RADIOFREQUENCY ELECTROMAGNETIC LEAKAGE FIELDS
FROM PLASTIC WELDING MACHINES.
Measurements and reducing measures.

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ABSTRACT

Operators of unshielded plastic welding machines are often exposed to radiofrequency (RF) electromagnetic leakage fields that substantially exceed all present occupational standards. Measurements show that the Swedish ceiling values ($S_E = S_H = 250 \text{ W/m}^2$) in many cases are exceeded at distances up to 1 meter from the electrode. To reduce the stray fields to an acceptable level at the location of the operator RF field suppression devices should be fitted to the machine.

We have studied the strength and the extent of the RF leakage field under various operating conditions and also investigated different methods for reducing the leakage field. The following measurements have been performed: E- and H-field strengths as a function of distance from the electrode, and as a function of load/tuning; the time dependence of $|E|^2$ for various combinations of tuning and welding times producing a welding seam with the same strength; isopower density curves for $S_E$ and $S_H = 250 \text{ W/m}^2$ with different types of RF emission control devices fitted to the machine; the RF voltage between the electrode and the welding table and the RF voltage on the machine casing.

By decreasing the RF power and increasing the welding time the field strengths at the location of the operator can be reduced to levels below the ceiling values.

The RF voltage between the electrode and the welding table ranged from 800 V up to 2100 V for the different plastic material that was welded. The RF voltage on certain parts on the chassis could be as high as 200 V. In order to reduce these voltages and the stray fields the mac-
hine should be equipped with a "large capacitive shield" in cases where this is possible.

INTRODUCTION

Many occupational and trade groups are working in the vicinity of devices that at the position of the operator produce radiofrequency (RF) leakage fields well in excess of all existing exposure standards. These devices include, for instance, glue dryers, induction heaters, and plastic welding machines. In the plastic industry the latter are employed to make a wide assortment of plastic or plastic-covered products including oil booms, tarpaulins, truck covers, rain and protective clothes, and many other items.

The plastic welding machine is the most common RF heat production device. The RF output power ranges from a few kilowatt (kW) to several tens of kW. The frequency most commonly used is 27.12 MHz. The plastic material to be welded is placed between the electrode/welding tool and the welding table. The electrode is pneumatically pressed onto the table. During the welding process an RF voltage is applied between the electrode and welding table. The RF energy produces a rapid heating of the plastic material, thereby fusing the layers together. After a short time period for cooling, the welded plastic or plastic fabric is removed. The entire operation cycle lasts from 0.5 to approximately 10 s depending on the size and the thickness of the material to be welded.

When the electrode system is unshielded and high RF output power is used, strong E-fields are often found in the vicinity of the electrode.
and strong H-fields surround the RF power strip. Measurements (Conover et al., 1977; 1980; Ruggera, 1977; Hietanen et al., 1979; Hansson Mild, 1980; Stuchly et al., 1980; Cox et al., 1981; Hannevik and Saxebøl, 1983)) have shown that operators of open plastic welding machines often are exposed to E- and H-fields of high strength when working close to the electrode. Parts of the body can be exposed to field strengths that substantially exceed all existing standards.

The protective measure normally undertaken is to retreat the operator from the RF emitting devices to a distance where the leakage field is reduced to an acceptable level. However, the operators often tend to neglect such safety distances since the RF energy penetrates the skin without activating the heat sensors, thus leading to a false sense of security.

Total shielding of the electrode system using box enclosures is possible when the products manufactured are small. Unfortunately, this technique is impracticable for many of the other processes presently being carried out.

The present study was undertaken to find various means for reducing the RF emission, thereby reducing the exposure of the operators working close to open plastic welding machines. The leakage field strengths were measured as a function of electrode size, tuning, welding time, number of layers and thickness of the plastic fabric to be welded.

RF field suppression devices such as a strip for return currents and "large capacitive shielding" were attached to the electrode system. The latter is a device that reduces the impedance of the return path for the RF current. These measures were then evaluated on the background
of the previous data from the unshielded machine.

MATERIAL AND METHODS

A small unshielded plastic welding machine (3 kW RF output power) was placed in the laboratory. The distance between the machine and the nearest wall was greater than 1 m.

