ARTIST II – Aerosol Trapping in the Steam Generator

Author and Co-author(s)	Lind, Terttaliisa; Suckow, Detlef; Güntay, Salih
Institution	Paul Scherrer Institut
Address	CH-5232 Villigen PSI
Tel., E-mail, Internet address	+41 (0)56 310 21 11, Terttaliisa.Lind@psi.ch; www.psi.ch
Duration of the Project	September 1, 2008 to August 31, 2011

ABSTRACT

Based on the need for aerosol and droplet retention data during a Steam Generator Tube Rupture (SGTR) accident, Paul Scherrer Institut (PSI) established an international cost share project called Aerosol Trapping In a Steam Generator (ARTIST). After completion of ARTIST on 31.12.2007, a continuation project ARTIST II was initiated to address issues raised in the ARTIST project, and to investigate certain phenomena not addressed in ARTIST. ARTIST II project concentrates on five phenomena: i) aerosol retention inside the broken tube, ii) aerosol retention in the tube bundle close to the tube breach, iii) aerosol retention inside a tube bundle flooded with water, iv) aerosol retention in a droplet separator flooded with water, and v) droplet retention in the steam dryer. In addition, work is carried out to apply the experimental results for risk analysis of SGTR accidents. During the first project year, preparatory experimental work was carried out to be able to generate aerosols in sufficiently high concentration for the tests, as well as to generate a «sticky» aerosol to be used in the tests. In addition, techniques for use of different aerosol materials were developed. Work on droplet retention was also started with preparatory work, including literature study on droplet generation in flashing jets, as well as instrument calibration and testing of monodisperse droplet generation.

Aerosol retention tests were conducted in two project phases, retention in the flooded separator, and retention in the flooded bundle. In total, three tests were carried out in the flooded separator, and four tests in the flooded bundle. In the flooded separator, aerosol retention was found to be very high in all the test conditions. No significant difference in decontamination factor was measured with different flow rates or different particle sizes. In the flooded bundle, particle size and gas flow rate were found to affect the decontamination factor significantly.

Project goals

Despite improvements in steam generator (SG) design, manufacturing and modes of operation, SG tube rupture (SGTR) events occasionally occur during PWR operation, which underlines the need to pay particular attention to SGTR sequences. A particular safety challenge arises from an SGTR in combination with other failures such that a core melt occurs, in which case there may be a direct path by which radioactive fission products can be transported to the environment. Sequences of this kind are referred to as containment bypass and, despite their low probability, represent a significant or even dominant contribution to the overall public risk.

Based on the need for aerosol and droplet retention data during an SGTR, Paul Scherrer Institut (PSI) has built a model steam generator called Aerosol Trapping In a Steam Generator (ARTIST), which allows the gathering of data both at the separate effect and integral levels, as well as simulation of selected accident management procedures [1-3]. The ARTIST facility is a scaled-down model of the FRAMATOME 33/19 type SG in operation at the Swiss power Plant Beznau 1136 MWth PWR (KKB). An international collaboration project ARTIST was carried out in 2002 – 2007 to perform SGTR-related tests in the ARTIST facility. A continuation project ARTIST II was initiated to address issues raised in the ARTIST project, and investigate certain phenomena not addressed in ARTIST. ARTIST II project concentrates on five phenomena addressed in five project phases:

***Phase I:* Aerosol retention in SG tubes under dry conditions.** In this phase, in-tube aerosol deposition/resuspension is studied under high velocity conditions (up to 300 m/s). Aerosol type, size, concentration, and gas flow rate may be varied. Four tests are carried out in this phase.

***Phase II:* Aerosol retention in the break vicinity under dry conditions.** Aerosol deposition/resuspension at very high velocities is addressed. The break gas flow rate as well as the aerosol size and material are varied. The total of five tests are foreseen for this phase.

***Phase V:* Aerosol retention in the bundle section under flooded pool conditions with small submersion.** Aerosols are scrubbed in the water pool mainly through inertial impaction and diffusiophoresis (condensation) in the vicinity of the break. Aerosol particle size and gas flow rate through the break are varied in four tests.

