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PHASE II MICROWAVE CONCRETE DECONTAMINATION RESULTS*

Terry L. White, Don Foster, Jr., C. Thomas Wilson and Chuck R. Schaich, Oak Ridge National Laboratory

ABSTRACT

We report on the results of the second phase of a four-phase program at Oak Ridge National Laboratory (ORNL) to develop a system to decontaminate concrete using microwave energy. The microwave energy is directed at the concrete surface through the use of an optimized wave guide antenna, or applicator, and this energy rapidly heats the free water present in the interstitial spaces of the concrete matrix. The resulting steam pressure causes the surface to burst in much the same way popcorn pops in a home microwave oven. Each steam explosion removes several square centimeters of concrete surface that are collected by a highly integrated wave guide and vacuum system. We call this process the microwave concrete decontamination, or MCD, process. The MCD process is fast, generates little dust, and avoids mechanical impacts. The concrete particles from this steam explosion are small enough to be removed by a vacuum system, yet less than 1% of the debris is small enough to pose an airborne contamination hazard. In the first phase of the program the principle of microwaves concrete removal concrete surfaces was demonstrated.[1] In these experiments, concrete slabs were placed on a translator and moved beneath a stationary microwave system. The second phase demonstrated the ability to mobilize the technology to remove the surfaces from concrete floors. Area and volume concrete removal rates of 10.4 cm^2/s and 4.9 cm^3/s, respectively, at 18 GHz were demonstrated. These rates are more than double those obtained in Phase I of the program. Deeper contamination can be removed by using a longer residence time under the applicator to create multiple explosions in the same area or by taking multiple passes over previously removed areas. Both techniques have been successfully demonstrated. Small test sections of painted and oil-soaked concrete have also been removed in a single pass. Concrete with embedded metal anchors on the surface has also been removed, although with some increased variability of removal depth. Microwave leakage should not pose any operational hazard to personnel, since the observed leakage was much less than the regulatory standard.

SCOPE AND PURPOSE

The purpose of Phase II of the microwave decontamination system development was to demonstrate the ability to mobilize the equipment necessary to remove concrete surfaces from floors. This required the integration of all necessary subsystems on a mobile cart.

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The cart was designed to move in a straight line with limited manual steering capability. Tests were carried out on noncontaminated surfaces, simulating various conditions expected to be encountered in actual decontamination scenarios. These included painted concrete surfaces, oil soaked concrete surfaces, and concrete surfaces with imbedded metal anchors. Different operating parameters were studied to provide a basis for the design of a Phase III prototype. The Phase III prototype will be fully robotic for deployment in a real-world decontamination demonstration. Estimated capital and operating costs for a final machine were generated from the fabrication of the prototype system and the concrete removal rate obtained with the unit.

SYSTEM DESCRIPTION

Figure 1 shows the overall MCD system used in Phase II testing. This system consists of a microwave high-voltage power supply, instrumentation, and controls.

