ARTIST II

Aerosol trapping in the steam generator

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ABSTRACT

A steam generator tube rupture (SGTR) in a pressurized water reactor (PWR) has a potential of causing extensive release of radioactive aerosols into the environment due to the possibility of the aerosols of by-passing the containment. Generally, no credit is taken for the retention of aerosols inside the steam generator, and consequently, the release fraction of the activity associated with SGTR may be overestimated.

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), with a continuation project ARTIST II. Experimental work in 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, methodology is developed to apply the experimental data from ARTIST program to assess the source term from SGTR severe accidents.

During the second project year, experimental work was carried out to investigate three of the phenomena addressed in ARTIST II, namely, aerosol retention inside the broken tube, aerosol retention in the tube bundle close to the break, as well as droplet retention in the dryer. The experiments for the aerosol retention are reported here. The droplet retention work was started by determining flow fields at the dryer inlet and outlet, and those results are presented here. The droplet retention work is still continuing, and it will be finished during the last project year.

Towards the end of the project, a significant part of the work is devoted to summarizing the results from the whole project as well as to applying the ARTIST experimental data for the risk analysis of SGTR accidents. Description of the methodology developed to evaluate the source term for SGTR severe accidents is given in this report. For induced SGTR, in addition, a methodology was developed to assess the probability for the degraded steam generator to rupture first in the reactor coolant pressure boundary induced by severe accident thermal challenge and tube flaws due to foreign object wear.

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 ARTIST (Aerosol Trapping In a Steam Generator), which allows the gathering of data both at the separate effect and integral levels, as well as simulation of selected accident management procedures [1]. The ARTIST facility is a scaled-down model of the FRAMATOME 33/19 type SG in operation at the Swiss power Plant Beznau (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 to investigate certain phenomena not addressed in ARTIST. ARTIST II project concentrates on aerosol retention addressing severe accident scenarios, as well as on droplet retention addressing design basis accidents.

Following experimental work is included in ARTIST II: i) Aerosol retention in SG tubes under dry conditions, ii) aerosol retention in the break vicinity under dry conditions, iii) aerosol retention in the bundle section under flooded bundle conditions with small water submersion, iv) aerosol retention in the flooded separator, and v) droplet retention in the dryer section under dry conditions. In addition to experimental work, a methodology is developed to apply the experimental data from ARTIST to assess the source term from SGTR severe accidents.

During the second year, experimental work was carried out for determination of the aerosol retention inside the broken tube and of the aerosol retention in the break vicinity. In addition, experiments were started for the determination of droplet retention in the dryer section of the steam generator. This work is still on-going, and will be completed during the last project year.

The methodology that is developed to assess the source term from SGTR is based on the use of i) an accident progression event tree (APET) to determine a particular accident sequence, ii) use of plant level codes (e.g., MELCOR) to calculate specific conditions during the incident at the plant, iii) application of the ARTIST experimental data for successive retention stages in the steam generator, and iv) integration of the data into a Monte Carlo program to analyze the probability distribution of the release fraction of radioactive compounds. For severe accident induced SGTR, in addition, the probability of a tube rupture in the steam generator due to the thermal challenge and foreign object wear is calculated.

Work carried out and results obtained

Experimental work on aerosol retention inside the broken tube

Aerosol retention inside the tube was measured under high velocity conditions (up to 300 m/s) inside a straight tube and a U-tube. The aim of the experiments was to investigate the dynamic nature of aerosol retention with high aerosol concentration, as well as to investigate the effect of particle bounce and resuspension from the tube walls. Therefore, two different particle types were used in the experiments, spherical, solid SiO_2 particles with aerodynamic mass median diameter (AMMD) = 1.4 µm, and liquid droplets of Di-Ethyl-Hexyl-Sebacat (DEHS). The solid particles were used to investigate the dynamics of the aerosol retention with high aerosol con-

Test	Tube geometry	Aerosol	Inlet pressure [bar]	Mass flow rate [kg/h]	Effects Studied
A10	Straight tube	SiO_2	4.0	300	High aerosol concentration, straight tube
A11	Straight tube	DEHS	4.0	300	No bounce, straight tube
A12	U-tube	SiO_2	4.0	235	No bounce, U-tube
A13	U-tube	DEHS	4.0	235	High aerosol concentration, U-tube

Table 1: *Tests conducted in Phase I for aerosol retention inside the steam generator tube.*

centration, as the same particles were used in earlier in-tube aerosol retention tests in ARTIST, where aerosol concentration in the test section was lower than in the present tests. The effect of particle bounce and resuspension on the aerosol retention was investigated using DEHS droplets, as fine droplets are known not to bounce, i.e., their sticking coefficient upon impaction is one (1). The test matrix for the single tube tests is presented in Table 1.
As the test series was carried out in the end of the project year, the results are not reported here, but will be reported in the final project report.

