Are classical process safety concepts relevant to nanotechnology applications?

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Abstract. The answer to the question posed by the title of this paper is yes – with adaptation to the specific hazards and challenges found in the field of nanotechnology. The validity of this affirmative response is demonstrated by relating key process safety concepts to various aspects of the nanotechnology industry in which these concepts are either already practised or could be further applied. This is accomplished by drawing on the current author’s experience in process safety practice and education as well as a review of the relevant literature on the safety of nanomaterials and their production. The process safety concepts selected for analysis include: (i) risk management, (ii) inherently safer design, (iii) human error and human factors, (iv) safety management systems, and (v) safety culture.

1. Introduction
Process safety deals with the prevention and mitigation of process hazards leading to fires, explosions and releases of toxic materials. Process safety is therefore focused on processing facilities and is different in scope than occupational safety, which is aimed more at protection of the individual. It should be noted, however, that process safety and occupational safety have several common features; further, the distinction between a process incident such as a fire, and an occupational incident such as a fall from height, may be quite meaningless to the affected worker. This is especially the case with nanomaterials and the accompanying concern with the uncertain nature of chronic health hazards. Nevertheless, attention to process safety issues does afford the possibility of an integrated approach to loss prevention that considers harm to people, property (asset) damage, production (business) interruption, and degradation of the natural environment.

The ensuing sections contain an analysis of the following process safety concepts in terms of their relevance to the safety of nanomaterial production and handling:

- risk management,
- inherently safer design,
- human error and human factors,
- safety management systems, and
- safety culture.

Each topic is first defined and then described from a process safety perspective. This is followed by an analysis of existing and potential applications to the field of nanotechnology. The five topics listed above were selected because, collectively, they form a body of knowledge that is at the forefront of current emphasis in process safety education, research and practice.
2. Risk management

Functional definitions of hazard, risk and risk management according to Wilson and McCutcheon [1] are as follows:

**Hazard**: The potential of a machine, equipment, process, material or physical factor in the working environment to cause harm to people, environment, assets or production.

**Risk**: The possibility of injury, loss or environmental incident created by a hazard. The significance of risk is a function of the probability of an unwanted incident and the severity of its consequence.

**Risk Management**: The complete process of understanding risk, risk assessment, and decision making to ensure effective risk controls are in place and implemented. Risk management begins with actively identifying possible hazards leading to the ongoing management of those risks deemed to be acceptable.

2.1. Process safety features

A conceptual framework of the risk management process for process safety concerns is given in figure 1; embodied in this fundamental flowchart is the cycle of risk analysis, which enables risk assessment,

![Risk Management Process](image)

**Figure 1.** Risk management process (adapted from Amyotte and McCutcheon [2]).

which in turn enables risk management. In essence, process safety practitioners *analyze risk* (for probability and consequences), so they can *assess risk* (with respect to acceptability), so they can
ultimately manage risk. As shown in figure 1, it is not possible to commence this cycle without first effectively identifying the hazards of concern.

2.2. Nanotechnology applications

The UK Health & Safety Executive’s document *Reducing Risks, Protecting People* [3] comments in section 32:

...as the most obvious risks have been tackled, new and less visible hazards have emerged and gained prominence. Typical examples include those arising from technologies such as biotechnology, and processes emitting gases which contribute to global warming and ozone depletion. One frequent characteristic of these new hazards is that it can be very difficult to define precisely the risks they may give rise to, even when scientific knowledge is pushed to the limit. The processes that may give rise to risks are only partially understood with the result that regulatory decisions must frequently be based on limited data and considerable scientific and technological uncertainties. The control measures required by regulation should reflect the nature of the uncertainties and err on the side of health and safety.

Reference [3] (sections 87 and 88) distinguishes between uncertainty and ignorance, with ignorance indicating a lack of awareness of risk-influencing factors as would exist when hazard identification is incomplete. Uncertainty is defined as a state of knowledge in which, although risk-influencing factors have been identified, it is not possible to precisely describe the likelihood of any adverse effects or the magnitude of the effects themselves [3]. Figure 2 in Appendix 1 of Reference [3] identifies procedures for attempting to deal with uncertainty when assessing risks. With increasing uncertainty of likelihood, it is recommended that emphasis be placed on consequences (i.e., the event is considered by focusing solely on the consequences); with increasing uncertainty of consequences, it is recommended that the focus be on putative (supposed) consequences and scenarios. Significant uncertainty in both likelihood and consequences trends toward ignorance [3].

