

REFERENCE 4

MFN 06-032

Research Report
ENE25/5/99

**EXPERIMENTAL RESULTS ON
AEROSOL DEPOSITION IN A HEAT
EXCHANGER TUBE**

Jouni Hokkinen
Jorma Jokiniemi
Ari Auvinen
Jouni Mäkynen

Research Report
ENE25/5/99

Experimental Results on Aerosol Deposition in a Heat Exchanger Tube

Jouni Hokkinen
Jorma Jokiniemi*
Ari Auvinen
Jouni Mäkynen

VTT Energy
P.O. Box 1401, FIN-02044 VTT, FINLAND
Phone +358 0 4561, Telefax +358 0 456 7021

*corresponding author (jorma.jokiniemi@vtt.fi)

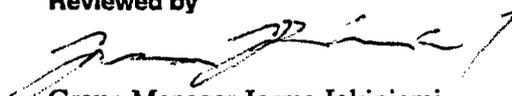
Espoo, 15.12.1999

Research organisation and address VTT Energy, Aerosol Technology P.O. Box 1401 FIN-02044 VTT, FINLAND	Customer Teollisuuden Voima Oy FIN-27160 Olkiluoto, Finland				
Project manager Dr. Jorma Jokiniemi.	Contact person Mikko Kosonen				
Diary code ENE25-7T-97	Order reference 815098/ETP 1.10.1998				
Project title and reference code Uuden sukupolven ydinvoimalaitosten toimivuus käytännön olosuhteissa 25ALESBWR	<table border="1"> <tr> <th>Report Identification & Pages</th> <th>Date</th> </tr> <tr> <td>ENE25/5/99 17 p. + figures 19 p.</td> <td>15.12.1999</td> </tr> </table>	Report Identification & Pages	Date	ENE25/5/99 17 p. + figures 19 p.	15.12.1999
Report Identification & Pages	Date				
ENE25/5/99 17 p. + figures 19 p.	15.12.1999				

Report title and author(s)
Experimental Results on Aerosol Deposition in a Heat Exchanger Tube
 Jouni Hokkinen, Jorma Jokiniemi, Ari Auvinen, Jouni Mäkynen

Summary

Part A	
A.1 Introduction	3
A.2 Experimental set-up	3
A.2.1 Aerosol generation and the main flow channel	3
A.2.2 Aerosol sampling and dilution	4
A.2.3 Measuring instruments	5
A.2.3.1 Berner Low Pressure Impactor	5
A.2.3.2 TEOM 1400A	6
A.2.3.3 Electron microscopy	6
A.3 Experiments	7
A.3.1 Temperature and flow characteristics	7
A.3.2 Aerosol measurements	8
A.4 Results	9
A.4.1 Mass size distribution	9
A.4.2 Deposition	10
A.5 Discussion and conclusions	11
A.6 Future work	11
Part B	
B.1 Introduction	13
B.2 Victoria tests 58 and 59	14
B.3 Victoria tests 61 and 62	16
B.5 Conclusions	17

Principal author or Project manager  Research Assistant Jouni Hokkinen	Reviewed by  Group Manager Jorma Jokiniemi
Approved by  Deputy Research Manager Olli Tiihonen	Availability statement

Part A

A.1 Introduction	3
A.2 Experimental set-up	3
A.2.1 Aerosol generation and the main flow channel	3
A.2.2 Aerosol sampling and dilution	4
A.2.3 Measuring instruments	5
A.2.3.1 Berner Low Pressure Impactor	5
A.2.3.2 TEOM 1400A	6
A.2.3.3 Electron microscopy	6
A.3 Experiments	7
A.3.1 Temperature and flow characteristics	7
A.3.2 Aerosol measurements	8
A.4 Results	9
A.4.1 Mass size distribution	9
A.4.2 Deposition	10
A.5 Discussion and conclusions	11
A.6 Future work	11
A.7 References	12

14 figures

Part B

B.1 Introduction	13
B.2 Victoria tests 58 and 59	14
B.3 Victoria tests 61 and 62	16
B.5 Conclusions	17
B.7 References	17

5 figures

PART A

Experimental results on aerosol deposition in a heat exchanger tube

A.1 Introduction

The aim of the work was to investigate aerosol behavior in a heat exchanger. The heat exchanger is modeling one tube of a Passive Containment Condenser, PCC that is used in the European Simplified Boiling Water Reactor, ESBWR. ESBWR is a new generation nuclear power plant designed by General Electric and its European partners (Posta and Rao, 1996). Similar tests have been done also with the AIDA, Aerosol Impaction and Deposition Analysis, test facility (Dehbi et al. 1997).

To investigate the aerosol deposition in the heat exchanger polydisperse aerosol is produced and the mass concentration of the aerosol is measured before and after the heat exchanger. Also the size distribution of the aerosol is characterized.

The experiments are performed with insoluble (Ag) particles in three environments: dry, low steam and high steam conditions. Furthermore, hygroscopic (CsOH) particles are investigated in high steam conditions.

A.2 Experimental Set-up

A.2.1 Aerosol generation and the main flow channel

A schematic picture of the facility is presented in figure A1. Two different precursor solutions were prepared for the experiments. Inert silver aerosol was produced from 4.0 wt-% AgNO_3 water solution. Silver and CsOH aerosol was produced from water solution containing 4.0 wt-% AgNO_3 , 1.7 wt-% CsOH and 3.9 wt-% HNO_3 . Nitric acid was added to the liquid in order to prevent the formation of silver oxide.

Aerosol droplets were generated from precursor solution with an ultrasonic nebulizer. In a nebulizer a piezoelectric crystal produces ultrasonic waves that are focused near the surface of a liquid. The waves shatter the liquid to small droplets that go out with a small gas flow. The droplet size produced with the nebulizer is dependent on the surface tension and density of the liquid and on the excitation frequency. The nitrogen flow rate through the nebulizer was set to 8.0 l/min (NTP). To allow easy handling of the nebulizer, the system also had a bypass for it.

The aerosol flow produced with the nebulizer was directed through an ENTECH ETF 20/18-11-L tube furnace. At the center of the furnace there was a 1200 mm long ceramic tube made out of 99.7% alumina. The inside diameter of the

tube was 22 mm. It was heated through radiative heat transfer with Two-Shank KANTHAL SUPER 1900 3/6 molybdenum disilicide heating elements. In order to obtain an uniform wall temperature profile, the furnace was divided into two zones each containing ten elements. Each zone was controlled with one PID control unit. An Eurotherm 2408 P4 was applied as a primary controller and the secondary zone was operated with an Eurotherm 2208 CC controller. The total heated length of the furnace was 800 mm. In these experiments the temperature of the furnace was set to 1000°C. When the flow entered the furnace, water evaporated from the droplets and AgNO₃ decomposed at 440°C forming pure silver particles. When there was CsOH in the droplets, it vaporized approximately at 600°C and exited the furnace in a gaseous form.

After the furnace there was a mixer that combined the aerosol flow from the furnace to the main gas flow so that the total flow rate was 100 l/min (NTP). The main flow was either nitrogen or a mixture of steam and nitrogen. Both flows were controlled with proper critical orifices. Steam for the experiment was produced with a VEIT 2365 steam generator and filtered with a porous stainless steel filter. The temperature of the main flow was 200°C. during the rapid quenching in the mixer the CsOH vapor condensed on existing silver particles. Between the mixer and the heat exchanger there was a 15 cm long straight tube in order to allow the particles to mix uniformly in the turbulent gas flow.

The vertical heat exchanger models one tube of the PCC. The heat exchanger was built so that the inner tube was removable. Total length of the removable tube was 100 cm and length of the cooled area was 80 cm. The inner diameter of the tube was 22 mm and wall thickness 1.5 mm. A schematic picture of the deposition tube with dimensions is presented in figure A1. The inner tube was changed after every experiment for possible later examination. The deposition tube was cooled by water flowing upward between the deposition and an outer tube. The flow rate of the cooling water was 2.8-3 l/min and the inlet temperature varied depending on an experiment between 8.5°C and 11.5°C. During an experiment the inlet temperature of the cooling water was constant. The temperature gradient of the deposition tube was measured from outside with type-K thermocouples. Below the heat exchanger there was a bucket, where the condensed water was collected. The gas flow was directed to fume hood with a wide hose. There were also a pressure gauge and a safety valve, since the ceramic tube in the furnace can not withstand high pressure.

A.2.2 Aerosol sampling and dilution

In order to determine the deposition of the particles the flow was sampled from the beginning and from the end of the heat exchanger as shown in figure A1. The sampling nozzles were stainless steel tubes with an inner diameter of 4.0 mm. Both sample lines were made out of a 1/2 inch tube and they were approximately of the same length, which made the diffusion losses similar. Due to their placing in the laboratory the difference in the length of the lines was 6 cm. The sample lines were heated up to 200°C in order to avoid condensation and thermophoretic deposition before the diluter.

The sample flow had to be quenched for the aerosol measurements, because the instruments could not withstand high temperature. For this reason the sample flow was diluted with ambient nitrogen in a porous tube diluter, which prevented deposition during the quenching process. The dilution ratio was selected so that water would not condense into the tubes, even if they were not heated. Depending on the dilution ratio the flow temperature after dilution was 25-30°C. It was monitored with a thermocouple placed before the filter.

After the diluter the flow was divided to the measuring instruments and to a bypass line. The bypass line had two critical orifices. One was used only to increase the dilution ratio and the other was applied in the impactor measurements, when the impactors were not used. Before the critical orifices there was a filter to prevent deposition to the orifices. Since the pressure in the experimental line was constant, the flow through the bypass line did not change. Also the flow to the measuring instruments was constant during the experiments. For this reason the sample flow rate and the dilution ratio could be controlled by adjusting the dilution flow. This was done by placing a critical orifice into the dilution line and controlling the pressure upstream the orifice.

A.2.3 Measuring instruments

A.2.3.1 Berner Low Pressure Impactor

The particle size distribution was measured with a Berner low pressure impactor (BLPI). It is an 11 stage cascade impactor, which is capable of classifying small particles down to 0.0324 μm of diameter, because of the low pressure applied in the last stages.

An impactor stage is composed of circular nozzles and a flat plate placed perpendicular to the flow path. Each impactor stage has a characteristic cut-off diameter D_{50} . Particles, which have an aerodynamic diameter larger than the cut-off diameter, can not follow the gas stream lines and collected to the stage. In a cascade impactor smaller particles are passed on to the successive stages.

When the impactor stages are weighted after the collection, an aerosol mass size distribution based on the aerodynamic diameter of the particles is obtained. Stokes diameter of the particles can be calculated by dividing the aerodynamic diameter with the density of the aerosol material. Stokes diameter is the same as the physical diameter, if the particles are spherical. The cut-off diameters for BLPI with a flow rate of 24.7 l/min (NTP) are presented in table A1.

In order to obtain the elemental composition of particles, the impactor foils from multicomponent aerosol experiments were also analyzed with ICP mass spectrometer.

Impactor Stage	Aerodynamic D ₅₀ [μm]	Stokes D ₅₀ for Silver [μm]
1.	0.0324	0.010
2.	0.0636	0.020
3.	0.0926	0.029
4.	0.168	0.052
5.	0.337	0.104
6.	0.535	0.165
7.	0.973	0.300
8.	1.98	0.611
9.	3.77	1.16
10.	7.33	2.26
11.	15.66	4.83

Table A1. The cut off diameters of BLPI with a flow rate of 24.7 l/min (293 K, 101.3 kPa).

A.2.3.2 TEOM 1400a

Tapered Element Oscillating Microbalance (TEOM) is an aerosol mass monitoring device by Rupprecht and Patashnick Co. In a TEOM gas flows through an oscillating tapered element, which have a particle collection filter on the top. TEOM monitors the changes of the element frequency and thus the mass collected to the filter on-line.

TEOM 1400a has a built-in mass flow meter, which allows the flow to be set between 0.5 and 5 l/min (NTP). In these experiments a flow rate of 3 l/min was selected. The gas flow was heated to 50°C in order to avoid condensation to the particles and to the filter. With this method the mass concentration of dry particles could be measured.

A.2.3.3 Electron microscopy

Silver particles were collected on a TEM grid so that their morphology and size could be studied with electron microscopy. The overview of the particles was obtained using LEO DSM 982 GEMINI digital scanning electron microscope (SEM). It uses a Schottky field emission (SFE) filament for the production of the electron beam. Since the SFE-filament is very bright, the diameter of the beam can be only 1-2 nm and a very good spatial resolution up to 2-3 nm can be achieved. In order to minimize the aberrations, the acceleration column of the microscope is only 20 cm long and there are no cross-overs of the beam before it is focused on the sample. The acceleration voltage of the electron beam can be chosen between 200 V and 30 kV. Unlike in traditional scanning electron microscopes, a high resolution image can be obtained with a low acceleration voltage, because the beam can be decelerated before it hits the sample. With a

low voltage beam the information is coming only from the surface of the sample. This feature makes the LEO DSM 982 GEMINI an optimal instrument for aerosol particle imaging.

The structure of the ultra fine particles was studied with Philips CM 200 transmission electron microscope (TEM). It uses a similar SFE-filament as the SEM. The acceleration voltage is significantly higher though, which enables TEM to obtain atomic resolution images. The acceleration voltage can be raised up to 200 kV.

A.3 Experiments

A.3.1 Temperature and flow characteristics

The average temperature of the 8.0 l/min (NTP) aerosol flow exiting from the furnace was 640°C. The temperature decreased a little in the tube between the furnace and the mixer, although the tube was insulated. In the mixer the temperature decreased further, since the main gas flow of 92 l/min (NTP) was heated only to 200°C. Upon entering the heat exchanger, the temperature of the flow was measure to be 205±5°C with all gas mixtures. The temperature and flow characteristics are presented in table A2.

Flow Inlet (NTP)		Flow Outlet (NTP) [l/min]	Temp. Inlet [°C]	Temp. Outlet [°C]	Amount Condensed H ₂ O [g/min]	Temp. Condensed H ₂ O [°C]
N ₂ [l/min]	Steam [g/min]					
100	-	100	205	116	-	-
75	18.4	86	207	129	9.5	38
25	60.5	46	203	150	43.3	39

Table A2. Temperature and flow characteristics in the heat exchanger.

