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Vacuum Cleaner Modifications Leading to Reduced ESD Hazards

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MASTER

Abstract

After a series of meetings held in response to an Unsatisfactory Report on the use of vacuum cleaners, an experimental study of commonly available vacuum cleaners was conducted. The object of the study was to evaluate the effectiveness of the cleaners as electrostatic generators. The electrical charges generated by the machine can inadvertently be transferred in normal operations to electroexplosive devices (EEDs), thereby creating a potentially hazardous situation. In the course of this study, it was determined that many inexpensive commercial cleaners could be used safely providing certain modifications were made. Details of the required modification and rationale for the modification are presented in this report.

Contents

Introduction.....	7
Non-Conducting Hose Tests	9
Conducting Hose Tests	10
Venturi Vacuums	12
Attachment Charging.....	14
Bonding Procedures.....	15
Touch-off Equilibration	15
Dust Electrification	16
Conclusion and Recommendation.....	18

Illustrations

1	Typical Electroexplosive Device (EED)	8
2	Vacuum Cleaner/System Configured with Non-Conducting Hose.....	9
3	Vacuum Cleaner/System Configurations (Conducting Container, Conducting Hose	10
4	Modified shop•vac®.....	11
5	Feedback Wiring Detail	11
6	Laminated Bag Modifications for Use with Venturi Vacuum Cleaner.....	12
7	Experimental Arrangement for Conducting Bag Venturi Vacuum Evaluation	13
8	Venturi Cleaner with Metallized Vacuum Bag (Note vibrating reed sensor)	13
9	System Charging Resulting from use of Plastic Attachments.....	14
10	System Charging Resulting from use of Non-conducting Hose and Conducting Attachment	14
11	Touch-off Equilibration Procedure	15
12	Setup Schematic for Touch-off Measurements.....	16
13	Setup Schematic for Dust Electrification Test	17
14	Setup for Dust Electrification Test	17

Vacuum Cleaner Modifications Leading to Reduced ESD Hazards

Introduction

The electrostatic discharge (ESD) from a person or an object that has become electrically charged is a very real and practical potential threat environment to the safe handling and reliable operation of advanced weapons. Personnel routinely become charged to and maintain voltage levels of 6 to 12 kV or more from triboelectric processes associated with normal daily activity such as walking or rising from furniture. Furthermore, particularly under conditions of low humidity, an individual operating a vacuum cleaner can develop substantially higher voltage with respect to the surroundings.

Perhaps the most widely used American utility vacuum cleaner in both light industry and the home workshop is the "wet/dry" vacuum. Because of its popularity, and those features which make this device almost a workshop necessity, it has found a place in many maintenance facilities. It is durable, reliable, inexpensive (typically, less than \$40.00 with attachments) and easy to use. Unfortunately, it is a very effective electrostatic charge generator. According to anecdotal accounts, given operation in the very low relative humidities encountered in home workshops during wintertime, a typical sawdust removal in a darkened workshop is accompanied by a spectacular coronal discharge which illuminates the tank assembly and the pick-up hose. These reports are given credence by a series of laboratory measurements in which the hose attachment attained voltages in excess of 50 kV resulting from intake of abrasive sand. Apparently, the corona discharge from the vacuum system establishes a limit on further charge accumulation.

An evaluation of the wet/dry vacuum from the standpoint of nuclear and personal safety is informative. The Underwriters Laboratory (UL) requires that a three-conductor grounding cord and plug be used to provide power to these devices. Reasons for this arrangement are given in UL sanctioned owner's manuals. For present purposes, it can be assumed that the power head, that is, the motor including the fan, is "grounded" by means of the "green" lead. The green lead presumably reaches an "earthed counterpoise." It is likely that the third or "neutral" wire eventually reaches the center tap of the 220 V pole transformer in a typical power distribution system. Any surge on the line induced by a nearby lightning stroke, for example, after some attenuation depending on the effectiveness of the counterpoise, could pass on to the power head. Accordingly, the following general requirements of nuclear explosive safety must be observed:

Nuclear explosives must be isolated from all sources of, and return paths for, ac power. In particular, nuclear explosives must be isolated from what is commonly referred to as "green ground," which could be connected to the grounded, neutral portion of an ac power distribution system. This requirement precludes the use of any "explosion proof" vacuum cleaner that contains a low resistance path from the working end of the hose to "green ground."

