ARTIST: A Cooperative safety project to study fission product retention in a ruptured steam generator

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Abstract: Sequences such as a steam generator tube rupture (SGTR) with stuck-open relief valve represent a significant public risk by virtue of the open path for release of radioactivity. The release may be lessened by deposition of fission products on the steam generator (SG) tubes and other structures or by scrubbing in the secondary coolant. The absence of empirical data, the complexity of the geometry and controlling processes, however, make the retention difficult to quantify and credit for it is typically not taken in risk assessments. The ARTIST experimental program to be conducted at Paul Scherrer Institut, Switzerland, will simulate the flow and retention of aerosol-borne fission products in the SG secondary, and thus provide a unique database to support safety assessments and analytical models. The project, foreseen in seven phases, will study phenomena at the separate effect and integral levels, and also address accident management (AM) issues. The prescribed values of the controlling parameters (aerosol size, aerosol type, gas flow velocity, residence time, etc) cover the range expected in severe and design basis accident scenarios.

1. BACKGROUND AND MOTIVATION

Steam generator (SG) tubing is subject to a variety of degradation processes that can lead to cracks, thinning and, potentially, rupture. Despite improvements in SG design, manufacturing and modes of operation, SG tube rupture (SGTR) events occasionally occur during PWR operation worldwide which underline 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. Although probabilistic safety assessments (PSA) typically take little or no account of any retention of fission products in the secondary side [1], 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 retention data during an SGTR, PSI has built a model steam generator called ARTIST (Aerosol Trapping In a Steam Generator) that will allow the gathering of data both at the separate effect and integral levels, as well as simulation of selected accident management procedures [2].The ARTIST facility is a scaled-down model of the FRAMATOME 33/19 type SG in operation at the 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.

2. SUMMARY OF the REFERENCE PLANT TRANSIENT

In order to scale the ARTIST facility, a detailed simulation has been conducted to determine base case parameters. An SGTR with other failures leading to core damage has been chosen as the base sequence, because it has been identified as a major risk contributor in the PSA study for KKB [3]. Details of the simulations can be found in [2].

The assumed initiating event is a double-ended guillotine break near the bottom of the hot side of one of the SG tubes (Beznau is a two-loop PWR; for convenience the faulted and intact SGs are referred to as SGA and SGB, respectively). The reactor protection, emergency coolant systems (ECS) and auxiliary feedwater (AFW) systems function normally. However, it is assumed that no operator-initiated measures are taken in the early stages of the sequence. Overfilling of the faulted SG secondary causes the relief valve (RV) to stick open, hence leading to a long term loss of cooling and a consequent core melt and release of fission products. Among the essential features of the transient are:

- both the primary and secondary sides of the faulted SG are completely void before the core starts to heat up and remain so throughout the rest of the sequence;
- the intact SG is depressurized to ambient pressure by operator action before the onset of core degradation;
- accumulation of hydrogen in the intact steam generator impedes the condensation of steam and limits the primary side depressurization such that the flow is choked at the break.

Representative conditions during the period of activity release are presented in Table 1.

Parameter	**Value**
Time period of interest	80000 - 90000 s
Decay heat level	7 MW (0.5%)
Primary side total pressure	0.5 Mpa
Primary side steam pressure	0.1 - 0.4 Mpa
Secondary side pressure	0.1 Mpa
Break flow (hot side)	0.20 kg/s
Break flow (cold side)	0.05 kg/s
Break fluid temperature	1000 K
SGA structure temperature	650 K
Fission product release rate into the secondary side	12 g/s

Table 1 : Conditions at time of release

3. TEST SECTION SCALING AND RIG CAPABILITIES

The test rig will be connected to the PSI aerosol generation system (DRAGON) which provides a flow of single or multi-component aerosol in a steam or steam/non-condensable carrier gas. The aerosols can be generated by two methods: either by the evaporation-condensation technique through the use of a plasma torch, or by a fluidized bed generator. The aerosol flow and characteristics can be controlled in a stable manner.

The ARTIST test section is composed of several modules to simulate the SG secondary, as shown in Figure 1. These are:

- a scaled (1:24 number of tubes) tube bundle of diameter 57.3 cm containing 264 straight tubes of outer diameter 19 mm and maximum height 3.8 m;
- the U-bend section of the SG tubes;
- a tube sheet plate;
- three support plates spaced 1.1 m apart;
- one separator unit of actual size;
- one dryer cell of actual size.

