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Advanced Validation Risk-Informed Approach for the Flooding Tool Based Upon Smooth Particle Hydrodynamics

- Validation and Development Status of NEUTRINO

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March 2018

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ABSTRACT

Risk-Informed validation is to focus advanced validation on high-priority and critical elements of the RISMC methods and tools that can best be addressed by this targeted approach to validation. Initial validation focus will be on the RISMC flooding analysis computer software based upon Smoothed Particle Hydrodynamics (SPH), NEUTRINO.

The NEUTRINO code is a SPH-based CFD software adopted as one of the RISMC modeling tools for external hazards analysis. This document discusses the validation and development activities of NEUTRINO, especially in relation to its simulation capability for flooding hazards analysis. In order to draw meaningful conclusions from the discussion, we first analyzed the potential risks to nuclear power plants in flooding scenarios (e.g., hazard modes, industry/regulatory concerns, etc.). Then, an initial high-level PIRT was proposed to define the key phenomena relevant to the analysis of flooding hazards. Finally, based on the framework of this PIRT analysis, the validation and development efforts that have been conducted to date for NEUTRINO were discussed. This analysis helped to determine the sufficiency, efficiency, and adequacy of the current code development and validation efforts for NEUTRINO.

PREFACE

Document Version

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ACRONYMS

CFD	Computational Fluid Dynamics
CSAU	Code Scaling, Applicability, and Uncertainty
DOE	Department of Energy
LWRS	Light Water Reactor Sustainability
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PRA	Probability Risk Assessment
RIMM	Risk Informed Margin Management
RISMC	Risk Informed Safety Margin Characterization
SPH	Smoothed Particle Hydrodynamics
SPRA	Seismic Probabilistic Risk Assessment
SSC	System, Structure, and Component

Validation and Development Status of the NEUTRINO for Flooding Hazard Analysis

1. INTRODUCTION

1.1 Background

The Fukushima accident of Nuclear Power Plants (NPP) in Japan occurred as a result of the combination of a major seismic event and subsequent tsunami. After this event, US NRC conducted a thorough review on the accident and its regulation processes to determine if the regulatory system requires additional improvements. The activity was specifically made by a task force called the ‘near-term task force’; the recommendations based on its activity were summarized in the report SECY-11-0137 [1]. The report implies that although the current NPP design bases requirements related to flooding and seismic hazards are primarily determined deterministically, NRC may require insights beyond that. This naturally increases the need of improved methods and tools for the nuclear industry to pursue license.

The traditional methods and approaches used for NRC regulation were entirely deterministic and focused on engineering margin assessment. In this approach, the plant structures, systems, and components (SSCs) are required to be designed to satisfy acceptance criteria such that a minimum level of margin can be achieved over some specific design load of interest. NRC specifies many of the methods and models to be used for such analyses to ensure the conservativeness of the results supporting its regulatory decision. This conservative approach, however, has long been criticized within community because it ignores the “realistic” risk significance of plant SSCs and other various risk factors (e.g., operator action, redundancy) that can substantially influence the event scenario and consequence. Also, the large databases of experimental, analytical research and experience of reactor operation indicated that such conservative approach was somewhat misdirected and sometimes led to non-conservative results [2].

This has motivated the development of more advanced safety analysis strategy that reflects the “realistic” risk-based perspective. Specifically, in US since the early 1990s the probabilistic and risk-informed safety analysis methods have been introduced to the NPP licensing process (e.g., CSAU, PRA). As a result, the NRC regulatory framework currently incorporates both deterministic and probabilistic perspectives for a range of different applications (i.e., accident analysis). This NRC regulation applies also to the natural hazards such as external flooding event which is the main concern of the present work. The benefits of applying the risk-informed approach in NPP licensing can be summarized as follows [3]:

(i) the risk-informed approach can provide a technical basis for understanding the “realistic” hazards to NPP while reducing the unnecessary conservatism (i.e., realistic safety risks, probabilities of occurrence and consequences of the full spectrum of potential accidents and/or operational transients)

(ii) technical basis can be established for managing the NPP hazards in advance,

(iii) it makes it possible to estimate economic risks of any safety decision,

(vi) optimum balance between the cost and plant safety can be pursued.

Despite the above benefits, however, the NPP PRAs (Probabilistic Risk Assessments) or risk-informed regulations of NRC have focused primarily on internal events. The NPP PRAs of external hazards (e.g., earthquake, flood, and high wind) has relatively been much less studied. In general, evaluating the plant responses to the external hazards is very difficult because of the phenomenological complexity involved with multi-scales and multi-physics. This means that it is hard to achieve reliable risk insights from those analyses and large uncertainties exist for the analysis results. As a result, the NPP design bases requirements related to external hazards rely heavily on deterministic approach until recently. Nonetheless, the recent advancement of computer technology/resources, numerical methods, and physical knowledge accumulated over the past decades provides high potential for the improvement of PRA results applied to external events. It is noted that the tools and methods that have been used to conduct external event PRAs have largely remained static in spite of the fact that the US regulatory framework has continuously evolved over time. This implies that there is still much room to improve the quality of PRA (e.g., reliable assessment of facility risk, plant SSCs that are more risk-significant) by developing the new set of tools and methods that can reflect the modern development in science and technology.

The Risk-Informed Safety Margin Characterization (RISMC) R&D Pathway aims to develop and demonstrate an advanced risk assessment method that is coupled to advanced safety margin quantification. Within this new analysis framework, the physics models (i.e., RISMC tools) provide advanced representation of NPP accident scenarios, state of plant SSCs, and safety margin quantification, and the results affect the probabilistic risk assessment. This research is driven on the needs of nuclear industry. The end goal of RISMC R&D Pathway is to provide advanced Risk Informed Margin Management (RIMM) approach that can support the NPP decision makers' decisions for relevant and realistic industry applications. For reliable risk insight (via probabilistic model or PRA) as well as advanced safety margin quantification (via physics model), a set of new tools and methods is being developed while their capabilities are demonstrated through validation activities. In particular, for the industry application # 2 (i.e., multiple external hazards) that is of current interest, the research has been conducted to represent more meaningful external event scenarios and consequences by applying an advanced tools that will [3, 4]:

- *Identify, model and analyze the appropriate physics that needs to be included to determine plant vulnerabilities related to external events.*

- *Manage the communication and interactions between different physics modeling and analysis technologies.*

- *Provide the computational infrastructure for plant representation, scenario depiction, and physics prediction.*

