EXPERIMENTAL INVESTIGATION OF DEBRIS BED AGGLOMERATION AND PARTICLE SIZE DISTRIBUTION USING WO3-ZRO2 MELT

Pavel Kudinov, Dmitry Grishchenko, Alexander Konovalenko and Aram Karbojian
Division of Nuclear Power Safety, Royal Institute of Technology (KTH)
Roslagstullsbacken 21, D5, Stockholm, 106 91, Sweden
pkudinov@kth.se, dmitry@safety.sci.kth.se, kono@kth.se, karbojan@kth.se

ABSTRACT

Nordic BWR severe accident management strategy employs reactor cavity flooding to terminate ex-vessel accident progression. Corium melt released from the reactor pressure vessel is expected to fragment and form a porous debris bed. Success of the SAM strategy is contingent upon possibility to remove the decay heat generated in the debris bed by natural circulation of the coolant. Properties of the debris bed such as particle size, porosity and shape of the bed determine resistance for the coolant flow and thus dryout heat flux. Agglomeration of incompletely solidified debris can create additional obstacles for coolant circulation and thus reduce debris coolability margin.

The goal of DEFOR (debris bed formation) experimental work is to provide data necessary for the development of analytical models and approaches for prediction of debris bed formation and agglomeration phenomena. Different corium simulant materials are used in the experiments. Liquid melt jet fragmentation and debris bed formation are considered at different conditions such as melt release (jet diameter, free fall height. etc.), melt superheat, water subcooling and water pool depth. A series of confirmatory DEFOR-A experiments has been carried out with ZrO_2-WO_3 simulant material. The data on particle size distribution, debris bed porosity and agglomeration is in good agreement with the previous DEFOR-S, DEFOR-A and FARO tests. On average, larger particles were obtained with ZrO_2-WO_3 melt than with previously used Bi_2O_3-WO_3, size distributions for both melt simulant materials are within the ranges of size distributions observed in FARO tests. The difference between particle sizes in the tests with free falling jets was found to be insignificant. There is a tendency to form slightly larger particles only in the tests with submerged nozzles where melt is released under water with initially small jet velocity. Initial jet velocity also seems to have no visible effect on the fraction of agglomerated debris.

KEYWORDS
Severe accident, melt-coolant interactions, debris agglomeration.

1. INTRODUCTION

The severe accident management (SAM) in Nordic boiling water reactors (BWRs) relies on ex-vessel core debris coolability [1]. In the case of core meltdown and vessel failure, melt is poured into a deep pool of water located under the reactor. The melt is expected to fragment, quench, and form a debris bed that is coolable by natural circulation of water. Success of the SAM strategy is contingent upon (i) properties of the debris bed and thus the coolability of the bed, as well as (ii) potential for energetic interactions between hot liquid melt and volatile coolant (steam explosion). Both non-coolable debris bed and steam explosion pose credible threats to containment integrity.

Coolability of the bed is determined by the properties of the bed. The properties depend on the debris bed formation phenomena and conditions of melt ejection from the vessel. Phenomenology of ex-vessel debris bed formation and coolability is quite complex Figure 1, it includes (i) jet breakup, (ii) melt droplet sedimentation and interaction with water pool; (iii) debris agglomeration; (iv) particle spreading by pool flows; (v) debris bed self-levelling by vapor flows; (vi) debris bed coolability; (vii) post-dryout behavior with possible remelting, etc. The physical phenomena involved are tightly coupled.

Debris bed cooling is provided by heat transfer to the water that enters the porous bed interior by filtration from the pool. Steam generated inside the debris bed is escaping predominantly upwards, generating two-phase convection flows in the pool and changing conditions for fuel-coolant interaction (FCI). In turn, FCI phenomena affect particle properties (size distribution and morphology) [2]. Particle properties, packing and lateral redistribution affect the debris bed coolability phenomena. The large-scale circulation in the pool can spread effectively the falling corium particles over the basemat floor, distributing the sedimentation flux beyond the projection area of particle source [3], [4], [5], [6]. Debris is gradually spreading under the influence of steam production in the bed, resulting in self-leveling of the settled portion of the debris and changing the shape of debris bed with time [7]. This can serve as an additional physical mechanism that prevents formation of a tall non-coolable debris bed [8].

