Neutron-physical characteristics modeling of light water reactors critical corium slurry in water

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Abstract. In this paper, the idea of modifying the benchmark by increasing effective multiplication factor value in the considered system without increasing the number of particles under consideration and fuel enrichment is discussed. The technology of data transmission, processing and comparison of the results of neutron-physical calculations using three modern codes developed in different countries and implementing the Monte Carlo method has been worked out. For the corium and water mixture parameters search, the method conventionally called the gradient descent method is used. The search method for areas of critical state corium slurry in water is described. This method can be used to justify nuclear safety in the corium extraction and transportation processes. The methodology is based on the combined use of 1-D and 3-D criticality calculations capabilities of the SCALE 6.2 program pack. Fall of corium particles in water simulation benchmark version is formulated. The possibility of using the algorithm to find the parameters of a corium and water mixture is demonstrated. This benchmark includes the critical state of corium slurry in water and assumes the use of regular structures in the formation of geometric models. The proposed version of the critical benchmark for the corium particles in water state contains 55% fuel.

1. Introduction
At present, the safety of nuclear energy is a key factor in determining the competitiveness of nuclear energy compared to other types of electricity generation, including thermal power, hydropower, as well as alternative methods of generating electricity such as the use of wind, solar and tidal energy. Natural disasters, design errors, operator errors and all the factors that followed, led to the fact that in 2011 the largest accident in the history of nuclear energy occurred at the Japanese nuclear power plant Fukushima-1. As a result of the black down of the emergency cooling systems, a residual energy release removal problem arose in the core. This led to the core melting in the reactors of power units 1, 2, 3 and to the corium formation, which consists of structural materials and irradiated nuclear fuel.

Sooner or later, the final decision to remove this formed corium from the power unit vessel will be made. The problem is that the molten fuel and construction materials are partially or completely submerged. Moreover, groundwater comes from the soil. In connection with the above factors, the question arises as to whether during the corium extraction and transportation processes, a critical system formed by particles of the extracted corium and water will not arise.
To prevent criticality, mitigation measures for severe accidents require boron to be added to water-cooled systems as it is a strong neutron absorber, especially for thermal neutrons. However, severe damage causes some cooling water leakage as well as groundwater inflow into the reactor buildings. Subcriticality of corium and water is constantly monitored [8]. Since no signs of criticality have yet been found, it is assumed that the state of the corium is subcritical [2].

The corium criticality was first calculated and thoroughly investigated after the severe accident at Three Mile Island Block 2 (TMI-2) in 1979. After that, research on the severe accident practically stopped and was fully resumed only after the Fukushima accident [3]. Before, there is no data to check the reliability of the corium criticality calculations. Meanwhile, the first preliminary calculations of the criticality of the Fukushima Daiichi nuclear power plant were recently published [4].

So far, very different models of corium particles and their distributions have been used to calculate criticality [5-11]. The first distinction can be made between homogeneous models and heterogeneous models. In homogeneous model, fuel and water are homogeneously mixed; In heterogeneous model, the fuel particles are immersed and surrounded by water. Among all heterogeneous models that have been used, it is also possible to distinguish between different types of particles (spheres or cylindrical pins) and spatial distributions (cubic, triangular, hexagonal and dodecahedral lattices). In most works, the choice of the model is not justified; only a few studies support choices with physical arguments that guarantee conservative outcomes. Obviously, there are no general criteria for modeling debris beds, and the scope and suitability of possible approaches are still unclear.

2. Critical benchmark condition formulation

In works [12-14], a unique possibility of coupling-calculations carrying out was realized. These calculations are carried out with code for calculating the dynamics of the corium particles in the water layer spatial distribution and codes of neutron-physical calculations for such systems criticality analyzing. The technology of data transmission, processing and comparison of the results of neutron-physical calculations using three modern codes developed in different countries and implementing the Monte Carlo method has been worked out. The calculations were carried out on the basis of the problem, which we will call the pilot version of the benchmark for corium-water system properties calculation. A significant drawback of the existing benchmark version is its deep subcriticality. The overwhelming majority of benchmarks for the effective neutron multiplication factor ($K_{\text{eff}}$) calculation are formulated for $K_{\text{eff}} \approx 1$. There are only few benchmark with $K_{\text{eff}}$ around 0.8 exist. It is believed that in such problems it is not possible to substantiate the possibility of realizing its own spectrum.

In this paper, we discuss the idea of modifying the benchmark by increasing $K_{\text{eff}}$ value in the considered system without increasing the number of particles under consideration and fuel enrichment. It seems promising to develop a benchmark version for the critical state when $K_{\text{eff}} > 0.95$ without increasing the difficulty (without increasing the number of corium particles in the computational system $N_{\text{krit}} < 1000$) for particles distribution calculation codes and neutron-physical calculations codes. When developing the benchmark version, that include the system critical state, the capabilities of the SCALE 6.2 program pack were used: XSDRNPM - 1-D transport code based on the method of discrete ordinates and KENO-VI - code based on the Monte Carlo method used to calculate the multiplication factor and related functionals of 3-D systems.

The task is to find such a situation that the following conditions are simultaneously fulfilled:

- corium particles in water should provide a neutron multiplication factor $K_{\text{eff}} \geq 1$;
- the particles should be close to each other;
- particles in water should not occupy a large volume;
- these particles must have a small mass;

For the condition $K_{\text{eff}} = 1$, it is necessary to obtain the dependence of the number of particles in the calculated critical model $N_{\text{krit}} (a, b, \gamma)$, where: $a$ – size of corium particle in slurry, $b$ – placing step of corium particles in slurry, $\gamma$ - proportion of fuel in corium.
The problem of the simultaneous fulfillment of these conditions is related to the fact that inequality (1) must be observed.

$$\text{MIN} \{ N_{krit} (a, h, \gamma) \} \neq \text{MAX} \{ K_{x} (a, h, \gamma) \}$$

(1)

Therefore, the idea proposed in many works to make a start from the multiplication factor calculations results of an infinite slurry of corium particles in water turns out to be ineffective.

