REVIEW OF CURRENT NUCLEAR VACUUM SYSTEMS TECHNOLOGIES

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ABSTRACT

Nearly all industrial operations generate unwanted dust, particulate matter, and/or liquid wastes. 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 - a serious concern for processes involving hazardous, radioactive, or nuclear materials.

Several varieties of vacuum systems have been proposed and/or are commercially available for clean up of both solid and liquid hazardous and nuclear materials. A review of current technologies highlights both the advantages and disadvantages of the various systems, and demonstrates the need for a system designed to address issues specific to hazardous and nuclear material cleanup.

A review of previous and current hazardous/nuclear material cleanup technologies is presented. From simple conventional vacuums modified for use in industrial operations, to systems specifically engineered for such purposes, the advantages and disadvantages are examined in light of the following criteria:

- Minimal worker exposure
- Minimal secondary waste generation
- Reduced equipment maintenance and consumable parts
- Simplicity of design, yet fully compatible with all waste types
- Ease of use.

The work effort reviews past, existing and proposed technologies in light of such considerations. Accomplishments of selected systems are presented, including identified areas where technological improvements could be suggested.

INTRODUCTION

Industrial operations, ranging from traditional manufacturing processes to specialized site operations such as decontamination and decommissioning (D&D) activities, generate unwanted dust, particulate matter, and/or liquid wastes. 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 to use

WHAT IS THE CONSUMER'S CONCERN, AND BY WHAT SYMPTOMS IS IT MANIFESTED?

Industrial operations involving hazardous and nuclear materials can result in undesirable worker exposure to the hazardous/radioactive material(s). However, proper collection of errant shavings, tailings, dust and miscellaneous particles in the work place can help to reduce worker exposure to ambient particles.

For traditional manufacturing operations involving non-hazardous/non-radioactive materials, a generic industrial grade vacuum cleaner may be appropriate. Most typical systems use an electric or air-operated motor to drive an impellor fan, creating a vacuum. A variety of hoses and/or piping can be attached so that the motor/fan unit can be remotely located. The vacuum draws material through a filter, either collecting particulate matter directly on the filter, or, providing a canister to collect the matter. Typical systems are very efficient at removing larger particles, such as wood, plastic or metal shavings. The systems are extremely popular due to their low cost, ease of operation, and effectiveness for their intended purpose. Most systems are also easy to modify for specific user needs, and often the only waste generated during use is the collected material, and an occasional filter. However, extremely fine particulate matter, such as concrete dust, may pass through roughing filters and enter the motor assembly (or be exhausted), so care must be taken to ensure that filter size is appropriate for the task at hand. Filters must be replaced (or, in some cases, cleaned) when clogged, and the canister must be emptied when full. Depending on the model, the system may be equipped to handle dry and/or wet materials. Standard commercial/industrial systems are generally not suitable for use in hazardous or radioactive environments unless the basic units have been modified.

Consequently, cleanup technologies for use in hazardous/radioactive environments have included standard industrial vacuum systems, modified for use in hazardous/radioactive work zones. However, such systems rarely address the specific concerns necessary for containment of hazardous or radioactive materials. For example, most commercial systems employ a plastic or metal drum (or canister), which can easily degrade when subjected to corrosive materials. Also, as hinted above, these systems are not manufactured to address the concerns associate with extremely fine airborne particulates. Consequently, fine particulates can pass through roughing filters, causing degradation of the motor assembly and even pass through the motor exhaust and be discharged into the local atmosphere.

This presents enormous concerns in the areas of worker exposure. Material that is discharged through a vacuum cleaner exhaust enters ambient air, and can be readily inhaled by workers in the general locale. Only specialized equipment, such as a self-contained breathing apparatus or an enclosed work area with its own exhaust, can prevent workers from inhaling the contaminants.

Systems designed specifically for use with hazardous and/or radioactive material are usually more complex for several reasons. First, contaminated material entering the vacuum system potentially contaminates all parts of the system. At a minimum, this implies that many, if not all parts of the vacuum system potentially become contaminated, secondary waste. Secondary waste includes all physical parts of the vacuum system that are exposed to the collected material. In typical drum vacuum systems, this includes the hose (and attachments), the filters, the collection vessel (drum), and often the motor (potentially, the entire system) – all of which must be disposed as hazardous/radioactive waste. Additionally, filters become clogged, and require that the worker disassemble the unit to manually change the filter(s) – again, increasing worker exposure to material on the filter. For smaller spills and dust materials, the volume of secondary waste can greatly exceed the volume of the original waste material. Proper disposal of contaminated waste is extremely expensive, so, in addition to worker exposure concerns, there is an economic incentive to minimize secondary waste generation.

