SUBMICRON SEPARATION AND CONTAINMENT – WITHOUT THE FILTER!

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Abstract – *The U.S. Department of Energy (DOE) continues to emphasize the need for accelerated cleanup of its sites, including the decontamination and decommissioning (D&D) of former production facilities. At the same time, safeguarding the site personnel, the environment, and potentially affected interests outside the waste management professional field is of paramount importance. The need to balance both the accelerated cleanup, and the safeguarding of all, has spawned innovate, yet highly efficient cleanup technologies. One innovative approach capitalizes on a well-documented technology, cyclonic separation, to effectively remove particles down to sub-micron sizes (0.2 µm), the size often encountered as "dust particles" and airborne particulates during cleanup operations – without using traditional filtration techniques. Fine particulates may include radioactive and/or hazardous components, and may represent exposure pathways to cleanup personnel and the environment. Effective removal of particulates is essential to reducing worker exposure and achieving the ALARA principles desired during cleanup. As recent as a decade ago, cyclonic separators were deemed incapable of separating or removing particles less than 10 µm in size. Recent advances, however, are breaking new ground in separator efficiencies. Independent laboratory tests confirm a cyclone can remove particles down to the 0.2 µm effective diameter range - (comparable to a standard HEPA filter, with a typical efficiency rating in the 0.3 µm range). Additionally, the cyclonic separator removes the particles from the air-stream, and simultaneously collects the particles in an enclosed container to prevent clogging of downstream filters. The collection container is easily removed for disposal, with minimal possibility of re-introduction of the particles to the operating environment - thereby further reducing operator exposure. The work effort reviews the basic engineering design principles and objectives of the technology, including a history of its applications and ability to solve current waste management issues. The results of an independent laboratory evaluation are examined to determine the effectiveness and efficiency of the system presented in exceeding the design parameters and a comparison to more traditional hazardous and nuclear material vacuum systems. The system is being evaluated for use in additional fields where contamination at the sub-micron level can lead to significant manufacturing defects or harmful exposure to the environment. Potential application of the technology in the microelectronics, life sciences and other hazardous materials environments (including chemical and biological weapons) will be briefly examined.*

I. INTRODUCTION

Often, decontamination and decommissioning (D&D) effort includes cleaning up contaminated facilities that are no longer needed or no longer in use. The work activities include disassembling components and then recycling or packaging them as waste. Depending on the location and waste type, the waste may be disposed on site or sent to an offsite disposal facility. The facility is decontaminated and either released for reuse or demolished.

The scope of D&D efforts throughout the Department of Energy (DOE) alone is staggering. For example, a recent study revealed that there are more than 7,000 radioactively contaminated buildings located on DOE sites that formerly produced nuclear defense materials and must now be decontaminated, and approximately 700 buildings that are to be fully decommissioned. Additionally, there are some 180,000 metric tons of scrap metal within these facilities that must be remediated[1]. Due to the nature of the work conducted in these buildings, a mixture of various waste types can be expected. At a minimum, anticipated waste types may include some or all of the following:

- Sanitary waste;
- Industrial waste;
- Hazardous waste;
- Low-level waste (LLW);
- Intermediate level waste (ILW)
- High-level waste (HLW)
- Mixed waste; and
- Transuranic (TRU) waste

Clearly, D&D work represents a significant portion of the overall effort to remediate the Cold War legacy.

Large-scale demolition projects, such as building demolition often receive the most media attention. Heavy machinery, and sometime explosives, may be required to topple large buildings. Even these activities, however can create unwanted secondary wastes. When a building collapses, for example, a large cloud of dust expands outward from the demolition site. The dust cloud carries with it particulates, and, potentially, hazardous or radioactive material from prior building operations.