***Phase VI:* Droplet retention in separator and dryer sections under dry conditions.** This phase deals with Design Basis Accident (DBA) type phenomena, i.e. the potential for «primary bypass», whereby a break at the top of the tube bundle sprays fine primary liquid droplets that might find their way to the environment through, for example, a stuck-open safety valve. Carrier gas flow rates and droplet sizes are varied.

***Phase VIII:* Aerosol retention in the flooded separator, new phase not included in ARTIST.** If the breach happens at the top of the bundle and the secondary side is flooded to a level just above the separator outlet, aerosols are retained by pool scrubbing mechanisms in conjunction with the interactions of bubble swarm with the internals of the separator. While it is expected that the DF is high as a result of bubble interactions with the internals of the separator, the nature of the two phase low in the separator section is complex due to the swirling, and it is not possible to estimate the DF precisely from previous pool scrubbing investigations. Three tests are carried out to investigate the effect of gas flow rate and particle size on the retention.

The goals for the year 2009 were to carry out preliminary testing to develop methods for aerosol generation needed for the aerosol retention tests, as well as start preparations for tests on droplet retention. Specifically, methods were developed to feed aerosol particles in sufficient concentration, use different aerosol materials, and to generate «sticky» aerosols used in Phases I and II. For droplet retention work, instruments were setup and calibrated against each other, and monodisperse droplet generation was developed. In project year 2009, tests were to be conducted in Phases V and VIII, flooded bundle and flooded separator. The goal for the year 2010 is to carry out aerosol tests in Phases I and II as well as start Phase VI tests for droplet retention. Last project year will be devoted to finish Phase VI tests, to make a synthesis of the results of ARTIST and ARTIST II projects, use ARTIST data for SGTR risk assessment, as well as to develop models based on ARTIST and ARTIST II data.

Work carried out and results obtained

Experiments in Phase V

Methods

The Phase V set of experiments was focused on aerosol retention in the water when the steam generator bundle is flooded with water but the water level is only 0.30 m above the tube break. The break was a full 1D guillotine type opening of the tube. The water temperature was kept at room temperature and relatively constant to exclude the effect of the change in the water temperature in the retention. The main emphasis of the experiments was to study the effect of the high velocity jet being discharged from the tube break into the bundle where the jet direction and velocity are changed due to the presence of the tubes close to the break exit. The aerosol particles are diverted from the flow and impact on the tube surfaces. At the same time, bubbles are formed in the water pool, and aerosol retention takes place due to aerosol – bubble interactions, as well as bubble – bundle interactions. The effect of the particle size and gas flow rate on the retention were investigated.

The tests were conducted in the ARTIST mock-up test facility with the ARTIST tube bundle inside the facility. The bundle had 270 straight tubes with the height of 3.8 m and the outer diameter of 19.08 mm. The tube break was installed close to the center of the facility at 250 mm above the tube sheet. The facility consisted of an inlet section with gas feed, aerosol generation, mixing chamber (MB2) for mixing aerosol and the main gas flow, inlet aerosol measurement section, steam generator bundle with the tube with 1-D guillotine break, outlet collector, and an outlet aerosol measurement section. The main carrier gas flow was dry nitrogen. The facility was filled with water up to 0.30 m above the middle of the guillotine tube break.

Aerosol was generated with a two-fluid spray nozzle. In all the tests, the feeding powder was mixed with ethanol and fed into the nozzle. The spray was fed into the mixing chamber, where it was mixed with the main flow of dry nitrogen. The nitrogen flow and the mixing chamber were heated to evaporate the ethanol droplets from the feeding spray. Mono-disperse, spherical SiO_2 particles were used to generate the aerosol. Two different particle sizes were used in the tests, with aerodynamic mass median diameter (AMMD) = 1.4 µm and 3.7 µm.

Aerosol size distributions and concentrations were determined simultaneously at the test section inlet and outlet. Filter samplings were used to determine particle mass concentration and decontamination factor. Relative particle mass concentration at the inlet was determined downstream of the mixing chamber with a photometer (CT65S, Sigrist Photometer AG). Electrical low-pressure impactors (ELPI; Dekati Ltd.) and optical particle counters (OPC; Palas PCS 2010A) were used to determine the particle size distribution on-line, and the time-dependence of the particle concentration at the inlet and outlet.

