

**CT98-2234: Feasibility of a new generation of test  
apparatus for airborne particulate systems**

**SYNTHESIS REPORT  
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## **PROJECT SUMMARY CONTRACT SMT4-CT98-2234**

### ***Background***

At present, large-scale complex facilities such as wind tunnels and test cabins are needed to develop and test aerosol samplers (e.g. personal samplers on manikins), biosafety cabinets and ventilation systems. Full-scale tests are time-consuming and can only be carried out in the small number of institutes that have suitable facilities. It is theoretically possible to dimensionally scale these experiments, while at the same time retaining dynamic similarity, and thus obtain the same results on different scales. To date however scaled aerosol test systems have not been implemented and validated. The motivation for this project is the very significant cost savings that could result from a successful implementation of scaled aerosol testing. Measurements carried out on a reduced scale will employ much faster measurement techniques, be less costly and therefore accessible to a wider range of potential users.

### ***Objectives***

The aim of this project is to reduce the dimensions of aerosol test specimens and systems by up to one-fifth of full scale. The validity of the results is established by comparing full-scale and small-scale aspiration-efficiency measurements on a selection of typical dust monitoring inlets.

### ***Work Programme***

The first step was to develop the scaling methodology and to verify it by means of computational fluid dynamics. Scaled test systems for both calm air and for moving air scenarios were then constructed. Experiments were carried out on at least three different scales, simulating different external conditions (i.e. wind speed, orientation). These provide examples of typical applications for the scaled test systems. The results were analysed to deduce the range of conditions for which scale-invariance was obtained. Publications, conference and meeting presentations have been prepared to disseminate the results from the research.

### ***Results and Achievements***

Five experimental systems suited to carrying out aspiration measurements on different scales were developed, commissioned and evaluated. Four of the systems were wind tunnels, ranging in cross-section from 30 cm to 2 m, and one a calm-air chamber. Experimental tests were carried out in moving air on four different test inlets, and on scales ranging from full size to one-fifth scale. Size-dependent losses of particles in the test system were also measured. The results verified that scaling principles can be applied to aerosol test systems, provided that gravity is not a dominant effect within the system, and that the practical realisation ensures that losses of particles are matched in both the test and reference measurements. This latter constraint is difficult to achieve and is the main factor limiting practical application of the methodology.

Keywords: Aerosols, scale invariance, airborne particles, workplace, air pollution



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## 1. INTRODUCTION

At present, large-scale complex facilities such as wind tunnels and test cabins are needed to develop and test aerosol samplers (e.g. personal samplers on manikins), biosafety cabinets and ventilation systems. Full-scale tests are time-consuming and can only be carried out in the small number of institutes that have suitable facilities. It is theoretically possible to dimensionally scale these experiments, while at the same time retaining dynamic similarity, and thus obtain the same results on different scales. To date however scaled aerosol test systems have not been implemented and validated. The motivation for this project is the very significant cost savings that could result from a successful implementation of scaled aerosol testing. Tests carried out on a reduced scale will employ much faster measurement techniques, be less costly and therefore accessible to a wider range of potential users.

## 2. THE CONSORTIUM

The project was carried out by the following partners:

HSL: The Health and Safety Laboratory, Sheffield, UK, acting as Coordinator;

FHG: The Fraunhofer-Institute of Toxicology and Aerosol Research, Hannover, Germany;

ISAC: The Institute for Atmospheric and Climatic Science, Bologna, Italy;

LU: The Division of Working Environment at Lund University, Lund, Sweden;

BU: The Physics Department of Bologna University, Bologna, Italy;

BIO: BiOikòs srl, Bologna, Italy (subcontractor to ISAC);

IOM: The Institute of Occupational Medicine, Edinburgh, UK (subcontractor to HSL);

NIWL: The Swedish National Institute for Working Life, Solna, Sweden (subcontractor to LU).

Brief organisational descriptions are given at the end of this report.