The ARTIST Components

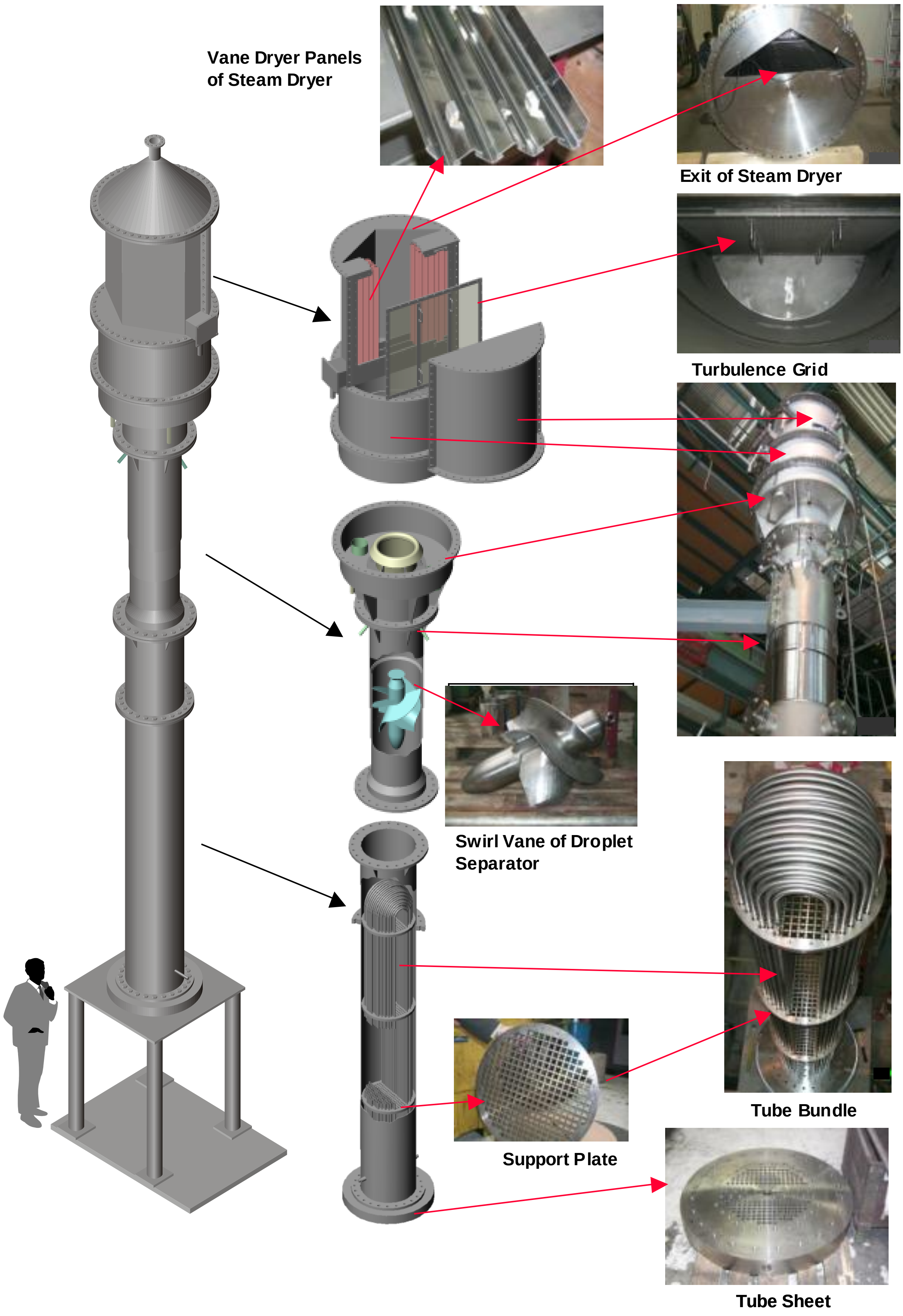

Figure 1: Schematic of the ARTIST facility

The bundle diameter is considered large enough to reproduce the jet behavior as the momentum is dissipated after it emerges from the break, provided the break is not too close to the shroud and oriented towards it. The tubes have a diameter, thickness, and pitch that are identical to the real unit. The spacing of 1.1 m between support plates is also preserved. However, the tube length is only about 40% of the real unit.