Results

Four tests were conducted in Phase V for aerosol retention in the flooded bundle, Table 1. The first two tests were carried out with a low flow rate of 50 kg/h with two different aerosol particle sizes. The last two tests were carried out with a high flow rate of 625 kg/h, again with two different aerosol particle sizes. In this way, the effect of the flow rate on the particle retention was investigated as well as the effect of the particle size. An example of the monodisperse particle size distribution of the aerosol particles used in the tests is given for Test E09 in which particles with AMMD = 1.4 µm were used with the flow rate of 625 kg/h, Figure 1.

Decontamination factor (aerosol particle concentration at the test section inlet divided by the concentration at the test section outlet) in the flooded bundle was found to increase with both the flow rate and the particle size. The decontamination factor was relatively independent of time and fed aerosol mass in the low flow rate tests with 50 kg/h, Figure 2. However, larger particles were retained more efficiently than smaller particles. In the high flow rate tests with 625 kg/h the decontamination factor showed some decrease with time, i.e., with increased cumulative aerosol mass in the water pool. Even in these tests, large particles were retained more efficiently than small particles. Particle inertial effects clearly had a large influence on the retention in the flooded bundle as can be seen from Figure 3, where decontamination factor increases with increasing particle Stokes number Stk.

Test	Facility	Aerosol AMMD [µm]	Inlet pressure [bar]	Mass flow rate [kg/h]	Effects Studied
E07	ARTIST mock-up bundle	1.4	1.1	50	Low flow rate, small particle size
E08	ARTIST mock-up bundle	3.7	1.1	50	Low flow rate, large particle size
E09	ARTIST mock-up bundle	1.4	4.8	625	High flow rate, small particle size
E10	ARTIST mock-up bundle	3.7	4.8	625	High flow rate, large particle size