Sample content can be a significant issue for the containment system. For example, corrosive liquids that are vacuumed present an obvious concern. Many commercially available systems employ a plastic or metal containment vessel, which may be readily destroyed by repeated contact with corrosive materials. Degradation of containment vessels requires replacement of the vessel (or, replacement of the entire system), which in turn leads to larger secondary waste generation and repeated costs associated with replacement parts. Some specialty systems allow the operator to request glass-lined containment vessels, designed to resist corrosion.

Next, particle size is of significant concern. When working with radionuclides, for example, studies have shown that a large percentage of radioactivity can be attributed to particles smaller than 1 μm in size[1]. Traditional bag filters and paper filters, often employed in industrial operations, are designed for much larger particle size entrapment, and generally are not suitable for removal of particles down to 1 μm. Particles that pass through the main filter are typically discharged directly into ambient air or ventilated. Systems engineered specifically for use in radioactive particle environments often rely on the use of high-efficiency particulate air (HEPA) filters. HEPA filters are extremely efficient at removing small particles. In fact, the Defense Nuclear Facilities Safety Board has opined that HEPA filters are, “…the final physical barrier to the release of material to the atmosphere and thereby serve to protect workers, the public, and the environment.[2]” Accordingly, the use of HEPA filters in the nuclear industry has been well documented. As with bag filters, however, HEPA filters can become clogged and their efficiency can degrade with use or exposure. Recently, the United States Nuclear Regulatory Commission issued an information notice to alert users about service condition limitations of HEPA filters that are used in ventilation systems[3]. The notice was issued in response to a condition identified at Consolidated Edison’s Indian Point 2 Nuclear Power Plant in which HEPA filters failed and clogged a fan intake screen. Failure and degradation of the HEPA filters was attributed to (1) excess water which increased filter loading and distortion, (2) inadequate surveillance, and (3) a lack of a pre-determined service life. Additionally, the U. S. Department of Energy sponsored its own research into HEPA filter degradation following the failure of several HEPA filters at the Rocky Flats Environmental Technology Site[4]. The filters had repeatedly been subjected to wetting. Clearly, the need to protect the HEPA filter from moisture had been documented.

Regularly scheduled filter replacement can be performed to reduce the opportunity of filter clogging, and may offset the degradation of the filter due to moisture exposure. However, workers are exposed to materials on the filter (and materials contained in a collection canister) during filter replacement. Precautions taken to reduce worker exposure may include protective outerwear, and may require that the filter replacement process take place within a designated, enclosed contamination zone work area. In each case, significant worker protection measures must be taken. Protective clothing must be disposed as secondary waste, again increasing the volume of contaminated secondary waste.

A final concern, especially when dealing with radioactive substances, is that of nuclear criticality. Nuclear criticality safety has been a concern since the early days of the nuclear industry, and has been defined as, “…the art of avoiding an accidental nuclear excursion[5].” Neutron-absorbing materials, such as the well-known boron Raschig rings, have been suggested for use within vacuum systems to safeguard against criticality. Although desirable from a criticality viewpoint, the absorbing rings require a substantial increase in size and weight of the vacuum system. The issue associated with nuclear criticality safety is not whether nuclear materials should be contained, but what are the dimensions of a container that will ensure criticality is avoided? Extensive studies have been conducted to determine maximum container size (see, for example, the work of H.C. Paxton and N. L. Provost[6] or the work of H. C. Paxton, J. T. Thomas, Dixon Callahan, and E. B. Johnson[7].) Traditional vacuum systems, including modifications of industrial vacuum systems, often employ collection drums for the accumulation of collected material. Drums vary in size, but typically range from about 3.5 gallon capacity to

55-gallon capacity. In non-hazardous and non-nuclear operations, larger collection drums are viewed as a system enhancement, because the larger drum capacity translates to fewer emptying efforts. Such systems, however, do not consider factors regarding volume of collected radioactive material. Care must be taken, when working with radioactive material, that the collected material does not reach critical mass. Therefore, carefully calculated container geometries are a requirement when working in radionuclide environments.

