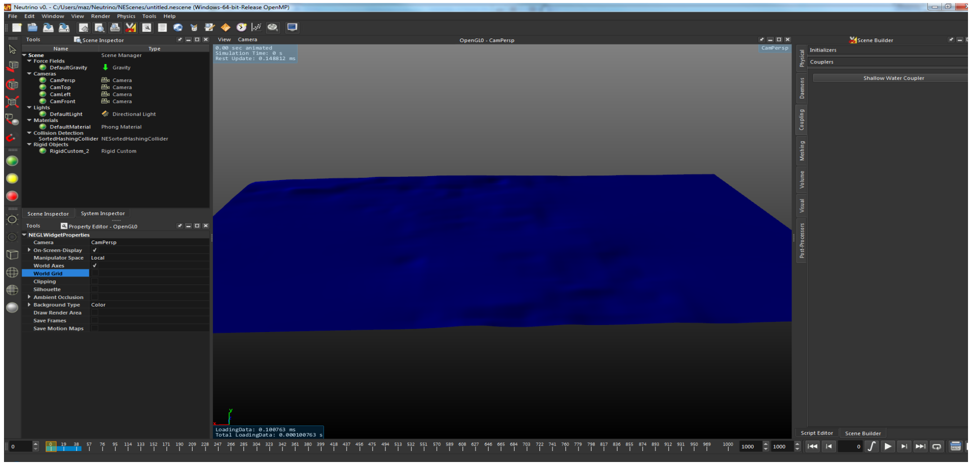
III. Case Study

- A LIP event occurred in a U.S PWR
  - Heavy rainfall plus degraded site drain system
  - Water accumulated on the ground of Building C
  - Water entered underground pipe tunnel when the level exceeds the height of the curb of man hole
  - Flood seal of one penetration between the pipe tunnel and the Auxiliary Building was missing, and water began entering -0.5 ft level of AB
  - Water entered into ECCS pump room sumps at the -10.0 ft level of AB from the -0.5 ft floor drains
  - When pump sump level triggered high-high alarms, operators closed ECCS sump isolation valves to prevent flooding of the ECCS pump rooms
  - However, the water level in -0.5 ft level of AB continued to rise
  - Operators control the AB flooding by cycling ECCS sump isolation valves
  - The event was terminated after the rains subsided and the storm drain was working
  - No safety related equipment inoperable during the event

III. Case Study (Cont.)

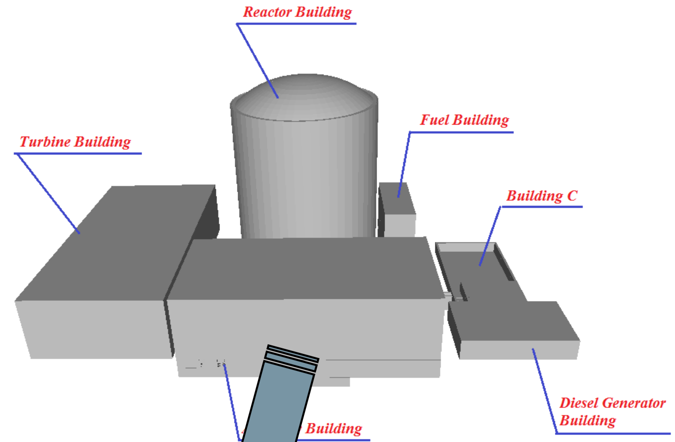
- 3D Site Terrain Model
  - Developed a web-based Web Terrain Mapper API
  - Using public available Google Maps Elevation API
  - Used for this proof of concept project