1.2 RISMC Methodology

As discussed, the goal of RISMC R&D Pathway is to support plant decisions using the advanced risk-informed margins management strategy with the aim to improve economics, reliability, and sustain safety of current NPPs [5]. The RISMC approach can optimize plant safety and performance via a novel interaction between probabilistic risk simulation and mechanistic codes for plant-level physics. The new functionality allows the risk simulation module to serve as a “scenario generator” that feeds information to the mechanistic codes. The effort fits with the goals of the RISMC Pathway, which are twofold [5]:

1. *Develop and demonstrate a risk-assessment method coupled to (physics-based) safety margin analysis. The method can be used by NPP decision-makers as part of their margin management strategies.*
2. *Create an advanced RISMC Toolkit. The RISMC Toolkit enables a more accurate representation of a NPP safety margins and its associated influence on operations and economics.*

When evaluating the safety margin, what we want to understand is not just the frequency of an event like core damage, but how close we are (or not) to key safety-related events and how might we increase our safety margin through proper application of Risk Informed Margin Management (RIMM). In general terms, a “margin” is usually characterized in one of two ways:

- A deterministic margin, typically defined by the ratio (or, alternatively, the difference) of a capacity (i.e., strength) over the load
- A probabilistic margin, defined by the probability that the load exceeds the capacity

A probabilistic safety margin is a numerical value quantifying the probability that a safety metric (e.g., for an important process observable such as clad temperature) will be exceeded under accident scenario conditions.

The RISMC Pathway uses the probabilistic margin approach to quantify impacts to reliability and safety. As part of the quantification, we use both probabilistic (via risk simulation) and mechanistic (via physics models) 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 pathway R&D is mostly studied by computer software simulation and development, under the availability of advanced mechanistic and probabilistic simulation tools. Current RISMC toolkits to model plan behavior and determining safety margins are shown in Figure 1.

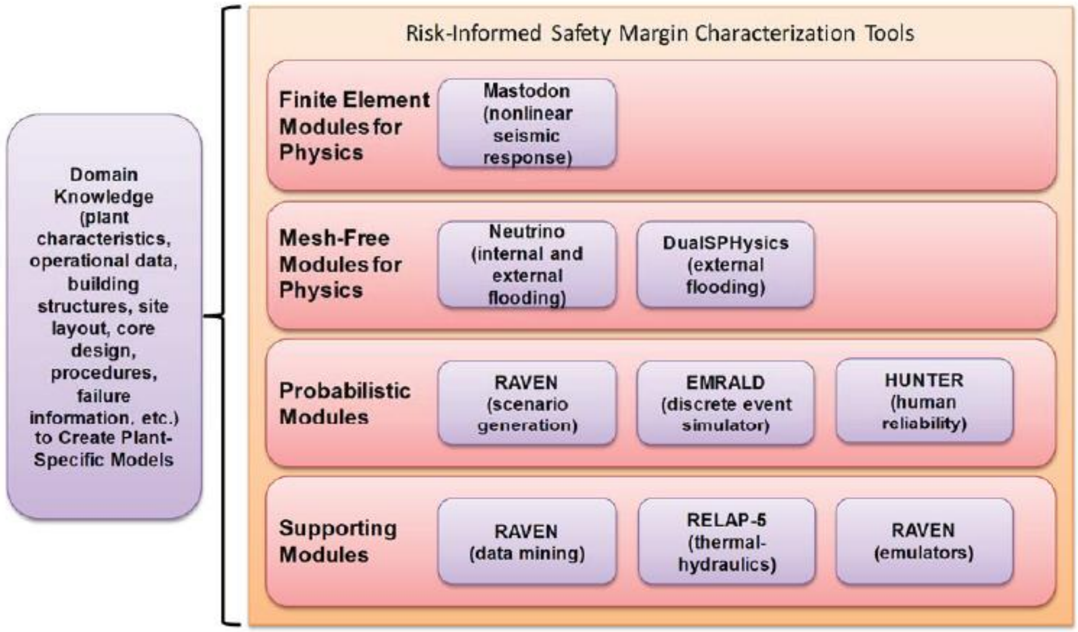

Figure 1. Software modules used to perform RISMC-specific analysis (as of 2017)

1.3 Project Scope and Objective

This report concerns the development and validation activities of NEUTRINO, SPH-based CFD software adopted as one of the RISMC toolkit for flooding hazard analysis. As part of the RISMC pathway, some researches were already performed to investigate the general capability of SPH method for the external hazards analysis [4, 6]. This early demonstration process revealed that the SPH method is generally applicable to the analysis of various types of multi-hazard events that have been considered in the Industry Application #2 (i.e., multiple external hazards). In the RISMC context, the predictive capability of physics-based simulation code is crucial because the failure of plant SSCs predicted by the code simulations contributes to the PRA analysis as well as the safety margin characterization.

The present work aims to discuss the development and validation status/efforts of NEUTRINO. We discuss the NEUTRINO's development status, ongoing validation activities, and current simulation capabilities. Additionally, the experimental effort within RISMC Pathway to provide high-fidelity validation data for NEUTRINO is described. Finally, to identify the true needs of further validation and development for NEUTRINO, efforts are made to propose the initial high-level PIRT which provides key information needed to analyze the flooding hazards.

1.4 Collaboration with Other Projects

The work has been closely coordinated with the Nuclear Energy University Program's Integrated Research Project (IRP) on "Development and Application of a Data-Driven Methodology for Validation of Risk-Informed Safety Margin Characterization Models" by North Carolina State University (IRP-16-10918). The goal of the IRP program is to develop and demonstrate a data-driven methodology for validation of advanced computer models used in nuclear power plant safety analysis. Specifically, the advanced computer models are those in the toolkit developed to support risk-informed safety margin characterization (RISMC), an integrated deterministic/probabilistic safety analysis methodology developed in the Department of Energy's Light Water Reactor Sustainability (LWRS) program.

2. NEUTRINO AND SMOOTHED PARTICLE HYDRODYNAMICS (SPH)

2.1 Overview

NEUTRINO is CFD software adopted as one of the RISMC tools for physics-based numerical analysis of NPP external hazards (e.g., flood, high-wind, and seismic events). To mimic the dynamics of continuum fluids, NEUTRINO employs a mesh-free particle-based (Lagrangian) computational method called Smoothed Particle Hydrodynamics (SPH). This section introduces briefly the general theory of SPH and discusses the main features of NUETRINO employing the SPH method.

