STEAM GENERATOR TUBE RUPTURE SCENARIOS

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CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

ABBERVIATIONS:

AM	Accident management
AMMD	Aerodynamic Mass Median Diameter
BC	Base case
BLPI	Berner Low Pressure Impactor
D	Tube equivalent diameter
DF	Decontamination factor
ECC	Emergency core cooling
ECCS	Emergency core cooling system
EFW	Early feedwater recovery
EOP	Emergency operation procedure
FBG	Fluidized bed generator
FP	Fission product
FW	Feedwater
GSD	Geometric standard deviation
MSGTR	Multiple steam generator tube rupture
MSIV	Main steam isolation valve
NC	Non-condensable
NPP	Nuclear power plant
OPC	Optical Particle Counter
PIV	Particle Image Velocimetry
PORV	Power operated relief valve
PSA	Probabilistic safety assessment
PWR	Pressurized water reactor
RCP	Reactor coolant pump
RCS	Reactor coolant system
Re	Reynolds number
SG	Steam generator
SGCB	Steam generator collector break
SGTR	Steam Generator Tube Rupture
Stk	Stokes number
TEOM	Tapered element oscillating microbalance
WP	Work package
VVER	Russian type pressurized water reactor

SYMBOLS:

$\eta_{ST}(i,k)$	individual efficiency of a single tube for particle size k
N_{bins}	Number of particle bins
N_{tubes}	Number of tubes over which deposition is considered

EXECUTIVE SUMMARY

Steam generator reliability and performance are serious concerns in the operation of pressurized water reactors. The aim of the SGTR project was to provide a database of fission product retention in steam generator tube rupture sequences and models, which could be applied to estimate the effectiveness of different accident management strategies in these kind of accidents. The data have been urgently needed, since there has not been any reliable database available on fission product retention, and since these type of accidents are risk dominant in many PWRs operated in European countries.

In WP1 the important accident scenarios for steam generator tube rupture were determined from existing PSA level 2 analysis, and by performing additional analyses with system level codes. From these results the boundary conditions for the experimental studies were defined. In WP2, scaled-down models of a western PWR type steam generator and a VVER-440 steam generator were used to analyze the retention of fission products in the steam generator tubes and in the secondary side. Small-scale facilities were used to study the local deposition phenomena. The parameters in the experiments enveloped a wide range of predicted conditions for the reference plants. The main boundary conditions considered were dry and wet conditions in the secondary side, number of broken tubes, the break location(s) and dimension(s), the break flow, the simulated fission product concentrations and flooding rate.

It can be concluded that in the primary side highly turbulent flow in the broken tube is expected and existing deposition models predict high DF in these conditions. However, resuspension becomes dominant in these conditions and the experimentally observed DF is only 1.1-1.2 for dry aerosols. Hygroscopic aerosols would increase the DF, but this effect was not measured in the SGTR project. In the secondary side DF is larger than in the primary side, but still rather low at dry conditions and dry aerosol. With the flooded bundle the DF was significant and it varied from 100 to 5000 depending on the water height, mass flow rate and the steam mass fraction. When steam was present, condensation inside the tube caused aerosol deposition on the tube surface and nearly blocked the break. In the separate effect studies it was observed that the aerosol retention at the break stage of a dry steam generator was low and non-uniform. Neither break type nor orientation affected the results significantly, when the gas flow rates exceeded 100 kg/h. In the primary side the effect of flow and aerosol material on deposition and resuspension were measured with radio-tracer techniques on-line. The results are of great value for deposition/resuspension model development. The plant evaluations showed that the accident management measures and the newly developed models influence not only the deposition of fission products, but also the thermal hydraulics, the sequence of events and as a result the fission product behavior.

The SGTR project made an important step forward to resolve uncertainties of physical models, especially in the aerosol deposition and mechanical resuspension in turbulent flows, even though there are still open questions. The way to reach more exact prediction for aerosol retention in the steam generator during a SGTR accident should be looked for in the future.

A. OBJECTIVES AND SCOPE

Steam generator (SG) reliability and performance are serious concerns in the operation of pressurised water reactors. In particular, steam generator tubing is subject to a variety of degradation processes that can lead to tube cracking, wall thinning, and potential leakage or rupture [1]. Over the last decade, a considerable effort has been spent to understand these degradation processes and to improve related preventive and corrective actions as well as operational aspects. However, steam generator tube leakage incidents have proven that such occurrence cannot be completely ruled out. If a steam generator tube ruptures during a severe accident, radionuclides may leak from primary circuit to the secondary side and bypass the containment. According to most probabilistic safety assessment (PSA) studies, a significant fraction of fission products are assumed to flow through an unisolated break in a SG. The assumption is based on an expert elicitation panel, since no experimental data of this phenomenon is available to verify it [2].

The retention of fission products in the steam generator tubes and in the secondary side was poorly understood at the beginning of the project. Most related experimental programs have concentrated on the initial stages of deposition. Much less attention has been paid to situations where the deposition/resuspension/revaporisation are changing as the aerosol deposit layers are getting thicker [3]. The understanding of fission product retention under realistic steam generator conditions are needed in order to design efficient accident management procedures. This is considered very important, since steam generator tube ruptures are included in the risk dominant sequences. Thus, the first objective of the SGTR project was to generate a comprehensive database on fission product retention in a steam generator. The second objective was to verify and develop predictive models to support accident management interventions during SGTR sequences.

The severe accident management procedures are designed to minimise the release from the defected SG. Current accident management actions foresee flooding of the secondary side through the emergency feedwater system and depressurisation of the primary system in an attempt to suppress the release of fission products. These actions may significantly reduce the source term in SGTR of accidents. However, there has been no appropriate database or associated model to estimate it. A further strategic goal of the project was to demonstrate the effectiveness of the accident management interventions in reducing the source term even for severe accidents that lead to a by-pass of the containment. The results of the project are applicable to various pressurised water reactors, including vertical steam generators (western PWRs) and horizontal steam generators (VVERs).

B. WORK PROGRAMME

The project was carried out as parallel studies for vertical and horizontal steam generators. The work was divided in four work packages (WPs). The description of each WP is given below.

B.1 Accident Scenarios and Experimental Boundary Conditions (WP1)

Work within WP1 was focused on determining the most important steam generator tube rupture sequences. Specific accident scenarios were selected and analyzed with the MELCOR code. Experimental matrices for integral studies of vertical and horizontal SGs were determined based on the results of the calculations and the scaling assumptions.

B.2 Experimental Investigations (WP2)

The experiments were divided into integral and separate effect studies. The integral experiments were conducted in scaled-down versions of steam generators representing western PWRs (Beznau - Switzerland and Borssele - The Netherlands NPP) and VVERs (Loviisa - Finland and Dukovany - Czech Republic NPP). The main objective was to develop integral and separate effect databases to assess the capability of the accident management measures, and to develop and verify associated mathematical models. The dry and wet conditions in the secondary side of SG were studied. Other test parameters were the number of broken tubes, the break locations and dimensions, flow rates, aerosol concentrations and the flooding rate.

B.3 Model Development (WP3)

The objective of the WP3 was to develop new physical models capable of predicting the local deposition phenomena in the primary and secondary sides of the SG. The models were needed to quantify the aerosol deposition by turbulence, thermophoresis and diffusiophoresis inside a tube, and by inertial impaction, thermophoresis and diffusiophoresis on the secondary side structures. The databases obtained in WP2 formed a basis of the model development.

B.4 Plant Evaluations (WP4)

The objective of the WP4 was to include the models developed in WP3 into the system level codes, and to see their effect on the aerosol retention in SGTR cases. The most important accident scenarios for the reference PWRs and VVER-440s were analyzed based on the results obtained from the experiments and model development. In addition, effectiveness of different accident management measures was tested.

C. WORK PERFORMED AND RESULTS

In WP1 the most important accident scenarios for steam generator tube rupture cases were determined from existing PSA level 2 analysis, and by performing additional analyses with the system level codes. From these results the boundary conditions for the experimental studies were defined. In WP2 scaled-down models of a western PWR type steam generator and a VVER-440 steam generator were used to analyze the retention of fission products in the steam generator tubes and in the secondary side. Small-scale facilities were used to study the local deposition phenomena. The parameters in the experiments enveloped a wide range of predicted conditions for the reference plants. The main boundary conditions considered were dry and wet conditions in the secondary side, number of broken tubes, the break location(s) and dimension(s), the break flow, the simulant fission product concentrations and flooding rate.

C.1 State of the Art Report

The state of the art in SGTR accidents is described in two reports [4, 5]. The first report describes the most important deposition mechanisms in SGTR cases. It was concluded that

even though the deposition mechanisms acting on SGTR scenarios are known, their magnitude and importance in different SGTR conditions is not understood. Thus, experimental data is needed to justify the relevant deposition mechanisms and their magnitude. The second report gives a general description of SGTR events both within design basis and beyond design basis situations.

C.2 Accident Scenarios and Boundary Conditions (WP1)

C.2.1 Vertical Steam Generators

The most important SGTR scenarios for vertical SG were determined by NRG. The results produced from the MELCOR (by NRG) and SCDAP/RELAP5 analyses performed earlier by PSI were used to define the range of essential boundary conditions shown in Table I.

The most dominant SGTR accident scenario for vertical steam generators was based on information from the Beznau and Borssele PSA's, and on discussions between PSI and NRG. The chosen representative scenario can be described as follows:

- Guillotine break of 1 tube at the tube sheet,
- Automatic isolation of the SG's with the Main Steam Isolation Valves (MSIVs)
- Automatic scram,
- Emergency Core Cooling System (ECCS), High Pressure Injection is available until RWST depletion,
- Reactor Coolant System (RCS) pumps functional until primary side voiding,
- Failed SG safety relief valve is damaged due to water ingression and stays stuck open,
- Opening of the intact SG safety valve ("steam dump") after start of core heatup,
- Recovery phase, restart of feed water to the failed SG after massive core relocation.

The Base Case as calculated here presents a 1 tube guillotine failure case with a consequentially stuck open SRV and the availability of Accumulators, the high pressure ECCS system until the tank is empty and the Reactor Coolant pumps until voiding. Steam dump at the intact SG is performed on basis of start of core heatup. Recovery of Feedwater to the failed SG is assumed after extensive core damage. In this scenario high pressure, high steam temperature and large masses of fission product are produced. The resulting boundary conditions, presented in table I, should be considered as maximal values. To study the effect of a larger break in the SG, a second 'worst case' scenario with the assumption of a 3-tube failure is analyzed. This scenario results in lower primary, but in higher secondary pressures. The flow of steam and aerosols through the break is also higher.

The more prototypical accident scenarios for determination of the experimental boundary conditions are two scenarios with earlier Feedwater recovery. In the FW case the Feedwater is recovered after failure of the top part of the core. In the fourth scenario (EFW) the Feedwater system is recovered after heatup of the top part of the core, which also triggers the performance of the steam dump. The boundary conditions based on these two scenarios are also presented in table I.