A schematic diagram of the construction of the tool circuit is shown in Fig. 1. Mechanically it consists of a coil and an adjustable plate capacitor connected through a strip conductor to the electrode. The circuit is unbalanced and inductively to the anode circuit of the RF oscillator. One of the coil terminals is connected to the 50 Hz AC mains ground inside the machine casing.

The RF generator circuit is commonly tuned to 27.12 MHz in the Industrial-Scientific-Medical band, while the tool circuit is tuned to a natural resonance frequency of approximately 29 MHz.

The RF output power is controlled by changing the resonance frequency of the tool circuit. Higher power is obtained by decreasing the frequency difference between the two circuits. This is done by changing the capacitance of the adjustable capacitor in the tool circuit, i.e. tuning. The settings of the tuning is visually given with a scale extending from 0-10.

To reduce the RF voltage in the vicinity of the electrode, and thereby reduce the leakage field strength, a conductor with low impedance must be connected between the welding table (A) and an area on the casing where the RF voltage is lower. This type of device is commonly called
"large capacitive shielding", see further Fig. 2.

Plastic welding machines designed for one phase AC power usually produce RF output powers less than about 3 kW. The RF voltage is then amplitude modulated (AM) with 100 Hz, because the AC mains voltage after high-voltage transformation is full-wave rectified and applied unfiltered to the anode of the RF power tube. If the machine is connected to three phase AC mains the modulation depth can in most cases be neglected.

The field strengths were measured with a Holaday HI-3002 isotropic broadband meter (Holaday Industries, Inc.). This instrument gives the readings in (field strength units)$^2$ and to facilitate comparison between E- and H-fields the equivalent power density value was calculated according to the formulas $S_E = \frac{E^2}{377}$ and $S_H = 377 H^2$ W/m$^2$.

The probe was attached to a long plexiglass rod connected to a movable, rigid, camera support. The distance between the probe and the nearest metallic part of the camera support was 1 meter, thus ensuring that the measurements were performed in an undistorted RF field.

To locate the probe in a reproducible way at an arbitrary point in front of the machine, the measurement system also included two lasers, each of which were placed on a vertically adjustable support placed on a carrier moving on a rail. One laser moved parallel to the machine (y-direction), and the other in front of and transverse (x-direction) to the machine. One laser was equipped with an optical device diverging the beam to a plane. The probe was placed at the point of intersection between the beam and the plane. The height was measured with a
ruler and the x-and y-positions read on scales near the carriers. With this system the positioning accuracy was estimated to ±0.5 cm and, thus, such that errors caused by false probe positions can be disregarded.

The quality and the strength of a welding seam depends on a variety of adjustable parameters such as RF output power and welding time. In order to control as many of these parameters as possible the machine was adjusted to produce a welding seam of the same strength after shift of electrodes, attachment of strips for return current or "large capacitive shielding". The electrode was always allowed to reach operating temperature before the measurements were taken. The strength of the welding seam was controlled by visual inspection.

Throughout all experiments the press force was kept constant. This is not a critical parameter but optimum welding results are obtained only within certain limits (Abele, 1973).

**Isopower density curves**

To find the extent of the leakage fields near an unshielded machine under various operating conditions and with different types of RF emission suppression devices attached to the electrode system, the following measurements were taken:

The E- and H-field strengths were measured in a cubic lattice pattern with 0.1 m distance between the measurement points. From these points curves for $S_E$ and $S_H = 250 \text{ W/m}^2$ (equal to the Swedish ceiling value and also the newly proposed Food and Drug Administration, (FDA, 1984) guideline in the United States) have been interpolated for eve-
ry plane. By compiling these isopower density curves three dimensional like drawings of the leakage fields were obtained.

Conover et al. (1980) found that 70% of the plastic welding machines had a duty cycle lower than 0.2. Since the Swedish 6-minutes average standard value is 50 W/m², the ceiling value thus determines the minimum allowed distance to the electrode.

**RF voltage measurements**

Measurements of the voltage between the electrode and the welding table and the voltage on the machine casing were accomplished with a Hewlett Packard voltmeter, type 410C, equipped with a capacitive voltage divider, type 1104A.

