ARTIST – Aerosol Trapping in the Steam Generator

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ABSTRACT

Based on the need for aerosol and droplet retention data during a Steam Generator Tube Rupture (SGTR) accident, Paul Scherrer Institut (PSI) has established an international cost share project called Aerosol Trapping In a Steam Generator (ARTIST). The project allowed the gathering of data both at the separate effect and integral levels, as well as simulation of selected accident management procedures. The international collaboration project ARTIST was started in 2002 to perform SGTR-related tests in the ARTIST facility and continued until the end of 2007. A dozen project partners participated in the project not only by financial contributions but by contributing in the area of model development and simulations as well as by performing accompanying dedicated separate effect experimental investigations. The project was constructed in seven distinct phases depending on the underlying set of key phenomena depending on in which part of the Steam Generator they occur.

Phase I: Aerosol retention in steam generator (SG) tubes under dry conditions. Particle size had a significant effect on retention with very low concentration. With high particle concentrations (60 mg/Nm^3 and more), the retention in the tube was found to be dynamic with high retention periods, and periods with resuspension of the deposits. Limited steam condensation increased the retention significantly.

Phase II: Aerosol retention in the break vicinity under dry conditions. The break stage showed high potential for aerosol retention. The particle size had a significant effect on retention in the break stage.

Phase III: Aerosol retention in the bundle far from the break, under dry conditions. Retention in the far field was found to be small. Particle deposition was mainly taking place on the support plates by impaction and turbulent deposition, and uniformly as a very thin layer on the tube surfaces.

Phase IV: Aerosol retention in the separator and dryer under dry conditions. Decontamination factor (DF) in the separator and dryer was found to be relatively constant throughout the test. No significant difference in DF in tests with only separator, and with both separator and dryer was measured. The flow rate had only a small effect on the overall retention.

Phase V: Aerosol retention in the bundle section under flooded pool conditions. The decontamination factors were very high in the two tests conducted, DF being higher with the low flow rate. The scrubbing was more effective for the low flow rate test due to higher gas residence times in the pool.

Phase VI: Droplet retention in separator and dryer sections under dry conditions. Droplet retention in the separator and dryer increased with increasing droplet size and with decreasing carrier gas mass flow rate. The trend was similar for the retention in the swirl vane. The droplet retention in the upper part of the droplet separator was smaller than in the swirl vane, and relatively independent of the droplet size or carrier gas mass flow rate.

Phase VII: Integral mock-up tests. The results of the tests in integral mock-up facility were consistent with the results of separate effect tests. They showed that in dry conditions, major part of the retention took place in the vicinity of the break.

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 (Guentay et al., 2001). 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. Although probabilistic safety assessments (PSA) typically take little or no account of any retention of fission products in the secondary side (USNRC, 1990), the complex geometry of the tube bank, support plates, separators and dryers provides a large surface area on which fission products may be trapped. The presence of liquid water in the SG bundle may further augment the retention. However, the processes that control the retention are complex and there are no reliable models or empirical data with which to perform assessments.

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), Figures 1 and 2, which allows the gathering of data both at the separate effect and integral levels, as well as simulation of selected accident management procedures (Güntay et al., 1999: Güntay et al., 2002: Güntay, 2004). 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); however, accident situations relating to PWR's of other design and power rating can readily be investigated. The main concern for scaling the ARTIST facility was to build a model which conserves the essential thermal-hydraulic and aerosol parameters, provides flexibility to represent a range of plant conditions, while at the same time remain within the constraints imposed by the experimental resources of PSI.

An international collaboration project ARTIST was started in 2002 to perform SGTR-related tests in the ARTIST facility. After review of the available data and models, it was decided that several open issues warranted further investigation in the framework of the ARTIST project. The consortium project ran until the end of 2007. Seven distinct phases were included in the test program:

Phase I: Aerosol retention in SG tubes under dry conditions. In this phase, in-tube aerosol deposition/resuspension was studied under high velocity conditions (up to 300 m/s). Tube length, bend curvature, and aerosol type, size and concentration were varied.

