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The objective of this study was to design and install a shield on a radiofrequency (RF) dielectric heater used in the water bed industry and to determine its effectiveness in reducing worker exposures. In work sites where industrial dielectric heating is utilized, occupational RF radiation exposures frequently exceed occupational exposure limits. A water bed manufacturer that used dielectric heaters in its production operations agreed to participate in this developmental study. The mean-squared (ms) RF electric (E^2) and magnetic (H^2) field strengths, the root-mean-squared (rms) RF-induced foot current and the heater frequency were measured for each unit. A heater utilizing a common sealing process and producing high worker exposures was selected for this study. The water bed mattress is a large, bulky product and can not be contained inside the shield. Thus, the shield required a slot or opening to allow passage of the material between the applicator plates for sealing while minimizing the leakage of RF radiation. An RF engineering firm designed, fabricated, and installed the shield. Operator exposures were measured before and after installing the shield to determine the shield's effectiveness in reducing RF exposures. Using these data, average exposure reduction factors were calculated: ms *E*-field strength (E^2)—213 times; ms *H*-field strength (H^2)—10.8 times; rms foot current—4.3 times. Thus, the shield was effective in reducing the operators' RF exposure from the heater. Murray, W.E.; Conover, D.L.; Edwards, R.M.; Werren, D.M.; Cox, C.; Smith, J.M.: The Effectiveness of a Shield in Reducing Operator Exposure to Radiofrequency Radiation from a Dielectric Heater. Appl. Occup. Environ. Hyg. 7(9):586–592; 1992.

Introduction

Radiofrequency (RF) radiation in the frequency range 10 kHz–300 GHz is employed in a multitude of industrial, scientific, and medical applications. RF heaters operating at frequencies of 3–100 MHz are used to heat, melt, or cure nonmetallic (dielectric) materials that are poor conductors of heat or electricity, such as plastic, rubber, and glue. In RF dielectric heating, materials are heated uniformly and quickly. Generally, the RF energy is applied to an object for several seconds to heat the material. The RF source then remains off until the next piece of material is processed.

There are about 100,000 RF heaters in use in the United States and over 250,000 workers exposed to RF emissions.[1] Some common uses of heaters include (1) the manufacture of many plastic products such as toys, vinyl loose-leaf binders, rain apparel, waterproof containers, furniture slipcovers, and packaging materials; (2) the processing of wood laminates and veneers, including glue setting; (3) the embossing and drying of textiles, papers, plastics, and leathers; and (4) the curing of materials that include plasticized polyvinyl chlorides, wood resins, polyurethane foams, concrete binders, rubber tires, and phenolic and other plastic resins.

Studies by scientists at the National Institute for Occupational Safety and Health (NIOSH) show that exposure levels for dielectric heat sealers can exceed occupational exposure limits.[2,3] Worker exposures to RF radiation can be reduced by using administrative controls, work practices, and engineering controls, with the latter being the most effective exposure reduction techniques.

The objective of this study was to design and install a shield on an RF heater used in the water bed industry and to determine its effectiveness in reducing worker exposures. There were several reasons for selecting this industry to carry out the study. First, in prior field studies high exposures were reported.[4] Second, most manufacturers are small businesses employing less than 50 workers. NIOSH has sponsored a Small Business Initiative for several years because these companies have limited resources to address safety and health concerns. Third, this industry presented a challenge to design an effective shield for a procedure where the product being heated could not be enclosed inside the shield.

Most RF shields are designed for heaters where the product is smaller than the base plate. In such applications, a box

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shield is very effective in reducing emissions because it is possible to contain the product within the shield and still maintain good electrical contact between the shield and the base plate of the heater. Good electrical contact is needed to maintain the current flow on the inside of the shield to minimize RF leakage fields. However, when sealing a large product such as a water bed mattress (about 2 m maximum length or width), the edges of the material overlap the base plate. A typical box shield could not be used because the overlapping material would prevent the shield from being in good electrical contact with the base plate.[1,5] Thus, a new shield design or a modification of an existing design was needed for the heaters used in manufacturing water bed mattresses.

