NANO SILVER – WHY IT IS SO HOT NOW?

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ABSTRACT

Senjen and Illuminato[1] of Friends of the Earth have claimed that nanosilver (AgNP) is an extreme germ killer which presents a growing threat to public health. Volpe[2] and Height[3] of Silver Nanotechnology Working Group (SNWG) have been arguing to the USEPA[4] that AgNP poses a unique property for its size <100 nm in one dimension. They argued that the functionality of AgNP used in antimicrobial applications is not unique and not a new material. It is identical to all EPA-registered silver products for decades where any antimicrobial functionality is achieved via release of silver ions (Ag+). Nevertheless, will the "safety" of AgNP become a real "Nano-Titanic" and prevent a sustainable industrial system for this "red-hot" nanotechnology development?

Keywords: nanosilver (AgNP), life cycle, exergy, triz in dfss (dflss-g), waste minimization.

1. GENERAL APPROACH

To assess the safety of nanosilver at Konkuk University we have embarked on a Design for Lean Six Sigma based Waste Minimization research program with an international cross functional team. We have begun our study on the life cycle assessment of AgNP starting with the use of process mapping. In this paper, we will highlight our literature research findings in the life cycle assessment of AgNP. We are applying exergy analysis, TRIZ in Design for Lean Six Sigma - "Green" (DFLSS-G) to determine whether the nanosilver safety in environment is an old problem for silver, or an entirely new challenge. In any case, whether it is an old or new problem, we must deal with it seriously. As Luoma[5] stated – "Nanosilver – there is no silver lining".

2. SILVER AND NANOSILVER

Unlike most inert materials, it has been known for centuries that silver has an antiseptic effect. In ancient times, Greeks used silver vessels for drinking water storage. Koreans have also chosen silver to make their metal chopsticks. Recently, silver has found use in everyday products such as antimicrobial products, consumer products, and electronic products. The antiseptic effect gives an extra dimension in dealing with the life cycle assessment of silver.

Nanosilver can be made with different shapes such as particles, wires, and rods. Due to its enormous surface reactivity, AgNP has found utility in everyday products that require antibiotic performance, such as food contact materials, textiles and fabrics, appliances, consumer products, children's toys, infant products, 'health' supplements, cosmetics and pharmaceuticals[6].

Despite the fact that nanosilver effectively kills bacteria and thus becomes biocidal, many scientists are still not certain of its safety to humans,. Thus, safety has become a very sensitive and potentially critical issue for companies that make products containing nanosilver. A rigorous material flow analysis is needed to quantitatively assess the environmental impact of AgNP emission.

3. MATERIAL FLOW ANALYSIS

Using a material flow analysis (MFA), Johnson et al.[7] in their "anthropogenic cycling of silver in 1997" study have found that North America and Europe have the biggest share of use of silver products on a per capita basis. They found that global silver discards are approximately 57% of the silver mined and only 57% of the silver entering waste management globally is recycled. The amount of silver entering landfills globally is comparable to the amount found in tailings. Eckelman and Graedel[8] reported that more than 13 Gg of silver are emitted annually to the environment globally. The tailings and landfills make up almost three-fourths of the total emission.

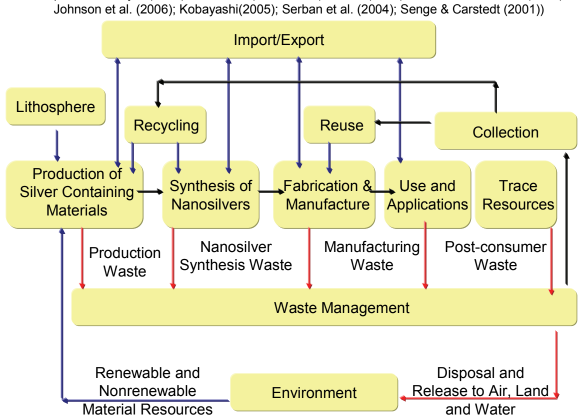
4. LIFE CYCLE ASSESSMENT

The quality of our life is improved by our industrial system, but the current system is creating unintended and serious consequences for the environment at a global level. For nanotechnology, to minimize these consequences, one must be able to transform all sources of waste and toxicity into "technical" or "biological nutrients". We can then reuse them indefinitely without harm to living systems.

