Using radioactive material to evaluate decontamination of contaminated electronics

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Abstract
Electronic materials are used everywhere and can get easily contaminated by their use in the field/laboratory. The goal of this project was to use radioactive material to track the effectiveness of a cleaning procedure using an off-the-shelf cleaning gel. Radioactive potassium bromide (KBr) was used as a model contaminant in four contamination scenarios to gauge the effectiveness of a cleaning gel in the decontamination of contaminated raspberry pi's. The investigated decontamination technique was found to be 75–97% effective in removing contamination from the tested electronic devices. 95% of the contaminated electronic devices retained their functionality post-decontamination.

Introduction
Electronic devices are utilized everywhere, making their functionality a necessity in current day society. With today's electronic devices becoming smaller and more complex than ever before, cleaning the contamination from electronic devices becomes more challenging. Dirty electronic devices can be vulnerable to many types of problems such as: parasitic leakage (energy wasted when in an "off" or "standby" state) [1, 2], electrochemical migration (dissolution and movement of metal ions in the presence of an electric potential) [3], delamination (material cracking, breaking, bubbling, or being broken into thin layers) [4], and shorting, which can greatly influence device performance/functionality. Therefore, it is important to understand the nature of the contamination on the electronic device to determine the best approach to remove it. Most electronic cleaning agents are specifically designed for use on electronic components, exhibiting nonconductive behavior, effectively remove dust, dirt, and other contaminants, while leaving no residue, are fast to dry, are plastic-safe, exhibit low odor, are inexpensive, and nonflammable making them safe for use on circuit boards or other electrical components.

A main challenge in the development of electronic cleaners is that electronic components can be contaminated with several different types of contaminants. One of these contaminants is organic contaminants, which include rosin solder pastes and fluxes, highly hygroscopic polar compounds or non-polar resins, in addition to non-polar oils and greases. Organic contaminants can be removed with specialty cleaning materials. An additional contaminant is inorganic contaminants, which consists of flux and solder paste activators, which consist of acids, bases, corrosive salts, and halogens. Inorganic contamination can be extremely difficult to remove and usually require more aggressive cleaning methods to remove contaminants. Water also tends to act as a contaminant on microelectronics as it can often be trapped in small areas on circuit boards and tight-fitting components. Water contamination can often be treated with water absorbing materials. The most troublesome contaminant are particulate contaminants. Particulate contaminants (e.g. dust, dirt, cloth fibers and metal chips) range in sizes from submicroscopic to large enough to be seen with the naked eye and are difficult to remove because their insolubility, preventing removal by water or a cleaning fluid. Particulate contaminants bond electrostatically to electronic component surfaces, thus the larger the particulate contaminant, the often harder it is to remove. Cleaning materials need to break the particulate/ component surface bond in order to remove the particulate. Cleaning fluids for particulates will contain slightly conductive molecules to break the static bond of the contaminant and displace, or float, the particulate off the electronic device.

To measure the effectiveness of a cleaning method, the amount of material present on an electronic device before and after the item has been cleaned must be quantified. An attractive approach is to employ radioactive materials as a model contaminant. The quantity of radioactive material can be accurately measured on a contaminated device providing an accurate degree of contamination and decontamination before and after a cleaning event, respectively. Radioactive material has been used extensively as a tracer to understand the transport of materials after a nuclear incident [5–7]. Radioactive material can also be used to understand the location/makeup of building materials [8], or locations of materials [9]. Radioactive materials also can aid in examining the transport through the body of molecules and pharmaceuticals [10–14]. This manuscript describes the use of radioactive material to track the degree of contamination and a decontamination procedure for the cleaning of contaminated electronic devices using an off-the-shelf cleaning gel.

Experimental

Potassium bromide was purchased from International Crystal Laboratories (99.999% purity) and was used as received. Cyber Clean® cleaning gel (160 g) was manufactured by JOKER Ltd. Switzerland, and purchased from the Canadian Tire Store in Medicine Hat, Alberta Canada and used as received. Raspberry pi's (Pi 3 Model B +) were purchased from PiShop.ca and used as received.

Contamination of the raspberry pi's

In this manuscript, contamination refers to the addition of non-radioactive (cold) or radioactive (hot) potassium bromide to raspberry pi's. The contamination scenarios can be seen in Fig. 1.