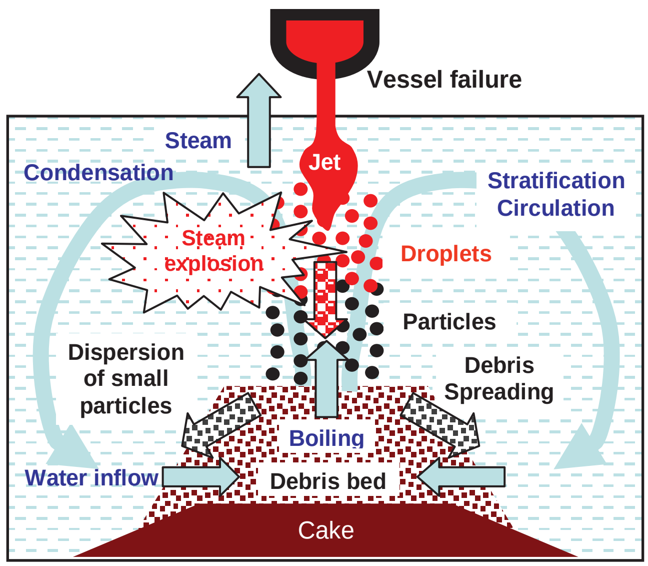


Figure 1. Severe accident phenomena in Nordic BWR.

If melt is not completely solidified prior to settlement on top of the debris bed, agglomeration of the debris and even “cake” formation is possible [9], [10], [2]. Agglomeration of the debris bed can negatively affect debris bed coolability [11].

The goal of DEFOR (Debris Bed Formation) experimental work is to provide data necessary for the development of analytical models and approaches for prediction of debris bed formation and agglomeration phenomena using different melt simulant materials. Liquid melt jet fragmentation and debris bed formation are considered at different conditions such as melt release (jet diameter, free fall height etc.), melt superheat, water subcooling and water pool depth. The data obtained in the previous DEFOR-A [9], [10] tests with Bi_2O_3-WO_3 (eutectic) melt (melting temperature 870°C) was used for development and validation of modeling approaches for prediction of agglomerated debris in various scenarios of melt ejection [12], [13] using FCI code VAPEX-P. Computational costs of running a multidimensional FCI code (such as VAPEX-P) are prohibitive when parametric analysis is needed in order to quantify the influence of uncertainties in the scenarios of melt release from the vessel. Therefore a computationally efficient surrogate model was developed for sensitivity and uncertainty analysis of debris agglomeration in plant accident conditions [14].

The goal of this work is to provide confirmatory data on debris agglomeration phenomena using new, higher melting temperature (1231°C) simulant material – eutectic mixture of ZrO_2-WO_3. Liquid melt jet fragmentation and debris bed formation are considered at different conditions such as melt release (jet diameter, free fall height. etc.), melt superheat, water subcooling and water pool depth. Particle size distribution and fraction of agglomerated debris are measured in the experiments.

2. EXPERIMENTAL FACILITY

DEFOR (Debris Bed Formation) facility was developed for studies of melt fragmentation, particle and debris bed formation and agglomeration in deep water pool. The installation consists of (i) an induction furnace for melt generation, (ii) a funnel for melt deliver, (iii) a test section with optional metallic sample, and (iv) external water heating system. The scheme of the installation is given in Figure 2, Figure 3. The furnace is composed of a (i) SiC crucible inductively heated with a 45kW medium-frequency (up to 30 kHZ) generator and (ii) an opened housing connected to a tilting mechanism for crucible leaning and melt delivery into the funnel. The furnace can provide melting of corium simulant materials at temperatures up to 1600°C and melt volume up to 10 liters. It is equipped with three bottom thermocouples and one lateral thermocouple for temperature control. The funnel is equipped with nozzle which allows jet diameters from 10 to 25 mm. A K-type thermocouple is positioned inside the nozzle for the temperature measurement of the delivered melt.