The type of RF heater used in this study (Figure 1) has six major components: (1) a power supply provides high voltage to an oscillator, (2) the oscillator generates RF energy, (3) an applicator contains parallel-plate electrodes where the material to be heated is placed, (4) a press yoke supports the top applicator plate, (5) a base plate supports the bottom applicator plate, and (6) control switches regulate the process.

During heater operation, the operator is usually stationed within 1 m of the heater and is reactively coupled to the RF source. Because of reactive coupling, the operator is connected to an electrical RF circuit that includes the heater and other conductive objects in the workplace.[6] Figure 2 depicts such an exposure situation for an RF heater operator. Reactive coupling includes both electric and magnetic

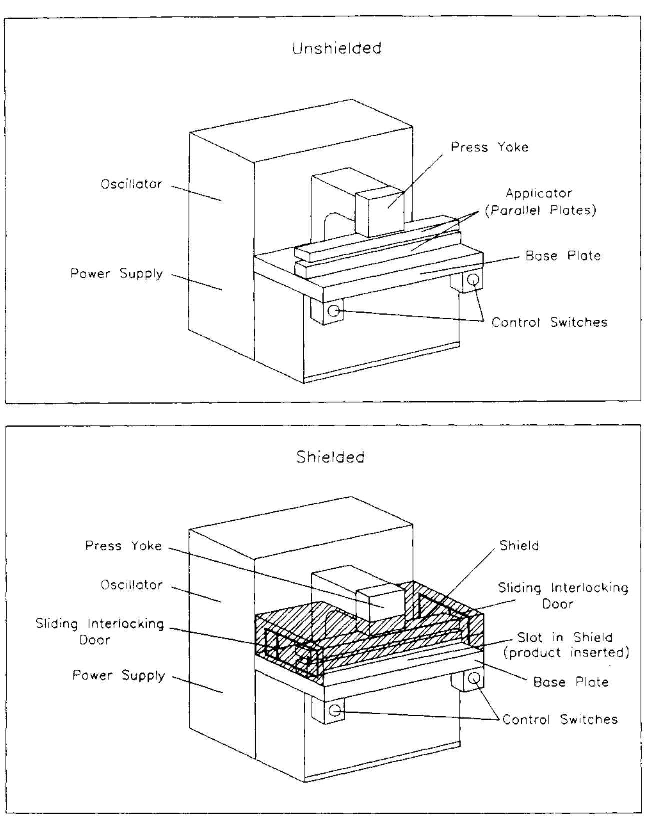

FIGURE 1. RF heater used in study: unshielded and shielded.

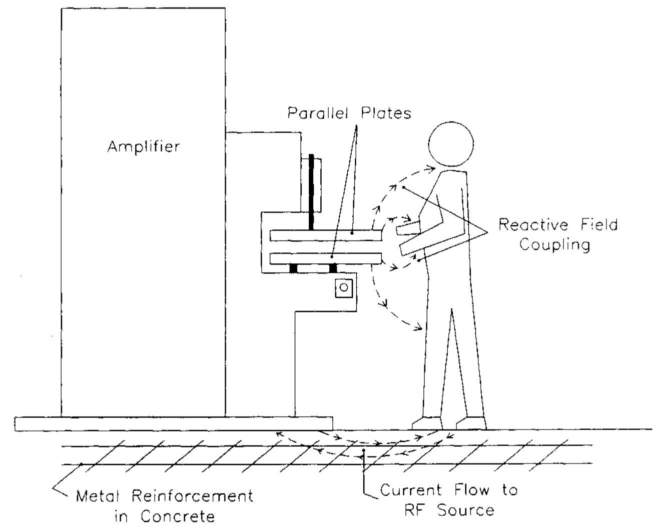

FIGURE 2. Typical RF heater exposure situation.

tor. Reactive coupling includes both electric and magnetic field coupling.[7,8] This reactive coupling causes the absorption of RF energy by the operator and induces a current flow in the operator's body. The measurement of these body currents is a good indicator of the RF energy absorbed by the operator's body.[6–9] At present, it is possible to measure E-field induced current only in a worker's extremities, namely, foot, ankle, arm, and wrist.

