



# Environmental Nanovectors Emerging Science Initiative Project Progress Report 2006/2007

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## Executive Summary

Considerable progress has been made on the two sub-projects that comprise the ESI Environmental Nanovectors project. In Sub-project 1 on the Fate and Transport of Nanoparticles/Nanovectors in Soil and Water, field flow fractionation (FFF), high resolution X-ray diffraction and synchrotron techniques have been applied to separate and analyse synthetic and natural nanoparticles particles of different sizes without artificially perturbing their chemistry. Flow-FFF has been applied to study nanoparticulate zinc oxide distribution in soil solutions. Coupling of this instrument to an inductively coupled plasma mass spectrometer is being investigated as a new tool for obtaining information on the size fractionation of nanoparticles. Isotope dilution studies are being applied to measure the labile zinc pool in zinc oxide dispersions in soil solutions.

Synthetic iron oxide nanoparticles have been synthesised and analysed by FFF. The prospect for application of these techniques for studies of nanoparticulate iron associated with acid sulphate soils is being pursued.

Preliminary experiments have investigated potential degradable coatings that might be used for nanoparticles that to transport nutrient elements such as calcium and zinc through upper soil layers to nutrient-deficient sub-layers.

In Sub-project 2, on the Bioavailability of Nanovectors and Associated Contaminants, studies of nanoparticulate zinc oxide have found that nanoparticles are sufficiently soluble in freshwaters, that the concentrations of dissolved zinc is sufficient to cause toxicity to sensitive algae to the same extent as occurred from bulk zinc oxide or zinc chloride. Detailed physical examinations using transmission electron microscopy and dynamic light scattering revealed the extent of nanoparticle aggregation that occurred and equilibrium dialysis was used to separate soluble zinc. The findings highlighted deficiencies in some published studies and demonstrated the need for characterisation studies.

In an attempt to find less soluble nanoparticles and better assess nanoparticulate bioavailability, cerium oxide is currently being examined with additional studies of titanium dioxide. Conditions are being sought that minimise particle aggregation. These studies have benefited from a four-month attachment of Dr Jamie Lead from the University of Birmingham.

At CMIT, zinc radioisotopes are being used to study the toxicology of zinc oxide in dermal care products in association with Prof. Brian Gulson at Macquarie University.

The Project has already resulted in six publications and a number of presentations at international meetings. Strong national and international linkages have been formed with a number of key groups, and the reputation of the project team in this area is now well-established.

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## Introduction

This initiative aims to advance our understanding of the potential environmental impacts of engineered nanoparticles. In the haste to exploit this technology, scant attention has been paid to the potential impact on the environment. Although the world market for nanoparticles is approaching one billion dollars, neither government regulations nor labelling requirements exist in any country and the impacts of this emergent technology are unknown.

In medicine, nanovectors are particles less than 1000 nm in diameter used to carry anti-cancer drugs to sites of action in the human body. The term environmental nanovectors has been introduced to describe the role of nanoparticles in facilitating the transport of contaminants or other agents in the air, water or soil environment.

Ultimately, the work seeks to determine if both synthetic and natural nanoparticles that enter natural water systems are bioavailable and toxic to sensitive aquatic biota either via direct cellular uptake or through accumulation in the food chain. The initial focus is on nanoparticulate metal oxides. The environmental fate and pathways of nanoparticles in soils is also being studied, to determine their potential as vectors to transport nutrients, ameliorants and biocides to plant roots enhancing the productivity of potentially infertile soils. This project also aims to develop a quantitative method for separation and identification of inorganic and organic nanovectors in complex aqueous matrices. The research builds on CSIRO's expertise in environmental contaminants research in aquatic and terrestrial systems.

The immediate outcomes of the research will be to inform the public debate on the nature of the threats posed by nanoparticles in the environment and in the longer term, to influence the design of nanoparticles to ensure minimal environmental impacts.

This report provides an update on progress in this project for the 06/07 period, and anticipated milestones for 07/08, in the Sub-project areas of:

1. Fate and Transport of Nanoparticles/Nanovectors in Soil and Water
2. Bioavailability of Nanovectors and Associated Contaminants

## Sub-project 1

### Fate and Transport of Nanoparticles/Nanovectors in Soil and Water

#### Objective

To improve our understanding of the primary factors influencing nanoparticle/nanovector transport and stability of contaminant-nanovector associations.

The specific objectives of this two-year project include:

Development of experimental equipment, procedures and analytical methods for quantitative separation and identification of low concentrations of reactive nanovectors in complex aqueous matrices

Identification of key physico-chemical characteristics controlling nanoparticle/nanovector partitioning between solid and solution phases and their transformation in the environment

Assessing the nanovector potential of nanoparticles, i.e. determining the extent that natural and synthetic nanoparticles can sequester other contaminants, and the chemical factors affecting contaminant release (direct links with Sub-project 2).

