Shielding Effectiveness of Improved Microwave-Protective Suits

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Abstract —**The shielding effectiveness of microwave-protective suits was determined by measuring the attenuation of sections of fabric by a waveguide-transmission-loss method. The attenuation of the entire suit on a full-sized phantom man model was determined by measuring the E fields at the surface of ten locations on the phantom by diode sensors during exposure to 915- and 2450-MHz radiation fields from standard gain horns in an anechoic chamber. The results indicate that both the material attenuation and the design of the suit contribute to its shielding effectiveness. A novel material which is fire retardant and provides good ventilation was tested. The attenuation of the fabric is 35 to 40 dB for the frequency range of 1.5 to 11 GHz and 28–35 dB for frequencies between 0.65 and 1.15 GHz. The final version of the suit has at least 25 dB shielding at 2450 MHz for the ten locations tested and 20 dB at 915 MHz at the head and torso of the model. It is concluded that the suit can provide good protection for microwave frequencies in the 0.65 to 11 GHz range in which the tests were made. More work is needed in developing a suit for broadcasting and shortwave bands.**

I. Introduction

THE INCREASING USE and fear of microwave radiation have emphasized the need for a well-designed protective suit. Over the past 40 years there has been a need for the protection of workers who are exposed to high-intensity microwave radiation used for industrial, medical, and military applications. The increasingly stringent safety standards [1], [2] have resulted in a number of new materials on the market that are suitable for microwave shielding. Many of them are metal-coated fabrics to reflect RF energy [3], [4]. However, these materials are not suitable for making protective suits, despite their excellent reflectivity, because of their high flammability, poor ventilation, and poor washability.

In a companion paper [5], we discuss the methods and test results of measuring the shielding effectiveness of four older designs of microwave-protective suits at 2450 MHz. The four suits were the Wave Guarde suit, used by AT&T; the suit used by the U.S. Navy; the Invascreen suit, made by the Invertag Electronics and Telecommunication Company in Switzerland; and a prototype suit developed jointly by Milliken & Company and Body Guard, which is a division of Lion Uniform. Results show that the Navy suit provided the best performance: 34.5 to 48.7 dB attenuation for horizontally and vertically polarized fields. The Wave Guarde suit was the second best, with a shielding effectiveness of 13.2 to 33.7 dB. The Invascreen and Milliken suits displayed reasonable attenuation for vertical polarization but poor protection for horizontal polarization. Tables I and II show the attenuations at 2450 MHz and the characteristics of the fabrics of the four suits. It is clearly shown that whereas the Navy suit is excellent for protection from microwave radiation, its flammability makes it dangerous to wear. The flammability is a concern when used in high-intensity microwave fields, since sparks can be induced at strong field spots. In addition, the suits are more difficult to remove than street clothes because of the special closures.

In this paper, we extend our work on an improved Milliken/Body Guard suit over a wider frequency band. The material attenuation was tested from 0.65 to 11 GHz. The effect of washing the fabric on attenuation was studied. The shielding effectiveness of the complete suit with hood

TABLE I
ATTENUATION (dB) OF FABRIC MATERIALS OF FOUR MICROWAVE-PROTECTIVE SUITS AT 2450 MHz WITH E PARALLEL AND PERPENDICULAR TO WARP

Suit	Parallel	Perpendicular
Wave Guarde	45	42
U.S. Navy	46	47
Invascreen	32	20
Milliken	36	38

TABLE II
SUMMARY OF FABRIC CHARACTERISTICS OF FOUR MICROWAVE-PROTECTIVE SUITS

Suit	Attenuation	Flammability	Ventilation
Wave Guarde	Excellent	Very high	Excellent
U.S. Navy	Excellent	Very high	Excellent
Invascreen	Fair	High	Poor
Milliken	Very good	Low	Good

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at ten locations on a full-sized man model was measured for both 915 and 2450 MHz. To compare this suit with the best protective suit that we have tested, data on the Navy suit at 915 and 2450 MHz are also presented. During the study, many versions of the fabric and the design of the suit were tested. Only the results of the final version are presented.