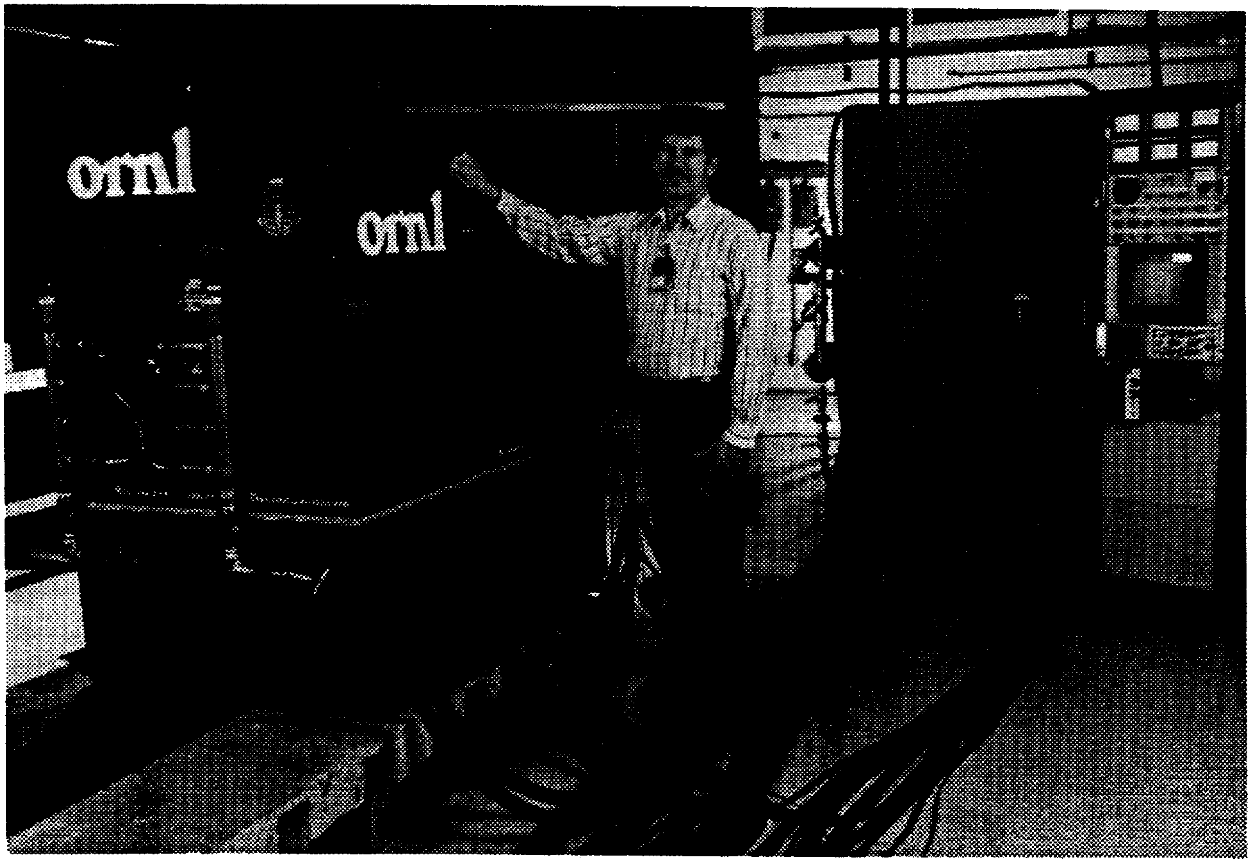

Fig. 1 The mobile microwave concrete decontamination system.

Electrical power (480 V 3-phase, 120 A) and plant cooling water (15 gal/min) are supplied to these systems. The smaller, fully mobile cart contains the microwave tube and wave guide system along with a vacuum system and a 55-gal drum for collecting the concrete debris. The mobile cart is tethered to the main power supply that supplies the electrical power and cooling to the cart. A PC-based data acquisition system and rack-mounted controls for the cart speed and microwave power are located near the power supply.

Microwave Frequency

The frequency of the microwave generator chosen for this series of tests was 18 GHz. This is a much higher frequency than the 2.45 and .896 GHz used in previously published work[2,3] and higher than the 2.45 and 10.6 GHz frequencies used in the Phase I experiments. The higher 18-GHz frequency preferentially heats near the concrete surface compared with the wave amplitudes of all lower frequencies as shown in Fig 2.