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

The most commonly employed methodologies for collection of smaller amounts of hazardous and/or radioactive dust and spills have included generic drum vacuum systems similar to a commercial Shop-Vac®. Some vacuum systems have been engineered for industrial, commercial, and/or cleanroom environments, and some have been modified for specific use with hazardous and/or radioactive materials. However, most commercially available designs focus attention on cleaning and containing the extraneous material, with little or no mention of reduced worker exposure, criticality safety or secondary waste generation in the product’s literature.

Some vacuum systems have been engineered specifically for use in hazardous and/or radioactive environments. For example, Joseph D. Zeren patented (U.S. Patent 5,301,388) a critically safe vacuum system (represented in Figure 1) for use with wet or dry radioactive materials, such as plutonium oxide[8]. Zeren acknowledges that, for safety reasons, radioactive materials must be contained in vessels with well-defined geometric and capacity criteria. Accordingly, the system patented by Zeren is designed and constructed such that radioactive material is collected in 4 canisters, physically separated from the motor assembly. The canisters are sized (geometrically and spatially) to ensure criticality is not achieved, even when the canisters are filled to capacity with radioactive material. A unique feature, and true advantage of this design, is that neutron-absorbing material is not required. As a result, the system recognizes a relatively larger capacity of collected material, with an overall reduction in system size and weight. To a large extent, the system is manufactured from stainless steel, facilitating clean out of the system. Primary usage of the device as originally designed includes manual cleanup of both liquid (wet) and solid (dry) radioactive material. Each canister contains a removable cloth filter for use with dry material, and is fitted with an inner screen that collects and removes larger particulate material and other debris that may be vacuumed along with liquids. A floating ball valve is positioned at the top of the central cylinder. When collected liquids force the float ball to rise, the float valve closes, and suction is terminated, ensuring against an overflow. Manual adjustment of the screens is required to raise the screens from the bottom of the canister(s). A valve is position at the bottom of the system to facilitate drainage of collected liquids; however, the liquids must be drained into specially designed holding tanks to ensure that criticality is not achieved. Finally, a sound muffler may also be added at the exhaust point to reduce noise. The system is flexible, allowing for additional filters to be fitted based on the type of material to be vacuumed. The system is mounted on a wheeled cart, making it readily transportable. A long, flexible hose allows the user to locate the unit at some distance from the material to be vacuumed. The system is approximately six (6) feet tall; opposite canisters a spaced at a minimum interval of 24 inches (center to center).

Filter bags, made of heavy-duty canvas cloth or fiberglass, are employed in the canisters to collect dry particulate material. Filter material and mesh size is not of significant importance, because a nuclear grade HEPA filter is employed for final filtering. HEPA filters typically achieve an efficiency removal rating of 99.97% of particles down to 0.3 μm. The upper portion of the system is removable, allowing access to the system's interior. The HEPA filter is held in place by eight spring-loaded cables, allowing for easy removal and replacement. Replacement of the filter bags must be performed in enclosed areas to minimize the potential of releasing airborne particles. However, frequent filter replacement means increased worker exposure during replacement. The concerns associated with minimizing worker exposure, as well as minimizing secondary waste generation were not discussed in the literature available for this review.