2.2 General Theory of SPH

Smoothed Particle Hydrodynamics (SPH) is mesh-free particle-based (Lagrangian) computational method for solving the equations of hydrodynamics. The mathematical formulation was originally derived by Lucy [7] and Gingold and Monaghan [8]. The SPH algorithms are currently used in a wide area of disciplines in research, including astrophysics, geophysics and engineering. In SPH, the flow properties are evaluated by approximating the flow quantities (e.g., density) at sampled positions from a set of known quantities of the neighboring particles. In the following, the fundamental concept and mathematical formulation of SPH is introduced which is based primarily on the discussion from D. Price [9]. It is noted that this section summarizes only the key concept of the SPH method and thus, readers are advised to refer to the reference [6] for more details.

- *Fluid density estimate in SPH*

First and foremost, to understand the fundamentals of SPH it is important to understand how the density of a fluid is evaluated over the computation domain. In SPH, the fluid density is computed based on an arbitrary distribution of point mass particles (note that in SPH context the Lagrangian particles have mass, volume, pressure, density, etc.). Specifically, the density at a given position is estimated via a weighted sum over the neighboring particles. The values of weight decrease with distance from a sampling point (i.e., center of sampling volume) according to a scale parameter (that is, the density estimate is "smoothed"). In a mathematical form, the density estimate can be expressed as

$$\rho(\vec{r}) = \sum_{b=1}^{N} m_b W(\vec{r} - \vec{r}_b, h) \tag{1}$$

where m_b denotes the mass of individual particles, W is the weight function [1/m^3], h is the scale parameter (or smoothing length) that determines the fall-off rate of W as a function of the particle spacing, and N is the total number of particles within a sampling volume. It is noted that by mass conservation $\int \rho dV = \sum_{b=1}^{N} m_b$ should be satisfied, implying that in Eq. (1) W is normalized as $\int_V W(\vec{r} - \vec{r}_b, h) dV' = 1$.

Thus, the accuracy of density estimated by Eq. (1) depends essentially on the choice of weight function W which is also referred to as 'smoothing kernel'. To ensure the reliable performance of SPH simulation, W is required to have several properties to be good smoothing kernel [9]:

(i) positive and smooth (to be differentiable), and decreases monotonically with relative distance (note that W tends to approach delta function as $h \to 0$);

(ii) symmetric with respect to $(\vec{r} - \vec{r}_b)$, i.e., $W(\vec{r} - \vec{r}_b, h) \equiv W(\left|\vec{r} - \vec{r}_b\right|, h)$;

(iii) central-flatted shape (i.e., Bell-shaped) to keep the density estimate from being excessively sensitive to a small change in the position of a nearby neighbor.

Considering (i)–(iii), Gaussian distribution shape is a natural choice for the smoothing kernel (W) as it satisfies all the above properties well:

$$W(\vec{r} - \vec{r}_b, h) = \frac{\sigma}{h^d} \exp[-\frac{(\vec{r} - \vec{r}_b)^2}{h^2}] \tag{2}$$

where d is the number of spatial dimensions and σ is normalization constants that are given by [$1/\pi^{0.5}$, $1/\pi$, $1/\pi^{1.5}$] in [1, 2, 3] dimensions, respectively.

Eq. (2) is ideal in terms of providing a good density estimate, but is not practically feasible because it requires considering all of the particles in the domain including those that are located very far. Considering that the neighboring particles' contribution quickly decreases with distance, the better choice would be to employ a function that is Gaussian-like in shape but truncated at both ends at a finite radius. It is noted that such function (smoothing kernel W) enables a more efficient estimate of fluid density, but the density estimate becomes more sensitive to the local distribution of neighboring particles. One of the most widely adopted smoothing kernel in this context is Schoenberg (1946) B-spine function. The Eq. (3) below shows an example of the simplest B-spline function that can be used for SPH simulation (this is also employed by NEUTRINO), i.e., a cubic spline truncated at $2h$ [9]:

$$w(q)=\sigma\cdot\begin{cases}\frac{1}{4}(2-q)^3-(1-q)^3, & 0\le q\le 1\\ \frac{1}{4}(2-q)^3, & 1\le q<2\\ 0, & q\ge 2\end{cases} \tag{3}$$

where $w(q)\equiv h^d\cdot W(\left|\vec{r}-\vec{r}_b\right|,h)$, d is the number of spatial dimensions, $q=\left|\vec{r}-\vec{r}_b\right|/h$, and σ is normalization constants given by [2/3, 10/(7π), 1/ π] in [1, 2, 3] dimensions, respectively.

- *Estimate of smoothing length (h)*

Another key concept that characterizes the SPH algorithm and has significant impact on the simulation results is the smoothing length (h) [see Eq. (1)–(3)]. Given particle distribution in the domain, resolving both clustered and sparse particle regions as fairly as possible is desirable. This implies that we can determine the smoothing length (at least roughly) by associating the smoothing length h with the mean local particle spacing or local particle density [i.e., $h(\vec{r})\propto[n(\vec{r})]^{-d}$ (where n denotes the local number density of particles and d is the number of spatial dimensions)]. In this way, the smoothing length h will become shorter in clustered particle regions, while the h will become longer in sparse particle regions. Therefore, with the equal mass of individual particles in the SPH context, the smoothing length can be considered inversely proportional to the density. This leads to the idea that the density ρ and smoothing length h are mutually dependent as follows:

$$\rho(\vec{r}_a)=\sum_b m_b W[\vec{r}_a-\vec{r}_b,h(\vec{r}_a)];\quad h(\vec{r}_a)=\eta\cdot\left(\frac{m_a}{\rho_a}\right)^{-d} \tag{4}$$

where η is a parameter introduced to estimate the smoothing length corresponding to the units of the mean particle spacing $(m_a/\rho_a)^{-d}$; $\rho(\vec{r}_a)$ indicates the density estimated at particle location a.

Eq. (4) is used in most modern SPH codes, where the equations for ρ and h are solved simultaneously using so-called root-finding algorithms (e.g., Newton-Raphson or Bisection method). Also, coupling the two equations in Eq. (4) plays a role in keeping the constant mass inside the smoothing sphere [9, 10]:

$$M_{tot,a}=\int_{V_a}\rho dV\approx\frac{4}{3}\pi R_K^3\rho_a \tag{5}$$

where $M_{tot,a}$ is the total mass at particle location a and R_K is the kernel radius [for example, $2h$ for the cubic spline, as shown in Eq. (3)].

