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Evaluation of an Innovative Use of Removable Thin Film Coating Technology for the Abatement of Hazardous Contaminants

Margaret E. Lumia¹, Charles Gentile¹, Michael Gochfeld², Philip Efthimion¹, and Mark Robson³

¹Princeton University, Plasma Physics Laboratory, Princeton, New Jersey

²UMDNJ–Robert Wood Johnson Medical School, Piscataway, New Jersey

³Rutgers University, School of Environmental and Biological Sciences, New Brunswick, New Jersey

Abstract

This study evaluates a new decontamination technique for the mitigation and abatement of hazardous particulates. The traditional decontamination methods used to clean facilities and equipment are time-consuming, prolonging workers' exposure time, may generate airborne hazards, and can be expensive. The use of removable thin film coating as a decontamination technique for surface contamination proved to be a more efficient method of decontamination. This method was tested at three different sites on different hazardous metals. One application of the coating reduced the levels of these metals 90% and had an average reduction of one magnitude. The paired t-tests that were performed for each metal demonstrated that there was a statistically significant reduction of the metal after the use of the coating: lead ($p = 0.03$), beryllium ($p = 0.05$), aluminum ($p = 0.006$), iron ($p = 0.0001$), and copper ($p = 0.004$). The Kendall tau-b correlation coefficient demonstrates that there was a positive correlation between the initial levels of contamination and the removal efficiency for all the samples taken from different locations on the floor for each of the three sites. This new decontamination technique worked efficiently, requiring only one application, which decreased exposure time and did not generate any airborne dust.

Keywords

abatement; contaminants; hazardous; thin film coating

Introduction

There are many industrial processes that contaminate facilities and equipment with hazardous particulates. This can be an expensive problem, usually necessitating extensive decontamination procedures and discarding and replacing equipment. The presence of

hazardous materials, in fine ($<10\mu\text{m}$) or coarse ($>10\mu\text{m}$) particulate matter, also presents industrial hygiene issues in the workplace.

There is the possibility of employees being overexposed during the decontamination process to these hazardous particulates, which can result in illness and even death. Most industrial processes that include machining of hazardous metals such as beryllium and lead require that these areas be decontaminated on a regular basis. Due to the potentially hazardous properties of metal dust and particulates, a decontamination technique that is efficient, does not generate airborne dust, and is safe is desirable.

Currently, decontamination methods used for beryllium and other metals include the wet method, a high-efficiency particulate vacuum, or sticky cloths.⁽¹⁾ Also, many machinists clean their shops with brooms, generating airborne dusts. Not only are these processes expensive and time-consuming, but they must be done on a regular basis, increasing the potential for overexposure to the employees. A study⁽²⁾ was conducted to determine if using a removable thin film coating technology was more cost-efficient than steam vacuum cleaning technology at a radioactive contaminated facility at the Savannah River Site National Laboratory. The results of the study demonstrated that the coating technology was most cost-efficient in reducing labor; two mechanics and one health physicist completed the job in 4.35 hr vs. 70.4 hr for the same number of workers using steam vacuum cleaning technology. The steam vacuum cleaning technology was less expensive in the equipment and waste disposal areas. However, in the demobilization area, the coating technology cost \$139 with only 1 hr of cleanup vs. \$5503 for 48 hr of cleanup with the steam vacuum cleaning technology. Overall, the coating technology had a 33% cost saving over the steam vacuum cleaning technology.

Due to the success of the removable thin film coating in decontaminating radioactive contamination, it is believed that this technology will also be successful in decreasing the amount of time it takes to decontaminate other materials, such as metals, in reducing the exposure time to the workers, and will not generate airborne dust during the process. This technology has been used to decontaminate commercial nuclear facilities since the early 1980s.⁽³⁾ The loosely adherent, paint-like coating decontaminates radioactive equipment, prevents contamination, and fixes contamination in place.

Strippable paint and stripcoat are other names for this product. Strippable paint is commonly used as a temporary protective coating in paint booths. A review of the literature has found that this technology is frequently used proactively as a barrier, mostly in the automotive field, rather than as decontamination method. Arbitrarily limiting the use of removable thin film coating for radioactive contamination or as a temporary protective layer eliminates the possibility of using this coating as a decontamination method on other particulate contaminants, such as heavy metals.