## 3. THE TECHNICAL WORKPROGRAMME (WP = WORK PACKAGE)

The project was divided into four work packages. WP 1 was concerned with theoretical and computational verification of scaling relationships. The objective was to develop a scaling methodology for airborne particle flows, and to verify this methodology using computational fluid dynamics. WP 2 was concerned with practical realisation of novel small-scale test apparatus. The objective was to assess the practical feasibility of realising novel small-scale test apparatus. WP 3 was concerned with verification of scale-invariant test results. The objective was to establish the validity of the results obtained using the novel test apparatus by

carrying out both full-scale and small-scale tests on a selection of simplified particle size-selective inlets. WP 4 covered analysis, reporting, assessment and exploitation of the results. The objective was to evaluate the results of the project, and to maximise the impact of the project through publications and presentations.

#### **4. OVERVIEW OF THE RESULTS OF THE WORK**

##### **WP 1 : Theoretical and computational verification of scaling relationships**

Relevant literature on the theoretical basis for scaling of particle flows was reviewed in order to develop a scaling methodology for moving air scenarios. A scaling approach was recommended, making the simplifying assumption that the inlet aspiration efficiency is primarily a function of only four variables. In principle, scale-invariance could be achieved by scaling down the physical dimensions of both sampling inlets and particles, while simultaneously scaling up the air velocities and inlet flow rates by the same constant factor. This scaling methodology was investigated and confirmed using Computational Fluid Dynamic simulations of aerosol sampling inlets. CFD simulations were also carried out for three test inlets later used for preliminary experiments with the novel test systems (see WP2 below). The simulation results were compared with the experimental data. A fair level of agreement between the CFD simulations and experimental results was achieved.

The problem of scaling in calm air sampling was also reviewed and it was shown that although scaling was theoretically possible, it could not be practically implemented using standard laboratory techniques. An experimental approach for numerically modelling calm air aspiration efficiency using a small subset of governing variables was devised.

##### **WP 2 : Realisation of novel test apparatus**

Four wind tunnels on different scales were deployed for use in this project. The wind tunnel systems covered a very wide range of dimensions giving the capacity to test the scaling methodology for scale factors up to around eight, although the limit for investigation was a factor of five. A preliminary experiment, testing the same set of sampling inlets, was designed and carried out in each wind tunnel facility. The results from each wind tunnel system were compared, to identify the factors determining the accuracy and precision of results.

A calm air test system was set up, consisting of a dust chamber into which particles fall by sedimentation. The system was similar to calm air chambers previously developed for tests on full-size samplers, and preliminary experiments were carried out to verify that the published results of previous tests could be reproduced.

### **WP 3 : Verification of scale-invariant test results**

The Consortium agreed to test four different test objects in the moving air systems, two relevant to workplace aerosol sampling, and two to ambient aerosol sampling. These were:

- Caltool mouth (as developed in project CT98-2254)
- IOM sampler on Caltool chest
- TSP inlet
- Dichot inlet

The first two are unidirectional inlets that require testing in specified orientations with respect to the external wind. Caltool is a simulated, breathing, life-size simplified human shape, whose mouth has been designed to have the same aspiration characteristics as the human mouth. In use, the aerosol mass collected by an inhalable aerosol sampler mounted on the torso of Caltool (such as the IOM sampler used here) is compared directly to the reference mass collected by Caltool mouth. The Dichot and TSP inlets are omnidirectional samplers used for monitoring pollution in the ambient atmosphere. Each test inlet was manufactured on three different scales, ranging from double-scale TSP, to one-fifth-scale Caltool. The experimental plan drawn up for the moving-air experiment ensured that each small-scale test inlet would be tested in at least two different wind tunnels. Tests on the scaled inlets were carried out using the methodology developed in WP2. Supplementary experiments were also carried out to investigate losses of particles within the different test systems, and to assess the impact these had on the results obtained.