The rationale for having a bundle diameter of 0.57 m is that this width is large enough to reproduce the momentum dissipation of the jet which emerges from the broken tube. To gain reasonable confidence that the outer wall (shroud) would not be a factor in the aerosol retention, a computational Fluid Dynamics (CFD) simulation was performed [4]. The CFD simulation is based on the CFX code and produced detailed predictions of the flow field in the break stage. Three distinct breaks were analyzed based on data collected from past SGTR event:

- A fish-mouthed horizontal jet on the periphery of the tube bank and pointing towards the center of the bundle;
- An axis-symmetric horizontal break at the center of the bundle;
- A central break at the tube sheet with the jet pointing upwards.

The simulations were conducted with a nominal break size (1 diameter) and a flow rate of 936 kg/h, which corresponds to choked flow conditions. The gas and structure temperatures are assumed to be 573 K, while the primary and secondary pressures are 5 bar and 1 bar, respectively. These data represent mean values at the time of fission product release following an SGTR.

The CFD simulations revealed the following important results:

- The static pressure on the shroud surface is almost the same everywhere, meaning that the presence of the wall has very little impact on the jet behavior.
- The region of high velocities is localized around the break region and confined to a small volume which encompasses approximately the five tube rows which surround the broken tube.
- At the tube support plate of the break stage the flow has spread out across the whole flow area, although not quite uniformly. The maximum velocities at the support plate level are on the order of 10 m/s, or about 1/20 of the velocity at jet exit.

Based on these results, it is concluded that the number of tubes in ARTIST is adequate to reproduce 1 to 1 the aerosol retention in the vicinity of the break (i.e. the break stage).

The tube length is made smaller due to laboratory height and infrastructure limitations, and hence there are just three bundle stages compared to the 9 existing in the real plant. This should however not have a big impact on the extrapolation of the results because beyond the break stage, it is expected that the flow will even out across the bundle free area, so that the stage-to-stage decontamination factor (DF) remains approximately the same for all the sections, and therefore the study of aerosol retention in two “far-field“ bundle stages is enough to extrapolate the results to more stages.

The other problem introduced by the shorter length is that of residence time, which might be important for thermophoresis. This issue can be dealt with by choosing a smaller carrier gas flow rate in the far field stages to replicate the correct residence time. The parameters characterizing the Beznau SG and ARTIST model are given in Table 2. The important ratios shown in bold are comparable.

4. MAJOR PHENOMENA IN SG SECONDARY

To design the ARTIST test matrix, it is necessary to determine what the expected controlling phenomena are. The latter depend on whether the reference sequence is a severe accident in which case the secondary side conditions may be dry or wet, or a design basis accident in which case the primary coolant is single phase liquid but superheated with respect to the secondary side.

Parameter	Unit	Beznau	ARTIST
Number of tubes	-	3238 (U tube)	264 (straight)
Number of dryers	-	12	1
Number of separators	-	12	1
Maximum tube height	m	9.0	3.8
Bundle diameter	m	2.68	0.57
Total cross sectional area of bundle	m^2	5.641	0.258
Area occupied by the tubes	m^2	1.846	0.0755
Free flow area in bundle section	m^2	3.790	0.185
Physical diameter of free area in bundle region	m	2.2	0.48
Physical diameter of free area in support plate	m	1.275	0.26
Free area per flow channel in support plate	m^2	**$1.97\ 10^{-4}$**	**$1.97\ 10^{-4}$**
Tube inside diameter	mm	**16.7**	**16.7**
Surface/volume ratio	m^2/m^3	**102.2**	**87.2**
Ratio of the free area in bundle to that of the support plate	-	**2.97**	**3.49**
Hydraulic diameter in bundle region, cm	cm	**3.1**	**3.1**
Porosity	-	**0.67**	**0.71**

Table 2: Important geometric parameters in the bundle section for Beznau plant and ARTIST

4.1. Dry SG in severe accident conditions

The following mechanisms can potentially account for aerosol retention in dry SG secondary side conditions:

- turbulent deposition inside the ruptured tube;
- inertial and turbulent deposition in the secondary side;
- thermophoresis;
- gravitational settling;
- agglomeration (leading to enhanced gravitational settling)

The reference calculation suggests that choked flow conditions at the break are typical, with velocities in the broken tube of a few 100 m/s. Previous studies by Liu and Agarwal [5] indicate that turbulent deposition is the dominant mechanism at such velocities and the retention is primarily a function of the tube length to diameter ratio for aerosol sizes of interest (Aerodynamic Mass Median Diameter (AMMD) greater than 0.3 μm). Retention may be offset by resuspension, to an extent which is as yet uncertain. Therefore it is important to preserve the flow and aerosol characteristics inside the tube so that the results are directly applicable.