II. Methods

Details of the exposure chamber, fabrication of the full-sized man model, design of the diode field detectors, and calibration of diodes at 2450 MHz are described elsewhere [5]. Only a summary of the methods is described here.

Initial tests of the suit fabric attenuation were conducted by the waveguide-transmission-loss method. The signal generator transmitted a signal through a section of waveguide to a power meter, or a network analyzer system, where power was noted and compared with the value when the fabric was inserted between the flanges of the waveguide section. Reflections from the material were absorbed in an isolator between the generator and the waveguide (Fig. 1). In this study, the waveguides consisted of WR-90, WR-137, WR-284, WR-430, and WR-975 to cover the frequency band of 0.65 to 11 GHz. The signal generators and isolators were selected or adjusted for proper frequency ranges. Sweep generators, an HP-8410 network analyzer, and an HP-7045 plotter were used to provide plots of the fabric attenuation as a function of frequency.

The overall effectiveness of the suits was determined by comparisons of the electric field strength and specific absorption rate (SAR) of energy values as a function of position at the surface of the synthetic tissue of the full-sized phantom man model exposed with and without the suit. All exposures from a 0–10-kW klystron source were conducted in a large (12 ft×24 ft×12 ft) anechoic chamber with wall absorber capable of minimizing reflections over a frequency range of 450 MHz through 100 GHz. Each HP 5082-2810 Schottky diode was calibrated by placement in contact with a flat phantom block exposed to 915 or 2450 MHz radiation at normal incidence. The output voltages of these diodes, shown in Table III for 915-MHz calibration and Table IV for 2450-MHz calibration, were measured as a function of the incident power density. The sensitivity of the system was increased by modulating the microwave source at 100 percent with a 1000-Hz square wave and reading the diode output voltages with an HP 415E standing wave ratio meter. Reliable readings were obtained from the diodes for incident power densities as low as 0.1 μW/cm^2 at 915 MHz and 0.05 μW/cm^2 at 2450 MHz at the surface of the phantom block. Ten of the calibrated diodes were placed at various locations on the front surface of the phantom man model: forehead, neck, heart, liver, shoulder, elbow, wrist, groin, knee, and ankle. Two spare diodes were later used to replace diodes that failed after prolonged handling of the model.

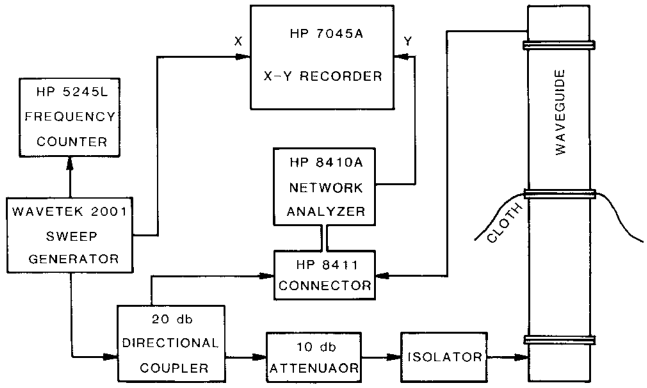

Fig. 1. Schematic of equipment used for measuring attenuation of suit fabrics.

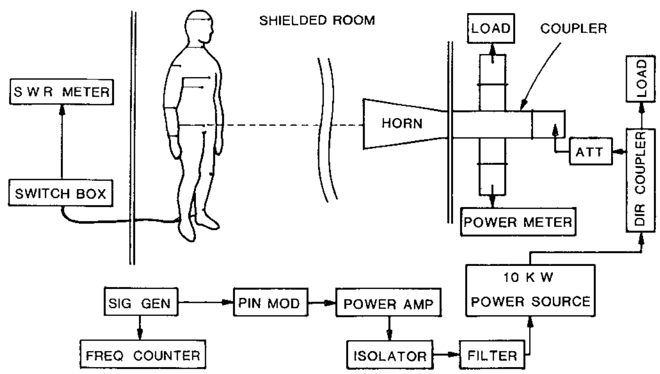

Fig. 2. Equipment arrangement for exposing bare phantom man to low-power microwave radiation.