Effective decontamination prior to demolition is a key to minimizing the spread of particulates. During routine worker operations, waste dust and particulates can be readily tracked to other work locations, and airborne particulates can be spread through ventilation systems to all locations within a building, and even vented outside the building. Processes that routinely involve the use of hazardous and/or radioactive materials are of particular concern, because dust and spills may contain the hazardous/radioactive material, and the potential exists for increased worker exposure until the errant material is cleaned or removed and properly disposed.

The industry has recognized this potential concern, and has responded by developing several types of "vacuum cleaner" systems designed to effectively and efficiently remove errant material. Industrial operations vary widely in scope and types of materials encountered. Consequently, the type of "vacuum system" required for clean-up activities varies. For example, some systems have been developed to handle only dry materials, while others can handle dry and liquid materials. Industrial grade vacuum systems have been developed that may not be specifically engineered to address the special requirements encountered when working with hazardous or radioactive material. Although industrial grade systems may be suitable for some operations, if they are not specifically engineered (or modified) for use in hazardous/radioactive environments, they may complicate the potential for increased worker exposure during routine use, replacement, cleanup and maintenance of the vacuum systems, and by generating a significant volume of secondary waste.

A system ideally designed for use in hazardous and/or radioactive environments should:

- Minimize worker exposure to the materials during all phases of the cleanup process, including equipment maintenance;
- Minimize secondary waste generation, including the vacuum itself – thus a robust and dependable unit, that is easy to maintain and clean;
- Reduce equipment maintenance and consumable parts – easy and safe maintenance;
- Be engineered for maximum simplicity of design (fewest necessary components), yet be engineered to safely cleanup hazardous and radioactive material; and
- Be engineered for ease of use

II. WHAT TECHNOLOGIES HAVE BEEN TRIED AND ARE CURRENTLY AVAILABLE TO ADDRESS THESE CONCERNS?

The most-commonly employed vacuum systems consist of an outer drum or canister, which may also serve as the primary collection container for the vacuumed waste. The canister contains a filter (or series of filters) that permits airflow, but trap particulates. A vacuum head creates an internal pressure drop, and draws an air stream into the canister. The ability of the system to trap minute particles is usually a function of the vacuum strength, the airflow volume, and the pore size of the filter(s). Some systems have been designed with a series of progressively finer filters. For example, a bag filter (or roughing filter) may be utilized to trap larger particles, such as wood chips, metal shavings, etc. An interior filter, perhaps a High Efficiency Particulate Air (HEPA) filter may be used to trap particles as low as 0.3 microns. Larger, heavier particles drop to the bottom of the collection container. Lighter, smaller particles may adhere to the filter walls or filter material, and may eventual cause the filter to fail. The collection vessel may be emptied and reused, but a failed filter is usually replaced, and the failed filter itself is disposed.

Many adaptations have been added to the basic systems, such as external hose attachments, air-powered vacuum heads (for use in oxygen-enriched environments or with potential explosives) wheeled canisters, and so on.

III. WHAT INNOVATIVE USE OF TECHNOLOGY IS BEING PROPOSED?

In recent years, cyclonic separators have emerged to the forefront. As the name implies, cyclonic separators use a controlled cyclone to separate and remove particles from an air stream. A cyclonic separator usually consists of a vertical cylinder, with a tangential inlet, arranged so that an airflow stream enters the chamber and begins to spiral, creating centrifugal forces[2] (See Figure 1.). The centrifugal force drives heavier particles to the outer edges of the cyclone, where the drag of the spinning air combined with gravitational forces cause the particles to fall[3, 4]. Lighter particles remain in the carrier material (air stream). The centrifugal force created may range from about 5 times that of gravitational pull, to approximately 2500 times that of gravity, depending on the size of the unit[5]. Cyclonic separators are receiving increased popularity because they are simple to design and build, and usually have no moving internal parts. Additionally, cyclonic separators can operate at elevated temperature and pressure[6], including temperatures in excess of 1000°C and pressures in excess of 500 atmospheres[7]. Water cyclonic separators, also known as hydrocyclones, can be used to separate fluids of differing densities[8]. Perhaps the most widely recognized use of cyclonic separators is the so-called "bagless" home vacuum cleaner. Many commercially available systems are equipped with a translucent plastic separator, so one can view the particles spinning inside.

