# Prevention through design concepts for sustainable development of nanomaterials

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## ABSTRACT

Nanotechnology has the potential to provide great benefit to society, but it must be developed responsibly. This responsibility involves addressing any adverse human and environmental impacts of the technology associated with engineered nanomaterials. Workers are among the first people in any society to be exposed to the potential health hazards caused by the products of new technology, and their exposure to any new material is often greater than for the general population. Therefore, worker safety and health can be seen as the core of responsible development. Prevention through Design (PtD) is a comprehensive approach for addressing worker safety and health issues by "designing out" hazards and minimizing residual risks.

***Keywords***: prevention through design, sustainable, nanomaterials.

## 1 INTRODUCTION

In August 2012, The National Institute for Occupational Safety and Health (NIOSH) Prevention through Design (PtD) program and the NIOSH Nanotechnology Research Center collaborated with the State University New York at Albany, College of Nanoscale Science & Engineering to hold a "Safe Nano Design" workshop. The purpose of the workshop was to develop guidance for safe commercialization of nanotechnology products, resulting in guidelines for the safe synthesis of nanoparticles and associated products by means of a PtD approach. The conference illustrated application of PtD principles at the molecular level as well as during the process phase.

The safe commercialization of nano products should focus on: 1) efforts to develop safer nano molecules that have the same functionality as those they are developed to replace; 2) process containment and control, based on the considerations of risk of exposure to workers; and 3) management system approaches for including occupational safety and health into the nanoparticle synthesis process, product development, and product manufacture.

### 1.1 Prevention through Design

Anticipating and "designing out" occupational hazards in facilities, work methods and operations, processes, equipment, tools, products, new technologies, and the organization of work is the most effective way of preventing occupational injuries, illnesses and fatalities [1]. PtD utilizes the traditional hierarchy of controls by focusing on hazard elimination and substitution followed by risk minimization through the application of engineering controls and warning systems applied during design, re-design, and retrofit activities (Figure 1) [2].

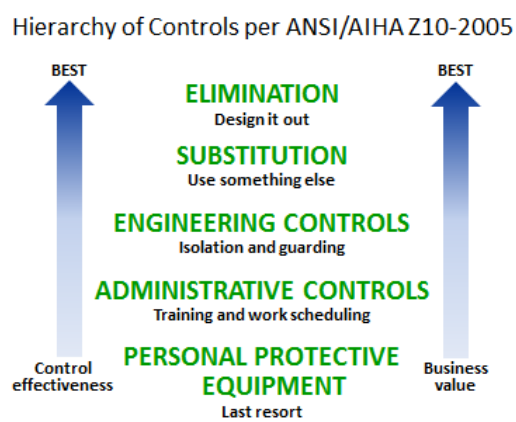


Figure 1. Heirarchy of Controls as per American National Standards Institute (ANSI) / American Industrial Hygiene Associaiton (AIHA) Z10-2005 Standard.

In addition to reducing the risk of serious injury and illness, significant business costs savings are associated with hazard elimination and the application of engineering controls to minimize risks. As businesses adopt hazard control measures higher in the "hierarchy of controls," i.e., designing-out hazards and minimizing risks, the business value increases. These improvements in business value are related not only to lower worker compensation rates and health care costs to care for injured workers but also to achieving faster time to market, improved operational efficiency, improved employee morale, decreased employee absenteeism and turnover, higher product quality, and increased market share [3].

Elimination and substitution, while most effective at reducing hazards, also tend to be the most difficult to implement in an existing nanomaterial production or use process. If the process is still at the design or development stage, elimination and substitution of hazards may be inexpensive and simple to implement. For an existing process, major changes in equipment and procedures may be required to eliminate or substitute for a hazard.

## 2 SAFER MOLECULES

Experimental studies in rodents and cell cultures have shown that the toxicity of some nanomaterials can be greater than that observed in larger-scale materials of similar chemical composition. For nanomaterials, it is recognized that properties such as size, form factor, shape, surface functionalization, surface charge, and aggregation state can have profound effects on a particle's toxicological properties and interactions with biological systems [4]. It may be possible to change a nanomaterial property to be less toxic while maintaining the functionality of the nanomaterial. Less toxic solvents or other materials used during production should also be considered for substitution when possible.