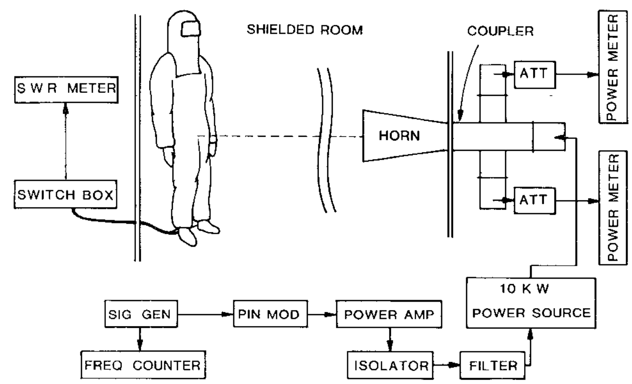

Fig. 3. Equipment arrangement for exposing phantom man wearing a protective suit to high-power microwave radiation.

The shielding effectiveness of the suits was determined by initial exposure of the model without the suit at a relatively low power density within the range of calibration of each diode (Fig. 2). Then the model was exposed with the suit on to a power density sufficiently high to produce the same reading as previously read by each diode (Fig. 3). The ratio of the input powers to the horn was recorded as the shielding effectiveness of the suit at each diode location. The maximum incident power density was as high as 65 mW/cm^2 for both 915- and 2450-MHz exposures. The model was exposed either in a vertical position parallel to the E field or in a horizontal position perpendicular to E field at a distance of 397 cm from a 14.1-dB gain horn

TABLE III
CALIBRATION OF DIODE SENSORS IN CONTACT WITH PHANTOM MUSCLE AT 915 MHz: HP-415E SWR METER READING VERSUS INCIDENT POWER DENSITY ($\mu W/cm^2$)

Diode SWR meter reading (-db)	Diode Numbers 1	2	3	4	5	6	7	8	9	10	11	12
35	43.91	47.02	58.40	44.95	57.94	60.12	58.28	98.65	16.67	110.63	48.52	60.24
37	27.36	29.43	36.44	28.16	36.10	37.48	36.33	61.39	10.44	68.74	29.89	37.48
39	17.13	18.28	22.76	17.59	22.30	23.45	22.65	38.28	6.53	42.76	18.62	23.34
41	10.56	11.27	14.03	10.84	13.91	14.37	14.03	23.80	4.06	26.56	11.39	14.37
43	6.51	6.94	8.65	6.70	8.58	8.89	8.66	14.71	2.52	16.44	6.99	8.86
45	3.97	4.23	5.24	4.10	5.28	5.44	5.30	9.00	1.55	10.05	4.25	5.38
47	2.41	2.59	3.16	2.48	3.16	3.29	3.18	5.27	.94	6.10	2.58	3.23
49	1.43	1.56	1.85	1.46	1.86	1.95	1.90	3.25	.57	3.66	1.53	1.86
51	1.00	1.07	1.28	1.01	1.30	1.33	1.53	2.20	.38	2.50	1.02	1.31
53	.61	.67	.81	.63	.81	.84	.82	1.39	.24	1.59	.65	.81
55	.37	.41	.49	.39	.51	.52	.49	.85	.15	.98	.39	.48
57	.21	.23	.29	.22	.29	.29	.28	.52	.09	.60	.24	.22

TABLE IV
CALIBRATION OF DIODE SENSORS IN CONTACT WITH PHANTOM MUSCLE AT 2450 MHz: HP-415E SWR METER READING VERSUS INCIDENT POWER DENSITY ($\mu W/cm^2$)