Strengthen collaboration with other research groups in Australia and overseas.

#### Highlights

Relatively new approaches such as the use of field flow fractionation (FFF), high resolution X-ray diffraction and synchrotron techniques are being applied to separate and analyse synthetic and natural nanoparticles particles of different sizes without artificially perturbing their chemistry.

Paper published [Gimbert LJ., RE. Hamon, PS Casey and P J Worsfold (2007). Partitioning and stability of engineered ZnO nanoparticles in soil suspensions using flow field-flow fractionation, *Environmental Chemistry*, 4, 8–10]. Draft review paper prepared, three conference presentations and a contribution to the new edition of the Australian Nanotechnology Capability and Commercial Potential Report.

#### Progress

CSIRO staff involved – Rob Fitzpatrick (CLW), Mark Smith (CLW), Mark Raven (CLW), Rebecca Hamon (previously in CLW), Phil Casey (CMIT), Mike McLaughlin (CLW), Danni Oliver (CLW), Stuart McClure (CLW/U. Adelaide), Rai Kookana (CLW)

Collaborators – Jamie Lead (School of Geography, Earth and Environmental Sciences, University of Birmingham, UK), David Chittleborough (Adelaide University), Ron Beckett (Monash University), Jason Kirby (CLW), Paul Shand (CLW), Laura Gimbert and Paul Worsfold (School of Earth, Ocean and Environmental Sciences, University of Plymouth).

Research in the first year or so of the ESI has concentrated on:

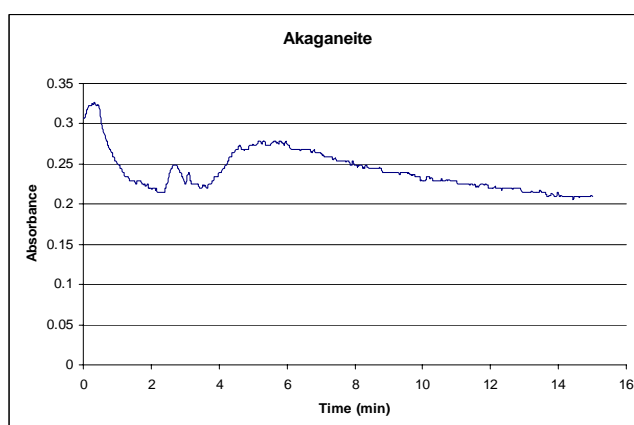
#### **Review paper**

A review of the potential environmental impact of nanoparticles is nearing completion. This review focuses on the lack of information in the literature on the nature and amount of nanoparticles in the environment and the affect they have on soil and aquatic organisms. A distinction between natural and synthetic nanoparticles is made. The potential benefit of

nanoparticles on soil remediation is discussed as well as the potential negative impact of the transport of trace metals, organic matter on the soil.

### **Field flow fractionation (FFF)**

We have undertaken extensive training on the field flow fractionation (FFF) instrument and the inductively coupled mass spectrometer (ICP-MS) to develop a quantitative continuous measure of the size distribution and composition of inorganic and organic nanovectors in complex aqueous matrices. The FFF instrument is fully operational and in the process of being calibrated using synthetic nanoparticles of iron oxide. First samples have been run through to demonstrate instrument is working and that the particles injected can be detected at the end of the experiment. The light scattering detector has been installed and training has been undertaken on its operation. A sample of synthetic akaganéite ( $\beta$ -FeOOH) was injected into the channel and the fractogram is shown in figure 1.



**Figure 1. FFF fractogram of a synthetic akaganéite sample**

The paper by Gimbert *et al.* reports preliminary results for the determination of engineered ZnO nanoparticles using flow field-flow fractionation (FIFFF). This separation technique was used to determine the particle size distributions (PSDs) of ZnO nanoparticles spiked in soil suspensions. Before FIFFF analysis, the soil was prepared in suspension form, shaken overnight and gravitationally settled to extract the  $<1\text{-}\mu\text{m}$  fraction. The effect of aging was also investigated using soil samples incubated with known concentrations of ZnO nanoparticles for 7 and 14 days. The results show that FIFFF can be used to determine the PSD of engineered nanoparticles and monitor their partitioning and stability in soil suspensions.