In this study, three different locations, the Tokamak Fusion Test Reactor basement, a beryllium machine shop, and an active machine shop, contaminated with different hazardous metals, were chosen to analyze the efficiency of the coating as a decontamination method. The first location was the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma

Physics Laboratory (PPPL). The laboratory is managed by Princeton University and is funded by the U.S. Department of Energy, Office of Science. The TFTR operated at PPPL from 1982 to 1997⁽⁴⁾ and set a number of world records, including a plasma temperature of 510 million degrees centigrade, the highest ever produced in a lab. In 1999, PPPL commenced the TFTR Decontamination and Decommissioning (D&D) Project, whose objective was to completely remove TFTR in a safe, efficient, and cost-effective manner.⁽⁵⁾

The safe removal of lead shielding at the PPL was a major component of work during the D&D Project.⁽⁶⁾ The physical aspects of this project started at the beginning of October 1999. Throughout 1999, 2000, and 2001, approximately 250,000 pounds of lead were safely removed from the TFTR test cell and test cell basement. Typically, the lead was in the form of bricks each weighing approximately 27 pounds that were used as radiation shielding around TFTR's diagnostics. After years of use, many of the bricks were coated with a layer of white powder. Analysis of this powder revealed inorganic lead oxide. During brick removal, the powder had a tendency to become airborne and resettle on other surfaces throughout the work area, with most of it settling onto the basement floor.

This redeposition was a serious concern in the TFTR test cell and test cell basement where there was a high number of workers performing collateral tasks associated with TFTR D&D.⁽⁶⁾ Applying the coating to the contaminating area, letting it cure, removing it, and bringing the lead dusts levels below the U.S. Department of Housing and Urban Development (HUD) guideline of 50 $\mu\text{g}/\text{ft}^2$ only took about 128 person hours to complete.

However, the traditional wet method took over 3000 person hours and did not result in bringing the lead levels below the HUD guideline. This noteworthy decrease in person hours also decreased the exposure time to lead dust for the workers and the amount of time spent in personal protective equipment, including full face respirators, which places stress on the workers.

The existence of lead oxide presented both airborne exposure and surface contamination issues for the workers in the field who were removing this material.⁽⁶⁾ The workers were required to wear disposable protective clothing, which was discarded before leaving the contamination area, and full face air-purifying respirators. The workers were also entered into a blood lead level medical surveillance program. The presence of the surface lead dust contamination also created issues with the equipment and structural elements, such as metal beams and wooden shelves. These objects, which were coated with the lead dust, had to be disposed of as hazardous waste, substantially increasing disposal costs.

The second location was at the old beryllium machine shop at Los Alamos National Laboratory (LANL). In 1953, all machines and equipment were moved from an old facility into the shops at building SM-39.⁽⁷⁾ Operations in the new shops included lathes, a mill, a surface grinder, and drill press, all within a hood enclosure.⁽⁸⁾

The beryllium machine shops were washed down weekly and sampled to ensure that loose beryllium dust levels were below 15 $\mu\text{g}/\text{ft}^2$.⁽⁸⁾ In 2002, the shops in building SM-39 began the process of being decommissioned and decontaminated. Once the project is completed the area will be free released and reclassified as a nonberyllium area.

Beryllium has been used for various operations related to weapons production at LANL since 1943.⁽⁷⁾ Machining and firing tests resulted in beryllium being released not only in the work area but also into the environment. Machining, grinding, sanding, and other general handling of beryllium and beryllium components occur in the machine shop as well as in experimental areas. There are industrial hygiene records from 1949 to 1989 that indicate beryllium metal was processed in shops and metallurgical labs. Soluble beryllium salts were used in chemical labs at 20 different technical areas within LANL.