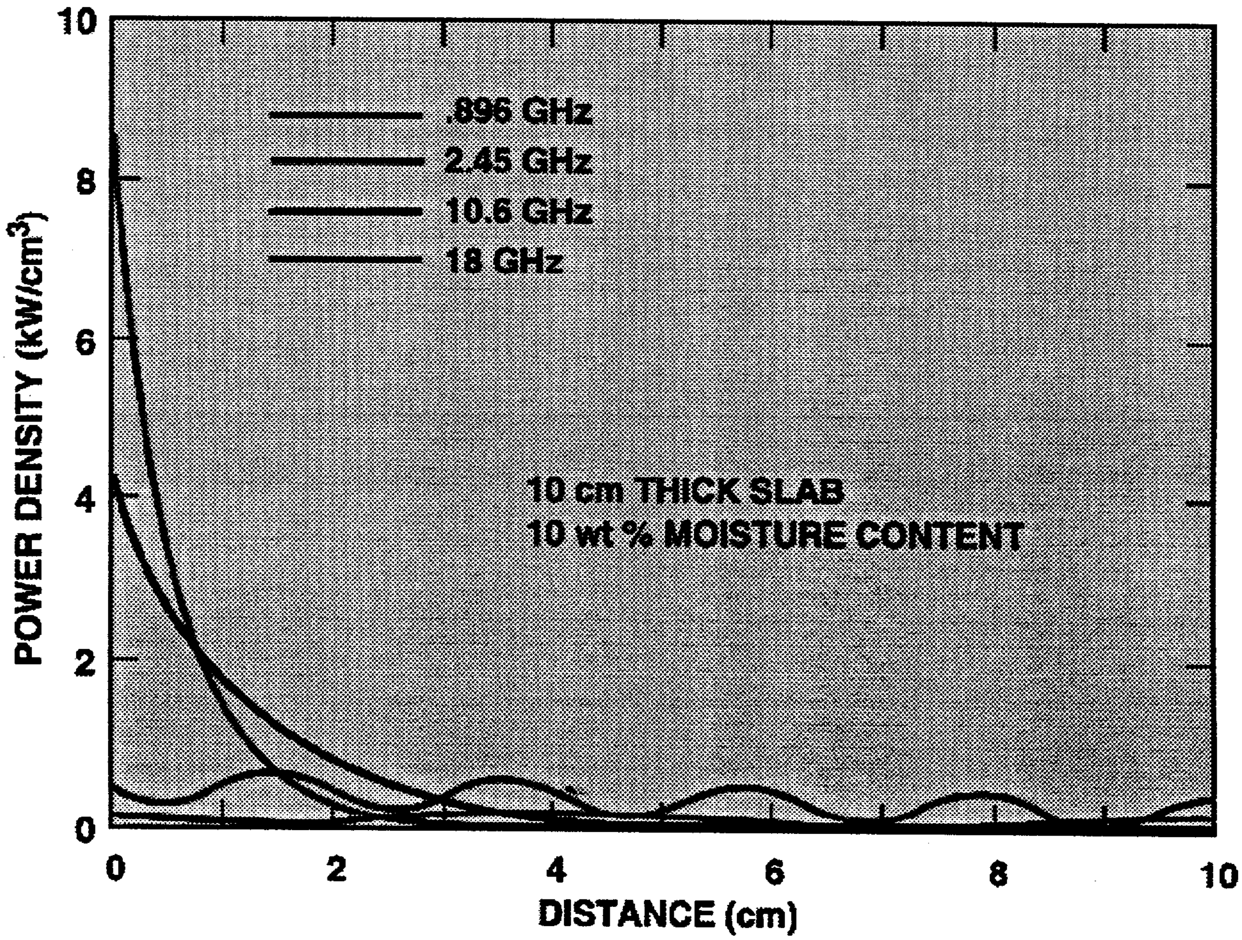

Fig 2. Initial microwave power density in concrete versus distance and frequency for 4 kW of incident microwave power.

This causes the uppermost 5 mm of concrete, where most of the surface contamination resides, to be removed very efficiently. The 18 GHz generator was available for loan from the U. S. Department Of Energy (DOE) Fusion Program at no cost to the DOE

Waste Research and Development Program. In addition, the 18-GHz, 15-kW generator was considerably more powerful than the 10.6-GHz, 10-kW generator or the 2.45-GHz, 6-kW generator used in Phase I. Therefore, higher removal rates and speeds were predicted. The rectangular wave guide size for transmitting microwave energy from the 18-GHz generator (1.78 by 1 cm) is considerably smaller than the wave guide used for 2.45-GHz generator (7.62 by 3.81 cm) and is therefore more compact and lightweight for integrating into a robot arm for positioning the applicator on floors and walls.

Microwave Applicator

The applicator used in Phase II represents a significant improvement over Phase I. Besides spreading the microwave energy over a larger area, 10 by 14 cm compared to the 3-cm diameter spot in Phase I, the applicator minimized any reflected microwave energy and eliminated the need for a bulky, expensive microwave circulator (protection device). Scattered microwave energy off the concrete floor that could constitute a safety hazard was also minimized due to the efficient design of the applicator. The microwave applicator was highly integrated with a 350 ft^3/min vacuum collection system for concrete debris. In addition, the applicator design had unrestricted real-time video monitoring of the actual removal process, which allowed for greater operator control and improved understanding of the dynamics of the removal process.

