REMOVAL OF CONTAMINATED CONCRETE SURFACES BY MICROWAVE HEATING-PHASE I RESULTS*

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ABSTRACT

Oak Ridge National Laboratory (ORNL) is developing a microwave heating process to remove radiologically contaminated surface layers from concrete. The microwave energy is directed at the concrete surface and heats the concrete and free water present in the concrete matrix. Continued heating produces steam-pressure-induced mechanical stresses that cause the concrete surface to burst. 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. The first phase of this program has demonstrated reliable removal of non contaminated concrete surfaces at frequencies of 2.45 GHz and 10.6 GHz. Continuous concrete removal rates of 1.07 cm^3/s with 5.2 kW of 2.45-GHz power and 2.11 cm^3/s with 3.6 kW of 10.6-GHz power have been demonstrated. Figures-of-merit for microwave removal of concrete have been calculated to be 0.21 $cm^3/s/kW$ at 2.45 GHz and 0.59 $cm^3/s/kW$ at 10.6 GHz. The amount of concrete removed in a single pass can be controlled by choosing the frequency and power of the microwave system.

INTRODUCTION

Residual radioactive contamination of concrete structures exists at nearly every Department of Energy (DOE) laboratory or plant. Needs for the removal of radioactive contamination as well as hazardous contamination have been identified. The DOE must develop methods to reduce the volumes of wastes by decontamination, recycling, densification, and reduction of process residues. Normally, only the surface layers of concrete are contaminated, and systems are needed for the economical removal of these layers. In addition, the DOE must develop new technologies that are faster, better, cheaper, and safer than present technologies so that the decontamination and decommissioning of these sites are done in a cost-effective and timely manner.

Present mechanical techniques for removing contaminated concrete surfaces, while fast, have a number of shortcomings. Impact breaking machines generate large amounts of dust, requiring elaborate abatement measures. These machines must work the floors wet to suppress dust generation, but this can force soluble contamination deeper into the fresh cracks in the concrete, thus limiting the amount of contamination removed. The impact of the mechanical chisels also drives contamination deeper into the concrete. High-pressure water sprayers produce huge volumes of secondary contaminated waste water, and some means for recycling the waste water must be used. Again, soluble contamination is very difficult to remove using wet techniques. Steel shot blasters use high-velocity steel shot to remove surface contamination and produce a high proportion of dust in the debris. Also, the shot blasters are slow and require wet surfaces to suppress dust generation.

Groups in Japan and in the United Kingdom (U.K.) have investigated the feasibility of using microwaves to remove contaminated concrete layers. In 1987, a group from the Japan Atomic Energy Research Institute (JAERI) reported on a mobile microwave decontaminator (1) that could remove as much as a 3-cm layer of concrete in a single pass. This group quoted a continuous removal rate of 11.1 cm^3/s with 15 kW of microwave power at a frequency of 2.45 GHz. This removal rate is equal to that of the fastest commercial mechanical concrete breaking machines. In 1989, a group from the Harwell Laboratory in the U.K. reported on a fixed microwave demolition experiment (2) that could remove approximately 10 cm of concrete in a single explosion. They quoted a removal rate of 16 cm^3/s with 25 kW of microwave power at a frequency of 896 MHz. A one-dimensional time-dependent heat transfer model was developed by the Harwell group to predict the temperature profile in the concrete as a function of time, frequency, and the location of steel reinforcing rods in the concrete.

ORNL has completed some initial testing of a microwave heating process to remove concrete surfaces and plans to further develop this technique. The process is fast, generates little dust, avoids mechanical impacts, and is dry. The microwave energy is directed at the concrete surface using a specialized waveguide applicator and heats the concrete and free water present in the concrete matrix. Continued heating produces thermal and steam-pressure-induced mechanical stresses that cause the concrete surface to burst. 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. This paper covers the results of the Phase I experiments designed to demonstrate, at the bench scale, the concept of the removal of contaminated concrete surfaces using microwave heating.

SYSTEM DESCRIPTION

Safe, reliable, and efficient removal of the concrete surface with acceptably low dust generation rates constitutes a successful proof-of-principle test for the microwave decontamination process. While the JAERI prototype showed that concrete can be removed quite easily, no information was

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given on the amount of microwave energy leaking out of the interface between the concrete floor and the applicator. If the amount of microwave leakage exceeds the ANSI standard (3) of 5 mW/cm^2, then appropriate measures must be taken to ameliorate this exposure. The effect of steel reinforcing structures in the concrete on the reliability of the microwave removal process needs to be investigated further.