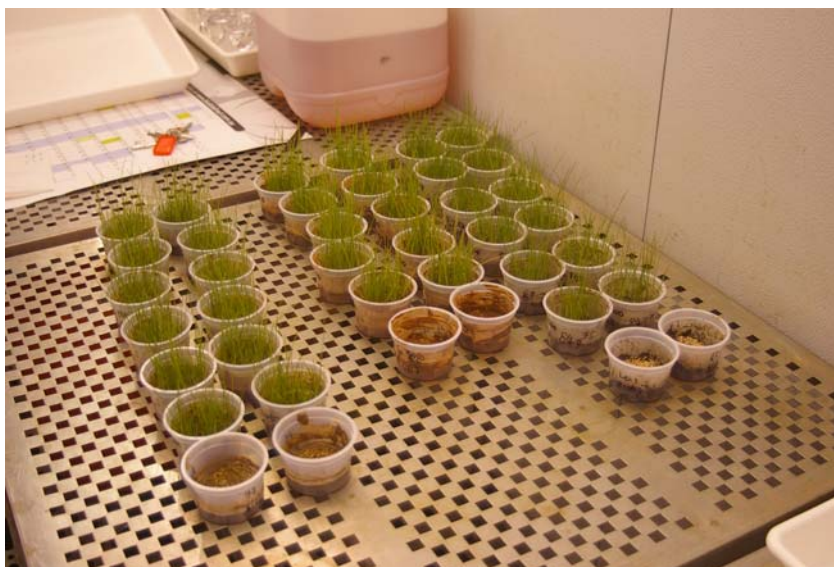
### **Stirred flow cell**

After much consultation, including trips to Melbourne to meet with manufacturers, a stirred flow cell unit was built using Teflon. This unit is designed to separate particles based on their relative sizes. The Teflon stirred flow cell will be used to separate pesticide nanoparticles.

### **Determination of zinc labile pool in soils from ZnO nanoparticles**

Isotope dilution is a very useful technique to determine the labile metal pool, the amount of metal in soil in equilibrium with the soil solution. This method will be used to determine how much zinc from ZnO nanoparticles dissolves and remains in the labile zinc pool in soil, and is subsequently available to the plant.

Initially,  $\text{ZnSO}_4$  was used to establish whether the toxicity of ZnO nanoparticles is a function of their solubility in water and also to find out the critical threshold for zinc toxicity in the soils used. Range finding experiments were then conducted to establish a toxicity curve for the ZnO nanoparticles (30 nm diameter) to rye grass. Control experiments were performed to distinguish the toxicity of the ZnO nanoparticles relative to the surfactant they are stabilised in (sodium lauryl sulfate).



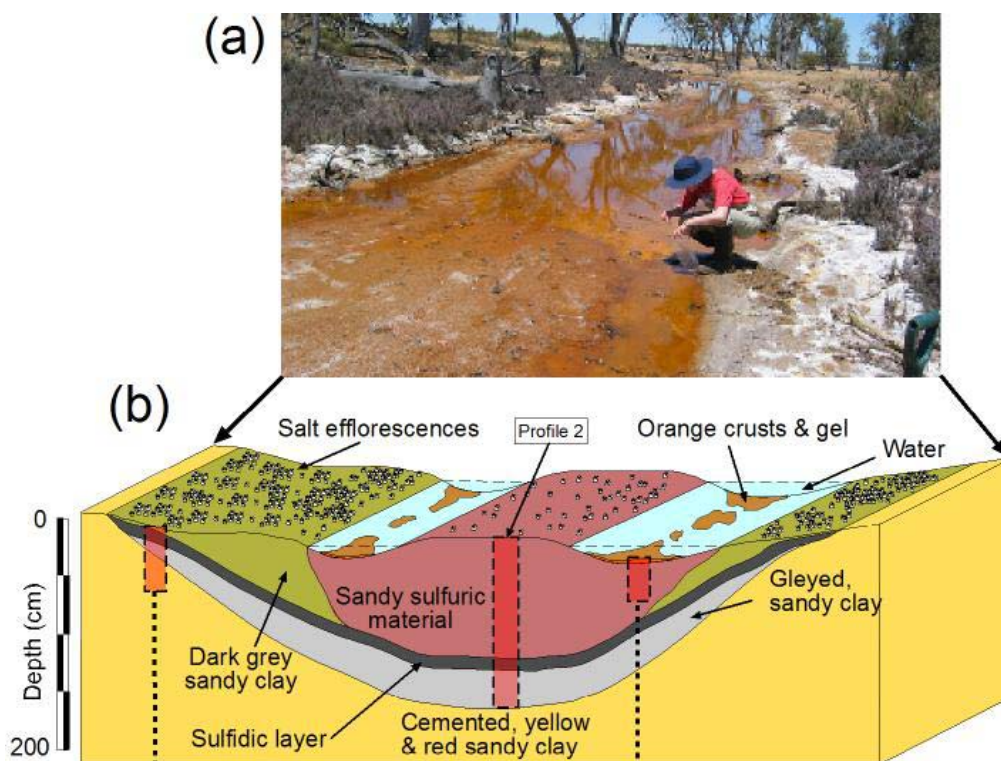
**Figure 2. ZnO toxicity experiments using rye grass**