One aspect of PtD, grounded in molecular design, seeks to minimize nanomaterial toxicity by rational modification of physical properties. One of the largest hurdles to overcome in property-driven molecular design is the specificity of effective formulation techniques to a given material; those modifications which reduce toxicity in one nanomaterial probably will not do so for another which is structurally dissimilar. That relationship between a particle's physical and chemical properties and the biological effects it induces is being investigated by several research facilities. Differences in physicochemical properties can lead to different interactions within cells [5]. For instance, the pH of a nanomaterial suspension as compared to its isoelectric point is one of the most important factors in determining that material's agglomeration state. This in turn dictates how the material interacts with a cell surface and governs cell viability. Similarly, metal oxide oxidation state has a marked impact on cellular uptake. These and similar observations should serve as an impetus for further research into the mechanisms by which cells interact with nanoparticles and the way particle physicochemical characteristics shape those mechanisms. This research would facilitate the prediction of nanomaterial interactions in novel biological environments and the prediction of unknown material interactions in known biological matrices.

Nanotoxicologic testing at NIOSH has shown that purification and functionalization of some multi-walled carbon nanotubes with the -COOH group dramatically reduced the cytotoxicity and inflammasome activation [6].

## 3 PROCESS CONTAINMENT AND CONTROL

Although the development of safer nanomaterials is an important goal, it is also important to include proper containment of materials in the workplace. The initial levels of containment include product, process, and equipment modifications. Only after efforts have been made to design the process to reduce potential emissions sources should engineering controls be considered.

Engineering controls are used to remove a hazard or place a barrier between the worker and the hazard. Well-designed engineering controls can be highly effective in protecting workers and will typically be independent of worker interactions to provide this high level of protection. The initial cost of engineering controls can be higher than the cost of administrative controls or personal protective equipment, but over the longer term, operating costs are frequently lower, and in some instances, can provide a cost savings in other areas of the process.

It is important to design engineering controls that do not interfere with the productivity and ease of processing for the worker. If engineering controls make the operation more difficult, there will be a strong motivation by the operator to circumvent these controls. Ideally, engineering controls should make the operation easier to perform rather than more difficult. NIOSH has published containment strategies for nanomaterial production facilities which can minimize worker exposures in the laboratory and in manufacturing facilities [7, 8].

Batchtype processes involved in the production of nanomaterials include operating reactors, mixing, drying, and thermal treatment. Exposure-causing activities at production plants and laboratories employing nanomaterials include harvesting (e.g., scraping materials out of reactors), bagging, packaging, and reactor cleaning. Downstream activities that may release nanomaterials include bag dumping, manual transfer between processes, mixing or compounding, powder sifting, and machining of parts that contain nanomaterials. Many of the basic methods of producing nanomaterials occur in an enclosure or reactor, which may be operated under positive pressure. Exposure can occur due to leakage from the reactor or when a worker's activities involve direct manipulation of nanomaterials or during periodic cleaning of the reactor.

Spray drying procedures should be carefully managed as emissions during offloading of collection containers can pose a risk to occupational safety and health. The design of the spray drying work procedure should include isolation of the process and containment of materials during the critical product removal stage. These considerations exemplify


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cautious prevention by means of establishing an exposure-likelihood hierarchy among the work tasks to be performed.

A variety of dust control methods have been used and evaluated in many industries and may be applicable to the processes used in the manufacturing and processing of nanomaterials [9]. These methods include the enclosure of material-conveying equipment, such as belt and screw conveyers, as well as the use of pneumatic conveyance systems. Other work practices have been used to reduce the aerosolization of dust during bag filling, including minimizing leak paths by securing the bag to the outlet spout and wetting the outside of the bag to prevent surface dust from becoming airborne. Research over the years in a variety of industrial settings has shown that water spray application is effective in lowering respirable dust levels [10]. The use of an atomization nozzle was shown to be one of the most effective water-spray delivery systems in dust knockdown performance tests. Water sprays lower respirable dust concentrations by knocking down the dust, fibers, and particles, and they also can induce airflow to direct the remaining dust away from the workers.