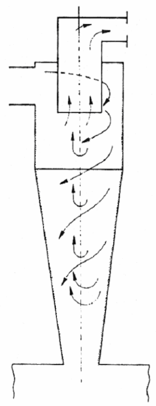


Figure 1 Cyclone Schematic

This paper reviews the application of a cyclonic separator for use in the remediation of hazardous and nuclear materials, and reviews an independent laboratory comparison of the proposed separator with a traditional vacuum system.

IV. CYCLONIC SEPARATORS – THE BASICS

Within the last decade, cyclonic separators were not viewed as being efficient at removing particles less than 10 microns in size[9] (designated in the literature as "PM-10" or alternatively, "<10 µm"). This is a concern because it potentially exposes the motor to the particles not removed by the cyclone. An accumulation of fine particles on the motor and fan blades can lead to decreased performance and eventual failure of the motor. To achieve more efficient removal of finer particles, many cyclonic separators systems insert a filter between the cyclone and the motor assembly. Unfortunately, the filter may restrict airflow, and may provide a false sense of security – users have delayed filter maintenance and replacement until the airflow is too restrictive, or until motor failure occurs. In an attempt to accomplish efficient separation at the sub PM-10 range, researchers have also developed a set of multiple cyclones connected in series. The concept is that each down-stream cyclone is not challenged by particles previously removed; therefore, more efficient separation can be achieved.

An understanding of the mechanics of cyclonic separators demonstrates how cyclonic separators can be enhanced to achieve efficient separation at levels well beyond the PM-10 range.

There are two major orientations of cyclonic separators – axial and tangential[10]. In the axial orientation, the air stream enters from the top of the cyclone and is forced to move tangentially by a grating placed near the top. In the tangential orientation (shown in Figure 1), the airflow enters the cyclone perpendicular to the vertical axis and tangent to the center of the body. Operation within the cyclone is similar for both orientations. In both arrangements, the air stream enters the cylinder and is forced to spin in a vortex as it proceeds down the cylinder.

The centripetal force F required to keep an object of mass m moving at a velocity v on a circular path of radius r can be calculated using[11]:

$$F = mv^2/r \qquad \text{(Equation 1)}$$

From Equation 1, it can be reasoned that particles with a larger mass require a greater force (for a given velocity and radius) to continue moving along their circular path. Particles that do not experience the force required to maintain their path "drop out" of the air stream, fall to the bottom of the cyclone, and can be collected for disposal.

The bottom portion of the main cyclone body is usually conical in shape. As the air stream enters the conical portion, the radius r decreases, and the force required to keep a particle of mass m in the air stream increases. Because there is no net increase in the force, the particles drop out of the air stream.

The efficiency of cyclonic separators is dependent upon the diameter of the main body and upon the pressure drop between the inlet and outlet of the cyclone[12]. Accordingly, efficiency can be increased by:

- Reducing cyclonic diameter;
- Reducing outlet diameter;
- Reducing cone diameter; or
- Increasing body length.

Unfortunately, the methods used to increasing efficiency can adversely impact capacity. Note that cyclone capacity can be increased by:

- Increasing the cyclone diameter;
- Increasing the inlet diameter;
- Increasing the outlet diameter; or
- Increasing the cyclone body length.

Additional consideration in the design of cyclonic separators include frictional forces encountered when particles strike the inside of the cyclone body, irregular air currents within the cylinder, and turbulence at the tangential point of entry which can create back pressure losses.

V. INDEPENDENT LABORATORY COMPARISON OF THE TRADITIONAL TECHNOLOGY AND THE INNOVATIVE TECHNOLOGY

A vacuum system has been developed that incorporates the mechanics described above. The system has specifically been designed to vacuum and remove plutonium and uranium oxides- -products associated with the Cold War production efforts throughout the DOE complex. However, independent laboratory confirmation of the system was required to validate overall performance.