Near the break location, the local gas velocities are also expected to be of the order of 100 m/s or greater for a horizontal break flow predominantly across the nearby tubes. The aerosol retention deposition on a single cylinder has been correlated by Douglas and Ilias [6] as a function of the Stokes number, *Stk*, defined as

$$Stk = \frac{\rho_p d_p^2 U C_s}{18 \mu D}$$

where ρ_p and d_p are the particle density and geometric diameter, U the gas velocity, C_s the slip factor, ρ the viscosity, D the cylinder diameter, and τ is the particle relaxation time.

In order to reproduce the aerosol retention locally, the flow rate should be the same as the full break flow, giving an average bundle axial velocity of 4.1 m/s. However the average velocity in the bundle is simulated better by scaling the flow rate by the rig/plant flow area (1:20.5) to give a velocity of 0.2 m/s. These two contrasting scale ratios have implications for simulating the flow and aerosol retention in the main part of the bundle. In particular the measured retention in the break stage will include a contribution due to impaction at the support plate.

Away from the break the flow spreads out and moves upwards towards the support plates. The flow is then channeled through the small support plate openings that surround the tubes and around which some impaction is expected to take place. Again, this aerosol removal depends on the local Stokes number [7]. The flow beyond the last support plate is mainly in the vertical direction, and some retention by turbulent deposition is expected on U-bends tubes.

The ARTIST model contains one full size separator and one dryer instead of the 12 units in the Beznau plant. Mean velocities between 0.1 m/s and 1 m/s are expected in these upper structures, and some retention due to impaction and interception is foreseen [2].

The incoming gas may be some hundreds of degrees hotter than the bundle structures, in which case thermophoresis is an important removal mechanism. The thermophoretic velocity primarily depends on thermal gradient and is a mild function of particle size [8]. Assuming a maximum temperature difference of 500 °C and a representative distance of 1 cm between the subchannel centerline and tube wall, it is estimated that thermophoretic velocities produce aerosol displacements of the order of 0.3 cm per stage [2], which is comparable with the distance to the tube wall. Thermophoresis is therefore likely to be significant.

Because of the short residence times in the SG secondary side (less than 1 minute), agglomeration and gravity settling are shown to be insignificant [2].

4.2. Wet SG in severe accident conditions

A possible AM measure is to refill the faulted SG in order to re-establish heat removal and to provide a pool where the incoming aerosols can be scrubbed. Data from the POSEIDON experiments [9] conducted in bare pools at PSI indicate that a DF of 10 or more can be obtained even with shallow water depths. In the context of an SGTR, the aerosol retention is expected to be more effective in view of the high velocity of the gas and the dense structures which help disintegrate the incoming jet into a multitude of smaller bubbles with a greater potential for scrubbing.

4.3. Wet SG in design basis accident conditions

The potential transfer of primary liquid in the form of droplets (“primary bypass”) to the environment during an SGTR event constitutes one of the major uncertainties in estimating the radiological release. A European Benchmark exercise [[1]] has shown that for many countries, primary bypass dominates the radiological release. The most severe case of radiological Design Basis Accident (DBA) happens when a break occurs at the top of a steam generator (SG) tube bundle which is uncovered. A two-phase mixture is formed at the break. This break flow mixes with the boiling steam (if any), and the whole two-phase mixture moves upwards towards the droplet separator and dryer sections. An important release of radioactivity occurs if the fine droplets are not retained by the separators and dryers. To simulate droplet retention in the separator and dryer, it is necessary to replicate the range of droplet Stokes number, i.e. the gas velocity and droplet diameters. Estimates for the latter are up 1 m/s and 10-50 μm AMMD respectively.

5. BREAK CONFIGURATION

The ARTIST facility provides for a variety of break configurations. Although the scaling effort has focused on the double-ended guillotine break, evidence from actual SGTR events shows that fish-mouth breaks and narrow cracks are more common. These considerations are be kept in mind for the final test matrix. The flexibility of configuration will make it possible to address particular safety concerns and also investigate the influence of break geometry and location on release. The various choices of break configuration will make it possible to address the effects of symmetry, multiple breaks which may be separate or interacting, etc.