C.2.2 Horizontal Steam Generators

According to the PSA Level 2 study performed for the Loviisa NPP, the steam generator tube rupture (SGTR) and the collector break (SGCB) leading to a severe accident contribute a significant fraction of the core damage frequency within bypass sequences. The SGCB category includes also multiple tube ruptures (MSGTR). MELCOR calculations were performed on these types of scenarios to define the boundary conditions for the HORIZON experiments. The calculations included SGTR and SGCB sequences for Loviisa as the reference plant, and Dukovany as another VVER-440 plant with very similar nuclear steam supply and turbine systems.

The SGCB scenarios for Loviisa were calculated earlier by VTT, and those for Dukovany and all SGTR scenarios for both plants by NRI using MELCOR 1.8.3. For Dukovany, the differences in pressurizer and secondary system valves design, settings, and operating procedures compared to the Loviisa plant were taken into account.

Based on agreement between NRI and Fortum, the following base case scenario was defined:

- Double ended break of 1 tube at the hot primary collector, the uppermost tube of the sheet
- Primary makeup recovering the water loss for about 5 minutes, then stopped
- Automatic SCRAM, turbine shutdown and ECC start signal
- ECC high pressure injection does not work and RCP stops
- Operator isolates the SG's with the MSIV's 10 minutes after SCRAM
- Measures to control the primary-to-secondary leakage sequence fail
- The SG safety valve stucks open after the first opening
- The feed water is permanently stopped to the failed SG
- The water level in the five intact SGs is kept constant
- Depressurisation of primary system with PORV's when core exit temperature reaches 450 °C
- No feed water recovery to the failed SG.

Other scenarios similar to the base case have also been analyzed. The break location, size and accident management procedures have been varied. The overview and the range of the boundary conditions have been obtained based on these analyses and are shown in Table II. The successful isolation of the failed SG on the steam side was assumed in other cases except in scenario LO5.

Some general conclusion can also be made from the analyses. SGTR scenarios assume primary system depressurisation at the core damage, which is included in accident management procedures both at Loviisa and Dukovany. A hypothetical case, LO1A, was calculated in order to verify the effect of depressurisation. By comparing the cases LO1A and LO1 it can be seen that the amount of aerosols is reduced by a factor of about 20. In addition, it can be concluded that the primary collector rupture has very different characteristcs than either simple or multiple (up to 5 tubes) tube ruptures.

C.3 Experimental Investigations (WP2)

C.3.1 Separate Effect Studies of Vertical Steam Generators

The separate effect studies of vertical steam generators have been conducted in the CIEMAT PECA facility, which was properly modified and conditioned for that purpose. The PECA facility set-up used in the SGTR separate effect tests basically consists of [6]:

1. Two injection lines, one designed for supplying air at relatively high flow rates from a compressor, and the other for the aerosol injection.
2. The vessel, containing the tube mini-bundle.
3. The associated instrumentation and sampling stations.

There was one sampling at the injection line for the Optical Particle Counter (OPC) aimed at determining the aerosol size distribution and quantifying the mass concentration at the inlet. Within the vessel atmosphere eight samplings were taken to six filters and two cascade impactors, from which the mass concentration exiting the tube mini-bundle was estimated. Figure 1 shows a scheme of PECA.

The test mini-bundle is a scaled mock-up of the first stage of the steam generator tube bundle. It is specifically designed by PSI for the separate effect test studies performed in PECA facility. It consists of a squared arrangement housing inside a total of 117 tubes plus four supporting rods placed in the corners. The mini-bundle allows two possible locations of the broken tube. One place is just at the center of the structure and the other place is three tubes away from the center. Figure 2 gives a picture of the mini-bundle.

The design of the experimental matrix came from the analysis of the prototypical boundary conditions estimated with MELCOR and SCDAP/RELAP5 codes, the experimental matrix for ARTIST and the PECA capacities and limitations [6, 7]. The boundary conditions were room temperature and inlet pressure of 2.8 bar. The carrier gas was air and the aerosol product used was prefabricated TiO_2 particles. The experimental matrix covered two types of break, guillotine and fish-mouth, two possible location of the break (central and periphery), two possible break orientations (facing tube and facing diagonal), and three different inlet gas flow rates (75, 150 and 250 kg/h). Within the fish-mouth break type, two different broken area have been covered: fish-mouth 1D and fish-mouth 0.5D, where D denotes the tube equivalent diameter. The experimental matrix is shown in Table III.

In all tests the inlet aerosol size distribution and the inlet aerosol mass concentration were measured with the OPC. The outlet aerosol size distribution was measured with a cascade impactor. The outlet mass concentration was derived from six filter and impactor samplings from the vessel. From these measurements inlet and outlet aerosol masses were estimated. The mass deposited on several selected tubes was collected and extrapolated to estimate the total aerosol mass in the mini-bundle.

The inlet aerosol size distributions had an AMMD around 6 μm in most tests. The values of AMMD were in the range of 3 μm at the outlet. Inlet and outlet size distributions showed evidences of particle fragmentation as well as agglomeration that could take place inside the bundle (Figure 3).

The main result of the separate effect studies was a rather low global retention in the mini-bundle within the range of boundary conditions tested, being below 20% in all the

experiments [8]. The deposition of aerosols on the tubes was not uniform along the mini-bundle. The nearest tubes to the break showed important deposits forming crusts while the outer tubes showed a thin layer of aerosols.

Concerning the break type the retention results showed qualitative differences (Figure 4) In the case of guillotine break, the pattern showed a square symmetry. The tubes up to third neighbours collected almost the 70 % of the mass retained by the mini-bundle. In the fish-mouth tests the deposition patterns had a triangular shape, where the tubes located far from the break point had a low individual deposition. However, these far tubes taken together represented up to 40% of the total retention in the mini-bundle. On the other hand, quantitative differences between guillotine and fish-mouth retention was found only for the lowest inlet gas flow rate.

Concerning the influence of the inlet gas flow rate, important differences among the tests were found only at the lowest flow rate (75 kg/h). At 75 kg/h the retention was higher except for the case of guillotine break, where no clear trend of the retention versus flow rate could be established (Figure 5).

In addition to the aerosol deposition tests, some experiments were performed in order to measure the particle velocities at the break exit using Particle Image Velocimetry (PIV) technique. Guillotine and fish-mouth 1D break configurations have been used for these tests. However, due to uncertainties no quantitative data can be drawn from these studies. The measurement uncertainties resulted mostly from the light reflections from the metallic tube surfaces, which affected the image contrast.

C.3.2 Integral Experiments of Vertical Steam Generators

The integral tests of vertical steam generators were conducted in a representative scaled-down model of the Beznau reference PWR steam generator, called ARTIST facility operated by PSI. The facility consists of a bundle, shroud, flooding system and aerosol sampling stations (Figure 6). Only the bundle section of ARTIST (including a break stage, two far-field stages and a U-bend section) was used in this project (Figure 7).

The ARTIST test section was directly connected to the DRAGON aerosol generation facility. The aerosol mixture was transported to the ARTIST test section by carrier gas composed of steam and non-condensable gas (N_2) in desired proportions. Aerosols were produced via Fluidized Bed aerosol Generators (FBG) in conjunction with a venturi injection system. In this program, prefabricated TiO_2 powder was used with a primary particle size of 0.035 μm (AMMD).

A sophisticated aerosol measurement system was attached at the inlet and outlet piping to characterize the aerosol particle size and concentration as well as the gas flow rates, the gas pressure and gas/water temperature. The aerosol characterization was performed using state-of-the-art instruments. Two photometers provided relative aerosol concentration in real-time at the inlet and outlet. The size distributions were measured with Berner Low-Pressure (BLPI) and Andersen impactors, and the integral concentration measurements were performed with membrane filters.

The actual conditions for the experiments tests were derived from the RELAP5/SCDAP calculations [9] and from report D010 [10], while keeping in mind the practical limits imposed by ARTIST facility. Five tests comprised the PSI EU-SGTR experiments. The first three tests dealt with the aerosol retention in the break stage under dry (A01 and A05) and wet (A02) conditions. Test A05 was a repetition of the test A01. The other two tests addressed accident management (AM) issues whereby the SG bundle goes from a fully dry state to a fully flooded state. Test (A03) was performed with a non-condensable (NC) rich carrier gas, while test (A04) was performed with a steam rich mixture. The test matrix is shown in Table IV. An axis-symmetric guillotine break was used and located 300 mm above the tube sheet in the middle of the bundle. The aerosol AMMD's at the inlet were 2.25-3.70 μm, while at the outlet, the AMMD's were in the range of 0.49-0.84 μm.

The following conclusions can be drawn from the investigations of integral effects in a vertical SG bundle (Table V):

- When the bundle is dry, and the full break flow directed into the bundle (test A05), the DF is typically small, i.e. between 2.5 and 3. There is strong evidence that the aerosols (at least the type used) disintegrate into smaller particles because of the sonic conditions at the break. This obviously promotes particle escape from the secondary and lowers the overall DF. Further investigation needs to be performed to determine the influence of the type of aerosol.

- With the dry bundle, and a small flow reproducing the far-field velocities (test A03), the DF is of the order of 5, implying better decontamination than with the full flow. This can be explained by the somewhat lower particle disintegration than witnessed with the larger flow. The far-field retention implies a DF of the order of 1.9 per stage, which, for SG with 9 or more stages, can translate in overall DF's of several hundreds when the break is located near the tubesheet region.

- With a bundle flooded just above the break and a steam/noncondensable mixture (test A02), the DF is between 45 and 112 for the full flow and 482 for the small flow (typical of far-field). This implies again that the far field stages are more efficient at trapping aerosols than the break stage.

- For the far-field conditions, under a flooded bundle and in presence of steam (test A04), the DF is roughly of the same order regardless of the water height, i.e. in the range from 482 to 1081. A large fraction of the aerosols is scrubbed at the break level because of strong diffusiophoresis and impaction of the incoming jet on the water interface. The additional water head beyond the break stage has only a secondary influence on the magnitude of decontamination.

- For the far-field conditions, under a flooded bundle and in absence of steam (test A03), the DF increases exponentially from 124 to 5739 when the water height in the bundle increases from 1.30 m to 3.6 m. The aerosol removal rate is roughly constant with height, and hence the DF is solely a function of residence time in the water pool (water height).

- When steam is present in the carrier gas under flooded secondary (test A02 and A04), condensation inside the tube causes aerosol deposition and produces blockage near the break, with a subsequent primary pressure rise. This has implications for real plant conditions, as aerosol deposits inside the broken tube will cause more flow to be diverted to the intact tubes, with a corresponding reduction in the source term to the secondary.

C.3.3 Separate Effect Studies of Horizontal Steam Generators

The separate effect experiments of horizontal steam generators were conducted in PSAERO facility. The separate effect experiments were designed to complement the integral experiments conducted with the HORIZON facility. The objective of the experiments was to gain mechanistic understanding about aerosol behaviour in the steam generator tubes.

