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# Experimental investigation of particulate debris spreading in a pool

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ABSTRACT

Termination of severe accident progression by core debris cooling in a deep pool of water under reactor vessel is considered in several designs of light water reactors. However, success of this accident mitigation strategy is contingent upon the effectiveness of heat removal by natural circulation from the debris bed. It is assumed that a porous bed will be formed in the pool in the process of core melt fragmentation and quenching. Debris bed coolability depends on its properties and system conditions. The properties of the bed, including its geometry are the outcomes of the debris bed formation process. Spreading of the debris particles in the pool by two-phase turbulent flows induced by the heat generated in the bed can affect the shape of the bed and thus influence its coolability.

The goal of this work is to provide experimental data on spreading of solid particles in the pool by large-scale two-phase flow. The aim is to provide data necessary for understanding of separate effects and for development and validation of models and codes. Validated codes can be then used for prediction of debris bed formation under prototypic severe accident conditions. In PDS-P (Particulate Debris Spreading in the Pool) experiments, air injection at the bottom of the test section is employed as a means to create large-scale flow in the pool in isothermal conditions. The test section is a rectangular tank with a 2D slice geometry, it has fixed width (72 mm), adjustable length (up to 1.5 m) and allows water filling to the depth of up to 1 m. Variable pool length and depth allows studying two-phase circulating flows of different characteristic sizes and patterns. The average void fraction in the pool is determined by video recording and subsequent image processing. Particles are supplied from the top of the facility above the water surface. Results of several series of PDS-P experiments are reported in this paper. The influence of the gas flow rate, pool dimensions, particle density and size on spreading of the particles is addressed. A preliminary scaling approach is proposed and shown to provide good agreement with the experimental findings.



## 1. Introduction

In order to prevent containment basemat penetration after melt release from the vessel in a hypothetical severe accident (SA) in Nordic type BWR reactors, the lower drywell is flooded with water. When released from the reactor vessel (RV) into a several meters deep water pool, molten corium is expected to fragment, be quenched and form a porous debris bed. In order to avoid corium debris bed dryout and re-melting, the decay heat should be removed by evaporation of water driven by the natural circulation of coolant through the bed. The properties of the debris bed (particles size, bed porosity, bed geometry, etc.) and SA scenario conditions (e.g. system pressure) can affect coolability of the bed. Analytical and experimental studies (Yakush et al., 2012; Yakush and Kudinov, 2009; Takasuo et al., 2011) suggested that geometrical configuration of the debris bed is one of the main factors influencing the bed coolability. A tall debris bed can hardly be coolable and, in contrast, the same mass of the corium material can be cooled easily if the debris is spread uniformly over the whole available basemat area (Yakush et al., 2012).

The shape of the debris bed is affected by debris particle transport:

i. after settlement on the debris bed;
ii. in the water pool above the bed.

Debris bed self-leveling occurs due to the mechanical energy of two phase flow in the porous bed. Pioneering experiments conducted with metallic powders showed that, indeed, coolant boiling

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**Nomenclature**

| | |
|---|---|
| $\alpha$ | total void fraction in the pool |
| $\alpha_{eff}$ | effective void fraction in the pool |
| $a_i$ | area of the $i$th catcher |
| $A_{tot}$ | total area available at the pool bottom for particle spreading |
| c | center gas injection in the pool, used in test numbering as NOPc |
| $C_d$ | drag coefficient for particle |
| $d_p$ | particle diameter (effective) |
| $\phi$ | effective or average particle spreading angle |
| GL | glass material, used in test numbering |
| $H_{pool}$, $H_p$, $H$ | pool depth (height) |
| $L_{pool}$, $L_p$, $L$ | pool length |
| $m_i$ | mass of the particulate material found in $i$th catcher |
| $\tilde{m}_i$ | dimensionless mass fraction per area of the material found in $i$th catcher |
| $M_{tot}$ | total mass of the particulate material |
| NOP | no particles of particle-free test, used in test numbering |
| $Q_g$ | gas mass flow rate |
| $\rho_c'$ | modified density of water (coolant) |
| $\rho_p$ | density of the particulate material |
| $R_c$ | debris bed center of mass |
| $R_{spr}$ | average horizontal spreading distance for particles |
| RV | reactor vessel |
| $r_i$ | $i$th catcher position measured from the gas injection chamber |
| s | side gas injection in the pool, used in test numbering as NOPs, SSs or GLs |
| SA | severe accident |
| SS | stainless steel material, used in test numbering |
| $U_{g,sf}$ | gas superficial velocity |
| $U_t$ | terminal velocity of the particle |

promotes debris self-leveling, influences the horizontal velocity of vertically falling particles, affecting thus the repose angle of the bed (Alvarez and Amblard, 1982). The effectiveness of particulate debris bed spreading has been considered in the experimental and theoretical studies (Zhang et al., 2010, 2011; Cheng et al., 2014; Konovalenko et al., 2012; Basso et al., 2014a,b; Jasmin Sudha et al., 2015). As was shown in the experiments, debris self-leveling occurs due to particle motion in the top layer of the debris bed ().

