A Review of Experimental Studies about Formation and Coolability of Ex-vessel Debris Bed in a Pre-flooded Reactor Cavity

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1. Introduction

A severe accident is defined as the most critical type of incident that can occur at a nuclear power plant, involving significant core damage and the potential release of radioactive materials into the environment. Following the Fukushima accident, the need to demonstrate the safety of nuclear power plants even in the event of a severe accident became increasingly important, leading to changes in severe accident management strategies. The strategy currently adopted in South Korea is In-Vessel Retention through External Reactor Vessel Cooling (IVR-ERVC), an effective severe accident management strategy aimed at terminating the progression of a severe accident within the reactor and thereby reducing the likelihood of reactor containment failure. However, the technical applicability and feasibility of the IVR-ERVC design for high-power reactors still require validation, especially considering the uncertainties in physical models, initial conditions, and assessment methodologies [1]. If the molten core material inside the reactor is not adequately cooled in the flooded cavity, it may be expelled out of the reactor vessel. Consequently, phenomena such as Molten Core Concrete Interaction (MCCI) and Fuel Coolant Interaction (FCI) could occur, potentially compromising the structural integrity of the containment vessel [1]. Therefore, to prevent such scenarios, it is crucial to understand the complex phenomena that occur when the molten material interacts with water in the flooded cavity and to assess its coolability.

In this study, three key factors deemed critical in the process from ex-vessel release of molten material to its eventual cooling by water have been identified, and the study is structured based on experiments related to these factors. The three factors are particle size distribution, debris bed formation, and coolability, with representative experiments including FARO, DEFOR, PDS, TROI, COOLOCE, POMECO, and STYX. This paper focuses on these selected factors shown in Table I, providing explanations of the corresponding experiments and their major findings. The purpose of this literature survey is to summarize the results of key experiments related to the flooded cavity, identify the limitations of existing research, and contribute to identifying research topics that could reduce uncertainties in ex-vessel severe accidents.

Table I. The introduction of experiments involved in this paper.

Area	**Organization**	**Experiment of Program**	**Key factor**
Europe	European Commission-Joint Research Centre, JRC	FARO	Particle size distribution, Debris bed formation
Sweden	Royal Institute of Technology, KTH	DEFOR-E	Particle size distribution, Debris bed formation
		DEFOR-A	Particle size distribution, Debris bed formation
		PDS	Particle size distribution, Debris bed formation
Finland	Technical research centre of Finland, VTT	COOLOCE	Coolability-geometry, flooding type
Sweden	Royal Institute of Technology, KTH	POMECO	Coolability-particle properties
Finland	Technical research centre of Finland, VTT	STYX	Coolability-flooding type, particle properties
Germany	IKE	DEBRIS	Coolability-flooding type, particle properties

2. Experiments for Formation and Coolability of Debris Bed

In this section, various experiments and their major results are described according to each key factor.

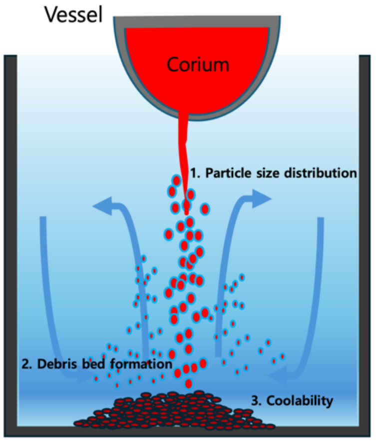


Figure 1. Conceptual diagram of formation and coolability of ex-vessel debris bed in a pre-flooded reactor cavity.

2.1. Particle size distribution

If molten corium escapes the vessel, it will come into contact with the water pre-flooded in the cavity. The high-temperature corium undergoes fragmentation upon interaction with the subcooled water and subsequently settles at the bottom of the cavity. The characteristics of the settled particles significantly influence the formation of the debris bed and its coolability, making an understanding of these formation properties a critical aspect of severe accident management. Experiments such as FARO in Europe, DEFOR in Sweden, and TROI in Korea have been conducted to investigate the particle size distribution during ex-vessel severe accident scenarios.