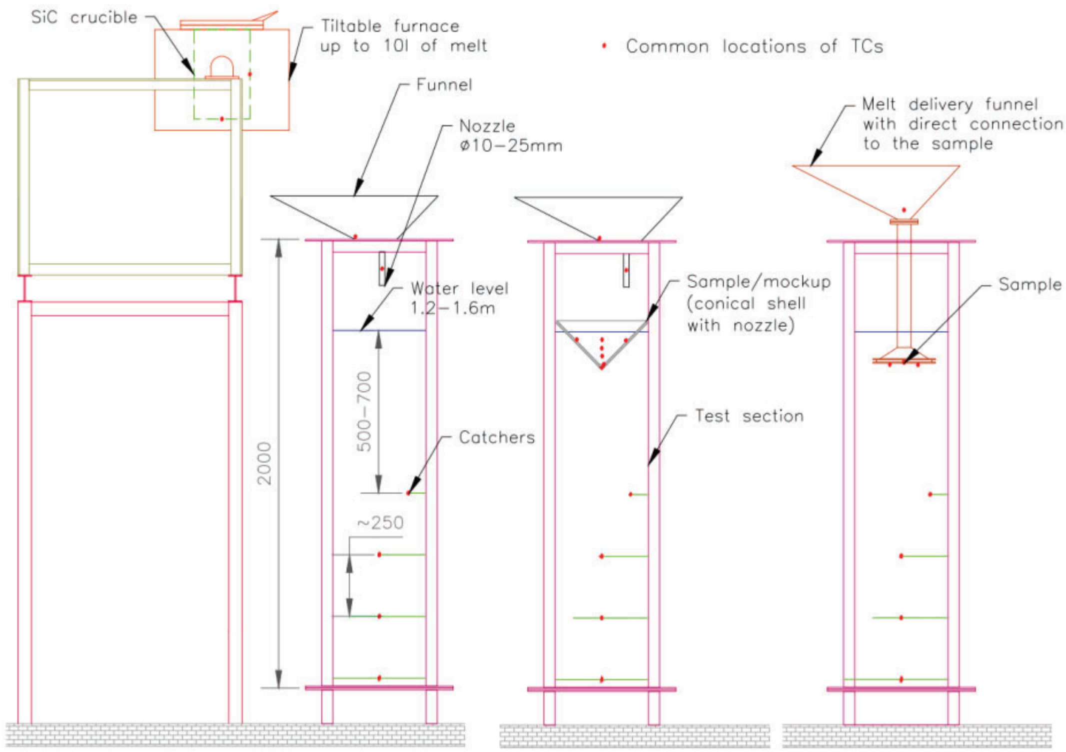
The DEFOR test section is a vertical 2.0 m tank with approximately rectangular cross section 0.5x0.5 m filled up with tap water. The water for the tests is heated in an external tank to a predefined temperature and is poured into the test section shortly before the melt delivery. Visual observation of the melt release and melt-coolant interaction is performed through a number of rectangular Plexiglas windows installed on lateral sides of the test section. Commonly up to five cameras are used to record the melt-coolant interaction, including a number of high-speed cameras with up to 735 frames per second.

Inside the test section 4 debris catchers are positioned at different elevations (Figure 2, Figure 3). Vertical location of the catcher can be adjusted according to test requirements. Each catcher is covering one of four quadrants of the test vessel cross section and collects melt fragments ejected from the jet. This allows assessment of the water pool depth on debris bed formation: agglomeration and local particle size distribution. The water pool depth and depth of the top catcher are chosen to ensure complete breakup of the melt jet. This is required to avoid the possible effect of the catchers on jet fragmentation and breakup length.

The water temperature inside the test section is measured along the walls at several elevations; the debris temperature is measured on every catcher by 2 thermocouples installed in the vicinity of the jet. In addition several TCs can be placed above the water level. The exact positioning and number of thermocouples varies from test to test.

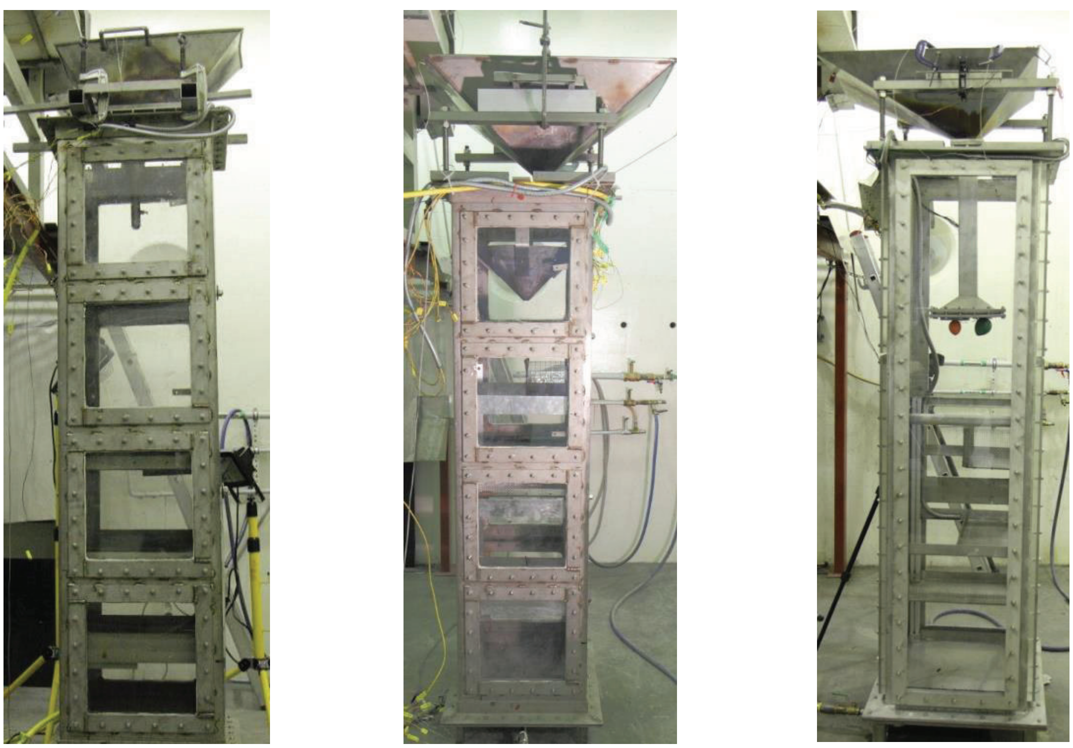
The installation is placed inside a concrete containment for personnel safety (danger of steam explosion, melt splashes etc.) and is controlled remotely.