The power head of a conventional, UL-approved vacuum cleaner is doubly insulated to protect the operator. Therefore, a surge on the line cannot be propagated to an assembly undergoing maintenance; that is, nuclear safety is not compromised.

The motor which moves the fan is very powerful, typically 1 to 3 horsepower. The high power is achieved by using a universal motor; that is, a dc series motor adapted for ac use. Electric current passes through the field windings and reaches the armature of the motor by means of carbon brushes which contact the commutator. Because of the sparking between brushes and the commutator, the common wet/dry vacuum is not approved by the UL for use in "explosive environments."

"Explosion proof" industrial type vacuum cleaners approved for use in UL class I or II environments have motors that are totally enclosed so that commutator sparking provides no threat when operated in those environments associated with flour milling, refinery operations, or any activity resulting in accumulations of ignitable dust or vapors. Typically, heat exchangers cool the totally enclosed, high-powered (3 - 4 HP) motors used and electrical continuity is maintained from the grounding plug at the end of the power cord to the metallic attachments to the conducting vacuum hose. Although this arrangement eliminates the hazards associated with electrostatic discharges (ESD), unfortunately, nuclear safety is compromised because the ground for the power distribution system becomes connected to an explosive device. If non-conductive vacuum attachments or pneumatic extensions are used to circumvent the nuclear safety hazard, these modifications introduce an ESD hazard.

It should be noted here that maintenance operations on electroexplosive devices (EEDs) are never performed in UL class I or II environments. The explosives themselves are always contained, that is, enclosed in a metallic, plastic, or ceramic shell.

Figure 1 shows a typical EED. A fine bridgewire, imbedded in a sensitive explosive mix serves as an electrothermal converter. When an electrical current passes through the bridgewire its temperature rises; and, if the temperature is great enough, the sensitive mix is initiated, it explodes and detonates the secondary explosive.

Initiation of the explosive mix can also result inadvertently if an electrical arc occurs between either pin and the metal case, that is, a pin-to-case discharge. This can be avoided by shunting the pin and case by either a spark gap or large resistance. Most modern EEDs are protected this way. However, some of the older EEDs are not protected and an arc path can be established through the primary explosive by inadvertent application of only a few kilovolts. In some cases initiation can occur if the energy applied exceeds 0.1 micro joule. The electrostatic charge required to produce the arc is generated very efficiently by the vacuum. The resulting hazard can be mitigated by either attenuating the charge induced by the vacuum process or by ensuring that the attachments, operator, and EED (leads and case) are all at the same electrical potential. Elaboration on both options are presented in this report.

The question addressed next is whether or not a shop•vac®¹ (or comparable) cleaner may be safely used to clean loose dirt, dust or other foreign matter from weapon assemblies in view of the ESD hazard introduced by these cleaners. The answer is yes, provided a simple electrical modification is made on the cleaner.

Figure 1. Typical Electroexplosive Device (EED)

¹ shop•vac® corp., Williamsport, PA (for present purposes, the term "shop vac" is regarded as generic; no endorsement of a particular brand is implied).

Non-Conducting Hose Tests

Figure 2 shows two vacuum/system test configurations using a non-conducting hose. Both vacuums were made by shop•vac®; the plastic and metal containers were models 500 and 600A, respectively. The system on the right side is the "victim," and as the hose attachment approaches or touches the system, charge on the hose is transferred to it. The resistance between a conducting point on the tank and laboratory ground was found to be greater than $10\text{ G}\Omega$, the largest resistance that can be measured using a PROSTAT model PRS-800 megohmmeter. For all the tests described here the resistance between the tank and ground can be considered infinite. All voltage and resistance measurements are referenced to laboratory ground which is the copper pipe system used to distribute cooling water to various laboratory power supplies. The block labeled *system* is some conductive object bonded to an EED. This system makes physical contact with the hose by means of an accessory attachment, for example, a crevice tool or gulper nozzle. In all tests, abrasive sand was used to simulate dust. However, little difference was noted between observed electric field intensities resulting from ingestion of either abrasive sand or ordinary desert sand.