Figure 1 gives an overview of a silver/nanosilver product's life cycle as food and waste in industrial metabolism. The metabolization of resources should be optimized in thermodynamic terms exergy. Dewulfn and Van Langenhove [18] have previously applied exergy analysis as a quantitative tool in the thermodynamic optimization of the life cycle of plastics.

Figure 1 - A Silver/Nanosilver Product's Life Cycle as **Food** and **Waste** in Industrial Metabolism [7-16]

Adopted from Geyer (2008): Lem et al. (2009, 2006), Muller (2007); Eikelman & Graedel (2007); Johnson et al. (2006); Kobayashi(2005); Serban et al. (2004); Senge & Carstedt (2001))



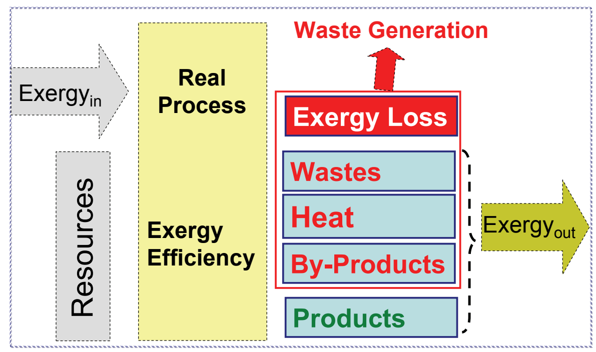
5. WASTE MINIMIZATION

Waste generation is a critical limitation for any sustainable industrial system[9]. Senge and Carstedt[16] offered a view of why industry produces waste and suggested that a synthetic process can emulate nature to reduce the waste using a cyclic industrial system. This is accomplished by focusing on three key aspects of the manufacturing process: (a) resource productivity, (b) cleaning products, and (c) re-manufacturing, recycle, and composting. One example of this approach is reycling of nylon 6 carpet[17]. This type of cyclic process has addressed and overcome the economic, technical, and logistical barriers to commercialize a closed loop recycling process and recover caprolactam from waste nylon 6 materials.

Waste generation is unavoidable so waste minimization becomes a fundamental requirement for economic feasibility. Based on the exergy ananlysis by Dewulf et al. [19], in Figure 2, Lem et al.[10] have shown that waste generation in a real process is more than just exergy loss (destroyed) in industrial metabolism.

Figure 2 - Waste Generation and Exergy Loss[18]

(Adopted from Dewulf et al, 2008)



$$\text{Exergy}_{in} = \text{Exergy}_{out} + \text{Exergy Loss}$$

Resources = Products + **[ByProducts + Heat + Wastes]+ [Exergy Loss]**

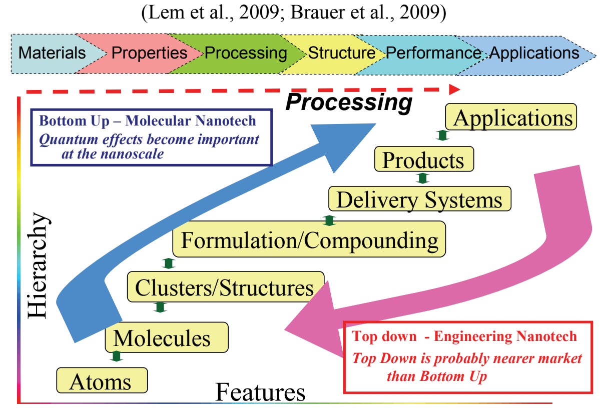
6. NANOPRODUCTS

Nanoproducts can be made in two ways: top-down and bottom-up. A top-down approach is essentially tearing down of a device to gain insight into its components, materials and compositions. A bottom-up approach is the piecing together of materials to give rise to components and finally to build a device.

