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Article *in* Journal of Nuclear Engineering and Radiation Science · April 2017

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Evaluation of Hydrogel Technologies for the Decontamination of ^{137}Cs From Building Material Surfaces

One of the preparation steps for a possible radiological attack is the capability of fast and effective decontamination of critical infrastructure. This study describes the implementation of a test plan at an intermediate scale (between bench scale and large scale or wide area) to evaluate decontamination procedures, materials, technologies, and techniques for removal of radioactive material from various surfaces. Two radioisotopes were tested: cesium-137 (^{137}Cs) and the short-lived simulant to ^{137}Cs, rubidium-86 (^{86}Rb). Two types of decontamination hydrogel products were evaluated: DeconGel™ and Argonne SuperGel. Tests were conducted at the assigned Chemical, Biological, Radiological, and Nuclear (CBRN) Israel Defense Forces (IDFs) Home Front Command facility, and at the Nuclear Research Center Negev (NRCN), Israel. Results from these tests indicated similar removal and operational parameters for ^{86}Rb and ^{137}Cs, as expected from the chemical similarity of both elements. These results proved that the short-lived radioisotope ^{86}Rb can be used in future experiments to simulate ^{137}Cs. Results and conclusions from these experiments are presented and compared to results from laboratory-scale experiments performed on small coupons. In general, both hydrogel decontamination products may be used as a viable option to decontaminate large surfaces in a real-world event, removing between 30% to 90% of the contamination, depending on the surface type and porosity. However, both products may leave behind absorbed contamination that will need to be addressed at a later stage. Yet, the likelihood of resuspension through use of these products is reduced. [DOI: 10.1115/1.4036458]

Keywords: CBRN, radiological attack, decontamination, hydrogel

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Manuscript received November 7, 2016; final manuscript received April 6, 2017; published online May 25, 2017. Assoc. Editor: Jean Koch.

1 Introduction

In order to prepare for a possible radiological attack, capability to decontaminate critical infrastructure (transportation [1], power, communications, medical, and essential government services) must be evaluated. Available decontamination technologies must be evaluated for performance on a range of surfaces that might be contaminated following a wide-area event. This evaluation must go beyond bench scale to ascertain whether the tested technologies will be effective under large-scale, real-life scenarios.

Despite some commonalities in a typical radiological dispersal device (RDD) scenario, each radioisotope is different in the size distribution of its aerosol particles after an explosion [2] and in its bonding strength to the surface. Therefore, every isotope exhibits different properties that may significantly affect the selection and implementation of decontamination techniques, as demonstrated in many previous tests by the U.S. Environmental Protection Agency (EPA) [3–8]. Furthermore, other variables and factors related to RDDs are significant in determining location, concentration, total volume, and associated activity levels of contamination and possible use of decontamination techniques [9,10].

Although the terms "RDD" and "Dirty Bomb" are used interchangeably in technical literature, RDDs could also include other means of dispersal of radioactive material. A radiological event can disperse radioactive contamination over a large geographic area. All surfaces in an urban area (buildings, cars, roads, etc.) and media (soil, water, and/or vegetation) impacted by a radiological event could be contaminated [11]. Radioactive contamination could also be deposited on exterior surfaces, such as roofs, sidewalks, streets, building walls, vehicles, and equipment, and on interior surfaces via the ventilation systems, and resuspension due to pedestrian movement. Surface deposits such as fine particulate matter may be removed easily or may stick to surfaces. Loose surface contamination could be mobilized by physical interaction, wind, or precipitation. Moreover, sanitary or storm drains can be contaminated by runoff from precipitation, leading to subsequent contamination of waterways [12,13]. Contamination can become fixed if bonded to or imbedded in the affected surface (in pores, cracks, or crevices) [14,15].

In the past few years, EPA has evaluated the effectiveness of peelable/strippable coating gels in the removal of radioisotopes from test surfaces [3,16–19]. EPA's experiments were conducted in the laboratory using small coupons (0.15×0.15 meter (m)) and relatively long-lived radioactive materials (^{137}Cs, ^{60}Co, ^{85}Sr, and ^{243}Am). Major differences between the study presented here and most previous EPA studies are in the size of the test surfaces (1.5×2 m) and in the use of the short-lived radioisotope ^{86}Rb (half-life ($t_{1/2}$) = 18.642 days, energy $E\gamma = 1076.772$ kilo-electron volt (keV)) as a simulant to ^{137}Cs ($t_{1/2} = 30.17$ yrs (yr), $E\gamma = 661.7$ keV). Similarity between these two isotopes was demonstrated earlier in small-scale laboratory experiments using 30×30 millimeter (mm) concrete and ceramics coupons [20]. Use of bigger surfaces allowed us to better evaluate the operational parameters needed to conduct a large-scale outdoor decontamination process.