- Equations of fluid motion and energy

As discussed in [9], in the context of solving the "fully conservative" SPH algorithm, freedom is only allowed while deriving the formulation for density estimate. This means that the rest of the SPH algorithm, such as the equations for fluid motion and energy, can be derived based on that formulation. The detailed derivation is well described in [9], beginning with the introduction of the discrete Lagrangian.

The ultimate form of the SPH formulations, i.e., the governing equations for mass, momentum, and energy, is given as follows:

· *Mass conservation:* $\rho_a = \sum_b m_b W[\vec{r}_a - \vec{r}_b, h_a]; \qquad h = h(\rho)$ (6)

· *Momentum conservation:* $\frac{d\vec{u}_a}{dt} = -\sum_b m_b [\frac{P_a}{\Omega_a \rho_a^2} \nabla_a W_{ab}(h_a) + \frac{P_b}{\Omega_b \rho_b^2} \nabla_a W_{ab}(h_b)]$ (7)

· *Energy conservation (no dissipation):*

$$\frac{de_a}{dt} = -\sum_b m_b [\frac{P_a}{\Omega_a \rho_a^2} \vec{u}_b \cdot \nabla_a W_{ab}(h_a) + \frac{P_b}{\Omega_b \rho_b^2} \vec{u}_a \cdot \nabla_a W_{ab}(h_b)] \tag{8}$$

(where *e* is the total specific energy (=0.5u^2+*I, where I* is the internal energy), *u* is the velocity, *P* is the pressure, $\Omega_a \equiv [1 - \frac{\partial h_a}{\partial \rho_a} \sum_b m_b \frac{\partial W_{ab}(h_a)}{\partial h_a}]$, $W_{ab}(h_a) \equiv W(\vec{r}_a - \vec{r}_b, h_a)$, and the subscripts refer to the particle location, e.g., $\rho_a = \rho(\vec{r}_a)$, $h_a = h(\vec{r}_a)$.).

In the practical application of SPH method, there are several important subjects that are not discussed in this section but need special attention, such as artificial compressibility, artificial viscosity, particle searching algorithm, and boundary handling method. Some of these are discussed in relation to the validation results of NEUTRINO in Section 4.

2.3 NEUTRINO [11]

NEUTRINO is a SPH-based CFD software developed by Centroid Lab. The code was originally developed for dealing with astrophysical, compressible fluid flows, and later, the application domain was extended to a wide variety of problems such as non-Newtonian fluids, granular flows, and solid deformation and fracture. The NEUTRINO is optimized for high performance computing with parallel nodes and has advanced graphical user-interface. The Implicit Incompressible SPH solver (IISPH) is used as base fluid solver. The IISPH computes pressure implicitly by solving a pressure Poisson equation via iteration until it meets the incompressibility criterion.

In the following, the numerical algorithm employed in NEUTRINO is briefly explained.

The fluid density is solved in NEUTRINO based on semi-implicit (discretized) form of continuity equation as follows:

$$\frac{D\rho}{Dt} = -\rho \vec{\nabla} \cdot \vec{u} \tag{9}$$

$$\frac{\rho_a(t+\Delta t) - \rho_a(t)}{\Delta t} = \sum_b m_b \vec{u}_{ab}(t+\Delta t) \cdot \vec{\nabla} W_{ab}(t) \tag{10}$$

It is noted that the density estimate by Eq. (10) is somewhat different from the traditional SPH density approximation shown in Eq. (1). Specifically, the SPH approximation is applied to velocity divergence part in Eq. (10) based on the continuity equation [Eq. (9)], instead of directly applying the SPH approximation to the density estimate. This is because the traditional approach can cause a density decrease near the fluids interface where the support regions are not well covered by particles. Another important thing to note is that despite the solver name of IISPH (incompressible flow solver), NEUTRINO does not strictly enforce the incompressibility criterion while resolving the density [this is why the velocity divergence term still remains in Eq. (9)]. In other words, the weakly compressible formula is applied and it leads to so-called artificial compressibility. This is to avoid extra computational cost required to keep the density to be constant during the simulation.

Let us now explain how the density and pressure is estimated in NEUTRINO. In Eq. (10), the unknown velocity $\vec{u}_{ab}(t+\Delta t)$ is coupled with unknown pressure; therefore, $\vec{u}_{ab}(t+\Delta t)$ is initially predicted using known non-pressure forces such as gravity, surface tension and viscosity [see Eq. (11) below]. Then, this velocity is used in Eq. (10) to determine the density $\rho_a(t+\Delta t)$.

$$\frac{\vec{u}_{ab}(t+\Delta t) - \vec{u}_a(t)}{\Delta t} = \frac{F_a}{m_b} \tag{11}$$

The pressure force F^p and pressure p can be estimated based on the following relations:

$$\Delta t^2 \sum_b m_b \left(\frac{F_a^p(t)}{m_a} - \frac{F_b^p(t)}{m_b}\right) \cdot \vec{\nabla} W_{ab}(t) = \rho_0 - \rho_a(t+\Delta t) \tag{12}$$

$$F_a^p(t) = -m_a \sum_b m_b \left(\frac{p_a(t)}{\rho_a^2(t)} - \frac{p_b(t)}{\rho_b^2(t)}\right) \vec{\nabla} W_{ab}(t) \tag{13}$$

$$\sum_b a_{ab} p_b = b_a = \rho_0 - \rho_a(t + \Delta t) \tag{14}$$

where ρ_0 is the reference density.

The unknown velocity $\vec{u}_{ab}(t+\Delta t)$ can be estimated using Eq. (15) below, once the pressure (p) is calculated for each particle (denoted by subscripts a,b):

$$u_a(t+\Delta t) = u_{ab}(t+\Delta t) + \Delta t F_a^p(t) / m_a \tag{15}$$

Then, Eq. (15) is used to update the position of each particle.

As for the time integration, two different numerical schemes are available in NEUTRINO, (i) Euler-Cromer integration and (ii) Verlet integration.

For other details of the algorithms employed in NEUTRINO (e.g., artificial viscosity, boundary handling, fluid-structure interaction solver), the readers are advised to refer to the code manual [11].