Phase II: Aerosol retention in the break vicinity under dry conditions. Aerosol deposition/resuspension at very high velocities was addressed. The break gas flow rate as well as the aerosol size and material were varied.

Phase III: Aerosol retention in the bundle far from the break, under dry conditions. Aerosol deposition in the developed flow conditions was studied at relatively small velocities (less than 1 m/s) in the area where the flow had evened out across the secondary side flow area. The gas flow rate, particle size and the length of the test section tubes were varied.

Phase IV: Aerosol retention in the separator and dryer under dry conditions. This phase studied aerosol impaction and interception due to complex 3D flows in the upper components of the SG. The gas flow rate was varied.

Phase V: Aerosol retention in the bundle section under flooded pool conditions. This phase investigated condensation-induced aerosol scrubbing by the SG water pool as well as inertial impaction upon the structures. The break flow rate and pool submergence were varied. For accident management purposes, water injection in the dry secondary side is an option in order to quench the hot structures and provide a pool where the incoming aerosols can be scrubbed. Aerosols are scrubbed in the water pool mainly through inertial impaction and diffusiophoresis (condensation) in the vicinity of the break. Away from the break, the remaining gas breaks up in smaller bubbles that rise in the pool, and periodically squirt out of the support plate narrow constrictions. In this latter phase, removal of aerosol is mainly due to centrifugal impaction and gravitational settling during bubble rise.

Phase VI: Droplet retention in separator and dryer sections under dry conditions. This phase dealt 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. Air-liquid nozzles that create droplets with prototypical diameters were used (Dehbi et al., 2001a,b). Carrier gas flow rates and droplet sizes were varied to match prototypical Stokes numbers.

Phase VII: Integral mock-up tests. The seventh set of experiments was integral in nature and was focused on aerosol retention in the whole model steam generator. The conditions of the tests were determined based on insight gained from the results of the other phases, and different particle materials and sizes were used in the tests.

Dedicated experimental facilities for each of these phases were designed and built. In addition to these experimental facilities many systems were developed: sophisticated aerosol and thermal-hydraulic measurement and data acquisition systems, process control and visualization system, aerosol generation systems, calibration and test/development systems for advanced aerosol/droplet generation techniques.

Work Carried Out and Results Obtained

In total, 42 aerosol tests were carried out in the ARTIST program. In addition, extensive testing was conducted with the droplet facility. In the following, the main results are presented for each phase of the program.

Phase I: 14 tests were conducted in Phase-I, in-tube retention. The first in-tube retention tests were carried out by inserting a single tube into the ARTIST mock-up facility. After the first three tests, a dedicated single-tube test facility was constructed. All the rest of the test program was conducted in the dedicated single-tube test facility. The facility consisted of an inlet section with gas feed, aerosol generation, mixing volume (mixing chamber) for mixing aerosol and the main gas flow, inlet aerosol measurement section, tube reduction, test tube, expansion, and an outlet aerosol measurement section. Four different tube geometries were used in the tests: i) straight, 9 m long tube, ii) 19.0 m long U-tube with a 83 mm bend curvature, iii) 19.8 m long U-tube with a 384 mm bend curvature, and iv) 5.3 m long tube with 4.7 m long straight section. Tests were carried out at dry conditions with pure, non-condensable gas, except for one test, in which a small fraction of steam was added to primarily reduce the particle bounce and resuspension from the tube walls. In the tests, we used four different aerosol materials, different particle sizes (aerodynamic mass median diameter AMMD = 0.4 µm – 5 µm), both spherical and agglomerate particles, Figures 3 and 4, and different particle concentrations.