**Poorly crystalline nanoparticulate Fe-minerals and metal transport in soils and waters**

Acid sulfate soils (ASS) are soil materials in which sulfuric acid may be produced from iron sulfides or has been produced leaving various nanoparticulate iron-containing minerals in amounts that have a long lasting effect on soil and water characteristics (Figure 3). Under anaerobic or reducing conditions sulfidic soil materials are characterized by the presence of nanoparticulate iron disulfides (e.g. pyrite,  $\text{FeS}_2$ ) and monosulfides (e.g. mackinawite,  $\text{FeS}$ ), which are referred to as Monosulfidic Black Ooze (MBO). MBO is a poorly characterized nanoparticulate material known to be a mixture of iron sulfides and organic matter. Sulfidic and sulfuric materials often contain elevated metal concentrations (Al, Cu, Pb, Cr, Pb, Zn, Mg and rare earth elements). Oxidation of sulfides to produce sulfuric acid mobilize toxic elements, which may also include an assemblage of nanoparticulate Fe-oxyhydroxysulfates (e.g. schwertmannite:  $\text{Fe}_8\text{O}_8(\text{OH})_6\text{SO}_4$ , sideronatrite:  $\text{Na}_2\text{Fe}(\text{SO}_4)_2 \cdot \text{OH} \cdot 3\text{H}_2\text{O}$ ) and Fe-oxyhydroxides (ferrihydrite:  $\text{Fe}_8(\text{HO})_8 4\text{H}_2\text{O}$  and akaganéite:  $\beta\text{-FeOOH}$ ). Types of Fe-containing minerals are indicative of rapidly changing local environments and variations in redox, pH and rates of availability of S and other elements. As such, there is a need to better characterise synthetic and natural poorly crystalline nanoparticulate Fe- minerals and metal transport in soils and waters (Figure 3).

**Synthetic and natural iron oxide nanoparticles**

We have synthesised several Fe-oxide/oxyhydroxide minerals of varying sizes with the aim of showing that the FFF can be used to determine their size and in the long term, enable us to take samples of acid sulfate soils to determine the composition and size of the Fe-containing minerals involved. Ultimately, we aim to attach particles to the iron oxides nanoparticles to see how these nanovectors behave in the environment (e.g. size distribution of the nanoparticulate Fe-containing minerals as a function of pH). Preliminary results have demonstrated that synthetic akaganéite (<100 nm) was able to be passed through the FFF channel and detected at the other end (Figure 1).



**Figure 3. Schematic cross-section through a drain in the Western Australian wheatbelt showing acid sulfate soils with orange crusts and gels comprising nanoparticulate akaganéite, schwertmannite, ferrihydrite and iron oxidising bacteria in surface waters, which underlie layers of: (i) sulfuric material (pH <3.5), (ii) black sulfidic material (pH >4) and (iii) monosulfidic black ooze (MBO). White salt efflorescences occur on the sides of the drain.**

### **Biodegradable/Charge-Neutral Coated Nanoparticles for Deep Ground Nutrient Delivery.**

Only a limited amount of activity has been undertaken in this area. The challenge here is to control surface charge of nutrient nanoparticles containing for example  $Zn^{2+}$  or  $Ca^{2+}$  using charge neutral (bio)degradable coatings. The concept is to design a coating that has a degree of water resistance, is charge neutral and yet degradable so as to allow the transport by water of these nutrients through upper soil layers (avoiding sorption onto charged soil components) to nutrient deficient sub-layers. At this depth, the coating is required to degrade (physically or biologically) and thus releasing the nutrient nanoparticle. A requirement is that the particles must be delivered to the top soil either as a dispersion or emulsion with a nominal particle size of <50nm.

Candidate coating materials (for use with ZnO) are being surveyed and those considered range from natural oils, glycerolates to biopolymers and others. Preliminary work using nanophase glycerolates has been limited by the formation of hard micro-agglomerates.

### **Future Work (milestones for coming year)**

- Calibrate the FFF and light scattering detector such that particle size can be estimated directly from the fractogram. Continue developing methods for the separation of mixtures of particles of varying sizes. Optimise carrier solvents to best mimic the natural environment whilst preventing aggregation of the nanoparticles.
- Full scale trials with soil water samples being taken on regular intervals to trace nanoparticles in soils. Spiking with  $Zn^{65}$  will enable us to distinguish between the fixed and available pool of Zn in soils.