Diode SWR meter reading (-db)	Diode Numbers 1	2	3	4	5	6	7	8	9	10	11	12
35	9.12	11.88	9.26	10.68	10.24	9.88	10.06	13.62	3.16	18.58	6.58	10.52
37	5.72	7.42	5.80	6.68	6.42	6.16	6.30	8.52	1.98	11.66	4.12	6.58
39	3.58	4.62	3.62	4.20	4.00	3.86	3.94	5.36	1.24	7.26	2.58	4.14
41	2.20	2.88	2.26	2.60	2.48	2.40	2.44	3.32	.772	4.48	1.60	2.56
43	1.47	1.78	1.39	1.61	1.53	1.48	1.51	2.06	.478	2.78	.996	1.58
45	.834	1.09	.850	.990	.938	.906	.922	1.26	.294	1.71	.612	.970
47	.504	.658	.514	.600	.568	.552	.556	.768	.179	1.03	.370	.582
49	.298	.390	.300	.354	.336	.326	.326	.458	.107	.612	.220	.348
51	.202	.270	.212	.244	.234	.220	.224	.308	.0728	.420	.154	.238
53	.129	.172	.132	.149	.146	.142	.139	.196	.0470	.266	.0960	.151
55	.786	.107	.0810	.093	.0886	.0866	.0866	.120	.0278	.163	.0606	.146
57	.438	.061	.0474	.049	.0508	.0526	.0472	.0704	.0162	.0922	.0352	.041

source operating at 915 MHz or at 458 cm from a 13.9-dB standard-gain horn source at 2450 MHz, in the far zone fields. Diode readings with the sensor dipole oriented parallel and perpendicular to the E fields were recorded for both vertical and horizontal model orientations. SAR values were calculated according to Guy *et al.* [5] by relating the diode readings to the measured and theoretical SAR when the diode was mounted at the surface of the exposed flat-plate phantom model. The conversion factor was found to be 0.23 W/kg and 0.4 W/kg for an incident power density of 1 mW/cm^2 at 915 and 2450 MHz, respectively, for the flat plate. For example, from Table III, a diode reading of 35 dB (diode #1), corresponding to an incident power density of 43.9 μW/cm^2, would be equivalent to an SAR of $(0.23)(0.0439) = 0.010$ W/kg at 915 MHz. We would expect that the relation between the diode reading and the SAR would hold regardless of the position in which it was mounted at the surface of the phantom man.

Using the two methods described above, the attenuation of the Milliken fabric over the frequency range 0.65 to 11 GHz was tested. To study the effect of washes, the attenuations of the material after 10 and 25 home or industrial washes were measured at 2450 MHz. The shielding effectiveness of the Milliken/Body Guard suit and the Navy suit at the ten anatomical locations on the model mentioned before was evaluated for 915 and 2450 MHz.

III. Results

A. Fabric Attenuation

Figure 4 shows the results of the fabric attenuation measurements. From 1.5 to 11 GHz, the attenuation was at least 35 dB for the E field aligned with both the warp and the fill direction of the fabric weave. The warp is in the lengthwise direction of the fabric as output from a loom and the fill is the width of the fabric, which in general is 4–6 ft. At the frequency range of 0.65 to 1.15 GHz, the attenuation was between 28 and 35 dB for both polarizations. These data indicate that, for frequencies lower than 2.2 GHz, the attenuation for E field parallel to the warp direction of the fabric weave has higher values than the attenuation with the field parallel to the fill direction of the weave. The difference in attenuation between the warp and the fill direction is probably related to some breakage of the metal fibers due to the tension in the fill direction during weaving of the fabric. This breakage was detected by X-ray examination of the material at the Milliken Company.

Table V lists the attenuation (mean $\pm$SD) for the fabric at 2450-MHz transmission after home or industrial washing of the fabric 10 and 25 times. Ten home or industrial washes caused a 3–5-dB drop in attenuation with the transmitted E field parallel to the warp direction of the wave, with no change when the transmitted E field was parallel to the fill direction. However, the 25 home washes produced a decrease of 2 dB attenuation for the transmitted E field parallel to the fill direction of the fabric.