With all gas compositions the flow Reynolds number at the heat exchanger inlet was approximately 4700. The condensation to the heat exchanger naturally increased, when there was more steam in the gas flow. Steam condensation led to a decreased flow rate and affected thus the Reynolds number of the flow. With pure nitrogen, the flow Reynolds number increased with decreasing temperature up to 5800 at the outlet of the heat exchanger. With the medium steam flow, the Reynolds number stayed approximately in a constant value of 4700. With the greatest steam mass fraction, the flow Reynolds number decreased to 2400. The gas temperature at the outlet of the heat exchanger was measured from the center of the flow channel. It increased with the increasing steam mass fraction from 116°C to 150°C as presented in table A2. Cooling water was flowing from the bottom to the top of the heat exchanger.

Temperature of the 3.0 l/min cooling water flow was 11.6° at the inlet. The cooling water temperature at the outlet was 13.0°C with the pure nitrogen flow, 14.0°C with the medium steam flow and 20.3°C with the high steam flow.

A.3.2 Aerosol measurements

In total, eight deposition experiments were carried out with aerosol measuring instruments. The experimental matrix is presented in table A3. In the first four experiments, the effect of deposition on aerosol mass size distribution was studied using Berner low pressure impactors (BLPI). Four impactor samples were taken during each experiment: Two from the heat exchanger inlet and two from the outlet. The sampling times varied between 15 and 30 minutes. In the fourth experiment, also the elemental composition of the particles collected on the impactor foils was analyzed with an ICP mass spectrometer.

Exp.	Precursor solution	N ₂ flow [l/min] (NTP)	H ₂ O flow [mol/min]	H ₂ O / N ₂ Molar ratio	Measuring Instruments
1.	4.0 % AgNO ₃	100	-	0 / 100	BLPI
2.	4.0 % AgNO ₃	75	1.02	23 / 75	BLPI
3.	4.0 % AgNO ₃	33	3.36	75 / 33	BLPI
4.	4.0 % AgNO ₃ 1.7 % CsOH 3.9 % HNO ₃	25	3.36	75 / 25	BLPI ICP-MS
5.	4.0 % AgNO ₃	100	-	0 / 100	TEOM SEM
6.	4.0 % AgNO ₃	75	1.02	23 / 75	TEOM
7.	4.0 % AgNO ₃	25	3.36	75 / 25	TEOM
8.	4.0 % AgNO ₃ 1.7 % CsOH 3.9 % HNO ₃	25	3.36	75 / 25	TEOM

Table A3. The experimental matrix of aerosol deposition studies.

After the size distribution measurements, a similar set of experiments was conducted using TEOM 1400a on-line mass monitor to measure the aerosol mass concentration. The deposition could be calculated from the concentration difference between the inlet and the outlet of the heat exchanger. In each experiment eight to ten measurements were conducted by swapping the sampling between the heat exchanger ends in between. The duration of one TEOM measurement was ten minutes. In addition to this, silver particles were collected on TEM grids in the fifth experiment for electron microscope analysis. Since the aerosol concentration was not known, several samples were taken by varying the collection time between 6 and 60 seconds. The flow through the TEM collector was 0.3 l/min (NTP).

The effect of two parameters on the deposition process was studied. At first the steam volume fraction in the gas flow was varied between zero and 75 percents as presented in table A3. It was expected that diffusiophoresis caused by the steam condensation would be an important deposition mechanism in the heat exchanger. In order to quantify the effect of diffusiophoresis, non-hygroscopic silver particles were used as aerosol material in these experiments. The effect of aerosol material itself was studied in experiments 4 and 8, by adding hygroscopic CsOH to the particles. The behavior of hygroscopic aerosol was thus studied only in steam rich conditions.

A.4 Results

A.4.1 Mass size distribution

The particle mass size distributions measured with BLPI were not very much affected by deposition. When the size distributions from the heat exchanger inlet and outlet are compared in figures A2 to A9, only a slight depletion of big particles can be observed. This phenomenon was most probably caused by turbulent impaction. The aerodynamic mass median diameter (AMMD) of silver particles calculated from the distribution varied between 0.80 and 0.95 μm . This corresponds to a Stokes diameter varying from 0.25 to 0.30 μm . This variation was within the statistical accuracy of the measurements.

The aerosol material had a profound effect on the mass size distribution. Silver particles formed an unimodal distribution, but when CsOH was added to the precursor solution, the distributions became bimodal as can be seen in figures A8 and A9. This was explained by studying the scanning electron microscope pictures of the silver particles. Figure A10 presents an overview of the silver particles. It can be seen that in addition to a few large particles, there are also a large number of very small particles. The small particles can not be seen in the mass size distribution. However, since they possess a very large surface area, most of the CsOH vapor will condense on their surface leading to the observed bimodal distribution in experiments four and eight.

The large silver particles are spherical as can be seen in figure A11. This means that the calculated Stokes diameter corresponds to their physical diameter. The large particles are formed in the furnace, when water has

evaporated from the droplets. The small, 20 to 30 nm, particles are most likely nucleated from silver, which has been vaporized in the furnace. From figures A12 and A13, taken with the transmission electron microscope, it can be seen that also the small particles are approximately spherical. Silver atoms have formed clear crystal structure to the interior of the small particles, but their surface seems to be amorphous.

One series of impactor foils from experiment four was analyzed with an ICP-mass spectrometer. The mass proportions of Ag and Cs were measured from two samples of every impactor stage. The results are presented in figure A14. They confirm the assumption that CsOH condensed on the small silver particles. The values on X-axis are geometric means of impactor cut-off diameters. The masses of A and B samples agree very well. They are also similar to weighed masses of impactor foils as can be seen by comparing figures A8 and A4. According to ICP-MS analysis overall mass proportion of Ag and Cs on the impactor foils was 30 % Cs and 70 % Ag. In precursor solution the mass proportion is 37 % Cs and 63 % Ag. The difference is as expected, because some CsOH vapor condenses also on the tube walls after the furnace.

A.4.2 Deposition

Average percentage of deposited particulate mass in all four experiments measured with TEOM1400a is presented in table A4.

Flow [l/min] (NTP)	Aerosol material	Deposition [%]
100 N ₂	Ag	4.3
23 H ₂ O 75 N ₂	Ag	17.2
75 H ₂ O 25 N ₂	Ag	52.8
75 H ₂ O 25 N ₂	Ag + CsOH	53.4

Table A4. Average deposited mass in experiments.

With a 100 l/min (NTP) nitrogen flow the deposition to the heat exchanger was less than 5% of the particle mass. It can be concluded that the thermophoresis and turbulent impaction, which are the main deposition phenomena in dry gas flow, were relatively weak in these experiments. With the low water content flow, the deposition rate was significantly higher, in average 17% of the particle mass. This increase was caused by diffusiophoresis. As expected the deposition rate increased further with the steam rich flow. On average 52.8 % of the silver particles deposited in the experiment. The addition of hygroscopic CsOH to the aerosol did not have a significantly influence on the deposition

rate. The calculated result, 53.4% of the aerosol mass, agreed well with the previous measurements.

The inner tube of the heat exchanger was changed after every experiment. Visually only a small amount of deposited material could be observed in any of the tubes. It was concluded that in dry experiments the deposition velocity was very slow. In steam rich conditions obviously the condensed water washed most of the deposited particles out of the tube. Some of this material accumulated to the bend after the heat exchanger.

A.5 Discussion and conclusions

With high steam flow rate the dominating deposition mechanism is diffusiophoresis as expected. The effect of thermophoresis and turbulent eddy impaction is small. Less than 5 % of particle mass is deposited in dry gas. The amount of deposited material in the heat exchanger is small in all cases as the particles are flushed away with the condensed water. Thus sticky deposit, which decrease heat transfer and may cause blockage of the tube did not form in these experiments.

Deposition is almost independent of the particle size. A slightly higher depletion of large particles could however be seen. That is probably caused by turbulent impaction. Between two different size distributions no difference in deposited mass fraction was observed in highly condensing conditions.

Aerosol size distribution with CsOH was bimodal. CsOH mainly condensed on very small silver particles, because their total surface area was much larger than the area of bigger particles. The total amount of deposited mass was independent of the aerosol material and size distribution.

A.6 Future work

The aerosol generation of the ultrasonic nebulizer was not stable. The production rate oscillated slightly and grew linearly during the experiment. The rate was also too small that the deposition could have blocked the heat exchanger. The aerosol should be produced in another way, by vaporizing in the furnace. That would allow higher particle concentration and constant mass flow rate. CsOH has to be changed to CsI as CsOH may not be quite suitable for vaporization.

Much less effort is necessary to place in size distribution measurement development. The only addition needed is an accurate dilution gas control to get good measurements on the aerosol mass concentrations. The dilution ratio in the sampling line has to be known exactly when the mass concentration is measured. Because of some reason it changed during or between the measurements. The measured mass concentrations are therefore only approximate. The dilution flow has to be controlled with a more accurate way than critical orifice like a mass flow meter and controller. An another

improvement would be a real time measurement of the dilution ratio. That could be done with a tracer gas. If a specific gas whose concentration can be measured easily were added to the main flow, the dilution ratio would be known in real time.

Diffusiophoretic deposition rate should be studied in various steam - nitrogen conditions, with steam mass fractions ranging from 25 % to 75 %. The total flow rate can be changed if some other flow Reynolds number in the heat exchanger is desired.

The condensation and diffusiophoresis results will be validated with FLUENT calculations.

The temperature of the cooling water is only about 10°C and depends on the outdoor temperature. In ESBWR the cooling water can be boiling. Different temperatures of the cooling water could be tested between 20°C and 80°C. As adjusting the flow rate of the cooling water is quite tedious job, some better method to control it need to be built. One possibility could be a gravity driven flow from a heated pool hanging from the ceiling.

To investigate the deposition in the heat exchanger radioactive tracers could be used. The radioactivity would then be measured with gamma detectors along the tube to solve the deposition profile and mass balance in the end. The technique for this already exists and it is also accurate and fast. Gamma scanning could be done also on-line to observe deposit behavior during an experiment. This would allow some very useful and unique data.

A.7 References

A.Dehti, D.Suckow, S.Guentay (1997) AIDA Experiments: Aerosol Impact on the Performance of the SBWR Passive Containment Condenser Model, ALPHA 711, TM-49-AIDA-1-97, Paul Scherrer Institute.

B.A. Posta and A.S.Rao (1996) European Simplified Boiling Water Reactor (ESBWR Plant), 4th Int. Conf. Of Nucl. Eng., New Orleans, LA, USA.