In PSAERO facility the aerosol behaviour was studied in a straight 3-m long stainless steel tube (Figure 8). The inner diameter of the tube was 13 mm and the length of the measured section was 2 meters. Aerosol deposition and the movement of the deposited material was determined by activating the aerosol in a nuclear reactor and applying sequentially placed scintillation detectors in online measurements. The final deposition profile was obtained after the experiment by scanning the facility with a similar gamma detector. When inactive aerosol was used in an experiment, the deposition was determined by sampling with quartz fibre filters from the inlet and outlet of the steam generator tube.

In the experiments polydisperse copper aerosol was produced from prefabricated powder using TOPAS SAG 410 dry powder aerosol generator. In some experiments copper aerosol was coated with either dry or liquid NaOH. The particle morphology was studied with a scanning electron microscope (SEM). The particles were observed to be separate, nearly spherical and dense. The particle size distribution was determined with Berner low-pressure impactors (BLPI). The aerosol mass size distribution was bimodal and it could be presented as a sum of two lognormal distributions (Figure 9). The smaller peak, with aerodynamic mass median diameter (AMMD) of 0.66 μm and logarithm of the geometric standard deviation ($\ln\sigma_g$) of 0.65, contained 17% of the aerosol mass. The AMMD of the larger peak was 8.31 μm and $\ln\sigma_g$ was 0.88. Aerosol mass size distribution did not change during the experiments.

The test matrix for the resuspension experiments is presented in Table VI. In PSAERO experiments the aerosol was always deposited with a constant gas flow rate. In the first two experiments, deposition and resuspension phenomena were studied using a high flow rate. From experiment three on, the flow rate during the deposition phase was low. After the deposition phase the gas flow rate was increased stepwise and the deposition profile in the tube was measured online using radioactive tracer. The effect of material properties on the deposition-resuspension phenomena was studied by changing the aerosol generation in experiment five and by changing gas composition in experiment six.

As a result, the mass of particles in the tube was obtained as a function of time and location. From that information the resuspension into a pure gas flow could be calculated. Both spatial and time resolutions of the developed online technique were much better than expected. Three distinctly different resuspension processes were found in the experiments:

- Very little aerosol deposited in experiments conducted with constant high flow rate, because the deposited particles were immediately resuspended from the surface. The resuspension could thus be observed only from the effective deposition velocity.
- In experiments three, four and six the deposition velocity was much higher, because the flow rate during the deposition phase was substantially decreased. In these experiments, resuspension took place practically only, when the flow was accelerated.
- Lastly, significant resuspension took place in experiment five even during a constant low flow rate. The reason for the different resuspension behaviour was that the surface properties of the particles were modified. Only in the fifth experiment, resuspension was a time dependent process.

Since the resuspension processes are inherently different, each of them would need to be separately modelled. Such models should also be coupled with a turbulent deposition model.

The flow rate during the deposition phase had a very significant impact on the strength particles adhered to the surface. As evident in (Figure 10), particles deposited in a higher flow rate were much harder to resuspend than was the case with a lower flow rate**.** In order to quantify this effect, experiments were compared using normalised friction velocity. Normalisation was done to the value of friction velocity during the deposition phase. As can be seen in (Figure 11), results from experiment 4 could be predicted with a function fitted to experiment 3 by applying normalised friction velocity.

According to deposition models the most important deposition mechanisms were turbulent impaction and settling. The largest particles should have deposited by turbulent impaction near the inlet of the tube. However, the calculated deposition profile was much steeper than the one observed in the experiments. The probable reason for the discrepancy was that the impaction of large particles must have caused erosion. A significant fraction of the already deposited particles were knocked of from the surface and subsequently deposited further downstream. The impaction of particles likely also packed the deposit near the inlet. Therefore, the resuspension was first observed close to the outlet of the tube, where the deposit was mainly formed by settling.

Results from these experiments were very well comparable to previous studies on resuspension conducted with polydisperse aerosol [11]. However, experiments with monodisperse aerosol without an exception result in a much higher resuspension. It is likely, that the adherence of polydisperse aerosol is much better, because particles in the deposit layer have more contacts to other particles than is the case with monodisperse aerosol. A major problem in resuspension modelling is that the effect of particle size distribution is not taken into account. However, the diameter of a particle is customarily a very important parameter. Parameters derived from experiments, conducted with monodisperse particles, should be used with caution in models describing the behaviour of polydisperse aerosol.

C.3.4 Integral Studies of Horizontal Steam Generators

The integral experiments of the horizontal steam generator were carried out in HORIZON facility (Figure 12). The aerosol deposition on to steam generator tubes depends on the break type and location. The experiments carried out in the HORIZON facility are shown in Table VII. Eight of the experiments are considered as aerosol experiments. These

experiments have a suffix "-A" after the experiment number. Thermal hydraulic experiments were used for testing of the aerosol experiments, and these have a suffix of numbers in increasing order starting from 1.

Aerosols used in the experiments were generated by vaporizing CsI in the vertical high temperature flow reactor. A steam flow through the reactor was used to carry the aerosol material from the reactor. After the furnace aerosol flow was mixed with the superheated main steam flow.

The fraction of deposited amount of aerosols in tubes was analyzed by Tapered Element Oscillating Microbalance (TEOM) and filters during the experiments and by chemical analysis after the experiments. In addition, some simple calculations based on thermal-hydraulic results on aerosol AMMD were carried out. These results are summarized in Table VIII. The table also shows the measured AMMD and GSD values in the experiments.

From the experimental results achieved with the HORIZON facility, it appears that the deposition models at lower Reynolds numbers (Re) are adequate for modeling the deposition within the horizontal steam generator tubes. At higher Re, turbulent impaction is dominant deposition mechanism. The deposition models predict very high deposition velocities, but the experimental results do not support the idea of plain deposition. Instead, the effect of resuspension should be taken into account, as well. Furthermore, the effect of diffusiophoresis in cases with flooded secondary side may become important, but it is not evident that the flooding would decrease the amount of aerosol flowing from the primary to secondary side significantly.

C.4 Model Development

C.4.1 Aerosol Deposition Model for the Primary Side of the Steam Generator

In this task a submodel for aerosol deposition in the primary side of steam generator tubes was developed. At first, most important deposition mechanisms in SGTR conditions were reviewed. The cases considered were (a) broken tube with highly turbulent flow; (b) unbroken tubes with low turbulent flow and (c) unbroken tubes in collector break case with laminar flow. In these cases at dry conditions the most important deposition mechanisms are (1) turbulent impaction; (2) thermophoresis and (3) gravitational settling. The most appropriate models for these mechanisms were searched based on literature data and implemented in a computer code AERORESUSLOG [12].

The code AERORESUSLOG is a one-dimensional steady-state model to estimate aerosol particle deposition and possible resuspension for horizontal tube flow. The flow field of steam and/or air is calculated using correlations for heat and mass transfer. The mass concentration of the aerosol entering the tube is a lognormal mass-size distribution divided into different size classes (bins). Particle deposition due to thermophoresis, turbulent impaction and gravitational settling is calculated in each size bin. Thereafter the resuspension fraction of deposited particle mass is estimated and the mass concentration for each size bin is corrected with the net deposition.

The deposition mechanisms are fairly well understood and validated with experimental data. However, in turbulent flow resuspension becomes important and this phenomena is not

well known. Resuspension is a mechanism of detachment of aerosol particles from a surface and its transport away from that surface. In contrary to deposition, mechanisms responsible for resuspension are less understood and more difficult to predict. Currently there are some models trying to predict resuspension but fail to do so under more general conditions. The quasi-static *rock 'n' roll model* by Reeks and Hall [13] was in reasonable good agreement with different experiments [14]. In this model it is assumed that the distribution of asperity contacts of particles and surface is reduced to a two-dimensional model of two-point asperity contact (Figure 13). When exposed to a turbulent flow the particle, rather than oscillating vertically, oscillates about a pivot, P, until contact with the other asperity, Q, is broken. When this happens it is assumed that the lift force is either sufficient to break the contact at P and the particle resuspends or it rolls until the adhesion at a single-point contact is sufficiently low for the particle to resuspend. This model was implemented in AERORESUSLOG to describe resuspension in SGTR conditions.

HORIZON experiments were calculated with the AERORESUSLOG code. In experiment simulating the case of intact tubes (c) settling is the dominant deposition mechanism because of long residence time (Re=940) and in case of unbroken tubes in SGTR (b) (Re=3800) thermophoresis becomes dominant. No resuspension is expected in these cases due to low or intermediate Reynolds numbers. Calculated results agree well with the measured values and thus we can conclude that for the low and intermediate conditions, where resuspension is not expected, the deposition models currently used in most severe accident codes are valid.

In cases simulating the broken tubes (a) due to high Reynolds number (Re=70,000-140,000) resuspension becomes dominant. When the results of the resuspension model implemented in AERORESUSLOG were compared with experimental results from HORIZON and PSAERO it became evident that the results are inconsistent. This is understandable because the model does not include a description of several important parameters affecting resuspension as the dependense of adhesion on deposit physico-chemical properties, polydisperse particle size distribution, system geometry etc. Thus, a better model is needed to describe resuspension in SGTR conditions.

C.4.2 Aerosol Deposition Model for the Secondary Side of the Steam Generator

The specific objective of this task was to develop a model capable of estimating particle deposition in the secondary side of a steam generator under anticipated conditions of SGTR sequences. The model scope was focused on what is called hereafter “near field deposition” under dry conditions. Namely, particle removal onto closer surfaces to tube breach location (i.e., the nearest tubes within the same SG stage), when no water is present in the secondary side. Thus, structures other than SG tubes are not considered.

The model is based on the “filter concept”, that is an aerosol flowing through a bundle of obstacles is submitted to forces that tend to clean up the gas by removing particles onto obstacle surfaces. Two major hypotheses lie under this approach:

- Gas is seen as a viscous fluid flowing transverse to tubes
- Filtration is considered uniform at any plane perpendicular to incoming gas flow direction.

By setting basic filtration equations and taking some approximations and dimensions of a prototypical steam generator a final equation to estimate tube bundle efficiency was derived:

$$\eta_{TB} = 1 - \boldsymbol{exp}\left\{-\frac{3}{2}\cdot\left[1+(-1)^{Ntubes+1}\cdot\prod_{i}^{Ntubes}\left(\sum_{k}^{Nbins} y(k)\cdot\eta_{ST}(i,k)-1\right)\right]\right\} \qquad \text{(eq.)}$$

where *Ntubes* is the number of tubes over which deposition is considered (i.e., filtration depth) and $\eta_{ST}(i,k)$ is the individual efficiency of a single tube for particles of size k (*Nbins* is the number of particle bins). Under foreseen SGTR conditions, the major depletion mechanisms removing particles were turbulent deposition and inertial impaction. The former domain extends over a Stokes number (Stk) ranging from 0 up to 0.1. From this upper bound to higher Stokes numbers, inertial impaction becomes dominant.