Methods and Materials

Study Plant

A water bed mattress manufacturer located near Cincinnati, Ohio, agreed to participate in this study. There are 13 RF heaters installed at the plant site, most of which are used routinely. Between 15 and 25 employees operate the heaters. The plant layout is shown in Figure 3.

RF Measurements

The operating frequency of each heater was measured with a Global Specialties Corporation (New Haven, Connecticut) Continental Mini Max frequency counter model MM50. (Mention of commercial products does not constitute an endorsement by NIOSH.) The mean-squared (ms) electric (E^2) and ms magnetic (H^2) field strength and root-mean-squared (rms) induced foot current were measured for each heater operator. A Holaday Industries (Eden Prairie, Minnesota) HI-3003 broadband isotropic survey meter with a model STE-03 electric field probe (0.5–6000 MHz) and a model STH-02 magnetic field probe (5–300 MHz) was used to measure each worker's exposure to electric and magnetic fields under near-field conditions. The Holaday meter and probes were calibrated by the manufacturer and the calibrations were verified using standards traceable to the National Institute of Standards and Technology (NIST). The ms field strengths were measured with the operator present at a distance of about 10 cm (recommended by the Institute of Electrical and Electronics Engineers[9]) from the

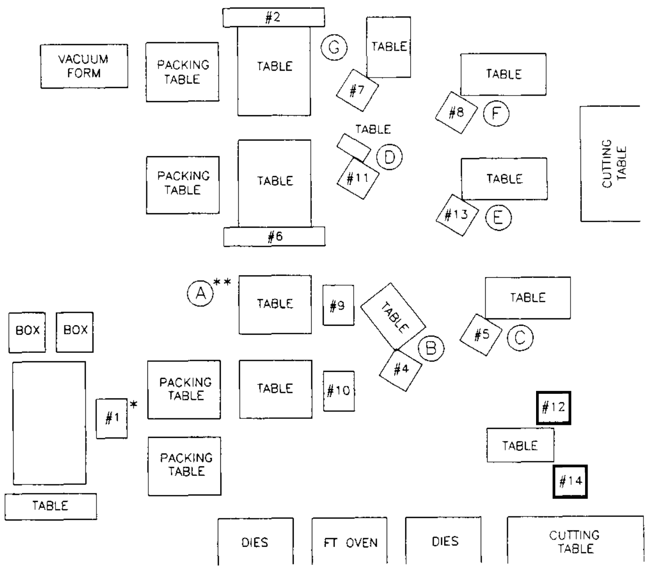

FIGURE 3. Layout of water bed plant. *Numbers refer to company identification on RF heaters. **Letters refer to locations where measurements were made in addition to heater 9.

plane of the operator's body. Exposure measurements were made at the operator's neck, waist, crotch, and knee.

Foot currents were determined by measuring the RF voltage (rms) developed across a known impedance of a foot current sensor with a Ballantine Laboratories (Boonton, New Jersey) model 3440A RF voltmeter.[7] The sensor is a platform consisting of two copper plates separated by a Plexiglas sheet and connected with a low resistance resistor (see Figure 4). The voltage readings were divided by the appropriate impedance value to calculate the foot current. The impedance value was measured with a Hewlett-Packard (Rockaway, New Jersey) model 4815A vector-impedance meter using the technique of Gandhi *et al.*[7] The RF voltmeter and RF voltage probe were calibrated by the vendors (traceable to NIST) over the frequency range 0.5–108 MHz.