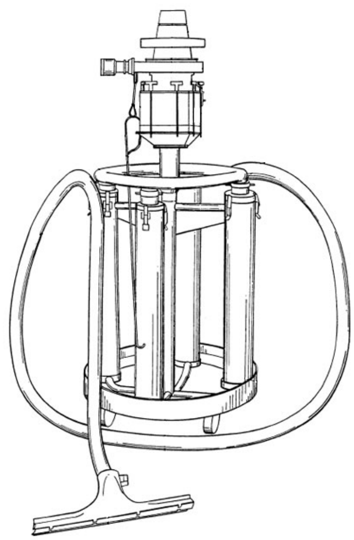

Figure 1. Representation of U.S. Patent 5,301,388

Joseph D. Zeren[9] (U.S. Patent 5,273,561, represented in Figure 2) also proposed a physically compact vacuum system specifically designed for stationary use in a small enclosure such as a glove box. The compact design (slightly less than 10 inches high [excluding the powerhead] by 12 inches in diameter) makes the system extremely portable and well suited for use in small, enclosed areas. Even so, the collection volume is in excess of 240 cubic inches of either wet or dry material. The system is designed for cleanup of both wet and dry radioactive material, and is sized such that criticality is not achieved, even when filled to capacity with plutonium oxide. Because the system is geometrically designed to ensure against criticality, neutron absorption devices are not required. Further, the system is manufactured primarily from stainless steel to prevent corrosion and leakage. Care has been taken to ensure that the motor's cooling and exhaust openings are fitted with a shroud to prevent spray from entering. A float valve is positioned such that the operator cannot overfill the collection vessel with liquid material. A significant advantage to this smaller system is that it is "position insensitive" during operation. Redundant automatic vacuum check/liquid drain valves release liquid through drains, if the system is operated in a position other than upright (if, for example, the system were accidentally tipped over during use). The liquid drain valves will even prevent overfilling in the event that a sprinkler system were to be activated within a glove box or hot cell.

The system makes use of two commercially available cloth or paper filter bags, but because it was designed for use inside a small enclosure, the system does not have its own HEPA filter. The filter bags must be cleaned or removed while the system is contained within the glove box. Likewise, the collection vessel must also be emptied inside the glove box or work area. Additionally, because the entire vacuum system resides inside a glove box, the system becomes contaminated during use and must be disposed as contaminated secondary waste. Worker exposure to collected material was minimal, except during maintenance.

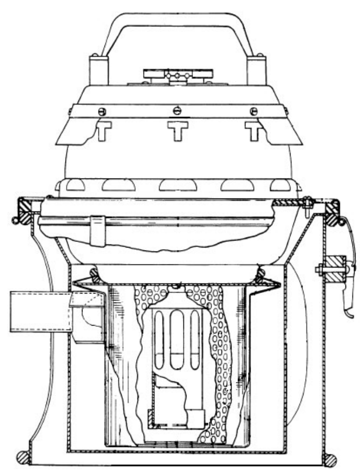

Figure 2. Representation of U.S. Patent 5,273,561

Roger R. Stoutenburgh recognized the need for a system that not only collected material, but also contained the collected material in a manner that reduced the risk to human health and well being from handling the material improperly. Additional advantageous considerations addressed by Stoutenburgh include a design that:

- Permits a repetitive and controllable vacuum pressure;
- Is hand-held and therefore easily used;
- Provides a means for easy identification and/or labeling of the material in the container;
- Is equipped with lead shielding and/or a glass lining to protect against radioactivity and corrosive materials (respectively); and
- Can be manufactured easily and inexpensively for widespread use.

Consequently, a system proposed by Roger Stoutenburgh[10] (U.S. Patent 5,491, 345, represented in Figure 3) was designed specifically for pick-up and containment of hazardous fluids or particulate material or waste. The system is sufficiently robust to address a broad definition of hazardous material, including chemical and radioactive substances, corrosive agents, poisons, biomedical and other health-endangering materials. The system consists of a self-contained sealed vacuum canister unit. Conceptually, the unit is somewhat analogous to an aerosol spray can operating in reverse. A vacuum is created inside the unit by connecting a conduit to a vacuum source, and then opening the unit’s release valve. During use the external vacuum is disconnected. The conduit is positioned next to the material to be siphoned, and the release valve is pressed. The vacuum inside the unit draws the material into the unit.

A significant advantage of this system is that minute particles (such as those that might pass through a filter) are not discharged through an exhaust port to ambient atmosphere. Instead, all material is collected inside the container. Because the system is sized to fit within a human hand, and because the valve is operated by finger pressure, the entire unit is readily portable, easy to handle, and can be conveniently stored in the work area for immediate use. Although it is necessary to establish a predetermined vacuum inside the canister, there is no need for an external power supply. The attached conduit can reach into extremely small spaces, allowing the operator to effectively clean even the smallest of spills. Further, the inside of the canister can be lined with glass (for use in corrosive environments) or lead (for use in radioactive environments). When the unit is full, or when the vacuum is exhausted, the complete canister is easily labeled and disposed. Although the canister is easy to use, and extremely portable, it may not be suitable for cleanup of larger volumes of material. Particulate material to be vacuumed must be of small enough particle size so as to not effectively block the conduit tube or release valve. The unit may conceivably be used more than one time, but it is the responsibility of the operator to ensure that only compatible materials are siphoned into the container. Also, because each canister is disposed, secondary waste volumes can be significant.