Figure 2. Vacuum Cleaner/System Configured with Non-Conducting Hose. (Dashed lines indicate pneumatic continuity).

Two electrostatic fieldmeters were used to determine electric field strengths. One was a PROSTAT model PFM-711A fieldmeter with a digital readout; the other was a MONROE model 245 fieldmeter with an analog readout. Both instruments use a vibrating reed sensor and a phase sensitive detector so that the measurement is essentially drift free.

All tests were performed in the Sandia EM Analysis and Test Department ESD laboratory. Electrostatic fieldmeters were used to detect charge buildup on the plastic container and non-conducting hose resulting from the uptake of a small amount of sand. The hose attachment (and hose) attained a maximum voltage in excess of 50 kV, negative, while the container attained a voltage of 8 kV, positive, that is, as the non-conducting hose becomes negatively charged, the tank becomes positively charged. Although the physics is probably much more complex, it may be postulated that a dust particle colliding with the vacuum hose loses an electron to the hose in a triboelectric exchange. The dust particle, which is now positively charged as a result of loss of an electron, is propelled by the high-velocity air stream into the container where it gives up its positive charge to the container.

No essential difference in the charge buildup phenomena for the two shop•vac® units was observed when a conducting container was substituted for the plastic container. However, the plastic container of a

Hoover vacuum attained a voltage of 30 kV, positive.² The higher voltage can be attributed to the greater mass of charged particulate processed by the larger, more powerful Hoover. Irrespective of manufacturer, maximum voltages attained by non-conducting hose appears to be limited by coronal discharge.

Tests performed using sand clearly were designed for maximum charge buildup. However, hose charging occurred even with ambient air particulate uptake. The maximum voltage attained by the hose was -6 kV at the attachment end; the minimum voltage was zero at the container end of the hose. The container itself charged to 2 kV positive maximum. It is notable that the charge distribution along the hose does not decrease uniformly to zero. Instead, successive maximum and minimum occur in the unipolar charge distribution along the hose.

Conducting Hose Tests

Normally, vacuum hose and attachment accessories are non-conducting. Separate conducting hoses priced under \$50 are available from a number of vendors. The hose used in these tests was manufactured by the Lamson Corporation³ and consists of a plastic hose reinforced by a steel helix. A "pig-tail" at the female end of the hose provides an electrical connection with the helix. The other end of the helix is connected electrically to a metallic male termination.

Figure 3 shows schematically the experimental arrangement for the conducting hose tests. In the first setup, the conducting hose was electrically isolated from the container. The maximum voltage attained by the hose from sand uptake was -8 kV; the container charged to +800 V.

Figure 3. Vacuum Cleaner/System Configurations (Conducting Container, Conducting Hose)

Proceeding on the assumption that the negative charge on the hose could be neutralized by the positive charge on the container, an ammeter was placed electrically in series between hose and container. A current of 5 μ A was observed during sand uptake and the voltage on the hose decreased to 800 V.

Because the electrostatic energy stored in a capacitor is proportional to the square of the voltage, the energy constituting the ESD hazard is attenuated by a factor somewhere between four and six orders of magnitude.

² Hoover Power Max II® Model C9029, Hoover Company, North Canon, OH, 44720.

³ Centrifugal Air Systems, P. O. Box 4857, Syracuse, NY 13221.

By means of a BK Precision Model 820 capacitance meter, the capacitance of the conducting hose was determined to be 50 pF. The total electrostatic energy threat to a victim system ($CV^2/2$) is only 16 μ J if a conducting hose attachment is electrically connected to the conducting tank. Details of the modification to a shop•vac® are shown in Figures 4 and 5. Without the modification, that is, the same vacuum with a non-conducting hose, threat energies as high as 60 mJ are possible. Even higher threat energies (of the order of tenths of a joule) would result if the more powerful vacuum systems are used.

Figure 4. Modified shop•vac®

Figure 5. Feedback Wiring Detail

Venturi Vacuums

From a nuclear safety standpoint, the venturi vacuum cleaner is unsurpassed. The device is driven by compressed air, has no moving parts, and has no electrical connections. Essentially, a venturi cleaner consists of a short tube with a tapered constriction in the middle that causes an increase in the flow velocity of air in the constriction with a corresponding decrease in air pressure thereby creating a suction. The air exhausts through a porous canvas bag which retains debris taken in by a conventional vacuum hose with attachments.