The Phase I experimental setup is shown in Fig. 1. It consists of a fixed microwave generator, a waveguide transmission system, a waveguide applicator, a concrete slab test specimen, a heavy-duty translator, a vacuum system, and experimental diagnostics. In this phase of the program, a 6-kW, 2.45-GHz generator and a 10-kW, 10.6-GHz generator were used at different times to remove uncontaminated surrogate concrete surfaces. By using these two frequencies, we were able to study the effect of the heating frequency on the depth of the removed concrete and on the efficiency of surface removal. The experimental area was in an existing metal room to contain microwave power leakage and ejected concrete debris. The access door was interlocked to prohibit operation of the generator with the door open.

Fig. 1. ORNL Microwave concrete decontamination -- Phase I experiment.

In a typical run, microwave power is transmitted to the applicator through a waveguide transmission system. At 2.45 GHz, a 7.21-cm x 3.4-cm rectangular waveguide is used; at 10.6 GHz, a 2.29-cm x 1.01-cm waveguide is used. Both waveguide systems could feed the same applicator (10.9 cm x 5.46 cm) by using a series of tapered waveguide transitions that can adapt to either waveguide size. The waveguide applicator was designed to minimize reflections from the concrete surface at both frequencies and has a set of four wheels that can be adjusted to set the spacing between the applicator and the concrete surface. Forward and reflected microwave power levels are monitored by waveguide directional couplers located above the applicator. The amount of microwave power scattered from above the applicator/concrete interface is measured by a calibrated microwave radiation monitor. The amount of microwave power transmitted through the concrete slab is measured by a waveguide horn antenna and detector mounted underneath the slab.

Six 1.22-m x 0.46-m x 0.10-m concrete slabs were fabricated for testing. All slabs were fabricated with ordinary concrete containing aggregate with a 9.5-mm average diameter. The six slabs were divided into three pairs; the first pair had no metal reinforcement, the second pair had a 5.6-mm-diam wire mesh, and the third pair had a grid of 1.27-cm-diam steel reinforcing rods. The plane of the metal structures was located at least 5 cm beneath the surface of the concrete slab. The concrete was allowed to cure for at least 60 days before the microwave experiments began. No special care was taken to ensure that the slab surfaces were smooth or flat.

In the experiments, the concrete slabs are supported by a 150-kg capacity translator that can move a slab at a speed adjustable up to 12.5 mm/s. The translator consists of a motor-driven platform with a maximum traverse range of approximately 1.22 m. Adjustable limit switches are used to establish the traverse range and to prevent the concrete slab from moving beyond the applicator. As a safety precaution, the limit switches are connected to the microwave generator external interlock and will shut off the generator at the end of travel of the translator. A dc output voltage, proportional to translator position, was also implemented so that position and speed changes could be recorded during the experimental runs. Two troughs filled with water are placed under the concrete slab to absorb any excess microwave power that penetrates through the slab. The microwave transmission detector was mounted above the troughs and below the concrete slab.

Other diagnostics on the experiment include an infrared sensor that continuously monitors the surface temperature of the concrete, located 4 cm behind the applicator. A hand-held thermocouple probe is used to measure the temperature in selected spots after operations cease. A color video camera and pickup microphone record the concrete removal process during the experimental runs. An infrared camera is used to measure the surface temperature profiles as a false color video image. The surface temperature profiles are closely related to the applied microwave power levels, and these profiles can be optimized for maximum removal of the concrete surface.

EXPERIMENTAL RESULTS

Both static and dynamic tests were conducted at 2.45 GHz and 10.6 GHz. The static tests measure the amount of time required to produce a single crater in the concrete surface at a fixed power level. The concrete surface was not moved relative to the 7.2-cm x 3.4-cm applicator in these tests. In early static tests at a frequency of 2.45 GHz, a 3.1-cm^3 crater (6.4-mm depth) from a 22-year-old concrete floor was removed in about 59 s at the 6-kW power level. The removal process was accompanied by a single popping noise, after which the power was removed. The initial surface temperature in the crater after shutdown was about 115°C and continued to rise over a period of several minutes indicating that the temperature beneath the crater was much higher. Two of the attempts to remove concrete were unsuccessful. In those cases where concrete was not removed, cracks opened in the floor, allowing steam to escape. The floor was completely dry prior to testing. In most cases, steam and small amounts of water could be seen diffusing to the surface, several centimeters away from the edge of the waveguide applicator, due to the intense local heating. The source of the water is believed to be absorbed free water and hydrated water in the concrete matrix. The major source of heating in the concrete is believed to be the presence of water, which dominates the microwave absorption processes in most building materials. (4) We believe that the microwave power was absorbed too deep within the floor, which may not burst apart reliably because of the strength of the thick layer of overlying concrete and because of the relatively small subsurface heating area.