The experimental plan drawn up for the calm-air experiment was designed to estimate the aspiration efficiency function as a quadratic response surface depending on four variables. Simple tubular test inlets were manufactured from conductive plastic. The internal and external diameters of the test samplers, the particle sizes of the test aerosol, and the flow rates of the test samplers were all chosen to give balanced coverage of variables over the ranges of interest. Tests were carried out using the methodology developed in WP2.

**WP 4 : Analysis, reporting, assessment and exploitation of results**

The data from the moving air tests were analysed to assess systematic and random experimental errors. Random errors in the data were due to spatial and temporal fluctuations in the particle concentration and size distribution. In general, the small-scale results had experimental errors of similar magnitude to full-scale results. Systematic errors occurred when the losses of particles in the test inlets were different from the losses in the reference inlet samples taken for each test. Where present, systematic errors may prevent verification of the scaling principle as they influence the mean sampling efficiency. A detailed analysis of the particle loss data concluded that systematic errors were indeed present in the data for the TSP and dichot inlets due to unavoidable losses within the test inlets. For these inlets, scale-invariance was in general not observed. For the Caltool however, systematic errors were concluded to be insignificant. Although some of the IOM-on-Caltool results were not statistically significant due to random experimental errors, the scaling principle was indeed verified by the Caltool results. For the Caltool mouth inlet, the small scale results were indistinguishable from full-scale results.

Very large cost savings resulted from carrying out tests on reduced scales. The initial work in setting up a small scale test system was found to be just as onerous as setting up a full-scale system although facility costs are lower. Once the system is running well, tests with a small-scale system take a matter of minutes to perform, allowing the entire particle size range to be covered in typically less than 20 minutes. Hence overall, cost savings of more than 2 orders of magnitude can be made by testing in a small-scale system.

The analysis of the data from the calm air experiment demonstrated that it was possible to model calm-air aspiration efficiency as a function of only three dimensionless variables; other variables included in the experiment proved to be unimportant. An empirical model was fitted to the results obtained within the project, and this allows the calm-air aspiration efficiency to be predicted numerically for many practical situations. This model is a considerable improvement over previous models for calm-air aspiration efficiency and will be of great benefit to the designers of new sampling systems.

Other work carried out included the dissemination of the project and its results. Several scientific papers were prepared and submitted for publication. The work was also presented

at conferences. A full list of publications and presentations is given at the end of this report. Plans are in hand to write several further papers and to present the final results at international conferences. Other dissemination efforts included the development of an exhibit, website and video depicting this and related EU-funded projects, under the umbrella title ‘Joining forces against dust’. This work was funded as an accompanying measure (CT98-6541). The web address is [www.nomoredust.org.uk](http://www.nomoredust.org.uk), which will be maintained until at least 2003.

## 5. CONCLUSIONS

Overall this project was a partial success. We demonstrated how scaling principles can be applied to aerosol test systems, at least under the following restricted circumstances:

- For dimensional scales down to one fifth of full scale (although results are less successful at extreme scales)
- For inlets where the geometry allows losses in the test system to be minimised, and matched in both test and reference samples
- And for the purposes of practical realisation, to moving-air systems only.

Our results showed it is not at all a simple matter to obtain reproducible, repeatable, unbiased data in a small-scale test system, however the cost savings make it worthwhile to pursue further. Efforts are necessary to convince the aerosol science community and manufacturers of aerosol devices that small-scale testing is a viable alternative to full-scale testing. Some practical steps needed to simplify the experimental procedures were identified by the project team. Detailed recommendations for how to take the work forward are given in final report.

## 6. PUBLICATIONS AND CONFERENCE PRESENTATIONS

### ***Publications submitted***

Numerical determination of personal aerosol sampler aspiration efficiency, by Lo Savio, S, Paradisi, P, Tampieri, F, Belosi, F, Morigi, M.P and Agostini, S. This paper has been accepted for publication in Applied Occupational and Environmental Hygiene.