Inhalation is considered the primary route of exposure for workers.⁽⁹⁾ A noncancerous health end point is chronic beryllium disease (CBD), also known as berylliosis.⁽⁹⁾ Inhalation exposure to beryllium and beryllium compounds can result in CBD, which is an inflammatory lung disease. It is evident that there is an exposure-response relationship to beryllium.⁽⁹⁾ Several studies have shown that workers chronically exposed to beryllium and beryllium compounds, even at the beryllium permissible exposure limit (PEL) of $2 \mu\text{g}/\text{m}^3$ did develop CBD.⁽⁹⁾

There is epidemiologic data available that suggests that lung cancer is a health end point for workers with inhalation exposure to beryllium and beryllium compounds. For airborne particles, the lung is the target organ for both humans and animals.⁽¹⁰⁾ The safe human chronic air concentration (RfC) is $2\text{E-}2 \mu\text{g}/\text{m}^3$. This is 1/10 of the adjusted adverse effect level for beryllium sensitization and CBD in workers. It is estimated that the human lung cancer risk is $2.4\text{E-}3$ for exposure to $1 \mu\text{g}/\text{m}^3$ of beryllium.⁽⁹⁾

The final site was an active machine shop at the PPPL. During machining operations such as grinding, polishing, cutting, drilling, and during cleanup, the workers have inhalational exposure to metal particulates and dusts. The usual methods for cleaning a machine shop, sweeping with a broom and vacuuming, stir up the metal dust causing airborne contamination. This dust resettles onto the machinery, floors, and other surfaces.

Occupational exposure to metal dusts and particulates can induce a variety of lung disorders and disease, including parenchymal diseases, airway disorders, and cancer.⁽¹¹⁾ Pneumoconiosis is an example of a parenchymal disease that can occur because of occupational exposure to metal dusts. The machine shop at PPPL most frequently machined aluminum, copper, and iron.

Methods

The three study sites were chosen opportunistically; there was a need for cleanup and a willingness on the part of site management to try a new method. This study employed quantitative methods to determine if the efficiency of the removable thin film coating was statistically significant. Because of the hazardous properties of the different metals, a decontamination technique that is safe to the workers, efficient, and economical is desirable. One such technique is the use of removable thin film coating. To determine the efficiency of the coating, wipe samples were used to collect an initial level of the contaminant present at each location. They were also used to collect a final level of the contaminant present after

the removal of the coating to determine the amount of contaminant left from various locations within each site.

Wipe Sampling

Individuals trained in surface wipe sampling techniques collected samples of the contaminant before and after the use of the removable thin film coating, which were subsequently analyzed and recorded as pre and post levels. The method used to collect the samples was based on NIOSH 9100 “Lead in Surface Wipe Sample” of the *NIOSH Manual of Analytical Methods*.

The wipes used conformed to ASTM E 1792. Each wipe was a 15 cm × 15 cm rayon substrate pre-moistened with deionized water and individually wrapped. At each of the three sites, several different sample locations were marked. In each location, two sample areas were marked adjacent to each other. The first area determined the initial level of contamination, and the second area determined what the contamination level was after the use of the removable thin film coating.

Three areas of the TFTR test cell basement had diagnostic equipment with lead brick shielding. After each area was cleared of the lead bricks, the workers wiped the floor surface areas, metal structural beams, and wooden shelves with Windex and then used a HEPA filter vacuum to remove any lead dust. The metal structural beams and wooden shelves were all removed and disposed of as hazardous waste; only the floor was left, which became the focus of the decontamination project.

The floor of the TFTR basement was made of a boronated concrete. Boron was incorporated into the concrete to attenuate any neutrons generated from the reactor. Initially, the floor was cleaned with a HEPA vacuum and water. However, this was very time-consuming, taking over 3000 person hours and did not result in lead levels below the HUD guideline of 50 µg/ft². To determine if the use of removable thin film technology was a viable decontamination method, 17 floor locations in the PPPL TFTR basement, with two samplings areas in each location, were first marked, using a 12 inch × 12 inch template, and then sampled for lead.

Nine locations with two sampling areas were marked using a 10 cm × 10 cm template at the old beryllium machine shop and then sampled for beryllium. The sample areas fell into two categories: (1) accessible occupied areas, and (2) limited access mechanical spaces. The accessible occupied areas were the floors, walls, milling machines, and countertops. The limited access mechanical space included the baghouse, ventilation ductwork, and light fixtures. Each location was large enough for the template to fit, and all the locations except for the grinder tabletop were clean of any oil or liquid substances. The grinder tabletop was coated with a layer of cutting fluid and oil.