EXPERIMENTS

In the Phase II dynamic tests, a mobile cart was used to remove concrete surfaces. Initial tests were carried out in the high bay area of Building 9201-2 at the Oak Ridge Y-12 Plant. An aluminum stage 5.48 m long by 78.7 cm wide by 26.7 cm high was built to support the weight of the cart (680 kg) and to elevate the cart so that cut slabs of concrete could be placed along the stage flush with the top of the stage, as shown in Fig. 1. The slabs were supported off the floor by a system of aluminum braces that allowed the underside of the slabs to be accessed. A microwave transmission diagnostic was placed in this region to measure the amount of microwave energy that might penetrate through the slabs. The slabs were 1.2 to 3.6 m long and 35 to 61 cm wide. The top surfaces of the slabs had a typical sidewalk finish, and the sides were smooth as a result of the diamond saw cutting required for slab removal. The bottoms of the slabs were rough and irregular due to the uneven gravel beds employed during the fabrication of the slabs. Because of this, the slab thickness varied from 12 to 18 cm. The age of the concrete slabs could not be precisely determined, but they were estimated to be approximately 20 to 30 years old. The shorter length concrete slabs came from old sidewalks at ORNL, and the longer length slabs came from concrete parking pads at the Oak Ridge Y-12 Plant. The slabs did not contain any steel reinforcing rods. However, the Phase I results showed that the presence of steel reinforcement had a minor effect on the microwave removal of concrete at 2.45 GHz. This is because the steel mesh and rods lie normally 5 cm or more beneath the surface of the concrete and the microwave fields have decayed to low levels at this depth, as shown in Fig 2. This rationale is even more true for the 18-GHz frequency. Final field testing was conducted in Building 3034 at ORNL. The MCD system was used to remove selected concrete surfaces from the building floor. The building drawings indicate that the concrete floor was poured around 1960.

RESULTS

Forward and reflected microwave power was measured to determine the net power incident on the concrete surface. An array of three detectors located around the applicator measured the scattered power leaking from around the applicator. A microwave detector on the 55-gal vacuum collection drum measured the amount of microwave power present in the drum. Power transmitted through the slab was also measured. Cart position and speed were controlled and documented for each test. A sensor monitored the vacuum in the applicator (4~6 in. of water) during operation. Also, a thermocouple measured the applicator temperature. A color video camera and pickup microphone recorded the concrete removal process during the experimental runs. All data was recorded on a 486 PC running Labview 2.5 for Windows. Data were displayed and processed with Mathcad 4.0 for Windows. Figure 3 shows a typical steam explosion.

Fig 3. A typical steam explosion that removes several square centimeters of concrete surface.

Concrete Removal

To estimate the volume of removed concrete debris the clean trenches in the concrete were filled with fine sea sand. The sand was leveled with the surrounding slab surface so that all cavities in the slab were filled. Excess sand was carefully scraped and brushed away from the filled cavities. The sand was vacuumed up and the weight gain of the filter bag was measured. The weight of the sand was divided by its measured density to calculate the approximate volume of removed concrete. These measurements were conducted for the first few long runs. To obtain the volume removal rate the measured volume was divided by the duration of the run. To obtain the average depth of removal the volume was divided by the average width and length of the run. To obtain the area removal rate the speed was multiplied by the average width of the trench. The new Phase II applicator produced trenches 9~10 cm wide by 4~5 mm deep at speeds as high as 1.1 cm/s. This gave an area removal rate of 10.4 cm^2/s and a volume removal rate of 4.5~4.9 cm^3/s. The area removal rate was about 250% higher than that obtained in Phase I, and the volume removal rate was about 210% higher than it was in Phase I. The cross-sectional shape of the trenches in Phase II is flatter than that of the trenches cut in Phase I because the heated concrete surface has more uniform illumination. Other factors affecting the removal efficiency include the translation speed and the way in which the microwave power is distributed over the area to be heated.

Microwave Leakage

The microwave leakage at 18 GHz from the applicator was well below the American National Standards Institute (ANSI) standard[4] of 5 mW/cm^2. This was true even if 5-mm trenches were cut between the applicator and the surface of the slab for the microwave energy to propagate. The low leakage may be explained by the high losses in concrete at 18 GHz and the fact that almost all the energy is absorbed in the first pass due to the efficient applicator design. After several dozen runs the drum detector and two of the scattered microwave detectors were removed because they did not reveal any hazardous leakage levels and their removal simplified the cart instrumentation and data acquisition. The remaining scattered microwave detector was retained as a personnel safety interlock but was seldom tripped in any tests.

Painted Surfaces

Historically, some rad-contaminated concrete surfaces have been painted to fix the contamination present at the surface. To investigate the effect of paint on the microwave removal process, a 20-cm-long section of concrete was painted with a two-part epoxy paint sealer commonly used to fix contamination to concrete surfaces. The paint was allowed to cure in order for the paint to reach its full bond strength. The cart was started at 0.9 cm/s on bare concrete and driven over the painted section. Upon heating, the paint could be observed to soften, and then the paint and concrete were explosively removed in much the same fashion as unpainted (plain) concrete. The speed of the applicator was lowered from 0.5 to 0.7 cm/s to achieve removal depths similar to those of plain concrete. Some microwave energy was absorbed in the paint. However, the amount of energy deposited in the paint was insufficient to cause any fire or smoke from the heated paint. The concrete debris appeared to have a larger particle size as a result of the paint's binding some smaller pieces together.