Experimental methods for investigation of the debris bed formation phenomena in DEFOR test facility are described in detail in [9], [11], [10], [2].



a b c

Figure 2. DEFOR facility: a) setup for A01-11;15, b) A12-14;16 and c) A17-21.



a b c

Figure 3. DEFOR-A a) setup for A01-11;15, b) A12-14;16 and c) A17-21.

In the DEFOR-A12-14;16 configuration (Figure 2b and Figure 3b) a low melting temperature funnel is installed at the top of the water pool to study (i) wall and nozzle ablation during melt release and (ii) effect of melt release directly into water on resulting debris size distribution and agglomeration. The funnel is designed as a conical shell with 90 degree angle and with single hole at the bottom (apex). Being partially immersed into water and provided 45° inclination angle of the lateral surface allows efficient heat removal due to intense natural convection flows increasing the critical heat flux limit in comparison with a not-inclined (horizontal) surface.

In the DEFOR-A17-A21 tests the experimental configuration (Figure 2c and Figure 3c) new DEFOR test section has been designed and manufactured providing (i) larger windows from all four sides for a better visual observation; (ii) rigid construction preventing wall vibrations. The geometry of the sample for melt interactions (nozzle ablation and plugging) with low melting temperature material in DEFOR-A17-A21 tests is chosen to be a flat horizontal plate. It was assumed that nozzle length to diameter ratio is one of the key parameters.

The material of the sample (lead) has melting temperature (327°C) lower than that of the melt (870°C or 1231°C), but higher than Leidenfrost temperature to allow for dryout on the wall. The difference between melting temperatures of the melt simulant and the sample material is 540°C for Bi_2O_3-WO_3 and 1000°C for ZrO_2-WO_3 eutectic mixtures respectively.

After each test the debris beds from every catcher undergo systematic analysis for debris bed topology, total porosity, fraction of agglomerated debris, mass of cake and particle size distribution. The data is than plotted as a function of catcher depth and compared to other tests in terms of the melt superheat, water subcooling, melt release conditions and melt material.

3. EXPERIMENTAL RESULTS

Primary tasks of the DEFOR-A10-A21 tests addressed in this work are:

i. Compare experimental data on debris bed agglomeration and melt jet fragmentation with previous DEFOR-A and DEFOR-S test results obtained with already validated Bi_2O_3-WO_3 simulant, and FARO tests results obtained with prototypic corium mixtures.
ii. Assess the effect of the melt jet free fall height and melt release under water level on the particle size distribution.

Discussion of the results on the melt interaction with the low melting temperature sample is beyond the scope of this work.

I total, more than 20 DEFOR-A tests have been carried (Table I). In the first test series (A1-A9 [9], [10], [11]) Bi_2O_3-WO_3 (eutectic) melt with melting temperature 870°C was used. Second test series (A10-A21) was carried out using ZrO_2-WO_3 (eutectic) melt with melting temperature 1231°C. Debris bed topology, total porosity, agglomerated mass, and particle size distribution were measured in each test. Melt was released above or below the water surface in order to assess the effect of the jet velocity on the particle size distribution. Analysis of experimental data suggests that fraction of agglomerated debris decreases rapidly with the depth of the coolant as noticeable in Figure 5 for the whole set of experiments (A1-A21). Data on fraction of agglomerated debris from the new DEFOR-A tests agrees well with previously obtained results in the DEFOR-A and DEFOR-S experiments where smaller amount of melt (about 1.0 liter) was used [2]. We found that water subcooling is of minor importance until thermal stresses start to induce solid particle fracture.