A data base to develop individual models for eddy deposition and impaction was set up based on open literature [15, 16, 17]. Nonetheless, none of databases gathered resemble closely conditions anticipated in SGTR sequences. More than a hundred of experimental measurements were compiled and from them two expressions were derived:

$$\eta_{ST}^{tbt} = 4.38\ 10^{-2} + 7.13\ 10^{-2}\ \boldsymbol{ln}(Stk) \qquad \text{(eq.)}$$

$$\eta_{ST}^{imp} = \frac{0.75}{1+29.31\cdot\boldsymbol{exp}(-3.85\cdot Stk^{0.5})} \qquad \text{(eq.)}$$

Worth to mention that Stokes number in the above expressions is calculated by accounting for drag forces other than the Stokes one to give this formulation a general nature.

All those equations were encapsulated into a highly modular FORTRAN-90 code, called ARISG-I (Aerosol Retention In Steam Generators), structured such as shown in the flowchart (Figure 14). As noted in the flowchart one of the key variables in the assessment of filter efficiency of the tube bundle is the gas velocity. There is not a simple way to model velocity evolution across tube bundle and a very simplified approach based on mass and momentum conservation has been adopted. It is gas velocity along with particle size distribution the major variables needed in the ARISG-I input deck.

Unfortunately no quantitative data on inlet gas velocity could be taken with a reasonable accuracy in WP2, so that ARISG-I validation was not feasible. Instead, a qualitative assessment was carried out by defining a base case scenario and by running a set of calculations to confirm consistency of observations. In order to illustrate this exercise the results obtained for particle size distribution and gas velocity are summarised in Figure 15 and Figure 16. The base case assumed a gas velocity of 100 m/s and an AMMD around 1 μm (GSD=1.5). The parametric case on size distribution moved towards bigger particles (AMMD=6.82 μm; GSD=1.5).

As can be noted, the results are expressed in terms of a normalized efficiency (i.e., maximum efficiency is set to be 100%). In the case of the size distribution of smaller particles,

the contribution of each tube to total efficiency would decrease with depth in the bundle. In the case of the size distribution of bigger particles, the trend disruption from second to third tube shows the transition from an inertial to a turbulent deposition regime in some particle bins. This emphasizes the importance of considering turbulent deposition to deal with small particles.

In Figure 16 gas velocity ranged from 1 m/s to 750 m/s, thus covering the anticipated range in the SGTR sequences. As expected, the higher velocity the greater bundle collection efficiency.

In summary, ARISG-I model is an approximate single-D approach that provides a way to assess particle retention in the secondary side of a dry steam generator during a SGTR sequence. Nonetheless, it should be considered just a first step forward in the modeling. Major contributions to further develop the model would involve investigations on "in-bundle" gas velocity, individual mechanisms responsible for aerosol deposition under representative conditions, deposited particle removal from surfaces, etc. In addition, an extensive validation exercise should be carried out when data will be made available.

C.5 Plant Evaluations

C.5.1 Plant Evaluations of the Vertical Steam Generator

Based on the performed calculations within WP1 and the experience from the SGTR project, new calculations within WP4 were performed for the vertical type SG. The purpose of these MELCOR calculations was to determine the effect of the newly developed FP retention models on the calculated fission product releases to the environment and the impact of accident management measures.

The calculations show that the accident management measures and the newly developed models influence not only the deposition of fission products, but also the thermal hydraulics, the sequence of the events and (as a result) the fission product behavior.

With respect to accident management measures the calculations show also that an early injection of feedwater to the broken SG, a high feedwater flow rate and a high level in the broken SG decrease the release to the environment.

Furthermore the calculations show that it is possible to implement the newly developed fission product models in the MELCOR model and to calculate additional deposition of fission products on the primary side and secondary side of the broken steam generator using the newly developed models.

C.5.2. Plant Evaluations of the Horizontal Steam Generator

The first task within WP4 for the horizontal type SG was to make a more detailed evaluation of the analyses in WP1 described in [18] and conclusions for them concerning the accident management. For single tube rupture, the primary system depressurization was found to be a very effective accident management procedure. The mitigation of the release of radioactivity from the broken tube in a case of a single tube rupture was about 20 times higher than would be without depressurization (Table II). Primary depressurization is also effective (though slightly less than in a single tube break) for five tubes break. However, it cannot be

used for the collector break, because the primary system is already at low pressure. The primary depressurization is already a standard accident management procedure in Loviisa NPP. It has also been introduced for Dukovany NPP as a final EOP (severe accident management, in which it is also included, is being developed at present for this plant).

An important accident mitigation factor that takes place even if no accident management is taken into account, is the aerosol deposition on the secondary side far field tubes and SG shell. This phenomenon was confirmed for vertical type SG in the ARTIST experiment [19], and it was included in the plant calculations for horizontal SG [18]. All these conclusions are also shortly mentioned in Ref. [20].

The second task was to study the emergency flooding of the secondary side of the failed SG at the onset of core damage as an accident management procedure. It was studied on the LO1 and LOM2 cases (Table II) for the Loviisa NPP, i.e. single and five tube ruptures, and on the DUC2 collector break scenario for the Dukovany NPP (Table II). Due to late initiation of the flooding, propagation of core damage was expected. However, the core damage was prevented in all cases and a stabilized state was reached. For the collector break though the core temperature raised to about 1100K. The results of this study are described in the report [21].

The third task was to include the models developed in WP2 and WP3 for the assessment of aerosol retention in the broken tube and near the break on the secondary side. A two-tier strategy was applied. The results of the plant calculation obtained in the first stage with MELCOR 1.8.3 were used in the detailed model of the broken tube in the second phase [20]. The second stage included two steps: a detailed thermal-hydraulic calculation of the broken tube with MELCOR 1.8.5, and the aerosol deposition calculation with the modified AERORESUSLOG program developed by VTT. The application of this method to the plant calculation showed only small retention in the primary tubes and a little higher deposition on the near field bundle secondary side, where the DF was close to 1.6 [20]. The main reason of small retention on the primary side of SG tubes was aerosol resuspension.

CONCLUSION

Steam generator reliability and performance are serious concerns in the operation of pressurized water reactors. The aim of the SGTR project was to provide a database of fission product retention in steam generator tube rupture sequences and models, which could be applied to estimate the effectiveness of different accident management strategies in these kind of accidents. The data have been urgently needed, since there has not been any reliable database available on fission product retention, and since these type of accidents are risk dominant in many PWRs operated in European countries.

The specific accident scenarios were selected and analyzed for both PWR and VVER-440 steam generators with the MELCOR code. Based on the analyzed results, the prototypical boundary conditions for the experiments were determined. The experimental matrices for integral and separate effect studies were defined based on these results while keeping in mind the practical limits of the test facilities.

The integral experiments of vertical steam generators were conducted in a scaled-down model of the reference steam generator called ARTIST facility. The decontamination factor of different scenarios, dry and wet, was obtained. It was observed that the DF was low for TiO_2 aerosols, when the bundle was dry. With the flooded bundle the DF was significant and it varied from 100 to 5000 depending on the water height, mass flow rate and the steam mass fraction. When the steam was present, the condensation inside the tube caused aerosol deposition inside the tube and nearly blocked the break.

The separate effect studies of vertical steam generators were conducted in the PECA facility. The experiments complemented and extended the information obtained from the large scale-tests done with the ARTIST facility. It was observed that the aerosol retention at the break stage of a dry steam generator was low and non-uniform. The type and the orientation of the break did not result in quantitative differences in the mass removed from the aerosol source coming to the secondary side of the vertical steam generator under the conditions investigated, when the gas flowrate was above a certain threshold (100 kg/h). However, the deposition patterns of a guillotine and fish-mouth break were remarkably different. In addition, an attempt to measure gas injection velocity at the break exit by PIV was made, but there are still large uncertainties of the actual velocity.

The model, ARISG-I, capable of estimating the aerosol retention in the secondary side of a dry steam generator was developed. The model is based on the filter concept, and is focused on “near filed deposition”. Although a great progress has been made, it should be considered as a first step forward in modeling such scenarios. More experimental data would be needed to further improve and validate the model.

The integral experiments of horizontal steam generator were conducted in the HORIZON facility. The experimental results showed that the deposition models are adequate at low Re for modeling the deposition within horizontal tubes. At high Re the models predict high deposition velocities. However, the experiments do not support the idea of plain deposition at high Re, and the resuspension should be taken into account as well.

The separate effect experiments of horizontal steam generators were conducted in the PSAERO facility. Mechanistic understanding of aerosol behaviour in a steam generator tube was obtained by measuring the deposition profile online with a radioactive tracer method. Three distinctly different resuspension processes were observed to take place in the experiments. These were: immediate resuspension into a high gas flow, resuspension due to flow acceleration and time dependent resuspension during a relatively low gas flow rate. When results from these experiments were compared to previous studies, it was noted that polydisperse aerosol adheres to the surface much better than monodisperse aerosol. Also aerosol material and flow rate during the deposition phase both had a very significant impact on the adherence. The effect of flow rate could be modelled by using a new concept of normalised friction velocity as a parameter. However, there is still a need to develop a general resuspension model for SGTR conditions.

The plant evaluations using the newly developed fission product retention models described here, serves in a combination with the plant calculation for rough estimation of the effect of aerosol deposition on the primary side and the near-field tube bundle secondary side

during a severe accident with horizontal SG tube rupture. The plant evaluations showed that the accident management measures and the newly developed models influence not only the deposition of fission products, but also the thermal hydraulics, the sequence of events and as a result the fission product behavior.

The SGTR project made an important step forward to resolve uncertainties of physical models, especially in the aerosol mechanical resuspension, even though there are still open questions. The way to reach more exact prediction of the effect aerosol retention in the steam generator during a SGTR accident should be looked for in the future.

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Table I. Range of boundary conditions obtained for SGTR sequences of vertical SGs.

SGTR scenario	Timing of interest [1000 s]	Pressure [bar]		Steam temp [K]		Flow through SG breaks [g/s]		SG Water level
		Prim.	Sec.	Prim.	Sec.	Steam	Aerosols	
Base case (BC)	178 – 188	30	3.1	500	500	1300	1.18	0
3-tubes failure (3T)	89 – 100	18	5.0	475	475	2000	5.16	0
Feedwater recovery (FW)	178 – 180	8	1.1	450	450	600	0.67	0
Early FW recovery (EFW)	139 – 143	33	3.3	500	500	1500	0.05	0

Table II. Range of boundary conditions obtained for SGTR and SGCB sequences of horizontal SGs.

SGTR Scenario		Average Pressure [bar]		Average Steam Temperature [K]		Average flow through break [g/s][1]		
#	Description[2]	Prim.	Sec.	Prim.[3]	Sec.	Steam	Aeros.	CsI
LO1	Loviisa SGTR Stuck-open SG relief valve	2-8	1.5	473-573	473	150	0.06	0.006
LO1A	Like LO1, no primary depressurization	50-95	2	673-1073	573-873	2000	1	0.1
LO2	Like LO1, break location cold collector	2-8	1.5	453-523	473	150	0.03	0.003
LO3	Like LO1, break loc. other loop	2-8	1.5	473-573	473	200	0.04	0.004
LO5	Main steam isolation and feedwater failure	2-10	1.2	473-623	473	200	0.04	0.004
LOM1	Loviisa MSGTR Like LO1, 2 tubes	2-10	1.5	453-623	453	250	0.2	0.02
LOM2	Like LO1, 5 tubes	1.5-9	1.5	473-673	453	150	0.7	0.07
DUC1	Dukovany SGCB Stuck open relief valve to atmosphere	2-4	2-3	473-673	453	1000-4500	6	0.9
DUC2	Stuck open SG relief valve	2-7	2-6	473-773	473	1000-4000	7	0.6

[1] From the onset of core damage. The average flow is given, in reality, the flow of gases and aerosols varies by about a factor of 10. It is much higher at the start of fission product release.
[2] SG primary and secondary side water level zero or negligible for all scenarios.
[3] In the hot collector, cold collector for LO2.