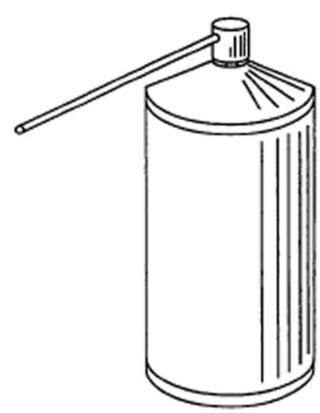

Figure 3. Representation of U.S. Patent 5,491, 345

A system proposed by John McCracken (U. S. patented pending, represented in Figure 4) employs multiple separation stages to enhance separation, especially of minute particulate material. In the first separation stage, a cyclone separator precipitates larger particles without requiring filtration. Instead, centrifugal force and expansion are employed to achieve highly efficient separation of larger particles. Cyclonic vacuum action has been well documented in the art (for example, see the work of James Hugh Croggon[11], U.S. Patent 6,425,931). The work of Frank Twerdun[12] demonstrates the applicability of cyclonic vacuum technology. A system developed by Andrew Thomson[13] (U.S. patent 6,461,508) is specifically designed for separating dirt or dust from an airflow. Further, a system developed by Stavros Semanderes[14] (U.S. patent 6,417,751) employs polycyclonic vacuum collectors for virtually non-stop environmental remediation. Even the canister body of a cyclonic vacuum cleaner has been studied and developed (see, for example, the work of Michael Hammond[15], U.S. Patent D461,285). During operation, the system creates a series of (internal to the system) high and low-pressure zones that eventually deposit debris within the air onto the bottom of a containment drum. However, it has been demonstrated in the art that several factors are important in the design of cyclonic separators. For example, size is critical in determining the mass of the precipitated particles. Larger particles are separated and collected at the bottom of the cyclonic unit. In the system proposed by McCracken, material is deposited into a removable container, sized to ensure criticality is avoided even when filled to capacity with highly enriched uranium or plutonium. A translucent container (suitable for some applications) is available to allow the operator to visually determine the level of material in the container. For routine operations the container is the only part of the system that needs replacement. The small opening on the collection container ensures minimal worker exposure during replacement, and, for additional safety, the opening can be fitted with a control valve to virtually eliminate all potential for exposure. Additionally, the lower portion of the system can be fitted with a glovebag or glove box to further minimize worker exposure. The system is designed for use with wet or dry materials. Additionally, the system is engineered and designed from concept to production to ALARA principles.

In the second stage, a microfilter removes finer particulate material. The microfilter is physically elevated relative to the first stage collection container to ensure that particulate matter and/or liquids do not contact the microfiltration unit. The positioning of the microfilter is such that particulate matter is deposited from the air stream before contacting the microfilter, virtually eliminating the possibility of clogging. This filtration step also ensures that the system's motor is protected from even bacteria-sized particles. The final filtration utilizes an ULPA exhaust filter, further reducing the amount of material that could potentially be reintroduced into the ambient air. In a typical stream containing uranium oxide particles, overall collection efficiency can easily exceed 99.999% of particles down to 0.12 microns.

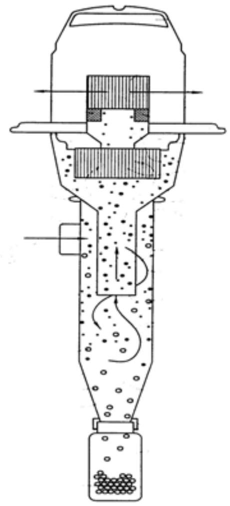

Figure 4. Representation of the Safe Vac System

Additional features include stainless steel construction for easy decontamination and a quiet, yet powerful vacuum motor. The system can be mounted on a wheeled cart, sized to safeguard against criticality even when operated adjacent to another similar unit. Conductive plastic hose and accessories provide additional worker protection. The standard unit is 44 inches tall by 15 in diameter, excluding the wheeled cart. The technology is scalable, and can be custom-designed for specific applications.