Table I. Ranges of the experimental parameters in DEFOR-A tests.

Parameters	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21
Melt temperature, K	1253	1246	1483	1221	1245	1279	1349	1255	1343	1644	1606	1618	1566	1740	1603	1621	1735	1693	1818	1791	1790
Melt superheat, K	110	103	-	78	102	136	206	112	200	150	102	114	62	196	100	117	231	189	314	287	286
Melt jet initial diameter, mm	10	20	20	20	10	12	25	25	20	20	20	20	10	15	20	15	2x20	2x20	30	30	30
Elevation of nozzle outlet, m	1.7	1.7	1.7	1.7	1.7	1.7	1.62	1.62	1.7	1.72	1.8	1.85	1.85	1.75	1.8	1.65	1.65	1.65	1.44	1.65	1.5
Jet free fall height, m	0.18	0.18	0.18	0.2	0.18	0.18	0.2	0.2	0.18	0.2	0.7	0.13	0.13	0.2	0.2	0.2	0	0	0	0	0
Duration of melt release, s	38	11	-	11	38	20	10	10	11	13	12	23	6.3	-	9.6	22	10	13	10	15	13
Melt volume, l	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	4	5	5	5	5	5
Average flow rate, l/s	0.079	0.273	-	0.273	0.079	0.15	0.3	0.3	0.273	0.19	0.16	0.097	0.155	-	0.208	0.125	0.354	0.254	0.44	0.25	0.333
Initial average melt jet velocity, m/s	1.01	0.87	-	0.87	1.01	1.33	0.61	0.61	0.87	0	0	0	0	-	1.01	-	-	-	-	-	-
Water pool depth, m	1.52	1.52	1.52	1.5	1.52	1.52	1.42	1.42	1.52	1.52	1.1	1.85	1.85	1.75	1.8	1.65	1.65	1.65	1.44	1.65	1.5
Water initial temperature, K	346	366	345	346	364	346	356	355	355	348	348	348	348	354	354	345	355	354	359	353	358
Water subcooling, K	27	7	28	27	9	27	17	18	18	25	25	25	25	19	19	28	18	19	14	20	15

In A10-12 tests melt release took around 12-13 sec in A10-A11 and 9.6 in A12. Out of 20.6 kg of the initial melt charge, in A10 test 17.08 kg of melt has been delivered into water, in the A11 this value has been somewhat smaller 13.39 kg. The difference can be attributed to the lower melt superheat in the A11 test.

Comparison of melt delivery into water for A10, A11 and A12 is provided in the Figure 4. In the snapshots a straight and coherent jet can be seen above the water level as well as its fast break up and fragmentation upon entrance into water. The melt front velocity at the initial water level (estimated assuming free fall acceleration from the nozzle outlet) is at least 2.0 and 3.7 m/sec for A10 and A11 tests respectively. The corresponding jet diameter (by mass conservation) is ~2 and ~1.5 cm. Thus, expected jet breakup level is above the level of the top catcher in both tests.

The effect of melt material can be considered by comparing similar tests in the first and second test series. In terms of the melt superheat and jet diameter the A10 and A11 tests can be compared to A7, A2, and A6. Agglomeration curve obtained in A10 test lies in between the curves of A7 and A2 tests being slightly closer to A2. This behavior agrees well with both melt superheat (A10 - 150°C, A7 - 200°C and A2 - 110°C) and jet diameter (A10 – 20 mm, A7 – 25 mm and A2 – 20 mm). Despite the fact that A11 test has larger jet free fall and thus higher jet velocity at the entrance into the water the data agrees well with A2, A6 tests with similar melt superheat. In terms of water subcooling and jet diameter at the water level, the closest to the A11 test is A6. It has slightly higher agglomeration on the top catcher which can be attributed to the higher melt superheat and experimental uncertainty due to proximity of the first catcher to the inherently instable jet leading edge. From the above considerations we can conclude that behavior of the new simulant material in terms of agglomeration agrees well with the results from the previous DEFOR-A tests series.