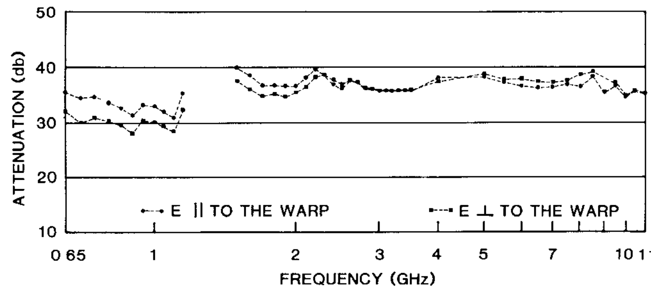

Fig. 4. Attenuation of Milliken fabric at various microwave frequencies.

TABLE V
EFFECTS OF HOME AND INDUSTRIAL WASHES ON THE ATTENUATION OF 2450-MHz MICROWAVE TRANSMISSION THROUGH THE MILLIKEN FABRIC

Condition	Attenuation (db)	
	E parallel to warp	E parallel to fill
No wash	39.55 ± 1.12 (N=6)	33.44 ± 2.98 (N=7)
10 home	33.27 ± 1.31 (N=6)	33.65 ± 1.24 (N=6)
10 industrial	34.43 ± 2.31 (N=5)	33.50 ± 0.63 (N=6)
25 home	35.63 ± 1.04 (N=6)	31.88 ± 0.41 (N=6)
25 industrial	31.45 ± 0.72 (N=6)	28.78 ± 0.97 (N=6)

The 25 industrial washes decreased the attenuation about 6 dB for the E field parallel to either the warp or the fill direction.

B. Milliken/Body Guard Suit Attenuation

Based on the diode calibration readings tabulated in Tables III and IV, the SAR's at various positions identified in Figs. 5 and 6 on the surface of the bare phantom model exposed to vertical incident electric fields at 915 and 2450 MHz were calculated as shown in Table VI. It is reported in the companion paper [5] that the vertical electric field is the major contributor to the total SAR. Therefore the horizontal field was not measured at the surface of the bare model for this case. It was found that the high SAR was measured at the ankle when the E field was parallel to the long axis of the man model. This is consistent with our previous findings showing increased induced current density and energy coupling in regions of narrow cross-sectional area of the body [6].

The SAR data of the Milliken/Body Guard suit at 915 MHz are listed in Table VII. Comparing the total SAR values with those for the bare model in Table VI, the shielding at the ten locations was calculated and is shown in the last column of Table VII and in Fig. 5. The shielding was at least 20 dB for the head, neck, and torso of the model. The 17.4-dB shielding at the shoulder for exposure to vertical polarization was low, and the shielding of 5.1 dB at the ankle was very low and obviously due to the proximity to the open cuff of the trousers.

The shielding values for 2450-MHz exposure obtained by comparing the SAR calculated for the clothed model (Table VIII) to that calculated for the bare model based on the diode readings are listed in the last column of Table