Particle size had a significant effect on retention with very low concentration. Small particles (AMMD = 0.42 µm – 0.76 µm) were retained more efficiently than larger particles (AMMD = 1.4 µm). Increasing particle concentration increased retention for AMMD = 1.4 µm particles. With high particle concentrations (60 mg/Nm^3 and more), the retention in the tube was found to be dynamic with high retention periods, and periods with resuspension of the deposits, Figure 5. Limited steam condensation increased the retention significantly. Agglomerate TiO_2 particles showed break-up in the tube.

Phase II: 9 tests were conducted in Phase-II, Retention in the break stage. The first two break stage tests were scoping tests carried out in the lower part of the ARTIST mock-up bundle. The aim of the scoping tests was to identify the main retention processes, as well as to determine the influence of the test conditions on them. In the scoping tests, it was noticed that aerosol measurements could not be carried out accurately by sampling from inside the tube bundle. Therefore, a dedicated break stage test facility was constructed. All the rest of the test program was conducted in the dedicated break stage test facility. The facility consisted of an inlet section with gas feed, aerosol generation, mixing chamber for mixing aerosol and the main gas flow, inlet aerosol measurement section, break stage test section, collector, and an outlet aerosol measurement section. All the tests were conducted with a Guillotine type break, and in dry conditions. In the tests, we used two different aerosol materials, different particle sizes (AMMD = 0.76 – 3.7 µm), both spherical and agglomerate particles, and different particle concentrations.

The break stage showed high potential for aerosol retention. The particle size had a significant effect on retention in the break stage, Figure 6. Large particles (AMMD = 3.7 µm) were retained more efficiently than smaller particles (AMMD = 1.4 µm and 0.76 µm). Increasing particle concentration during the test seemed to increase retention for AMMD = 3.7 µm particles. With constant aerosol concentration, retention was relatively constant with time, even in the long test that lasted for 12 hours, Figure 7. Agglomerate TiO_2 particles showed significant break-up in the break stage.

Phase III: Eight tests were conducted in Phase-III for retention in the far field. All the tests were carried out in dry conditions. Two first tests were scoping tests conducted in the ARTIST mock-up bundle with TiO_2 agglomerate aerosol with two different flow rates, 50 and 200 kg/h. All the other tests were carried out in the dedicated far field test facility. In these tests, spherical SiO_2 particles were used as aerosol material. Two different flow rates were used in the dedicated far field facility, 33 and 105 kg/h. 33 kg/h corresponds to the gas velocity during SGTR incident in a real steam generator when one tube is broken. 105 kg/h corresponds to the gas velocity in the far field during the ARTIST Phase-VII, integral mock-up facility tests. In the dedicated far field facility, 5 tests were performed with one far field stage, and one test with two far field stages. All the tests were carried out at atmospheric pressure at the test section inlet.

Retention in the far field was found to be small. Particle deposition was mainly taking place on the support plates by impaction and turbulent deposition, and uniformly as a very thin layer on the tube surfaces, Figure 8. In the tests with low flow rate of 33 kg/h and spherical SiO_2 particles with an AMMD of 3.7 µm, it was seen that towards the end of the test, SiO_2 particles carried a high electrical charge when entering the test section. At the same time, the retention in the far field increased. The increase in DF was presumed to be caused by the electrical charge of the particles. To eliminate the effect of electrical particle charge on the decontamination factor, one test (one far field stage, AMMD = 3.7 µm, 33 kg/h), was carried out in which the particles were neutralized before they entered the test facility. In this test, the decontamination factor was constant with time.