3. FLOODING EVENT INVESTIGATION

3.1 Characterization of Flooding Phenomena

The main purpose of this report is to assess the validation and development status of NEUTRINO, with a particular focus on the NEUTRINO's simulation capability for flooding hazards analysis. This activity aims eventually to understand the current technical basis for the flooding analysis and provide guidance for where there is a need for establishing additional database and/or code (NEUTRINO) capability. For this purpose, the general scope of code validation should first be identified. This requires fundamental understanding of the phenomenon, i.e., flooding. In Table 1, three different types of external hazards to NPP safety are characterized. Table 1 characterizes the potential (external) hazard based on (i) types of hazard source, (ii) hazard mode, (iii) associated physics, (iv) regulatory/industry concerns, and (v) potentially impacted SSCs near/on a NPP site. This helps to understand the fundamental features of the phenomena associated with each hazard and potential risk elements to NPP. Based on this understanding, the initial high-level PIRT applicable to the analysis of flooding hazards is established in the next section.

Table 1. Characterization of three different types of external hazards relevant to NPP safety

	Flooding	**Seismic**	**High-Wind**
Source type	River, sea, rain	Tectonic, volcanic, explosion	Straight-line wind, tornado, tropical storm
Primary hazard mode	Water rising, spray event, wave impact, debris impact	Ground motion (considering both ground displacement and duration)	Wind field dynamics, wind-generated missiles
Primary cause of SSCs failure	Water contact, pressure, debris impact	Wave-induced dislocation, soil-structure interaction	Pressure, debris impact
Regulatory / industry concerns	• Internal flooding (accompanied by pipe rupture) • Stream & river overtopping • Dam failure • Storm surge • Heavy rainfall (local intense precipitation) • Wave (tsunami, seiche) • Ice dam	SSCs failure related to soil-structure interaction (e.g., piping system failure, failure of adjacent dam / levee / dike), seismic-induced fire and flood (secondary impacts)	Direct impact on critical plant SSCs, potential impact of failures of non-safety-related SSCs on critical plant SSCs
Potentially affected SSCs near and on NPP site	Circuit breaker panels, computers, control room panels, valves, pumps, generators, offsite power circuits, etc.	Transmission poles, towers, and lines, site-access road, communication systems, pump, etc.	Transmission poles / tower, offsite power circuits, communication systems, site-access road, fire protection system, security systems, warehouse, etc.
References	NRC Generic Letter (GL) 88-20, Supplement 4 (IPEEE program) [12], Miller et al. [13], NRC webpage [14], S. Hess et al. [15], NRC documents [16-18]		

3.2 High-Level PIRT for Flooding Scenario

The PIRT (Phenomena Identification and Ranking Technique) is a method to systematically gather information from experts on a specific issue (e.g., NPP accident) and rank the importance of the information [19]. The ultimate goal is to support decision-making such as determining which information should have high priority for research on that subject. The PIRT was first developed in the late 1980s and has been successfully applied in nuclear technology such as nuclear reactor safety analysis [2]. This is also an essential sub-process for BEPU (Best Estimate Plus Uncertainty) analysis such as CSAU (Code Scaling, Applicability, and Uncertainty), the BEPU methodology acknowledged by the NRC. From a perspective of BEPU analysis, the importance of PIRT comes from the fact that the information obtained from the PIRT (i.e., relative importance of phenomena) is used to determine the code uncertainty input parameters and their realistic boundaries. In general, experts determine the relative importance of phenomena by taking into account their influence on the relevant plant safety metrics (e.g., peak cladding temperature). The standard PIRT process is detailed in Figure 2.

For the safety analysis of NPP, the PIRT process allows us to identify and prioritize the phenomena relevant to the specific NPP accidents so that we can properly analyze them. This process can therefore be useful to determine the overall validation scope of the flooding hazards analysis before we assess the validation and development activities of NEUTRINO. In the present work, as an initial step, the 'high-level PIRT' is proposed for the flooding hazard analysis. In establishing the high-level PIRT, instead of strictly following the process shown in Figure 2, the characteristics of flooding hazards were first classified based on the specific hazard modes and associated physics. This is a process similar to that discussed in ref. [15] which proposed an initial high-level PIRT for high-wind events (see Figure 3). It is noted that the phenomena decomposition used for the analysis of high-wind events [15], shown in Figure 3, can also be applied for the flooding phenomena decomposition, although the properties of fluids (i.e., wind vs. water) and thus potential risk elements to the NPPs are somewhat different.

Table 2 shows the initial high-level PIRT for the application of NEUTRINO to the flooding hazards analysis. In this table, the flooding-related phenomena are first characterized based on the hazard modes. Then, the phenomena are further decomposed according to the associated underlying physics. Finally, the degree of 'Importance' and 'Adequacy' are given for each decomposed phenomenon using three-level scale. The 'high' importance indicates that the phenomenon has a controlling impact on the consequence of the flooding events. Therefore, the high degree of simulation (or modeling) accuracy as well as the intensive validation effort is required for such phenomena. In Table 2, the 'adequacy' is evaluated in two aspects: the code (NEUTRINO) adequacy and validation adequacy. The code adequacy explains how adequate it is to represent the associated physics using NEUTRINO, given the current code development status. The validation adequacy is determined based on the validation efforts required; the 'high' validation adequacy means that the validation effort is mature enough, thus there is no much need for additional experimental and/or high-fidelity numerical data. This high-level PIRT will help to ensure the sufficiency and efficiency of the current code development and validation efforts.