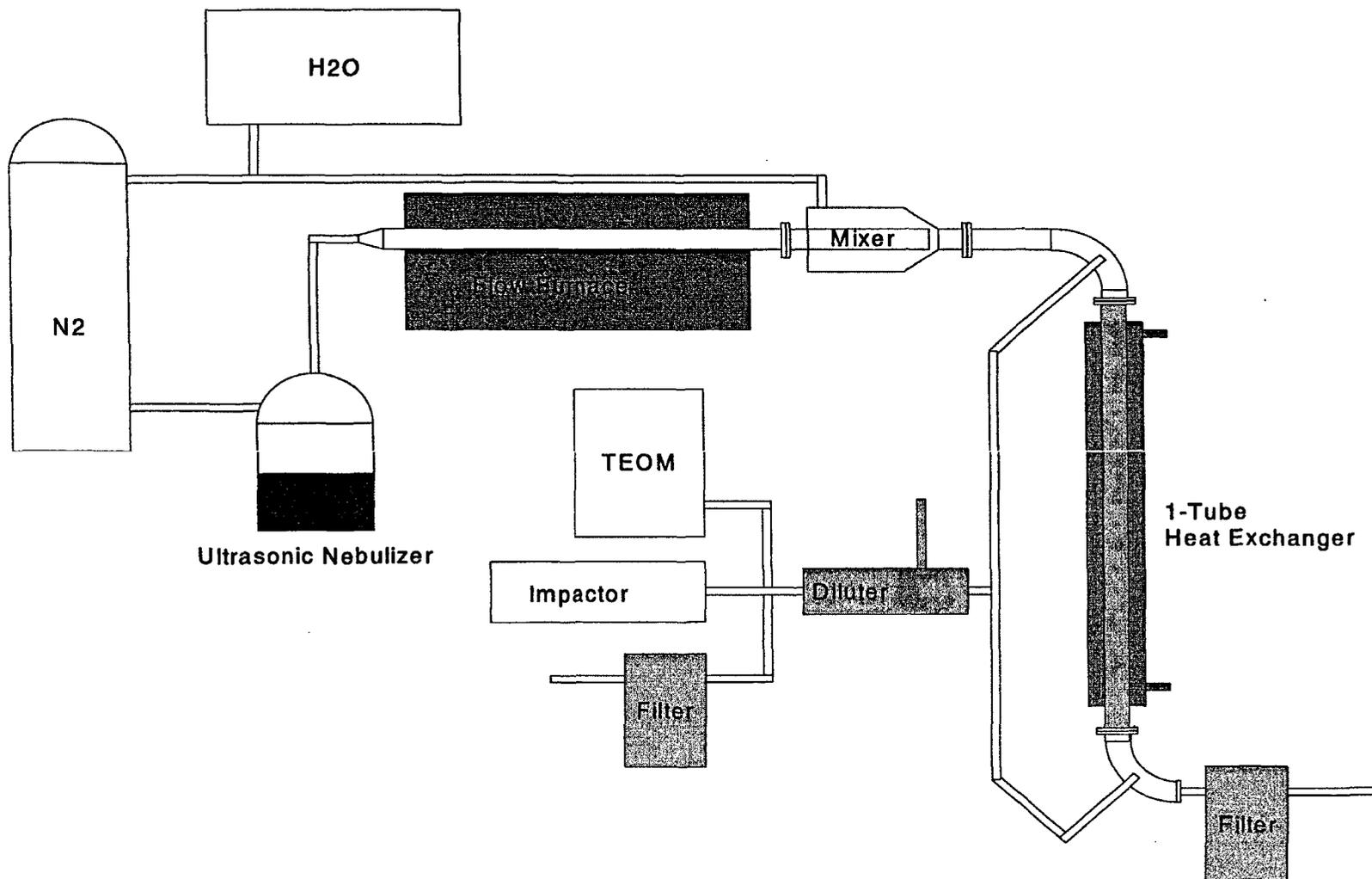


Figure A1. Experimental set-up

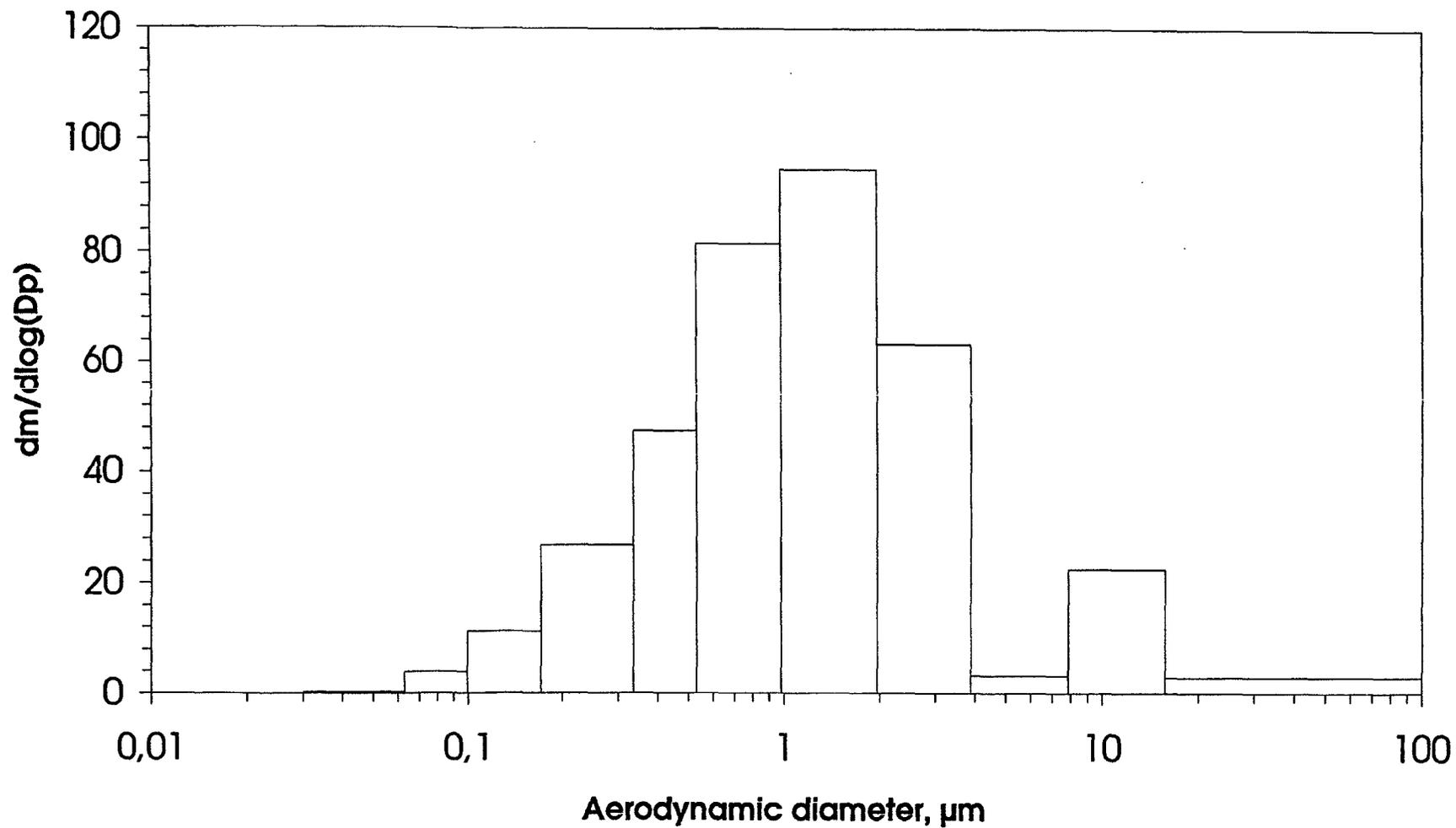


Figure A2. Aerosol mass size distribution from heat exchanger inlet in experiment 1.
N₂ flow 100 l/min (NTP), aerosol material Ag.

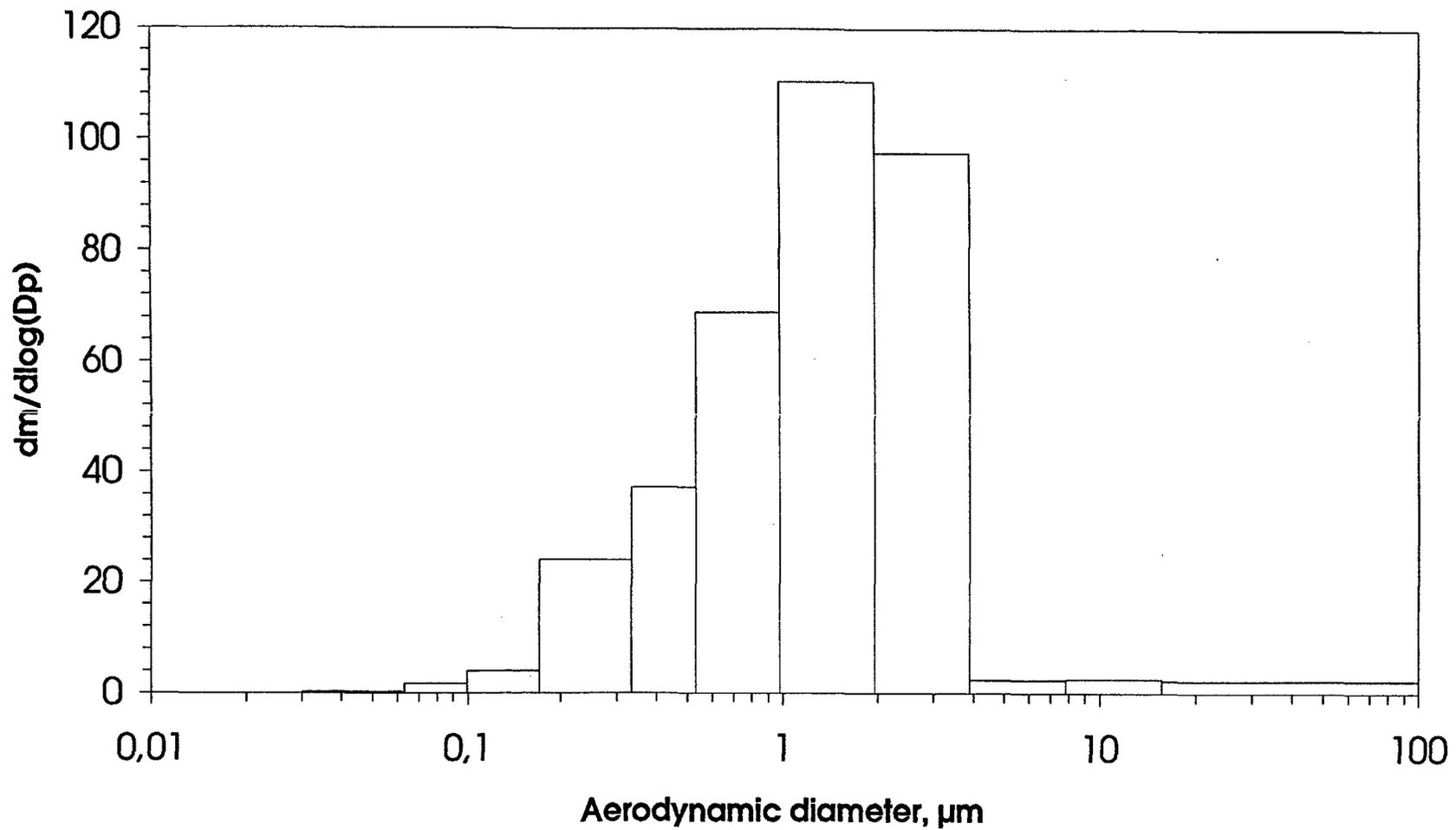


Figure A3. Aerosol mass size distribution from heat exchanger outlet in experiment 1.
N₂ flow 100 l/min (NTP), aerosol material Ag.

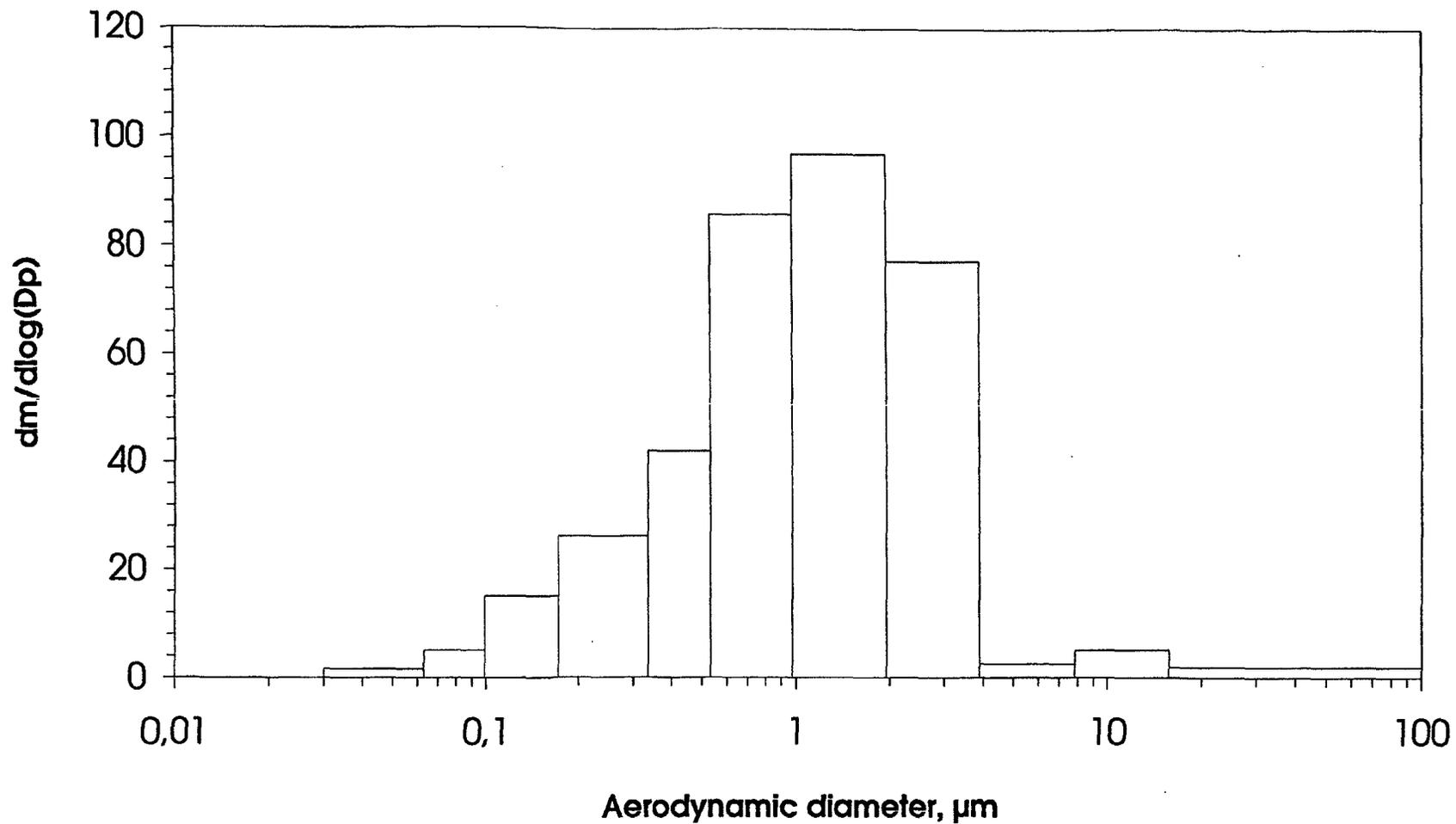


Figure A4. Aerosol mass size distribution from heat exchanger inlet in experiment 2.
H₂O flow 18.4 g/min N₂ flow 100 l/min (NTP), aerosol material Ag.