Table 1: *Tests conducted in Phase V for retention in the flooded bundle.*

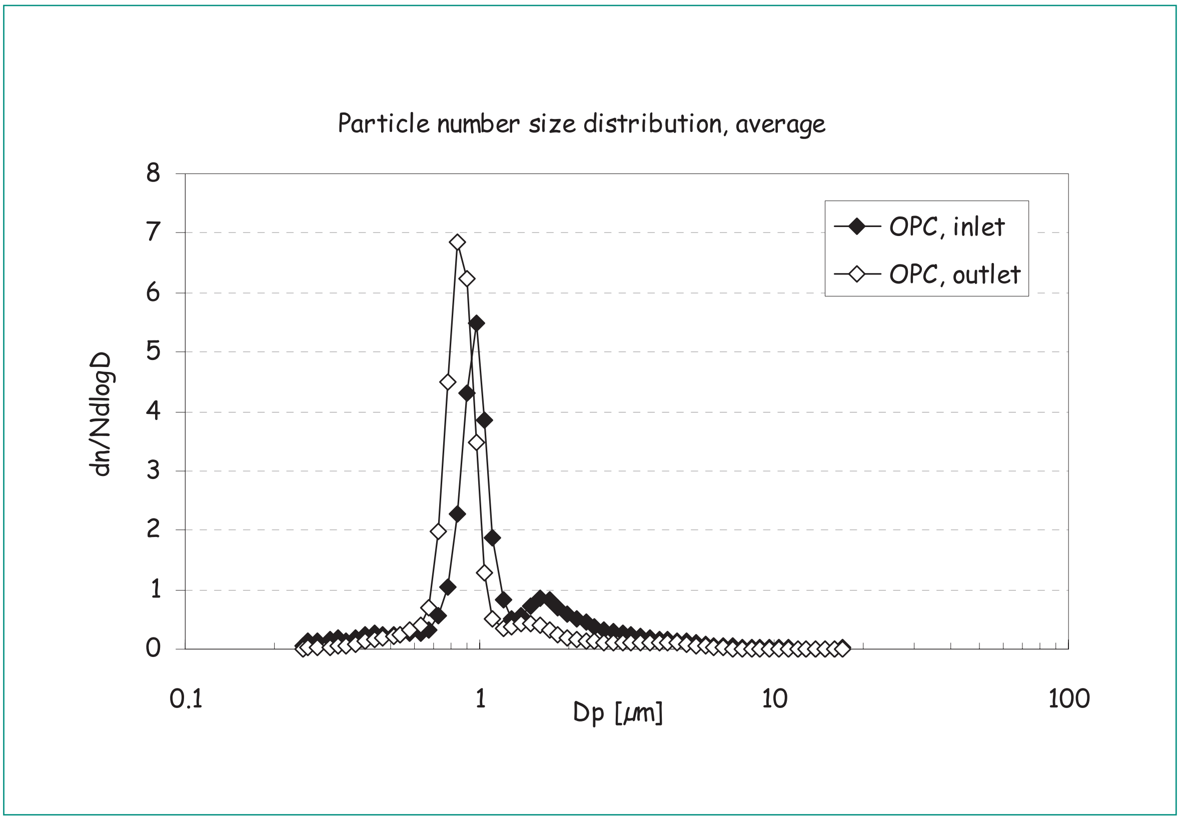

Figure 1: *The average particle size distributions at the test section inlet and outlet in Test E09.*

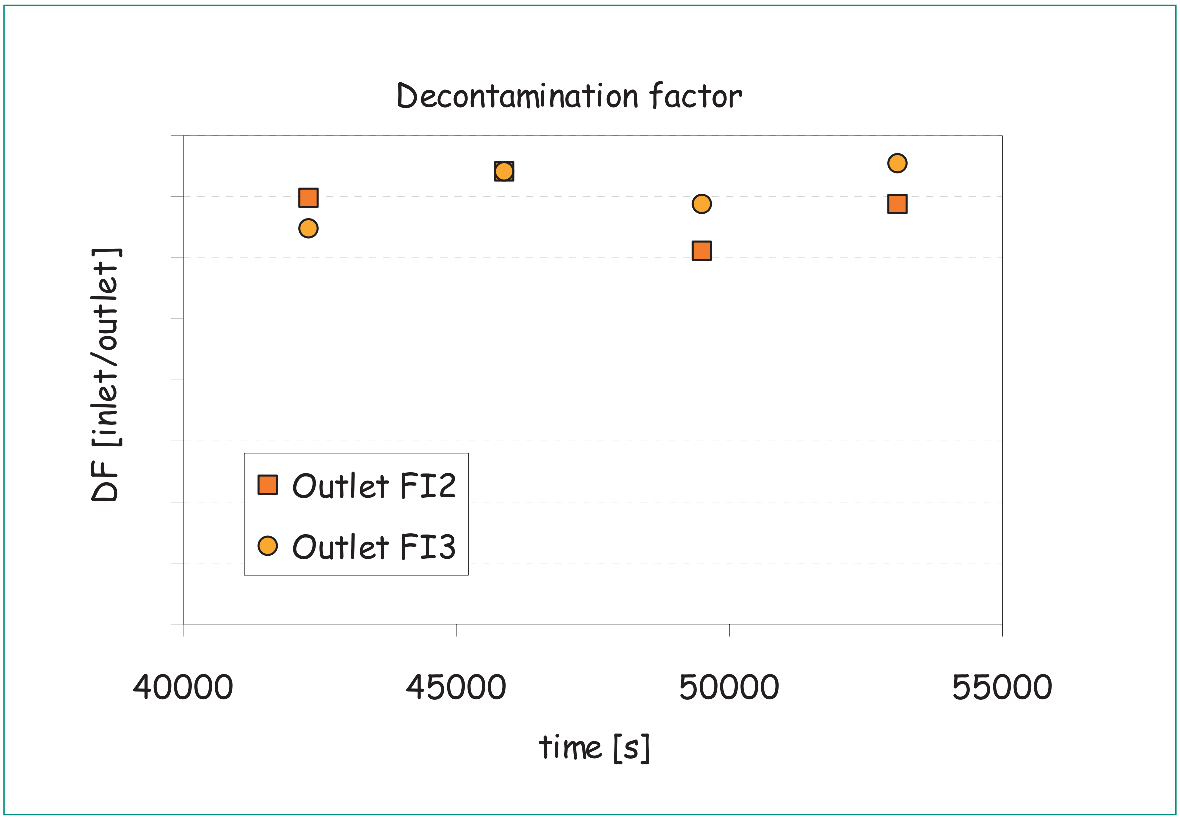

Figure 2: *Decontamination factor in Test E09 with low flow rate of 50 kg/h and particle AMMD = 1.4 μm.*