Oil-Soaked Surfaces

Concrete contaminated with Polychlorinated Biphenyl's (PCBs) can be found at many DOE sites. To investigate the effect of oil on the microwave removal process, a 40-cm-long section of concrete was soaked with standard hydrocarbon pump oil and allowed to stand for 24 h. The cart was started at 0.9 cm/s on dry concrete and driven over the oil-soaked section. Upon heating, the surface oil bubbled and then the oil and concrete were explosively removed in much the same fashion as plain concrete is removed. No significant reduction in speed was required, indicating that the oil did not directly absorb significant amounts of the microwave energy. After the trench was cut, the oil was observed to have penetrated to a depth of 2~3 mm. A single pass removal of 5 mm was observed. Again, no smoke or fire was generated by microwave-heated oil.

Metal Anchors

Surface metal structures in the concrete may affect the reliability of the microwave removal process as a result of metal objects changing the applicator electric fields. To investigate this effect four 0.5-in.-diam holes were drilled into the concrete slab, and a steel bolt anchor was placed in each hole, flush with the surface, to simulate a typical floor or wall attachment to the concrete. Concrete was removed to 5 mm around two holes and partially removed around the remaining two holes. No arcing was observed with any of the holes, but water boiled from the holes during microwave heating (no water was added during the drilling). This caused a reduction in the steam generation because the hole provided an efficient pathway for the water to escape. The reduction in steam pressure reduced the reliability of the microwave removal process.

ECONOMIC ANALYSIS

The cost analyses in Tables I, II, and III give a rough estimate of the capital and operating costs associated with a potential Phase III MCD system. The configurations vary with respect to the number of microwave tubes on a single mobile system and the frequency and power of each tube. These costs are relative and will be revised as the program progresses to later phases.

TABLE I. 6-kW, 2.45-GHz Microwave Concrete Decontamination system components

Total Power (kW)	1 x 6	2 x 6	3 x 6
Microwave Generator ($K)	13	26	39
Robotic Vehicle ($K)	50	50	50
Vacuum System ($K)	10	15	20
Wave Guide Systems ($K)	30	60	90
Instrumentation ($K)	20	30	40
Total Capital Costs ($K)	123	181	239
Removal Rate (ft^3/h)	0.14	0.32*	1.9*
Removal Rate (ft^2/h)	7.4	14~19*	22~36*
Operating Cost ($/$ft^2$)	13	7~5*	3~4*

TABLE II. 15-kW, 2.45-GHz Microwave Concrete Decontamination system components

Total Power (kW)	1 x 15	2 x 15	3 x 15
Microwave Generator ($K)	24	48	72
Robotic Vehicle ($K)	50	50	50
Vacuum System ($K)	10	15	20
Wave Guide Systems ($K)	30	60	90
Instrumentation ($K)	20	30	40
Total Capital Costs ($K)	134	203	272
Removal Rate (ft^3/h)	0.28	0.64*	3.8*
Removal Rate (ft^2/h)	15	30~39*	45~72*
Operating Cost ($/$ft^2$)	6	2~3*	1~2*

TABLE III. 15-kW, 18-GHz Microwave Concrete Decontamination system components

Total Power (kW)	1 x 15	2 x 15	3 x 15
Microwave Generator ($K)	120	240	360
Robotic Vehicle ($K)	60	60	60
Vacuum System ($K)	10	20	30
Wave Guide Systems ($K)	30	60	90
Instrumentation ($K)	20	30	40
Total Capital Costs ($K)	240	410	580
Removal Rate (ft^3/h)	0.62	1.44*	8.7*
Removal Rate (ft^2/h)	40	80~104*	120~192*
Operating Cost ($/$ft^2$)	2	0.9~1*	0.5~0.8*

* estimated

Capital Cost Basis

The estimated capital costs consist of two categories of costs. One category of costs includes those for subsystems obtained from various vendors off the shelf. The estimated costs for these subsystems are based on quotes from the manufacturers and include the high-voltage power supply, and high-power microwave tube(s); the vacuum system; and the robotic vehicle. These costs do not include discounts for multiple purchases. A second category of capital costs involves system integration costs. Integration systems include the wave guide transmission system and the instrumentation and control system. Costs for these subsystems are based on costs associated with the Phase II mobile system scaled as appropriate to fit the other potential configurations.