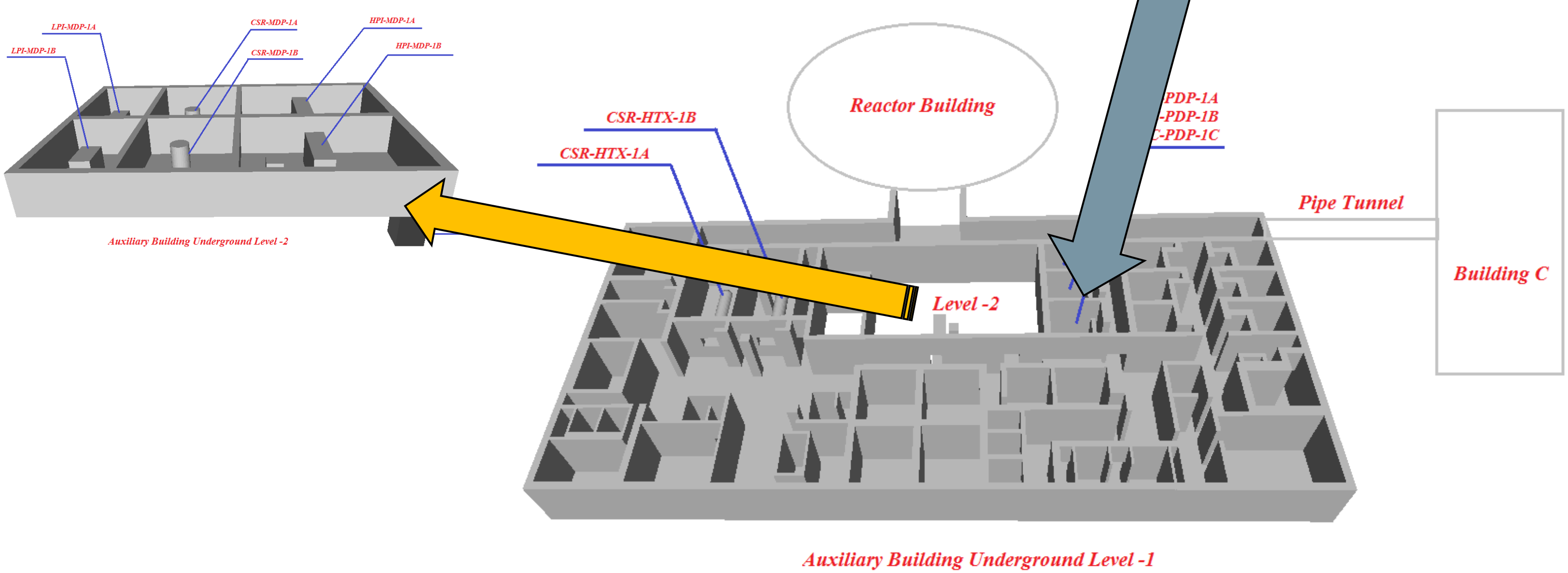




III. Case Study (Cont.)

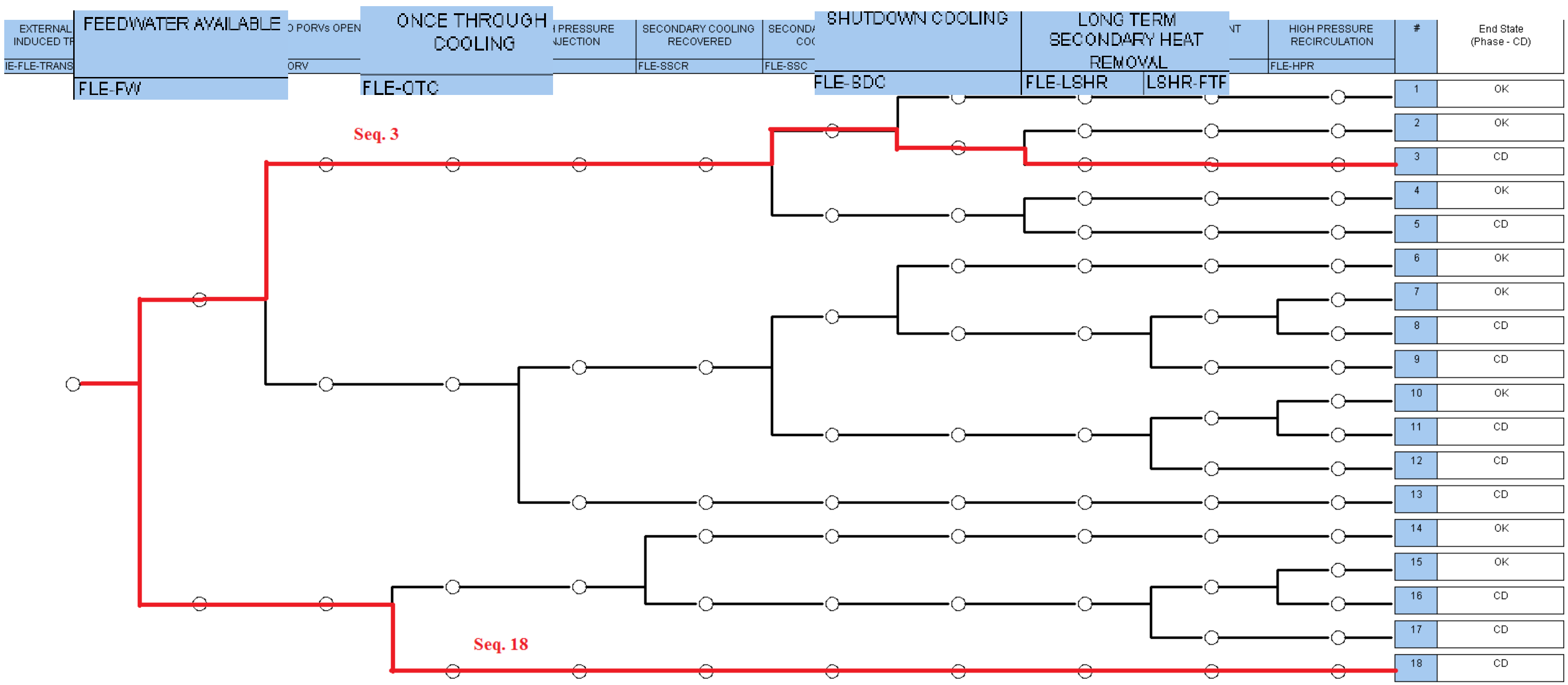
- 3D Plant Models
  - 3D model of a typical PWR
  - Level of details of 3D plant model be varying as needed