Experimental work on aerosol retention in the vicinity of the tube break

Aerosol deposition in the tube bundle close to the break was investigated in the dedicated break stage separate effect test facility. Tests were conducted to determine the effect of the gas flow rate, break geometry, and high aerosol concentration on the aerosol retention. In addition, one test was carried out to determine the effect of particle bounce and resuspension.
Considerable amount of aerosol was found to be retained in the vicinity of the break in all the tests. Photographs of the tube bundle after test B12, Figure 1, where the gas flow rate through the break was 358 kg/h and a 1-D guillotine break was used (1-D break has an opening area corresponding to the inner cross section area of the tube), show thick deposit layers of aerosol on the tube surfaces. In fact, the deposits were so thick, that part of the deposits had fallen off, as seen in Figure 1. Another noteworthy detail in Figure 1 is the fact that the surfaces of the tubes closest to the break do not have any deposit layer on them, presumably due to particle bounce caused by very high jet velocity.

Figure 1: *Aerosol deposit layer on the surface of the bundle tubes close to the tube break after Test B12.*

Flow velocity and droplet retention in the steam dryer

Droplet retention in the steam separator and dryer was determined earlier in the ARTIST project. However, due to the high retention efficiency of the separator, the droplet concentration at the dryer inlet was too low to determine the droplet retention efficiency of the dryer. Therefore, tests are conducted in ARTIST II to determine the droplet retention in the steam dryer. To be able to apply the results for computational fluid dynamics (CFD) simulations, the flow characteristics have to be known. For this reason, the work was started by determining the gas flow velocity at the steam dryer inlet and outlet. This work was finished during the second project year, and the work continues with the determination of the droplet retention in the dryer section during the last project year.
The gas flow velocity was determined at the separate effect droplet retention facility, Figure 2. The facility consists of 1:1 scale steam separator and dryer. A two-component Laser Doppler Anemometer (LDA) instrument was used for the velocity measurements at the

Test	Break geometry	Inlet pressure [bar]	Mass flow rate [kg/h]	Effects Studied
B08	1-D guillotine	2.9	363	Test with DEHS, sticky aerosol
B09	1-D fish mouth	2.8	358	High flow rate, fish-mouth
B10	0.5-D fish mouth	2.7	90	Low flow rate, fish-mouth
B11	0.5-D guillotine	2.9	90	Low flow rate, guillotine
B12	1-D guillotine	2.8	358	Reference test to ARTIST tests, high particle concentration

Table 2: *Tests conducted in Phase II for aerosol retention in the vicinity of the tube break.*