Scenarios #1, 2, and 3

250 ± 5 mg of potassium bromide were weighed out and placed in a 2/5-dram polyethylene vial (LA Container, EP338-NAA) and heat sealed. Vials containing unirradiated (Scenarios #1 and 2) or irradiated (Scenario #3) potassium bromide were passed into an Erlab™ Portable Pyramid Enclosure Glove Bag (Fisher Scientific Catalog #08-444-061) in a sealed plastic container, and the glove bag was sealed. Vials were removed from the plastic container and initially pierced with a 20-gauge needle to release any static buildup from irradiation. Then, using a razor blade, a triangle
was cut into the top of the vial and the contents of the vial were sprinkled on top of the raspberry pi as evenly as possible. Roughly 144 ± 30 mg of radioactive potassium bromide was transferred to the raspberry pi.

Scenario #4

Eight vials containing 250 ± 5 mg irradiated potassium bromide were passed into the glove bag in a sealed plastic container, and the glove bag was sealed. The tops of the eight 2/5-dram vials were cut off using a razor blade and were dropped into a spray bottle (Hula Home Mist Spray Bottle, 300 mL capacity) containing 50 mL distilled water. The radioactive KBr mixture was shaken in the spray bottle for 30 s to dissolve the radioactive potassium bromide. The spray bottle was used to contaminate a tray containing four raspberry pi's. The spray bottle delivered three sprays of the radioactive potassium bromide solution to the raspberry pi's. The raspberry pi's dried in the glove bag for 24 h prior to decontamination. Each raspberry pi exhibited an activity of 474 ±4Bq 0.0128 ± 0.0001 μCi) prior to decontamination.

Decontamination experiments

In this manuscript, decontamination refers to the removal of non-radioactive (cold) or radioactive (hot) potassium bromide to raspberry pi's.

All raspberry pi's were decontaminated in a workstation that consisted of an Erlab™ Portable Pyramid Enclosure Glove Bag (Fisher Scientific Catalog #08-444-061) with 5 sheets (20" x 30") of Thermo Scientific Nalgene™ Versi-Dry Standard Absorbent Rolls (purchased from Global Industrial) for a clean work surface, a plastic container (Rubbermaid Take Alongs Containers + Lids Square, 2.9 cups) holding eight pairs of extra-large latex gloves to place on the outside of the gloves of the glove bags, a 12" tweezers, three plastic containers (Signature SELECT Containers Storage Medium 3 Cups Tight Seal BPA Free purchased from Safeway) for the decontaminated Raspberry Pi to be placed in prior to being passed out of the glove bag into a gallon slider Ziploc type bag (Hefty Freezer Slider Bags Freezer Gallon) for gamma spectroscopic analysis. See Supporting Information, Figure S2, for pictures of decontamination layout.

160 g of the cleaning gel (Cyber Clean®)[15] was rolled and pressed over both sides of the raspberry pi, covering the entire surface of the raspberry pi (see Fig. 2). Encasing the

raspberry pi in the cleaning gel took approximately 30 s. The encased raspberry pi sat for five minutes before the cleaning gel was peeled off and discarded. The raspberry pi was then decontaminated with 4–5 small “putty balls” (~ 14–20 g each) rolled over the surface to cover any untreated areas and remove any cleaning gel stuck in tight spaces. Forceps were used to remove any cleaning gel that remained on the raspberry pi surface. The cleaned raspberry pi’s were placed in a clean Ziploc bag for removal from the glove bag and measurement on the gamma spectrometers.

Scenarios #1 and 2

To determine the amount of “cold” potassium bromide delivered to the raspberry pi’s, each of the seven raspberry pi’s were placed in a plastic container containing 100 mL distilled water. Water or methanol was used to dissolve the remaining potassium bromide, as potassium bromide is soluble in water and methanol [16]. The container was shaken for 30 s and allowed to sit for 5 min. The plastic containers were small enough to allow for the entire raspberry pi to be submersed in 100 mL of distilled water or methanol. 1 mL of water or methanol was removed and irradiated in the WSU nuclear reactor for 5 min.

Irradiation experiments

Scenarios #1 and 2

1.00 mL aliquot from the 100 mL distilled water or methanol solution containing potassium bromide dissolved off of the decontaminated raspberry pi was pipetted into a 2/5-dram polyethylene vial (LA Container, EP338-NAA) and heat sealed. The 2/5-dram vial was placed in a 2-dram polyethylene vial (LA Container, EP290-NAA) along with an empty 2/5-dram heat sealed vial, which was used as a spacer and blank. Each sample preparation was repeated five times to yield a total of six two-dram vials, which were placed on a rotating irradiation configuration for irradiation. The WSU nuclear reactor rotating irradiation configuration requires eight 2-dram vials (six samples and two empty vials) to fill the irradation configuration. Each irradiation rotated the samples at a rate of three revolutions/min for 300 s in the D8 (6.89×10^{12} neutrons cm^{-2} s^{-1} thermal flux and 1.35×10^{11} neutrons cm^{-2} s^{-1} epithermal flux) position at 1 MW of the 1.0 MW TRIGA nuclear reactor at the Washington State University Nuclear Science Center. Upon completion of the irradiation, the 2/5-dram vials containing the KBr solutions were placed in clean 2-dram vials for gamma spectroscopic analysis.