Fig. 1: *ARTIST facility (picture: ARTIST project).*

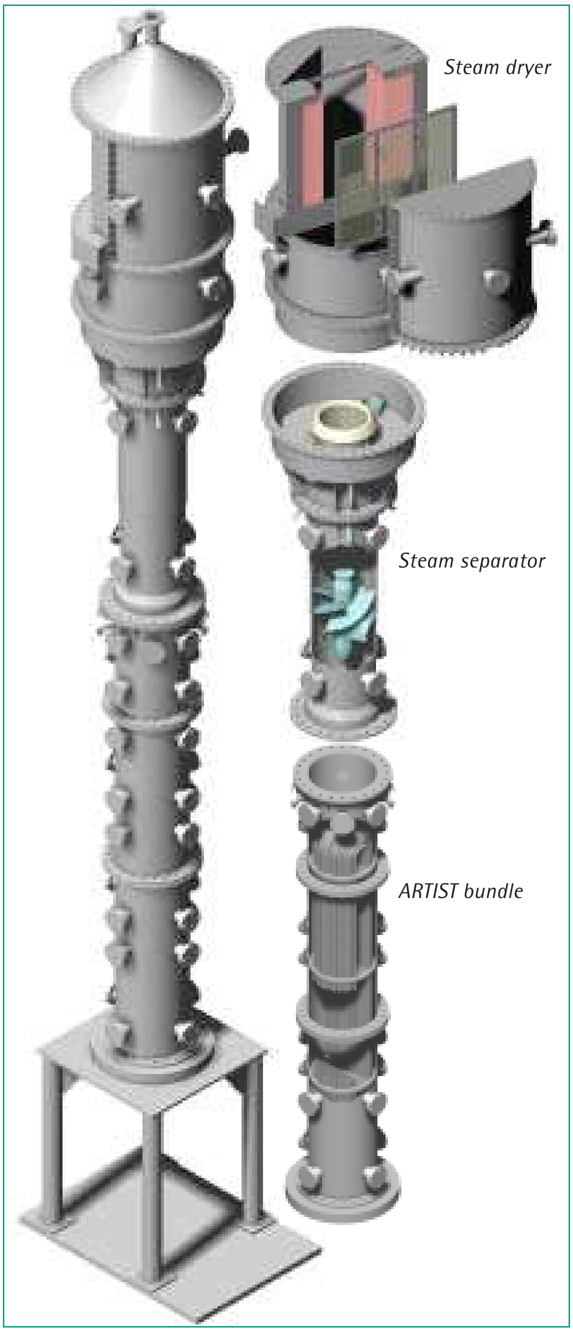

Fig. 2: *ARTIST integral mock-up facility (picture: ARTIST project)*

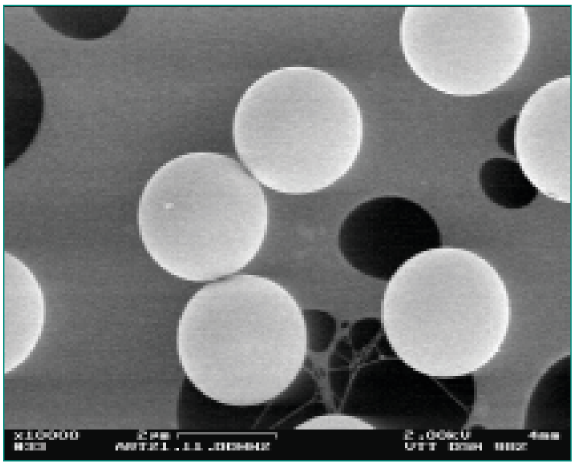

Fig. 3: *Spherical, monodisperse SiO_2 particles used in ARTIST tests (picture: Lind et al., 2008).*

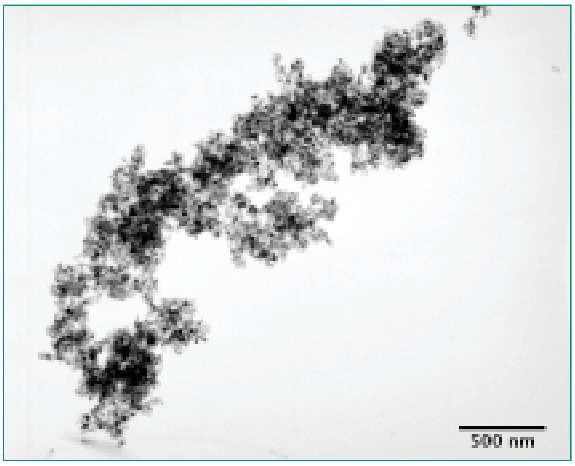

Fig. 4: *Agglomerate TiO_2 particles used in ARTIST tests (picture: Lind et al., 2008).*