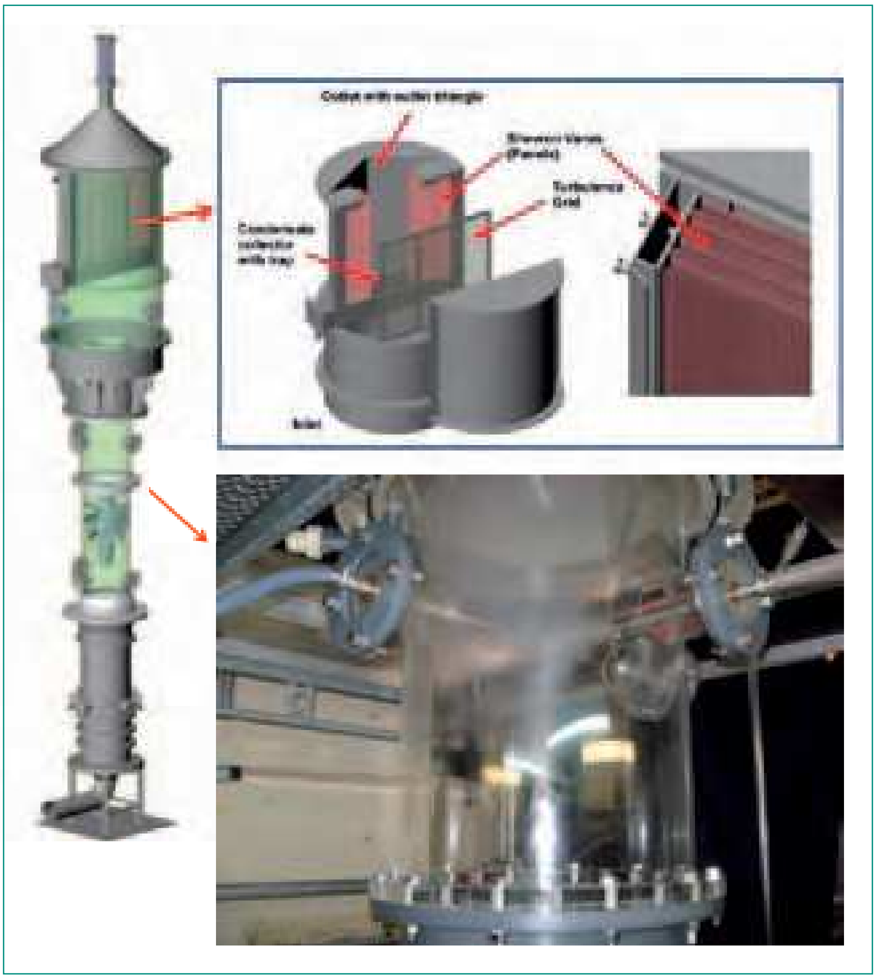

Figure 2: *Droplet retention test section with 1:1 scale droplet separator and dryer. The velocity was measured at the dryer inlet and outlet as close to the dryer panels as was possible.*

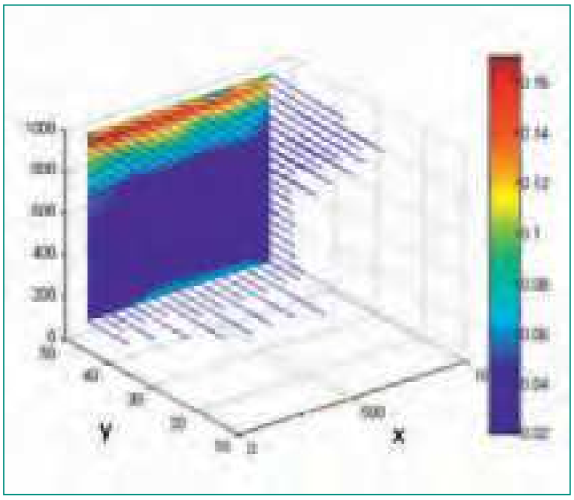

Figure 3: *Flow field at the dryer outlet with mass flow rate of 200 kg/h. The velocity scale in m/s.*

dryer inlet and outlet as close to the dryer panels as possible. For the velocity measurements, seed particles of polyethylene glycol with an average diameter of approximately 1 µm were fed at the outlet of the separator with a nebulizer.

The flow fields were characterized with four different dry air flow rates through the dryer, 50, 100, 200 and 800 kg/h. For all the flow rates, the flow field at the dryer inlet was affected by the swirl vane upstream of the dryer seen as a non-uniform velocity distribution, and higher velocities towards the walls of the inlet flow channel. In the dryer, the flow velocity decreased and the velocity differences caused by the swirl vane disappeared. Higher flow velocity was seen at the top of the dryer panels where the flow turned to go upwards towards the facility outlet, Figure 3.

SGTR severe accident risk analysis using ARTIST data

A methodology was developed to apply the experimental data from ARTIST program to assess the source term from SGTR severe accidents. The same methodology for source term estimation can be used for both spontaneous SGTR accidents and severe accident induced SGTR. For severe accident induced SGTR, in addition, a methodology was developed to assess the probability for the degraded steam generator to rupture first in the