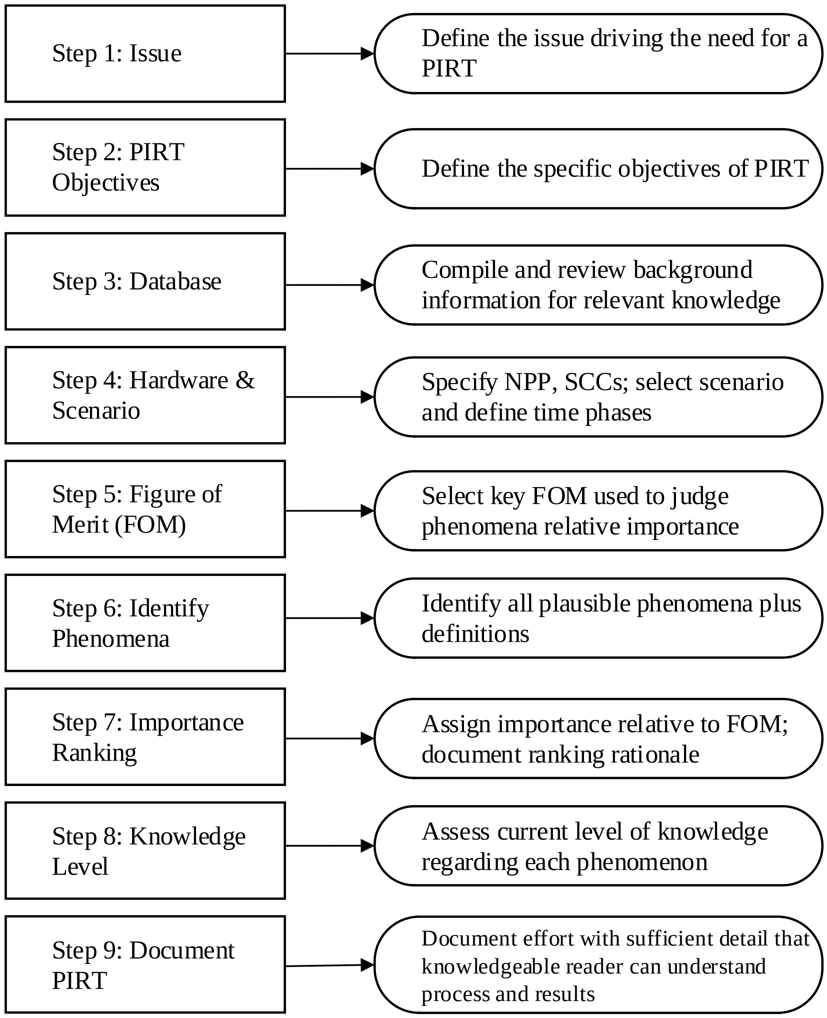

Figure 2. Standard process of PIRT proposed by Boyack and Wilson [20]

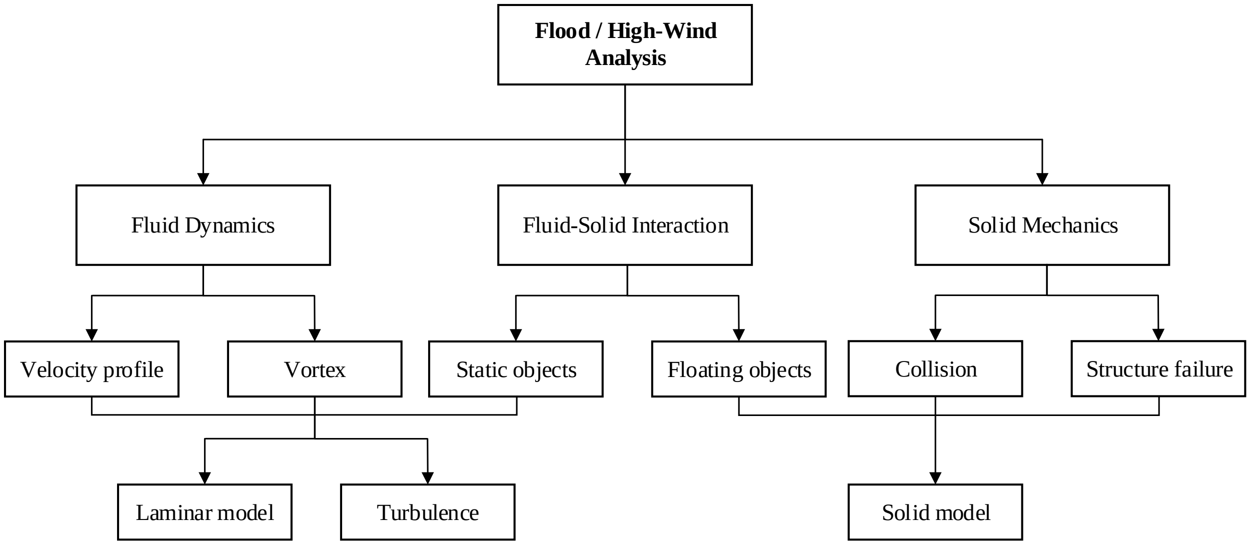

Figure 3. Phenomena decomposition and possible models needed for flood and high-wind events analysis with respect to the use of SPH approach [15]

Table 2. Initial high-level PIRT proposed for application of NEUTRINO to flooding events

Hazard mode	Phenomenon decomposition (simulation capability needed)	Importance	Adequacy	
			Code (NEUTRINO)	Validation
Water rising	Water level / wetting area	High	High	High
Pressure, wave impact	Velocity profile (wave propagation & dissipation)	High	High	High
	Vortex (turbulence)	Low	Medium	Medium
	Fluid-Solid Interaction (e.g., impact forces, spray)	High	Medium	Low
Debris impact	Buoyancy	Medium	High	High
	Fluid-solid interaction (e.g., debris travelling)	High	Medium	Low
	Solid-solid interaction (e.g., collision, force impact)	Medium	Low	Low

4. VALIDATION AND DEVELOPMENT ACTIVITIES FOR NEUTRINO

4.1 Code Validation and Development Activities

This section describes the recent activities of validation and development for NEUTRINO. In Table 3, the associated activities are summarized based on the initial high-level PIRT proposed in Table 2. The present work focuses particularly on the validation efforts to demonstrate the NEUTRINO's capability as a flooding analysis tool for RISMC. Also, the ongoing development activities to improve the simulation capabilities are briefly explained. The discussion below is based on the activities described in the references [11, 21-23]. Thus, readers are advised to refer to these references for more details about the validation results.

In the following, the validation and development activities for NEUTRINO are summarized and discussed based on the classification used in Table 2 (i.e., hazard mode and phenomena decomposition):

(i) Water level / wetting area

The rise of water level and wetting are the phenomena that are generally expected to take place in flooding scenario. In the sense that the water level, area of wetting, and their time-dependent evolution may have significant impact on the consequence and scenario of flooding events (e.g., failure of SSCs in NPP), the demonstration of the simulation capability is important. In the validation test of the "collapse of liquid column", in which the water is initially confined in a rectangular container and subsequently released, Lin [21] showed that SPH approach can successfully predict the decreasing level of water observed by two different experiments [24, 25]. Also, in the "Solitary Wave Past Shore" problem [11], the simulation results of NEUTRINO were shown to agree well with the experimental data for the wave properties of flowing water, including the elevation of water surface and flow depth.

As part of relevant code development effort, a new feature of Height-Field Source is being implemented in NEUTRINO, which will allow a new particle emitter node based on height.