Twenty-one locations with two sampling areas were marked for sampling, using a 10 cm × 10 cm template on the vinyl tiled floor of the PPPL active machine shop. The areas chosen were around the various machines and in the aiseways between each machine. These areas were sampled for aluminum, copper, and iron.

In all three sites, the first area in each location was used to determine the initial level of contaminant. The other area was sampled after the coating was removed to determine how much contaminant was left. The two adjacent sample areas for each location were assumed to have the same concentration and distribution of the contaminant. Having only one sample area at each location was not practical, as it could not be determined how much of the contaminant was removed during the initial wipe sampling.

Removable Thin Film Coating

In the second sample area of each location, a layer of the removable thin film coating was applied using a sponge brush. The coating was a water-based organic polymer.⁽³⁾ The coating was used straight from the manufacturer, the formula was not altered in any way, and the same brand of unaltered coating was used at each of the three locations.

The coating technology is designed to trap and fix particulates in the coating's matrix by adhesion. As the liquid polymer is spread over the contaminated area, it migrates into the micro-voids of the surface. Once the polymer starts to cure, it attracts, absorbs, and chemically binds to the contaminants.⁽³⁾ The coating can be applied to an existing contaminated area to fix and capture the particulates for removal. Once the curing process is completed, the coating traps the contaminant into the polymer matrix.⁽³⁾ The nature of the coating, after sufficient cure time, is such that it can typically be removed as one continuous entity.

According to the manufacturer, the coating can be applied using a paint sprayer. However, it was found that the sprayer frequently became clogged; therefore, the coating was applied using a foam sponge brush. The coating can be applied to almost any surface type. One of the concerns after the coating cured and was removed from the surfaces was if it left any residue. The use of a residual gas analyzer demonstrated that only water was left on the surface once the coating is removed. It was observed that if there was paint on the surface where the coating was being used, that some of the paint was removed along with the coating.

Laboratory Analysis of the Wipe Samples

Evaluation protocols required that the wipe samples be analyzed by laboratories recognized by AIHA's Laboratory Accreditation Program (IHLAP ISO/IEC 17025 Accreditation). All wipe samples were analyzed for beryllium, lead, iron, copper, or aluminum by inductively coupled plasma mass spectrometry using the Environmental Protection Agency modified SW 846 6010B;ICP;LEADWP. Quality control procedures in the laboratory included analyzing blanks that were submitted with each sample batch.

Some of the metal samples (post-remediation only) were reported as below the laboratory method detection limits (3 out of 89 samples), and the authors were concerned that this would affect the statistical significance of the removal efficiency of the removable thin film coating. None of the samples were below laboratory detection limits were from a single data set. Two of the samples were from the iron sample set, from two different sample locations; the third was from the aluminum sample set.

One approach recommended by Helsel⁽¹²⁾ was to set the censored data at one-half the limit of detection. The results were also analyzed using the conservative assumption that the post-remediation values were just at the minimum detection limit (MDL). This adjustment of the results to the MDL did not adversely affect the outcome of the removal efficiency. In any case, there were so few censored data that these analyses rendered similar results.

Statistical Analysis

Data were analyzed using SAS v. 9.1. A one-tailed paired t-test was used to determine if there was a significant reduction in amount of metal particulates after the use of the removable thin film coating. The removal was considered significant if $p < 0.05$. Because of the nonparametric data, Kendall tau-b correlation was chosen to measure the strength of association between the initial surface concentration and the percentage of removal efficiency

Results

Surface Wipe Samples

Lead surface dust levels were measured by wipe sampling at 17 different locations on the floor in the TFTR basement. The means for the pre and post levels were $2687.3 \mu\text{g}/\text{ft}^2$ and $111.2 \mu\text{g}/\text{ft}^2$, respectively, after the use of the removable thin films. The largest concentration of lead dust was located where the columns of lead bricks shielded the diagnostic equipment. A one-tail paired t-test was computed to determine if the use of the coating significantly reduced the lead surface dust contamination. Despite the small number of samples ($n = 17$), the results ($p = 0.03$) demonstrated that there was a statistically significant removal of the lead surface dust. The average removal efficiency was 82% (Table I). This reduction is better illustrated in Figure 1.