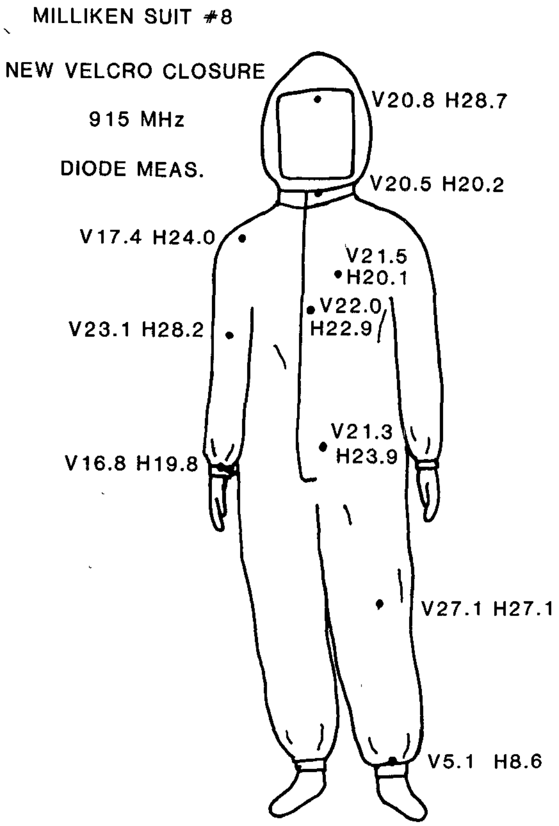

Fig. 5. Shielding effectiveness of Milliken and Body Guard suit exposed to 915-MHz vertically and horizontally polarized electric fields, denoted by V and H, respectively.

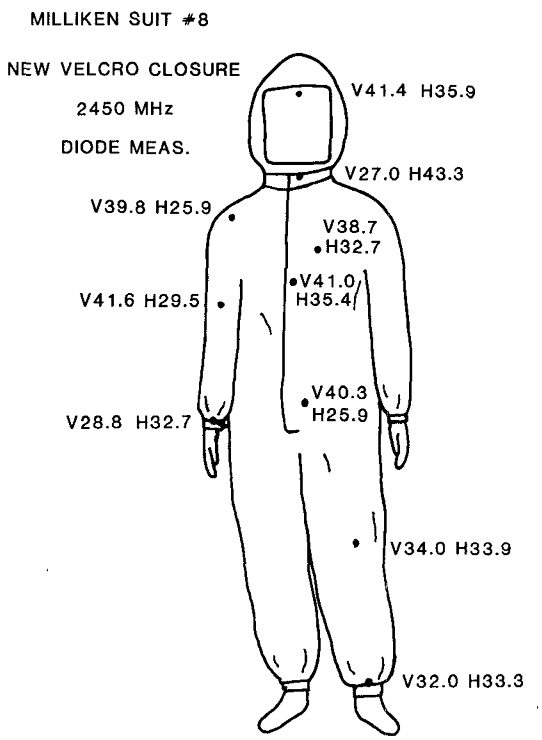

Fig. 6. Shielding effectiveness of Milliken and Body Guard suit exposed to 2450-MHz vertically and horizontally polarized electric fields, denoted by V and H, respectively.

TABLE VI
SPECIFIC ABSORPTION RATES (W/KG PER mW/cm^2) IN FULL-SIZED BARE MAN MODEL EXPOSED TO ELECTROMAGNETIC RADIATION WITH E FIELD PARALLEL TO LONG AXIS OF BODY

Diode	Parallel to exposure field	Perpendicular to exposure field
f = 915 MHz		
1	0.129	0.0769
2	0.199	0.0250
3	0.158	0.153
4	0.136	0.203
5	0.052	0.180
6	0.115	0.0474
7	0.229	0.0711
8	0.211	0.292
9	0.147	0.106
10	0.645	0.204
f= 2450 MHz		
1	0.124	0.080
2	0.207	0.145
3	0.234	0.161
4	0.205	0.184
5	0.193	0.122
6	0.211	0.127
7	0.162	0.0927
8	0.331	0.0748
9	0.157	0.189
10	0.138	0.749

TABLE VII
SPECIFIC ABSORPTION RATES (W/KG PER mW/cm^2) IN FULL-SIZED MAN MODEL WEARING MILLIKEN/BODY GUARDE SUIT EXPOSED TO 915-MHz ELECTROMAGNETIC FIELDS