(ii) Velocity profile

The NEUTRINO's ability to predict the wave profile and dissipation was tested with three different validation problems: (i) 2-D wave-packet propagation [22], (ii) sloshing tank [11, 22], and (iii) lid-driven cavity flow [11, 21]. For the test cases of (i) and (ii), the velocity profile was generally well reproduced, while some results revealed that the propagation of small amplitude waves was hard to predict. The simulation results of wave dissipation (and high-frequency noises) depended highly on how to calibrate the artificial viscosity. This requires more study (and improvement) via convergence test, viscosity formulation, etc. Additionally, in the validation problem of lid-driven cavity flow (iii) [21] some discrepancies were observed between the NEUTRINO and the fine-mesh FDM (Finite Difference Method) solutions. This is due possibly to the artificial compressibility that results inherently from the weakly-compressible formula of NEUTRINO (see Section 2.3). This issue also concerns the discussion in the references [11, 21] that the issues of particle vacancy, which usually degrades the simulation accuracy of NEUTRINO, may become severe as Reynolds number increases.

(iii) Vortex [11, 21]:

The predictive ability of NEUTRINO for the small-scale flow characteristic such as vortex was simply discussed in the reference [21, 26]. For the simulation of a constant flow past a fixed solid body, initial results of NEUTRINO seemed to predict well the characteristic flow patterns such as vortex shedding. It is noted, however, that the simulation accuracy was significantly influenced by the particle size being employed for the simulation; for instance, substantial loss of information was observed as the particle size became larger.

To improve the NEUTRINO's ability to represent the turbulence characteristic, efforts are being made to implement the RANS-averaged model while the LES IISPH model was recently implemented. However, in light of analyzing the flooding hazards that are expected to be dominated by large-scale flow features, the importance of this task is considered relatively low (see Table 2).

(iv) Fluid-solid interaction (e.g., impact forces, spray)

One of the main concerns of flooding scenario is the impact of slamming water on the solid structures. To demonstrate the simulation capability of the hydraulic forces acting on the solid bodies, Dam break problems were simulated using NEUTRINO and the results were compared with two experiments of Cummins et al. [27] and Aureli et al. [28], respectively. In comparison with the Cummins' data, the magnitude of impact force was predicted accurately overall, while the impact timing was well represented only at high resolution (specifically, less than 20 % error with particle size $\leq$0.02 m). In the validation case with Aureli's experiment where the impact forces were much less than those of Cummins' experiment, NEUTRINO overestimated the impact forces by about 1N with high-frequency noise compared to the experimental measurement. It is argued in [22] that this is likely related to the overestimation of air entrapment and cushion effect.

Additionally, the falling droplets can influence the performance of various SSCs on/near a NPP site (e.g., electronic device or equipment), thus such effect (i.e., water spray) may also need to be taken into account as the future validation problems in this category.

As code development efforts, the integration of a new rigid body solver, Chrono, is underway to improve the simulation capability of the fluid-solid interaction in NEUTRINO. The Chrono is known to be better validated for various engineering applications, thus is expected to be able to replace or complement the current rigid body solver Bullet Physics. Also, NEUTRINO is now be able to model the terrain (e.g., ground or sea floor) using a new node Rigid Topography. Coupling with shallow water (SW) model/finite element (ADCIRC) is another ongoing development effort for NEUTRINO.

(v) Buoyancy

Several tests were performed to demonstrate the NEUTRINO's ability to represent the effect of buoyancy. The tests were specifically conducted with a falling and a floating solid body (geometry: sphere or cuboid) in static water [11] while applying the various density ratios between the fluid and solid ($\rho_{solid}/\rho_{fluid}$). Then, the time-dependent trajectories of the solid bodies computed by NEUTRINO were compared with the analytic solution [22] and/or high-fidelity numerical solution [11]. The simply floating or falling solid bodies seemed to be represented relatively well, but larger deviation was observed when predicting the oscillating behavior. Also, there was a particular challenge when the solid-fluid density ratio was close to 1 (specifically, $\rho_{solid}/\rho_{fluid} \approx 0.9–1.2$) [22]. The drag force (friction) was another factor that affected the simulation result. Finally, it is important to note that special cares must be taken for the selection of boundary handling mode in NEUTRINO as it has significant impact on the simulation accuracy of the buoyancy effect [22]. For example, single-layer boundary mode is not recommended for the simulation of dynamic solids in fluid.

Currently, to further investigate the simulation issues related to buoyancy and drag force, the "medicine ball sinking" problem is being studied with the University of Toulon [22].

(vi) Fluid-solid interaction (e.g., debris travelling)

The interaction between the flowing liquid and solids that may lead to "debris travelling" is the main concern of this category. The buoyancy and drag forces are dominant factors that can affect the associated hazard scenario and consequence due to the dynamic debris. In combination with the efforts to investigate the buoyancy issues discussed above [i.e., (v)], studies are underway for the fluid pressure and drag forces acting on the solids.

(vii) Solid-solid interaction (e.g., collision, force impact)

The impact of dynamic solids on the solid structures is the primary concern of this category. This so-called solid-solid interaction is generally expected and may cause a wide range of damages to power plants and buildings during the flooding scenario. Nonetheless, no direct validation effort has yet been found in this category, thus more validation effort is required.

Table 3. Validation activities of NETRINO in relation to flooding hazards

Hazard mode	Phenomenon decomposition (simulation capability needed)	Validation cases performed	Remarks (observed issues/difficulties, ongoing activity)
Water rising	Water level / wetting area	Solitary wave past shore	· Height-field source implementation (in progress)
Pressure, wave impact	Velocity profile (wave propagation & dissipation)	Poisuelle flow, 2-D wave-packet propagation, Sloshing tank [29], Solitary wave past shore	· Difficult to reproduce small amplitude waves. · Need careful calibration of artificial viscosity.
	Vortex (turbulence, low Reynolds #)	Sloshing tank [29]	· LES IISPH model (implemented) · RANS model (in progress)
	Fluid-solid interaction (e.g., impact forces, spray)	Dam break problems (comparing with experimental data [27, 28])	· A new node for rigid topography (implemented; for ground or sea floor modeling). · Validation (dam break): Partially satisfactory in predicting the impact force magnitude and timing. · Expected potential issue (validation, dam break): overestimation of air entrapment, cushion effect. · Currently integrating a new rigid body solver (Chrono).
Debris impact	Buoyancy	Floating or falling solids in static water (sphere and cuboid); medicine ball sinking in water (in progress); tested the performance of single/double boundary layer option.	· Challenging as $\rho_{solid}/\rho_{fluid} \rightarrow 1$. · Single boundary layer option is not ideal for accuracy.
	Fluid-solid interaction (e.g., debris travelling)		· Investigating the buoyancy-coupled issues (e.g., fluid pressure and fluid friction forces acting on a solid; impact of individual forces). · Significant deficiency of single boundary layer mode for representing dynamic solids. · The code capability of vortex prediction may be important in the context of debris travelling.
	Solid-solid interaction (e.g., collision, force impact)		