The following is a description of experimental results and operational parameters derived from these large-scale tests conducted in Israel, and comparisons of those to results and factors from previous laboratory work by EPA on small coupons [3,5–10].

2 Experimental

The test program was conducted at two sites: the assigned Chemical, Biological, Radiological, and Nuclear (CBRN) Israel Defense Forces (IDFs) Home Front Command facility near the town of Ramla, where the short-lived radioisotope ^{86}Rb was used in two separate tests (during January and November 2015), and at the Nuclear Research Center Negev (NRCN) in southern Israel, where the relatively long-lived radioisotope ^{137}Cs was used (during March 2015).

Two types of decontamination hydrogel products, DeconGel™ and Argonne SuperGel, were applied at both sites. Four types of 1.5×2 m ceramics, concrete, marble, and limestone surfaces were used in the tests. All four types of surfaces were utilized at the Ramla site, in both horizontal and vertical positions, while only horizontal ceramics and concrete surfaces were used at NRCN.

Tests were conducted in three isolation chambers (two at the CBRN facility and one at NRCN). These chambers were used to control temperature, relative humidity (RH), and airflow conditions and to prevent spread of radioactive contamination outside the test facilities. The IsoArk decontamination isolation chambers, shown in Fig. 1, were designed and manufactured by Beth-El Industries, Ltd[2]. The concrete, ceramics, marble, and limestone test surfaces were manufactured by Tamar group[3]. Fourteen surfaces of 1.5×2 m and thickness of 0.15 m each were used in the experiments. Each surface was further divided into a grid of 0.25×0.25 m test squares. Twelve surfaces were utilized at the Ramla site and two were used at the NRCN site. The surfaces used at NRCN were divided by a small plastic separator to form four subsurfaces of 1.5×1 m each, in order to increase the number of parameters tested. The surfaces were prepared about 2 months before the tests and were allowed to equilibrate for 6 days under the controlled environmental conditions within the isolation chamber.

2.1 Radionuclides. Radioactive ^{86}Rb chloride and ^{137}Cs chloride salts dissolved in water were purchased from a certified supplier abroad and used without further purification. The total activity used in the experiments was 1.48 MBq of ^{137}Cs at the NRCN site, and 3.7 MBq and 37 MBq of ^{86}Rb in the first and second experiments, respectively, at the Ramla site.

The concentrated radioactive solutions were diluted and poured into common household spray bottles containing about 250 milliliter (mL) of distilled water (a different bottle was prepared for every surface). The activity per surface in each experiment is listed in Table 1.

2.2 Radiation Measurements. Radiation measurements were conducted using the Rotem Industries, Ltd. RAM-SURF portable surface contamination monitor[4], the Universal Detection Technology PDS-100-G personal radiation detector[5], and a conventional 2-in NaI(Tl) scintillation PM-11 detector[6], connected to a laptop via a digital signal processor (DSP) connection box built at NRCN.

The NaI(Tl) detector was placed inside a 40-mm-thick lead cylinder with only 1 mm of copper over the detector face, as shown in Figs. 2(*a*) and 2(*b*). The shielded detector was fitted with wheels and positioned at a fixed height of 0.25 m above the surface. During the surface measurement, the detector was moved from square to square to obtain a detailed map of the surface contamination.

The shielded 2-in NaI(Tl) detector was energy calibrated each day using a ^{60}Co calibration source.

2.3 Decontamination Gels. DeconGel™ 1120[7] (CBI Polymers, Inc., Honolulu, HI) is a ready-to-use, water-based, broad-application, peelable hydrogel that works by attracting the contaminant, binding to it physically and/or chemically, and upon cure, mechanically locking or encapsulating the contaminant in a polymer matrix. DeconGel™ is available in three versions, or viscosities, each developed for a specific decontamination use on various surfaces and areas.

[2] http://www.beth-el-group.com/
[3] http://www.tamar-group.com/
[4] http://www.rotem-radiation.co.il/product/ram-r-200-meter/
[5] http://www.rotem-radiation.co.il/file-downloads?file-id=385
[6] http://www.rotem-radiation.co.il/product/pm-11-detector/
[7] http://jrtassociates.com/pdfs/decongel2.pdf

Fig. 1 One of the IsoArk decontamination isolation chambers inside the CBRN building in Ramla

Table 1 Activity per surface used for each radionuclide

Radionuclide	Site	Number of surfaces used	Surface size (m)	Activity per surface (MBq)
^{86}Rb	Ramla (1)	6	$1.5 \times 2 \times 0.15$	0.618 ± 0.050[a]
^{86}Rb	Ramla (2)	6	$1.5 \times 2 \times 0.15$	6.18 ± 0.50[a]
^{137}Cs	NRCN	4	$1.5 \times 1 \times 0.15$	0.370 ± 0.040

[a]Listed activity of ^{86}Rb was calculated for the first experimental day.