Scenarios #3 and 4

Potassium bromide for irradiation was weighed out in polyethylene vials and quantitatively transferred out of the containers with plastic scoopulas to avoid metal contamination from metal-containing tools. 250 ± 5 mg of potassium bromide were placed in a 2/5-dram polyethylene vial and heat sealed. The 2/5-dram vial was placed in a 2-dram polyethylene vial along with an empty 2/5-dram heat sealed vial, which was used as a spacer and blank.

Each sample prep was repeated five times to yield six two-dram vials, which were placed on a rotating irradiation configuration for irradiation. Each rotating irradiation configuration was rotated at a rate of three revolutions/min and irradiated for 110 s in the D8 (8.01 X 10^{10} neutrons cm−2 s−1 thermal flux and 1.87 X 10^{9} neutrons cm−2 s−1 epithermal flux) position at 10 kW of the 1.0 MW TRIGA nuclear reactor at the Washington State University Nuclear Science Center.

Gamma spectroscopic analysis

Samples were measured with a 35% or 50% efficiency ORTEC high-purity germanium (HPGe) detector (Serial #'s 40-TP11543A or 40-TP21491A, respectively). HPGe detectors were calibrated (both energy and efficiency) using a mixed gamma button calibration source (EZ-2277–70-1), as provided by Eckert-Ziegler, to obtain the activity of Br-82 in the measured samples. Samples were placed on the detector face and data were collected for 5 or 15 min depending on the observed activity. All reported Br-82 activities are decay-corrected activities for the end of irradiation. For a picture of the gamma spectrometer setup at WSU, please see Supporting Information, Figure S3.

Functionality tests

Each raspberry pi underwent a functionality test prior to and after decontamination. Each functionality test aimed at testing the functionality of two USB ports, one connected to a keyboard, a second containing a blank USB stick for data transfer, the micro-SD card, which contained the raspberry pi operating system, testing software, and data to be transferred to/from the blank USB stick, and HDMI video port, and power connection. For photographs of the functionality tests, please see Supporting Information, Sect. 6.

Results and discussion

Electronic devices can be exposed to many different contaminants during their use. To evaluate the effectiveness of the decontamination of electronic devices exposed to different contamination environments, four different contamination scenarios were investigated (Fig. 1). The first scenario investigated the decontamination of cold (unirradiated) material placed on the electronic devices for a few minutes prior to decontamination, after shaking off all loose contamination. The second scenario examined the removal of the same material in the first scenario, but did not remove the loose contamination prior to decontamination. The third scenario looked at the removal of radioactive material immediately and 24 h after deposit on the electronic devices. The fourth scenario investigated the removal of radioactive material that was sprayed on the electronic devices, allowed to dry, and removed 24 h after deposition. In this study potassium bromide was used as a model contaminant, as it readily activates in a nuclear reactor and its presence can be easily quantified on a gamma spectrometer by measuring the activity of Br-82 [17]. Decontamination efficiency/percent of contamination removal was estimated by Eq. 1.

% Removal = $(1-C_t/C_o)$ x 100

where C_o = Average or individual measurement values of initial contamination activity, and C_t = Average or individual measurement values post-decontamination activity.

Choice of decontamination materials and decontamination method

An attractive cleaning material that has the potential to work with electronic devices are cleaning gels. Cleaning gels have gained in popularity with their ability to clean keyboards and automobile surfaces without leaving a residue. To investigate the effectiveness of cleaning gels in cleaning electronic devices, it was chosen to test the original cleaning gel, CyberClean®, which has claimed to be able to remove solid particles in hard to reach surfaces [15]. When compared to other cleaning materials, assessed by visual inspection and microscopic surface imaging of the raspberry pi's, the cleaning gel was found to be superior to wet wipes, duct tape, compressed air, and water. Initial tests showed that cleaning gels also appeared to be the most compatible material for cleaning electronic devices, in terms of surface interaction (e.g. damage, rust etc.), with its ability to clean the intricate landscape of microchips, resistors and capacitors, and retainment of functionality after decontamination.