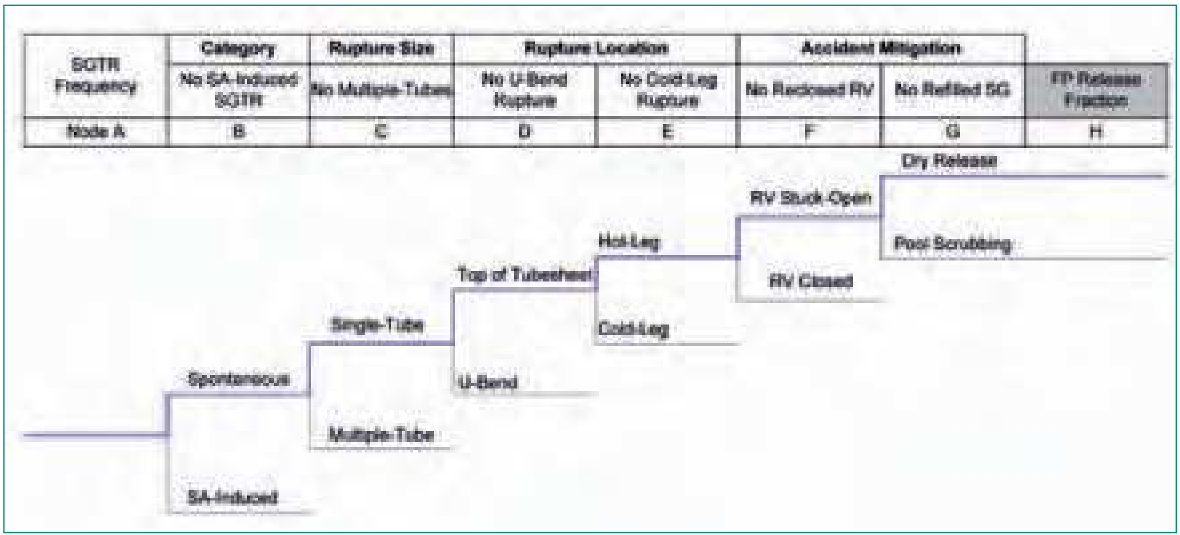

Figure 4: *SGTR Accident Progression Event Tree.*

reactor coolant pressure boundary induced by severe accident thermal challenge and tube flaws due to foreign object wear.

The source term evaluation is based on the following steps:

1) **A variety of SGTR scenarios** are considered based on SGTR accident progression event tree (APET), e.g., spontaneous or induced, single-tube or multiple-tube rupture, location of the rupture, etc., Figure 4.
2) For each scenario, **a series of retention stages** in the release path of the radioactive compounds are considered, Figure 5: circuit, SG inlet/outlet plenum, in-tube retention, break stage, far field, U-bend, separator and dryer, and steam dome. Retention caused by recirculation is taken into account as a lump parameter model.
3) For each retention stage, **time dependent thermal-hydraulic conditions** are calculated using system codes, e.g., MELCOR, SCDAP/RELAP5, SOPHAEROS.

An example for such calculation is given for the break stage fluid temperature as calculated by MELCOR and SCDAP/RELAP5 in Figure 6.