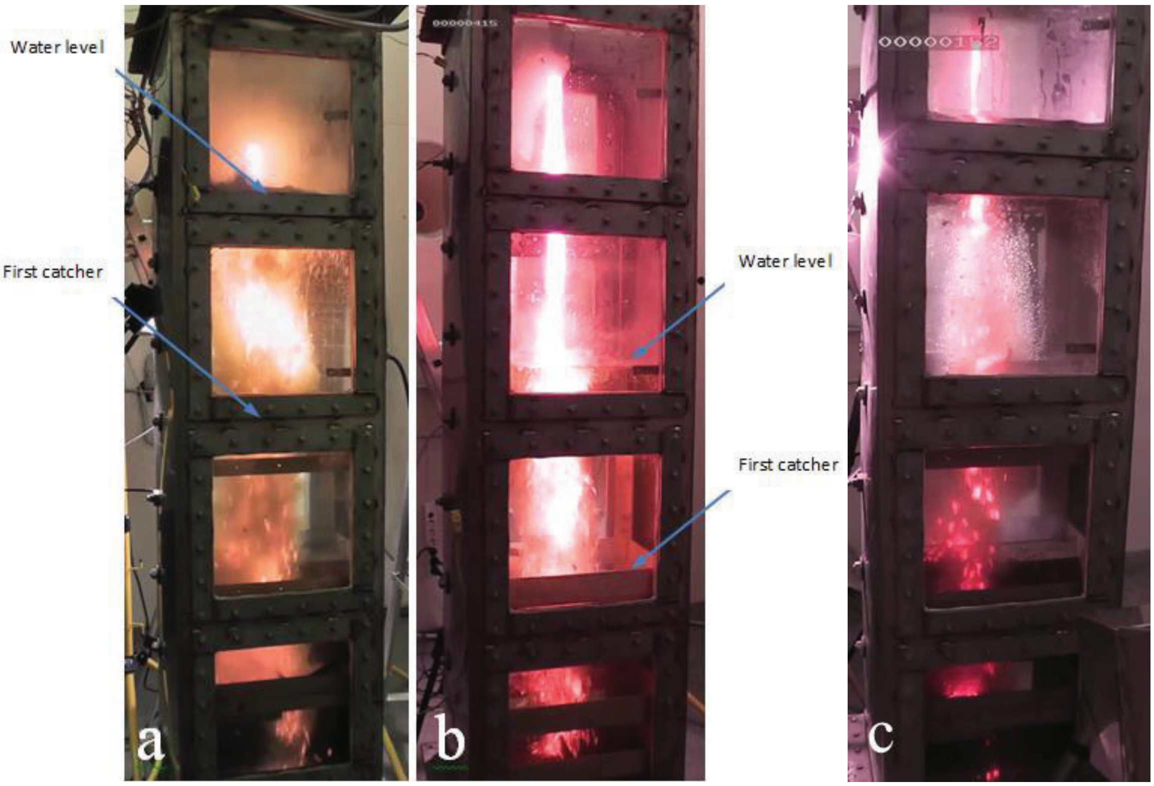
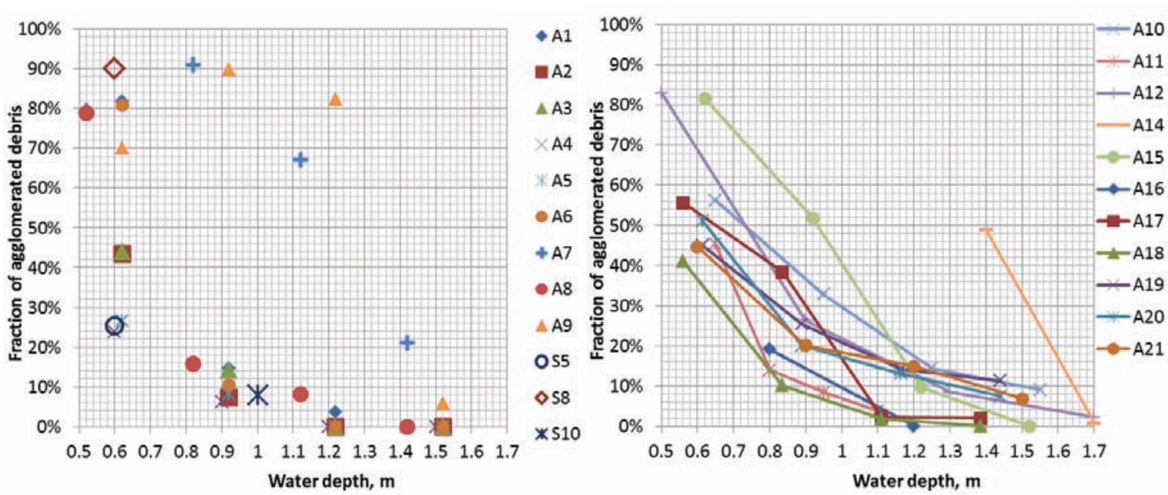