An ESD evaluation was made of an ATI Industries Model AT 560 M Mina-Vac⁴ venturi type cleaner along with a non-conducting hose attachment. The same test procedure used with the electric cleaners was followed with the same results. Uptake of abrasive sand led to several tens of kilovolts negative charge on the hose while the bag charged to a positive one kilovolt.

Following the reasoning described above, a conducting hose was substituted for the non-conducting hose and the bag was made conducting by an inner lining of hardware cloth and an outer layer of copper screen (see Figure 6). Electrical contact was established between the aluminum venturi tube, inner and outer screen, and the conducting hose to provide a mechanism whereby electrons from the hose would be neutralized by the positively charged screen. With these modifications the electrostatic potential of the conducting vacuum system was reduced to zero. The experimental arrangement is shown in Figure 7. Therefore, the system may be considered both ESD hazardless and explosion proof.

Figure 6. Laminated Bag Modifications for Use with Venturi Vacuum Cleaner

⁴ Snap-on Tools Corporation, 2425 W. Vineyard, Escondido, CA 92029-1222.

Figure 7. Experimental Arrangement for Conducting Bag Venturi Vacuum Evaluation

Subsequently, the complex bag was replaced by one fabricated from Z-CLOTH® type Z 5000N conductive fabric.⁵ Z cloth consists of a polyester fabric which is plated with either copper, nickel, or a combination of both.

Surface resistivity measurements were made on a Z-CLOTH sample provided by the manufacturer, Zippertubing. Surface resistivity of a material is the ratio of the potential gradient parallel to the current along its surface to the current per unit width of the surface and is numerically equal to the surface resistance between two electrodes forming opposite sides of a square. (The size of the square is immaterial.) Equipment used in the test consisted of a FLUKE model 77 multimeter, PROSTAT model PRF-911, concentric ring fixture and a PROSTAT model PTB-920 dual test bed. Surface and resistance measurements were made using the EOS/ESD-DS11.11-191 guidance. By multiplying these measurements (in ohms) by a factor of 10, estimates are obtained of the ASTM D257 equivalent surface resistivity in ohms/square.⁶ The ASTM surface resistivity of the Z-CLOTH was 5 ohms per square.

Figure 8 shows the venturi cleaner with a metallized vacuum bag. The mechanical durability of the bag is unknown. It should be noted, however, that normal use of the vacuum would be only for very short duration periods which would occur very rarely. It is assumed that the cleaner will be dedicated to only those operations involving subsystems incorporating EEDs.

Figure 8. Venturi Cleaner with Metallized Vacuum Bag (Note vibrating reed sensor)

⁵ Zippertubing® Co., P. O. Box 61129, Los Angeles, CA 90061.

⁶ American Society for Testing Materials.

Attachment Charging

In order to avoid compromise of nuclear safety when using an "explosion proof" vacuum cleaner, it has been suggested that non-conducting attachments be used with a conducting hose. The acceptability of this approach depends on the extent to which the attachment acquires a charge. Accordingly, a series of measurements were made to determine the efficacy of this process.

An "explosion proof" vacuum system was simulated by a shop•vac® model 500 cleaner with a conducting hose which was connected to laboratory ground. The attachment used was a 10-inch-long plastic crevice tool, an accessory supplied with the cleaner. A model 245 Monroe fieldmeter was used to determine that a copper foil wrap on the outer surface of the crevice tool attained a voltage in excess of 10 kV negative from the uptake of abrasive sand.

The external foil wrap on the crevice tool was electrically connected to an aerodynamic shape which charged to 1 kV by sand uptake (see Figure 9). The capacitance of the system referenced to laboratory ground was 2 nF and the corresponding charge ($Q = CV$) was 2 micro coulomb, which corresponds to a stored energy of 1 mJ. The relative humidity at the time of the test was 25 percent. Again, it should be noted that much larger threat energies are possible at lower relative humidities, especially if the more powerful vacuum systems are used. Therefore, plastic vacuum attachments should not be used in the vicinity of EEDs.