- Continue to conduct experiments with more complex synthetic and natural iron oxide/oxyhydroxide minerals of varying sizes such as those containing S. Complete detailed X-ray diffraction, SEM, TEM and synchrotron studies on synthetic and natural iron oxides.
- In situ reactivity of sideronatriite by Synchrotron based XRD and FFF: Sideronatriite forms as very small disordered crystals in ASS, which is not suitable for structure determination using laboratory based sources. Synchrotron based XRD and FFF will be used to study the formation of this mineral *in-situ* by studying synthetic and natural specimens of sideronatriite and investigate phase transformations during dehydration (i.e. sideronatriite to metasideronatriite), attempt to solve the crystal structures, and investigate the formation mechanism from sideronatriite to schwertmannite in solution.
- Studies with the stirred cell unit to determine whether: (i) pesticides with different sorption properties (i.e. different K<sub>oc</sub> values) are distributed onto the same size fractions of suspended sediment, and (ii) the distribution of the pesticides on the different size fractions remains the same across soils with varying amounts of organic carbon, since this is the main binding phase.
- Further assess candidate materials for charge neutral degradable coatings and develop the concept of designer nutrients for deep layer fertilisation

## Sub-project 2

### Bioavailability of Nanovectors and Associated Contaminants

#### Objective

To determine the bioavailability and toxicity of manufactured nanomaterials, examine their role as potential nanovectors for environmental contaminants and compare their behaviour to those of natural environmental nanovectors.

The specific objectives of this two-year project include:

Determine the mechanism of uptake of nanovectors by living organisms.

Determine the extent to which manufactured nanovectors can sequester other contaminants and facilitate their biouptake (linked to Sub-project 1)

Determine the extent of food chain bioaccumulation of nanomaterials and associated contaminants.

Strengthen collaboration with other research groups in Australia and overseas.

#### Highlights

Already there has been significant progress in this emerging area of nanotechnology, with CSIRO Land and Water now being one of the few research groups worldwide studying the environmental impacts of nanomaterials.

Our research on ZnO has highlighted the need for care in toxicity testing in ascribing toxicity to nanoparticles per se when the effects may be related, at least in part, to simple solubility, a factor overlooked in some previously published investigations.

Research in this area benefited from the 4-month attachment, at Lucas Heights, of Dr Jamie Lead, University of Birmingham. Dr Lead is an expert in the physical chemistry of nanoparticles, and will be involved in ongoing collaborations.

Strong links have been developed with the Nanosafe Australia, and with Assoc Professor Shuk Han Cheng, at City University Hong Kong (visited in July 2006), and involvement in an international nanotechnology panel within the Society of Environmental Toxicology and Chemistry.

Two papers produced [Rogers, NJ, Franklin, NM, Apte SC, Batley GE (2007). The importance of physical and chemical characterization in nanoparticle toxicity studies. *Integrated Environmental Assessment and Management* 3, 7– 8; Franklin NM, Rogers NJ, Apte SC, Batley GE, Casey PE (2007). Comparative toxicity of nanoscale ZnO, bulk ZnO and ZnCl<sub>2</sub> to a freshwater microalgae (*Pseudokirchnerilla subcapitata*): the importance of particle solubility. *Environmental Science and Technology*, submitted.] and contribution to new edition of Australian Nanotechnology Capability and Commercial Potential Report.

One invited [AQUANET, UK (2006)] and three submitted conference presentations [Interact, Perth, 2006; SETAC Europe, Porto, 2007]