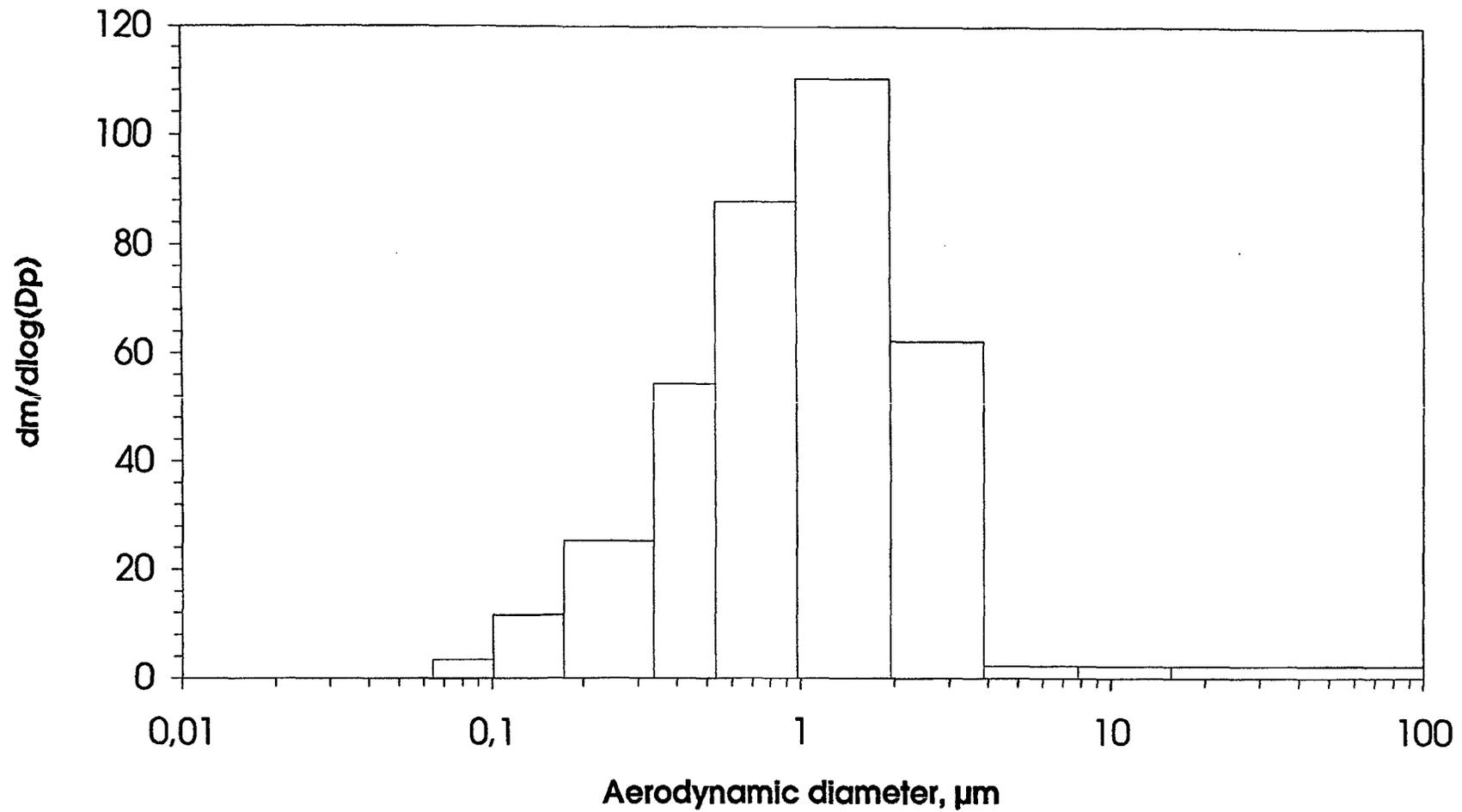


Figure A5. Aerosol mass size distribution from heat exchanger outlet in experiment 2.
H₂O flow 18.4 g/min N₂ flow 100 l/min (NTP), aerosol material Ag.

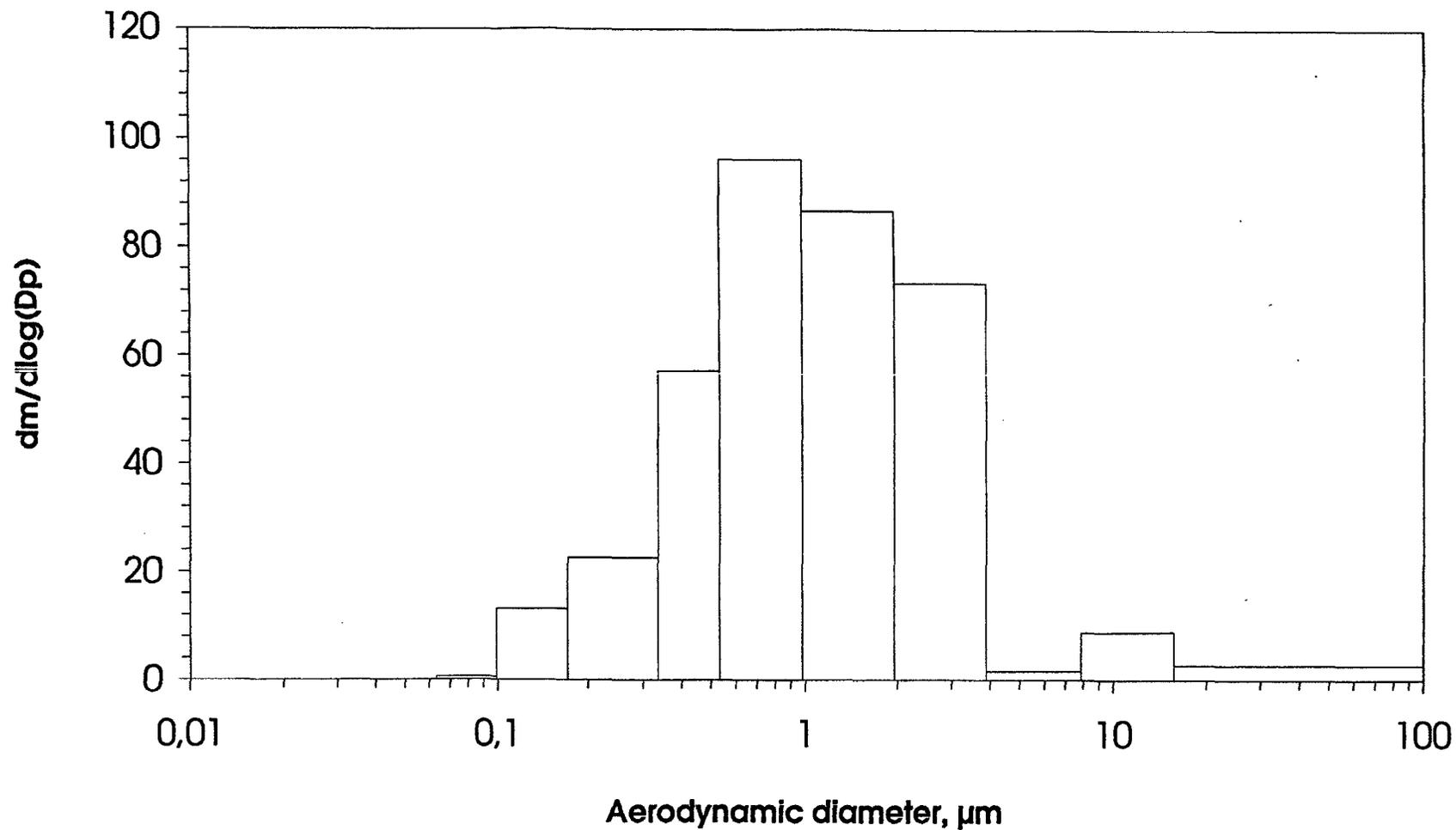


Figure A6. Aerosol mass size distribution from heat exchanger inlet in experiment 3.
H₂O flow 60.5 g/min N₂ flow 100 l/min (NTP), aerosol material Ag.

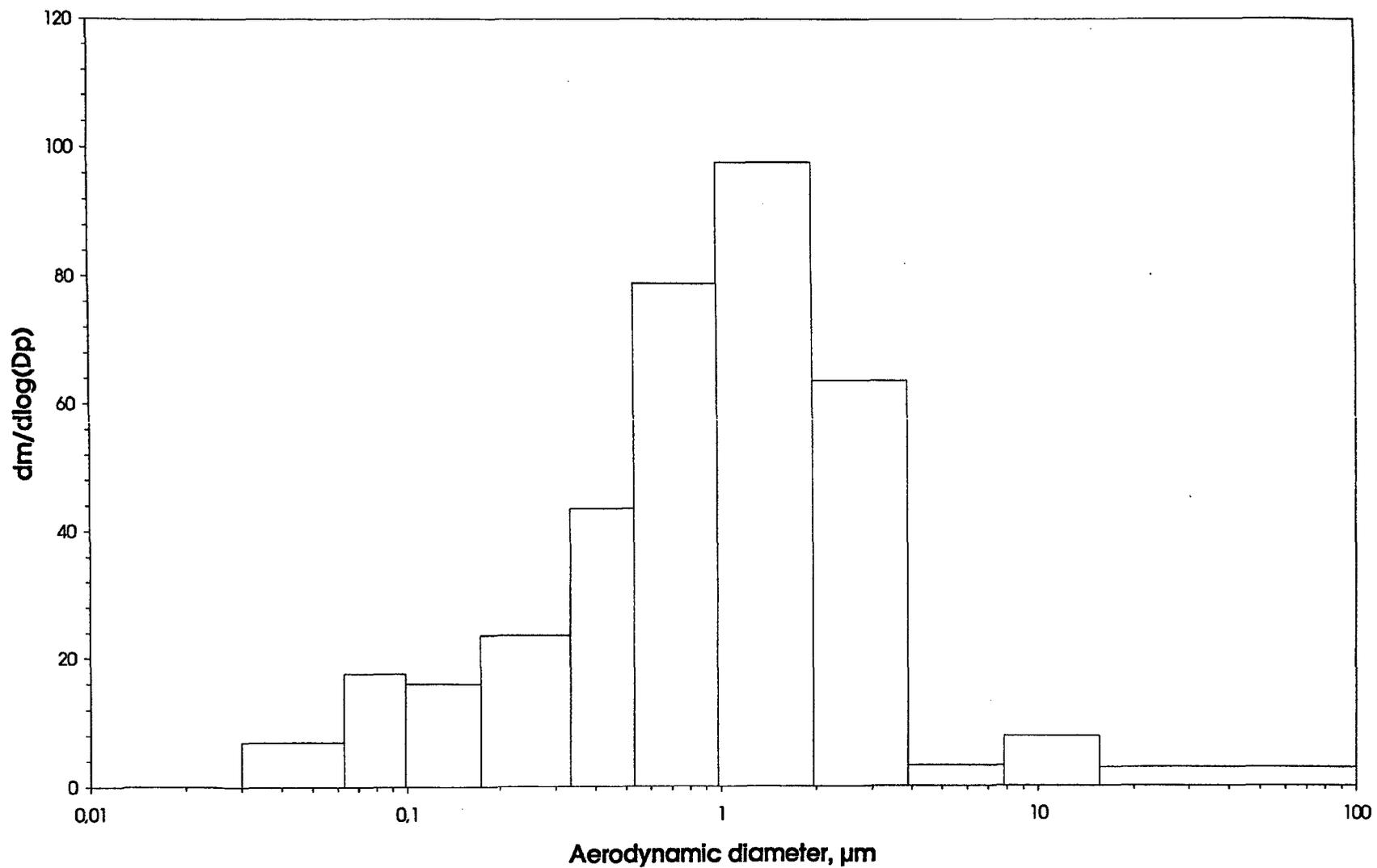


Figure A7. Aerosol mass size distribution from heat exchanger outlet in experiment 3. H₂O flow 60.5 g/min N₂ flow 100 l/min (NTP), aerosol material Ag.

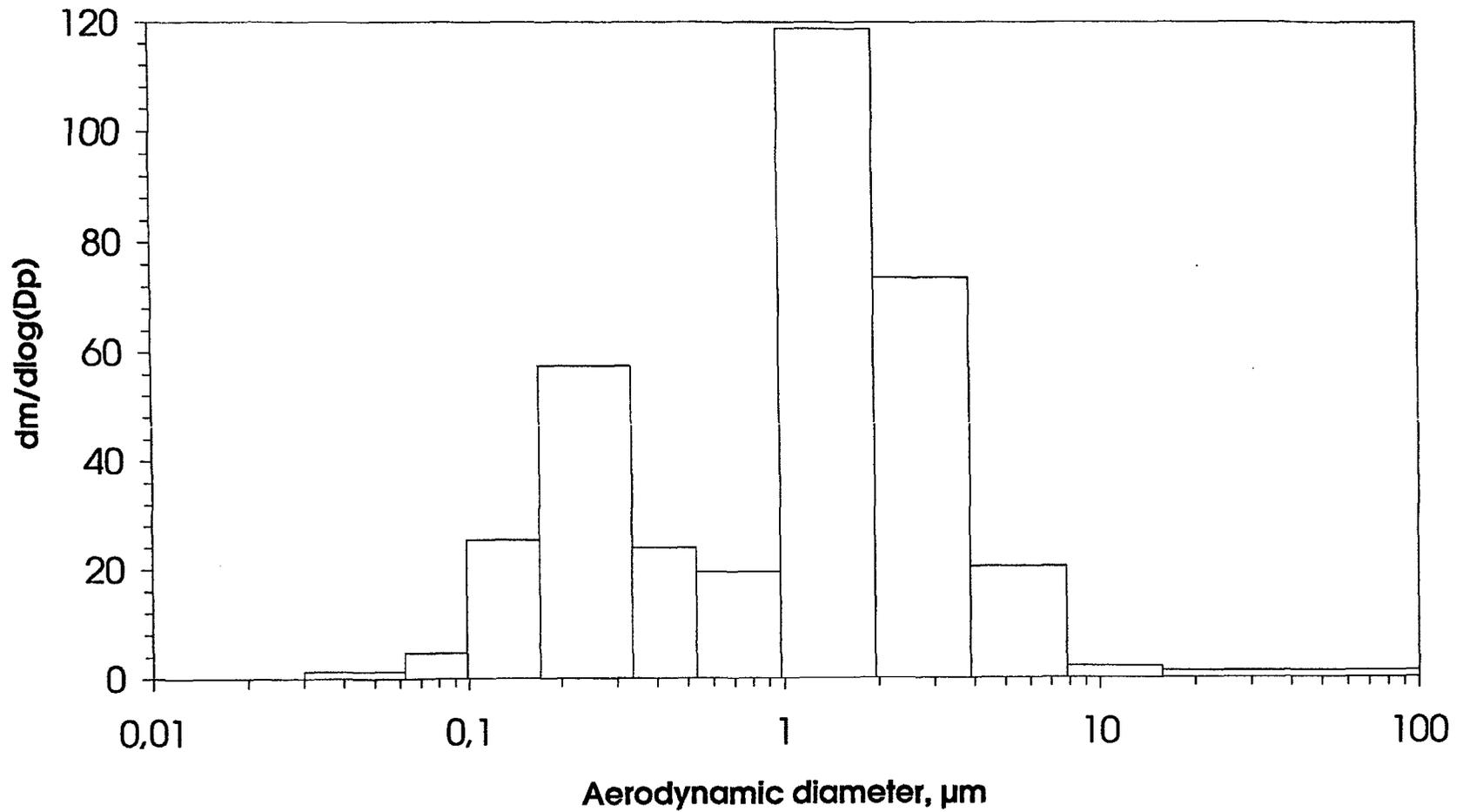


Figure A8. Aerosol mass size distribution from heat exchanger inlet in experiment 4.
H₂O flow 60.5 g/min N₂ flow 25 l/min (NTP), aerosol material Ag and CsOH