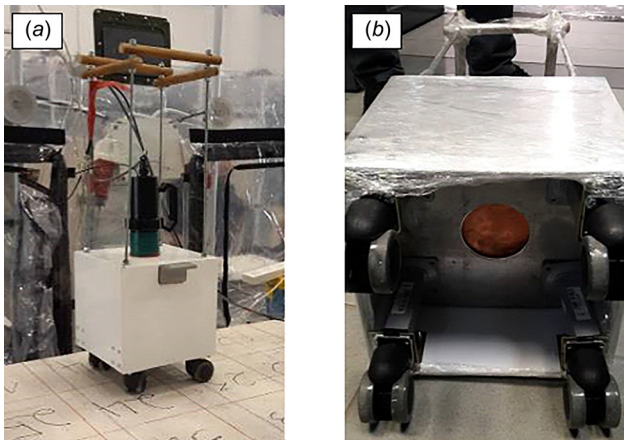

Fig. 2 (*a*) Two inch NaI(Tl) PM-11 scintillation detector surrounded by 40-mm lead shield (white block) and mounted on wheels. (*b*) Lower part of the detector shield facing the measured surface. Detector face shown at the center is shielded by 1 mm of copper.

Argonne SuperGel (Environmental Alternatives, Inc., Clarksburg, MD) is a gel system that can clean ^{137}Cs radioactive contamination from porous structures such as brick and concrete. The system uses engineered nanoparticles and a superabsorbent gel to clean buildings and monuments exposed to radioactive materials[8]. The two compounds necessary to make the Argonne SuperGel were purchased as dry powders. These compounds were mixed at the site with purified water using a torque-stirrer operating at 600 rounds per minute (rpm) until the entire dry polymer was hydrated (completion within about 15 min). The mixing process was performed about 0.5–1 h before application of the gel to the surface. Both gels were applied using a hand-held power sprayer[9] with a wide shot tip number 531. The main electric motor and gel bucket were left out of the isolation chamber, and a long hose was used to spray the gel into the chamber. The total volume of the system (sprayer, motor, and hose) was about 2 liter (l). The sprayer and hose were cleaned with water after every use. DeconGel^{TM} was stripped from the surface after a 48-h drying time. Argonne SuperGel was removed using an industrial vacuum cleaner[10]. In the first set of experiments, Argonne SuperGel was vacuumed from the surface after 60 minute (min). This time was found unsuitable due to drying of the gel; therefore, a shorter time of approximately 30 min was used in subsequent tests.

2.4 Temperature and Relative Humidity Measurements. Temperature and relative humidity at the Ramla test facility were controlled via a central air-conditioning system. Average values were 21 ± 1 degrees Celsius ($^{\circ}$C) and $43 \pm 5\%$, and $21 \pm 0.4\,^{\circ}$C and $61 \pm 8\%$ (the $\pm$ values are calculated standard deviations here and in the rest of this work) for temperature and humidity during the first and second experiments, respectively. The results presented here were measured outside of the isolation chambers. However, readings taken inside the chambers from time to time showed similar values. Temperature and humidity at the NRCN site were also controlled via a central air-conditioning system, maintaining fixed conditions of about $21 \pm 1.0\,^{\circ}$C and $50 \pm 5\%$. No continuous measurements of these parameters were recorded at the NRCN site.

2.5 Parameters Tested During the Experiment. Parameters tested during the experiments (listed in Table 2) are as follows: decontamination gel type (DeconGel^{TM} or Argonne SuperGel), surface type (ceramics, concrete, marble, or limestone), and time gap (48 or 96 h) before gel application to the surface.

The experimental procedure included nine steps: (1) background measurements, (2) surface contamination with 250 ml of ^{86}Rb or ^{137}Cs solution, (3) contamination level measurements, (4) application of the first gel layer (48 or 96 h after contamination), with about 6 l of gel applied per surface, (5) decontamination

[8]http://www.cse.anl.gov/pdfs/supergel_fact_sheet.pdf
[9]https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=513353
[10]https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=515894

Table 2 Parameters tested at Ramla and NRCN sites

Test location	Radioisotope	Gel type	Surface type and time elapsed before gel spraying (h) application (in h)		
Ramla (1)	^{86}Rb	DeconGel^{TM}	Concrete 48	Ceramics 48	Ceramics 96
		Argonne SuperGel	Concrete 48	Ceramics 48	Concrete 96
NRCN	^{137}Cs	DeconGel^{TM}	Concrete 48	Ceramics 48	
		Argonne SuperGel	Concrete 48	Ceramics 48	
Ramla (2)	^{86}Rb	DeconGel^{TM}	Concrete 48	Marble 48	Limestone 48
		Argonne SuperGel	Concrete 48	Marble 48	Limestone 48

process, (6) contamination level measurements after the first decontamination process, (7) application of the second gel layer, (8) decontamination process, and (9) contamination level measurements after the second decontamination process.