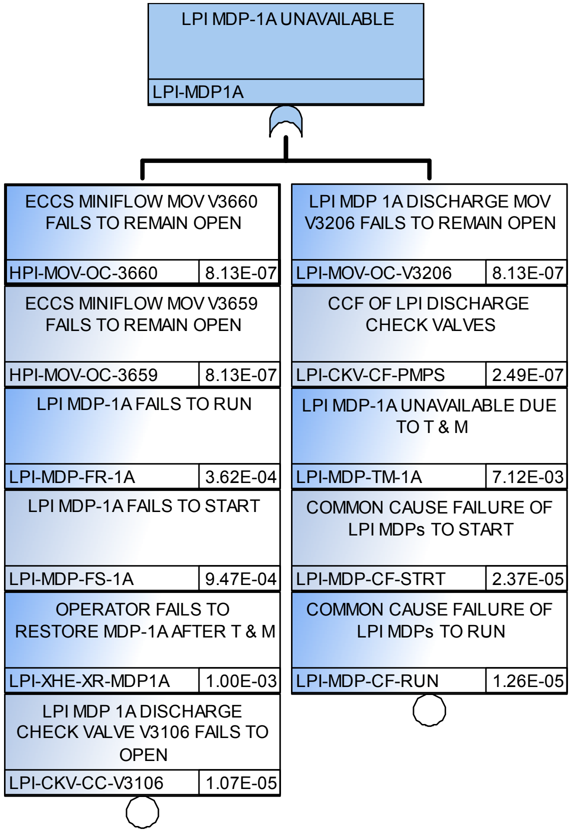
III. Case Study (Cont.)

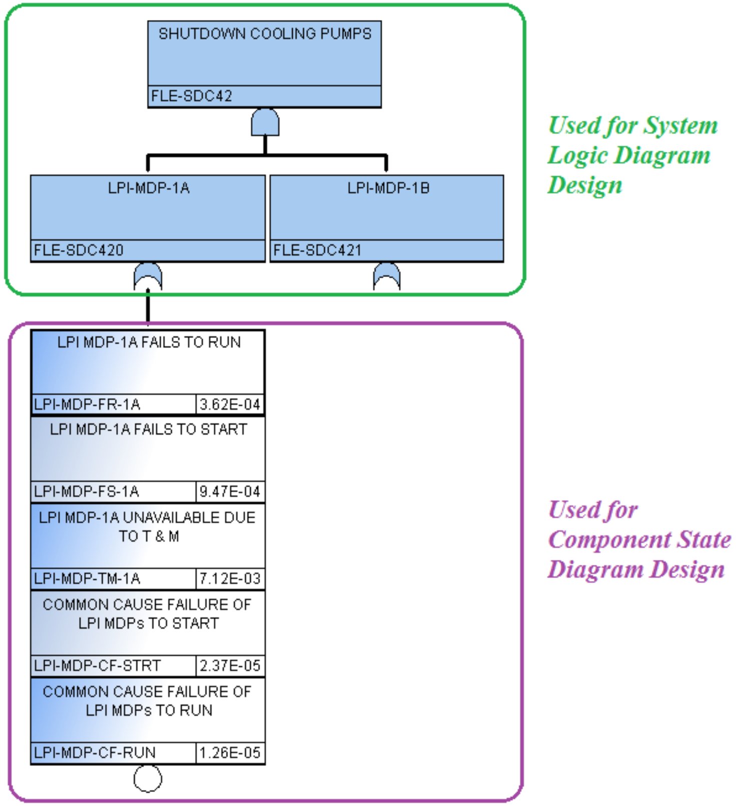
- Simplified SAPHIRE Model for the flood event
  - External Flood-Caused Transient Event Tree
  - Two Sequences for analysis
  - Seq. 3: IE * /FW * /PORV * /SSC * SDC * LSHR (failure of shutdown cooling and long term secondary heat removal)
  - Seq. 18: IE * FW * OTC (failure of feedwater and feed & bleed)