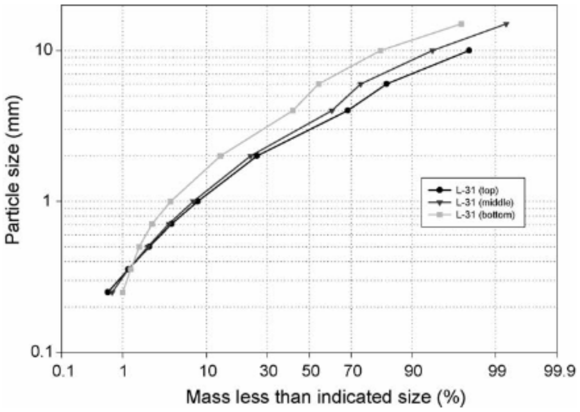


Figure 2. Particle size distribution at three elevations of the debris bed of FARO L-31 [2].

In the FARO experiments, the impact of debris bed depth was discerned from the L-31 experiment. The relationship between particle size and debris bed depth is illustrated in Figure 2. Particle size data were collected at three distinct elevations: near the top of the debris, at the midpoint, and close to the upper surface of the cake. Mean particle size was 3mm for upper part, 3.4mm for the middle part and 5.2mm for the lower part.

There are some significant results about particle size distribution in DEFOR experiments. In DEFOR-A10 and A11 tests, new simulant material was used to improve the visualization. It was ZrO_2-WO_3, and in previous DEFOR-A experiments, Bi_2O_3-WO_3 was used as simulant material. In DEFOR-A10 and A11 tests, simulated experiment with ZrO_2-WO_3 had overall larger particle size distribution than the previous DEFOR-A tests with Bi_2O_3-WO_3.

The influence of the melt initial temperature and jet initial velocity could be obtained by comparing DEFOR-A10 and DEFOR-A12 and it is shown in Figure 3. The low superheat of melt will cause fast crystallization and consequently large fragments. High jet velocity will enhance hydrodynamic instabilities in the pool, promote faster fragmentation and consequently, smaller particles [3].

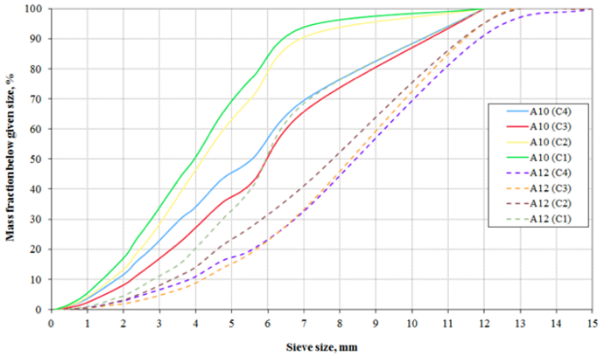


Figure 3. Cumulative mass fractions per catcher established in A10, 12 tests [3].

2.2. Debris bed formation

Critical factors in debris bed formation include cake formation and self-leveling. To evaluate the coolability of a debris bed, it is essential to understand whether water can effectively penetrate the interior of the debris bed.

2.2.1. Formation of cake

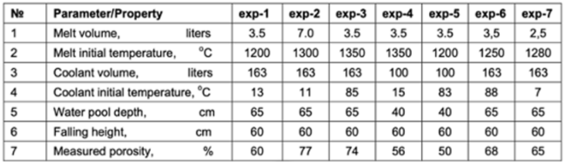
In FARO experiments [2], there were 12 experiments about debris data and there was no cake formation in L-11 and L-31. It can be concluded that adding Zr in melt caused efficient quenching than a test with no Zr metal (L-14) and promoted fragmentation of debris. There is also the influence of water depth on fraction of agglomerated debris. By comparing L-24 (2.02 m) and L-28 (1.44 m) experiments in Table II, we can conclude that as the water depth decreases, the formation of the cake is further enhanced [2]. This is because, in shallow water, the melt does not have sufficient time to totally fragment, leading to its deposition on the bottom in the form of a cake.