By use of the setup shown schematically in Figure 10, it was demonstrated that the same aerodynamic shape charged to 0.8 kV when a non-conducting hose and a conducting attachment were used. This illustrates the charge build up which results if an "explosion proof" vacuum cleaner is made "nuclear safe." Accordingly, "explosion proof" vacuum cleaners modified to satisfy the nuclear safety requirement should not be used in weapon assembly or maintenance areas unless the conducting attachment is electrically bonded to the assembly.

Figure 9. System Charging Resulting from use of Plastic Attachments

Figure 10. System Charging Resulting from use of Non-conducting Hose and Conducting Attachment

Bonding Procedures

Until vacuum cleaners employing the ESD mitigating techniques described here become commercially available, certain alternative procedures may be adopted to reduce the hazards associated with the use of conventional vacuum cleaners. These procedures require that conducting attachments should be isolated electrically from the hose (if the hose is conducting) and that the conducting attachment, for example, a crevice tool, be electrically bonded to the system, or component, on which vacuuming operations are to be performed. Non-conducting attachments should not be used.

There are three disadvantages associated with bonding techniques. First, the authors are unaware of a commercial supplier with a line of accessories provided with bonding leads, that is, a flexible conducting lead terminated at one end on the accessory and at the other by either a Mueller or alligator clip. Second, operational procedures directing technicians to bond to specific points must be written and administratively enforced. Third, the object to which bond is established will be elevated to the same potential as the accessory. It should be noted that any technician servicing the object will most likely be at ground potential. Therefore, before attempting any operation, the technician must equilibrate, that is, the technician must maintain contact with either the vacuum attachment or the object to which the attachment is bonded during the entire operation, in order to ensure that the technician and the object are at the same electrical potential. Equilibration can be established most reliably if the technician wears a wrist strap which is electrically bonded to the same point as the attachment.

Touch-off Equilibration

Military Standard Operating Procedures for handling EEDs specify touch-off operations which are administratively enforced using the two-man (or more) rule and strict adherence to written guidelines. In order to satisfy nuclear safety requirements the vacuum hose should be non-conductive and in order to equilibrate, attachments should be metallic. Figure 11 shows the proper touch-off equilibration procedure. The operator maintains touch with the generic system while holding a metallic gulper. Although the system will become charged by vacuuming, both system and operator will be at the same potential with respect to ground.

Figure 11. Touch-off Equilibration Procedure

Figure 12 is a schematic representation of the test setup used to determine the voltage attained by the cylindrical object in Figure 9, resulting from uptake of sand. The combined cylinder, dolly, and operator has a capacity of 370 pF. At a relative humidity of 25 percent, using an insulated hose and crevice tool, the system charged to -3 kV. By substituting a metallic crevice tool for the insulated tool, the system charged to only 600 V, at the same relative humidity. The electrostatic energy stored in the system resulting from the use of non-conducting and conducting crevice tools are 1.7 mJ and 67 μ J, respectively, that is, use of a conducting crevice tool resulted in an energy reduction by a factor of 25.

Figure 12. Setup Schematic for Touch-off Measurements

Dust Electrification

A series of experiments on the electrification of dust clouds was performed by Rudge just before WWI.^{7,8,9} Rudge observed that the raising of a cloud of dust is accompanied by the production of large charges of electricity. It follows that particulate material removed from a system might result in the system acquiring a charge opposite to that on the dust. Accordingly, a test was performed to obtain a bounding estimate of the charge retained by a simple system when dust was vacuumed from its surface.

Figure 13 shows schematically the test setup used to determine the charge acquired by a flat copper sheet of roughly 0.25-meter² area when sand was removed from its surface. The copper sheet was supported by a 1-cm-thick sheet of Lucite L placed on top of a concrete surface which was made conductive by application of a coating of ELIMSTAT® UXM-600, a water-borne urethane coating.¹⁰ The system (copper sheet, lucite dielectric, and conducting floor) capacitance was 267 pF. The resistance of the floor, measured between two points 36" apart according to EOS/ESD-DS7.1-1992 guidelines was 14 k ohms.¹¹ The modified shop•vac® with conducting hose and conducting gulper, conducting concrete surface and Monroe fieldmeter were bonded to a common ground. the test setup is shown pictorially in Figure 14.