III. Case Study (Cont.)

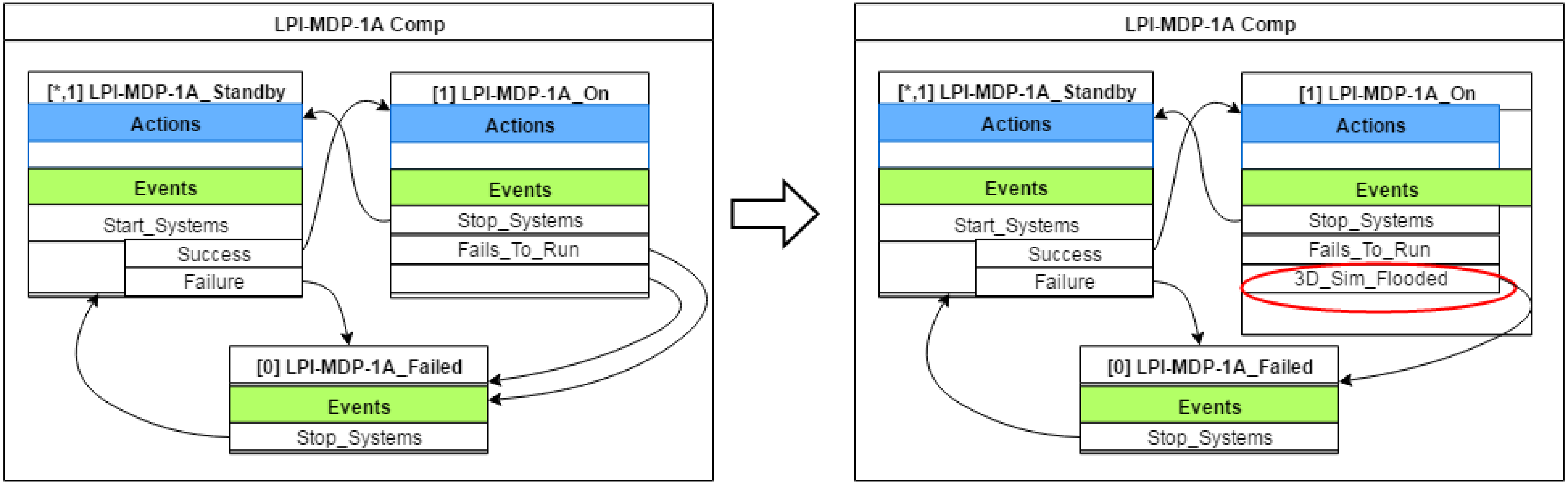
- Convert SAPHIRE Model to EMRALD Model
  - Convert fault trees in SAPHIRE to component state diagrams and system state diagrams





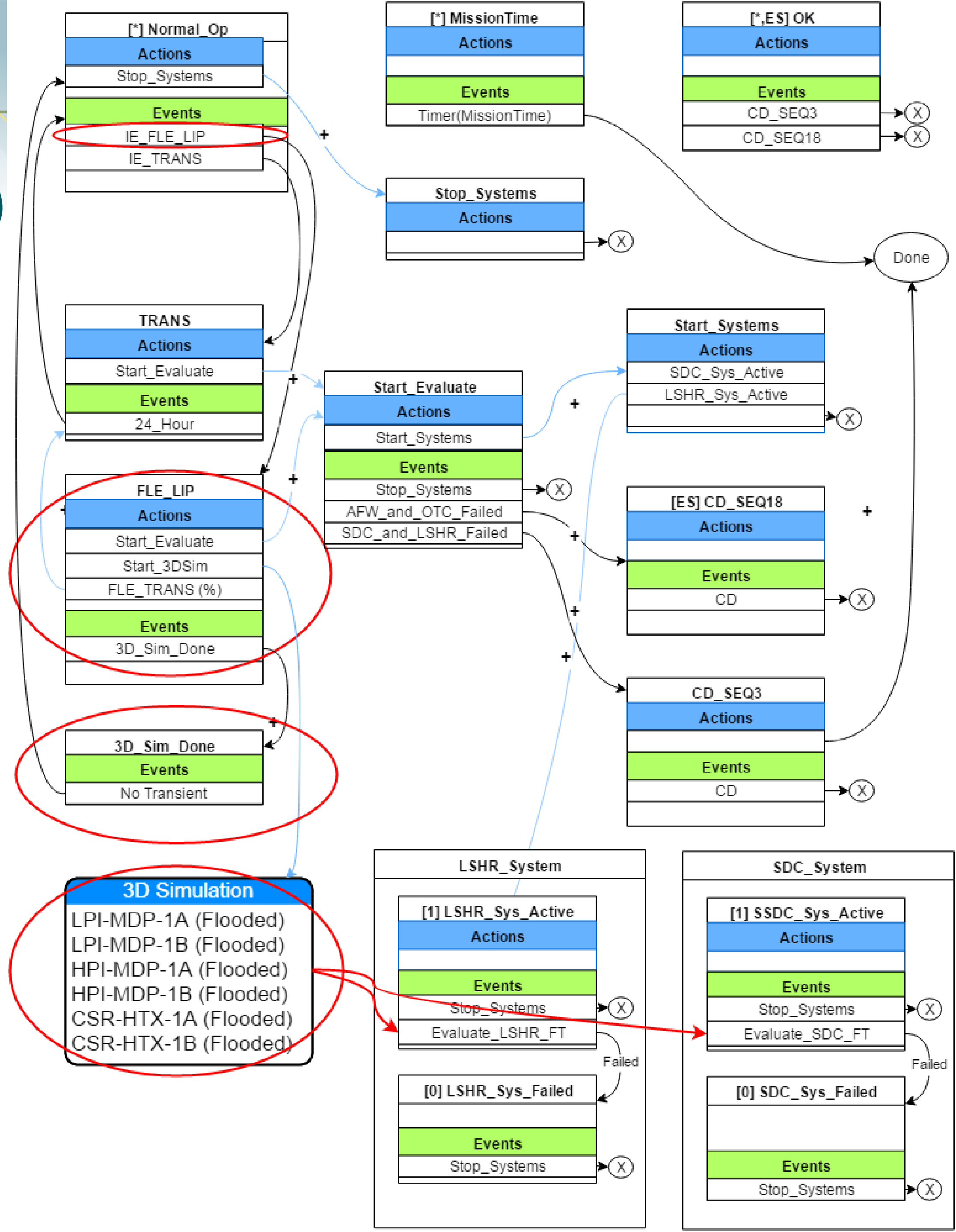
III. Case Study (Cont.)