The average percent of removal ($\%R$) was calculated for all tests according to Eq. (1) from the results obtained during the steps listed above, using EPA's methodology [3]

$$\%R = (1 - A_f/A_0) \times 100\% \quad (1)$$

where A_0 and A_f are average activities of the surfaces before and after the decontamination process, respectively.

3 Results

Typical results obtained at the Ramla site using (1) ^{86}Rb (contamination), ceramics (surface), and DeconGel^{TM} (contaminant remover gel); and (2) ^{86}Rb (contamination), concrete (surface), and Argonne SuperGel (contaminant remover gel) are shown in Figs. 3 and 4, respectively. All of the measurements were taken using the 2 in NaI(Tl) gamma detector shown in Fig. 2, and corrected according to the radioactive decay of ^{86}Rb.

Some qualitative results can be deduced from the results shown in Figs. 3 and 4:

- The second decontamination process improves decontamination performance for both surfaces and decontamination gels.
- Decontamination of a nonporous surface (e.g., ceramics) is generally easier than decontamination of a porous surface (e.g., concrete).

Typical $\%R$ values, calculated according to Eq. (1), for the results obtained at the Ramla site where ^{86}Rb was used, are presented in Fig. 5 (ceramics surface and DeconGel^{TM}) and in Fig. 6 (concrete surface and Argonne SuperGel).

Some qualitative results regarding the decontamination process can be deduced from the results shown in Figs. 5 and 6:

- Calculated %Rs for a nonporous surface (e.g., ceramics) are 70–85% and 80–95% after the first and second decontamination processes, respectively.

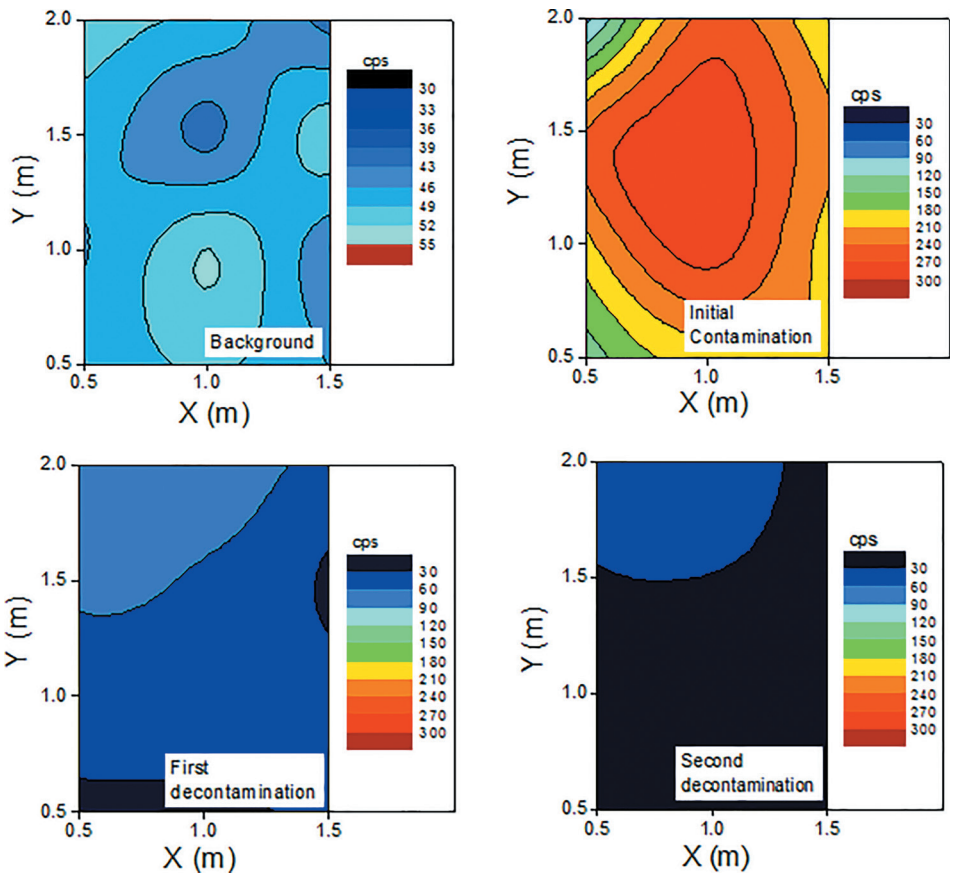

Fig. 3 Decontamination results measured for the radioisotope ^{86}Rb, on ceramics surface using DeconGel^{TM}

- Calculated %Rs for a porous surface (e.g., concrete) are 10–40% and 30–60% after the first and second decontamination processes, respectively.