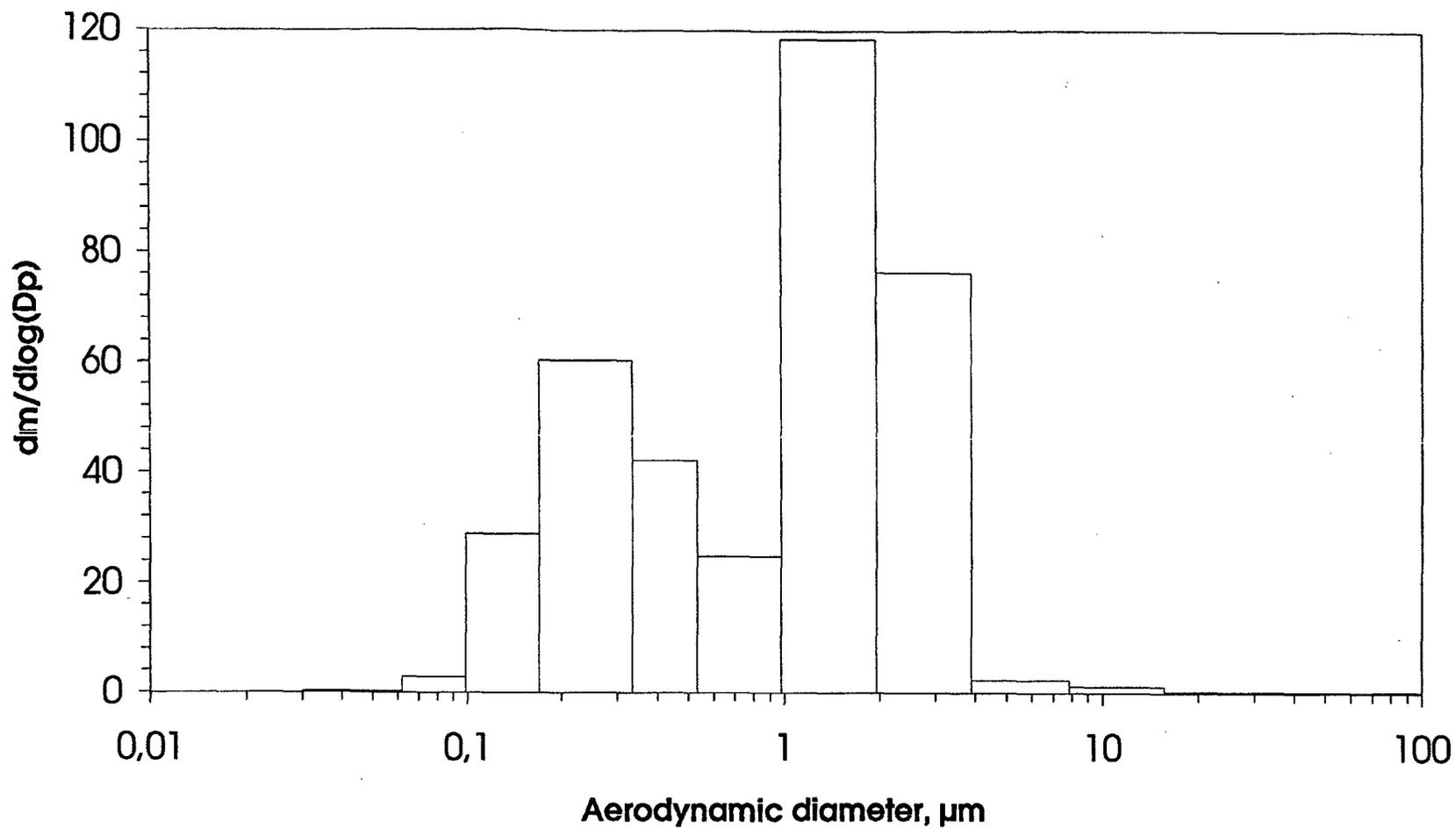


Figure A9. Aerosol mass size distribution from heat exchanger outlet in experiment 4.
H₂O flow 60.5 g/min N₂ flow 25 l/min (NTP), aerosol material Ag and CsOH

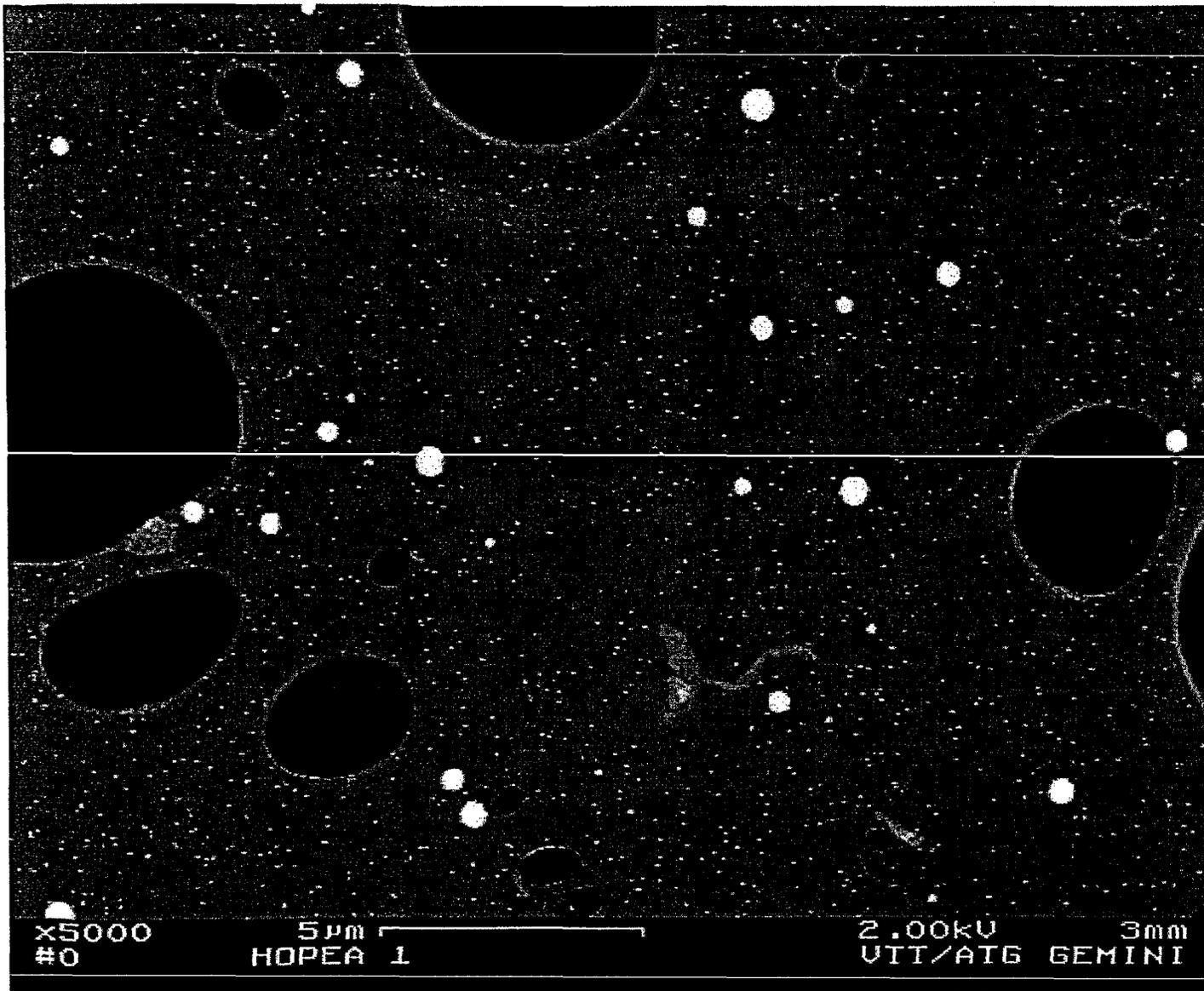


Figure A10. SEM picture of silver particles from experiment 1.

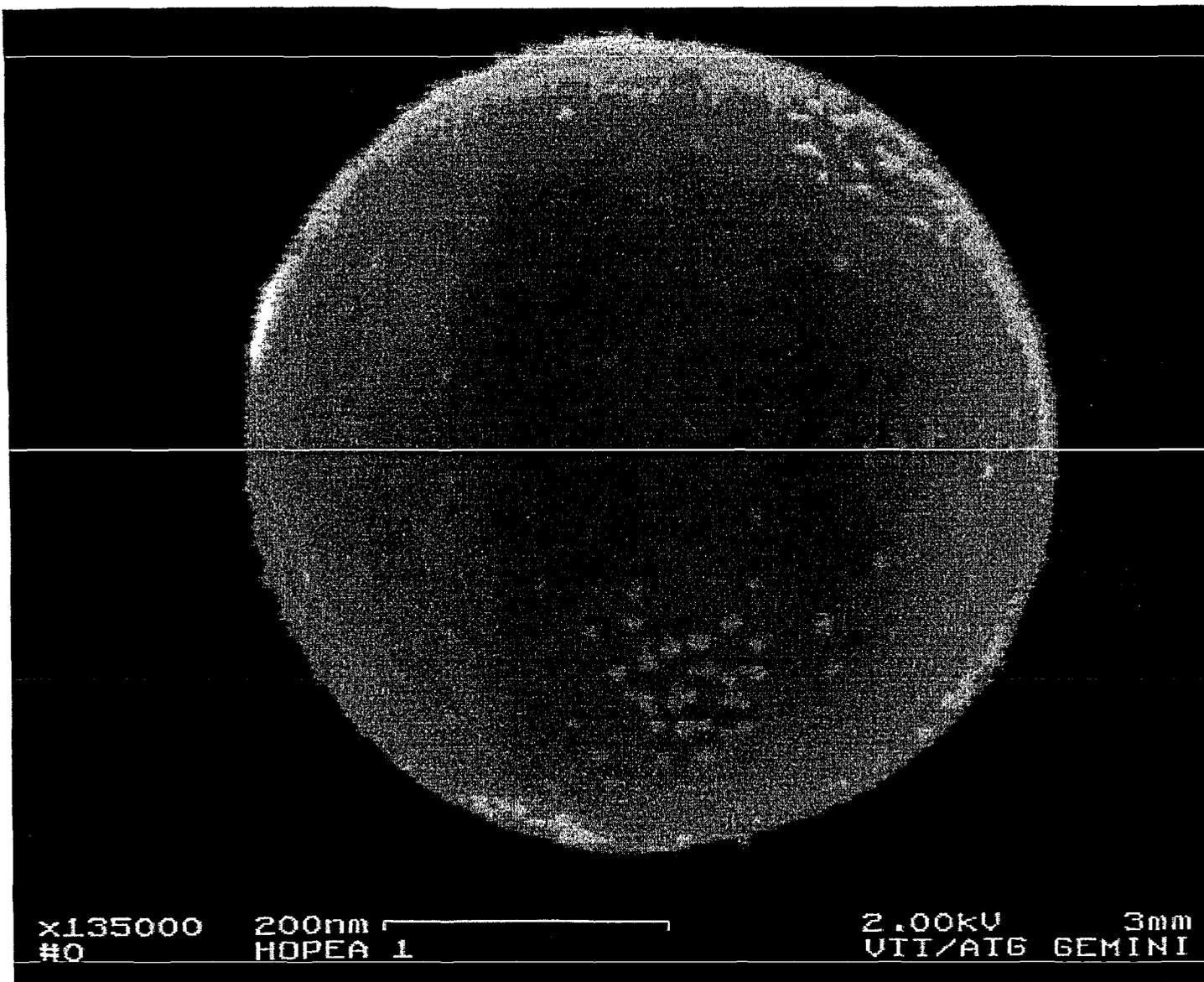
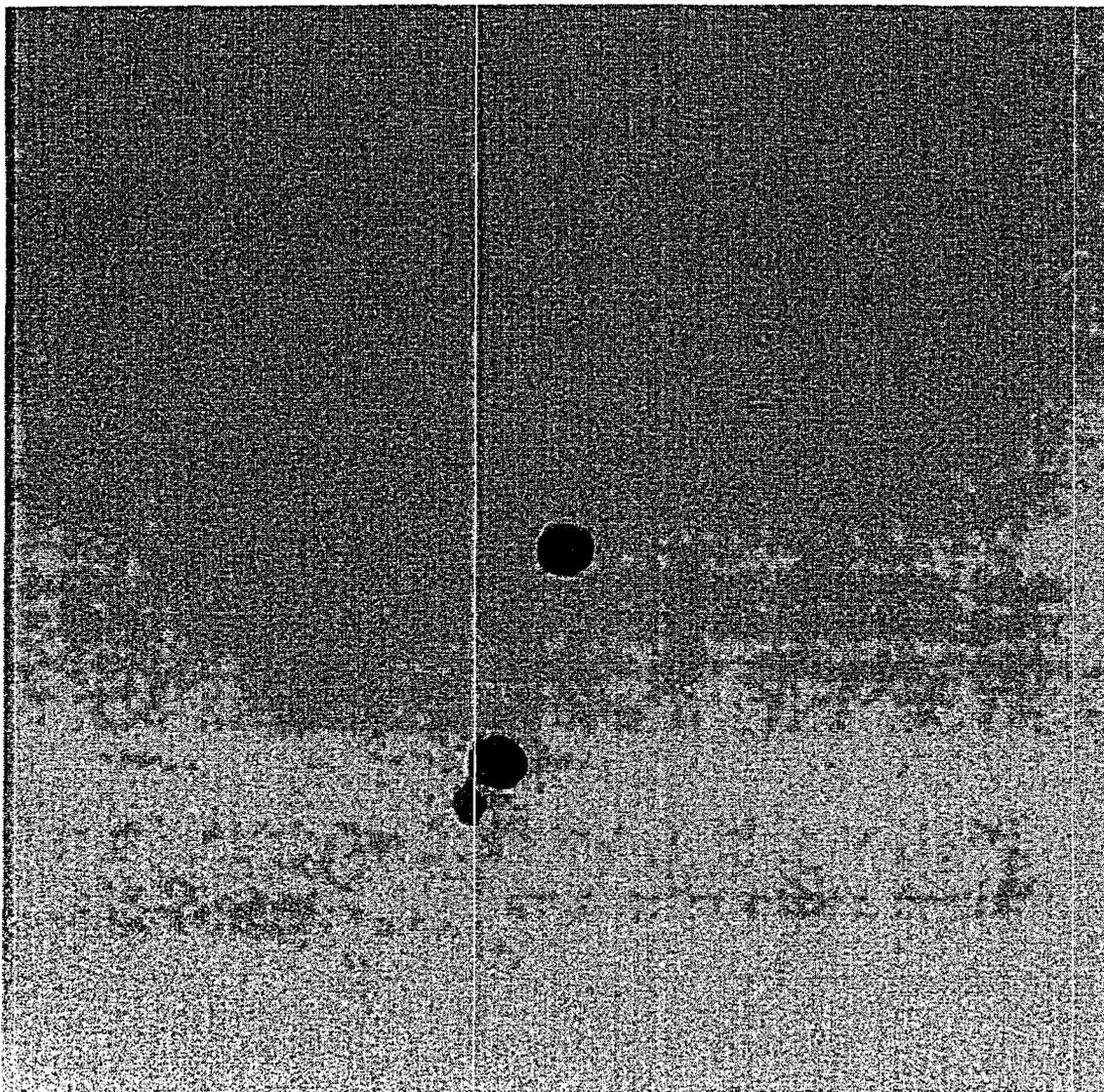