To decontaminate the contaminated raspberry pi's, a container of cleaning gel (160 g) was rolled and pressed over both sides of the raspberry pi, covering the entire surface of the raspberry pi (see Fig. 2). The encased raspberry pi sat for five minutes before the cleaning gel was peeled off and discarded, and the raspberry pi was decontaminated with 4–5 small "putty balls" (~ 14–20 g each) rolled over the surface to remove any cleaning gel stuck in tight spaces and treat any untreated surfaces from the cleaning gel wrap. The amount of potassium bromide contaminate removed from the raspberry pi's was measured by gamma spectroscopic analysis of the Br-82 gamma peaks and used to determine the decontamination efficiency using Eq. 1.

Contamination scenario #1

The first contamination scenario examined the adhered contamination of the raspberry pi's with solid potassium bromide powder. Polyethylene vials containing 250 mg of potassium bromide were pierced and the contents were shaken over the raspberry pi's. Samples were found to be contaminated with 144 ± 29 mg of KBr. To determine the amount of adhered material, the loose material was tapped off of the raspberry pi sample about 2 min after deposition and only the adhered material was attempted to be removed with the cleaning gel. About 80% (114 mg), on average, of the material deposited on the raspberry pi's was loose contamination, with about 20% (30 mg), on average, of the KBr was adhered to the raspberry pi's. Three of the seven raspberry pi's contaminated with potassium bromide were decontaminated with the cleaning gel. The remaining four raspberry pi's were used as controls without decontamination.

To determine the amount of potassium bromide delivered to the raspberry pi's, each of the seven raspberry pi's were placed in a plastic container containing 100 mL distilled water. Water was used to dissolve the remaining potassium bromide, as potassium bromide is very soluble in water (up to 47 g/100 mL of water) [16]. The container was shaken for 30 s and allowed to sit for 5 min. The plastic containers were small enough to allow for the entire raspberry pi to be submersed in 100 mL of distilled water. One mL of water was removed and irradiated in the WSU nuclear reactor for 5 min. Four raspberry pi's were contaminated with potassium bromide and not decontaminated to measure the amount of KBr transferred to the raspberry pi's, while three raspberry pi's were decontaminated with cleaning gel prior to being placed in the container with distilled water. The raspberry pi's were submersed in the distilled water for 24 h, before they were removed from water. From measuring the activity of Br-82 gamma peaks, the raspberry pi's were found to contain on average 8.1 ± 1.7 mg of KBr after decontamination, suggesting an average 73.0 ± 2.6% removal of the bound contamination with the cleaning gel.

Contamination scenario #2

The second contamination scenario investigated the decontamination of loose and adhered contamination on raspberry pi's that were contaminated by cold (unirradiated) potassium bromide. Decontamination of eight raspberry pi's were investigated in this scenario. Of the eight raspberry pi's, two were used as controls and were not decontaminated. Three of the raspberry pi's were decontaminated with cleaning gel and the resulting raspberry pi's were rinsed with 100 mL distilled water, as described in Scenario 1. The remaining three raspberry pi's were decontaminated with cleaning gel and were rinsed with 100 mL methanol. Methanol was used to reduce the possible loss of functionality from the use of water to dissolve the remaining potassium bromide. Potassium bromide is rather soluble in methanol (up to 2 g/ 100 mL of methanol) [16]. The three raspberry pi's that were rinsed with distilled water exhibited an average decontamination efficiency of 95.2 ± 0.5% (~ 6 mg of KBr remaining on the raspberry pi), while the three raspberry pi's rinsed with methanol, exhibited an average decontamination efficiency of 96.5 ± 0.5% (~ 2 mg of KBr remaining on the raspberry pi). The slight increase in decontamination efficiency of the methanol washed samples, when compared to the water washed samples, is believed to be insignificant and to be within measurement error of each other.