The beryllium surface dust levels were measured by wipe sampling at nine different locations throughout the beryllium machine shop. The sample areas fell into two categories: (1) accessible occupied areas, and (2) limited access mechanical spaces. The accessible occupied areas were the floors, walls, milling machines, and countertops. The limited access mechanical space included the baghouse, ventilation ductwork, and light fixtures. The means for the pre levels were $0.1728 \mu\text{g}/\text{cm}^2$ and $0.0644 \mu\text{g}/\text{cm}^2$ for the post levels after the use of the removable thin films.

The largest concentration of beryllium dust was located on the Bridgeport milling machine. The grinder tabletop sample was removed from the data set as an outlier. This one outlying sample may have been caused by cutting oil or lubricant that was present interfering with the coating's ability to adhere to the surface. A one-tail paired t-test (with and without the grinder tabletop sample) was computed to determine if the use of the coating significantly reduced the beryllium surface dust contamination. The results for both data sets, with and without the grinder table, (top $p = 0.05$) demonstrated that there was a statistically significant removal of the beryllium dust. The average removal efficiency was 88% (Table II).

The final facility where wipe samples were measured was the active machine shop at PPPL. Twenty-one samples for aluminum, iron, and copper were taken from the floor around the various machinery throughout the shop. The mean values pre and post use of the removable thin film were: aluminum $32.07 \mu\text{g}/\text{cm}^2$ (pre) and $1.64 \mu\text{g}/\text{cm}^2$ (post), iron $25.46 \mu\text{g}/\text{cm}^2$ (pre) and $1.97 \mu\text{g}/\text{cm}^2$ (post), and copper $3.98 \mu\text{g}/\text{cm}^2$ (pre) and $0.12 \mu\text{g}/\text{cm}^2$ (post). The one-tailed paired t test results were: aluminum ($p = 0.006$), iron ($p = 0.0001$), and copper ($p = 0.004$). The average removal efficiencies for all three metals were nearly the same: copper 90%, iron 88%, and aluminum 89%. The data also showed that there was an average one order of magnitude reduction of each metal dust (Table III).

Kendall Tau-B Correlation Coefficients

The data were not normally distributed; hence, a nonpara-metric test (Kendall tau-b) was used to avoid having to transform both variables (Table IV). Kendall tau-b correlation coefficients were computed to investigate the probability of removal of the contaminant with the removable thin film coating. All of the wipe samples, except for the ones collected at LANL, were taken from various locations on the floor. The LANL samples were taken from different surface locations throughout the machine shop.

All of the floor samples from the different locations and for the different contaminants indicated that there was a significant positive correlation between the initial contamination concentration and the percentage of removal efficiency as shown in Table IV. The results of the Kendall tau-b for the beryllium wipe samples at LANL did not produce a statistically significant correlation between the initial contamination concentration and the percent of removal efficiency. These samples were taken from different surface substrates within the machine shop. These areas include the floors, walls, light fixtures, milling machines, and from the ventilation ductwork.

Discussion

The first objective behind using the removable thin film coating technique at the different locations and on the different contaminants was to decontaminate the areas below the required levels to be considered cleaned. During decontamination of the TFTR basement, the coating worked in reducing the lead contamination below the HUD guideline of $50 \mu\text{g}/\text{ft}^2$. The beryllium machine shop was to be decontaminated to below the Department of Energy standard of $0.2 \mu\text{g}/100 \text{ cm}^2$.⁽¹⁾

After one application of the coating in the various accessible and nonaccessible locations, the mean beryllium level was $0.06 \mu\text{g}/\text{cm}^2$. Local site management decided that this level was low enough to release it for any nonberyllium activities without further remediation. The coating also worked well in decontaminating the metal dust from the PPPL machine shop areas, with an average of 89% removal rate after one application.

Another objective was to decrease the amount of time that it takes to decontaminate the areas, therefore decreasing the workers exposure time and preventing airborne dust from generating during the process. During the initial decontamination of the TFTR basement, multiple cleanings with water and Windex were done. This process took a long time (over

3,000 person hours) and did not reduce the levels of lead below the HUD guidelines. Only one application of the coating technology and 128 person hours were needed to reduce the amount of lead to a safe level. When this decontamination technology was applied to the PPPL machine shop, it did not generate any airborne dust, eliminating a health concern associated with the traditional methods of cleaning with a broom or vacuum.