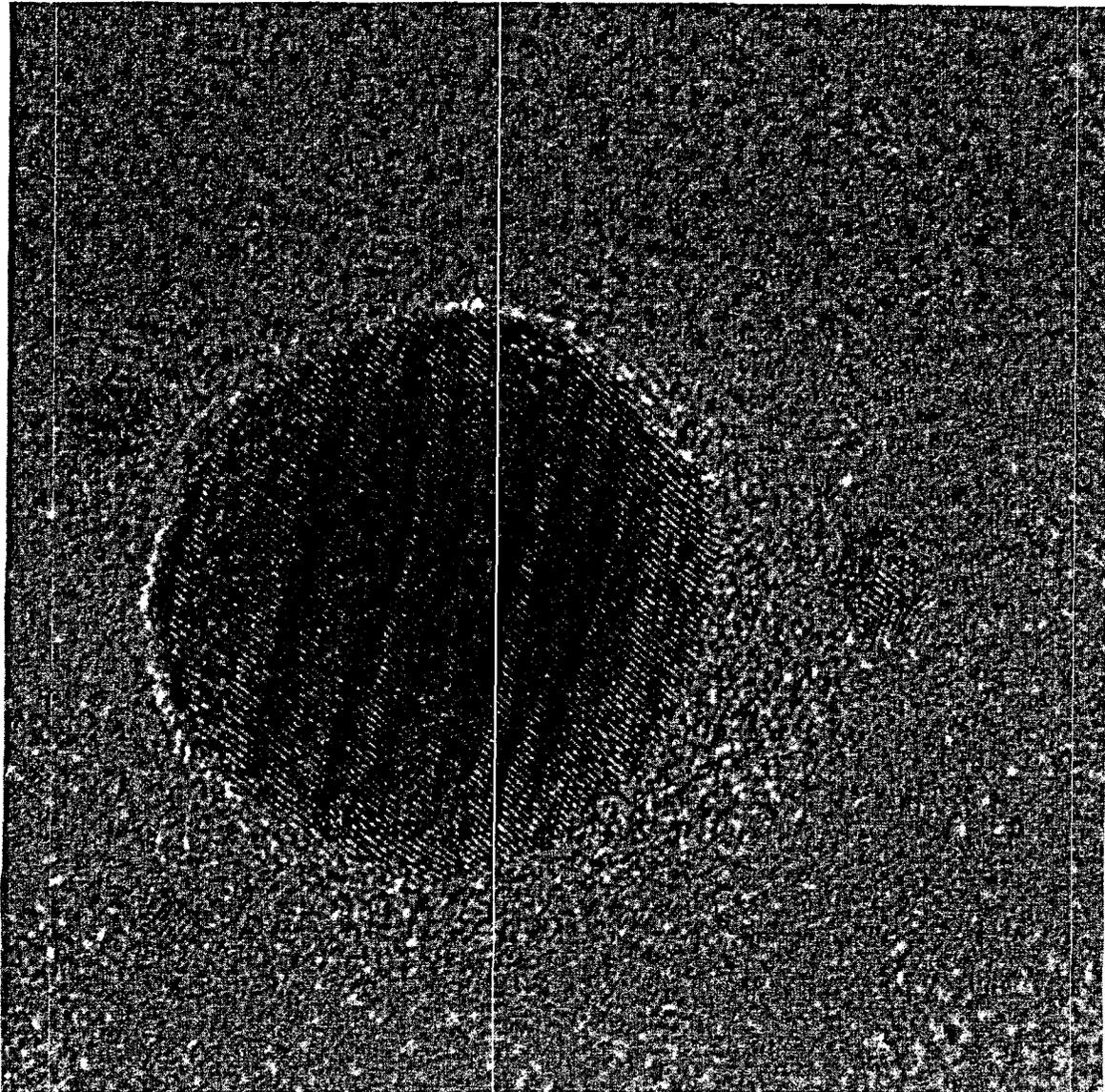
Figure A11. SEM picture of silver particle from experiment 1.



90.00 nm

X30000

Figure A12. TEM picture of silver particles from experiment 1.



5.00 nm
X470000

Figure A13. TEM picture of silver particles from experiment 1.

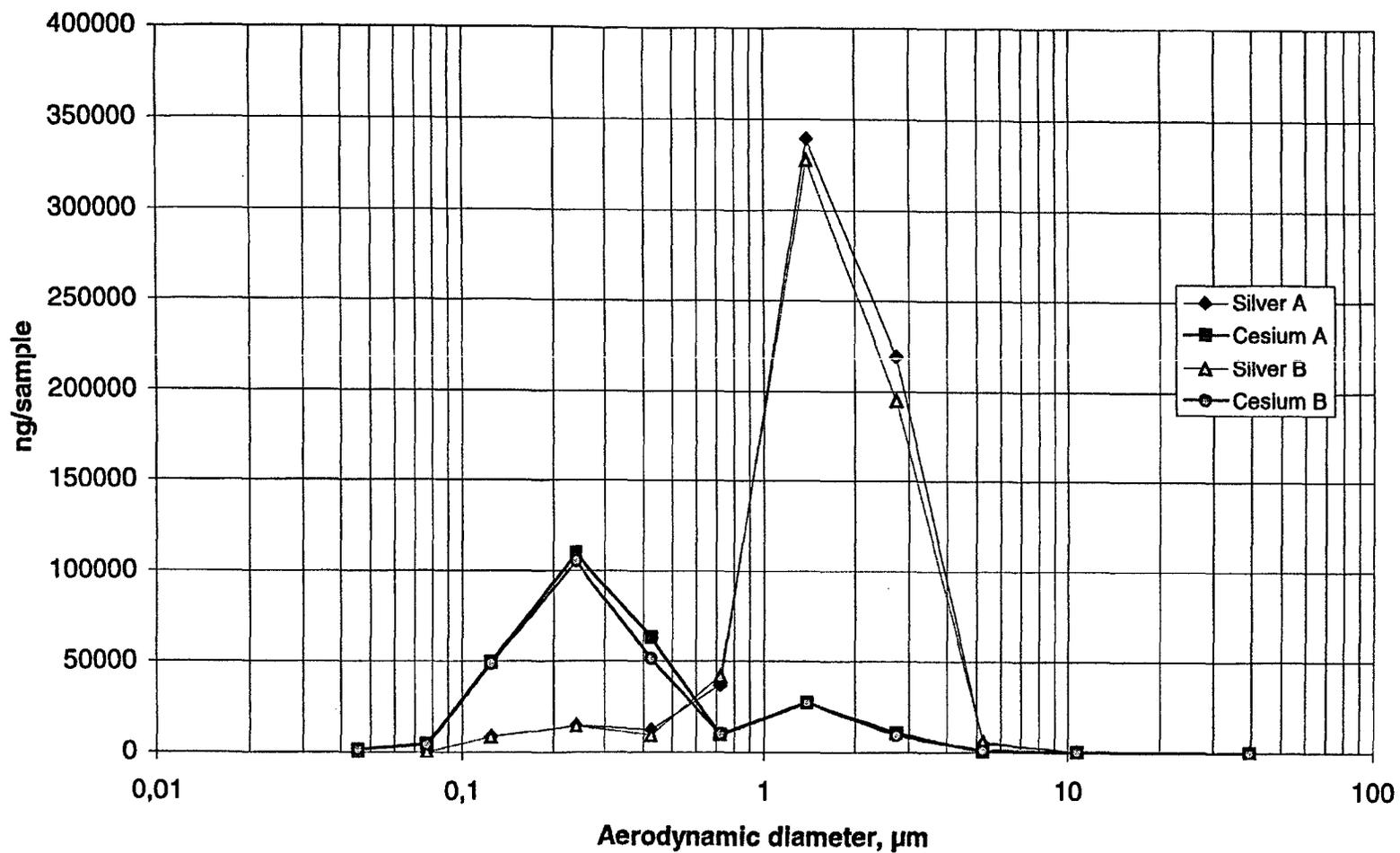


Figure A14. ICP- Mass Spectrometer analysis from experiment 4.

PART B

Application of VTT's AHMED and VICTORIA aerosol experiments to ESBWR containment

B.1 Introduction

The aerosol source to PCCs is from the containment. Containment aerosol behaviour has been studied at VTT since 1985. Two experimental programmes, AHMED and VICTORIA, have been carried out.

In the AHMED programme aerosol was injected in a well instrumented one cubic meter vessel. All gas temperatures were within ± 0.2 °C, surface temperatures were about 0.1 – 0.5 °C lower than the gas temperature and the vessel was mixed with low sedimentation area propeller immediately after aerosol injection. Relative humidity was from 22 % to 97 % and the aerosol materials were NaOH, CsOH, CsI and Ag. The aerosol behaviour of both hygroscopic materials (NaOH, CsOH and CsI) and inert material (Ag) was in good accordance with the code predictions that included a model for hygroscopic aerosols. Thus it could be concluded that the hygroscopic and dry aerosol behaviour are well understood (Mäkynen et al., 1997). Following are the technical specifications of the Victoria facility:

The VICTORIA FACILITY technical specifications are :

- Linear scaling ratio : 1/15.
- Pressure vessel height : 4.60 m.
- Pressure vessel diameter : 3.14 m.
- Maximum pressure : 3 bar.
- Upper compartment free volume : 17 m³.
- Total free volume : 22 m³.
- T-H measurements:
 - gas temperature 99 locations,
 - wall temperature 65 locations,
 - relative humidity 10 locations (± 1 %, RH < 90 %, ± 2 %, RH 90 - 100 %),
 - total pressure,
 - pressure differences and water level at 7 locations,
 - steam and air flow rates into the vessel,
 - local gas velocities with a fibre-optics Laser-Doppler anemometer system (LDA).
- Aerosol measurements :
 - TEOM on-line aerosol mass monitor,
 - CNC on-line aerosol particle number concentration monitor,
 - mass and chemical composition size distribution Berner type low pressure impactors (0.03- 15 μm),
 - dry aerodynamic size distribution by TSI aerodynamic particle sizer (APS),
 - dry number size distribution by electrical mobility analyser (DMA) (0.02 - 0.8 μm),
 - dry number size distribution by electrical low pressure impactor (ELPI) (0.01 - 5 μm),
 - on-line optical particle sizer (0.25 - 40 μm),.
- Aerosol generation:
 - soluble aerosol is generated by two opposite jet atomisers and virtual impactors (max. concentration $\equiv 5$ g/Nm³),
 - non-soluble aerosol is generated by chemical reaction tube furnace from soluble precursors at 900° C,
 - or
 - both soluble and insoluble aerosols with the LEFR reactor by vaporisation-condensation method.

B.2 Victoria tests 58 and 59

In the VICTORIA experiments first test series were carried out in a model containment that had two volumes divided with a plate that had two holes in opposite sides (Mäkynen et. al., 1998). The aerosol was injected into the lower compartment. Following is the description of the facility and test procedure for tests 58 and 59:

The VICTORIA facility is a scale model of the ice condenser containment of the Loviisa NPP (linear scale 1:15, volume scale 1:3375). The height of the pressure vessel is 4.6 m and the diameter is 3.14 m. The aerosols were generated by Opposite Jet Atomiser and Laminar Entrainment Flow Reactors. The maximum capacity of the steam generator was 25 g/s. The main deck, at the plant scale elevation of + 25.4, and the primary coolant pump rooms had been replaced with plywood plate, coated on both sides with phenolic resin. The upper level of this plate was now at +25.8 elevation. There were two round holes ($\varnothing = 125$ mm) at the edges of the plate (90° and 270° , $r = 13.80\text{m}/0.92$ m), through which the aerosols and the steam, injected into the lower compartment, could flow into the upper compartment of the containment. The collecting lines, through which samples were taken out of the upper and lower compartments of the containment, started from different locations inside the containment. To take samples BLPI-impactors use four lines. The starting points of all these lines were in the upper compartment of the containment.

Test number 58 was a CsOH experiment.

