NANODEVICE: Novel Concepts, Methods, and Technologies for the Production of Portable, Easy-to-use Devices for the Measurement and Analysis of Airborne Engineered Nanoparticles in Workplace Air

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Abstract. NANODEVICE is a research project funded by the European Commission in the context of the 7th Framework Programme. The duration is 48 months starting 1st of April 2009. Due to their unique properties, engineered nanoparticles (ENP) are now used for a myriad of novel applications, and have a great economic and technological importance. However, some of these properties, especially their surface reactivity, have raised health concerns due to their potential health effects. There is currently a shortage of field-worthy, cost-effective ways - especially in real time - for reliable assessment of exposure levels to ENP in workplace air. NANODEVICE will provide new information on the physico-chemical properties of engineered nanoparticles (ENP) and information about their toxicology. The main emphasis of the project is in the development of novel measuring devices to assess the exposure to ENP’s from workplace air. The purpose of the project is also to promote the safe use of ENP through guidance, standards and education, implementing of safety objectives in ENP production and handling, and promotion of safety related collaborations through an international nanosafety forum. The main project goal is to develop innovative concepts and reliable methods for characterizing ENP in workplace air with novel, portable and easy-to-use devices suitable for workplaces.

1. Background
One of the important challenges for assuring a safe production of engineered nanomaterials (ENM) and the promotion of the use of nanotechnologies is reliable assessment of exposure of workers to these materials in the occupational setting, i.e. during the production, storage, handling and preparation of nanotechnology-based products, see Schulte et al. [1]; Woskie et al. [2]. This information supports the assessment of potential hazards and risks of ENM, and subsequent management of possible risks associated with ENM [3,4].

2. Overall project goals
This four year project aims at developing several portable easy-to-use devices for the monitoring of the levels of ENM workplace aerosols with an emphasis on on-line monitoring of the exposure, and to effectively reach all the project goals through efficient management and coordination of the project activities.

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The key goals of the project include 1) characterization of chosen ENM such as carbon nanotubes (CNT) and metal oxides; 2) understanding of the association of ENM characteristics and their potential toxicity; 3) generation of realistic exposure scenarios for workplace exposure to ENM; 4) development of monitoring devices and measurement principles to capture the features and concentrations of ENM in aerosols in workplaces; 5) to develop testing and calibration processes to optimize the functioning of the devices in the measurement of exposure; and 6) to assure a major impact of the project and its results on the safe handling of ENM and the safety of nanotechnologies. Some of these goals were identified by [5] but the goals suggested in that paper have not been achieved so far.

The impact in the promoting of safe use of ENM and safe nanotechnologies will take place through training and dissemination information on the benefits of safe use of ENM handling and production by providing education and training, promoting international standardization of processes related to ENM, publishing a nanosafety handbook, organizing an international congress and other international events, and promoting international networking in the field of safe nanotechnologies. The impact will be focused on different user groups of ENM including the industry, social partners, workplaces, regulators, the scientific community, and the public at large. These groups will be reached by establishing a stakeholder group that consists of the representatives of these groups. The essence of the project and its goals are presented in Figure 1.

**Figure 1.** Essence of the NANODEVICE project.

The main project elements include 1) identification of reference and other testing materials for devices and toxicity; 2) identification of association between physical chemical metrics of the materials and their toxicity and mechanisms of toxicity; 3) identification of the range of concentrations in which the functioning of the devices to be developed should be optimal in workplaces to capture the critical range of concentrations of aerosols of engineered nanomaterials in workplaces; 4) development of affordable easy-to-use instruments to carry out exposure assessment to engineered nanomaterial aerosols in workplaces; 5) laboratory and field calibration of the testing of the instruments to assure their reliability; and 6) promotion of nanosafety in workplaces.
3. Work carried out during the course of the project to reach its goals

The work has been divided into several work packages (21) collected into six larger subprojects (SP) on 1) characterization; 2) association between ENM features and toxicity; 3) exposure scenarios in industrial processes associated with nanotechnologies; 4) development of instruments; 5) calibration and testing of the novel instruments; and 6) assuring impact of the results of the project.