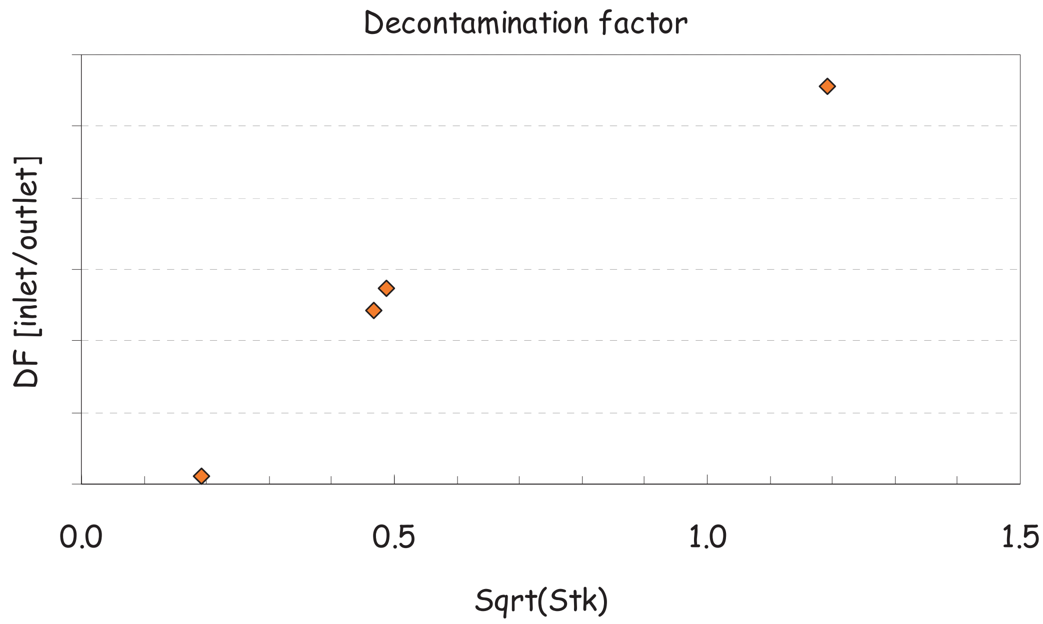

Figure 3: *Decontamination factor DF in flooded bundle tests as a function of the square root of the particle Stokes number Stk.*

Experiments in Phase VIII

Methods

The Phase VIII set of experiments was focused on aerosol retention in the water when the separator is flooded up to its outlet. The break was a full 1D guillotine type opening of the tube, oriented vertically with the gas discharging in the horizontal direction. The break was located at the elevation of the tube bundle where the tube bends start. The water temperature was kept at room temperature and relatively constant to exclude the effect of the change in the water temperature in the retention. The main emphasis of the experiments was to study the effect of the complex flow fields caused by the internals of the separator, e.g., the swirl vane, lid and the cyclones, on the aerosol retention by pool scrubbing in water pools. The effect of the particle size and gas flow rate on the retention was investigated.

The tests were conducted in the ARTIST mock-up test facility with the ARTIST separator and dryer. The ARTIST mock-up tube bundle was not installed to investigate the retention behaviour of the flooded separator alone, followed by the dryer. Separator and dryer units are one-to-one replicas of the separators and dryers in real-scale steam generators of the Framatome 33/19 design. The facility consisted of an inlet section with gas feed, aerosol generation, mixing chamber (MB2) for mixing aerosol and the main gas flow, inlet aerosol measurement section, steam generator tube with 1-D guillotine break at the level corresponding to the location where the tube bend section starts, separator and dryer units, outlet collector, and an outlet aerosol measurement section. The main carrier gas flow was dry nitrogen. The facility was filled with water up to the outlet of the separator, and 3.68 m above the middle of the guillotine tube break.

Aerosol was generated with a two-fluid spray nozzle similar to the tests in Phase V. Mono-disperse, spherical SiO_2 particles with two different particle sizes AMMD = 1.4 µm and 3.7 µm were used to generate the aerosol. Aerosol size distributions and concentrations were determined simultaneously at the test section inlet and outlet. Filter samplings were used to determine particle mass concentration and decontamination factor. Relative particle mass concentration at the inlet was determined downstream of the mixing chamber with a photometer (CT65S, Sigrist Photometer AG). Electrical low-pressure impactors (ELPI; Dekati Ltd.) and optical particle counters (OPC; Palas PCS 2010A) were used to determine the particle size distribution on-line, and the time-dependence of the particle concentration at the inlet and outlet.