Average %Rs and standard deviations after the first and second decontamination processes are listed in Table 3 for all four surfaces type (concrete, ceramics, marble, and limestone), two gel types (DeconGel^{TM} and Argonne SG), two radioisotopes (^{86}Rb and ^{137}Cs), and two gel application times (48 or 96 h). No significant difference was detected between %Rs calculated as a function of time before application of the gels; and as expected [20], no significant difference was detected between %Rs calculated as a function of the radioisotopes used (^{86}Rb or ^{137}Cs).

Data listed in Table 3 indicate the following:

- In most cases, average %Rs resulting from use of Argonne SuperGel exceed those resulting from use of DeconGel^{TM} by about 15%.
- Average %Rs resulting from the second cleaning process exceed those resulting from the first cleaning process by about 10%.

Operational parameters recorded during the decontamination processes are listed in Table 4. Some comments deduced from these parameters are listed below:

- Because of its tendency to stuck to the surface, DeconGel^{TM} is less suitable for decontamination of textured and porous surfaces (e.g., concrete or limestone) than Argonne SuperGel.
- The same instrumentation is needed to apply both materials. Removal of DeconGel^{TM} is done mostly by hand, while an industrial vacuum cleaner is necessary to remove Argonne SuperGel.
- Argonne SuperGel dries rapidly. Therefore, this gel should be vacuumed no more than 30–45 min after it is sprayed on the surface (this time is influenced by temperature and relative humidity on site). This result differs from the results obtained during previous EPA's experiments [9,10,14–16], in which the gel draying phenomena was not observed when the gel was vacuumed from the surfaces after 60 min.
- Preparation of both gels for use is not complicated, with an advantage to DeconGel^{TM} that comes as ready-to-use commercial product. Time needed to prepare the Argonne SuperGel on site was about 20 min for 10 l of compound. This time can be reduced by use of large industrial mixing equipment.
- Due to safety regulations, only skilled and authorized decontamination workers participated in the test. However, in a real situation, unskilled workers probably can conduct the decontamination after undergoing a short training.
- Both materials are not toxic.
- DeconGel^{TM} tends to stick to irregular and porous surfaces. Small fragments of these surfaces were observed sticking to the gel during the stripping process, causing minor damage to the surface.

4 Discussion and Conclusions

In Sec. 3, %Rs and some operational parameters involved in decontamination of ^{137}Cs and ^{86}Rb from different surfaces by use of hydrogels were presented. This section summarizes those results, compares them to results obtained from previous EPA experiments in which similar decontamination gels were applied to small coupons of 0.15×0.15 m and draws major conclusions from this comparison.