	SAR			
	E-field component parallel to exposure field	E-field component perpendicular to exposure field	Total	Shielding (db)
Exposed with E parallel to body				
1	5.82×10^{-4}	4.99×10^{-4}	1.08×10^{-3}	20.8
2	1.12×10^{-3}	6.59×10^{-4}	1.78×10^{-3}	20.5
3	4.11×10^{-4}	7.00×10^{-4}	1.11×10^{-3}	21.5
4	2.53×10^{-4}	6.03×10^{-4}	8.56×10^{-4}	22.0
5	4.22×10^{-4}	5.22×10^{-4}	9.44×10^{-4}	17.4
6	1.34×10^{-4}	4.36×10^{-4}	5.70×10^{-4}	23.1
7	2.99×10^{-3}	1.77×10^{-3}	4.76×10^{-3}	16.8
8	4.29×10^{-4}	1.10×10^{-3}	1.53×10^{-3}	21.3
9	7.48×10^{-5}	2.11×10^{-4}	2.86×10^{-4}	27.1
10	5.44×10^{-2}	1.46×10^{-1}	$2{,}00 \times 10^{-1}$	5.1
Exposed with E perpendicular to body				
1	5.97×10^{-5}	4.34×10^{-5}	1.04×10^{-4}	28.7
2	1.94×10^{-4}	4.57×10^{-5}	2.39×10^{-4}	20.2
3	1.21×10^{-3}	3.05×10^{-4}	1.51×10^{-3}	20.1
4	6.14×10^{-4}	4.17×10^{-4}	1.03×10^{-3}	22.9
5	6.40×10^{-4}	7.33×10^{-5}	7.14×10^{-4}	24.0
6	1.48×10^{-5}	5.77×10^{-5}	7.25×10^{-5}	28.2
7	8.35×10^{-5}	6.67×10^{-4}	7.50×10^{-4}	19.8
8	1.05×10^{-3}	1.39×10^{-4}	1.19×10^{-3}	23.9
9	1.85×10^{-4}	1.87×10^{-5}	2.04×10^{-4}	27.1
10	3.37×10^{-3}	2.47×10^{-2}	2.81×10^{-2}	8.6

VIII and in Fig. 6. The data show a shielding of at least 25 dB at the ten locations where the measurements were made.

C. U.S. Navy Suit

Since the Navy suit was known to have excellent shielding at 2450 MHz [5], its attenuation was also measured at 915 MHz for comparison purposes. Table IX shows the results. Again, the data indicate it has excellent shielding

TABLE VIII
SPECIFIC ABSORPTION RATES (W/KG PER mW/cm^2) IN FULL-SIZED MAN MODEL WEARING MILLIKEN/BODY GUARD SUIT EXPOSED TO 2450-MHZ ELECTROMAGNETIC FIELDS

	SAR			
	E-field component parallel to exposure field	E-field component perpendicular to exposure field	Total	Shielding (db)
Exposed with E parallel to body				
1	5.74×10^{-6}	3.25×10^{-6}	8.99×10^{-6}	41.4
2	3.98×10^{-4}	1.30×10^{-5}	4.11×10^{-4}	27.0
3	1.90×10^{-5}	1.28×10^{-5}	3.17×10^{-5}	38.7
4	1.30×10^{-5}	3.20×10^{-6}	1.62×10^{-5}	41.0
5	1.20×10^{-5}	8.19×10^{-6}	2.02×10^{-5}	39.8
6	7.37×10^{-6}	7.22×10^{-6}	1.46×10^{-5}	41.6
7	2.11×10^{-4}	2.21×10^{-6}	2.13×10^{-4}	28.8
8	1.82×10^{-5}	1.25×10^{-5}	3.06×10^{-5}	40.3
9	5.21×10^{-5}	1.18×10^{-5}	6.31×10^{-5}	34.0
10	2.69×10^{-4}	5.97×10^{-4}	8.66×10^{-4}	32.0
Exposed with E perpendicular to body				
1	1.04×10^{-5}	1.01×10^{-5}	2.06×10^{-5}	35.9
2	3.62×10^{-6}	3.19×10^{-6}	6.80×10^{-6}	43.3
3	7.50×10^{-5}	1.08×10^{-5}	8.58×10^{-5}	32.7
4	1.27×10^{-5}	4.10×10^{-5}	5.38×10^{-5}	35.4
5	2.85×10^{-4}	3.12×10^{-5}	3.16×10^{-4}	25.9
6	9.74×10^{-5}	4.41×10^{-5}	1.42×10^{-4}	29.5
7	1.00×10^{-5}	3.98×10^{-5}	4.98×10^{-5}	32.7
8	9.30×10^{-5}	9.96×10^{-5}	1.93×10^{-4}	25.9
9	4.81×10^{-5}	2.97×10^{-5}	7.78×10^{-5}	33.9
10	1.50×10^{-4}	1.98×10^{-4}	3.48×10^{-4}	33.3