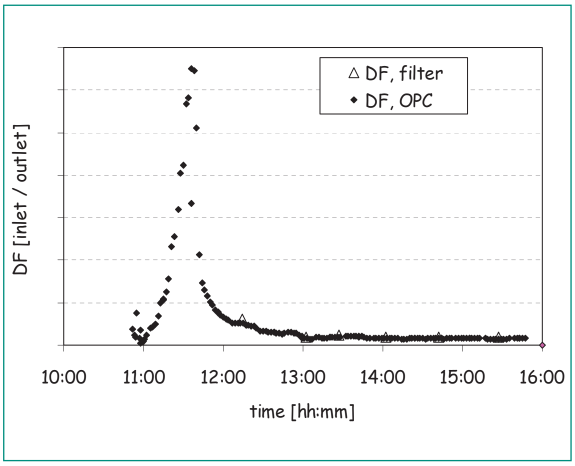

Fig. 5: *Decontamination factor in the single tube in the test with high concentration of spherical SiO_2 particles was dynamic with time (picture: Lind et al., 2008).*

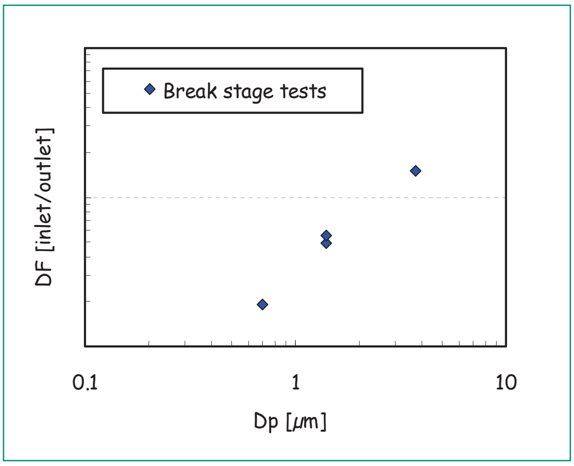

Fig. 6: *Decontamination factor in the break vicinity (Phase II) increased with increasing particle size (picture: Lind et al., 2008).*

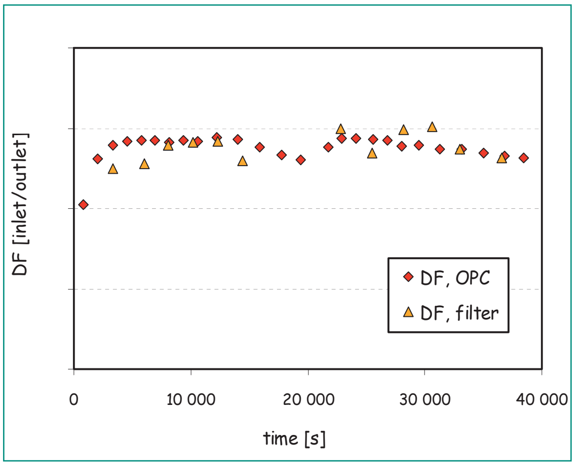

Fig. 7: *Decontamination factor in the break vicinity (Phase II) was constant in time with constant aerosol mass concentration (Picture: ARTIST project).*

Fig. 8: *A photograph of the ARTIST far field facility after a test with SiO_2 aerosol particles showing a thin layer of particle deposit on the tube and shroud surfaces (picture: Lind et al., 2008).*