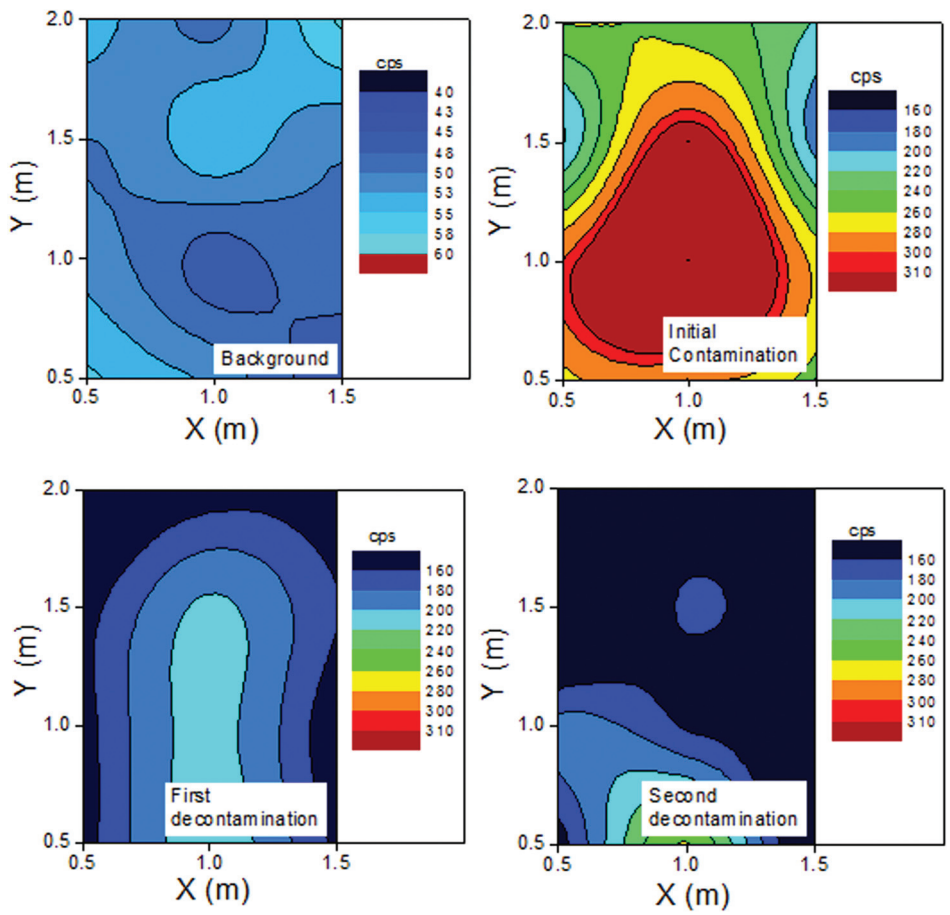

Fig. 4 Decontamination results measured for the radioisotope ^{86}Rb, on concrete surface using Argonne SuperGel

The average %Rs calculated for four surfaces (concrete, ceramics, limestone, and marble) and two decontamination gels (DeconGel^{TM} 1120 and Argonne SuperGel) after the second decontamination process are listed in Table 5. These results were calculated as an average over all of the ^{137}Cs and ^{86}Rb data obtained in this study. The results obtained by EPA under similar test conditions using small coupons [3,4,14] are also listed in Table 5 for comparison.

The following conclusions can be deduced from the results listed in Table 5:

- The decontamination effectiveness of Argonne SuperGel about 10% higher than that of DeconGel^{TM}.
- Overall effectiveness of decontamination from the smooth ceramics surface is about two to three times larger than those from porous concrete, marble, and limestone surfaces.
- Significant differences between some results reported in this work and previous EPA results are apparent. These differences can be explained by the use of different types of DeconGel^{TM} (1101, 1108, and 1120) and different types of marble (the one used in this study was significantly more porous).

Most operational parameters evaluated during the ^{86}Rb test conducted at the Ramla site, listed in Table 4, cannot be compared to the parameters calculated during EPA's experiments [3,5,14,15]. In the EPA's experiments, paint brushes were used to apply gels to small coupons. This process was relatively slow and took approximately 22 and 33 minute per square meter (min/m^2) for the applications of DeconGel^{TM} (1101 and 1108) and Argonne SuperGel on concrete, respectively. Comparable times measured in the present study during gels application by a professional paint sprayer were 3 ± 1 and 2 ± 1 min/m^2, for DeconGel^{TM} 1120 and Argonne SuperGel, respectively. Setup time for this spraying system was about 15 min, and two skilled workers were needed for its operation. However, total spraying time by use of this system was about an order of magnitude lower than the time needed for a worker to apply gel using a paint brush in EPA's tests. This system is suitable for small to medium-size surfaces or rooms. A more robust and self-mobile system will be needed to decontaminate larger areas, and time needed to apply the material this way will likely be less.

In the present study, removal time for DeconGel^{TM} (calculated for smooth surfaces only) was 4 ± 1 min/m^2, while that for Argonne SuperGel was 5 ± 1 min/m^2. Time needed to remove DeconGel^{TM} from porous surfaces is significantly longer because of the stronger attachment of the gel to the rough texture of the surface. Comparable times measured in EPA's experiments on concrete were 40 and 54 min/m^2 for DeconGel^{TM} and Argonne SuperGel, respectively. Again, comparisons between results from the small-scale EPA experiments and our medium-size experiments are not straightforward.

The removal of DeconGel^{TM} from the surface proceeded via a simple stripping process, almost regardless of surface size. Removal of Argonne SuperGel was conducted using an industrial vacuum cleaner initially equipped with a standard dust sucking head, not optimized for this process. Some modifications were made to this head during the experiments to facilitate the gel sucking process.

The volume of the dry DeconGel^{TM} 1120 compressed layers after the removal from concrete and ceramics surfaces was 1.2 ± 0.2 liter per square meter (l/m^2). The comparable volume measured by EPA for DeconGel^{TM} 1108 removed from concrete coupons was 0.25 l/m^2. However, viscosity of the new 1120 gel seems to be much lower than that of the 1108 gel used by the EPA. Therefore, a thicker layer of gel was needed to render it peelable from the surface, resulting in an increase of about 4.5 times in the volume of waste generated. The volume of Argonne SuperGel generated by the process of decontaminating surfaces was not directly measured in these experiments, and the material was fixed in vermiculite at the end of every process. This volume was, therefore, evaluated based on the volume of gel used to cover the surface as 2.0 ± 0.5 l/m^2. In a real cleaning process, a separate process of gel drying in a dedicated unit will be necessary to