Efficienza di ingresso dei campionatori personali: considerazioni ed aspetti critici, by F. Belosi, M.P Morigi, S. Agostini, F. Tampieri, S. LoSavio, P. Paradisi. Published in G. AIDII.

Determinazione dell’efficienza di ingresso dei campionatori personali mediante simulazioni numeriche, by F. Belosi, M.P Morigi, S. Agostini, F. Tampieri, S. LoSavio, P. Paradisi. Published in G. AIDII.

**Conference presentations made**

L.C Kenny, G. Beaumont, A. Gudmundsson and W. Koch(2000). Small-scale aerosol sampler testing systems. *J. Aerosol Sci.* Vol 31 suppl.1, S406

L.C.Kenny and A. Thorpe (2001). Small-scale aerosol sampling systems. Proceedings of the 12<sup>th</sup> Aerosol Society conference, Bath, UK.

S. LoSavio, P. Paradisi, F. Tampieri, F. Belosi, M.P. Morigi, S. Agostini (2002) Il contributo delle simulazioni numeriche (CFD) alla determinazione dell'efficienza di ingresso dei campionatori personali di aerosol. AIDII Conference, Viterbo Italy, May 2002

F. Belosi, M.P Morigi, S. Agostini, F. Tampieri, S. LoSavio, P. Paradisi (2002) Efficienza di aspirazione dei campionatori: lo stato della ricerca europea. AIDII Conference, Viterbo Italy, May 2002

**Publications in preparation**

- 1) Development of small-scale test systems for characterising aerosol sampling inlets in moving air
- 2) Characterisation of the inlet efficiency of the TSP and dichot sampling inlets in moving air
- 3) Investigation of a scaling methodology for aerosol inlet efficiency in calm air

**Conference presentations planned**

Andrew Thorpe, David Mark\* and Lee C. Kenny, Particle losses in a time-of-flight system for measuring reference concentrations in a wind tunnel . Presentation to be made at the 2002 AAAR conference, North Carolina, October 2002.

L.C Kenny, G. Beaumont, A. Gudmundsson and W. Koch, Aspiration and transfer efficiencies of the TSP and dichotomous PM sampling inlets. Presentation to be made at the 2003 AAAR PM conference, Pittsburgh, April 2003.

Presentation of the final results is planned for the 2003 European Aerosol Conference.

**Technical Reports available from the Coordinator**

Francesco Tampieri, Franco Belosi, Simone Lo Savio, Paolo Paradisi, Maria Pia Morigi, Giuseppina Maltoni Giacomelli and Sergio Agostini. (2000). Project CT98-2234: Feasibility of a new generation of test apparatus for airborne particulate systems. Technical Report on Task 1: Development and CFD simulation of scaling methodology.

Anders Gudmundssen (2000). SMT4-CT98-2234: Feasibility of a new generation of test apparatus for airborne particulate systems. Technical report on task 2: Construction of novel apparatus.

Wolfgang Koch (2001). SMT4-CT98-2234: Feasibility of a new generation of test apparatus for airborne particulate systems. Technical report on task 3: Testing of inlets on different scales.

Lee Kenny (2002). Feasibility of a new generation of test apparatus for airborne particulate systems. Technical report on task 4: Analysis of data.

## 7. DETAILED INFORMATION ON THE CONSORTIUM

### 7.1 Overview of the consortium

**Table 1 Participants and roles**

No.	Organisation	Type	Role	Country	Business activity	Function in project
P.1	HSL	OTH	C	GB	Research/services in workplace health and safety	Coord., Inv., Dev., Test., Steer.
P.2	FHG	ROR	P	DE	Research/services in air quality	Inv., Dev., Test., Steer.
P.3	ISAC	ROR	P	IT	Geophysical and environmental research	Inv., Mod., Cons., Steer.
P.4	LU	EDU	P	SE	Research/services in air quality	Inv., Dev., Test., Steer.
P.5	BU	EDU	AP (to P.3)	IT	Medical physics research	Inv., Cons., Steer.
P.6	BIO	IND1	S (to P.3)	IT	Research/services in workplace and environmental health and safety	Inv., Mod., Cons., Steer.
P.7	IOM	ROR	S (to P.1)	GB	Research/services in workplace health and safety	Inv., Dev., Test., Steer.
P.8	NIWL	ROR	S (to P.4)	SE	Research/services in workplace health and safety	Inv., Dev., Test., Steer.