The ms RF field strengths and rms foot currents were measured for the operators in their normal work positions and at several other locations before and after the shield was installed. All foot current measurements were made with the operators' hands at their sides. For the operators of heater 9, field strength and foot current measurements were made at least three times and average values were tabulated. Because of plant production requirements, repeat measurements could not be made at other nearby locations. Time-weighted averages were not calculated because the duty factor (fraction of time the RF power is on in a 6-min period) could change with the installation of the shield. All measurements were made under normal operating conditions.

Selection of Dielectric Heater

In selecting the heater to be shielded in this study, preliminary measurements (E^2, H^2, and foot current) were made to characterize the exposures to each of the 18 operators. Five heaters (numbers 1, 2, 6, 9, and 10 in Figure 3) each had two operators; the other eight heaters each had only one operator. Using the measured values obtained for each heater, the RF heater to be shielded was selected as follows. Each measurement value (E^2, H^2, and foot current) was compared to the levels measured at other heaters. The operation of each heater was observed to select a process commonly encountered in previous walk-through surveys of water bed plants.[4] Heater 9 was selected for the study because the exposures were relatively high compared to other heaters and this heater was used for a heating process (long-bar sealing) that is common in the water bed industry. Further, heater 9 contributed to the exposure of other workers stationed at distances of up to 9 m. This resulted from two factors — its high RF emissions and its central location in the plant.

Shield Design, Installation, and Evaluation

There are three criteria that must be met to design an RF shield that effectively reduces operator exposures.[1] First, the shield must have high conductivity so that the RF currents will flow on the interior surfaces of the shield; joints must be fabricated to also have high conductivity. Second, any openings in the shield should be small. The largest dimension of any opening in the shield should be parallel to the direction of the current flow to minimize RF leakage fields outside the shield. Third, the current in the shield walls should be minimized. This is accomplished by having separate conductors inside the cabinet to carry high currents.

The best designed shield will not function properly if it is not constructed and/or installed correctly. It is very important to maintain good electrical contact between the component parts of the shield, because small gaps can result in unacceptable levels of leakage radiation. In addition, safety and ergonomic hazards must be avoided in the design,

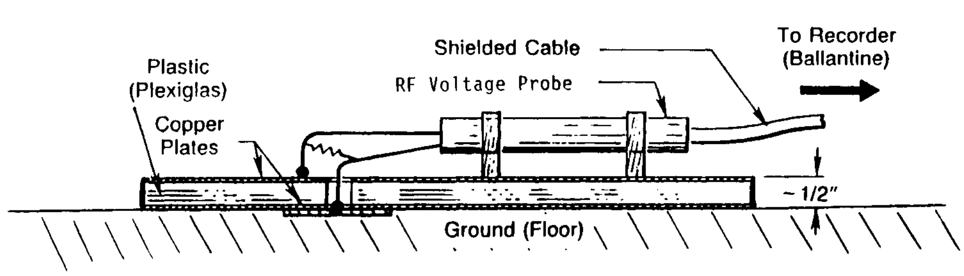

FIGURE 4. Foot current sensor.

TABLE I. RF Field Strength (E^2, H^2) and Induced Foot Current Measurements at Heater 9 Before and After Shield Installation[A]

Body Position	E^2 (V/m)^2, ms[B]		H^2 (A/m)^2, ms[B]		Foot Current (mA), rms[C]	
	Before	After	Before	After	Before	After
Left operator						
Neck	770,000	5000	2.8	0.36	—	—
Waist	430,000	3000	4.0	0.31	—	—
Crotch	610,000	1400	1.5	0.18	—	—
Knee	80,000	800	0.53	0.038	—	—
Foot	—	—	—	—	94.0	23.5
Right operator						
Neck	270,000	6600	3.6	0.36	—	—
Waist	260,000	3100	2.0	0.26	—	—
Crotch	410,000	700	1.1	0.11	—	—
Knee	110,000	700	0.59	0.038	—	—
Foot	—	—	—	—	33.4	7.4

[A]Each field strength and foot current value is the average of at least three measurements.
[B]Mean-squared (ms) field strength.
[C]Root-mean-squared (rms) foot current.

while interfering minimally with normal production operations. A good design must accommodate shielding, safety, ergonomic, product quality, and production requirements. A contract was awarded to an RF engineering firm to design, fabricate, and install the shield on the heater selected.