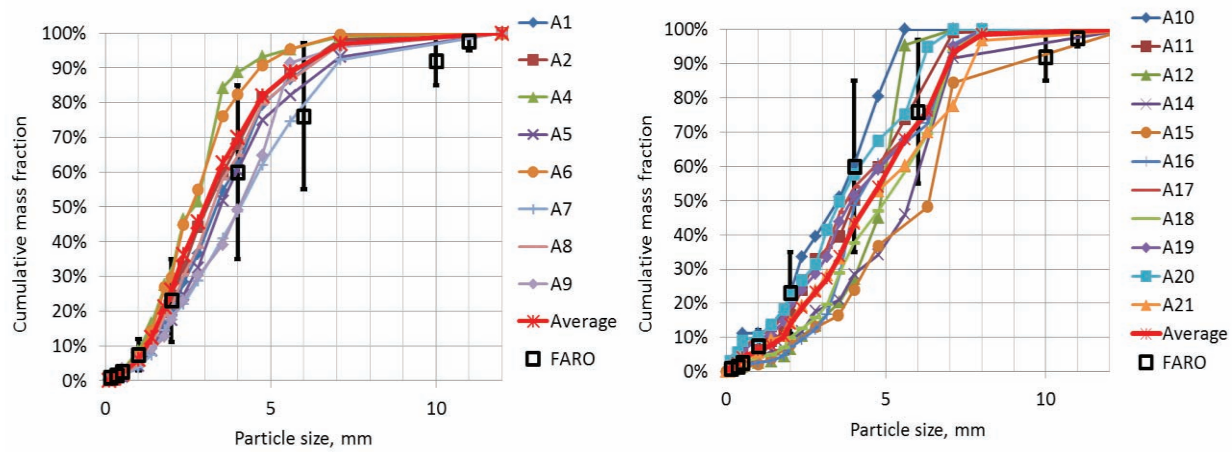
Figure 4. Melt pouring in A10 (a), A11 (b) and A15 (c) tests



a) b)

Figure 5. Debris bed agglomeration fraction as function of water pool depth for A1-A9, S8, S10 (a) and A10-A21 (b) tests.

The particle size distributions (Figure 6) were obtained by sieving the debris. For comparison, the previously obtained result from DEFOR-A1-A9 test series [9] is provided in Figure 6a. Distributions from the tests with higher melt superheat are located slightly below the average, corresponding to larger particles. Some variations in the data due to the inherent uncertainties in high temperature melt-coolant interaction experiments can be expected. The data from A10-A21 tests (Figure 6b) show on average larger particles obtained with ZrO_2-WO_3 in comparison with the previous tests with Bi_2O_3-WO_3. Both series are within the ranges of FARO [15] data.



a) b)

Figure 6. Cumulative mass fraction for the debris in DEFOR-A1-A9 (a) and DEOFR-A10-A21 (b) tests. For comparison, the data from FARO tests and averaged DEFOR curves for corresponding series of tests are provided.

4. CONCLUSIONS

The goal of DEFOR (debris bed formation) experimental work is to provide data necessary for the development of analytical models and approaches for prediction of debris bed formation and agglomeration phenomena. A series of DEFOR-A10-A21 tests has been carried out with higher melting temperature simulant material. Confirmatory A10, A11 tests provided reference data on the properties of the debris bed (such as particle, size distribution, debris bed porosity and agglomeration) with ZrO_2-WO_3 simulant material and different jet velocities. The data is in good agreement with the previous DEFOR-A1-A9 and FARO tests results and is used for comparison with the other DEFOR-A tests were a mockup of the vessel wall (sample) was implemented. On average, larger particles were obtained with ZrO_2-WO_3 melt than with Bi_2O_3-WO_3 in DEFOR-A. Particle size distributions in DEFOR-A series are closer to the size distributions in FARO tests with on average larger particles. While the difference between particle sizes in A10 and A11 tests with free falling jets is not important, there is a tendency for larger particle sizes in those tests with samples where melt was released under water with initially smaller jet velocity. Yet, the difference is not dramatic. Initial jet velocity also seems to have no visible effect on the fraction of agglomerated debris.