First CsOH aerosol was fed into the lower compartment using Opposite Jet Aerosol Generator (10.36 - 11.55). After that steam was fed into the lower compartment (3 g/s; 12.01 - 12.21). Aerosol mass (TEOM) and number (CNC) concentrations during the test were measured in the different locations of the vessel (used sampling lines were changed sequentially). Impactor samples (impactors inside vessel) were started at the time points 11.58, 12.22, 13.52 and 18.52. Detailed experimental procedure is given in the following list :

- ↳ Test start (zero) time 10.36
- ↳ Aerosol generation 10.36 - 11.55; 0-79 min; (100 lpm air); exhaust open
- ↳ Exhaust closed 12.01; 85 min
- ↳ Steam feed 3 g/s 12.01 - 12.21; 85 - 105 min
- ↳ Exhaust open 13.30; 174 min; (pressure difference 0 mbar)
- ↳ Sample flow ~3 lpm
- ↳ BLPI start times: 11.58, 12.22, 13.52 and 18.52 (82, 106, 196 and 496 min)
Durations 1, 1, 3 and 10 min; flow ~25 lpm.

Test number 59 was a CsOH + Ag test.

First Ag aerosol was fed into the lower compartment (9.43 - 10.28) using ultrasonic aerosol generator and Laminar Entrainment Flow reactor (vertical tube furnace). CsOH aerosol was fed into the lower compartment using Opposite Jet Aerosol Generator (10.35 - 11.24). After that steam was fed into the lower compartment (3 g/s; 11.30 - 11.50). Aerosol mass (TEOM) and number (CNC) concentrations during the test were measured in the different locations of the vessel (used sampling lines 1 - 3 were changed sequentially). Impactor samples (impactors inside vessel) were started at the time points 11.28, 11.52, 13.35.30 and 18.33. ELPI (Electrical Low Pressure impactor) and filter samples were also taken during the test (sampling lines I - III were also changed sequentially). Deposition coupons were also used in the test (table 3). The detailed experimental procedure is given in the following list :

- ⌘ Test zero time: 9.43
- ⌘ Aerosol generation (exhaust open)
 - ⇒ Ag feed : time 9.43 - 10.28; 0-45 min. (total input flow with dilution air 37 lpm air)
 - ⇒ CsOH feed: time 10.35 - 11.24; 52-101 min. (flow 100 lpm air)
- ⌘ exhaust closed 11.30; 107 min.
- ⌘ steam feed 3 g/s; time 11.30 - 11.50; 107-127 min.
- ⌘ exhaust open 12.43; 180 min.
- ⌘ Sample flow TEOM+CNC ~ 3 lpm and ELPI+filters ~ 4 lpm
BLPI start times: 11.28, 11.52, 13.35.30, 18.33 (105, 129, 232.5, 530 min.)

The evolution of aerosol concentration is presented in figures B.1 and B.2. Lines 1 and 2 are from the upper compartment where the T-H conditions were fairly homogeneous. The lower compartment, where aerosol was injected, was at saturated conditions. One can see that the concentration is at highest in the lower compartment at the end of aerosol injection, but decreases faster as compared to the upper compartment because of the saturated conditions. The relative humidities at the upper compartment are presented together with the impactor measurements. In test 58 impactor measurements give a bit higher concentrations as compared to TEOM measurements. The reason for this can be that there are some losses in the TEOM sampling lines even though they were heated. As CsOH is very hygroscopic and grows at humid conditions losses of large particles at sampling inlet are possible. The impactors were placed inside the VICTORIA vessel and thus the losses do not affect these results. In test 59, where non-hygroscopic silver aerosol was used, there are no losses as the impactor and TEOM measurements give exactly the same results.

The experimental results are tabulated in tables B.1 and B.2. One can see that the CsOH particles grow larger than Ag particles and also settle faster as expected.

Table B.1. Measured aerosol properties (Upper compartment) in the CsOH experiment (test 58).

Test conditions:

- CsOH feed ~5 mg/s from t = 0 - 79 min; AMMD ~2.3 μm ; GSD ~1.9
- steam feed 3 g/s from t = 85 - 105 min

Time[min]	RH [%]	Mass [mg/Nm^{-3}]	Cs [mg/Nm^{-3}]	Number [$\#/ \text{cm}^{-3}$]	AMMD [μm]	GSD
82	90	600	600	~ 8.0 E5	2.9	1.9
106.5	98	260	260	~ 2.4 E5	4.1	1.9
197.5	88	75	75	~ 5.0 E4	2.5	1.7
501	87	5.5	5.5	~ 1.7 E4	1.7	1.7

Table B.2. Measured aerosol properties (Upper compartment) in the CsOH-Ag experiment (test 59).

Test conditions:

- Ag feed from t = 0 - 45 min; AMMD ~2.1 μm ; GSD ~ 1.6
- CsOH feed ~5 mg/s from t = 52 - 101 min; AMMD ~2.3 μm ; GSD ~1.9
- steam feed 3 g/s from t = 107 - 127 min

Time[min]	RH [%]	Mass [mg/Nm^{-3}]	Cs [mg/Nm^{-3}]	Total Number [$\#/ \text{cm}^{-3}$]	AMM D [μm]	GSD	Ag [mg/Nm^{-3}]	AMM D [μm]	GSD
105	77	375	366	~ 7.0 E5	2.5	1.9	8.5	2.1	1.6
129	97	255	251	~ 4.0 E5	3.0	2.0	3.8	2.5	1.7
234	86	60	59	~ 1.0 E5	2.2	1.7	1.1	2.3	1.6
532.5	85	6	5.9	~ 3.0 E4	1.6	1.7	0.07	2.1	1.7

B.3 Victoria tests 61 and 62

Further VICTORIA experiments were performed in Loviisa ice condenser containment configuration with ice and without ice. There was a convection loop through the ice condensers. The configuration and sampling lines are presented in figure B.3 and the test procedure of test 61 in table B.3.

The convection loop gave a good mixing and saturated conditions were prevailing in both dome (line 1+impactors) part of the upper containment and in the lower compartment (line 3). There was stratification in the upper compartment between the ice condensers and saturated conditions were not reached in this part (line 2). The relative humidity was close to 90 % in the upper compartment and thus the aerosol removal was lower in this part. In figures B.4 and B.5 the measured concentrations in tests 61 (CsOH) and 62 (Ag) are presented. The different decay rate at saturated and non-saturated conditions is larger for hygroscopic CsOH aerosol than for non-hygroscopic silver particles.

Table B.3. Experimental procedure

- Vessel preheated - Exhaust closed	Time (min)
START	0
Ice condenser doors opened	
Aerosol injection line side (hot side)	0
Opposite section (cold side)	1
Steam injection	
5 g/s	0 - 55
2 g/s	55 - 371
off	371
Aerosol generation ~2.75 mg/s CsOH (~100 lpm air)	60 - 90
Sampling lines (sampling flow depends on the vessel pressure)	
lines 1-3 (TEOM)	0 - 360
lines I - III (ELPI and CNC)	58 - 360
Impactor samples (start time / duration)	
1	93 / 1.5
2	150 / 1.0
3	240 / 5.0
4	360.5 / 10.0

B.5 Conclusions

As a conclusion of the containment experiments performed at VTT we can say that the aerosol modelling is fairly accurate in the existing codes using hygroscopic models and sectional representation for the size distribution. The largest uncertainty lies on predicting the thermal-hydraulic conditions in aerosol models as condensation is very sensitive to relative humidity. Especially in complex geometries the accuracy of the current lumped parameter codes is only moderate. At saturated conditions the decay rate of hygroscopic particles is much higher as compared to inert particles. At lower relative humidities the difference is only moderate.

B.6 References

Mäkynen,J; Jokiniemi,J; Ahonen,P; Kauppinen,E; Zilliacus,R AHMED experiments on hygroscopic and inert aerosol behaviour in LWR containment conditions: experimental results, Nuclear Engineering and Design. Vol. 178 (1997), 45 - 59

Mäkynen,J; Jokiniemi,J; Silde,A; Kauppinen,E; Outa,S.; Routamo,T; Tuomisto,H Experimental and modelling studies on containment aerosol behaviour in the VICTORIA facility, Proceedings of the 3rd OECD Specialist Meeting on Nuclear Aerosols in Reactor Safety. Cologne, DE, 15 - 18 June 1998 (1998), 13 p.

Test 58; CsOH aerosol

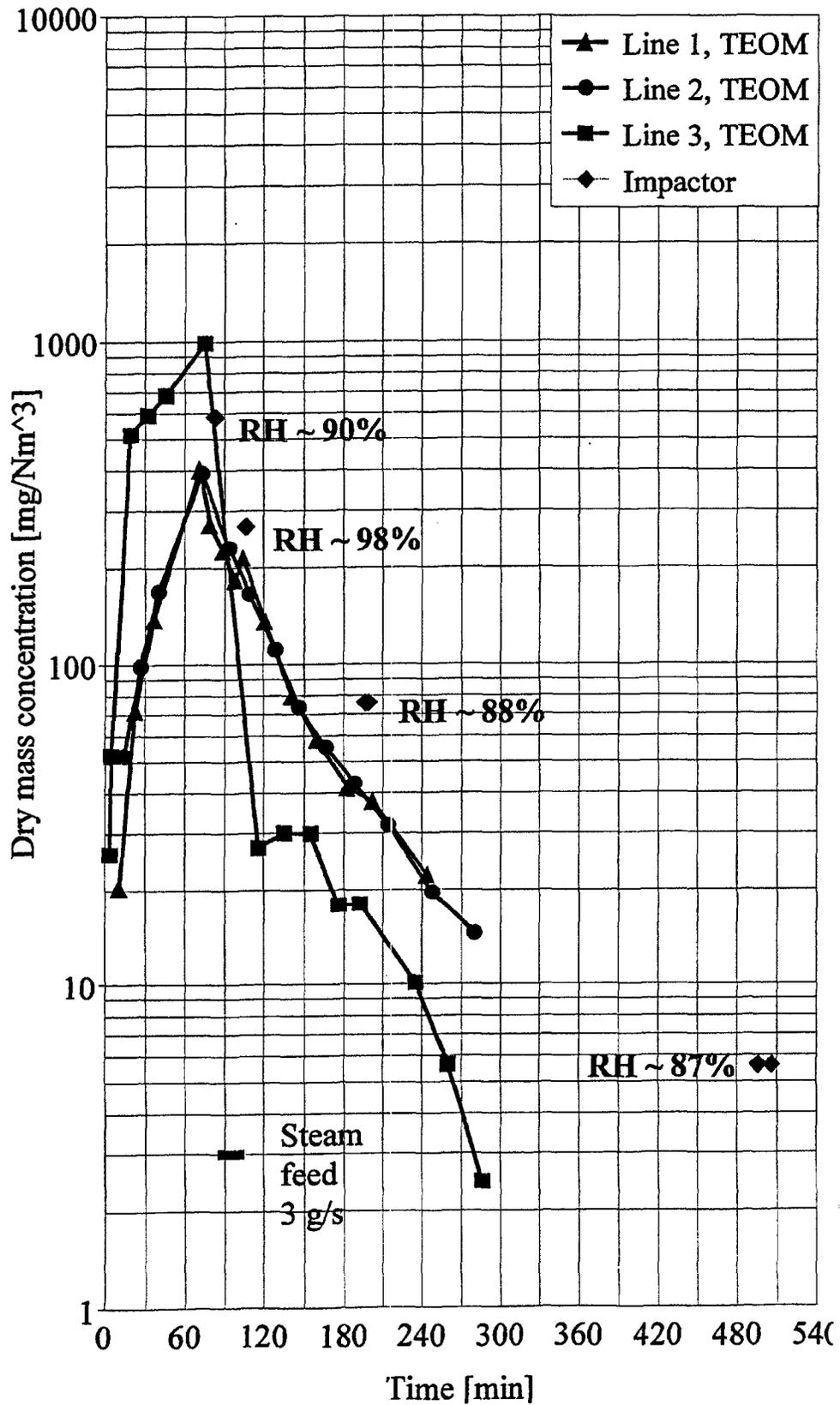


Figure B.1. CsOH aerosol mass concentrations in Victoria test 58.