Figure 3 gives a roadmap of top-down and bottom-up in development of nanoproducts under a value chain of "material – properties – processing – structure – performance – applications". This roadmap helps to identify the unmet needs from materials to/from applications in nanoproduct development and manufacture.

Figure 3 – Top-Down and Bottom-Up Development [6,10]

(Lem et al., 2009; Brauer et al., 2009)



Identify the Unmet Needs from Materials to/from Applications

Commercial AgNP products are very likely produced by a bottom-up process, whereas analysis of environmental impact by AgNP products is a top-down process (see Tolaymat et al. [20]).

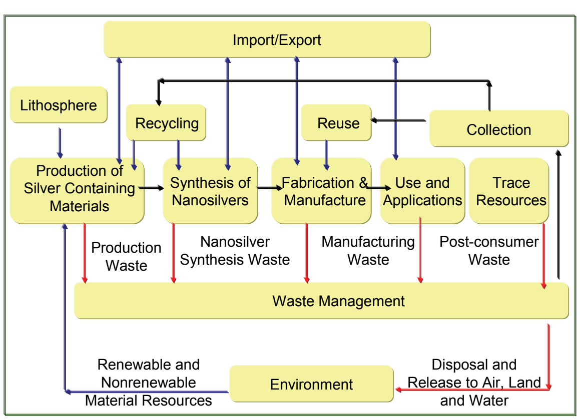
7. DESIGN FOR LEAN SIX SIGMA-GREEN (DFLSS-G)

We need to point out that waste minimization has been the background of the "Lean Six Sigma" methodology used to minimize wastes in manufacturing industries over the last few decades. Lean Six Sigma is a strategy that was developed to accelerate improvements in processes, products, and services, radically reduce manufacturing and/or administrative costs, and improve quality by relentlessly focusing on eliminating waste and reducing defects and variation. Design for Six Sigma (DFSS) is a tool for developing new products and processes "right from the start" for the triad in a project management - with the right quality, at the right cost, and at the right time [21-23]. Therefore, there is a need for Design for Lean Six Sigma – Green, where Green is for the environment and eco-products. Kobayashi [14] has used a product life planning methodology based on a quality function deployment (QFD) and a software tool to establish an *eco*-design concept of a product and its life cycle in multigenerational eco-products development.

8. DESIGN FOR LEAN SIX SIGMA/TRIZ

Serban et al.[15] have used a TRIZ approach to design for environment for over a product life cycle. Based on their work, we propose Design for Lean Six Sigma – Green with TRIZ to design AgNP eco-products and their life cycle as shown in Figure 4. From the mass balance of each step in the life cycle, the value generated is equal to the food resource available in each step minus the wastes at each step. Therefore, a summation of all the steps gives rise to the total value generated.

Figure 4 - DFLSS-G/TRIZ in Eco-Product Life Cycle Design

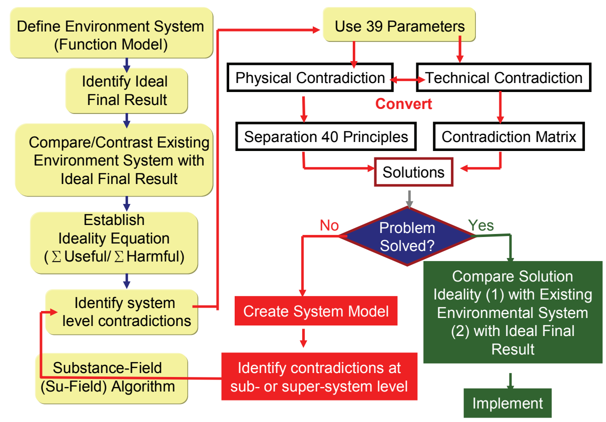


Total Value Performance = $\sum$ (Food Resource in Each Step) - $\sum$ (wastes) $_{\text{all sources}}$