Results

Shield Design

The staff of the engineering firm, in consultation with NIOSH scientists, designed a shield that attached to the yoke of the press and the base plate of the heater. On heater 9, the material to be sealed is placed between the applicator plates through a slot (1.27 m × 12.7 cm) provided in the front of the shield (see Figure 1). Because the material to be sealed is larger than the slot length, excess material is folded out of the way. The two operators then position the material through the opening in each side panel of the shield. Once the material is in place, the two sliding interlocked doors must be closed tightly before the RF power can be activated.

Several advantages are noted about the design. First, an attached shield is more effective at reducing emissions because there is better electrical contact between the shield and the parts of the machine to which it is attached. Second, a large number of fasteners attach the shield to the heater preventing the formation of gaps between the shield and the heater. Thus the leakage of RF currents that generate fields that radiate to the environment is minimized. Third, attaching the shield to the heater eliminates pinch points, because the operator's extremities cannot be trapped between the base plate and the shield. Fourth, the use of sliding doors allowed sufficient access for the operators to position the product. To reduce operator exposure, the doors were interlocked and had to be closed before the RF power could be activated.

TABLE II. Reduction Factors for E^2, H^2 and Foot Current at Heater 9

Body Position	E^2	H^2	Foot Current
Left operator			
Neck	154	7.8	—
Waist	143	12.9	—
Crotch	436	8.3	—
Knee	100	13.9	—
Foot	—	—	4.0
Right operator			
Neck	41	10.0	—
Waist	84	7.7	—
Crotch	586	10.0	—
Knee	157	15.5	—
Foot	—	—	4.5

Shield Effectiveness

The RF measurements were taken before and after the shield was installed on heater 9 to determine its effectiveness in reducing the RF field strengths and foot current; the results are shown in Table I. The heater, operating at a measured frequency of 26.2 MHz, was run by the same two operators during all measurements. Before installation, E^2 ranged from 80,000 to 770,000 (V/m)^2, H^2 from 0.53 to 4.0 (A/m)^2, and the foot current from 33.4 to 94.0 mA. After installation, E^2 ranged from 700 to 6,600 (V/m)^2, H^2 from 0.038 to 0.36 (A/m)^2, and the foot current from 7.4 to 23.5 mA.

In Table II the reduction factors for each operator of heater 9 are given by anatomical location. These factors were calculated by dividing the magnitude of the measured levels before shield installation by that obtained after installation. The reduction factor for E^2 ranged from 41 to 586, depending on anatomical location, with an average reduction by 213. The ms H-field strength (H^2) was reduced by a factor of 7.7 to 15.5, with an average reduction by 10.8. The foot current was reduced by an average factor of 4.25 (4.0 on the left operator, 4.5 on the right operator). The reduction factors varied considerably by anatomical location for each operator. The average reduction factor for E^2 was 208 for the

TABLE III. RF Field Strength (E^2, H^2) and Induced Foot Current Measurements at Two Nearby Dielectric Heaters Before and After Shield Installation on Heater 9[A,B]