6. SHORT INTRODUCTION TO THE ARTIST CONSORTIUM PROJECT

Since 1998, contacts have been established with more than a dozen organizations in order to build a consortium 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. A preliminary ARTIST test matrix was proposed to potential partners in June 2000. Based on the suggestions and comments received, the test matrix has been modified and the latest version fixed at the beginning of 2001 [[2]]. Seven distinct phases are foreseen within the ARTIST program:

1. Phase I: Aerosol retention in SG tubes under dry conditions. In this phase, in-tube aerosol deposition/resuspension will be studied under high flow conditions. Tube length, bend curvature, and aerosol type, size and concentration will be varied.
2. Phase II: Aerosol retention in the break vicinity under dry conditions. In this phase, aerosol deposition/resuspension at very high velocities will be addressed. The break gas flow rate and break type (fish-month, double-guillotine, vertical) will be varied.
3. Phase III: Aerosol retention in the bundle far from the break, under dry conditions. In this phase, aerosol deposition due to thermophoresis and impaction is studied at velocities, which are relatively small because the flow has evened out across the secondary side flow area. The gas flow rate and the gas-structures temperature differential will be varied.
4. Phase IV: Aerosol retention in the separator and dryer under dry conditions. This phase studies aerosol impaction and interception due to complex 3D flows in the upper components of the SG. The gas flow rate and the gas-structures temperature differential will be varied.
5. Phase V: Aerosol retention in the bundle section under flooded pool conditions. This phase investigates condensation-induced aerosol scrubbing by the SG water pool as well

as inertial impaction upon the structures. The break flow rate, pool submergence, carrier gas steam content and pool subcooling will be varied.

6. 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. Air-liquid nozzles that create droplets with typical diameters have already been tested [0]. In this phase, carrier gas flow rates and droplet sizes will be varied.
7. Phase VII: Integral tests. The seventh set of experiments is in integral nature and is focused on aerosol retention in the whole model steam generator. The conditions of the tests will be determined based on insight gained from the results of the previous phases.

7. INSTRUMENTATION

The main goal of the ARTIST experiments is to characterize aerosol retention in each section of the model SG, by measuring the aerosol concentration and thermal-hydraulic conditions at the inlet and outlet of each section. Supporting data will be provided by grab sampling and by use of representative surfaces. The proposed instrumentation will provide:

- The thermal-hydraulic conditions throughout the facility: carrier gas flow rate and composition, gas and wall temperature profiles, and pressure;
- Information on the flow distribution and typical velocities in the break stage, including jetting on the shroud, the far field and the upper separator and dryer regions;
- The real-time aerosol size distribution at the inlet and outlet of the ARTIST facility, and possible shifting of the distribution;
- The inlet and outlet aerosol concentration of each stage and corresponding DFs;
- Aerosol mass balance in the test section, including deposition fractions in the break stage, the rest of the bundle, and the separator and dryer regions.

State of the art aerosol instrumentation will be used, including: Andersen and low pressure Berner impactors, photometers, an on-line aerosol particle sizer (PCS-2000 from PALAS, Germany) and a droplet size optical analyzer (from Malvern, UK).

8. SUMMARY AND CURRENT STATUS

An experimental facility (ARTIST) to investigate aerosol and droplet in a PWR SG following an SGTR has been designed. The facility is a scaled representation of the FRAMATOME designed SG in the Beznau plant (KKB). The experimental program will provide data to address a range of issues. These include quantifying retention in a dry SG during a severe accident, AM measures to refill the SG, and droplet retention in the SG following a design basis accident. The construction is complete and shakedown tests are in progress.

Planning of the test matrix is in the final stages. A postulated reference severe accident SGTR sequence in KKB has been analyzed and used to define a baseline set of conditions as a starting point for the ARTIST experiments. Based on the analysis, the various aerosol retention mechanisms have been discussed and broadly quantified for the prevailing conditions. Scaling considerations show that different, indeed highly contrasting scale factors apply to capture the different mechanisms that take place in the various regions of the SG; in particular, different scaling principles apply locally near the break and globally. Test conditions have been defined corresponding to the reference case.

The baseline conditions apply to a particular plant and set of accident conditions; however, a range of plant designs and accident conditions can be accommodated by suitably defining the experimental conditions, via analogous scaling arguments.

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