A flow chart of the procedure to be used in our study is given in Figure 5 and a TRIZ approach in Design for Lean Six Sigma – Green for AgNP products life cycle is given in Table 1. We are using the following four step iterative approaches:

Figure.5 - Flow Chart for DFLSS-G with TRIZ [24]

(Adopted from Terninko et al, 1998)



<u>First:</u> determine the Voice of the Environment regarding the safety of the AgNP products using two extreme sides of the debate between Friends of Earth/USEPA and Silver Nanotechnology Work Group (SNWG) to obtain a resolution regarding "Conflict". We try to answer the question - could improving one technical characteristic to solve a problem cause other technical characteristics to worsen? Once the problem is defined, we need to define the system boundaries, quantify mass flows of AgNP, and to define several emission scenarios.

Table 1 - TRIZ Approach in DFLSS-G for AgNP Products Life Cycle

DFSS Phase	TRIZ Tools	Approach	Application to AgNP Product Life Cycle
Voice of the Customer	**1. Conflict Resolution, 2. Ideal Final Result, 3. Development of Measurement Systems.**	Identify the Problem	Step 1: Voice of the Environment (VOE) 1. Safety of AgNP Products. 2. Define Ideality Based QFD
Concept Development	**All**	1. Find The Principle that Needs to be Changed 2. Then Find the Principle that is an Undesired Secondary Effect.	Step 2: Conflict resolution 1. Example - Friends of Earth/USEPA vs. Silver Nanotechnology Work Group 2. Define Functionality/ Requirements
Detailed Design	**All**	1. Find the Principle that Needs to be Changed, 2. Then Find the Principle that is an Undesired Secondary Effect.	3. Use of Resources 4. Search for Previously Well-Solved Problems a. Examine 39 engineering parameters/40 principles. b. IP Landscaping
Optimize	**1. Conflict Resolution, 2. Trimming, 3. Subversion Analysis, 4. Problem Solving**	1. Look for Analogous Solutions 2. Adapt to the Potential Solution 3. Optimize – Ideality	Step 3: Review toxicity data for environmentally relevant silver compounds. Optimize wherever possible. Review earlier search for previously well-solved problems
Validate/ Implement	**1. Conflict Resolution, 2. Trimming, 3. Problem Solving**	Validate potential solution	Step 4: Gap Closing - Conflict resolution/Ideality Revisit

<u>Second:</u> search for previously well-solved problems by looking at the 39 engineering parameters/40 principles. Antimicrobial nanoscale silver is typically embedded within substrates, mainly a polymer, where any antimicrobial functionality is achieved via release of silver ions (Ag+).

The behavior of silver in environment will be reviewed, and a mass balance model applied to calculate predicted environmental concentrations. The uncertainty of the results is assessed and predicted concentrations are compared to experimental and empirical data (an example as reported by Benn and Westerhoff [25]).

Third: compile and predict the toxicity data for environmentally relevant silver compounds for noeffect concentrations. This material flow will be optimized based on a review of our earlier search for previously well-solved problems.

Fourth: evaluate and determine the potential for risk caused by the release of silver into environment using all available experimental data and literature data.

9. FUTURE STUDIES

In our Design for Lean Six Sigma based Waste Minimization research programs, we have begun our journey to study the life cycle assessment of nanosilver starting with the use of product life cycle process mapping and Design for Lean Six Sigma with TRIZ. We are planning to have more multidisciplinary and international interactions to characterization of AgNP products and their transformations in relevant biological and environmental media, in addition to systems and life-cycle approaches to nano-safety. We endorse the nanotoxicity evaluation advocated by Yu[26] from Korea Environment and Merchandise Testing Institute (KEMTI) to have a close collaboration between toxicologists and engineers.

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