Considerations such as those described above play a key role in assessing the risk arising from process hazards and explain, in part, the emphasis placed in the process industries on thorough scenario generation and hazard identification. Similar considerations apply to the nanotechnology field, as evidenced by the comments on knowledge uncertainty made in virtually every publication reviewed during preparation of the current paper (e.g., [4–10]). For example, Williams et al. [10] state that there is a critical lack of data concerning potential hazards, does-response relationships and exposure levels for most nanomaterials currently available. In a similar vein, Ferdous et al. [11] have demonstrated the use of fuzzy-based and evidence theory-based formulations to address data and dependency uncertainties, respectively, in fault and event tree analyses for process systems.

Williams et al. [10] also comment on the matter of risk perception in the case of new technologies such as nanotechnology, with perception acting essentially as a third component of risk in addition to likelihood and consequence severity. This again is not unlike the management of process risks related to activities such as waste disposal and the siting of hazardous facilities. An additional feature of process risk assessment can be found in nanotechnology applications – that of consciously defining the physical and analytical scopes for the analysis in terms of system boundaries and the nature of the hazards under consideration, respectively. This is evident in the need to describe, in the words of Williams et al. [10], the unit of analysis for which the risk is being assessed (marketed product, product components, production process, risks to the environment, or some combination of these factors). As with the process industries, nanotechnology risk assessments must consider a product’s lifecycle from research and development through to manufacture and ultimately disposal [10].

While toxicity concerns can be acute or chronic, fire and explosion hazard effects are usually of short duration but of high intensity [12]. Focused efforts [13–20] have been undertaken recently to address the fire and explosion impacts of various nanopowders such as carbon nanotubes and nano-sized aluminium. Vignes et al. [20] have adopted a process-safety approach incorporating fault trees as well as prevention and mitigation barriers in assessing the ignitability and explosivity risk of aluminum nanopowders.
3. Inherently safer design

Inherently safer design is a proactive approach in which hazards are eliminated or lessened so as to reduce risk without over-reliance on engineered (add-on) devices and procedural measures.

3.1. Process safety features

A number of principles to facilitate inherent safety implementation in the process industries have been developed; the four basic principles identified in table 1 have gained widespread acceptance [21]. These and other principles of inherent safety work in conjunction with other means of reducing risk within a framework commonly known as the hierarchy of controls. Inherent safety, being the most effective approach to risk reduction, sits at the top of the hierarchy – followed in order of decreasing effectiveness by passive engineered safety, active engineered safety, and finally procedural safety.

| Principle             | Description                                                                 |
|-----------------------|-----------------------------------------------------------------------------|
| Minimization          | Use smaller quantities of hazardous materials when the use of such materials cannot be avoided or eliminated. Perform a hazardous procedure as few times as possible when the procedure is unavoidable. |
| Substitution          | Replace a substance with a less hazardous material or processing route with one that does not involve hazardous material. Replace a hazardous procedure with one that is less hazardous. |
| Moderation            | Use hazardous materials in their least hazardous forms or identify processing options that involve less severe processing conditions. |
| Simplification        | Design processes, processing equipment, and procedures to eliminate opportunities for errors by eliminating excessive use of add-on safety features and protective devices. |

3.2. Nanotechnology applications

There is clear evidence of inherently safer design application in the nanotechnology field. The terms inherent safety and inherently safer design are seldom used in the nanotechnology literature, but this also is similar to the process industries. Although inherent safety has been named and formalized in the process safety literature since the late 1970s, it is only in the last decade or so that the concept has been more widely quoted as such [21].

A recent publication [22] has identified five principles of design for safer nanotechnology. As shown in table 2, each of these design principles has at least a partial foundation in the fundamental principles of inherent safety (table 1).

| Safer Nanotechnology Design | Inherently Safer Design |
|-----------------------------|-------------------------|
| Size, surface and structure | Moderation              |
| Alternative materials       | Substitution            |
| Functionalization           | Moderation              |
| Encapsulation               | Moderation              |
| Reduce the quantity         | Minimization            |

Other examples of inherent safety application to nanomaterial production and handling are given in table 3.
Table 3. Inherent safety examples drawn from the nanotechnology literature.

