Can Induction Plasma Technology be Nano-safe, “Green” and Energy Efficient?

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Abstract. With the rapid development of interest in the commercial scale production of nanopowders and nano-structured materials an increasing concern is being voiced about the safety measures that are taken in the design and construction of such facilities. This paper deals with such an important issue and describes the main design and manufacturing safeguards that were implemented during the design and commissioning of a recently inaugurated Tekna Advanced Materials powder production facility in Sherbrooke, Québec, Canada. The team of engineers from Tekna Plasma Systems was in charge of the design of multiple-units powder synthesis and processing facility to produce a wide range of nano- and micro-sized powders. The main design issues were process safety, environmental friendliness without compromising the overall processing economics. The bottom-up approach used was based on the integration of standard processing units, offered by Tekna Plasma Systems, housed in dedicated production facility equipped with process-specific hardware and operation procedures and safeguards in order to warrant the superior protection for process operators and the surrounding environment.

1. Introduction

The nanotechnology is considered as one of the four converging technologies for improving human performance [1] – the others being biotechnology, information technology and cognitive science. An intensive research effort in nanotechnology and especially in nanoparticles science is mirrored both by publication of many handbooks from general interest [2-4] to dedicated to specific powders like metallic [5] or to specific applications [6] and by increasing a number of companies launching their pilot or semi-industrial powder production.

An interest in wide spread mass-production of synthetic nanoparticles is responding to growing applications of such small size (< 100 nm) powders in different domains of industry like electronics (for Multi-Layered Ceramic Capacitors – MLCC), pigments and cosmetics (for sun screens) [7]. Some industry giants like Degussa AG, consider the nanotechnology as the most important technology of the future [8].
One of the possible technologies of nanopowders production is an induction plasma technology. The detailed description of the current development of nanopowders synthesis methods through the application of an induction plasma processing technology was published recently [9].

Tekna Plasma Systems Inc. (Sherbrooke, Qué. Canada) offers turn-key systems for both pilot scale and industrial production of wide variety of powders from micron-sized, through sub-micron- to nano-sized individual particles diameter. To answer the actual tendency in typical business model which is product’s diversification, it has been decided to launch a sister company offering both powder treating services and an actual, industrial scale, powder production for world-wide market using typical induction plasma system as offered by Tekna Plasma Systems. The team of engineers from Tekna put together their effort to design, build and operate industrial scale plasma facility having in mind the three aspects of technology: process safety and environmental protection without compromising sound economic foundation. This paper describes some of the problems encountered and proposed solutions undertaken at initial stages of operation of this enterprise.

2. Designing Considerations

Any industrial activity in Canada is controlled by federal, provincial and municipal authorities through corresponding laws and regulations. These include (among others) the disposal of all post-processing spent materials like ambient air evacuated from premises, cooling water and solid wastes generated in the process. Spent heat has to be evacuated through water evaporation process. The process safety management is one of the most accentuated aspects of any industrial activity and has to be dealt with adequately.

The type of industrial activity sought – commercialization of powdered materials synthesis, implies the presence of a variety of hazards related to both the technology used as well as to treated materials’/products’ physical and chemical properties. While the risks related to the technology are known and controlled, the products considered for production have to be analysed on the on-going base together with the diversification of powders offered.

Nanoparticles of engineered materials are defined as particulates having at least one dimension between 1 and 100 nm and are characterized by very unique physical and chemical properties which significantly differ from the bulk material’s ones. Their toxicities to humans and to ecosystems are currently investigated worldwide where some parameters like particle size, shape, surface area, charge, chemical properties, solubility, oxygen or nitrogen generation potential as well as degree of agglomeration may influence their toxicity.

At the initial stage of a plant design, when all of the future products to be manufactured in this facility were not clearly identified, the risks associated with the handling of ultrafine nanopowders was given major consideration independent of their chemical nature and toxicity. This required the following safety precautions:

- The control of exposure to the synthesized nanoparticles is strongly suggested [10] – such control may be practiced [11] by: lowering the dose, lowering the frequency and shortening the time of exposition as well as lowering the number of operators exposed;
- Another consequence of high specific surface area of nanoparticles is the pyrophoric nature of metallic nanopowders – this phenomenon as well as their thermal stability may be controlled by either passivation (partial superficial oxidation) process, and/or an encapsulation process [12,13];
- Collection of all residual materials from the processing units is to be handled by wet techniques during all maintenance operations.