Table II. FARO LWR test series—main experimental conditions and debris data [2]

Test	L-06	L-08	L-11	L-14	L-19	L-20	L-24	L-27	L-28	L-29	L-31
Experimental conditions											
Corium composition[a]	A	A	B	A	A	A	A	A	A	A	A
Melt mass[b] (kg)	18	44	151	125	157	96	177	117	175	39	92
Melt temperature (K)	2923	3023	2823	3123	3073	3173	3023	3023	3052	3070	2990
Melt release diameter[d] (mm)	100	100	100	100	100	100	100	100	50	50	50
Melt fall height in gas (m)	1.83	1.53	1.09	1.04	1.99	1.12	1.07	0.73	0.89	0.74	0.77
System pressure (MPa)	5	5.8	5	5	5	2	0.5	0.5	0.5	0.2	0.2
Gas phase	Steam/Ar	Steam/Ar	Steam/Ar	Steam/Ar	Steam[e]	Steam[e]	Steam[e]	Steam[e]	Steam[e]	Argon	Argon
Water depth (m)	0.87	1.00	2.00	2.05	1.10	1.97	2.02	1.47	1.44	1.48	1.45
Water temperature (K)	539	536	535	537	536	486	425	424	424	297	291
Water subcooling (K)	0	12	2	0	1	0	0	1	1	97	104
Water Mass (kg)	120	255	608	623	330	660	719	536	517	492	481
Debris bed data[f]											
Hard debris, cake (kg, %)	6, 33	14, 32	0, 0	20, 16	77, 49	21, 22	27, 16	26, 23	77, 48	39, 100	0, 0
Loose debris (kg, %)	12, 67	30, 68	146, 100	105, 84	80, 51	73, 78	141, 84	70, 77	84, 52	0, 0	83, 10
Mean loose debris size (mm)	4.5	3.8	3.5	4.8	3.7	4.4	2.6	Na[g]	3.0	–	3.4

The influence of water pool depth and initial temperature could be obtained by DEFOR-E01 ~ DEFOR-E07. The initial condition of seven experiments and main results are shown in Table III. It can be concluded that low coolant initial temperature promotes the cake formation, and the deeper water depth causes the bigger porosity [4].

Table III. DEFOR experimental conditions and main results. [4]



№	Parameter/Property	exp-1	exp-2	exp-3	exp-4	exp-5	exp-6	exp-7
1	Melt volume, liters	3.5	7.0	3.5	3.5	3.5	3,5	2,5
2	Melt initial temperature, °C	1200	1300	1350	1350	1200	1250	1280
3	Coolant volume, liters	163	163	163	100	100	163	163
4	Coolant initial temperature, °C	13	11	85	15	83	88	7
5	Water pool depth, cm	65	65	65	40	40	65	65
6	Falling height, cm	60	60	60	60	60	60	60
7	Measured porosity, %	60	77	74	56	50	68	65

2.2.2. Self-leveling

Self-leveling was studied in PDS experiment. The main results of PDS are that bulk volume of debris bed is immovable and particles moved only in the upper part of the bed. Also, PDS suggest that gas superficial velocity, friction forces between the particles, density and size of particles affects to spreading rate [5].

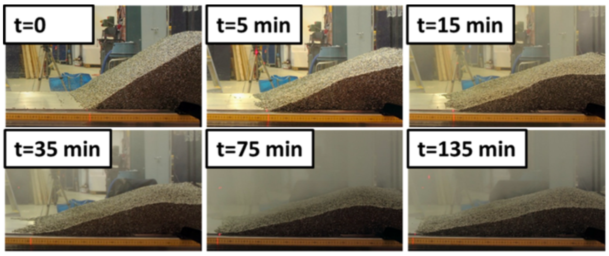


Figure 5. Images of the debris bed in PDS-E7 test taken at specified time (left top corner) after the beginning of experiment [5].