Management of the project aims at assuring effective and fluent flow of the work within the project and appropriate interactions between work packages and subprojects, and leadership, of the undertaking.

In the characterization subproject, work has been carried out to identify and characterize reference and model ENM aerosols and to build a nano-metal oxide reactor. Emphasis has also been on the production of well characterized carbon nanotubes (CNT). A part of the project has focused on exploring on the characteristics of different ENM by using visual technologies such as electron microscopy, and characterizing of ENM through using non-imaging techniques to delineate physical-chemical properties of ENM, see Borm et al. [6]. Association between ENM characteristics and their association with toxicity has been explored with a large variety of methods. This subproject has also provided a list of test aerosols to be used for the performance testing [7] of the instruments to be developed within the project.

One part of the project has been generating performance requirements to set specifications of the easy-to-use devices and portable devices to assess ENM-based evaluation of the limitations of presently available static devices. A part of this goal is to evaluate existing and future work place exposure scenarios. Furthermore the subproject has created sampling strategies for appropriate assessment of exposure to ENM. A key part of the project has focused on the development of novel on-line ENM measurement instruments with the capability to capture essential ENM features, as well as to produce innovative and new measurement principles aiming at discovering novel technologies capable of revealing essential ENM features with an association of toxic properties of given ENM, see Maynard et al. [5]; Murashov [3]. Several approaches have been chosen and work has been carried out to develop such instruments including the following principles: a) on-line, inexpensive, portable, on-line surface monitor; b) size discriminating number and surface area aerosol monitor and sampler; c) wide-range size-resolving aerosol monitoring and sampling system based on a personal size-resolved ENM selective sampler and an on-line monitor; d) high-sensitivity optical sensor for single particle number and mass allowing particle measurements at a 50-80 nm size range; e) high-sensitivity MEMS-based sensor for single-particle number and mass down to 10 nm; f) catalytic and surface-chemical aerosol monitor based on novel device concepts for new metrics proving information in a highly sensitive fashion and near real-time monitoring of catalytic activity and surface chemical groups of ENM; and g) nanofiber monitor that is a robust, portable, easy-to-use quasi real-time device to monitor airborne fibers in workplace environments [2,4,8].

A part of the project focusing on testing and calibration of the instruments has carried out work to establish the facilities and processes for testing and calibration of the instruments to be developed within the part of the project aiming at development of monitoring instruments both in laboratory conditions and in the field in work places A part of the project has aimed at maximizing the dissemination of the results of the project to a wide variety of target audiences, and finding ways to assure an impact of the project to promote safety of ENM and nanotechnologies, see Kahru and Savolainen [9]. Hence, tailored training courses and good practice guidelines have been prepared. A data-base supporting risk assessment of ENM based on the project results is under development by several partners and in collaboration with other EU-funded projects. Also information leaflets, posters and a project newsletter have been developed. Establishment of a strategy for the European and international standardization of all project results is under intensive preparation with different EU-funded projects and European Union stakeholders in this area. An advisory forum - ‘Annual Forum for Nanosafety’ - with the representation of leading experts and most qualified organizations from five continents has been supporting the project. Organizing an international congress on safety of engineered ENM and nanotechnologies is under preparation, and decision has been made to publish a
state-of-the-art nanosafety handbook based on the project. An ongoing internal mobility program has been established, and increased the internal cohesion of the project.

4. Main results achieved so far

4.1. Generation of well-characterized test aerosols of nanoparticles

4.1.1. Characterization: Reference materials have been characterized and the production of tailored ENM materials initiated. Commercially available ENM have been purchased and characterized. Iron catalyst particles have been characterized and preliminary tests have been performed of single walled carbon nanotube (SWCNT) synthesis with the concept reactor. A portable metal oxide particle generator, carrying out test measurements with TiO$_2$ and SiO$_2$ has been built; see Rossi et al. [10].