The large-scale turbulent two-phase flows (as illustrated in Fig. 1a) may affect the particle lateral spreading over the basemat (Yakush and Kudinov, 2009), preventing formation of a tall debris bed. Smaller particles are more effectively transported by the flow. In Fig. 1(b and c) from (Yakush and Kudinov, 2009), the flow field (white lines on the left), void fraction distribution (color map), particle trajectories (yellow lines) and bed shape (dashed line) are presented for simulation times of 30 min and 4 h. The debris bed is spread over the bottom of the pool, despite the fact that all particles are released from a relatively small source near the axis.

It should be noted that in some accident scenarios the pool can be initially subcooled. In this case, boiling in the pool can start when the hot water plume stemming from the debris bed approaches the surface and its temperature exceeds the local saturation temperature corresponding to the local hydrostatic pressure head. This effect was demonstrated in (Yakush and Kudinov, 2011). In recent studies (Kim et al., 2014), the influence of two-phase flow on sedimentation of the different in size particles has been investigated experimentally. Numerical approaches employing discrete element analysis for particle spreading are also under development (Kudinov and Dinh, 2007; Shamsuzzaman et al., 2014).

The goal of this work is to provide experimental data and scaling considerations for particle spreading in the pool by large-scale two-phase flows induced by gas injection from the pool bottom. The data are necessary for the development and validation of numerical codes for modeling the debris bed formation in prototypic severe accident conditions.

## 2. Experimental approach

The main goal of the work is to provide data for code validation. Therefore, selection of experimental parameters is based not only on consideration of severe accident (SA) conditions, but on the merits of experimental data for validation of different models. The general aim of the tests is to cover possible ranges of different regimes and parameters in order to provide data for understanding of importance of separate effects.

In the experiments, we quantify the distribution of particles along the pool bottom as a function of gas injection parameters. The technique is similar to that used in the studies on self-leveling and spreading of the particulate debris bed in PDS-C (Particulate Debris Spreading Closures) facilities reported in Konovalenko et al. (2012) and Basso et al. (2014b)). A detailed description of the measurement techniques is reported in Konovalenko et al. (2014). The test conditions and measured parameters for the new series of the tests are given below.

### 2.1. PDS-P facility and test conditions

The PDS-P (Particulate Debris Spreading in the Pool) facility consists of the following main parts: the particle delivery system, main water tank, the particle collection system, gas supply and flow rate measurement system (Konovalenko et al., 2014). The general view of the facility is illustrated in Fig. 2(a). A snapshot of facility operation is given in Fig. 2(b). The tests reported herein were performed with the following variable and fixed parameters (see Fig. 2 for definition of some parameters): the depth of water pool, $H_{pool}$, was either: 0.5, 0.7, or 0.9 m; the pool length, $L_{pool}$, was either: ~0.5; ~0.9[1] or 1.5 m; the tank width was fixed to 72 mm. These dimensions were chosen in order to preserve close to 2D geometry for the turbulent currents and particles spreading, i.e. the pool width was much smaller than the length and height of the pool. On the other hand, the pool width was much larger than the characteristic particle size in order to minimize the influence of particle-wall interaction. The water tank is made of 20 mm thick acrylic material. Several pairs of rigid bars are installed (as shown in Fig. 2) to minimize vibrations and bulging of the tank walls during air injection. The water temperature was kept within 15–18 °C.

The gas injection chamber was a rectangular box with the height 60 mm, length 200 mm, and width 70 mm. The air injecting holes in perforated top plate were 1 mm in diameter, the pitch size of the holes was 10 mm in both directions. The air mass flow rate, $Q_g$, is adjustable and provides uniform gas injection within the range of 2.2–14.5 g/s. The top limit of the range was selected in order to be able to achieve fluidization of settled debris bed at the highest values of $Q_g$.

Particles were delivered from the top boundary of the facility at the fixed height of 1.61 m above the top of the particle catchers through a funnel equipped with Archimedes screw as shown in Fig. 2(a) and schematically in Fig. 11. The particle delivery rate was varied in the range between 1 and 5 g/s in order to minimize

[1] The exact value of 0.894 m is rounded in the legends of the plots to 0.89 m or 0.9 m for the sake of brevity.