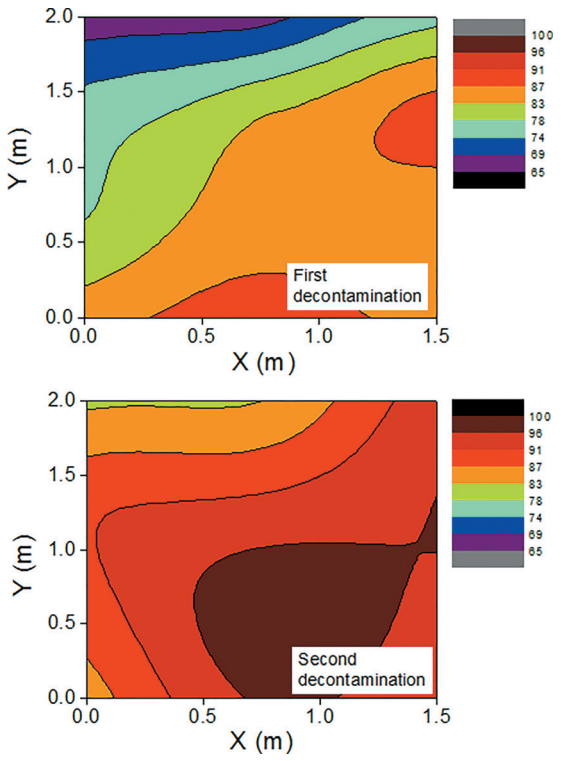

Fig. 5 ^{86}Rb calculated %*R* map plotted after the first and the second decontamination process, for ceramics surface and DeconGel^{TM}

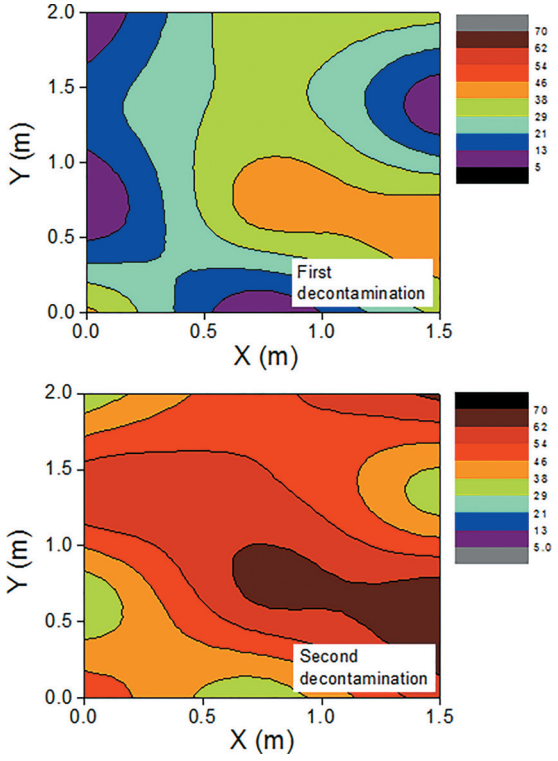

Fig. 6 ^{86}Rb calculated %*R* map plotted after the first and the second decontamination process, for concrete surface and Argonne SuperGel

Table 3 Average percent of removal (%*R*) and standard deviation after first and second decontamination processes

Surface type	Gel type	Radioisotope	%*R* after the first decontamination process	%*R* after the second decontamination process
Concrete	DeconGel™	^{86}Rb	24 ± 4	27 ± 4
	Argonne SuperGel		32 ± 6, 36 ± 9[a]	44 ± 8, 60 ± 13[a]
	DeconGel™	^{137}Cs	27 ± 4	34 ± (5)
	Argonne SuperGel		30 ± 5	46 ± 4
Ceramics	DeconGel™	^{86}Rb	66 ± 8, 82 ± 5[a]	90 ± 6
	Argonne SuperGel		82 ± (6)	92 ± (2)
	DeconGel™	^{137}Cs	64 ± 8	80 ± 4
	Argonne SuperGel		78 ± 4	86 ± 4
Marble	DeconGel™	^{86}Rb	17 ± 5	28 ± 3
	Argonne SuperGel		31 ± 5	38 ± 5
Limestone	DeconGel™		39 ± 6	45 ± 4
	Argonne SuperGel		26 ± 4	35 ± 5

[a]Values measured for gel application time of 96 h.