| Reference | Example                                                                                                                                  | Inherent Safety Principle |
|-----------|----------------------------------------------------------------------------------------------------------------------------------------|----------------------------|
| [5]       | Implications of form of nanomaterials (loose powder, liquid dispersion, agglomerated, aerosolized) for potential route of human and environmental exposure | Moderation                  |
| [8]       | Need for process-specific engineering controls if potential hazards cannot be eliminated or substituted with less hazardous substances Requirement for more stringent controls with operations having potential to aerosolize nanomaterials (e.g., handling dry powders, spray applications) than operations where nanomaterials are embedded in solid or liquid matrices | Minimization Substitution Moderation |
| [23]      | Growth of carbon nanotubes on micron-sized Al$_2$O$_3$ particles as carriers in production of composite carbon nanotubes                        | Substitution Moderation    |
| [24]      | Increase in deposition range during inhalation with reduction in particle size Relationship of particle toxicity to surface area               | Moderation                  |
| [25]      | Use of different crystal structures of TiO$_2$ as hazard reduction strategy (although noting reduced photocatalytic activity) Efforts to limit hazard of TiO$_2$ particles by application of coatings and dopant ions (while again noting reduced photocatalytic activity) Immobilization of TiO$_2$ nanoparticles on supports and substrates | Substitution Moderation Moderation |
| [26]      | Processes that produce a carbon nanotube product that is not easily dispersed Design of nanoparticles with substituent groups that minimize toxicity Avoidance of manipulation of nanomaterials as free particles on lab benches | Substitution Moderation Simplification |
| [27]      | Wet chemistry techniques for synthesis of aluminum nanopowder Broad importance of understanding and describing properties of nanomaterials (underlying chemistry and physics) | Substitution Minimization Substitution Moderation Simplification |
| [28]      | Use of alternate catalyst (e.g., iron in place of cobalt or nickel) in manufacturing processes for carbon nanotubes Product form factors for carbon nanotubes and TiO$_2$ | Substitution Moderation |
| [29]      | Various methods for synthesis of SiO$_2$ aerosol particles                                                              | Substitution                |
| [30]      | Reduced likelihood of exposure to engineered nanomaterials when embedded in polymers or other matrices in given products Need for hazard metrics related to surface chemistry of engineered nanomaterials | Substitution Moderation Moderation |

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4. Human error and human factors

*Human error* can be defined as any human action, or lack thereof, that exceeds or fails to achieve some limit of acceptability, where limits of human performance are defined by the system. *Human factors* are the environmental, organizational and job factors, and system design, task and human characteristics that influence behaviour and affect health and safety.

4.1. Process safety features

Human factor considerations in the process industries arise in a number of areas – e.g., the operator-process/equipment interface, use of administrative controls, and performance of human error assessments [31]. *Operator-process/equipment interface* refers to issues such as [31, 32]:

- the design of equipment increasing the potential for error (e.g., confusing equipment, positioning of dials, colour coding, different directions for on/off, etc.), and
- the need for a task analysis (a step-by-step approach to examine how a job is done) to determine what can go wrong during the task and how problem areas can be controlled.

*Administrative controls* require well-developed and -maintained safe work procedures, as well as an understanding of their role within the aforementioned hierarchy of controls. *Human error assessment* involves the use of appropriate techniques (both qualitative and quantitative) to estimate the likelihood and consequences of human error during operational and emergency scenarios.

4.2. Nanotechnology applications

One of the challenges for process safety in the new millennium is to overcome the fact that organizations have no memory [33]. Mannan et al. [33], with reference to the work of Professor Trevor Kletz, comment that organizations lose valuable incident information after about ten years because of personnel changes. One manifestation of this “brain drain” is in the lack of knowledge of facility workers with respect to the reasons for the existence of specific safety devices and protocols, as well as operating procedures, which may have been introduced following a process-related incident [33]. This can lead to human error during normal operations and emergency scenarios unless human factor issues, in particular organizational factors, are thoroughly considered.

Given the relative newness of the nanotechnology industry, it would seem opportune to heed the above lessons experienced with significant hardship by the process industries. Process-oriented techniques exist for estimation of human error probabilities (e.g., SLIM – Success Likelihood Index Methodology) and consequences (e.g., HAZOP – HAZard and OPerability analysis); these can be combined with risk matrices/graphs and safety barrier/bow-tie analyses to gain an overall picture of human error risk and the human factor considerations needed for risk reduction [34]. Application of such quantitative and semi-quantitative approaches to the processing of nanomaterials could prove valuable.