Results

Three tests were conducted in Phase-VIII for retention in the flooded separator, Table 2. Test H01 was conducted with the flow rate of 50 kg/h. The aerosol particles were AMMD = 1.4 µm SiO_2 particles. In the two other tests (H02 and H03), the flow rate was increased during the test step-wise with flow rates 50, 200, 360 and 650 kg/h. The test was conducted so that each flow rate was operated for 60 minutes with 15 minutes between the flow rates to change and stabilize the conditions. The effect of particle size on the retention was investigated by using AMMD = 1.4 µm particles in test H02, and AMMD = 3.7 µm particles in test H03. An example of the particle size distribution of the monodisperse particles used in the tests is shown in Figure 4 for Test H03, where particles with AMMD = 3.7 µm were used.
Decontamination factor in the flooded separator was found to be high in all the tests, in the order of several thousand. No significant difference in DF was measured with different flow rates or different particle sizes. According to the on-line instrumentation, the particle retention in all the tests was very high in the beginning of the test, with first rapid and then slow decrease with time, Figure 5. The high aerosol retention in the flooded separator was mainly due to the large water submersion of the break, combined with the complex flow pattern inside the flooded separator.

Phase VI results

The results of the droplet retention tests, as well as the literature work on flashing jets will be reported later.

National Cooperation

This work was carried out as an international collaboration program ARTIST II. Swiss nuclear power plants Beznau and Gösgen, as well as ENSI were partners in the program by co-funding the project. Two PhD projects are carried out in support of ARTIST program at EPFL.

International Cooperation

PSI is the coordinator of the project as well as the operating agent for conduction of the ARTIST II tests. The following international organizations are partners in the ARTIST II program: CIEMAT (Spain), CSN (Spain), JNES (Japan), NRG (The Netherlands), US NRC (USA), SNL (USA), University of Kuopio (Finland), and VTT (Finland). These organizations co-fund the ARTIST II project as well as provide technical contributions in form of model development, simulations, performing separate effect tests and providing aerosol instruments as well as technical services.
Two PhD students are working in support of ARTIST II project at universities in Spain and Finland.

Assessment 2009 and Perspectives for 2010

The project kick-off meeting was held on January 26–27, 2009 at PSI, Villigen. All the project partners were present at the kick-off meeting.
The experimental work was carried out according to the work plan in Year 2009. Preparatory tests were carried out for aerosol feeding for the aerosol retention tests, as well as for droplet feeding and instrument calibration. We succeeded in all of the preparatory tests, i.e., to feed high concentration of aerosols, to feed dif-

Test	Facility	Aerosol AMMD [µm]	Inlet pressure [bar]	Mass flow rate [kg/h]	Effects Studied
H01	ARTIST mock-up separator and dryer	1.4	1.34	50	Steady flow rate, time dependence
H02	ARTIST mock-up separator and dryer	1.4	1.38, 1.86, 2.85, 4.90	50, 200, 360, 650	Flow rate, particle size
H03	ARTIST mock-up separator and dryer	3.7	1.38, 1.86, 2.85, 4.96	50, 200, 360, 650	Flow rate, particle size