The process safety management strategies, resourced from recently published [14,15] guidelines, suggest to apply preferably more efficient engineering techniques like isolation/containment and local ventilation than the administrative measures or a personal protection equipment. The principle of multiple layers of prevention/protection [16] was to be exercised during the design process.
3. Processing Units – Nano-powders synthesis
The nano-powders synthesis unit was designed in a way that all operations, including products’
collection were to be carried out under total containment conditions (Figure 1) – the latter one either in
glove box equipped with air lock to transfer canned products or (in the case of regular production) in a
continuous liner packing collector.

![Figure 1. Image of the current 60 kW induction plasma nano-powder synthesis unit.](image)

4. Processing Cost Reduction Strategies
The components of operational costs of thermal plasma processing plant do not significantly differ
from those observed in typical chemical industries – excluding raw materials costs and waste disposal,
there are three main elements: cost of processing gases, electricity and manpower. The strategies to
lower these costs are discussed below.

Processing gases, pending requested products, include argon, hydrogen, oxygen, helium, etc. Some
of them like oxygen or hydrogen may be partially consumed in the process while all inert gases could
be easily recovered, at least partially, through their post process recompression and conditioning. Each
of the plasma processing units is equipped with such gas conditioning system allowing up to 90% gas
recycling. Hydrogen, usually relatively expensive among used gases, is offered on the industrial
market in compressed form stocked in standard tanks. Stocking of significant quantity of hydrogen
and daily handling of these tanks require specific care from the point of view of process safety. The
in-situ hydrogen on-demand generation (by electrolysis of water) offers significant scale economy and
lowers the process risk due to much smaller volume of stocked hydrogen. At the same time the gas
recycling process recovers the entire hydrogen contained in gases so the in-situ generation replaces
only the current hydrogen consumption and/or losses.

Electricity cost is strongly related to the efficiency of used processing equipment and its
throughput. Very special efforts were dedicated to optimize the high frequency plasma generation as
well as the raw material processing parameters.
Manpower required may be reduced by high automation of the processing units which run for hours without immediate and constant operator’s surveillance as well as by bulk (high volume) handling of products – the operator takes care of products handling and final packing. The high automation has another benefit – the significant increase of process safety by computer controlled sequencing of operations such as raw materials feeding, hopper purging, products pneumatic transport and separation thus avoiding human errors.

5. Building Infrastructure

The building was designed to house two separate production halls (one for nano-powders synthesis and the other for powder spheroidization process). It had separate access to the infrastructure mechanical room for all services including cooling water, gases supply (hydrogen) and distribution equipment, incoming fresh air heating as well as all storage tanks and spent cleaning water conditioning system. Only the cooling water system is described below.

As specified above, any spent heat from the process has to be evacuated to surrounding atmosphere through evaporation of water in cooling tower. Cooling water, originating usually from natural sources like lakes or rivers and operating in closed circuit at moderate temperature, is prone to proliferation of bacterial cultures. Because their presence in water lowers thermal efficiency of the heat exchange process, the bacterial charge is usually controlled by adding some bactericide substances as well as some pH stabilisers. Unfortunately such chemically charged spent water cannot be disposed directly to the environment – it has to be treated in specific units additionally increasing the cost of whole operation. On the other hand the outside air is frequently charged with solid particulates (charged with some bacteria) which will be collected in the cooling water (cooling tower is a very efficient scrubbing device). The presence of suspended solids and bacteria may cause the fouling of heat exchangers. These two major issues were taken into account in designing the processing premises.