- Add External Flood Elements into the EMRALD Model
  - Add external flood-induced failure events to component state diagrams



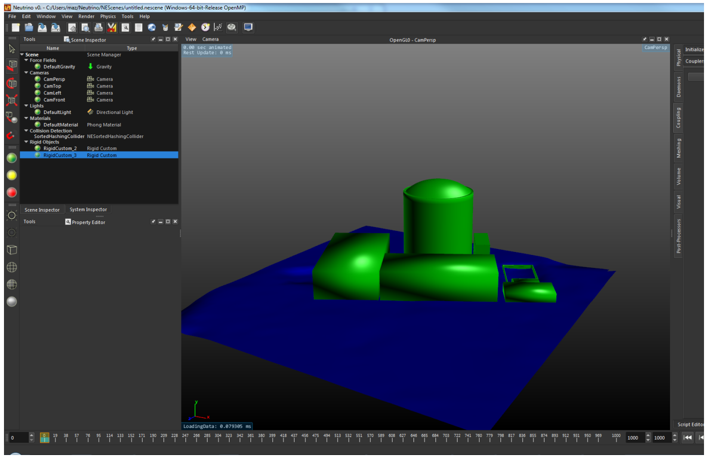
III. Case Study (Cont.)

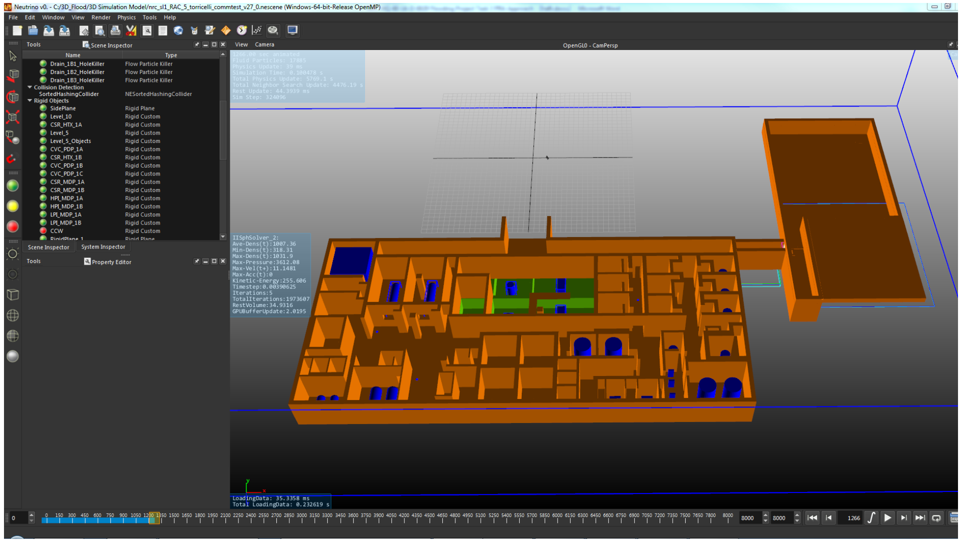
- Add External Flood Elements into the EMRALD Model
  - Add external flood-caused initiating event to plant state diagram
  - Add the tokens of 3D simulation results to plant state diagram