The system utilizes a single collection container of standard fixed size. The container was engineered to prevent the contents from achieving a criticality situation, which also implies that only smaller volumes of radioactive material can be collected before the container must be changed. Additionally, the system was designed to include state of the art technology, which carries the added burden of increased initial cost.

It is recognized that additional systems may exist beyond those presented here. The intent here is to present an overview of commercially available options, and to briefly examine some of the significant advantages and disadvantages to popular vacuum technologies available to the user. A comparison of nuclear vacuum system technology is summarized in Table I.

Table I. Comparison of Current Nuclear Vacuum System Technologies

	Specialty Systems	**Commercially-Available “Nuclear” Vacuum Systems**	**Drum or Canister Systems**
Operator Safety	• Minimal exposure. • Quickly sealed rigid, translucent container allows for fast, clean maintenance	• Increased exposure potential. • High-dose exposure risk is high, because airborne contaminants are reintroduced to the atmosphere during routine maintenance	• Increased exposure potential. • High-dose exposure risk is high, because airborne contaminants are reintroduced to the atmosphere during routine maintenance
Designed to ALARA Principals	Yes.	No	No.
Contaminant Extraction	Three Stages • Cyclonic separation • HEPA pre-filter protects motor and exhaust filter. • ULPA exhaust filter	Two Stages • Bag or roughing filters • HEPA exhaust filter usually standard.	One or Two Stages • Bag or roughing filters • Exhaust filters usually optional and may include HEPA option.
Filter Change	• Rarely. • Vast majority of contaminants are removed by cyclonic separation • Filters are physically separated from the containment vessel, thus minimizes potential operator exposure during maintenance.	• Frequent, due to potential clogging and potentially dangerous.	• Frequent • Increased worker exposure during filter change.
Secondary Waste Generation	Minimal. • Rigid collection vessel is sealed, labeled and used as disposal container. • Filters rarely need replacement.	Significant. • Paper filter bag, HEPA filter, and polyliner are disposable. • Entire system sometimes becomes part of secondary waste stream.	Significant. • In addition to collected material, all used filters must be disposed. • Entire system often becomes part of secondary waste stream.
Nuclear Criticality	• Criticality safe geometry.	• Not specifically designed for criticality safety. Special applications can be requested.	• Potentially unsafe geometry.
Dry or Wet Use	Dry or wet.	Depends upon model.	Depends upon model.
Power Requirements	120 VAC, Air operated available	120 VAC or Air Operated models	120 VAC

	Specialty Systems	Commercially-Available "Nuclear" Vacuum Systems	Drum or Canister Systems
Collection Container	• Translucent container is rigid allowing operator to monitor fill level and quickly seal. • Shielded containers available. • "Iris-valve" opening available	• Unable to determine fill level. • May require lifting and dumping, thereby exposing hazardous material back into the work environment.	• Unable to determine fill level. • May require lifting and dumping, thereby exposing hazardous material back into the work environment.
Lifetime Cost Factors	• Lower lifetime cost. • Higher initial cost. • Minimal maintenance • Maximizes worker safety. • Robust and dependable for a long service life.	• Higher lifetime cost. • Higher initial cost. • Frequent filter replacement costs. • High worker exposure potential. • Entire system often replaced.	• Higher lifetime cost. • Lower initial cost. • Frequent filter replacement costs. • High worker exposure potential. • Entire system often replaced.
Manufacturer / Distributor	Designed, Engineered, and Manufactured in the USA	Depends on model.	Depends on model.
Certifications	• Nuclear Suppliers Association (NSA) Certified • DOP certified HEPA filter, ASME AG-1 FC-3000 Specifications (Nuclear Grade) Tested per IES-RP-CC001.3 For Type B Filter • Laser-certified ULPA filter as per IES-RP-CC00.7	• Some models ISO 9001 certified. • Some meet ASME AG-1 FC-3000 Specifications (Nuclear Grade) Tested per IES-RP-CC001.3 For Type B Filter	• Depends on model

SUMMARY AND CONCLUSIONS

Production operations generate errant waste, which ultimately must be cleaned. One of the most efficient methods for cleaning errant materials is the use of a vacuum cleaner. Initially, vacuum cleaners in industrial applications mirrored those for residential applications, where the primary objective was to collect the errant material. For traditional, non-hazardous and non-nuclear operations, this methodology appears to meet the immediate need.

For hazardous and/or nuclear operations, however, 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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