2.3. Coolability

When corium is released outside the reactor and forms a debris bed in the cavity, sufficient cooling of the high-temperature debris bed by water is essential to prevent MCCI. The factors that influence coolability can be broadly categorized: particle characteristics, the geometry of the debris bed, and the flooding method. There have been previous studies simulating these factors, and we intend to review the experimental results and limitations of these studies.

2.3.1. Geometry

The geometry of the debris bed is critical because it determines the flooding mode by which water infiltrates the pores of the debris bed.

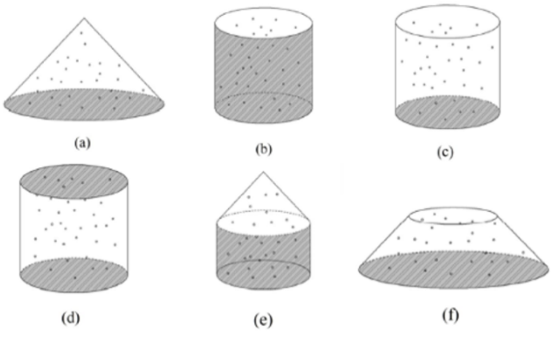


Figure 6. Test bed geometry variations: (a) conical, (b) top-flooded cylinder, (c) fully-flooded cylinder (open walls), (d) cylinder with lateral flooding. (e) cone on a cylindrical base, and (f) truncated cone. The shaded areas are impermeable walls; other surfaces are permeable [6].

In COOLOCE experiments, a test bed was constructed using zirconium-silica particles, and the geometries tested included conical, cylindrical, a cone on a cylindrical base, and truncated conical shapes. After submerging the test bed in water, power was increased until dryout was detected using thermocouples, allowing for the measurement of DHF and dryout power. The cone-on-cylindrical base model exhibited the highest DHF, attributed to water and steam flow through the conical upper portion. In contrast, the cylindrical model with top flooding showed the lowest DHF due to the inability of water to penetrate the upper region because of counter-current flow. The COOLOCE experiments also investigated the impact of multidimensional flooding modes, particle types, and degrees of subcooling [6].

2.3.2. Particle properties

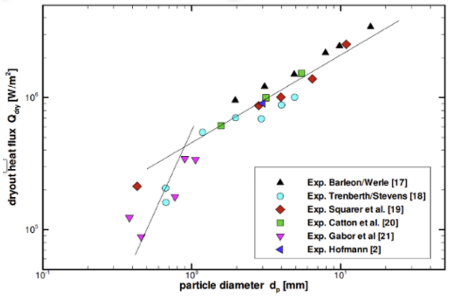
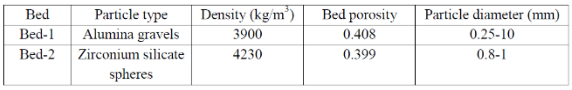


Figure 7. Dependence of the dryout heat flux on the particle diameter [7].

The properties of particles, specifically porosity and particle size, also influence coolability. Porosity is related to friction losses in the context of long-term cooling. Particle size is another factor that affects coolability. Smaller particles have smaller pores, leading to higher pressure losses and increased friction for fluid flows. Various experiments have shown that DHF increases as particle size increases. As depicted in Figure 7, two distinct regions can be identified: for smaller particles, DHF decreases sharply, while for sufficiently large particles, friction losses decrease, reducing the impact of diameter.