4.2. Association between physical, chemical and toxicological properties of ENP

Association between ENM properties and health effects: Methods for generating, analyzing, characterizing and reporting the electron microscopy analysis of nano-objects and agglomerates is in progress. Methods for dispersing powders for in-vitro testing have been circulated and used. Characterization included morphological electron microscopic analysis and EDS analysis on composition. Nanomaterials induced pro-inflammatory effects in the target cells with a marked potential to differentiate between toxic and less toxic materials. All ENM showed cytotoxicity which was relatively minor. TiO$_2$ induced a dose-dependent increase in DNA damage [10].

4.3. Processes in ENP production, use and exposure to ENP

For industrial processes, a survey was made and sent to achieve "Requirements for the newly developed devices". The questionnaire has been summarized and documented. For the description/evaluation of existing and future workplace exposure scenarios with an emphasis on exposure conditions, concurrent exposures, a preliminary analysis has been made using data from the EU FP6-funded project "NANOSH". Knowledge gaps were identified, with focus on the conceptual model. It was concluded that the input value of parameters for (both mathematical and CFD) modeling should be as realistic as possible. Furthermore, more data were needed with respect to ‘background’ aerosols, e.g. ranges of size distributions, particle number concentrations [2,11].

4.4. Device development

4.4.1. For Portable active surface area aerosol monitor, it was decided that the corona discharge is a way to charge the particles in the developed portable aerosol monitor. A prototype of a small corona charger has been built and evaluated. The prototype was also modeled and the model was verified against the experimental results. During this period, new concepts for a high voltage power supply for ECT charger, an isolated power supply design and electrometer for current measurement have been developed. These concepts are currently being tested.

4.4.2. For Size-discriminating number and surface area aerosol monitor and sampler, a pre-separator has been developed that includes a virtual impactor and a cyclone. Optimal settings for the pre-separator were developed. The charging efficiency has been tested and found to be in very good agreement with literature data.

4.4.3. For wide-range size-resolving aerosol monitoring & sampling system, 1) several numerical models for particle deposition in tubes, on plates and on nets for different geometrical and material setups have been developed; 2) several numerical models for particle deposition in a cyclone as a function of cyclone geometry and operating conditions have been developed; 3) the first prototype of the size fractionating nanoparticle personal ENM selective sampler has been manufactured; 4)
preliminary tests show that the performance is in the expected range of parameters; and 5) the first
draft of operation instruction has been prepared.

4.4.4. **For the High-sensitivity optical sensor for single-particle number and mass**, an optimized laser source and a highly sensitive receiver has turned out to be the most promising approach to detect the scattered light originating from small particles in the 100 nm-regime.

4.4.5. **For High-sensitivity MEMS-based sensor for single-particle number and mass**, 1) algorithm for detection and weighing of several particles with resonant beams has been developed; 2) proof of sensor principle by measuring micro particles with cantilevers and strings has been obtained; 3) Fabrication process for micro beams with perfect clamping has been established; and 4) an analytical model for actuation of cantilevers made from arbitrary materials has been established.

4.4.6. **For Catalytic and surface-chemical aerosol monitors to detect catalytically active ENM**, 1) several model ENP materials and suitable test reactions have been selected. The proof of principle for a simultaneous determination of particle size and a fluorescence signal on single particles was accomplished on a laboratory setup. A functional relationship between the amounts of a fluorescent dye on the surface of micron sized test particles could be established. Further work is planned using a fluorescent marker molecule specific to redox-active sites.

4.4.7. **For Nanofibre monitor**, 1) a working setup of a AFM measurement station to measure deposited nanoparticles on surfaces situated in a Clean room ISO class 1 has been established; 2) a selection of suitable surfaces for the later usage in the fiber monitor has been made; 3) first successful measurements with nanoparticles on the surfaces have been carried out; and 4) a CNT generator to produce CNTs for the later usage in the development of the fiber monitor has been developed.