Test 59; CsOH + Ag aerosol

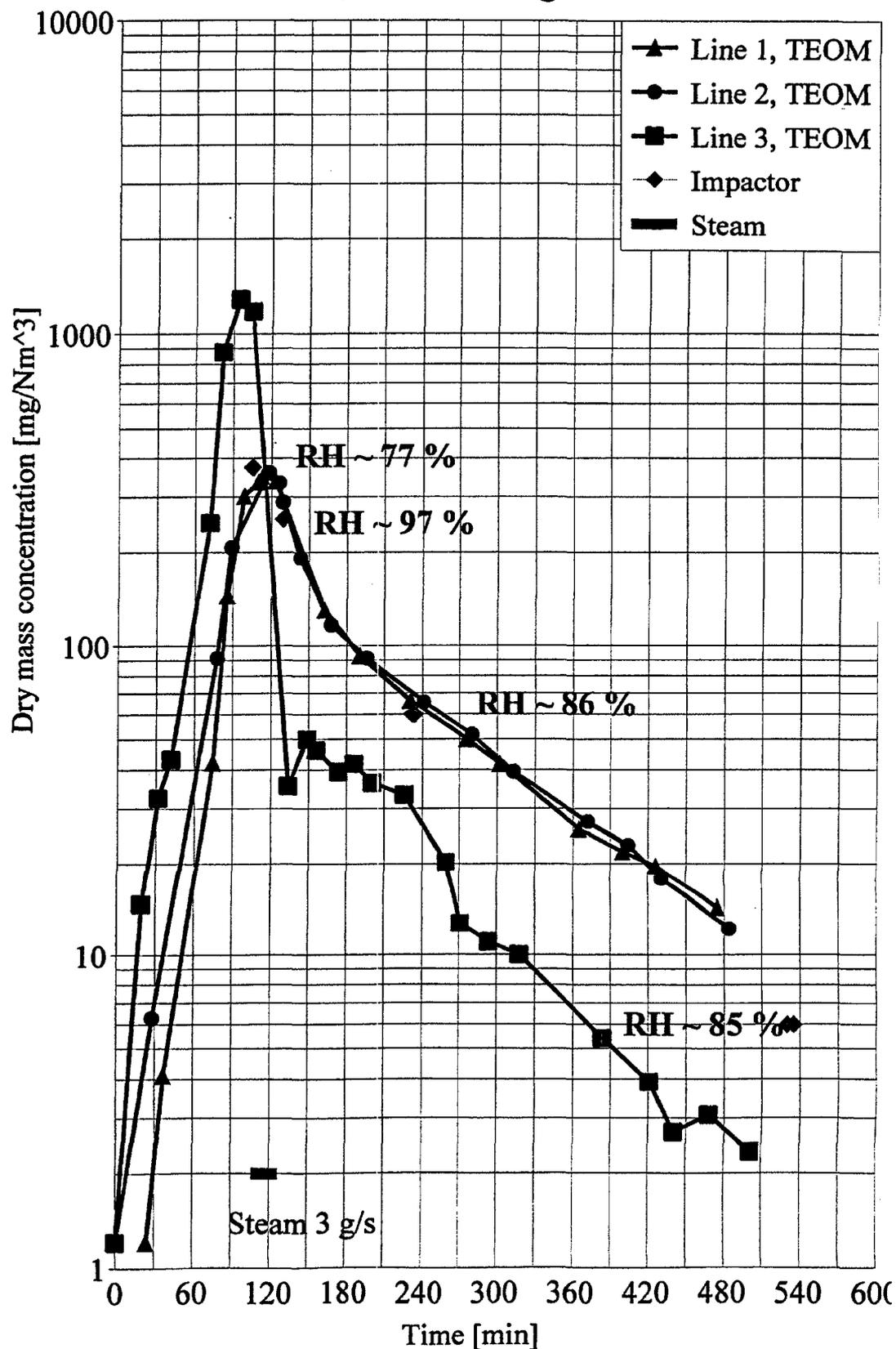
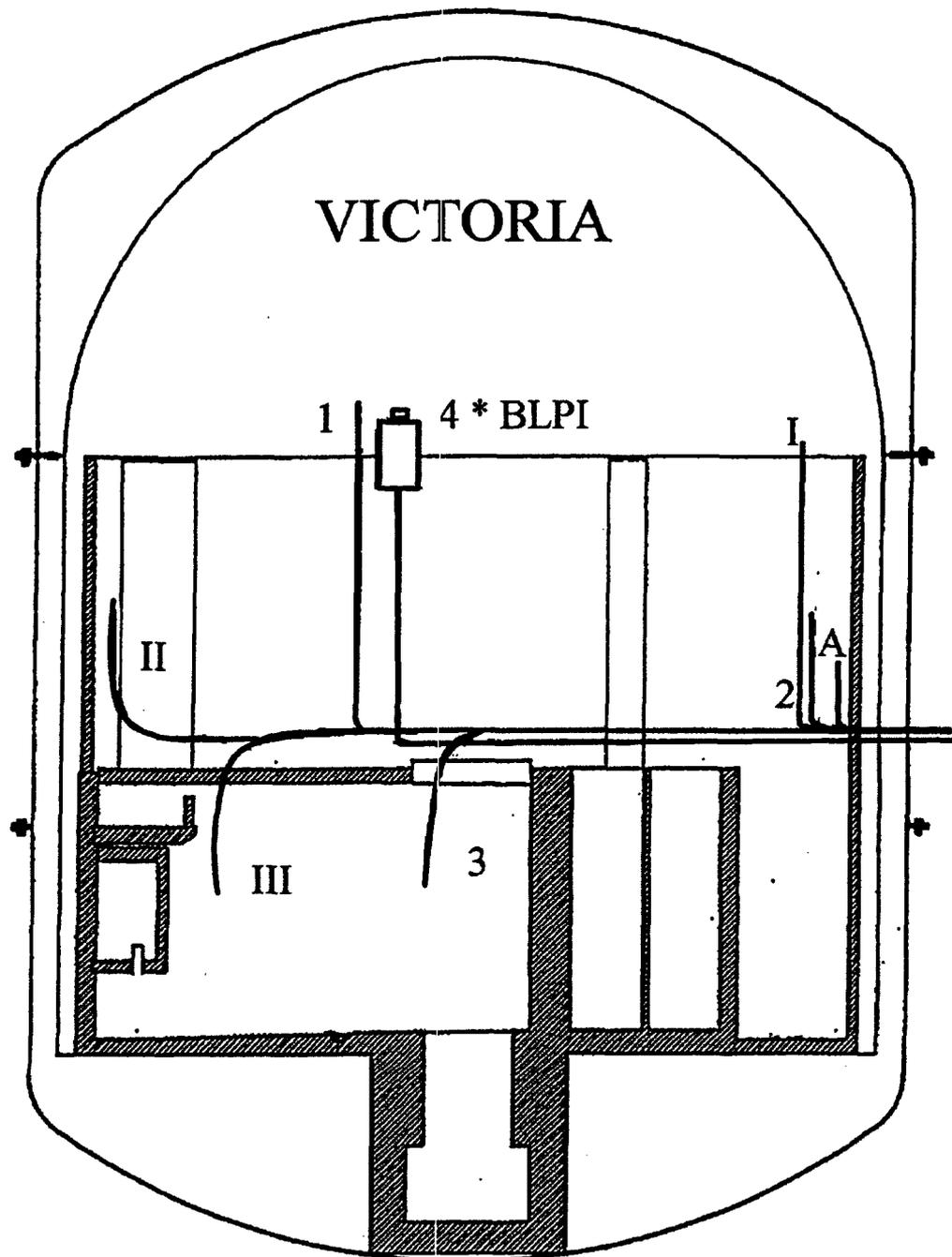


Figure B.2. Aerosol mass (CsOH+Ag) concentrations in Victoria test 59.



Heated and insulated aerosol sampling lines

I-III: ELPI (Electrical Low Pressure Impactor)

Size distribution and concentration (0.03-5 μm).

1-3: TEOM (Tapered Element Oscillating Microbalance)
and CNC (Condensation Nucleus Counter)

Mass and Number concentration.

Figure B.3. Schematic figure of aerosol sampling lines in Victoria tests 61 and 62.

Test 61

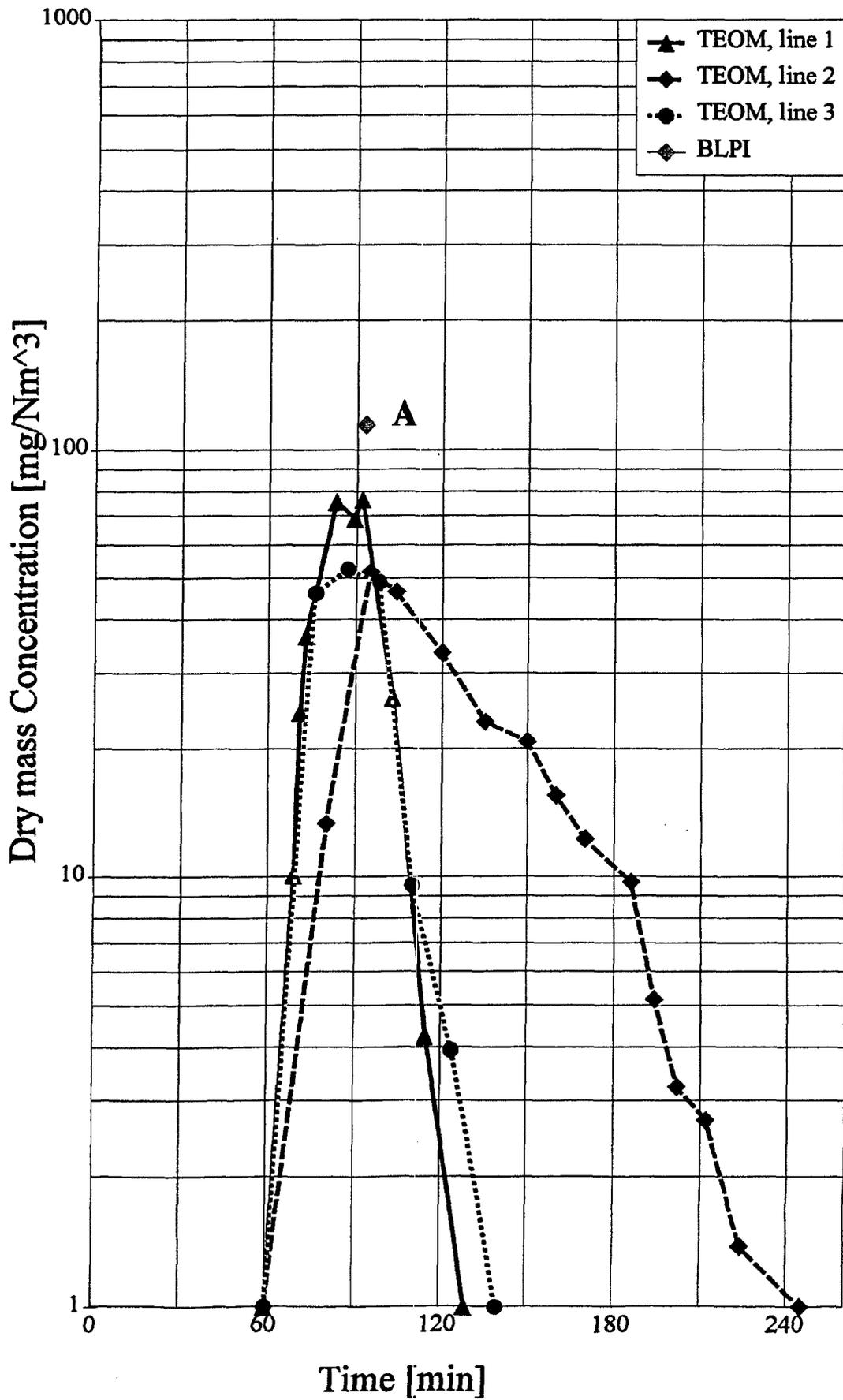


Figure B.4. CsOH aerosol mass concentrations in Victoria test 61.

TEST 62; TEOM

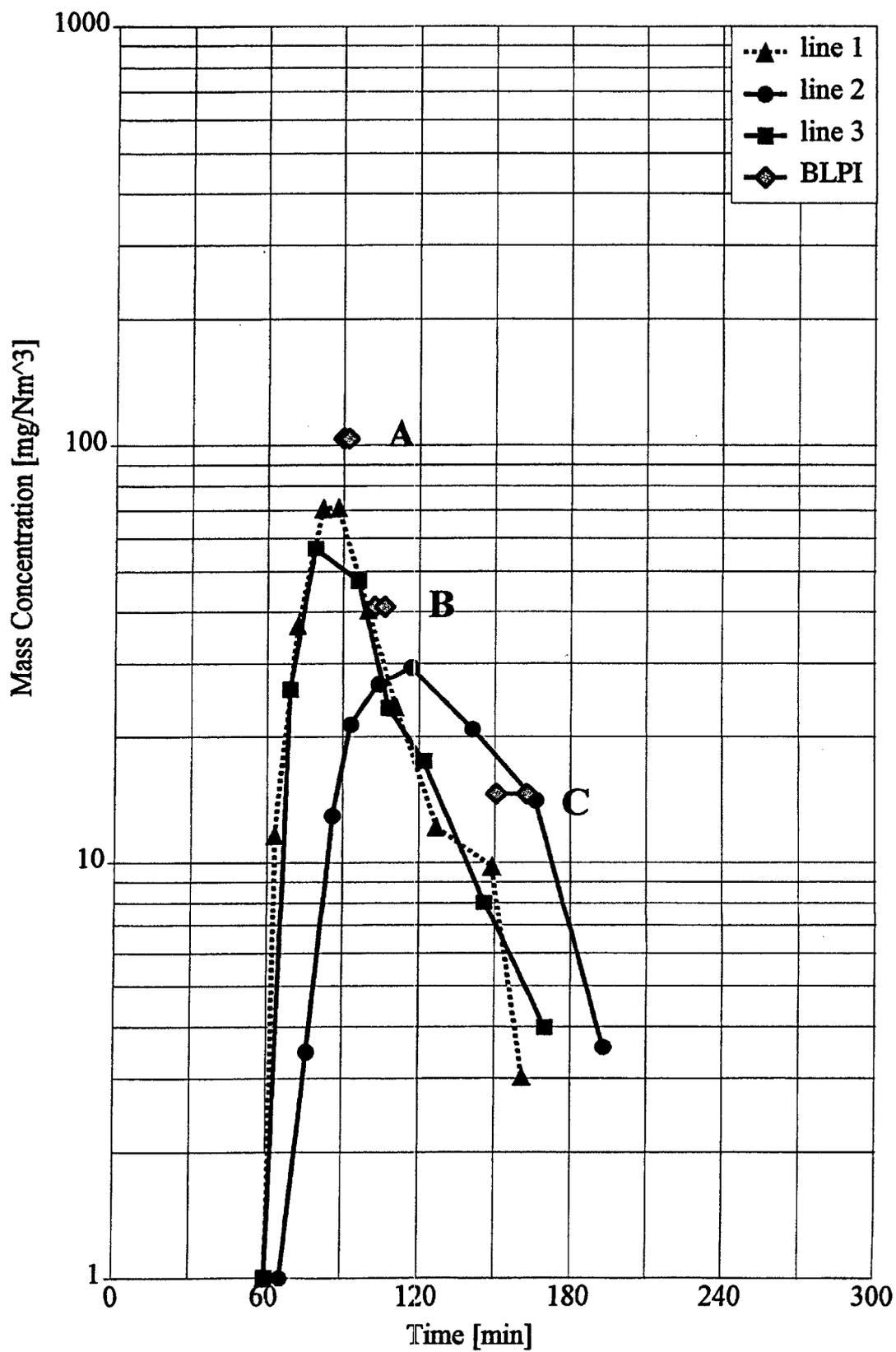


Figure B.4. Ag aerosol mass concentrations in Victoria test 62.