Table III. Test matrix for the separate effect experiments of vertical steam generators.

Test	**Break Type**		**Break location**		**Break orientation**		**Gas flow rate (kg/h)**			
Test	Fish	Guillotine	Central	Periphery	Facing tube	Facing diagonal		75	150	250
1	X(a)				X					X
2	X(a)				X		(d)			
3	X(b)				X				X	
4	X(b)				X					X
5	OPEN TEST (c)									
6	X(b)				X			X		
7	X(b)			X		X		X		
8	X(b)			X		X			X	
9	X(b)			X		X				X
10		X	X		X			X		
11		X	X		X				X	
12		X	X		X					X

a) 0.5 D Fish mouth
b) 1.0 D Fish mouth
c) Open test (Repetition of the test 2)
d) Reduce flow rate to a value at which flow velocity is equal to that of Test # 4

Table IV. Experimental matrix for the integral tests of vertical steam generators

Test	**Prim. side**		**Sec. side**		**Gas flow rate [kg/h]**	**NC mass fraction [%]**	**Sec. side**		**Aerosol size range (AMMD) [µm]**
	Press. [bar]	Temp. [ºC]	Press. [bar]	Temp. [ºC]			Water height [m]	Water temp. [ºC]	
A05, A01[1] (Dry)	4.6	23	1.0	23	650	100	N/A	N/A	1-3
A02 (Wet)	4.0	145	1.1	90-95	340	30	1.3	90-95	1-3
A03 (Dry-Wet AM NC rich)	1.2-1.6	20-40	1.0	20-40	110	100	0-3.8	20-40	1-3
A04 (Dry-Wet AM steam rich)	1.2-1.5	170	1.1	90-160[2]	63	23	0-3.8	90-95	1-3

[1] Aerosol measurement devices partly failed.
[2] At dry starting conditions.

Table V. Results of tests conducted in the ARTIST facility.

	Type	Test	AMMD µm		Water level above tube sheet m	DF	Phenomena			
			Inlet	Outlet			Disintegration	Impaction	Diffusiphoresis	Rise zone inertial removal
Break stage	Dry	A05	2.25	0.72	0	2.5-2.9	X	X		
	Wet	A02	3.14	0.84	1.30	45.7-112	X	X	X	
Far-field	AM-NC rich	A03	3.70	N/A	0	4.9		X		
					1.20	124		X		X
					2.30	1251		X		X
					3.60	5739		X		X
	AM-Steam rich	A04	2.92	0.49	0	4.6		X		
					1.33	482		X	X	X
					2.55	1081		X	X	X
					3.80	514		X	X	X

Table VI. The test matrix for the separate effect studies of horizontal steam generators.

Exp.	Dep. Flow rate [l/min]	Resusp. Flow rate [l/min]	Inlet *Re*	Gas inlet temp. [°C]	Gas	Aerosol material	Conc. [g/m^3]
1.	200	200	15500	218	N_2	Cu	7.1
2.	100	100	7700	224	N_2	Cu	5.6
3.	38.6	40 50 60 70 80 90 100	4680 5850 7030 8190 9350 10500 11700	22	N_2	Cu	10.4
4.	55.6	60 70 80	6980 8150 9310	22	N_2	Cu	6.7
5.	60	60 70 80	4490 5230 5980	252	N_2	Cu+NaOH	4.1
6.	60	60 70 80 90	4410 5160 5910 6660	239	N_2+H_2O	Cu+NaOH	3.6

Table VII. Experiments of HORIZON facility carried out within SGTR project.

Experiment identification	Special configuration				Conditions						Description
	CsI vessel	Mixer	Number of tubes used	Aerosol measurement from the hot chamber[a]	p_{hot} (kPa)	p_{cold} (kPa)	Total steam flow rate (g/s)	Steam flow rate through furnace (g/s)	Air flow through furnace (lpm)[b]	Approximate Reynolds number inside the tubes	
01-A	II	II	38	I	250	250	5	-	60	940	Aerosol exp., SGTR, intact tubes
03-1	II	III	38	-	250	250	V	V	-	V	TH-test, SGCB
03-A	II[c]	III	38	C	250	250	V	V	-	V	Aerosol exp., SGCB - Failed !
04-A	II[c]	III	38	C	270	270	23	1[d]	-	3800	Aerosol exp., SGCB
05-1	II[c]	III	2	-	V	V	V	-	-	V	TH-test, SGTR, defect tubes
05-2	II[c]	III	2	-	V	V	25	-	-	V	TH-test, SGTR, defect tubes
05-3	II[c]	III	1	-	V	V	25	-	-	V	TH-test, SGTR, defect tubes
05-A	II[c]	III	1	C	405	230	25	1	-	140 000	Aerosol exp., SGTR, defect tubes
06-A	II[c]	III	1	C	405	230	25	1	-	140 000	Aerosol exp., SGTR, defect tubes
07-A	II	IV	2	C	290	230	25	1	-	70 000	Aerosol exp., SGTR, defect tubes
08-A	II	IV	2	C	310	250	25	-	60	71 000	Aerosol exp., SGTR, defect tubes
09-1	II	IV	38	-	V	V	25	-	-	V	TH-test, SGCB, sec. side flooded
09-2	II	IV	38	-	V	V	25	-	60	V	TH-test, SGCB, sec. side flooded
09-A	II	IV	38	C	250	250	24	-	60	4100	Aerosol exp., SGCB, sec. side flooded

V Varying

[a] C - Hot chamber, I - Inlet of the hot chamber

[b] In normal conditions (p = 101325 Pa; T = 273.15 K)

[c] A metallic piece added above the CsI vessel to heat up the steam before entering the vessel

[d] Momentarily set to 3 g/s.

Table VIII. Aerosol size distribution in the hot chamber of the HORIZON facility and the amount of deposited aerosols in the tubes as fraction of the amount of injected into the tubes.

Experiment	Particle size distribution in the hot chamber		Deposited fraction			
	AMMD (µm)	GSD	TEOM	Filter	Chemical analyses	Calc.[a]
01-A	2.7	1.5	0.30	0.32	0.23	0.21
04-A	1.4	1.6	0.20[b]	0.51	0.03	0.03
06-A	1.9	1.6	0.90	0.97	0.19	1.00
07-A	1…2	N/A	N/A	0.94	0.23	0.94[c]
08-A	0.8	1.4	0.25	Err.[d]	0.10	0.25
09-A	1.3	1.6	N/A	N/A	0.25	N/A

[a] Calculated with the real particle size assuming density of 4510 kg/m^3

[b] Point estimate made from 290…320 min.

[c] Selected value corresponds to particle size of 0.67 µm.

[d] Results in negative value.

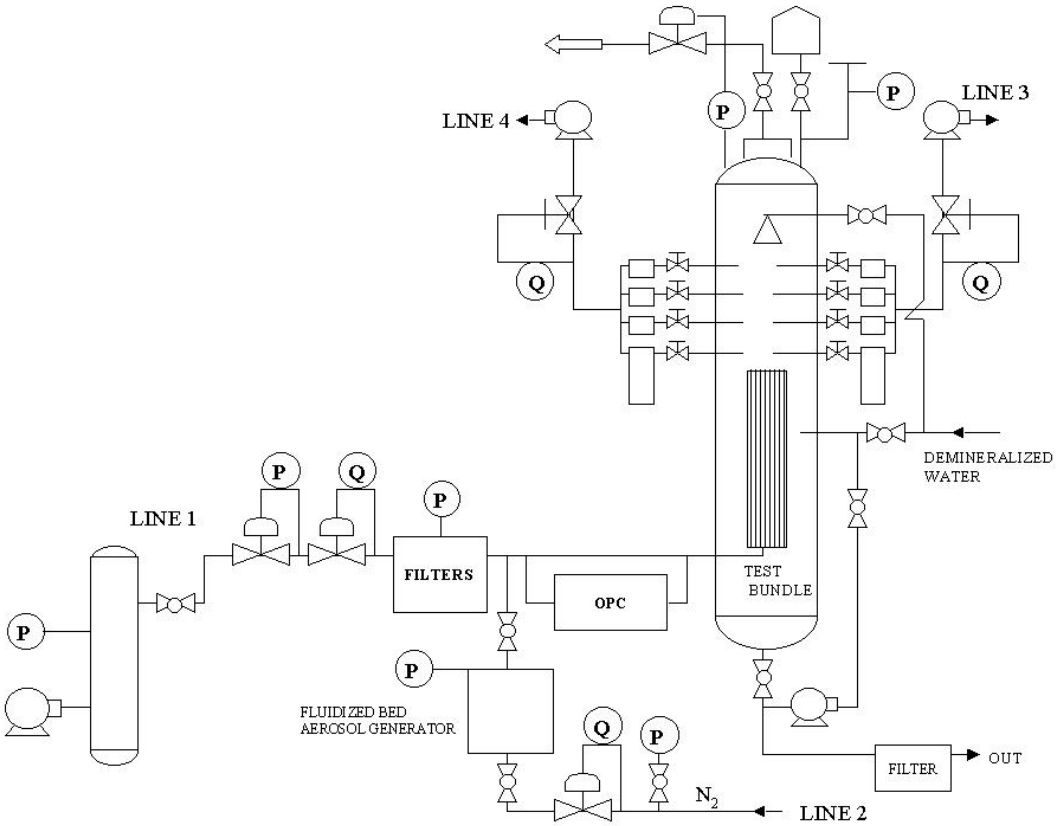

Figure 1. Scheme of the PECA facility.

Figure 2. Image of the tube mini-bundle.

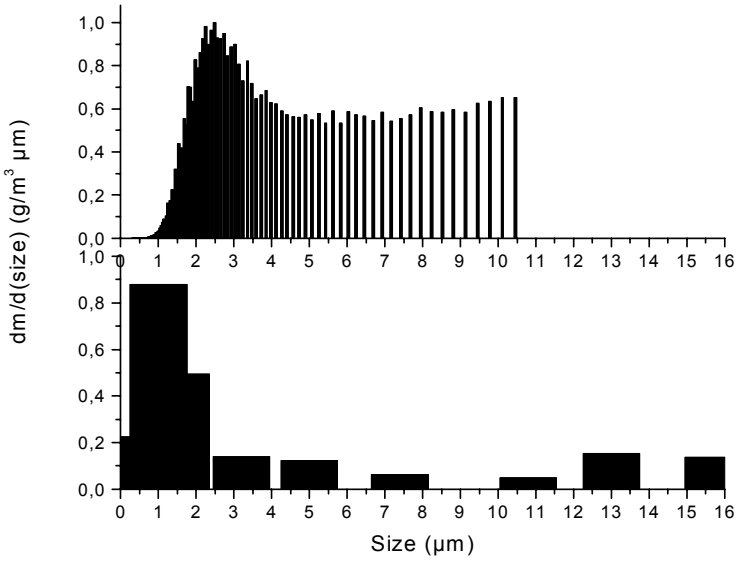

Figure 3. Inlet and outlet aerosol size distributions for test 10.