⁷ Rudge, W. A. D., "On the Electrification Associated with Dust-Clouds," *Phil. Mag.* **25**, pp 481-494, April 1913.

⁸ Rudge, W. A. D., "Electrification Produced During the Raising of a Cloud of Dust," *Roy. Soc., Proc., Ser. A.*, **90**, pp 256-272, May 28, 1914.

⁹ Rudge, W. A. D., "A Dust Electrical Machine," *Cambridge Phil. Soc. Proc.*, **17**, pp 249-250, September 8, 1913.

¹⁰ Manufactured by Walter G. Legge Co., Inc. 444 Central Ave., Peekskill, NY 10566.

¹¹ Electrical Overstress/Electro Static Discharge Association, 200 Liberty Plaza, Rome, NY 13440.

As the uptake of sand proceeded, the voltage of the copper sheet with respect to common ground varied between -30 to +10 volts. the variation may result from the capacitance between the sheet and the gulper, which varies as the gulper moves relative to the copper sheet. As the gulper moves, this capacitance varies, therefore resulting in observed voltage variation. The change of sign is not significant because the fieldmeter was operating in the most sensitive portion of its range, that is, the zero point could have drifted by 30 volts. In any event, the effect is so small that dust electrification may be dismissed as a hazard worthy of concern.

Figure 13. Setup Schematic for Dust Electrification Test

Figure 14. Setup for Dust Electrification Test

Conclusion and Recommendations

An evaluation of representative, commercially available vacuum cleaners commonly used in weapon assembly and maintenance areas has been made. Significant differences between these representative cleaners were found. The so-called "explosion proof" machines were excluded from the study because their use compromises nuclear safety; indeed, "explosion proof" cleaners should not be used. All models tested were found to be effective generators of electrostatic energy, typically 60 mJ at voltages in excess of 50 kV. Even greater energies and voltages would be expected in production environments where extremely low atmospheric humidity must be maintained. These energy sources could lead to the inadvertent initiation of sensitive electroexplosive devices. Accordingly, it is recommended that a standard cleaner design be designated as the most suitable for use in operations involving nuclear systems.

The threat posed by pneumatic devices can be mitigated by simple modifications to a commonly available type of commercial utility vacuum cleaners. Conducting hoses and conducting attachments should be used exclusively in vacuuming operations. Canvas dust collecting bags used in venturi-type cleaners should be replaced by metallized fabric bags; the venturi assembly itself should be metallic. Venturi type vacuum cleaners are preferred to electrically powered cleaners because the venturi cleaner is isolated from the electrical supply system and the facility ground. However, if compressed air is unavailable and electrical shop type cleaners must be used, these should be doubly insulated and the tank, which should be conducting must be isolated from the "green ground." Provision should be made to ensure that electrical contact between the tank, hose and attachments is made automatically when these machines are in use. On some models of tank cleaners the required modification consists simply of replacing a non-conducting rubber gasket by one that conducts. It should be emphasized that issues relative to radiation safety have not been addressed in this study; modifications recommended here are restricted to issues relevant to ESD safety. Suitability of changes recommended here should be endorsed by a radiation safety study.

It is recommended that negotiations be initiated between Sandia National Laboratories and commercial vendors for manufacture of a line of inexpensive, ESD-safe vacuum cleaner systems. Although the number of DoD and DOE facilities engaged in explosive assembly or maintenance operations are relatively few in number, the potential market for ESD-safe cleaners is large. The micro chips used in computers or communication are much more vulnerable to an ESD catastrophe than electroexplosives.

A less desirable, but alternative approach would be a technological transfer to small job shops. The jobbers could purchase conventional commercial cleaners, perform the necessary modifications described here for retail sale to a more restricted clientele.

Alternative procedures such as bonding to touch-off were also evaluated. Although acceptable from an ESD safety perspective, these practices are less desirable, the former because it is cumbersome, the latter because it further complicates administratively controlled operations.

Finally, a cursory study of dust electrification was made. It appears that the simple act of removing dust from a component results in negligible generation of electrostatic energy.

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