The wipe samples at all the locations where the coating was used on the floor had a significant positive correlation between the initial levels and the removal efficiency. However, when the coating was used on different substrates such as the milling machine, grinder table, and light fixtures, there was no significant correlation between the initial levels and the removal efficiency. This could be due to cutting oils and lubricants that were present on the machines interfering with removable thin film coating's adhesion to the surface.

However, because only one set of samples at each of these locations was taken, no conclusions can be made. Also, these substrates did not have a continuous flat surface like the floor, and the coating may not have been able to get into all the cracks and crevasses.

There were a few limitations with this study. One limitation is the assumption that the contaminants are evenly distributed across each sample location. The locations of the sample areas used to determine the initial concentration of the contaminants were adjacent to locations where the coating was applied. This was done because there was no way to determine how much of the contaminant was removed during the wipe sampling process, and it was thought that this was the best way to get the most accurate data. If costs were not a consideration, four adjacent samples would have been obtained to estimate the pre-cleanup loading. However, although the single adjacent sample is not a precise measure, there is no reason to assume that it introduces a systematic bias. Another limitation was the small number of samples and the lack of repeat samples. Despite these limitations the results demonstrated that the coating can be used successfully as a decontamination technique for hazardous particulates. It was less time-consuming, requiring a fraction of the person hours traditional methods need. The use of this technology was also less labor-intensive than the traditional decontamination methods, no set up of equipment is required, the coating is easily applied with either a brush, a paint roller, or a sprayer. Cleanup involves only peeling up the coating and disposing of it and the paint brushes or rollers. There is not a lot of equipment to be decontaminated after the process—only the paint sprayer, if used.

This material is widely available from a few different manufactures and costs about \$80 per gallon, which covers 50 square feet. Although the coating is expensive, there is a cost saving in labor and initial setup and cleanup of the area and equipment.

Conclusion

The results presented in this research indicate that the removable thin film coating technique performed well at decontaminating three different facilities contaminated with various hazardous particulates. The metals and dusts differed as did the surface finishes and configurations. The results indicated that for the variety of surfaces and metals in this study,

there was between 85–90% removal efficiency with one application of the coating. The paired t-tests that were performed for each metal demonstrated a statistically significant reduction of the metal after the use of the coating. This new decontamination technique worked efficiently, requiring only one application, thereby decreasing exposure time to the workers and preventing airborne dust from generating.

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Figure 1.
Lead surface dust reductions post use of the removable thin film coating.

Table I
Lead Surface Dust Reduction Pre and Post Use of the Coating

Sample Number	Pre ($\mu\text{g}/\text{ft}^2$)	Post ($\mu\text{g}/\text{ft}^2$)	Percent Removed
1	2000	8.4	99.58
2	6697	14.9	99.78
3	868	40.2	95.37
4	1180	76	93.56
5	491	32.9	93.30
6	529	48.7	90.79
7	721	298	58.67
8	645	145	77.52
9	309	194	37.22
10	229	134	41.48
11	316	86.2	72.72
12	1151	423	63.25
13	1763	321	81.79
14	207	14	93.24
15	21974	12.8	99.94
16	2934	20.6	99.30
17	3671	21.4	99.42
Arithmetic Mean	2687.4	111.2	82.17 ^A

^AThe arithmetic percent removed is the mean of the individual removal percents.

Table II
Beryllium Surface Dust Reduction Pre and Post Use of the Coating

Sample Number	Pre ($\mu\text{g}/\text{cm}^2$)	Post ($\mu\text{g}/\text{cm}^2$)	Percent Removed
1	0.0260	0.0007	97.15
2	0.2500	0.0036	98.58
3	0.9680	0.5070	47.62
4	0.0015	0.0000	97.33
5	0.0640	0.0003	99.48
6	0.0578	0.0008	98.55
7	0.0027	0.0005	82.64
8	0.0124	0.0023	81.69
Arithmetic Mean	0.1728	0.0644	87.88 ^A

^AThe arithmetic percent removed is the mean of the individual removal percents.