III. Case Study (Cont.)

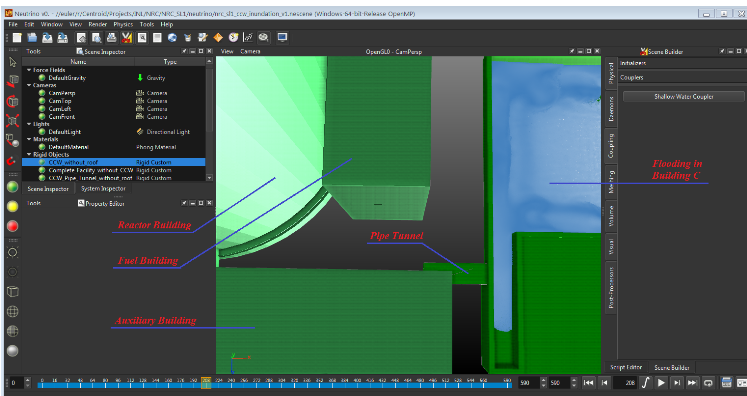
- 3D Simulation Models
- Neutrino software was used for this project
  - Smooth Particle Hydrodynamics (SPH)
  - Handle memory requirements for large simulations
  - Measure flooding parameters such as flood height, flow rate, pressure, etc.
- Potential area of future research

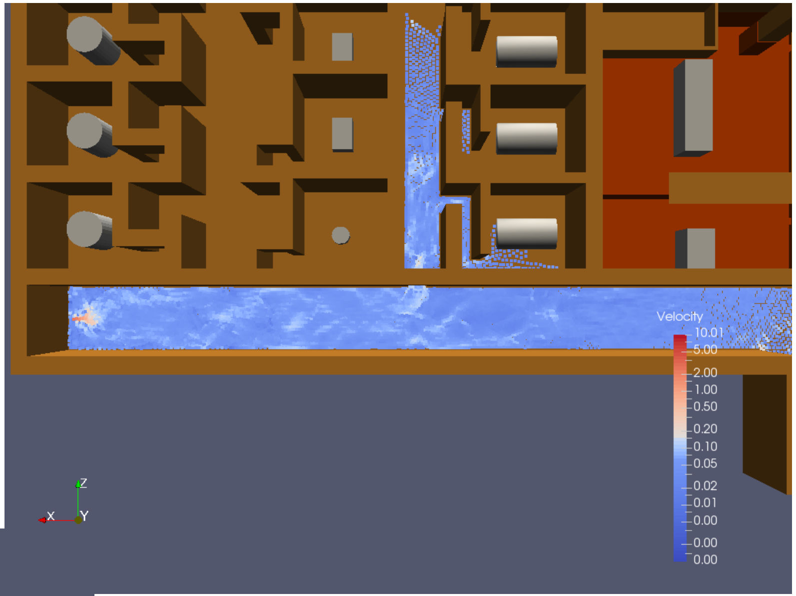


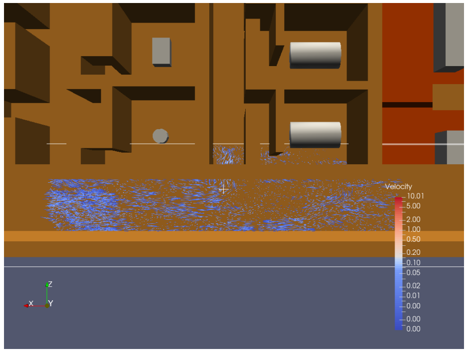


III. Case Study (Cont.)

- 3D Simulation Models







III. Case Study (Cont.)

- EMRALD with 3D Simulation Model Results
  - Run on 5 clustered Windows-based PC servers (Minion 1 – 5) for 3D flood simulations
  - 3D simulation results returned back to EMRALD for model quantification
  - A part of the quantification results

3-D Sim. Run	Flood Rate (gpm)	Seq. 18 Prob.	Seq. 3 Prob.	Component Failure
1-2	1010	1.1E-05	3.5E-06	CSR_MDP_1A_Failed, CSR_MDP_1B_Failed, HPI_MDP_1A_Failed, HPI_MDP_1B_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed
1-3	919	2.0E-07	2.0E-07	CSR_MDP_1A_Failed, CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed
1-4	731	7.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed
1-5	737	4.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1B_Failed
1-7	702	4.0E-07	0.0E+00	CCW_HTX_1B_Failed, CSR_MDP_1B_Failed, HPI_MDP_1B_Failed
1-8	700	2.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed
2-1	763	3.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1B_Failed
2-2	839	1.0E-07	1.0E-07	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, HPI_XHE_FB_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed
2-3	609	2.0E-07	0.0E+00	
2-5	873	5.0E-07	1.0E-07	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed
2-6	772	4.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1B_Failed
2-7	668	5.0E-07	0.0E+00	HPI_MDP_1B_Failed
2-8	992	5.0E-07	5.0E-07	CSR_MDP_1A_Failed, CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed