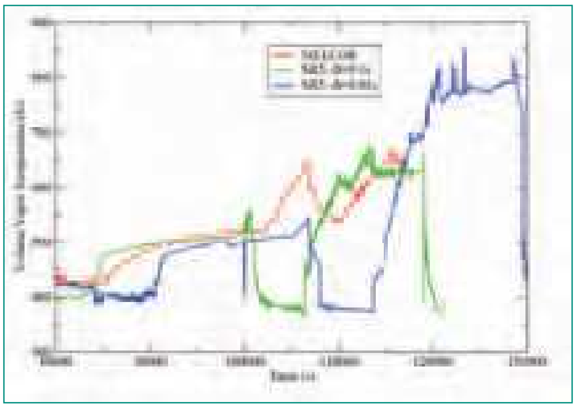

Figure 6: *Break stage fluid temperature calculated by MELCOR and SCDAP/RELAP5.*

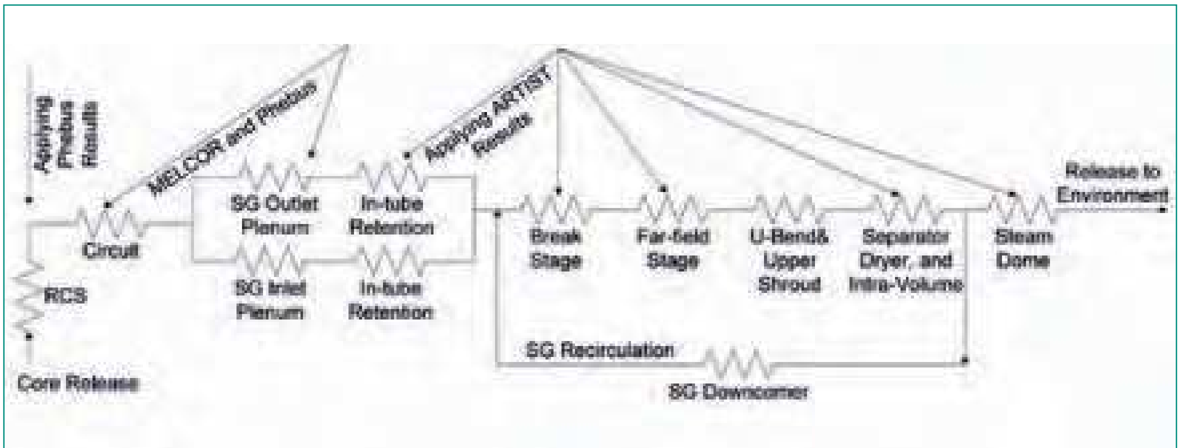

Figure 5: *Retention stages in the release path of the radioactive compounds.*

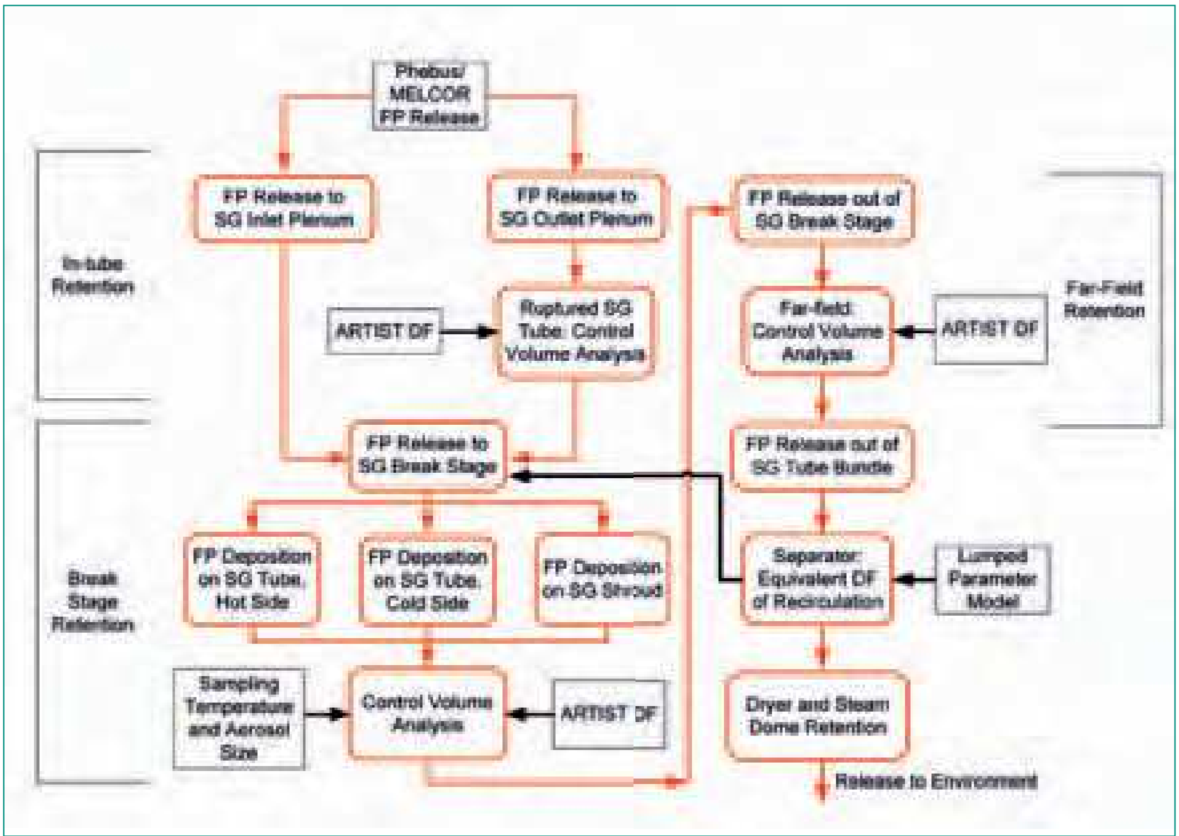

Figure 7: *Monte-Carlo program to sample TH-conditions, DF, and their error factors, and to analyze the probability distribution of the release fraction of the radioactive compounds.*