Table 4 Operational parameters evaluated during the tests, average values, and standard deviation

Parameter	Gel type	Average operational parameter value
Gel applying time (min/m^2)	DeconGel™	3 ± 1
	Argonne SuperGel	2 ± 1
Gel drying time (min)	DeconGel™	2880 ± 300
	Argonne SuperGel	30 ± 3
Gel removal time (min/m^2)	DeconGel™	4 ± 1[a]
	Argonne SuperGel	5 ± 1
Total decontamination time (min/m^2)	Both gels	7 ± 1[a]
Gel volume (l/m^2)	Both gels	2 ± 0.5
Waste volume (l/m^2)	DeconGel™	1.2 ± 0.2
	Argonne SuperGel	2 ± 0.5[b]

[a]Removal time for DeconGel™ was calculated here for the nonporous surfaces only. Removal time for porous surfaces with this gel is significantly longer.
[b]Volume of Argonne SuperGel was measured in the wet phase.
Note: L/m^2 = liters per square meter and min/m^2 = minutes per square meter.

Table 5 Final percent of removal (%*R*) and standard deviations calculated as a function of surface and gel types in this study as an average on all of the ^{137}Cs and ^{86}Rb tests and compared to the values calculated by the EPA

		Average %*R* after the second decontamination process (in %)	
Surface type	Gel type	This report	EPA's results
Concrete	DeconGel™	27 ± 4	45 ± 7[a], 67 ± 9[b]
	Argonne SuperGel	49 ± 8	71 ± 4
Marble	DeconGel™	28 ± 3	93 ± 1[b]
	Argonne SuperGel	38 ± 5	71 ± 4
Limestone	DeconGel™	45 ± 4	35 ± 13[b]
	Argonne SuperGel	35 ± 5	15 ± 6
Ceramics	DeconGel™	82 ± 5	—
	Argonne SuperGel	92 ± 2	—

[a]DeconGel™ 1101 was used by EPA in this test.
[b]DeconGel™ 1108 was used by EPA in this test.

decrease its volume and avoid dealing with a wet radioactive substance.

In conclusion, the DeconGel™ is suitable for decontamination of smooth and small surfaces, like those found in radioactive laboratories, whereas the Argonne SuperGel can be used for decontamination of any surface—including textured surfaces like concrete, limestone. Due to the fact that a vacuum cleaner is needed to remove Argonne SuperGel, whereas the removal of DeconGel™ can be done by hand, the overall decontamination process by use of DeconGel™ on a medium-size smooth surface is easier. On larger surfaces, the spraying and removing of Argonne SuperGel (using larger industrial equipment) is easier, especially if the surface is porous or irregular.

In general, the results of these tests indicate that in a real scenario, about 30–90% (depending on surface texture and absorbent properties) of the contamination originally measured on the surface will be removed by the decontamination gels, leaving contamination that penetrated the surface to a depth where its resuspension probability will be negligible. Therefore, these surfaces can be left for further treatment in later stages of the remediation process.

The following final conclusions concerning a possible real cleanup operation are based on the operational parameters listed in Table 4:

- A team of ten trained workers will need about 24 h of work and about 2200 l of hydrogel to clean a contaminated area of 1000 square meter (m^2).
- Decontamination of large areas will be a difficult, long, and expensive process for which preparations are needed (trained personnel, equipment, materials, etc.).

Acknowledgment

The authors of this paper want to thank the Technical Support Working Group (TSWG) and the Israeli Ministry of Defense (MOD) for financial support. Special thanks go to Dr. Christina Baxter from TSWG and Ester Krasner from MOD for the ongoing support and encouragement that made this work possible.

Nomenclature

A_f = final activity
A_i = initial activity
Am = americium
ANL = Argonne National Laboratory
Bq = becquerel (s), 1 Bq = 1 dps
C = degree(s) Celsius
CBI = Cellular Bioengineering, Incorporated
CBRN = Chemical, Biological, Radiological, and Nuclear
Cl = chlorine
cm = centimeter (s)
cm^2 = square centimeter (s)
cps = counts per second
Cs = cesium
dps = disintegration (s) per second, 1 dps = 1 Bq
DSP = digital signal processor
EAI = Environmental Alternatives, Inc
EPA = U.S. Environmental Protection Agency
eV = electron-volt (s)
$E\gamma$ = energy of a gamma ray
h = hour (s)
IDF = Israel Defense Force
keV = kilo electron volt (s)
l = liter (s)
l/m^2 = liters per square meter
m = meter (s)
m^2 = square meter (s)
MBq = million becquerel (s)
min = minutes
min/m^2 = minutes per square meter
ml = milliliter (s)
mm = millimeter
MOD = Ministry of Defense (Israel)
NaI(Tl) = sodium iodide with thallium activator
NRCN = Nuclear Research Center Negev (Israel)
PDS = personal radiation detector and search
Rb = rubidium
RDD = radiological dispersal device
RH = relative humidity
rpm = revolutions per minute
$t_{1/2}$ = half-life is the time required for a quantity to reduce to half its initial value
TSWG = Technical Support Working Group (U.S.)
$\%R$ = percent removal

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