A second series of static tests was conducted at 10.6 GHz with a larger 10.9-cm x 5.46-cm applicator on the same concrete floor as in the initial tests. ORNL modeling of the microwave heating profile in concrete suggested that surface heating was much faster and efficient at the higher frequency; therefore, surface removal would be much more reliable. We produced, on the average, a 2.6-cm^3 crater (1.7-mm depth) with 4.8 kW of 10.6 GHz in 15 s. The average final temperature was 69°C, and concrete was removed in every attempt. The improved reliability and fast removal are in good qualitative agreement with the ORNL model. Substantial improvements in the model must be made, however, before a comparison can be made. Another factor contributing to the improved reliability is that the applicator area is about 2.5 times larger than in the tests at 2.45 GHz. The larger heated area, along with the shallower heating zone, is believed to increase the efficiency of concrete removal.

In the dynamic tests, a precast concrete slab is moved by the translator with respect to the fixed applicator to simulate a mobile microwave floor removal machine. The larger applicator was used to cut trenches with average dimensions of 38 cm x 7 cm x 0.56 cm at 2.45 GHz and 35.5 cm x 7 cm x 0.52 cm at 10.6 GHz. These tests were done at a speed of 5 mm/s. Continuous concrete removal rates of 1.07 cm^3/s with 5.2 kW of 2.45-GHz power and 2.11 cm^3/s with 3.6 kW of 10.6-GHz power have been measured. Calculated figures-of-merit for microwave removal of concrete are 0.21 cm^3/s/kW at 2.45 GHz and 0.59 cm^3/s/kW at 10.6 GHz. The clear trend of higher removal rates at 10.6 GHz is due to the localization of the microwave energy in a thinner layer closer to the surface. For the same applicator size and power level, the power density would be higher in the higher-frequency case. The amount of concrete removed in a single pass can be controlled by choosing the frequency and power of the microwave system. 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.

The microwave leakage at 2.45 GHz from the applicator exceeded the ANSI standard of 5 mW/cm^2, but the leakage at 10.6 GHz was below this standard. We believe that the high absorption at 10.6 GHz is responsible for the lower leakage values. In any case, we believe that, with a properly designed applicator, the leakage levels can be reduced to acceptably safe levels at either frequency.

The presence of steel reinforcement had a minor effect on the microwave removal of concrete. We believe that this is because the steel mesh and rods were at least 5 cm beneath the surface of the concrete and the microwave fields may have decayed to low levels at this depth. Metal structures at the surface of the concrete can have a profound negative effect on the performance of the microwave removal process, and we do not recommend this process for metal surfaces.

Initially, the vacuum cleaner used to sweep up concrete particles was a 2.3-m^3/min high-efficiency particulate air (HEPA) canister vacuum. The vacuum was connected by a hose to a rectangular duct above the trailing end of the applicator. This system was not intended to collect all the particles immediately after the surface removal. After a run ended, the vacuum hose was disconnected from the duct and all loose debris in the vicinity of the applicator and concrete slab was manually vacuumed. Particle size distributions were determined by sifting the debris through a stack of progressively finer wire mesh screens and measuring the net weight gain of each mesh screen. In order to get better statistics, the debris from several continuous runs was combined for screening. The volume of removed debris was estimated by filling the clean holes and troughs in the concrete with fine sea sand. The sand was leveled with the surrounding slab surface so that it filled all cavities in the slab. 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. The results of a typical particle size distribution for removed concrete debris are shown in Fig. 2. Less than 1% of the debris is less than 1 mm in diameter, and therefore most of the debris should not pose an airborne contamination hazard. Figure 3 is a closer view of the trench cut in the concrete surface. The larger pieces of concrete were too big to be picked up by the small-capacity HEPA vacuum used in this phase of the program. The two trenches on the right were made in earlier runs and the larger debris were manually removed.