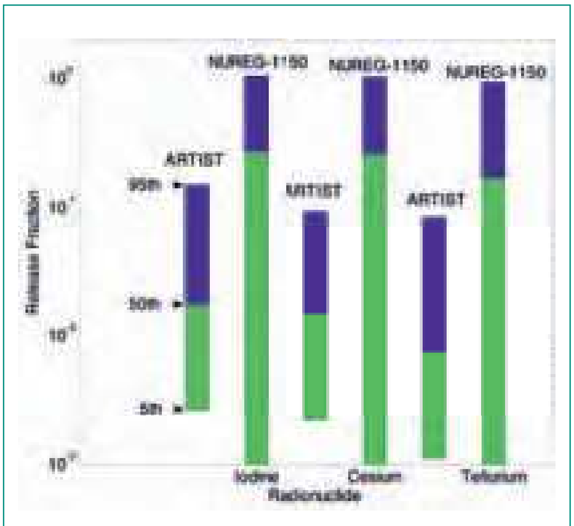

Figure 8: *Comparison of the release fractions using ARTIST experimental data to those in the NUREG-1150 analysis for volatile radionuclides.*

4) Based on the conditions predicted by the system codes, **appropriate ARTIST experimental data for aerosol retention** are applied at each retention stage. Here it is taken into account that fission products may be in the vapour phase and as aerosols, and that the ARTIST data are only applicable to the aerosol phase. Vapour condensation onto particles and walls is taken into account, including particle growth by condensation.

5) **Data are integrated into a Monte-Carlo program:** Decontamination factor (DF) values for a series of retention stages, error factors for DF values based on experimental data and expert judgment, and error factors for thermal-hydraulic conditions based on multiple code runs. Monte-Carlo program, Figure 7, samples thermal-hydraulic conditions and DF for a series of retention stages for the time series of a specific SGTR scenario to analyze the probability distribution of the release fraction of radioactive compounds.

An example calculation for a specific SGTR scenario in a Swiss power plant shows, Figure 8, that using the ARTIST experimental data and the methodology developed and described here, the uncertainties in the release fractions of radionuclides are significantly reduced compared to earlier analyses [2]. In addition, the steam generator clearly shows a retention capacity at least an order of magnitude larger than previously estimated.

National Cooperation

ARTIST II is an international collaboration research program. Swiss nuclear power plants Beznau and Gösgen, as well as ENSI are partners in the program by co-funding the project.

In support of the ARTIST II project, collaboration with Swiss Universities is carried out in the form of three PhD theses: i) during the second project year, a PhD work titled «Numerical investigation of particle-laden thermally driven turbulent flows in enclosure» was completed at EPFL with Prof. M.O. Deville as the supervisor, ii) a PhD work titled: «Large eddy simulation of particle removal inside a differentially heated cavity» is in its second year with Professors M.O. Deville (EPFL) and L. Kleiser (ETHZ) as supervisors, and iii) a new PhD work is started at ETH in Zurich in collaboration with Prof. H.-M. Prasser during the last project year; the tentative subject of the work is: «Bubble hydrodynamics in tube bundles».

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), Fortum (Finland), 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, and experimental work.

Two PhD students are working in support of ARTIST II project at universities in Spain and Finland.

Assessment 2010 and Perspectives for 2011

The work progressed according to the work plan during the second project year. The 2^{nd} project review committee meeting was organized at PSI January 25–26, 2010. All the partners, including PSI, presented their work accomplished during the first project year, and described their plans for the second and third years. All the plans were accepted as presented.

Experiments for determination of aerosol retention inside the tube (Phase I: In-tube) and in the break vicinity (Phase II: Break stage) were carried out during 2010. In addition, flow velocity measurements were conducted at the dryer section inlet and outlet. Droplet retention tests (Phase VI) were started, and will be continued during 2011.

Work was carried out to develop and refine **the methodology to re-evaluate the source term from severe accident by-pass scenarios** based on the experimental data from ARTIST. Treatment of the induced tube rupture in the presence of severe accident thermal challenge and tube flaws due to foreign object wear was added to the analysis.

Results of the work in ARTIST were presented **at three conferences:** i) The International Aerosol Conference, ii) CSARP meeting (Cooperative Severe Accident Research Program, US. NRC), and iii) ANS Winter Meeting (American Nuclear Society).

In the last project year, the final results of the aerosol retention tests will be reported. The experiments for the droplet retention in the dryer will be completed. A final report of the project will be prepared and distributed to the partners.

Publications

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[2] *US. NRC.* Severe accident risks, «An assessment of five US nuclear power plants.» US. Nuclear Regulatory Commission Report, NUREG-1150, 1990.