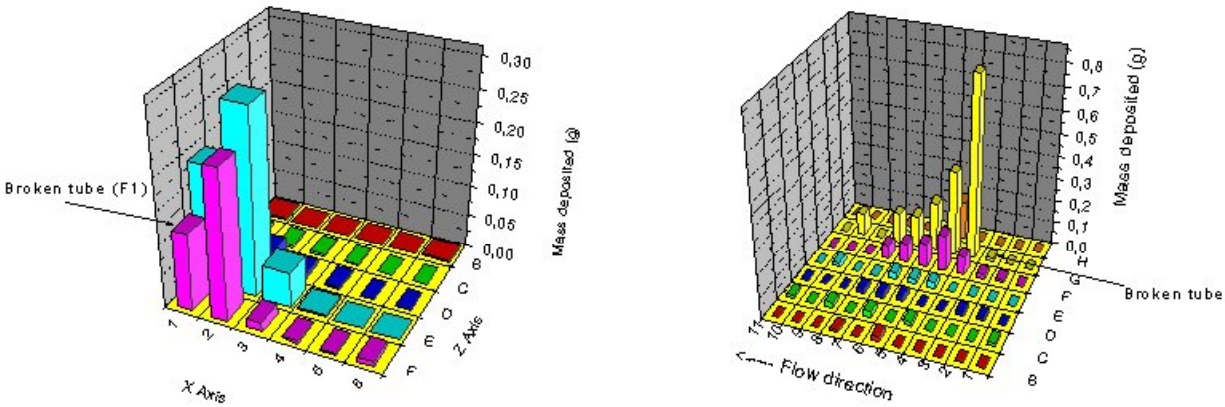

Figure 4. Deposition patterns for guillotine break (left, test 10) and fish-mouth break (right, test 6).

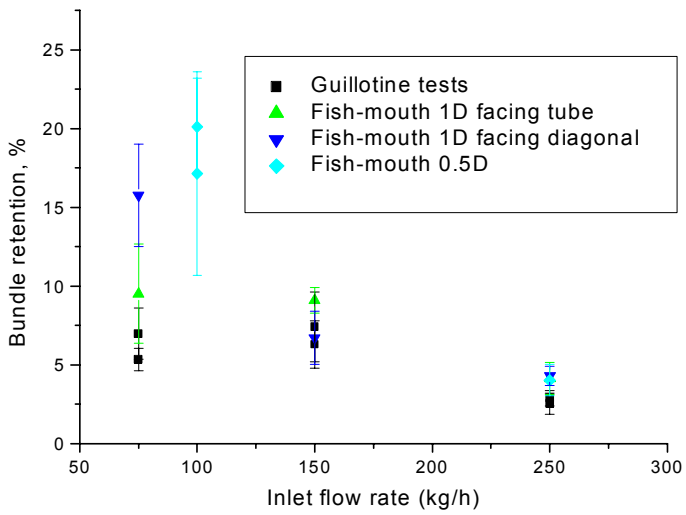

Figure 5. Retention in the mini-bundle versus inlet gas flow rate

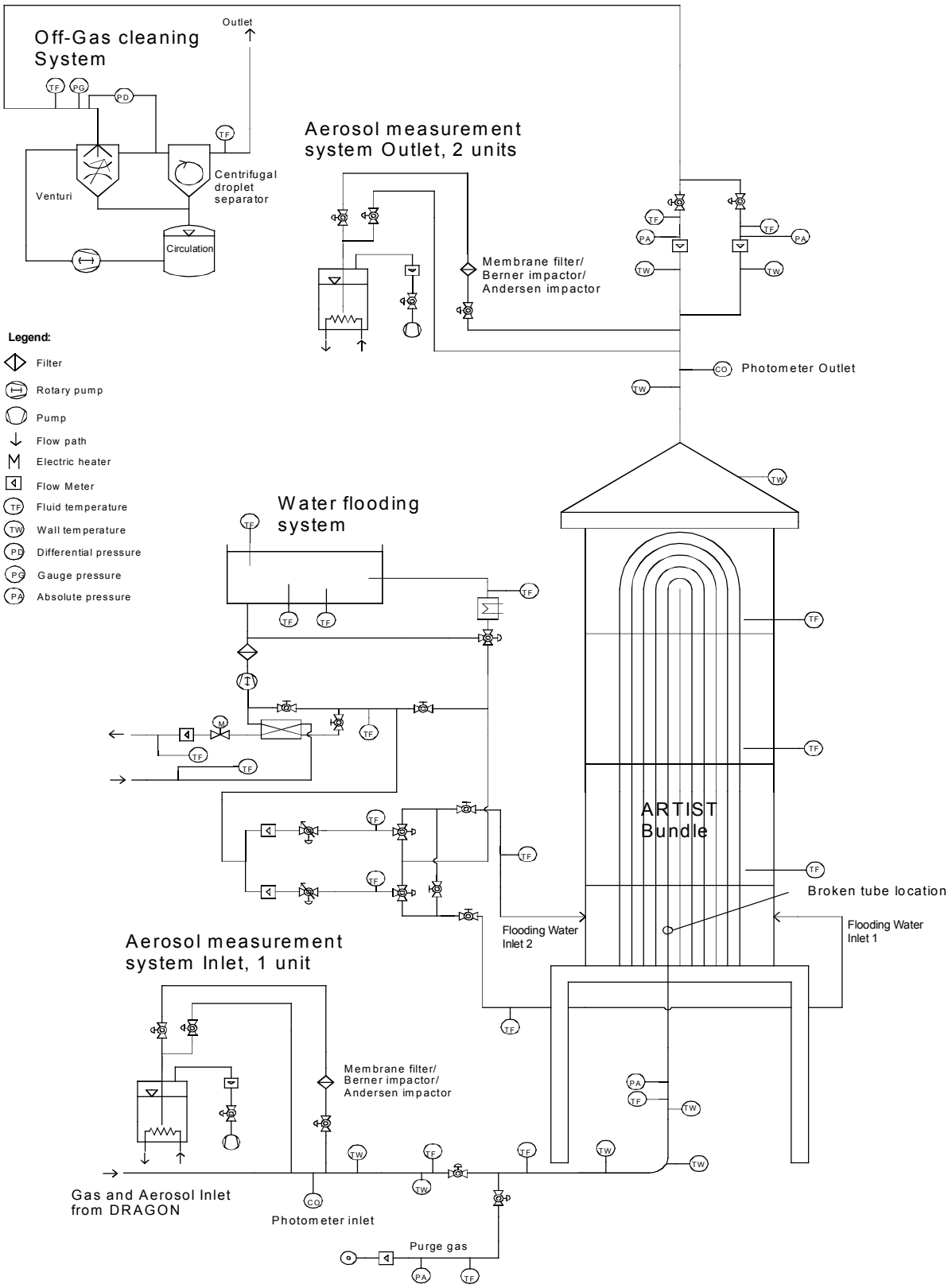

Figure 6. Schematic of the ARTIST bundle section.

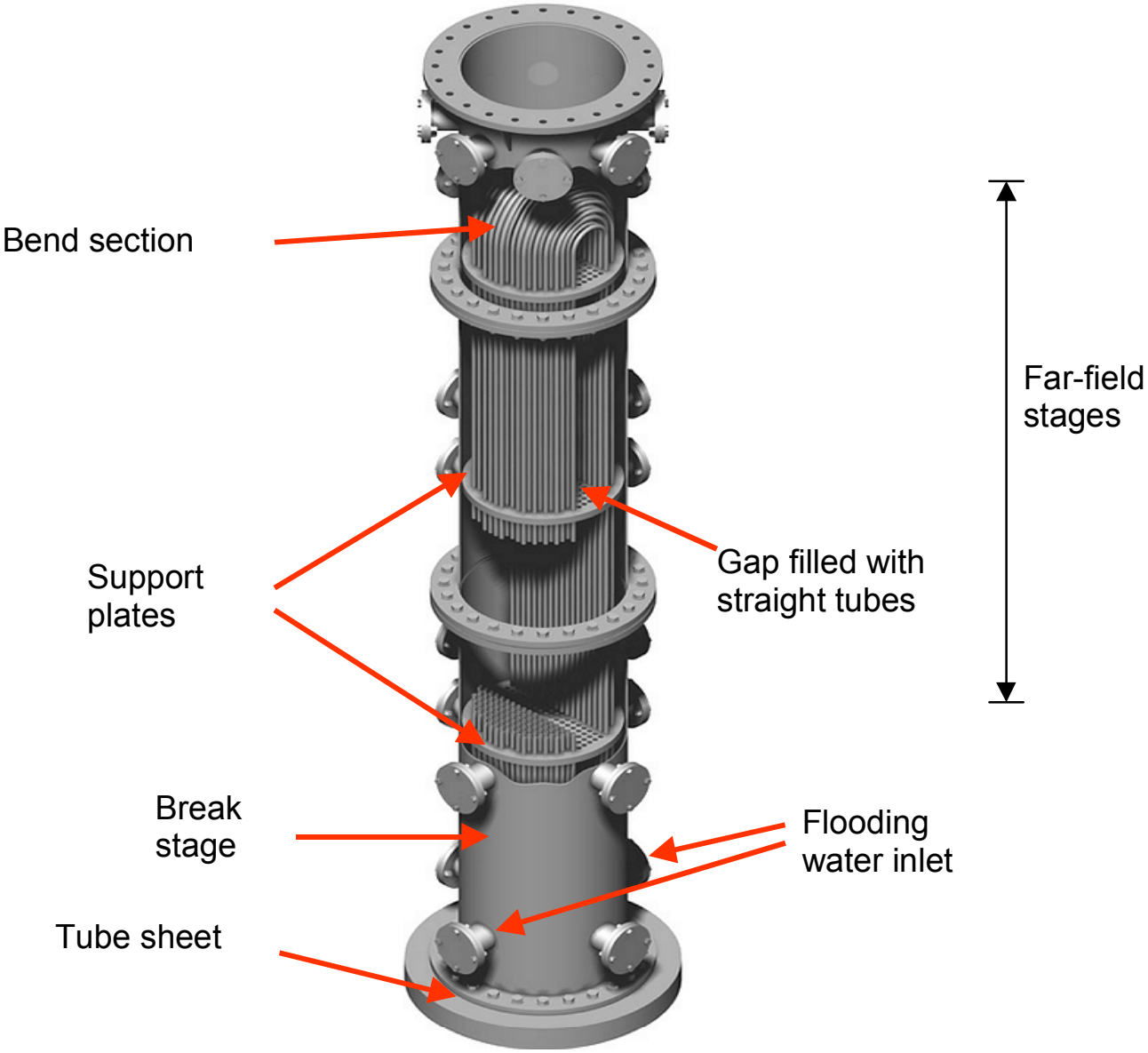

Figure 7. Schematic figure of the ARTIST bundle section.