Phase IV: Five tests were conducted in Phase-IV for retention in the separator and dryer. Because of the swirl imparted to the gas in the separator, and the zigzag geometry of the dryer panels in the dryer unit, aerosol retention is predominantly due to inertial impaction and some interception (especially in the dryer unit). The break flow is conjectured to go either entirely through a single separator and dryer, or split evenly among the numerous separator pipes. Therefore a large variation in the carrier gas flow rate (100 and 650 kg/h) was performed in order to address these two extreme conditions. To characterize the influence of each sub-component, two tests were performed with only the separator unit to isolate the separator retention behavior from the dryer unit. All the other three tests were carried out with both the separator and dryer. The boundary conditions were identical for the two test set-ups. All the tests were carried out at dry conditions. First four tests were conducted with agglomerate TiO_2 particles delivered by Nanophase. Two different flow rates were used, 100 and 650 kg/h. Two separator and dryer tests were carried out using TiO_2 particles and low (100 kg/h) and high (650 kg/h) flow rates, and the last test with spherical SiO_2 particles (AMMD = 3.7 µm) using an intermediate flow rate of 360 kg/h.

Decontamination factor in the separator and dryer was found to be relatively constant throughout the test. No significant difference in DF in tests with only the separator, and with both separator and dryer was measured. The flow rate had only a small effect on the overall retention. Decontamination factor was smaller with spherical SiO_2 particles than with TiO_2 agglomerates.

Phase V: In the ARTIST Phase V, retention in the flooded bundle, two tests were conducted under cold conditions to investigate decontamination due to inertial removal mechanisms. The first test was conducted with a high N_2 carrier gas flow rate of 645 kg/h, which is typical of a choked break flow at 5 bar primary pressure. The second test was conducted with an N_2 carrier gas flow rate of 45 kg/h, which reproduced the low velocities far from the break stage. Both tests were planned with a water level of 3.8 m above the tube sheet, i.e. the water covering the U-bend section. Preliminary testing showed that with a high mass flow rate of 645 kg/h, water droplets were carried away to the measurement piping above the bundle and nearly blocked it. A reduction of the water level to 3.2 m (just below the top-most support plate) eliminated the problem. The test with the low mass flow rate of 45 kg/h was carried out according to the plan with a submergence of 3.8 m. The break was of the axis-symmetric type (guillotine break), with an open area equivalent to one tube diameter, and was located close to the center of the bundle, 248 mm above the tube sheet. TiO_2 aerosol with AMMD in the range of 3–4 µm and Geometric Standard Deviation (GSD) about 2–3 was used. The decontamination factors were very high in both tests, DF being higher with the low flow rate. The scrubbing was more effective for the low flow rate test due to higher gas residence times in the pool.

Phase VI: Phase VI of the ARTIST program dealt with the potential for «primary by-pass» whereby a break at the top of the tube bundle causes generation of fine primary liquid droplets as a result of primary coolant flashing. The droplets could be partly retained by the separator and the dryer units, and partly might find their way to the environment through the safety valve during the time period between the start of the event until the operators are able to depressurize the primary system to stop the flow into the secondary side. Since droplets contain dissolved activity, quantification of their potential retention in the secondary side determines the radiological consequences of a tube rupture accident.

The droplet transport through the separator and dryer are determined by the droplet size and the velocity field in these units. Therefore, extensive velocity measurements were performed with a laser-Doppler anemometer (LDA) at different test section locations. The droplets for the experiments were generated with a two-fluid, air-assist, full-cone spraying nozzle. The droplet carrier gas mass flow rate ranged from 50 to 800 kg/h.

For the droplet retention tests, a known mass of Di-Ethyl-Hexyl-Sebacat (DEHS) simulating water droplets was injected with a spraying nozzle at the bottom of the test section. The retention in the swirl vane unit, the upper section of the droplet separator, and the dryer occurs by droplet impingement on surfaces. The impinged droplets create a downward flowing film. Two series of tests were conducted. In the first series, the droplet retention was measured by collecting this film for each component separately during the experiments, and for additional 10 h after the tests, into buckets. Retention in the test section was determined based on the mass collected. Additional data were obtained in the second test series by local droplet size measurements with a phase-Doppler anemometry system (PDA).