As a result of the successful Phase I experiments, a Phase II mobile prototype microwave concrete removal machine, shown schematically in Fig. 4, is being built at ORNL. This prototype consists of a large semimobile enclosure containing the microwave high-voltage power supply, instrumentation, and controls. Electrical power (480 V 3-phase, 100 kVA) and

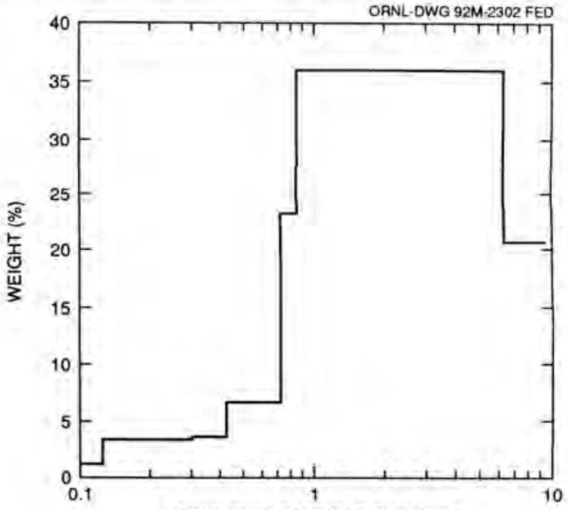

Fig. 2. Typical particle size distribution.

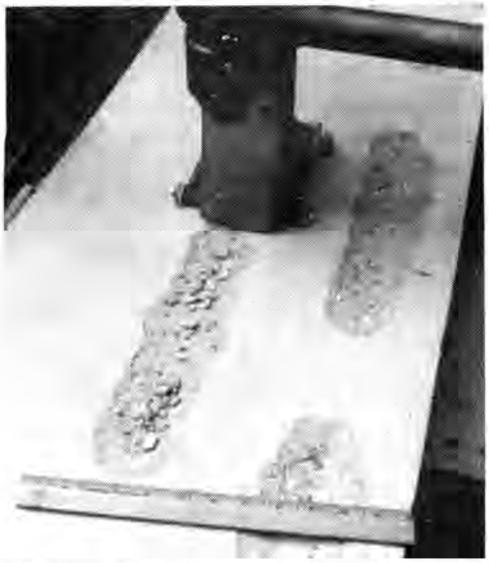

Fig. 3. Closeup of concrete trenches and removed debris.

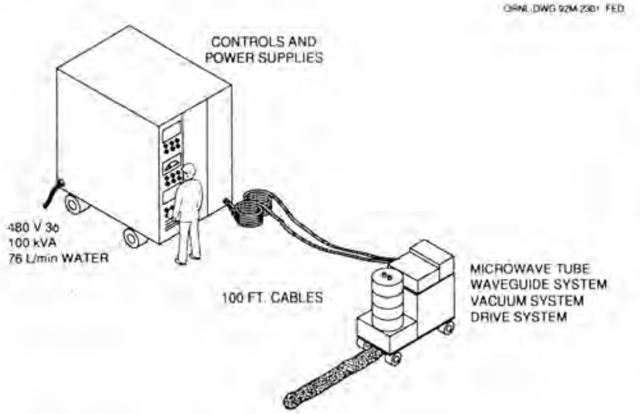

Fig. 4. Phase II mobile microwave concrete decontamination prototype.

plant water (76 L/min) would be supplied to these systems. The smaller, fully mobile unit contains the microwave tube and waveguide system along with a vacuum system and a drum for collecting the concrete debris. The mobile unit is tethered to the main enclosure, which supplies the electrical power and cooling to the mobile unit. The speed of the mobile unit and the microwave power are controlled from the main cabinet. Other activities in Phase II are the development of a rugged, compact, and electrically efficient microwave applicator that is better integrated with the required concrete debris collection system. The frequency- and temperature-dependent dielectric properties of concrete will be measured and the data will be used in a one-dimensional model (5) being developed at Florida International University to characterize the stresses generated in the concrete under the conditions of rapid microwave heating.

CONCLUSIONS

ORNL has completed some initial testing of a microwave heating process to remove concrete surfaces and plans to further develop this technique. In the dynamic tests, conducted with relatively simple equipment, we have demonstrated continuous concrete removal rates of 2.1 cm^3/s at 10.6 GHz with a figure-of-merit of 0.59 $cm^3/s/kW$. This figure-of-merit is comparable to that reported by the JAERI group (0.74 $cm^3/s/kW$) but was obtained at a power level of less than one-fourth of that used by their group. We have also established that frequencies higher than 2.45 GHz are better suited for high removal rates of shallow (less than 1 cm) surface contamination. We believe that with a scale-up of the power and with improvements to the applicator design to spread the microwave power over a larger area, concrete removal rates comparable to or exceeding those obtained with conventional equipment can be achieved. In addition, the microwave technique is a dry technique that generates little dust and avoids the need to work the concrete surfaces wet. In Phase II of our program, the Phase I equipment will be further optimized, scaled up, and made mobile to demonstrate most of the essential features required for an actual decommissioning application. Field tests of this equipment are planned for FY 1993.

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