Let us formulate the selected problem by setting constraints on the selected characteristics:

- \( K_{eff} > 0.95 \);
- \( N_{krit} < 1000 \div 2000 \) - number of particles in the number of particles in the calculation model.

Also, we will formulate possible additional restrictions on characteristics (in terms of reduction):

- size (volume) of critical slurry \( R_{krit} \);
- fuel mass in critical slurry \( M_{krit} \).

We are faced with an additional problem of the mismatch of the extreme values of the listed characteristics (2).

$$\text{MIN} \{ N_{krit} (a, h, \gamma) \} \neq \text{MIN} \{ M_{krit} (a, h, \gamma) \} \neq \text{MIN} \{ R_{krit} (a, h, \gamma) \}$$

(2)

3. Search method for corium-water slurry critical states

We will search for the parameters of a corium and water mixture using the method conventionally called the gradient descent method. Let us demonstrate the possibility of using the algorithm to find the parameters of a corium and water mixture, potentially satisfying the requirements of the developed benchmark. The composition of the corium was obtained taking into account the recommendations [16, 17]. To adjust the parameters of the developed benchmark, the dependences of the parameters of the three-dimensional model on the water-fuel ratio for the corium particle size of 2.4, 2.7 and 3 cm are graph at the figures 1-4.

![Figure 1. Dependence of the slurry unit cell multiplication factor on the water-fuel ratio for the size of corium particles: 1 - 2.4 cm, 2 - 2.7 cm, 3 - 3 cm, where (a) is for 100% fuel in debris case, (b) is for 38% fuel in debris case](image)
Figure 2. Dependence of the slurry particles critical number on the water-fuel ratio for the particle size of the corium: 1 - 2.4 cm, 2 - 2.7 cm, 3 - 3 cm where (a) is for 100% fuel in debris case, (b) is for 38% fuel in debris case.

Figure 3. Dependence of the slurry critical fuel mass on the water-fuel ratio for the particle size of corium: 1 - 2.4 cm, 2 - 2.7 cm, 3 - 3 cm, where (a) is for 100% fuel in debris case, (b) is for 38% fuel in debris case.

Figure 4. Dependence of the slurry critical radius on the water-fuel ratio for the size of corium particles: 1 - 2.4 cm, 2 - 2.7 cm, 3 - 3 cm, where (a) is for 100% fuel in debris case, (b) is for 38% fuel in debris case.
The data obtained for adjusting the parameters of the developed benchmark allow us to form a parameters range for which $K_{\text{eff}}$ calculations are carried out for 3-D models of the corium particles in water placement. It is assumed that the maximum $K_{\text{eff}}$ value will be reached when the corium particles are completely immersed in water, but before the process of hydrodynamic change of the initial configuration of the corium particles begins (figure 5).

Figure 5. Horizontal section of the calculation model at the maximum value of $K_{\text{eff}}$

Figure 6 shows the dependences of the multiplication factor of a 3-D model with 1000 particles slurry on the particle size for the step between the particles of 4 and 5 cm for the fuel fractions in the corium 38 and 100%. For the developed benchmark, promising options appear:

- for the proportion of fuel in the corium 38%, the particle size is 3.6 cm and the distance between the particles is 5 cm. Such a volume of corium is critical and contains 195 kg of fuel;
- with a particle size of 2.7 cm and a distance between particles of 4 cm. Such a volume of corium is subcritical and contains 82 kg of fuel.

Figure 6. Dependence of the multiplication factor of a 3-D model with 1000 particles slurry on the particle size for the step between particles: 2 and 2' - 4 cm, 3 and 3' - 5 cm
4. Critical benchmark modified version

The proposed version of the critical benchmark for the corium particles in water state contains 55% fuel. Figure 11 shows the selected types of options for the developed benchmark.

Table 1 shows the $K_{eff}$ values in the final version of the proposed benchmark options. Figure 7 shows the multiplication factor of a 3-D model of 1000 solids slurry for the benchmark options for different fuel fractions.

**Table 1.** $K_{eff}$ values of the final version of the proposed benchmark options

| case | $K_{eff}$ 100 % | $K_{eff}$ 55 % | $K_{eff}$ 38 % |
|------|-----------------|----------------|----------------|
| 1    | –               | –              | –              |
| 2    | 1,06816         | 0,95404        | 0,86519        |
| 3    | 1,12318         | 1,00684        | 0,91453        |
| 4    | 1,10062         | 0,97027        | 0,87246        |
| 5    | 0,92926         | 0,80858        | 0,71971        |
Figure 8. The multiplication factor of a 3-D model of 1000 particles slurry for benchmark options:
1 - fuel content in corium - 55%, 2 - 55%, 3 - 38%

5. Conclusions
A search method has been developed for areas of the critical state of corium particles slurry in water. The technique is based on the combined use of the SCALE 6.2 program pack capabilities: XSDRNPM code for 1-D calculation by the discrete ordinates method and KENO-VI code for calculating the 3-D systems multiplication factor of by the Monte Carlo method.

A benchmark version that simulates the fall of corium particles into water is formulated. The benchmark includes the critical state of corium slurry in water, the geometric models of the benchmark use regular structures.

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