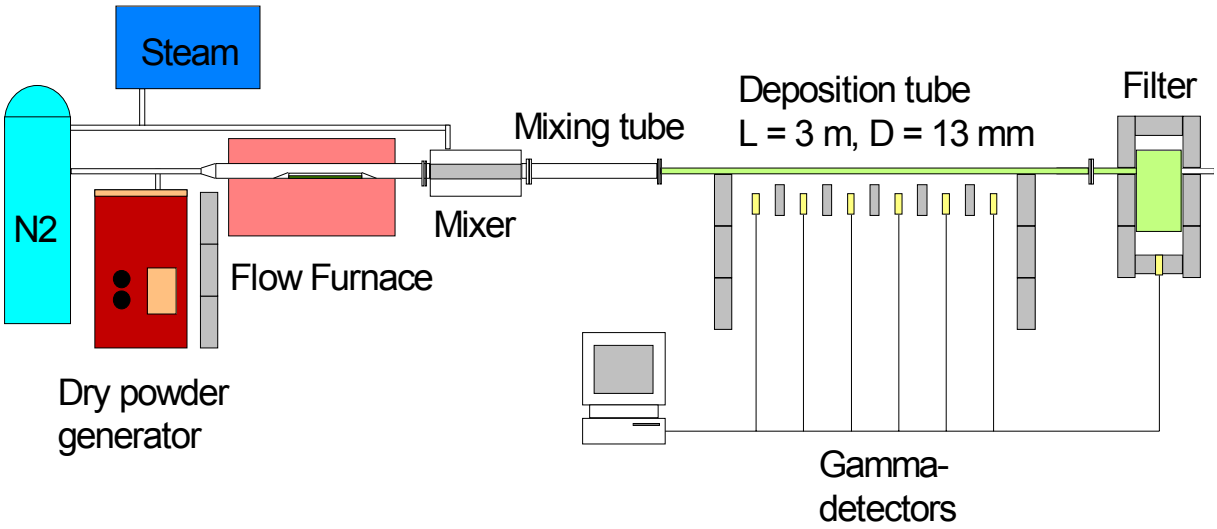

Figure 8. A schematic picture of the PSAERO facility.

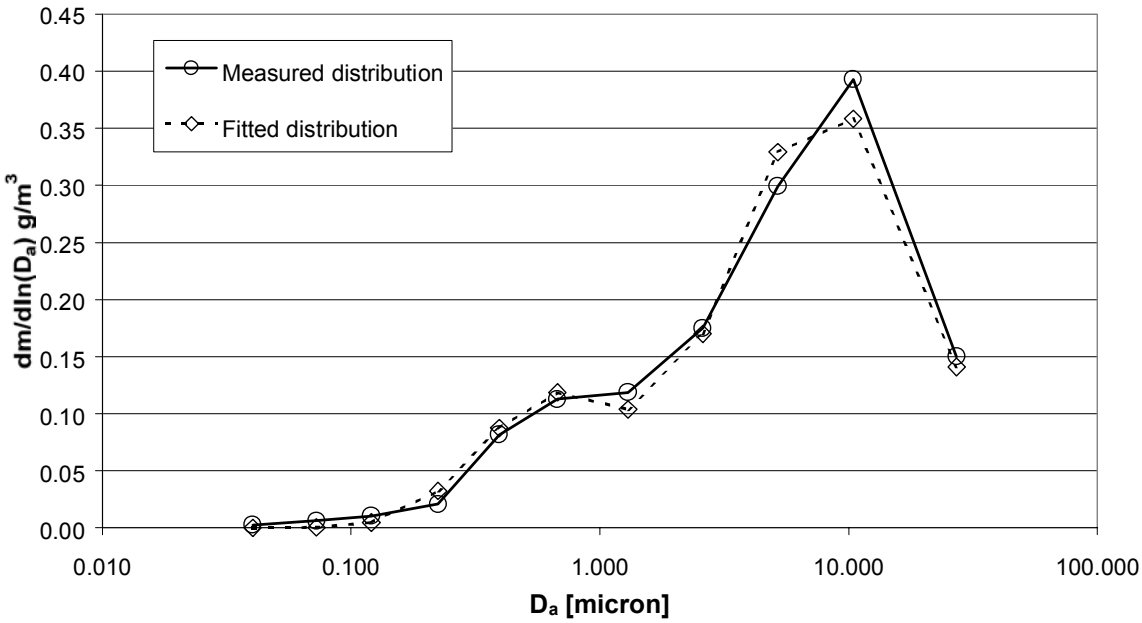

Figure 9. Aerodynamic mass size distribution of copper aerosol.

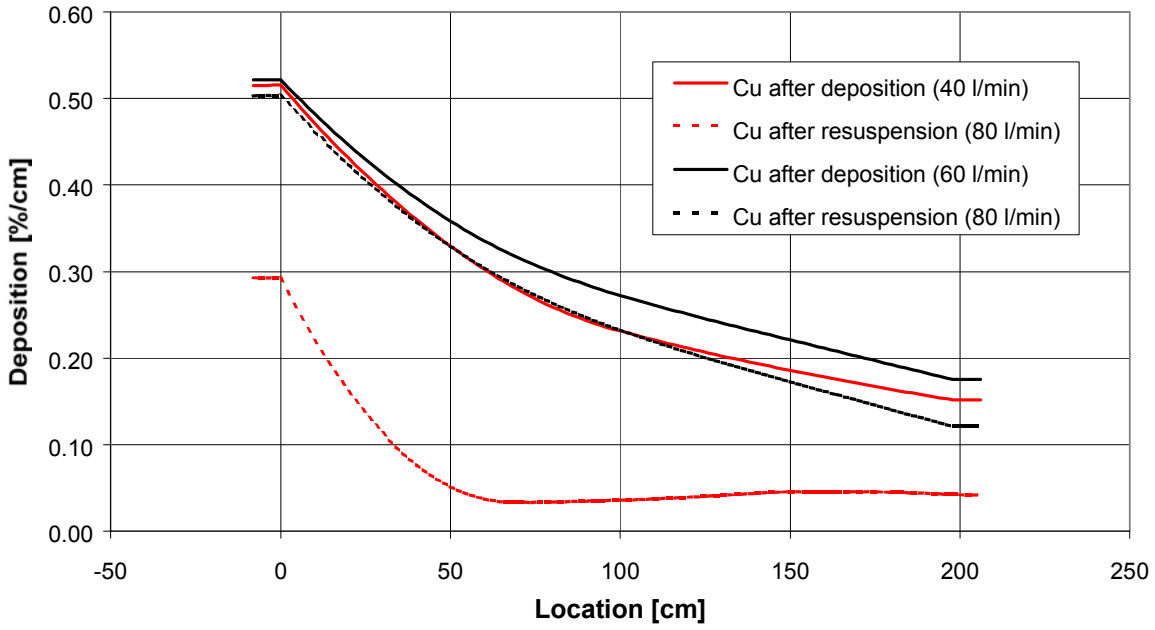

Figure 10. The profiles of aerosol deposit formed in two different flow rates.

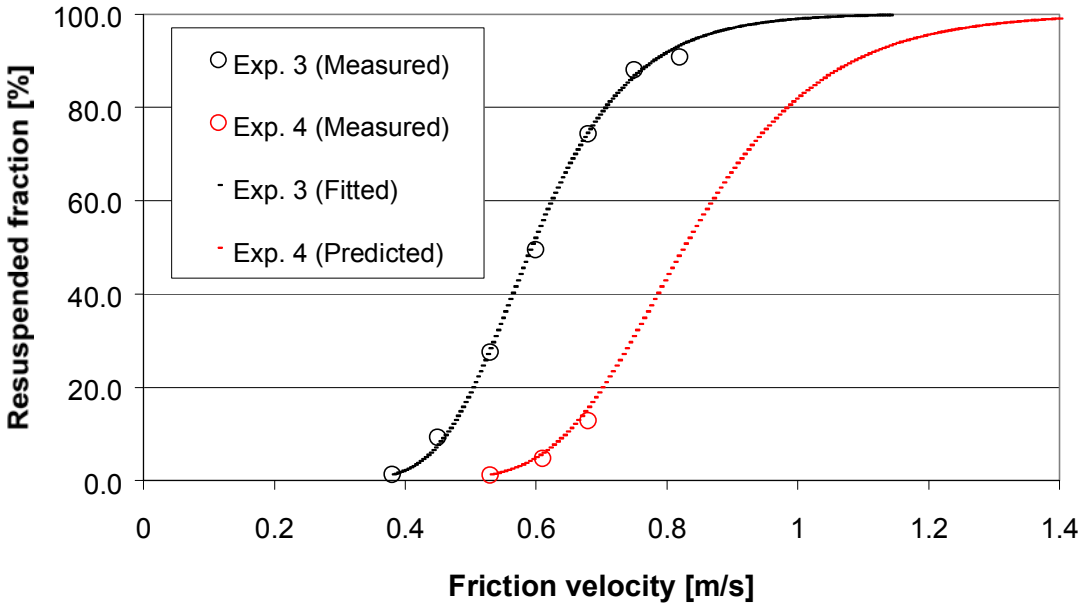

Figure 11. Resuspended fractions in experiments 3 and 4 as functions of friction velocity.????