Other nonventilation engineering controls include many devices developed for the pharmaceutical industry, including isolation containment systems [11]. One of the most common flexible isolation systems is glove box containment, which can be used as an enclosure around small-scale powder processes, such as mixing and drying. Rigid glove box isolation units also provide a method for isolating the worker from the process and are often used for medium-scale operations involving transfer of powders. Glove bags are similar to rigid glove boxes, but they are flexible and disposable.

Other PtD strategies can be considered for control:

- Limiting process inventories by producing the nanomaterials as they are consumed in the process.
- Operating a process at a lower energy state (e.g., lower temperature or pressure), which typically results in lower fugitive emissions and therefore safer operation.
- Using fail-safe devices where possible. Fail-safe devices are designed so that if they fail, the system reverts to a safer condition. An example of a fail-safe device is a valve controlling a reagent for a reaction. If the safe condition for the system is for this valve to be closed, the fail-safe valve would automatically close in the event of a failure.
- Installing a closed transport system to eliminate worker exposures during transport activities.

## 4 MANAGEMENT SYSTEMS AND APPROACHES

A systems approach to management encourages the view of an organization as a whole including an inventory of the workforce and material resources available; this way, substructures and subsystems may be organized and resources may be allocated to them in the most efficient and effective way. An effective management systems approach is invaluable to the safe commercialization of engineered nanomaterials through a PtD-enabled approach (Figure 2) [1]. An effective management system begins with an executive position statement which details all activities from bench-top to production to distribution and use. In the conceptual planning stages of a product, process, or facility that incorporates engineered nanomaterials, the executive position statement can be used to align goals in the integration of worker health and safety into each step. This step-by-step approach refines the decision-making process and enables the rational discovery of occupational hazards for elimination from the design process.


Figure 2. Components of an overall health and safety program that includes nanomaterial risk management.

It is important to consider procurement, manufacturing, and distribution environmental health and safety concerns whenever they are applicable. Considering work at the project level, execution should include safety reviews prior to startup, exhaustive Standard Operating Procedure (SOP) development, and extensive worker training. Through these methods, project managers can take a high-level view of the work to be done and ensure that no aspect of worker safety is overlooked. Of course, it is just as important to consider these aspects after the completion of the project, in the safe decommissioning of the worksite and disposal of engineered nanomaterials.

Exposures to engineered nanomaterials can be controlled by a comprehensive risk management program that includes task hazard/risk analysis, and following the hierarchy of controls previously mentioned. Implementing an effective risk management program should address the following elements of hazard surveillance:

- Hazard Identification: Is there reason to believe that the nanomaterial of interest could be harmful? What is known about the toxicologic properties? What is known about the safety properties?

- Exposure Assessment: Is there the potential for exposure to the nanomaterial or other chemical or physical hazards? Have all of the uses in the workplace been evaluated from receiving to maintenance on equipment?

- Exposure Control: What procedures are in place or should be developed to minimize or eliminate worker exposure(s)?

The answers to these questions will help to formulate a program that includes the following:

- A written health and safety policy covering all types of chemical and physical hazards in the workplace in accordance with the U.S. regulatory requirements.

- A clear delineation of roles and responsibilities for everyone involved.

- Effective measures for documentation, communication, and training.

- Incorporation of input from industrial hygiene and occupational health professionals as needed.

## 5 CONCLUSIONS

The safe commercialization of nano products should focus on: efforts to develop safer nano molecules that have the same functionality as those they are developed to replace; process containment and control, based on the considerations of risk of exposure to workers; and management system approaches for including occupational safety and health into the nanoparticle synthesis process, product development, and product manufacture. Nanomaterials can be designed to mitigate toxicity while maintaining functionality. At the process level various approaches can be designed in to protect workers from exposure to hazardous chemicals, including nanomaterials. Integrating the design effort at the molecular and process levels may have an even greater impact on worker safety and health.

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