Simpler, qualitative methods widely used in the process industries are also applicable to the nanotechnology field. For example, the What-If analysis technique can be used to generate hazardous, what-if-type scenarios with an accompanying assessment of the adequacy of existing safeguards:

- What if an individual selects PPE (personal protective equipment) that is not suitable for handling nanomaterials, but which is stored in close proximity to PPE appropriate for nanomaterials (e.g., specific respirators with a flexible hood, impervious gloves, etc. [24])?
- What if material from a nanomaterial-bearing waste stream is placed in the regular trash (counter to the advice of Hallock et al. [26])?
- What if the correct information is not entered on a waste label to clearly indicate that the waste bag contains nanosized particles (again, counter to the advice of Hallock et al. [26])?

These potential human errors are rooted in inadequate consideration of the relevant human factors. The first scenario is essentially one in which the individual has been “set up for failure” by an unnecessarily complex system (recall the inherent safety principle of simplification). The second and third scenarios highlight the facts that procedural safety is the least effective measure in the hierarchy of controls, and that procedures will not work without effective training in their use.
5. Safety management systems

Safety management systems are best-practice methods recognized and accepted worldwide for managing risk (related, for example, to health, occupational safety, process safety, equipment reliability, etc.). They typically consist of 10 – 20 program elements that must be carried out to manage the risks in an acceptable manner by actively monitoring company operations for concerns and taking proactive actions to correct potential problems.

5.1. Process safety features

Having an effective management system for process-related hazards (i.e., fires, explosions and releases of toxic materials) is a critical corporate objective in the chemical process industries. An approach widely used in the Canadian chemical industries is PSM, Process Safety Management (where PSM is defined as the application of management principles and systems to the identification, understanding and control of process hazards to prevent process-related injuries and accidents). The suite of PSM elements is shown in table 4, taken from the Process Safety Management Guide of the Canadian Society for Chemical Engineering (CSChE) [31]. The material in the CSChE PSM guide [31] is based on that developed by the Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers (AIChE), prior to the recent introduction by the CCPS of its 20-element risk-based process safety management system [35].

| Number | Element                                |
|--------|----------------------------------------|
| 1      | Accountability: objectives and goals   |
| 2      | Process knowledge and documentation    |
| 3      | Capital project review and design procedures |
| 4      | Process risk management                |
| 5      | Management of change                   |
| 6      | Process and equipment integrity        |
| 7      | Human factors                          |
| 8      | Training and performance               |
| 9      | Incident investigation                 |
| 10     | Company standards, codes and regulations |
| 11     | Audits and corrective actions          |
| 12     | Enhancement of process safety knowledge |

5.2. Nanotechnology applications

Sharatt [36] has made the somewhat provocative comments that:

*There are many chemical engineers doing bio, nano, and environmental work – and in many cases doing it pretty badly. What is worrying is not that the work is being attempted, but that it is so often disconnected from the core concepts of the discipline. Concepts of mass and energy balance and a systems approach have been widely abandoned in favour of blind empiricism...*

Whether or not one agrees with these statements, an appeal for a systems approach drawing on core concepts must surely include the need for a management system approach to safety. The precise nature and focus of such a management system (process safety, occupational safety, occupational hygiene, etc.) will be determined, in part, by the application areas within a given industry. With respect to nanomaterials, the following processes have been identified as posing significant exposure risk: (i) pouring or mixing liquids containing nanoparticles, (ii) generating gaseous nanoparticles in non-enclosed spaces, (iii) cleaning up spills or waste materials, (iv) machining, drilling or sanding (all of which can lead to nanoparticle aerosols), (v) spraying, weighing or blending powders containing nanoparticles, and (vi) cleaning and maintaining equipment and dust collectors [37].

Whether it is process hazards or individual exposures that are of concern, a safety management system for nanomaterial production and handling would be expected to contain elements similar to...
those shown in table 4 for PSM. In the current paper, reference has been made (even implicitly) to the need for consideration of process knowledge and documentation, process risk management (including hazard identification), human factors, training and performance, and enhancement of process safety knowledge (see table 4). Additionally, management of change (MOC) is a key safety management system element, particularly when the principles of inherently safer design are actively employed. Reijnders [25] has remarked on the possible release of TiO$_2$ nanoparticles when such particles are immobilized by linking them to large supports (e.g., due to photocatalytic degradation of carbon and synthetic organic polymer supports during application). Morose [22] has broadly commented that the use of alternative materials requires careful investigation of potential changes in hazards, product functionality and costs that may be introduced by such substitutions.