The results showed that droplet retention in the separator and dryer increased with increasing droplet size and with decreasing carrier gas mass flow rate. The trend was similar for the retention in the swirl vane. The droplet retention in the upper part of the droplet separator was smaller than in the swirl vane, and relatively independent of the droplet size or carrier gas mass flow rate. Droplet retention in the dryer was very small.

Phase VII: The ARTIST integral mock-up test facility was constructed for investigation of the aerosol retention in the secondary side of the steam generator during an SGTR incident. It consists of a tube bundle with a diameter of 0.57 m and height of 3.8 m and with a tube bend section at the top. The bundle has 276 tubes that have an outer diameter of 19.05 mm and arrayed in the tube sheet with a pitch of 27.84 mm. The facility has one steam separator and one dryer scaled 1:1. The test facility has been designed to enable the use of different gas mixtures, aerosol feed by different methods, and aerosol measurements at the inlet and outlet of the facility, as well as between different components of the test section.

Three tests were conducted in Phase VII for retention in the integral mock-up facility. The tests were conducted in dry conditions with three different aerosol particle types. First test was conducted using TiO_2 agglomerate particles (delivered by Degussa) as the aerosol material. Two subsequent tests were carried out with spherical SiO_2 particles, one with AMMD = 1.4 µm, the other with AMMD = 3.7 µm. The mass flow rate was an intermediate flow of 360 kg/h corresponding to a break in one steam generator tube. The main aim of the integral tests was to verify the consistency of the separate effect test data from Phases I to IV.

The decontamination factor (DF) was found to depend on the particle size. For spherical SiO_2 particles, DF was significantly higher for particles with AMMD = 3.7 µm than for particles with AMMD = 1.4 µm. The results were consistent with the results from separate effect tests. They showed that in dry conditions, major part of retention took place in the vicinity of the break.

TiO_2 agglomerates had an approximate AMMD = 3 µm at the test facility inlet. The particles deagglomerated into smaller particles in the bundle section before the second aerosol measurement location at the bundle outlet. After this, the particle size did not change in the separator and dryer, and the particle AMMD at the bundle outlet was the same as at the test facility outlet, approximately 0.7 µm. The spherical particles did not break up in the facility.

National Cooperation

This work was carried out as an international collaboration program ARTIST. Swiss nuclear power plants Beznau and Gösgen, as well as HSK (presently 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

The following international organizations were partners in the ARTIST program: AVN (Belgium), CIEMAT (Spain), CSN (Spain), HSE (UK), IRSN (France), JNES (Japan), Ringhals (Sweden), SKI (Sweden), UPM (Spain), US NRC (USA), US SNL (USA), University of Newcastle (UK), VTT (Finland). These organizations co-funded the ARTIST project as well as provided technical contributions in form of model development, simulations, performing separate effect tests and providing aerosol instruments as well as technical services.

PSI is the coordinator of the project as well as the operating agent for conduction of the ARTIST tests.

Four PhD theses and two MSc theses have been made in support of ARTIST program at universities in Belgium, Spain, UK, USA and Finland.

Assessment 2008 and Perspectives for 2009

The ARTIST program was completed 31.12.2007. Experimental data on aerosol and droplet retention in the steam generator tube rupture event were provided to the partners as planned and as approved by the program review committee. The 6th and the last program review committee meeting took place on January 23–25, 2008. The reporting from the PSI side as well as from the partners was completed in 2008. Partner contributions were conducted and reported as planned.

A follow-up international collaboration program ARTIST 2 was proposed on the merits of the ARTIST project and discussed with the partners in the last two years of the ARTIST project. The ARTIST 2 project with the same and additional partners has started on 1.9.2008. The kick-off meeting of the project will take place on January 26–27, 2009, to discuss and finalize the experimental program as well as the partner contributions. The rest of the year will be devoted to conduct the tests to be agreed upon by the project review committee.

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