Body Position	E^2 (V/m)^2, ms[C]		H^2 (A/m)^2, ms[C]		Foot Current (mA), rms[D]	
	Before	After	Before	After	Before	After
Heater 4 (B)						
Neck	7700	1100	0.065	0.005	—	—
Waist	4300	600	0.077	0.005	—	—
Crotch	2200	300	0.064	0.005	—	—
Knee	2100	300	0.060	0.008	—	—
Foot	—	—	—	—	137	12
Heater 11 (D)						
Neck	7300	600	0.017	0.004	—	—
Waist	16,000	600	0.012	0.004	—	—
Crotch	3500	1500	0.012	0.008	—	—
Knee	4900	1000	0.012	0.005	—	—
Foot	—	—	—	—	117	32.3

[A]Only heater 9 was generating RF fields.
[B]Repeat field strength and foot current measurements were not made.
[C]Mean-squared (ms) field strength.
[D]Root-mean-squared (rms) foot current.

left operator and 217 for the right operator. The values were even closer for H^2 (10.7 for the left and 10.8 for the right).

It was noted during the survey that the operators of other heaters received a measurable exposure from heater 9 in addition to that from the heater on which they were working. Thus, E^2, H^2 and foot current measurements were made at several other work stations throughout the plant before and after the shield was installed on heater 9. The locations at which these measurements were made are designated A, B, C, D, E, F, and G on Figure 3. These measurements were made when only heater 9 was operating. For heaters 4 (B) and 11 (D), E^2 and H^2 were measured at the same four anatomical locations of operators as those for heater 9. These heaters were located close to 9, at distances of 3.2 and 5.2 m away, respectively. The measurement data shown in Table III reflect the exposures from heater 9 to the operators at these locations when their heaters were not generating RF radiation. The reduction factors at these heaters are shown in Table IV. For heater 4 the average reduction factor for E^2 was 7.1, 12.2 for H^2, and 11.4 for the foot current. For heater 11, the average reduction factor for E^2 was 11.5, 2.8 for H^2, and 3.6 for the foot current.

Measurements of E^2 and foot current were made also at several other locations (locations A, C, E, F and G in Figure 3) before and after installation of the shield, because the subject heater (9) contributed to the exposure of workers at these locations. These data are shown in Table V. These locations were at heaters 5 (C), 13 (E), 8 (F), 2 (G) and at the end of the work table facing heater 9 (A). The approximate distance from heater 9 is also given in Table V. The reduction factors are shown in Table VI.

TABLE IV. Reduction Factors for E^2, H^2, and Foot Current at Heaters 4 and 11 After Shield Installation on Heater 9[A]

Body Position	E^2	H^2	Foot Current
Heater 4			
Neck	7.0	13.0	—
Waist	7.2	15.4	—
Crotch	7.3	12.8	—
Knee	7.0	7.5	—
Foot	—	—	11.4
Heater 11			
Neck	12.2	4.3	—
Waist	26.7	3.0	—
Crotch	2.3	1.5	—
Knee	4.9	2.4	—
Foot	—	—	3.6

[A]Only heater 9 was generating RF fields.

Discussion

The objective of this study was to design, fabricate, and install a shield on an RF heater (9) and to determine its effectiveness, reflected in the exposure reduction factors, in reducing operator exposures. These reduction factors were determined without correcting the exposure data for duty factor (time-weighted average) because the duty factor

TABLE V. E-Field Strength (E^2) and Foot Current Measurements at Nearby Locations Before and After Shield Installed on Heater 9[A,B]

Location (Heater No.)	Distance (m) from Heater 9	E^2 (V/m)^2, ms[C]		Foot Current (mA), rms[D]	
		Before	After	Before	After
A (9)	3.1	8,100	1,000	65.0	50.0
C (5)	5.2	9,300	950	123	11.3
E (13)	7.0	3,200	350	104	13.0
F (8)	9.1	4,400	200	60.4	18.9
G (2)	9.1	10,000	300	59.3	18.0

[A]Only heater 9 was generating RF fields.
[B]Repeat field strength and foot current measurements were not made.
[C]Mean-squared (ms) field strength.
[D]Root-mean-squared (rms) foot current.