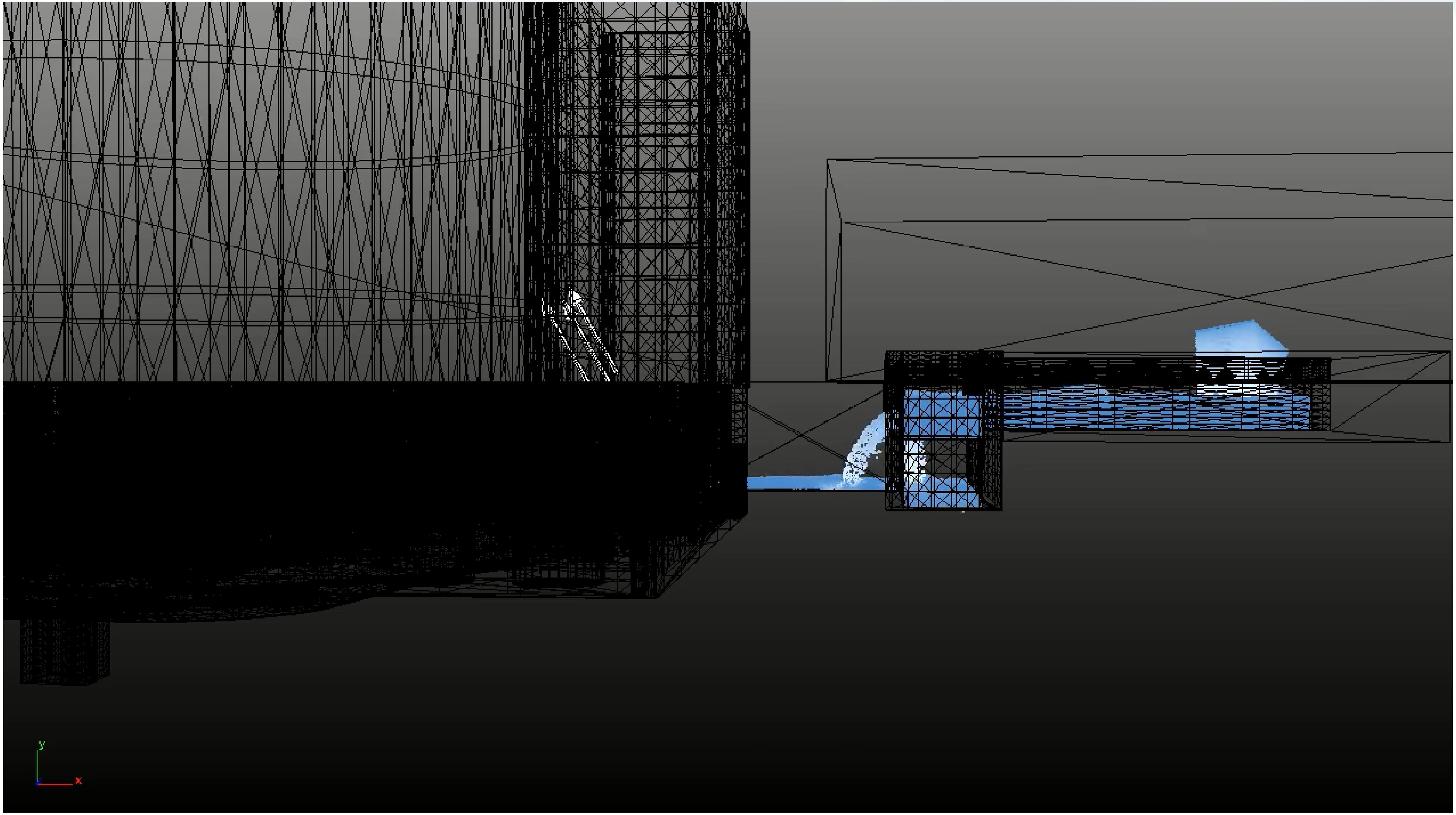
III. Case Study (Cont.)

- Compare EMRALD results with SAPHIRE results
  - Grouping EMRALD results by the flow rate and failure components -> 6 scenarios
  - Quantify SAPHIRE model with proper change sets for the 6 scenarios
  - EMRALD results seem to be consistent to those of SAPHIRE

Scenario	Component Failure	Seq.	SAPHIRE	EMRALD
1	None	Seq. 18	2.3E-07	2.0E-07
		Seq.3	5.0E-10	0.0E+00
2	HPI-B pump failed	Seq. 18	2.7E-07	4.5E-07
		Seq.3	7.7E-10	0.0E+00
3	HPI-B, and CSR-B pumps failed	Seq. 18	2.7E-07	3.8E-07
		Seq.3	7.7E-10	0.0E+00
4	LPI-B, HPI-B, and CSR-B pumps failed	Seq. 18	2.7E-07	4.0E-07
		Seq.3	1.9E-09	0.0E+00
5	All LPI and CSR pumps and HPI-B pump failed	Seq. 18	2.7E-07	3.8E-07
		Seq.3	1.3E-07	2.0E-07
6	All LPI, HPI, CSR pumps failed	Seq. 18	8.6E-06	1.3E-05
		Seq.3	3.2E-06	3.8E-06