TABLE IX
SHIELDING EFFECTIVENESS (DB) OF THE U.S. NAVY SUIT AT 915 AND 2450 MHZ

	915 MHz		2450 MHz	
Diode	E parallel	E perpendicular	E parallel	E perpendicular
1	31.1	36.7	48.7	43.2
2	34.6	39.5	43.3	44.3
3	32.7	46.3	38.9	42.4
4	31.1	46.0	43.9	45.5
5	27.6	44.1	46.9	41.6
6	31.9	37.1	43.5	35.4
7	35.6	40.0	42.6	43.6
8	28.8	49.0	42.7	34.5
9	34.5	48.8	38.7	36.4
10	9.0	43.9	40.5	39.6

effectiveness except for a low value at the ankle due to the opening at the back of the heel where the diode cables are passed through the suit. This is a measurement artifact.

IV. DISCUSSION

The microwave-protective suits have been available for more than a decade both in this country [7] and abroad [8]. However, they have not been used very much in practice. In general the suits have not been readily available, they are not convenient to use, staff personnel have not felt the need to wear them, and management personnel have lacked confidence in their effectiveness. With the increasing reports of biological effects of radio-frequency radiation at low power levels [9] and the low safety standards, there is an increasing need for more practical and effective microwave-protective suits. Such suits are not only useful to industrial or military applications, but some medical professions will also be benefited. For example, protective clothing may be useful for physicians and therapists while operating high-power RF sources during clinical hyperthermia treatment of cancers.

We have previously used the waveguide-transmission-loss method and the E-field sensitive diodes to measure the shielding effectiveness of four types of microwave-protective suits. The data from these previous measurements indicate that both the Wave Guarde and the Navy suit provide excellent microwave shielding, but their flammability constitutes a hazard. The tests indicated that the Invascreen suit did not have uniform attenuation for vertical and horizontal polarized fields. Although it is a well-designed suit, the material does not allow for the circulation of air. Therefore, it would be uncomfortable to wear, especially in a warm and humid environment.

For two years, Milliken & Company has been working on a material which is a hybrid of metal and Normex III (armide, a long-chain synthetic polyamide) fibers. This material is fire retardant, provides good ventilation, and can be washed up to 25 times. Our tests show that the fabric has 35 to 40 dB attenuation for the frequency range of 1.5 to 11 GHz and 28 to 35 dB for the frequency range of 0.65 to 0.115 GHz.

Comparing the attenuations of the Milliken/Body Guard suit at 915 MHz (Fig. 5) and 2450 MHz (Fig. 6) to that of the U.S. Navy suit (Table IX), it is clearly demonstrated that the Navy suit has better microwave protection. This superiority is due both to the high attenuation of the material (Table I) and the complete integration of the parts of the suit (both gloves and boots are continuous parts of the suit). This design was considered but the Milliken and Body Guard companies decided to leave the hands and feet free and uncovered in consideration of practicality in the field, for handling tools and climbing towers.

In conclusion, our tests indicate that the suit made by Milliken & Company and Body Guard, a division of Lion Uniform, can provide good protection for microwave frequencies above 650 MHz. More work is needed, however, to develop a suit suitable for protecting workers from high radiation levels at broadcasting (VHF) and shortwave (HF) frequencies.

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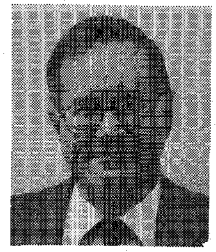

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