Contamination scenario #3

In Contamination Scenario #3, the raspberry pi's were contaminated with radioactive potassium bromide. Each of the eight raspberry pi's contaminated with radioactive potassium bromide exhibited an activity of 7104 ± 74 Bq (0.192 ± 0.002 μCi) prior to decontamination (Fig. 3). Two uncontaminated raspberry pi's were decontaminated with the cleaning gel and used as controls. Of the eight contaminated raspberry pi's, four were decontaminated with cleaning gel about 3 min after contamination and the other four were decontaminated with cleaning gel about 24 h after contamination. The four raspberry pi's decontaminated after 24 h each exhibited an average activity of 4440 ± 37 Bq (0.120 ± 0.001 μCi) prior to decontamination. The four raspberry pi's decontaminated three minutes after decontamination exhibited an average decontamination efficiency of 91.3 ± 2.5%. Gamma spectroscopic analysis of the cleaning gel revealed that the first wrapping of the raspberry pi removed > 90% of the radioactive material. The second "rolling step", removed on average about 0.5–1% of the initial radioactive material, which is within error of the first decontamination step. Allowing the material to sit on the raspberry pi's for 24 h were expected to result in more adhered material and less loose contaminants. Visual inspection of the raspberry pi's that sat for 24 h showed that the much of the radioactive KBr had become adhered to the raspberry pi and was no longer loose contamination (Fig. 3). Decontamination of the raspberry pi's after 24 h with the cleaning gel resulted in an average decontamination efficiency of 92.7 ± 1.5%, which is within error of the decontamination efficiency of the raspberry pi's decontaminated immediately after contamination. This result suggests that the investigated cleaning gel is effective in removing both loose and adhered contamination. Gamma Spectroscopic analysis of the cleaning gel used in the decontamination of the raspberry pi's after 24 h exhibited similar radioactive material distribution to what was observed in the decontamination of the raspberry pi's after 3 min, suggesting that the first decontamination wrap is effective in removing both loose and adhered contamination.

Contamination scenario #4

The fourth contamination scenario examined the decontamination of radioactive potassium bromide dissolved in distilled water and sprayed on four raspberry pi's (Fig. 4). The liquid sprayer was loaded with eight polyethylene vials (containing 2 g total) of radioactive potassium bromide in 50 mL water, resulting in a total activity of 203,500 Bq (5.5 μCi) for the potassium bromide solution residing within in the sprayer. Each spray from a squirt of the spray bottle delivered on average 474 ± 4 Bq (0.0128 ± 0.0001 μCi) of activity to the raspberry pi's. Four raspberry pi's, arranged in the configuration shown in Fig. 4, were sprayed a total of four times with the spray bottle. The liquid radioactive contamination was allowed to dry on the contaminated raspberry pi's in the glove bag for 24 h. One raspberry pi was not sprayed with the radioactive potassium bromide and decontaminated with the cleaning gel to serve as a control. Prior to decontamination, each raspberry pi was found to exhibit an average activity of 858 ± 11 Bq (0.0232 ± 0.0003 μCi). Decontamination of each of the raspberry pi's exhibited an average 75.2 ± 10.3% decontamination efficiency. Analysis of the cleaning gel after decontamination of the raspberry pi's on the gamma spectrometers revealed a slightly more effective "rolling" decontamination, removing an additional 1% of the radioactive KBr, when compared with the decontamination of raspberry pi's described in Scenario #3, but this value was still within error of the initial decontamination step.

Functionality tests

Since the goal of cleaning a contaminated electronic device is to reestablish functionality, after decontamination, each raspberry pi was tested to see if it retained functionality after the contamination and decontamination event. The functionality testing confirmed basic power function, booting ability, and display capabilities of the raspberry pi, the microSD reader, the USB ports, and the ability to transfer and display data. The execution of a script during the functionality test copied videos to a pro-Flash USB drive via rsync and played the video from the USB stick. Failure to transfer/copy/play the video were an indicator of an issue with the hardware. Of the 20 contaminated raspberry pi's examined in this study, only one raspberry pi failed the functionality test after decontamination. The raspberry pi that failed the functionality test was contaminated with radioactive KBr and the allowed the KBr to sit on the raspberry pi for 24 h, which resulted in a raspberry pi where the HDMI monitor connection would not work (no display). Based on these results, 95% of the contaminated raspberry pi's retained their functionality post decontamination. Surprisingly, even rust on the raspberry pi surfaces did not impair the functionality.

Conclusions

The vast use of electronic devices presents a critical need for a reliable cleaning material/procedure due to their potential to loss of function due to contamination. This study examines the decontamination of electronic devices, using raspberry pi's as a model electronic device, a cleaning gel to remove contamination, and contamination modeled by potassium bromide. Potassium bromide was used as a model contaminant due to its ability to dissolve in water, ability to be readily activated in a nuclear reactor, and ability to quantify its presence in a gamma spectrometer. To quantify the effectiveness of decontamination, the amount of potassium bromide removed from the raspberry pi by the decontamination procedure with the cleaning gel was quantified. Decontamination of the loose and adhered contamination with a cleaning gel was found to remove 70–90% of the contamination (Tables 1 and S1), which is comparable or better than currently reported decontamination gels [18–22]. In addition to the cleaning gel being effective in removing bound and loose contamination from electronic devices, functionality tests revealed that decontamination method of using a cleaning gel to remove contamination results in 95% of the electronic devices retaining their functionality. From the results described within, we have demonstrated that a cleaning gel presents an attractive option when an electronic device needs to be decontaminated/cleaned.

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