4.5. Calibration and testing of the functioning of new concepts, methods and pre-prototypes for measurement and analysis of airborne ENP

4.5.1. **For calibration, testing, and background distinction**, 1) a report on the adjustment of the nanoparticle calibration system for NANODEVICE which is in itself ready to use by developers; 2) a ready to use version of a primary discontinuous calibration tool for coagulation aerosols and an additional prototype for a continuously working similar system; and 3 the ready to use (for urban aerosol) Nano Test Facility, see Brouwer [11]; Woskie et al. [2].

4.5.2. **For testing of the devices in the field** 1) current existing instruments for measuring ultrafine and nanoparticles at workplaces were reviewed and checked for parallel application during the planned workplace comparisons; 2) Contact with the group of external technicians in Germany has been established and procedures how to distribute devices have been discussed. The draft of the questionnaire will be distributed among them to clarify the meaning of the questions; 3) a document on the sampling strategy has been drafted in a core group and discussed with external stakeholders in Germany, which also do measurements. The draft will be discussed within the consortium; and 4) it has been agreed that the partners concerned will deliver documents on the justification of their work on the pre-prototypes till summer 2010 [2,7].

4.6. SP6 Dissemination of the results and assuring impact of the NANODEVICE project

The overall goal of these activities is to fill the knowledge gaps that exits in our knowledge related to the safety of engineered nanomaterials, see e.g. Kahru and Savolainen [9]. Especially the role of dissemination of information and standardization will be emphasised in the exploitation of the results of the project [3,4,12].
Dissemination of the results and assuring impact Educational materials for nanosafety promotion and courses for different targeted audiences have been prepared. Brochures and posters on the project have been produced and newsletter is in a planning stage. Data-base to support risk assessment of ENM with other partners and other EU funded projects is underway. As to standardization, a scientifically categorized list (4 categories) of standards related to the NANODEVICE project outputs has been established, and a prioritized list of standards related to the NANODEVICE project outputs has been identified. Contacts to various relevant, national and international standardization committees have been established. Presentation on the standardization issues in general and on the status of work will take place during NANOSAFE Congress in Grenoble and during the Annual Safety Forum meeting in Berlin in March 2011. The advisory group 'Annual Forum for Nanosafety' with experts and organizations from five continents has been established. Preparations to organize an international congress on safety of engineered nanomaterials and nanotechnologies (SENN2012) are progressing well. The program committee is working actively, and the initial contents of the congress have been identified. Planning of a nanosafety handbook is ready, authors chosen and committed themselves. Currently, negotiations on the publications are ongoing with Springer. Human mobility program within NANODEVICE project has been initiated and actively ongoing.

5. The expected final results and their potential impact on safe nanotechnologies
The project results will have a marked societal impact especially on workplace safety in small and medium size enterprises and microenterprises through bringing into market affordable on-line measuring devices providing reliable exposure information on engineered nanomaterials. This will not only greatly increase our knowledge and understanding on the true workplace exposure to these materials. It will also support regulators and decision makers in making evidence based conclusions and actions on necessary measures to protect the workers from excessive exposure, especially the setting of occupational exposure limits for different types of engineered nanomaterials. One can expect remarkable savings to the industry through reliable exposure information at low or affordable expenses.

These outcomes of the project will also enable safe use of these materials, and promote safe production of engineered nanomaterials, and thereby increase the competitive edge of nanotechnologies through emphasizing safety aspects in all areas of nanotechnology applications.

The project has successfully moved toward its impact objectives as demonstrated by the successful progress of the technical and impact work. Stakeholder contacts will assure a marked further impact through making the project results more visible among ETUC and Business Europe partners, occupational safety and health and research community, among governments, and the Commission as well global organizations such as OECD, World Health Organization, ISO and CEN.

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