The chosen plant location does not allow use of any natural source of water (except rain) so it was decided to relay cooling process on city water with simultaneous collection of rain water. The characteristics of city water are the followings: low mineral charge and absence (or small, within the permitted limits) of bacterial charge - water is filtered and ozonized prior to its distribution and then slightly charged with chlorine to prevent bacterial growth in the distributing network. The temperature of such water varies from around 4-5°C during winter season to around 12°C during summertime. The rain water, collected exclusively on the building’s roof with relatively abundant average but difficult to foresee actual flowrate, may be charged with dissolved gases and some solids/bacteria. The economic analysis of the cost of investment to install separate rain water tank and gain over the city water economy (maximum water consumption to dissipate total plant power of 2.5 MW is around 1 kg/sec) indicated too lengthy payback period. It was decided to collect rain water directly in an oversized (28 m³) main cooling water tank located under the plant floor and equipped with overflow directed to outside in the case of significant rain outpour. Such solution imposed the elimination of usage of any substance to control the bacterial growth – instead the intense (> 40 000 µWs/cm²) ultraviolet radiation of circulated water has been applied. The solid particulates collected from cooling ambient air through scrubbing phenomenon are deposited at the tank bottom well by sedimentation and are periodically evacuated to outside by a sump pump.

The temperature of water leaving cooling tower is maintained at constant value no matter of heat load of incoming water by controlling the rotational speed of fans using frequency drive. During the heating season the incoming water heats up first the fresh air supply of production halls and then enters the cooling tower. During the high humidity periods (occurring mostly in July) where the ambient air is practically saturated with water, the city water arriving at ~ 12°C assures the adequate cooling of the plasma processing installations.

6. Safety barriers system

Process safety management principle suggests to build several sequential barrier’s layers for both prevention and or protection of the operator/environment etc. Typical Tekna’s processing unit is
automatically controlled through the Programmable Logic Controller (PLC). All the details of such system are beyond the scope of this paper - the following additional barriers are given as example:

First layer – to prevent a leak of nanoparticles to the working atmosphere:
- each processing unit is designed to withstand a deflagration;
- each processing unit is completely sealed during operation;
- raw materials and products are pneumatically transported;
- the products are collected either in bulk containers (250 l) for spheroidized powders or in glove box or continuous liner packing system for nano-sized products;
- the size of by-product collectors are chosen to minimize frequency of their opening;
- all processing vessels are inerted/padded by argon before the start-up as well as during raw material charging to the hopper;
- all flammable/pyrophoric powders are either passivated or encapsulated (application pending) before packing;

Second level barriers – to prevent exposure of operators to nano-particles:
- Effective local ventilation system consisting of three different arrestance filters where the final filter of fibrous type is HEPA class. Such fibrous type filters are known to be very efficient for collection of particles down to 4 nm – only at this size some thermal bouncing is expected – but such small size particles powders are not produced at plant;
- Wet cleaning operations are compulsory for each processing unit – the suspension is then evacuated through sealed conduits to a collection tank, where the powder is flocculated / coagulated and separated by sedimentation while the clean water is recycled into gray water system;
- Each operator is wearing a personal protective equipment including HEPA filtered forced air supplied hood;

Third level barriers – to prevent any leak of nano-particles to an external production hall environment:
- Production hall is kept under negative pressure as compared to outside;
- Air lock with forced recirculation/filtration exit from production hall;
- HEPA class filters at each evacuation port;
- Wet off gas cleaning after HEPA filtration for process units.

7. Conclusion
The bottom-up design approach from Tekna built standard thermal plasma processing units to entire production facility allowed to address and successfully resolve all major safety and economic issues involved with the production of advanced nano-sized materials by:
- Conceiving multiple – level barriers against nano-particle spill hazard;
- Minimizing the risk of exposure to hazardous materials through (among others) high level of process automation including final products packaging and separate production halls for higher hazard level materials;
- Establishing and implementing the adequate operational procedures;
- Cooling water cost reduction by recovery of rain / snow;
- Space heating by spent heat from plasma processing units;
- Minimizing the waste disposal costs through in-house recycling procedures and elimination of water conditioning chemicals (replaced by UV radiation);
- On-site, consumption regulated, production of hydrogen;
- Recycling (after conditioning) the major part of process gas.
The new facility is currently being operated since January 2010 and specific designing considerations are being confronted with operation experience.

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