Materials and Chemistry Laboratory, Inc. (MCL) is an independent analytical laboratory located on the East Tennessee Technology Park (a DOE site). Due to its location, the laboratory is familiar with traditional DOE facility operations, including Cold War production efforts.

MCL developed a performance measurement procedure[13] to evaluate the strengths of vacuum systems yet sufficiently challenge each system to identify potential weaknesses. The procedure was also used for comparative performance evaluation using a conventional vacuum system and a SafeVac system. For testing purposes, a local independent organization donated the use of a Minuteman Vacuum System Model Number 829123.

For testing and evaluation purposes, a non-radioactive mixture was prepared. In an attempt to thoroughly challenge the cyclone and to simultaneously emulate the density of nuclear materials mixed with dust and lighter materials, MCL developed a mixture of:

- 10 kg of iron oxide (Fe_2O_3), 99.5% <325 mesh
- 10 kg of Talc USP powder
- 1 kg of cerium oxide (CeO_2), 99.9% <5 micron

To assure homogeneity, the mixture was tumbled on a roll mill for 40 hours. Prior to each analytical evaluation, the mixture was again tumbled for 4 hours. The components of the mixture were evaluated for particle size distribution by scanning electron microscopy (SEM). Particle size determinations (calculated as effective diameter, in microns) are graphed in Figure 2 and summarized in Table 1. The maximum length and maximum width (perpendicular to the maximum length) were determined, and the effective diameter was calculated as the square root of one-half the length times one-half the width. As shown in Figure 2 the mixture was selected because it was anticipated that the vast majority of particles were below 10 microns in effective diameter, yet some particles in excess of 25 microns are present. To ascertain the cyclone's capability to remove smaller particles, it was necessary to determine the relative abundance of particles in the mixture below the 2.0-micron size, as shown in Figure 3.

Figure 2. Effective Particle Diameter of Mixture

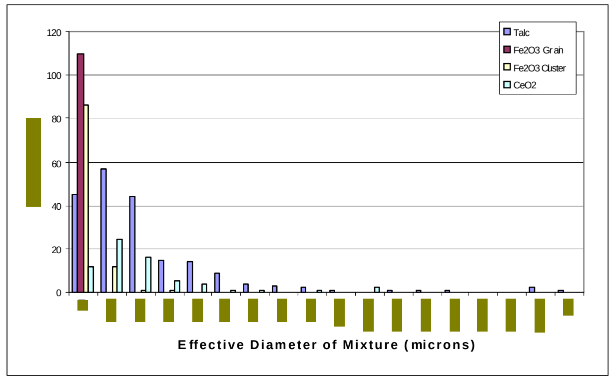


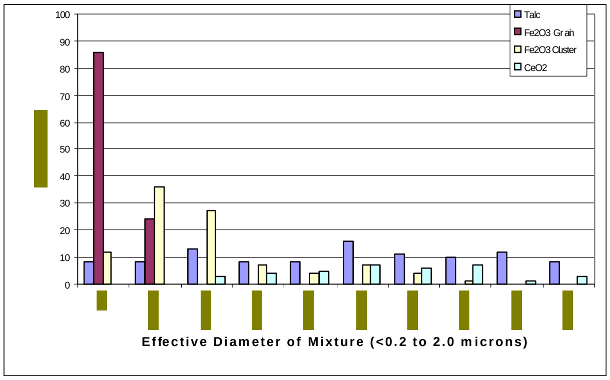
Table 1. Calculated Effective Particle Diameters (µm)

Mineral	Count	Ave.	Median	Max.	Min.	Range
Talc	200	2.92	1.94	47.51	0.12	47.39
Fe_2O_3 (grains)	110	0.16	0.16	0.26	0.08	0.18
Fe_2O_3 (clusters)	100	0.54	0.42	3.45	0.09	3.36
CeO_2	66	2.40	2.08	10.88	0.51	10.37