IV. Summary

- The objective of this project is to investigate dynamic approaches to model total plant response to flooding events
- Dynamic approaches could be used as an important tool
- EMRALD, the state based PRA modeling tool, could be an integrated dynamic PRA tool for external flood and other hazard analysis
- This proof-of-concept project is an exploratory research
- Not every element of flooding risk models can be simulated
- Simulation can also play a supplemental role
  - To support the development or enhancement of a static PRA with the insights from the dynamic analysis
  - To perform a stand alone analysis that focuses on specific issues with limited sequences and components (e.g., FLEX)
  - To validate or challenge some specific assumptions and inputs in the traditional static PRA models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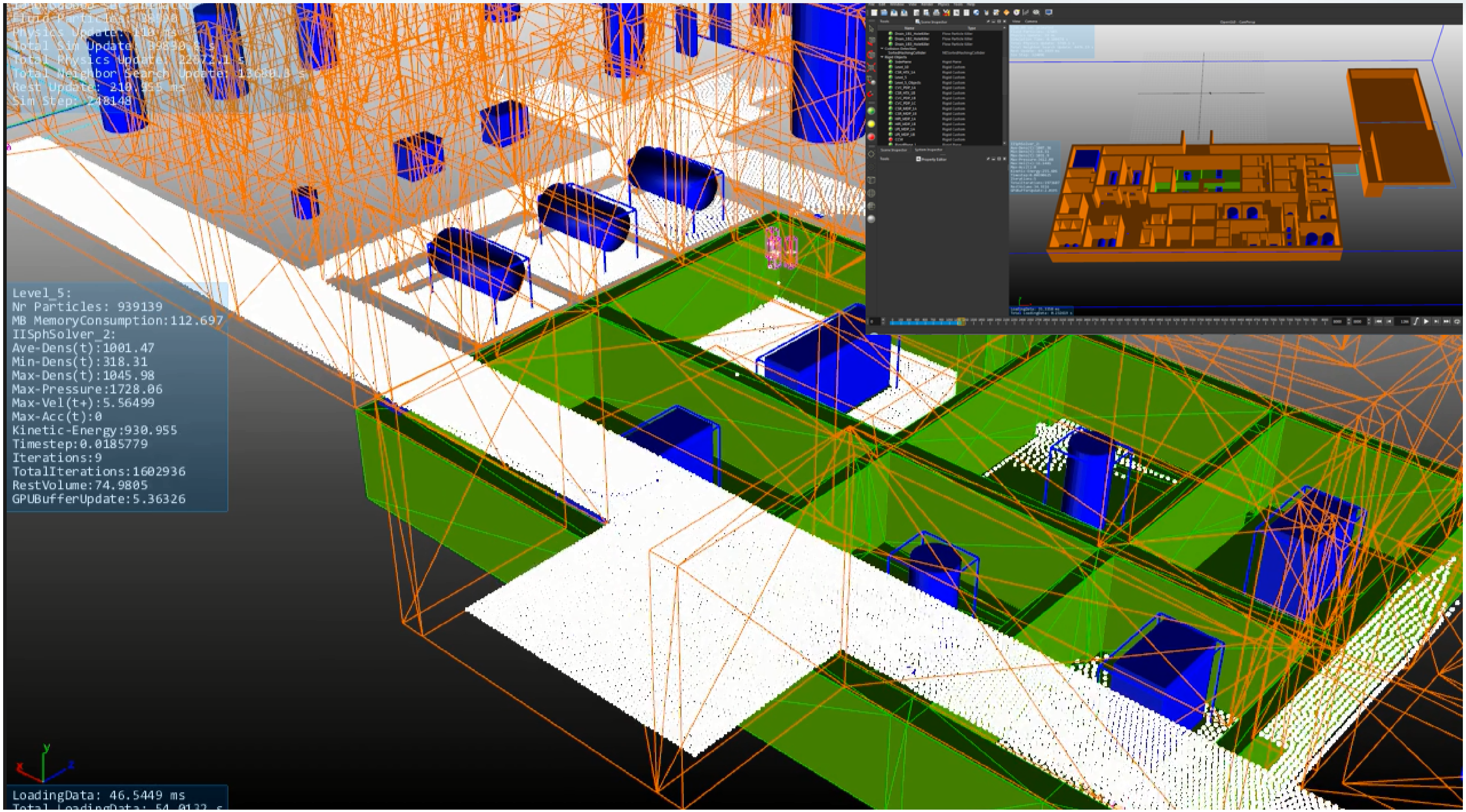
x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Min-Dens(t):318.31
Max-Dens(t):1045.98
Max-Pressure:1728.06
Max-Vel(t+):5.56499
Max-Acc(t):0
Kinetic-Energy:930.955
Timestep:0.0185779
Iterations:9
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Questions?

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