6. Safety culture
Safety culture has been defined by Hopkins [38] (with reference to an unpublished paper by Hudson) as a specific case of culture in which safety has a special place in the concerns of those who work in a given organization. The literature on safety culture places emphasis on attitudes and practices (especially collective practices) to varying degrees.

6.1. Process safety features
Hopkins [38] describes three concepts that address a company’s cultural approach to safety and makes the argument that the three are essentially alternative ways of talking about the same phenomena:

- safety culture (with reporting, just, learning, and flexible sub-cultures),
- collective mindfulness, and
- risk awareness.

Safety culture (as defined by any of the terms in the above list) dominates much of the current discussion around process safety worldwide, driven in large measure by the BP Texas City incident in 2005 [39]. Key points emerging from this discussion include the following [21]:

- typical occupational safety indicators such as lost-time injuries (LTIs) are inappropriate as primary indicators with respect to process safety,
- leading indicators are generally viewed as more useful than lagging indicators, and
- process-safety indicators must link to, and measure the effectiveness of, the various elements of the process safety management system in use.

6.2. Nanotechnology applications
The title of the recent paper by Guldenmund [40], Misunderstanding Safety Culture and its Relationship to Safety Management, is indicative of the strong and important linkage that exists between the safety management system approach and safety culture. A positive process safety culture must be the cornerstone of the first PSM element in table 4 (accountability: objectives and goals), as well as a unifying factor for each of the remaining elements. Quoting from a recent article [41] in The Chemical Engineer (a publication of the UK Institution of Chemical Engineers):

...Safety culture is how the night shift operates when it is alone without management watching... The argument goes that if managers are not sufficiently present they cannot reinforce the safety practices of their teams and this will inevitably lead to deviation from set operational routines... The result: the next Bhopal, Buncefield, or Gulf oil leak.

The nanotechnology world does not want, and neither should it need, a Bhopal, Buncefield or Gulf oil leak (all major and/or recent process/environmental incidents) to drive its safety culture. Simply put, nanotechnology industries cannot afford to ignore the hard safety lessons that have been learned and at times ignored by the chemical process industries. As noted by Stang and Sheremeta [42], whether or not one believes that the nanotechnology field raises unique ethical, economic, environmental, legal or social issues – nanotechnology will undoubtedly exacerbate and complicate these same issues. Lavoie [43], for example, has commented that the integration of some nanomaterials into products has outpaced what he has termed diligent safety research.
concern arises with TiO$_2$ nanoparticles in particular, which can penetrate the skin to a limited degree; contradictory research has demonstrated that some nanomaterials can be used safely with dermal contact [43]. These findings are similar to Horng’s comment [23] that growing concerns about the impact of nanoparticles are likely due to a significant disconnect between environment, health and safety research efforts and business development initiatives.

As mentioned earlier in section 2.2, an issue common to the nanotechnology and process industries is that of lifecycle consideration when conducting risk assessments. Savolainen et al. [30] have noted that while most nanoparticle-containing products are not likely to cause exposure while the nanoparticles remain embedded in the product matrix, other scenarios such as product waste processing can provide a different risk profile. Production of the nanoparticles themselves at the front-end of the process must also be considered as part of the lifecycle. Considerations surrounding product stewardship and supply chain management [44] are therefore key to building a positive safety culture in facilities processing and handling nanomaterials. The Royal Society’s call for a responsible nanotechnology code [4] is not unlike the Canadian and worldwide response to the 1984 disaster in Bhopal, India which involved the release of methyl isocyanate and the death of thousands of human beings – that of a program of Responsible Care® incorporating an ethical set of principles as well as a management system of codes and practices [44].

7. Concluding Remarks

The concepts of risk management, inherently safer design, human error and human factors, safety management systems, and safety culture are as relevant to the nanotechnology industries as they are to the process industries. Other process industry issues not discussed in the current paper (e.g., chemical security [45]) would also be expected to be pertinent to the nanotechnology field. Adaptation of specific process safety protocols to the production and handling of nanomaterials necessitates thoughtful consideration of challenges such as data uncertainty, public perception and lack of awareness of the full hierarchical suite of risk control measures.

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