Note that Fe_2O_3 was found both as individual grains and as clusters of grains, and were therefore evaluated both as grains and as clusters. Grain clusters were found to range from as little as two grains to more than 100 grains. Effective diameter of all particles ranged from a minimum of 0.08 microns (Fe_2O_3 grains) to a maximum of 47.51 microns (talc). This mixture was chosen because it represents what might be encountered during D&D activities. Larger particles (in this experiment, the CeO_2 and Talc) could be expected to clog downstream filters, possible causing failure. As previously noted, cyclonic separators had not been well documented for removing PM-10-sized particles. The mixture was anticipated to challenge both extremes simultaneously. Additionally, the distinctive reddish-brown color of the allowed for immediate visual confirmation of the material throughout the interior of both vacuum systems.

The two vacuum systems were evaluated alternately. Both were fitted with a Dwyer Thermal Anemometer Series 470 to monitor intake airflow rate. A significant decrease in flow rate could be indicative of filter clogging. Monitoring devices were attached to the exhaust outlet of each system. Ambient environmental conditions (temperature and humidity) were determined to ensure compatible conditions during testing. Each system vacuumed similar amounts of mixture described above, in 500-gram increments.

Figure 3. Effective Particle Diameter of Mixture (<2 microns)



After the final increment of the mixture was taken, each system was disassembled. All filters were removed, inspected and weighed to determine the amount of mixture deposited on each filter. The amount of mixture collected in the collection containers was also determined as shown in Tables 2 and 3.

Table 2. Recovery Efficiency - Cyclone Model

	Test 1	*Test 2*
Cyclone	94.0%	95.0%
HEPA Filter	3.1%	3.3%
ULPA Filter	0.3%	0.1%
Exhaust	Not Detectable	Not Detectable

Table 3. Recovery Efficiency - Traditional Model

	Test 1	*Test 2*
Canister	5.7%	2.9%
Collection Bag	87.0%	89.9%
Prefilter	5.7%	5.4%
Cloth Filter	0.03%	0.03%
HEPA Filter	0.01%	0.01%
Exhaust	Not Detectable	Not Detectable

III. CONCLUSIONS

Two separate tests were conducted for each vacuum system. Results indicated that the cyclonic separator removed 94% and 95% of the mixture (particle size less than 0.2 microns). An additional 3.4% of the material was collected on internal filters (a HEPA and an ULPA filter) downstream of the cyclone. The researchers were unable to detect (non-detect) any of the mixture at the exhaust. The balance of the mixture was found lining the system interior, primarily on the intake hose.

The traditional system employs a filter as the primary separation technique. Downstream filters are also employed. The tests revealed that Minuteman's primary filter removed 87% and 89.9% of the mixture. Downstream filters removed an additional 5.7% (first test) and 2.9% (second test) of the mixture.

The test demonstrated the ability to prepare homogeneous mixtures that would challenge a vacuum system's ability to remove sub-micron particles, and simultaneously potentially clog a filter. For use in D&D operations in potentially radioactive environments, a vacuum system would need to be able to remove the sub-micron particles. Due the work environment, it would be advantageous to employ a system in which filters would not easily nor readily clog – the need to exchange filters within a radiologically-contaminated zone would be even further complicated by the operators' reduced ability to maneuver while dressed in Tyvek suits.

For hazardous and/or nuclear operations, generic systems are inadequate. Often, generic systems do not compensate for hazardous properties such as corrosivity. Further, traditional vacuum technology, employing a pressure drop across a filtration membrane, does not adequately remove minute particles. For operations involving radionuclides, the removal of minute particulates is crucial. System developed specifically to address the unique requirements of hazardous and radionuclear materials have been presented, examined, and compared.

The need for nuclear vacuum systems has grown out of a need to clean errant material, and has developed into an increasingly popular science of its own.

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