TABLE VI. Reduction Factors for E^2 and Foot Current at Nearby Locations After Shield Installed on Heater 9[A]

Location	Distance (m) from Heater 9	E^2	Foot Current
A (9)	3.1	8.1	1.3
C (5)	5.2	9.8	10.9
E (13)	7.0	9.1	8.0
F (8)	9.1	22.0	3.2
G (2)	9.1	33.3	3.3

[A]Only heater 9 was generating RF fields.

could change with installation of the shield. The before and after measurements for heater 9 are shown in Table I. As expected, the data in Table I show that the distribution of *E*- and *H*-fields over the operator's body (i.e., at neck, waist, crotch, and knee locations) was changed by shield installation.[10] Consequently, the data in Table II show field strength reduction factors that vary with anatomical location.

The large reduction in E^2 and the moderate reduction in H^2 were expected. However, the decrease in the foot current was smaller than anticipated. The foot current is due primarily to the absorption of the *E*-field by the operator's body and is proportional to the rms *E*-field strength *(E)*.[6,7] Thus, to compare the reduction in *E*-field with that for the foot current, it is necessary to calculate the average reduction factor for the rms *E*-field strength. This was calculated by taking the average of the square roots of the reduction factors for the ms *E*-field strength (E^2) in Table II. The average reduction factor was determined to be 13.5, while the average reduction factor for the foot current is only 4.25. This reduction factor is about ⅓ the reduction factor for the *E*-field strength *(E)*. One possible explanation for this observation is that the operators surveyed in this study were reactively coupled to the heaters, leading to additional induced currents and RF energy absorption.[7,10] Field strength measurements alone do not account for the additional induced currents and energy absorption caused by reactive coupling.[6,7,9–12] Under reactive coupling conditions, foot current measurements are necessary to evaluate heater operator exposures adequately.[6,7,9,11,12]

The data in Tables I and III illustrate the expected spatial variability of E^2 and H^2 over the midplane of the operator's body on heaters 4, 9, and 11. Previous field strength data collected on RF heaters showed comparable spatial variability.[2,3,6,10] The reduction factors also varied considerably by anatomical location for both operators on heater 9.

Before the shield was installed on heater 9, its RF emissions contributed significantly to the *E*-field exposure and foot current of workers at distances of up to 9 m away (see Tables III and V). With only heater 9 emitting RF energy, the maximum E^2 ranged up to 16,000 V^2/m^2; the H^2 up to 0.077 A^2/m^2; and the foot current up to 137 mA. Shielding heater 9 reduced all of these exposures at other locations that could be attributed only to heater 9. As expected, at these other locations, the spatial distribution of *E*- and *H*-fields and foot current (relative to the shielded heater) was changed by shield installation (see Figure 3, Tables III and V). Consequently, the exposure reduction factors for field strengths and foot current at these other locations are dependent on their spatial location relative to the shielded heater (see Tables IV and VI, Figure 3).

Conclusions

The measurement data and experience obtained in this study have led us to several conclusions:

1. When the product being processed can not be contained within the shield, the design of a prototype shield becomes more complicated, requiring considerable RF engineering skill.
2. The use of a shield reduces the ms *E*-field strength (E^2) by a large factor. The ms *H*-field strength (H^2) and foot current are reduced also, but to a lesser extent.
3. The emissions from one RF heater can make a significant contribution to the exposure of workers at other locations that are up to 9 m away in the plant.
4. As noted many times before, the field strength exposures exhibit a large spatial variation over the operator's body. Thus, a measurement at one anatomical location does not determine worker exposure adequately.

The long-term impact of installing this shield has not been determined. Measurements to demonstrate its continued effectiveness in reducing RF exposure should be done for at least 6–12 months after installation. It would be especially useful to conduct follow-up measurements to determine its long-term durability. The effect of the shield on worker productivity and the production process should also be studied. Any effect the shield may have on product quality, production quotas, energy consumption, safety, or health concerns has not been evaluated at this time.

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