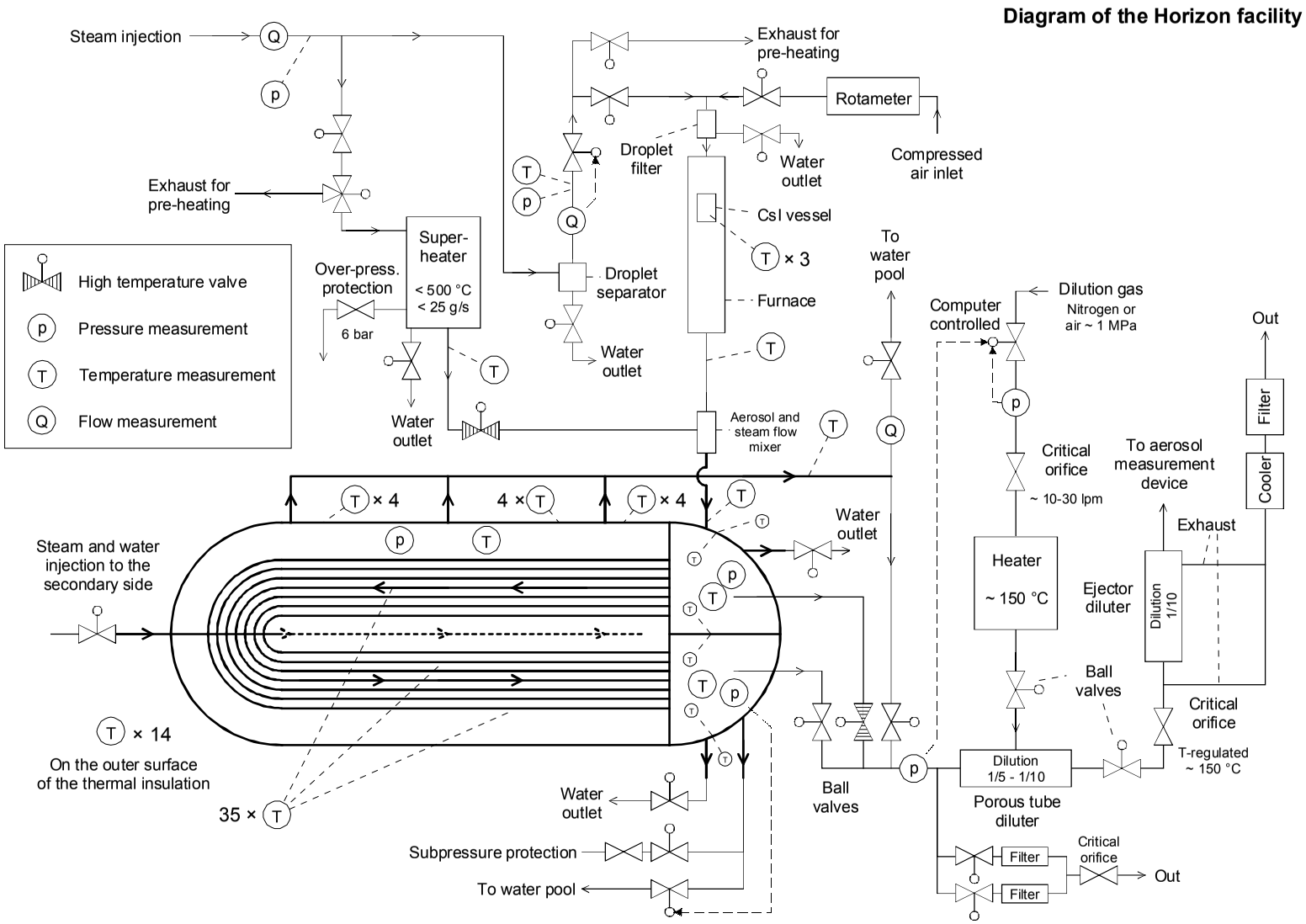

Figure 12. Diagram of the HORIZON facility.

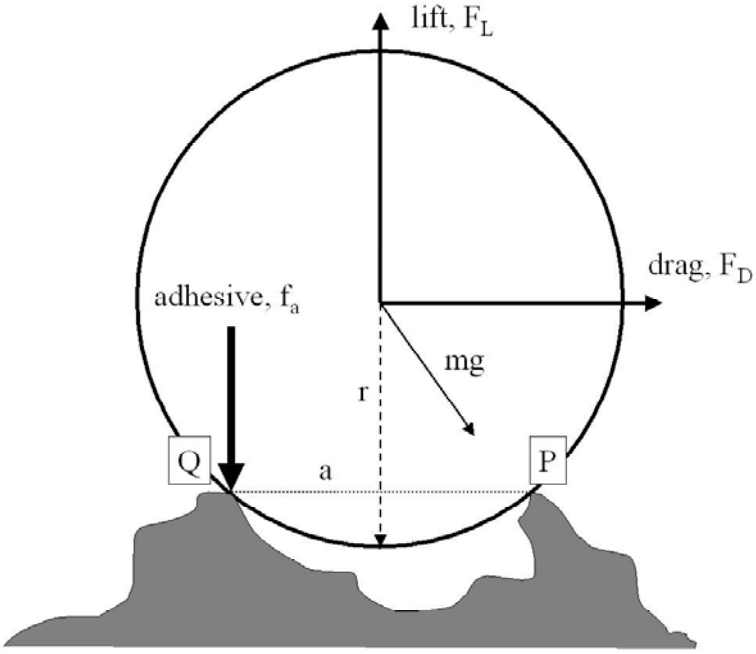

Figure 13. Particle-substrate contact for rock 'n' roll model.

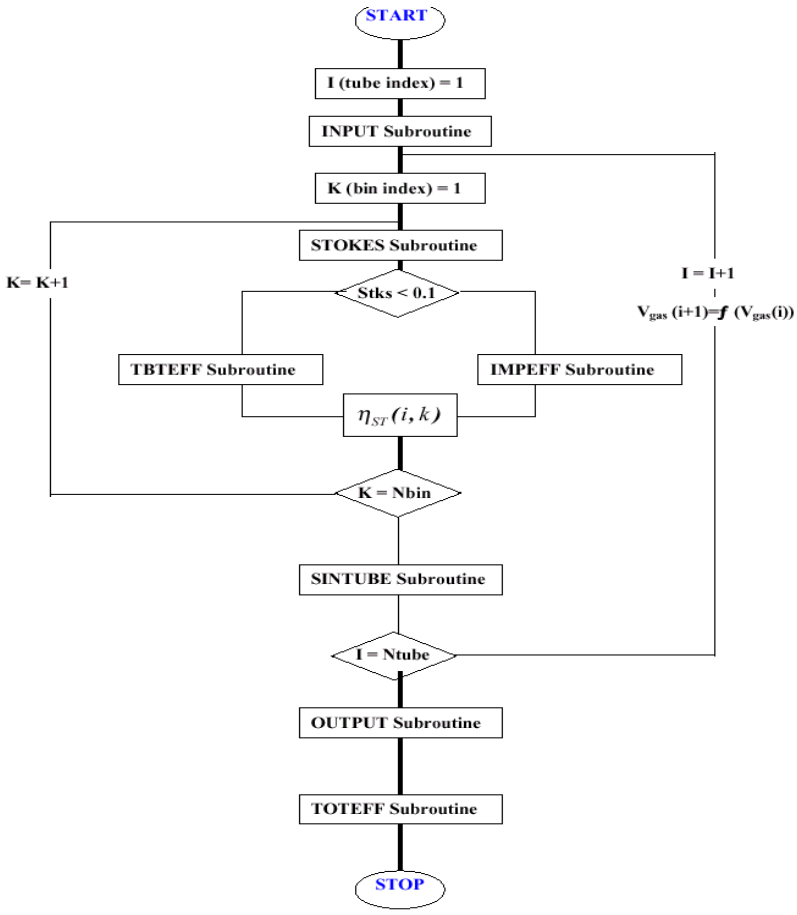

Figure 14. ARISG-I flowchart.

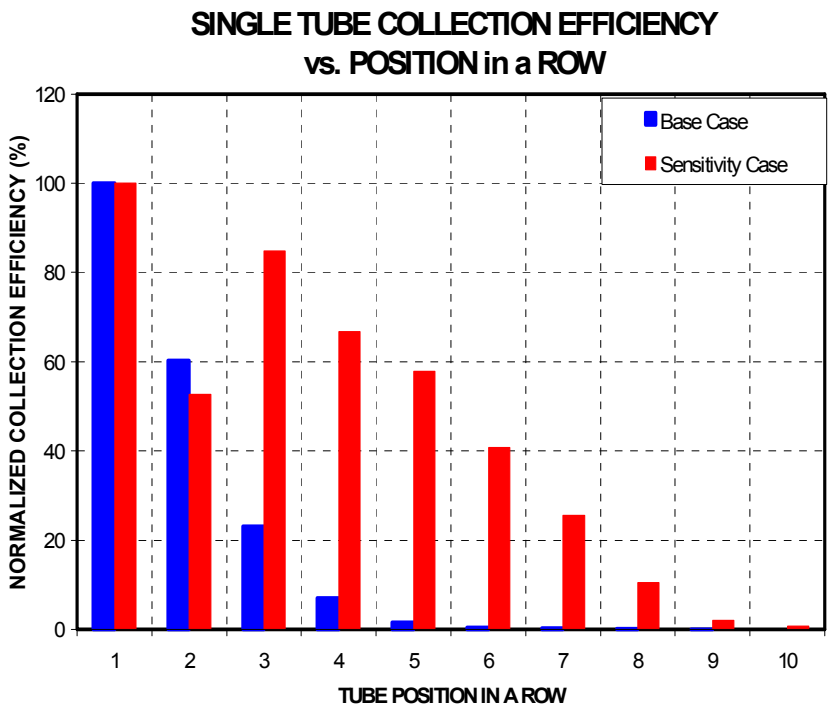

Figure 15. Influence of size distribution on particle collection efficiency.

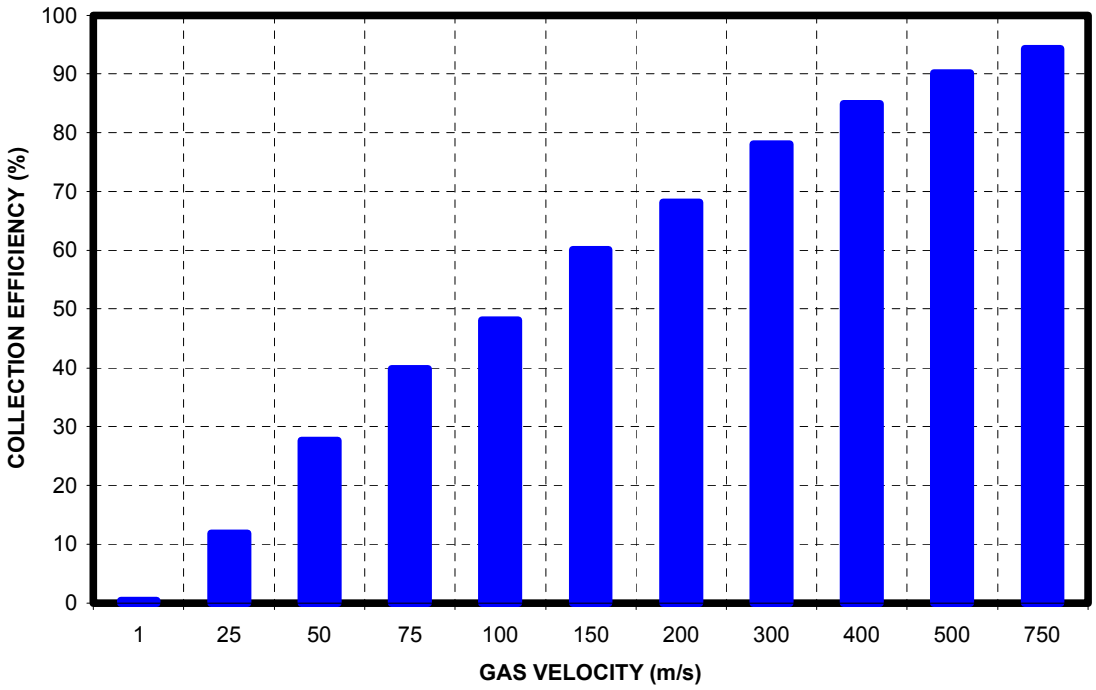

Figure 16. Influence of gas velocity on particle collection efficiency.