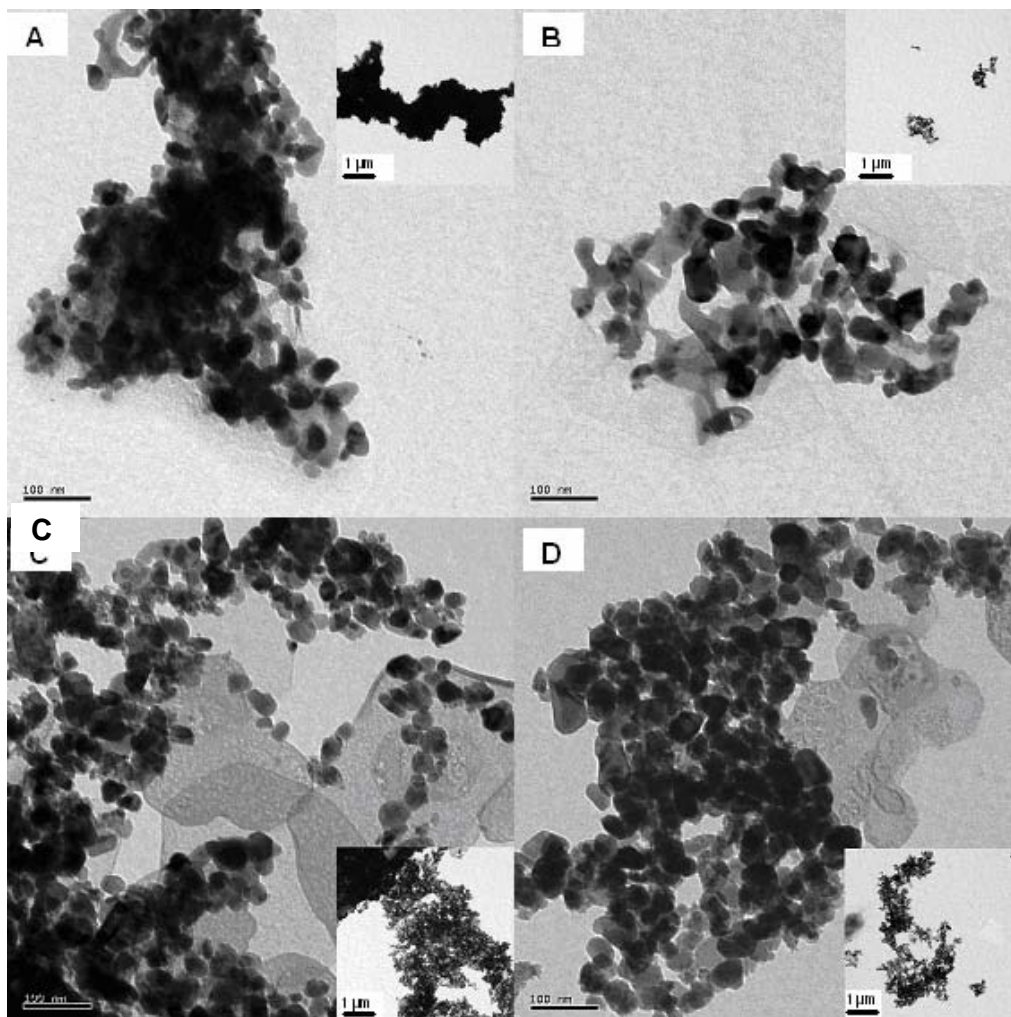
#### Progress

CSIRO staff involved – Simon Apte (CLW), Natasha Franklin (CLW), Nicola Rogers (CLW), Graeme Batley (CLW) and Phil Casey (CMIT)

Collaborators – Prof Jamie Lead (School of Geography, Earth and Environmental Sciences, University of Birmingham, UK), Dr Gerry Gadd (Institute of Materials and Engineering Science, ANSTO, Sydney).

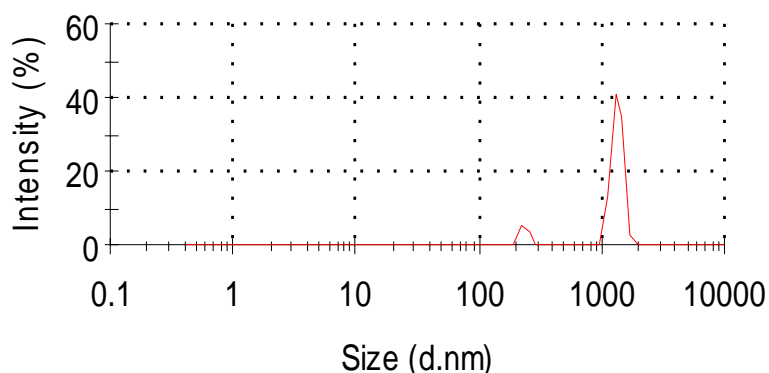
### **Characterisation and toxicity of ZnO nanoparticles**

Following discussions with Dr Phil Casey (CMIT), nanoparticulate zinc oxide, was chosen as a model nanoparticle for bioavailability studies. Initial research involved the physical characterization of ZnO supplied by the CMIT group as both a raw nanopowder and an aqueous dispersion using a nonionic surfactant, more typical of nanoparticle formulations (Figures 4 and 5).



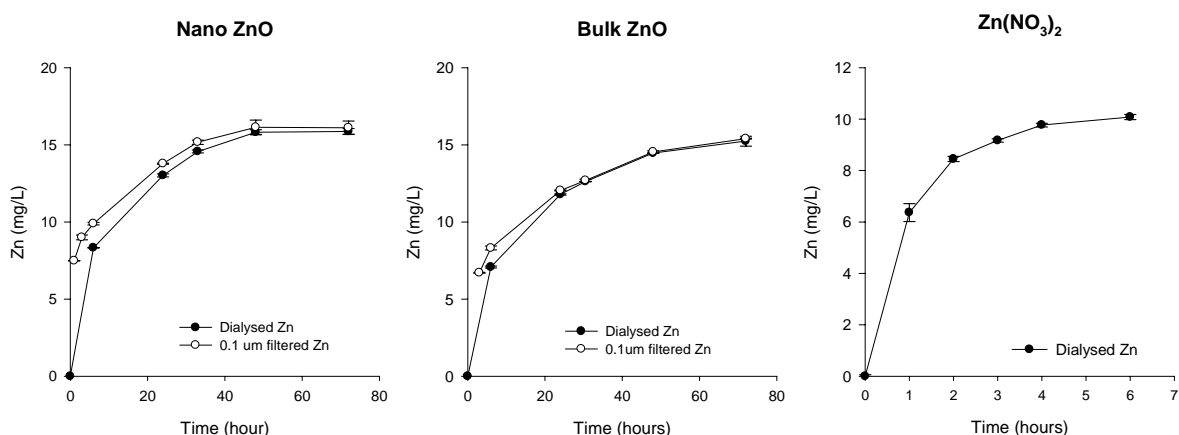
**Figure 4. TEM images of ZnO nanoparticles (100 mg/L) in algal test medium (pH 7.5). The inset picture illustrates the same sample but at a lower magnification. a) unsonicated nano-ZnO<sub>powder</sub>; b) sonicated nano-ZnO<sub>powder</sub>; c) unsonicated nano-ZnO<sub>dispersant</sub>; d) sonicated nano-ZnO<sub>dispersant</sub>**