Table 2: *Tests conducted in Phase VIII for retention in the flooded separator.*

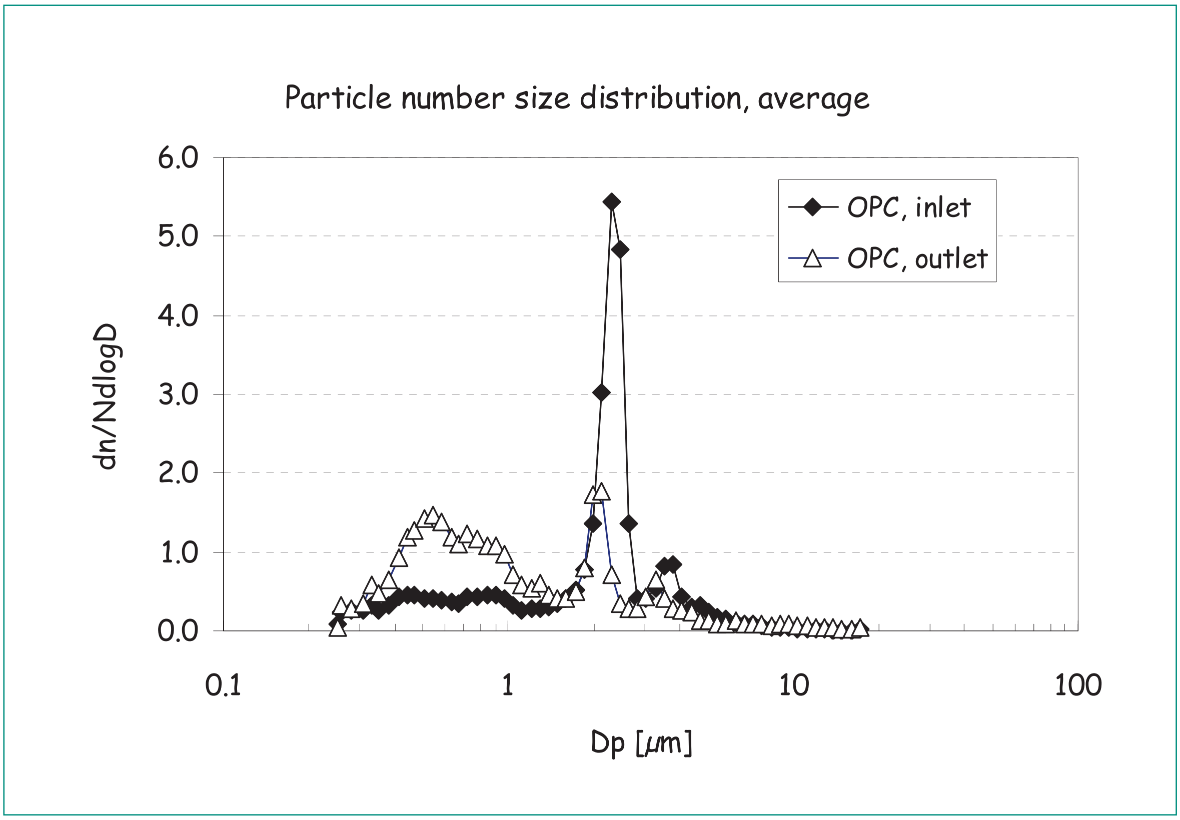

Figure 4: *Particle size distribution at the test section inlet and outlet in Test H03 in which particle AMMD was 3.7 µm.*