Key to abbreviations:

C = Co-ordinator; P = Partner; AP = Associated Partner; S = Subcontractor (all subcontractors are major, and are thus included also as partners).

Coord. = Co-ordination; Inv. = Investigation; Mod. = Modelling; Dev. = Development; Test. = Testing; Cons. = Consultancy; Steer. = Steering Committee.

### 7.2 Profile of individual partners and subcontractors

#### 7.2.1 Partner 1 (Co-ordinator): Health and Safety Laboratory (HSL)

Technical team leader: Dr Lee Kenny

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The Health and Safety Laboratory (HSL) is an agency of the UK Health and Safety Executive (HSE), which is responsible for enforcing workplace health and safety laws in the UK. HSL carries out research leading to the establishment of standards in the field of workplace health and safety.

### **7.2.2 Partner 2: Fraunhofer-Institute of Toxicology and Aerosol Research (FHG)**

Technical team leader: Dr Wolfgang Koch

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The Department of Aerosol Technology of the Fraunhofer-Institute of Toxicology and Aerosol Research is a well known and highly regarded group conducting research in the field of aerosol physics and technology as well as on health effects related to inhaled particles.

### **7.2.3 Partner 3: The Institute for Atmospheric and Climatic Science (ISAC)**

Technical team leader: Dr Francesco Tampieri

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The Institute for Atmospheric and Climatic Science is involved in many research activities, especially in the field of numerical modelling of flow dynamics at different scales, from geophysics to microphysics.

### **7.2.4 Partner 4: University of Lund (LU)**

Technical team leader: Dr Anders Gudmundssen

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The Division of Working Environment at Lund University is a renowned centre for aerosol research. division forms part of the Lund University Centre for Environmental Measuring Technology and its work is closely connected with the atmospheric chemistry and aerosol programmes of the Division of Nuclear Physics.

### **7.2.5 Partner 5 (Associated partner to Partner 3): Bologna University (BU)**

Technical team leader: Dr Maria Pia Morigi

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The Physics Department of Bologna University has an active aerosols laboratory. The research work carried out by this laboratory covers health and safety related problems both in workplaces and in the general environment.

**7.2.6 Partner 6 (Subcontractor to Partner 3): BiOikòS srl (BIO)**

Technical team leader: Dr Sergio Agostini  
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BiOikòs srl is a private company founded in 1992, that operates as industrial hygiene consultant for more than 100 companies in Northern Italy. The company performs evaluations of occupational health related problems by means of instrumental measurements in the field.

**7.2.7 Partner 7 (Subcontractor to Partner 1): Institute of Occupational Medicine (IOM)**

Technical team leader: Geoff Beaumont  
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 Fax: +44 131 667 0136  
 E-mail: [g.beaumont@iomhq.org.uk](mailto:g.beaumont@iomhq.org.uk)

The Institute of Occupational Medicine (IOM) has been at the forefront of development and testing of instrumentation for the sampling of airborne materials in the workplace over the last fifteen years. Notable contributions have included the first definition of the Inhalable Convention now accepted as the primary standard for workplace aerosol measurement.

**7.2.8 Partner 8 (Subcontractor to Partner 4): National Institute for Working Life (NIWL)**

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The Swedish National Institute for Working Life is the governmental institute for research into, and development of, several aspects of working life. The institute covers occupational health and safety as well as labour markets and work organisation.