Two different particle characterisation techniques, transmission electron microscopy and dynamic light scattering, were chosen for the initial studies. These were undertaken through collaborations with Barbara Bojarski (CSIRO, Molecular and Health Technologies) and Dr Gerry Gadd (ANSTO). It was found that, in freshwater, aggregation of ZnO nanoparticles (raw and surfactant-dispersed) was significant, resulting in flocs ranging from several hundred nanometers to several microns in size. Efforts to minimise aggregation through sonication and continued stirring techniques did not result in dispersed suspensions of ZnO nanoparticles.



**Figure 5. Example of typical particle size distribution of ZnO nanoparticles (ca 30 nm) measured by dynamic light scattering showing two distinct populations; one of several hundred nm, and the presence of larger aggregates of several microns diameter.**

In addition to thorough physical characterisation, understanding the aquatic chemistry of nanoparticles was equally important for aquatic toxicity investigations. We developed an equilibrium dialysis technique for assessing the aqueous solubility of nanoparticles. Measurements using spectrometric techniques demonstrated rapid dissolution of ZnO nanoparticles at circumneutral pH, with a saturation solubility in the mg/L range, similar to that of bulk ZnO (Figure 6). This was a surprise as ZnO was reported to be insoluble in water.



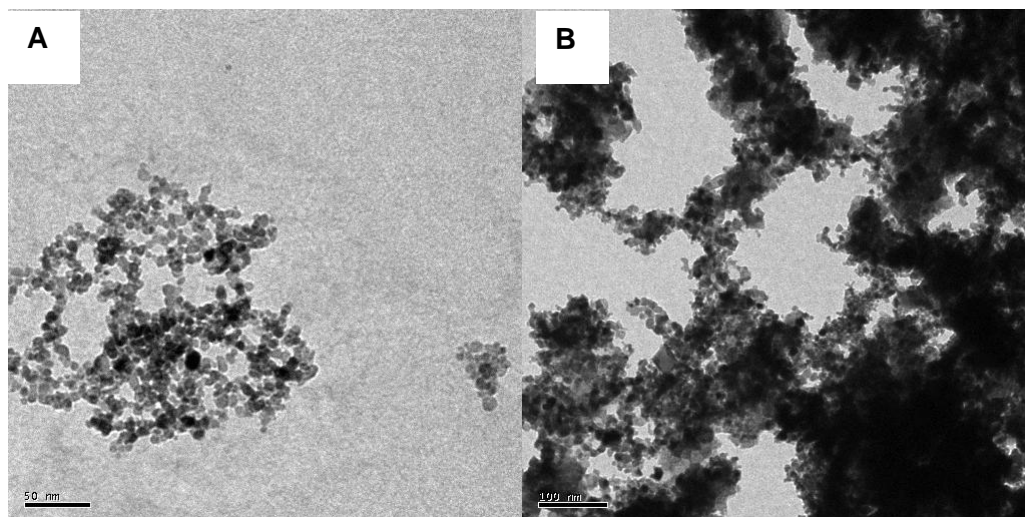
**Figure 6. Determination of nanoparticulate ZnO and bulk ZnO dissolution rate by equilibrium dialysis, with comparison to dissolved Zn(NO<sub>3</sub>)<sub>2</sub> solutions (pH 7.6).**

Toxicity testing on ZnO nanoparticles was undertaken using the sensitive freshwater alga *Pseudokirchneriella subcapitata*, and comparisons made with two reference toxicants, dissolved Zn (as ZnCl<sub>2</sub>) and bulk ZnO (non-nanoparticulate). Results revealed comparable toxicity for nanoparticulate ZnO, bulk ZnO and ZnCl<sub>2</sub> that was attributable solely to dissolved zinc and not any specific particle effects. These findings identified deficiencies in published research and highlighted the need for care in toxicity testing to ensure data are properly attributed to specific nanoparticle risks.

#### **Investigations of other nanoparticulate metal oxides**

Based on the ZnO findings, a less soluble compound was required to understand the toxic effects of nanoparticles per se. Studies have now commenced on CeO<sub>2</sub> and TiO<sub>2</sub> including evaluations of their aqueous solubilities, the extent of their dispersion or aggregation in freshwater, and characterisation of their physical properties.