Operating Cost Basis

The estimated operating costs are based solely on operating the equipment. The costs are expressed as cost per area removed and cost per volume removed. Costs do not include maintenance costs or waste disposal costs. Phase II equipment has operated thus far without an equipment failure, so maintenance costs have not been determined. These operating costs are based on the concrete removal rates achieved by the various equipment configurations and the assumption that one person would operate the equipment at a cost of $95.73/hr. Concrete removal rates for all of the single microwave tube configurations, except the 15-kW 2.45-GHz unit, have been determined experimentally as part of this program. The removal rates of multiple microwave MCD systems are projected rates, some of which will be verified in Phase III of the program. Volume removal rates are based on experimental results obtained by previous published work.[2] This study determined that two microwave systems in parallel had a volumetric removal rate 30% greater than that removed by two single systems. The same study showed that by using three microwave systems in parallel the volumetric removal rate was 14 times the removal rate of a single system. The previous study did not show the effect of multiple microwave systems on area removal rates. Therefore, the area removal rates for multiple microwave systems are assumed to be as much as 30% greater for two in parallel versus two operating independently and as much as 60% greater for three in parallel versus three operating independently. The effect of multiple magnetrons on area removal rates will be determined in Phase III. To estimate operating costs the hourly labor rate is divided by the area removal rate. Electrical costs are negligible compared with labor costs.

Other Cost Considerations

The total cost of decontaminating concrete structures must consider other factors besides the cost of concrete removal. Currently, disposal of low-level waste at ORNL is $85/ft^3. If transuranic-contaminated low-level waste disposal costs were the same, the microwave decontamination system would offer a potential savings of $43.5/ft^3 in disposal cost over other technologies that produce concrete debris (powders) that do not meet the Waste Isolation Pilot Plant Waste Acceptance Criteria. Those wastes in powder form that do not meet these criteria must be immobilized (i.e., grouted), which could result in a 50% volume increase.

COST RESULTS

Based on the work completed to date, this preliminary cost analysis shows that a MCD system can easily be developed to remove 3/16 in. of concrete at a cost of $2/ft^2$, when company personnel are used. Vendor quotations of $2.50/ft^2$ for 1/16 in. concrete floor removal using conventional scabbling are typical. Phase II resulted in a greater than 200% increase in concrete removal rates over Phase I results. As the final configuration and operating parameters of the Phase III MCD system are defined, further increases in concrete removal rates are expected, and reduced operating costs are anticipated. The MCD operating cost is also well below vendor quotations of $50~$70/ft^2$ for removal of 1/4 in. from concrete hot cell walls.

CONCLUSIONS

ORNL has completed Phase II testing of a mobile MCD system to remove concrete surfaces. Continuous-area and volume concrete removal rates of 10.4 cm^2/s and 4.9 cm^3/s, respectively, at 18 GHz were demonstrated. These rates are more than double those obtained in Phase I. The mobile prototype produces high removal rates, generates little dust, avoids mechanical surface impacts, and generates no liquid waste. The concrete particles generated by the MCD process are small enough to be removed by a vacuum system, yet less than 1% of the debris is small enough to pose an airborne contamination hazard. Deeper contamination can be removed by using a longer residence time under the applicator to create multiple explosions in the same area or by taking multiple passes over previously removed areas. Both techniques have been successfully demonstrated. Small test sections of painted and oil-soaked concrete have also been removed in a single pass. Concrete with embedded metal anchors on the surface have also been removed, although with some increased variability of removal depth. Microwave leakage should not pose any operational hazard to personnel because the observed leakage was much less than the 5-mW/cm^2 ANSI standard,[4] and the Phase III MCD system will be operated remotely. A preliminary operating cost analysis shows that the MCD system can easily be developed to remove 3/16 in. of concrete at a cost of $2/ft^2$.

REFERENCES

1. T. L. WHITE et al., "Removal of Contaminated Concrete Surfaces by Microwave Heating - Phase I Results," Proceedings of the 18th American Nuclear Society Symposium on Waste Management, Tucson, Arizona, (March 1992).

2. H. YASUNAKA et al., "Microwave Decontaminator for Concrete Surface Decontamination in JPDR," Proceedings of the International Decommissioning Symposium, Oct.4~8, pp. 109~115 (1987).

3. D. L. HILLS, "The Removal of Concrete Layers from Biological Shields by Microwaves," EUR 12185EN, Commission of the European Communities, Brussels (1989).

4. American National Standards Institute C 95.1-1982, "Standard Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 300 kHz to 100 GHz" (1982).