Table III

Surface Dust Concentrations Pre and Post Use of the Coating

Sample Number	Al			Fe			Cu		
	Pre ($\mu\text{g}/\text{cm}^2$)	Post ($\mu\text{g}/\text{cm}^2$)	Percent Removed	Pre ($\mu\text{g}/\text{cm}^2$)	Post ($\mu\text{g}/\text{cm}^2$)	Percent Removed	Pre ($\mu\text{g}/\text{cm}^2$)	Post ($\mu\text{g}/\text{cm}^2$)	Percent Removed
1	16.60	1.14	93.13	63.50	2.65	95.83	1.34	0.09	93.24
2	9.76	0.74	92.42	34.50	1.06	96.93	0.47	0.06	87.14
3	7.05	1.20	82.98	7.84	1.68	78.57	0.55	0.06	88.71
4	10.40	0.56	94.65	9.57	0.88	90.77	1.25	0.04	96.83
5	13.40	2.51	81.27	27.90	5.10	81.72	0.53	0.13	75.14
6	4.79	1.62	66.18	6.98	1.30	81.38	0.75	0.05	93.11
7	7.16	0.59	91.75	33.50	1.05	96.87	0.76	0.03	95.80
8	17.50	0.25	98.57	20.30	0.25	98.77	11.30	0.12	98.93
9	32.70	1.76	94.62	31.80	1.87	94.12	3.02	0.37	87.62
10	38.60	0.88	97.72	21.70	0.93	95.73	14.90	0.07	99.56
11	247.00	3.54	98.57	5.96	0.51	91.49	1.89	0.12	93.81
12	12.90	0.60	95.35	6.31	0.25	96.04	0.86	0.04	94.82
13	25.30	0.80	96.82	5.71	0.52	90.88	0.70	0.04	94.22
14	40.60	1.96	95.17	9.78	1.62	83.44	1.84	0.12	93.64
15	43.90	3.45	92.14	48.40	2.04	95.79	0.96	0.18	81.31
16	6.73	4.76	29.27	8.40	4.14	50.71	0.65	0.23	64.37
17	35.10	3.27	90.68	28.40	4.38	84.58	1.43	0.28	80.35
18	28.40	1.27	95.53	23.00	1.56	93.22	14.50	0.09	99.41
19	47.60	1.83	96.16	108.00	6.50	93.98	4.04	0.28	93.04
20	19.40	0.93	95.23	7.57	1.07	85.87	21.30	0.15	99.28
21	8.52	0.52	93.90	9.85	1.07	89.14	0.53	0.05	90.17
Arithmetic Mean	32.07	1.64	89.15 ^A	25.46	1.97	88.85 ^A	3.98	0.12	90.50 ^A

^AThe arithmetic percent removed is the mean of the individual removal percents.

Table IV
Kendall Tau-b Correlation Coefficients of the Various Metal Surface Dust Contaminants

Variable	N	Pre Mean	Post Mean	Percent Removed ^A	Correlation	Percent Removed vs. pre Kendall Tau (p)
Copper	21	3.98 $\mu\text{g}/\text{cm}^2$	0.12 $\mu\text{g}/\text{cm}^2$	91 $\pm$ 8.89		0.45 (p = 0.004)
Iron	21	25.46 $\mu\text{g}/\text{cm}^2$	1.97 $\mu\text{g}/\text{cm}^2$	89 $\pm$ 10.57		0.30 (p = 0.06)
Aluminum	21	32.07 $\mu\text{g}/\text{cm}^2$	1.64 $\mu\text{g}/\text{cm}^2$	89 $\pm$ 15.58		0.47 (p = 0.003)
Lead	17	2687.4 $\mu\text{g}/\text{ft}^2$	111.2 $\mu\text{g}/\text{ft}^2$	82 $\pm$ 20.68		0.59 (p = 0.001)
Beryllium	8	0.17 $\mu\text{g}/\text{cm}^2$	0.06 $\mu\text{g}/\text{cm}^2$	88 $\pm$ 17.83		0.22 (p = 0.40)

^AThe percent removed is the arithmetic mean of the individual removal percents.