ACKNOWLEDGMENTS

The work is supported by the Swedish Nuclear Radiation Protection Authority (SSM), Swedish Power Companies, Nordic Nuclear Safety Program (NKS), Swiss Federal Nuclear Safety Inspectorate (ENSI) under the APRI–MSWI program at the Royal Institute of Technology (KTH), Stockholm, Sweden.

REFERENCES

1. P. Kudinov, S. Galushin, S. Yakush, W. Villanueva, V.-A. Phung, D. Grishchenko, N. Dinh, "A Framework for Assessment of Severe Accident Management Effectiveness in Nordic BWR Plants," *Probabilistic Safety Assessment and Management PSAM 12*, June, Honolulu, Hawaii, Paper 154, (2014).
2. P. Kudinov, A. Karbojian, W. Ma, and T.-N. Dinh, "The DEFOR-S Experimental Study of Debris Formation with Corium Simulant Materials," *Nuclear Technology*, **170(1)**, pp. 219-230, (2010).
3. S. Yakush, P. Kudinov, "Effects of water pool subcooling on the debris bed spreading by coolant flow", *Proceedings of the International Conference on Advanced Nuclear Power Plants (ICAPP 2011)*, Nice, France, paper 11416, 14p., (2011).
4. S. Yakush and P. Kudinov, "Simulation of Ex-Vessel Debris Bed Formation and Coolability in a LWR Severe Accident," *Proceedings of ISAMM-2009*, Böttstein, Switzerland, October 26 - 28, (2009).
5. S.E. Yakush, P. Kudinov, T.-N. Dinh, "Multiscale simulations of self-organization in the formation and coolability of corium debris bed", *Proceedings of the 13th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-13)*, Kanazawa City, Japan, paper N13P1143, 13p., (2009).
6. A. Konovalenko, S. Basso, and P. Kudinov "Experiments and Characterization of the Two-Phase Flow Driven Particulate Debris Spreading in the Pool," *The 10th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-10)*, Okinawa, Japan, December 14-18, Paper 1257, (2014).
7. S. Basso, A. Konovalenko and P. Kudinov, "Development of scalable empirical closures for self-leveling of particulate debris bed," In *Proceedings of International Conference on Advanced Nuclear Power Plants (ICAPP-2014)*, Charlotte NC, USA, April 6-9, Paper 14330, (2014).
8. S. Basso, A. Konovalenko and P. Kudinov, "Sensitivity and Uncertainty Analysis for Predication of Particulate Debris Bed Self-Leveling in Prototypic SA conditions", *In Proceedings of International Conference on Advanced Nuclear Power Plants (ICAPP-2014)*, Charlotte NC, USA, April 6-9, paper 14329, (2014).
9. P. Kudinov, A. Karbojian, C.-T. Tran, W. Villanueva, "Experimental Data on Fraction of Agglomerated Debris Obtained in the DEFOR-A Melt-Coolant Interaction Tests with High Melting Temperature Simulant Materials," *Nuclear Engineering and Design*, **263**, Pages 284-295, (2013).
10. P. Kudinov, A. Karbojian, C.-T. Tran, W. Villanueva, "The DEFOR-A Experiment on Fraction of Agglomerated Debris as a Function of Water Pool Depth," *The 8th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-8)*, Shanghai, China, October 10-14, N8P0296, (2010).
11. S. Yakush and P. Kudinov, "Simulation of Ex-Vessel Debris Bed Formation and Coolability in a LWR Severe Accident," *Proceedings of ISAMM-2009*, Böttstein, Switzerland, October 26 - 28, (2009).
12. P. Kudinov and M.V. Davydov, "Development and validation of conservative-mechanistic and best estimate approaches to quantifying mass fractions of agglomerated debris," *Nuclear Engineering and Design*, **262**, pp. 452-461, (2013).
13. P. Kudinov, M. Davydov, G. Pohlner, M. Bürger, M. Buck, R. Meignen, "Validation of the FCI codes against DEFOR-A data on the mass fraction of agglomerated debris," *5th European Review Meeting on Severe Accident Research (ERMSAR-2012)* Cologne (Germany), March 21-23, paper 2.09, (2012).
14. P. Kudinov and M. Davydov, "Development of Surrogate Model for Prediction of Corium Debris Agglomeration," *In Proceedings of International Conference on Advanced Nuclear Power Plants (ICAPP-2014)*, Charlotte, USA, April 6-9, Paper 14366, (2014).
15. D. Magallon and I. Huhtiniemi, "Corium melt quenching tests at low pressure and subcooled water in FARO," *Nuclear Engineering and Design*, **204**, pp. 369-376, (2001).