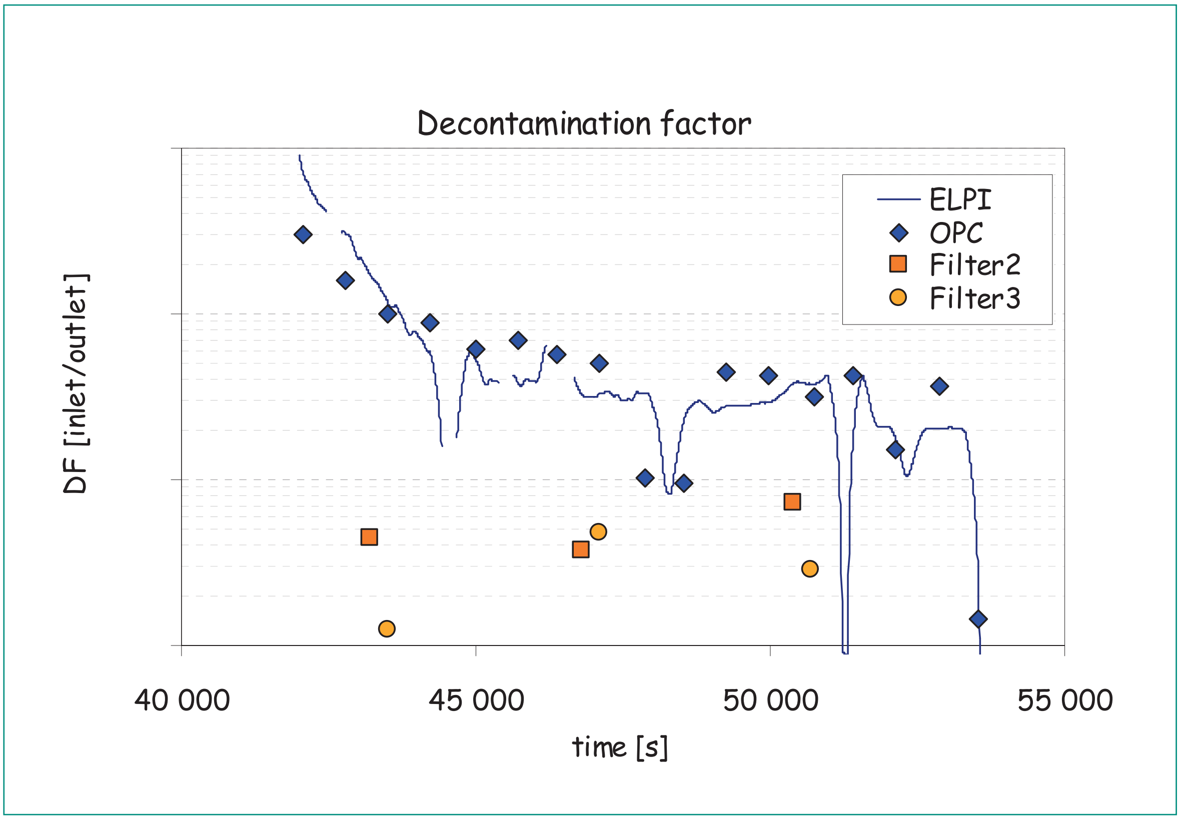

Figure 5: *Decontamination factor in test H01, where the gas flow rate was constant at 50 kg/h and particle AMMD = 1.4 µm.*

ferent aerosol materials, and to generate «sticky» aerosols. Mono-disperse droplets were generated using a vibrating orifice aerosol generator.

All the aerosol retention experiments in phases V and VIII were carried out. Quick look reports on these phases were prepared and distributed to the partners. The work will continue according to the plan in the second project year in 2010.

Publications

- *Y. Liao, S. Guentay:* Time Window for Steam Generator Secondary Side Reflooding to Mitigate Large Early Release Following SBO-Induced SGTR Accidents. Paper submitted to OECD/NEA Workshop for Implementation of Severe Accident Management (SAM) Measures, Paul Scherrer Institut, Villigen, Switzerland, Oct. 26–28, 2009.
- *Y. Liao, S. Güntay:* Potential Steam Generator Tube Rupture in the Presence of Severe Accident Thermal Challenge and Tube Flaws due to Foreign Object Wear, Nuclear Engineering Design, 2009, Volume 239, Issue 6, June 2009, Pages 1128–1135.
- *A. Dehbi:* A stochastic Langevin model of turbulent particle dispersion in the presence of thermo-phoresis. International Journal of Multiphase Flow, Volume 35, Issue 3, March 2009, Pages 219–226.
- *Lind, T., Danner, S., Guentay, S.:* Monodisperse fine aerosol generation using fluidized bed. Powder Technology (2010), doi:10.1016/j.powtec.2010.01.011.
- *Lind, T., Ammar, Y., Dehbi, A., Guentay, S:* Break-up mechanisms of TiO2 aerosol agglomerates in a PWR steam generator tube rupture conditions. Submitted for publication in Nuclear Engineering and Design.

References

[1] *Güntay, S., Birchley, J., Suckow, D., Dehbi, A.:* Aerosol Trapping in a Steam Generator (ARTIST): an Investigation of Aerosol and Iodine Behavior in the Secondary Side of a Steam Generator, 27^{th} Water Reactor Safety Information Meeting. Bethesda, MD, November 1999.

[2] *S. Güntay, A. Dehbi D. Suckow, J. Birchley:* ARTIST: An International Project Investigating Aerosol Retention in a Ruptured Steam Generator. Proceedings of the International Congress on Advanced Nuclear Power Plants (ICAPP), Embedded Topical Meeting, June 9–13, 2002, Hollywood, Florida, USA.

[3] *Güntay, S., Suckow, D., Dehbi, A., Kapulla, R.:* ARTIST: introduction and first results. Nucl. Eng. Design, 231, pp. 109–120 (2004).