For CeO<sub>2</sub> nanoparticles (ca 10-20 nm), particle characterisation using TEM and DLS revealed considerable aggregation of the primary particles in a freshwater media at circumneutral pH. Changes in pH had a dramatic effect on the particle size profile and zeta potential measurements (effective charge on the particle) (Figure 7 and Table 1), with only more acidic waters (e.g. pH 2.0) resulting in smaller aggregates of the primary particle.



**Figure 7. TEM images of CeO<sub>2</sub> nanoparticles in a freshwater media at (A) pH 2.0 and (B) pH 7.5**

**Table 1. Particle size and zeta potential results using dynamic light scattering (DLS) for CeO<sub>2</sub> nanoparticles at different pH values**

pH	Size (nm)	Zeta potential (mV)
7.5	Sub-micron to micron sized aggregates	-3
6.0	Sub-micron to micron sized aggregates	+11
2.0	Average peak sizes 60 nm, 200 nm	+40

The use of stabilising agents and surfactants is also being assessed in an attempt to obtain dispersed suspensions of CeO<sub>2</sub> nanoparticle at environmentally relevant pH values. To date, the anionic surfactant, sodium dodecylbenzenesulfonate (NaDDBS), has shown promising results in this regard, with a minimum particle size of <100 nm obtained at pH 6.5. We are currently trialling the low molecular weight organic metabolite, citrate.

The toxicity of CeO<sub>2</sub> nanoparticles is currently being investigated using our standard algal bioassay, with preliminary results indicating enhanced toxicity of nanoscale CeO<sub>2</sub> (without surfactant and known to be aggregated) compared to bulk CeO<sub>2</sub>. This is an important finding that requires further investigation. Experiments are also underway to assess the toxicity of NaDDBS and citrate, on algal growth in the absence of nanoparticles to ensure any negative effects are not due to the stabilising agents themselves.

Equilibrium dialysis experiments are currently in progress for CeO<sub>2</sub> (nanoscale and bulk), with work soon to begin on TiO<sub>2</sub>.

### ***Personal care: dermal studies***

Zinc oxide and titanium dioxide nanoparticles are being used in sunscreens and other personal care products. Zinc has five isotopes whose naturally occurring abundances range from Zn<sup>70</sup> at 0.6% to Zn<sup>65</sup> at 49%. Zn<sup>68</sup> with a natural abundance of 18.6% is the isotope of choice for studies of zinc oxide because of cost considerations. Many tracers are available from commercial suppliers and their price usually depends on the natural abundance, with the lower the natural abundance the higher the cost. In collaboration with Prof. Brian Gulson, Herbert Wong (Graduate School of the Environment, Macquarie University), Gavin Greenoak (Australian Photobiology Testing Facility, Sydney University) and Julie Trotter (Research School of Earth Sciences, Australian National University, Canberra) we are in the process of conducting investigations using Zn<sup>68</sup> as tracers in sunscreen products containing zinc oxide to determine *in vivo* their dermal absorption and excretion in humans.

Nano Zn<sup>68</sup>O has been prepared through proprietary methods by CMMT and a batch of sunscreen containing this nanoisotope phase has been prepared as a near commercial formulation. Preliminary *in vivo* trials are currently underway. The outcome of these trials will serve to determine the feasibility and protocol of the use of isotopes in transdermal studies. A complementary series of trials that target only the skin (rather than absorption and excretion) is currently being scoped and organised by Phil Casey in conjunction with Dr Ian Carlisle (Plastic and Reconstructive Surgeon).

A paper entitled *Stable Isotope Tracing - a way forward for Nanotechnology?* is being presented in May by Phil Casey in the Nanotech in Health, Environment & Society Session at Nanotech 2007 Conference and Trade Show, St Clara, US. This paper is an overview of the potential merits of stable isotope tracing as an investigative technique in nanotechnology toxicology and transport studies.

### **Future Work (milestones for coming year)**

- Continue collaboration with Dr Jamie Lead (returned to University of Birmingham from sabbatical at Lucas Heights) on CeO<sub>2</sub> nanoparticle characterisation, with his input on use of atomic force microscopy, field flow fractionation, and Brunauer–Emmett–Teller techniques to more thoroughly characterise nanoparticle suspensions in more complex matrixes, including natural waters with humic substances.
- Investigate the mechanism of uptake of metal oxide nanomaterials using flow cytometry to investigate changes in cell physiology and structure on exposure to nanoparticles. Given that a proposed mechanism of toxicity of many nanoparticles, including metal oxides, is the production of reactive oxygen species, development of a flow cytometric bioassay to measure oxidative stress will be investigated.
- Determine the extent of food chain bioaccumulation of nanomaterials and associated contaminants.
- Further assess the use of stable isotopes as an investigative technique in assessing nanoparticles and their toxicology in personal care/health