4.2 Experimental Activities

The high-quality experimental data is crucial in developing and validating the new (advanced) analysis tools and methods for RISMC research. Thus, efforts are being made to support the production of high-quality experimental data which are required to validate the RISMC tools, including NEUTRINO. The support is specifically made through a multi-partner External Hazards Experimental Group (EHEG). As the name implies, the EHEG supports the experimental activities related to the concerns of external hazards (e.g., seismic and flooding events), and was coordinated by INL for RISMC pathway. The EHEG consists of INL, other national laboratories, and universities to perform the necessary external hazard experiments [30]. The organization and operation of EHEG is expected to help efficiently communicate the technical expertise, experience, and testing data within the group. The databases developed by EHEG will be stored and be made available for use within RISMC through the INL Seismic Research Group website [https://seismic-esearch.inl.gov/SitePages/Home.aspx] [30].

Table 4 summarizes the focus area of research, expertise, and existing/developing research capabilities of each partner in EHEG. This is based primarily on the information given in the reference [30] (in Appendix A). Thus, readers are advised to refer to the reference for more details.

As part of specific effort to develop experimental data for flooding models validation, there is an experimental activity being made in George Washington University (GWU). The primary goal of the GWU experiment is to investigate the wave impact of water within a horizontal large rectangular tank. The tank is designed to allow the oscillations of entire body so that the external force can excite the water with better control than the traditional method of using wave paddle on one end of the tank. This facility can also useful for studying the seismic effects on NPP facilities (e.g., spent fuel pool). The large size (width) of tank allows the observation of 3D flows that may encounter in actual flooding scenario. Also, the tank design which allows the long-term continuous operation (oscillation) is expected to help produce the high-quality data with high statistical significance. Before specifying the design of experiment, the GWU research team performed a variety of CFD study with NEUTRINO for tank size, water level, object, forcing type (amplitude and frequency).

There is still large deficiency of experimental data that can be used for the development and validation of flooding analysis tool such as NEUTRINO. In order to achieve a RISMC goal in a timely and cost-effective manner, more strategic effort is required, as proposed in Table 3.

Table 4. Summary of EHEG partners and capabilities [23, 30]

<table>
<tr><th rowspan="2">No.</th><th rowspan="2">EHEG Partner</th><th colspan="2">Existing/future capabilities</th></tr>
<tr><th>Capability type (Exp / MM*)</th><th>Research focus area & capabilities</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">INL</td><td>MM</td><td>[Seismic, flooding]
- Non-linear soil structure interaction (NLSSI) simulation
- SPRA (multi-hazard risk analysis)
- Time-based stochastic analysis
- External hazard analysis at virtual NPP (future plan)</td></tr>
<tr><td>Exp</td><td>[Seismic]
- Geotechnical centrifuge
- Small scale structural dynamics lab (future plan)</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">University of Buffalo</td><td>MM</td><td>[Seismic]
- Experienced with analysis of seismic isolation components and systems; developed isolator unit elements for multiple NLSSI codes.
- SPRA (isolator and umbilical system analysis)
- Experienced with NLSSI simulation</td></tr>
<tr><td>Exp</td><td>[Seismic]
- Two high-performance, 6 DOF shake tables
- Nonstructural Component Simulator (NCS)
- Large-scale geotechnical laminar box
- Hybrid simulation systems</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">George Washington University</td><td>MM</td><td>Experienced with computer model benchmark and validation (including NETRINO)</td></tr>
<tr><td>Exp</td><td>[Seismic, flooding]
- Diagnostics development for time-based analysis and code validation
- Modal and tensile testers
- Dedicated high-bay space with strong floor
- Large, polyvalent, and transportable suite of advanced diagnostics proven on shake table</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">Purdue University</td><td>MM</td><td>[Seismic]
- NLSSI simulation & analysis</td></tr>
<tr><td>Exp</td><td>[Seismic]
- Wykeham Farrance unsaturated dynamic hollow cylinder device for testing hollow or solid specimens
- Automated triaxial testing (CKC) system for cyclic or monotonic loading test
- Automated MTS programmable load frame for stress- or strain-controlled dynamic or monotonic testing
- Small- and large-scale direct shear boxes, ring shear device and pull-out box
- Hydraulic static and cyclic actuators with up to 1000 kip capacity</td></tr>
<tr><td rowspan="2">5</td><td rowspan="2">University of Illinois at Urbana Champaign</td><td>MM</td><td>[Seismic]
- NLSSI simulation & analysis; soil constitutive modeling for NLSSI analysis</td></tr>
<tr><td>Exp</td><td>[Seismic]
- Multi-directional simple shear device for soil testing
- Monotonic and cyclic triaxial soil testing device
- Resonant column soil testing device</td></tr>
<tr><td>6</td><td>North Carolina State University</td><td>MM</td><td>[Seismic, flooding]
- Multi-hazard PRA; Bayesian analysis
- Vulnerability assessment for plant SSCs with UQ
- Fragility assessment of flood defense structures associated with flooding and seismic loads
- Equipment qualification (e.g., electrical cabinets and control panels); characterization of uncertainty in mounting arrangement.</td></tr>
<tr><td rowspan="2">7</td><td rowspan="2">Idaho State University</td><td>MM</td><td>[Flooding]
- SPH modeling for flood/tsunami</td></tr>
<tr><td>Exp</td><td>[Flooding]
Water flume and associated water storage/pumping</td></tr>
</table>

* Exp: experiment; MM: modeling and methods development

5. SUMMARY AND CONCLUSIONS

We discussed the validation and development activities of NEUTRINO, the SPH-based CFD software adopted by the RISMC Pathway for flooding hazards analysis. The main concern is to understand the NEUTRINO's (current) ability to simulate the various types of flooding hazards and to discuss the code validation, development, and validation data needs. At first, the potential risks of flooding phenomena to NPP (e.g., hazard modes, industry/regulatory concerns, etc.) were analyzed and characterized. Then, an initial high-level PIRT was proposed to define the relevant phenomena needed to analyze the flooding hazards. Based on the framework of this PIRT analysis, the validation and development efforts that have been conducted to date were discussed. This helped to determine the sufficiency, efficiency, and adequacy of the current code development and validation efforts. It is hoped that this work can help to establish the efficient future validation strategy for NEUTRINO.

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