Table IV. Details of beds in POMECO-HT [8]



Bed	Particle type	Density (kg/m^3)	Bed porosity	Particle diameter (mm)
Bed-1	Alumina gravels	3900	0.408	0.25-10
Bed-2	Zirconium silicate spheres	4230	0.399	0.8-1

A notable experiment in this context is the POMECO experiment conducted at KTH (Royal Institute of Technology). In this experiment, sand or particles with various sizes and porosities were uniformly heated, and water was injected from above. Temperature and DHF are measured using thermocouples. The initial experiments used a mixture of three sand samples, while the follow-up POMECO-HT [8] experiment employed alumina gravel and zirconium-silica spheres. The differences in the physical properties of the two beds used in POMECO-HT are presented in Table IV. The results showed that particles with higher porosity exhibited higher DHF, which is attributed to the greater space available for fluid flow. This experiment also included a setup with lower channels to consider multidimensional flooding and simulations of gas injection from below to mimic gases generated by MCCI.

2.3.3. Flooding type

The flooding type also significantly impacts the coolability of the debris bed, as it offers various possibilities for water to infiltrate the bed. Numerous experiments have been conducted to simulate these scenarios, with most setting up downcomers to create multidimensional flooding.

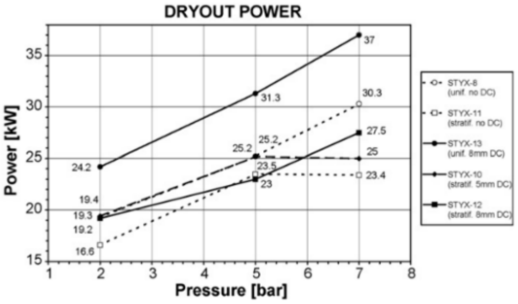


Figure 8. The measured dryout power in the stratified and homogeneous particle beds with and without downcomers [9]

In the STYX experiment, two lower channels of different sizes were established. Water was injected into a test bed filled with irregular alumina gravel particles and then heated to saturation temperature. Power was increased until dryout occurred, at which point temperature and DHF were measured. The experiments varied the presence of lower channels and pressure conditions. The results showed that heat flux increased by about 20-25% when lower channels were present, and the dryout zone was also found to be higher when using the lower channels [9], [10].

Using the downcomer, the DEBRIS experiment also simulated top, bottom, and lateral flooding. In the case of bottom flooding, the tank was placed below the test section to inject water from the bottom, while lateral flooding was simulated using a perforated downcomer. The DEBRIS experiment focused on measuring pressure drop and dryout heat flux, and the experimental results showed that the dryout heat flux during bottom flooding exhibited a significant difference compared to other flooding methods [11].

3. Conclusions

There are numerous uncertainties associated with severe accidents, particularly within a flooded cavity. Several experiments have been conducted to mitigate these uncertainties and to evaluate the coolability of released molten corium. Through a comparative review of previous studies, we identified key factors in assessing coolability and gained insights into the influence of various factors within a flooded cavity. Nonetheless, applying these experimental findings to real reactors presents challenges. For instance, when utilizing system codes to assess the coolability of a debris bed, the mass median diameter is often employed as the representative particle size. However, the porosity in such cases differs from that of a mixture composed of both large and small particles, potentially leading to variations in debris bed formation and its coolability. Furthermore, the sequence of released melt must be considered due to layer separation within the vessel. The DEFOR-E tests indicate that variations in melt material result in differences in particle size distribution. This suggests that changes in melt material will alter the particle size distribution, consequently affecting debris bed formation and its coolability. Additionally, there remains a paucity of experimental research on phenomena such as temperature stabilization post-dryout and the dry diffusion processes observed during 'localized' dryout. Future studies should focus on overcoming experimental limitations and enhancing the precision of system codes to better align with actual situations. This paper primarily focuses on the experimental studies listed in Table I. As part of our future research, we plan to incorporate additional studies performed by other countries. Furthermore, we intend to examine how the phenomena observed in these experiments are being implemented within system codes.

ACKNOWLEDGEMENT

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