**The relative E-field strength in the vicinity of the electrode**

In order to determine the relative strength and the direction of the E-field in front of the electrode, a dipole antenna connected to an amplifier was used. The dipole antenna indicates the field strength in one dimension. Since the probe has a wide dynamic range, very strong E-fields could be measured.

The measurements were performed in the symmetry plane in front of the machine, where the E-component parallel with the electrode was zero. The same method was used to study the direction and the relative strength of the E-field in the area between the strip for return current, the "large capacitive shielding", the welding table and the wall of the RF generator.
RESULTS

Resonance frequency

Fig. 3 shows the resonance frequency of the tool circuit measured with a grid-dip meter as a function of the settings of the adjustable capacitor, i.e. for different tunings.

The resonance frequency was measured both before and after the welding process. With 2 layers of PVC-coated plastic fabric the frequency decreased 0.2 - 0.5 MHz after welding.

The strength of the leakage fields is proportional to the RF output power and thus is a function of the tuning, as shown in Fig. 4.

The time dependence of the leakage field strength

The leakage field strength changes during the welding process. After a rapid rise to an initial value, the E-field strength slowly rises during the welding period to a maximum value. In Fig. 5 the time dependence for two different settings of the tuning is shown. The time delay in the beginning and at the end depends on the time constant of the recorder used. The areas under the curves are approximately equal, indicating that the amount of energy needed in both cases is the same. A welding seam with the same strength can thus be produced with either a short welding time and a high RF output power or a longer welding time combined with a lower RF output. In the latter case the leakage field strength is considerably reduced.

Distance dependence
The field strengths decrease very rapidly with distance from the electrode. In our measurements a $1/r^2$ dependence was found, Fig. 6. The distance dependence was found to not vary with the RF output power.

**RF voltage measurements**

The voltage measurements were done during welding of two layers of a polyvinylchloride fabric with a total weight of 600 g/m$^2$. A 29 cm bar electrode with a cross section of 56 cm$^2$ was used, and the welding time was chosen to be 5 s. The tuning was set at 7.0 for producing the best seam. The time dependence of the RF voltage is the same as that shown for the E-field, see Fig. 5. During the welding process a voltage of 200 V was measured on the control panel in the upper front of the machine. On the front of the welding table and on the lower part of the front of the casing the highest voltage found was 40 V. At the foot contact the voltage was 15 V.

When the "large capacitive shielding" was mounted on the electrode system the potential on the upper part of the machine decreased to 45 V. The voltage on the welding table was 15 V, and on the lower part of the machine and on the foot contact the voltage was not measurable.

As a consequence of the high voltage on the upper front part of the machine case the isopower density curves (see Figs. 7 to 10) extend further out from the machine. When the "large capacitive shielding" was fitted behind the electrode, the voltage on all machine parts was reduced and the isopower density curves are closer to the electrode. The hazardous area ($S_E$ or/and $S_H > 250 \, W/m^2$) is then restrained.
to be well within the area of the welding table.

In order to examine how the tension between the electrode and the welding table depends on various material properties, measurements were done when PVC-coated fabric of various total weight and type of basic fabric were welded. The machine was equipped with a bar electrode - 45 cm long and with a cross-section of 50 cm². The welding time was set to 5 s. The tuning was chosen such that a good seam was produced during the welding process. In Table 1 the various materials, tunings, and the measured RF voltage are given.

The voltage ranged from 800 V to 2100 V depending on the type of PVC-coated fabric to be welded. The leakage field strength is approximately proportional to the measured voltage. Thus, $S_E$ and $S_H$ both can change 6 to 7 times merely by a change of the PVC coated fabric to be welded.

**Direction of the E-field in vicinity of the electrode**

The E-field lines emanate radially from the electrode surface, and the highest field strength was found in the area between the electrode and the welding table. Outside the welding table the directions are more or less vertical. When the "large capacitive shielding" is attached to the machine the field strength in front of the machine is considerably reduced. In order to understand how this shielding can serve as an RF field suppressing device, measurements of the directions and the relative strength of the E-field between the electrode and the generator wall were done. The measurements showed that the E-field was converging to a point on the generator wall 12-15 cm above the welding table cf Fig. 11. This point thus had the lowest RF voltage in this area.
DISCUSSION

RF voltage

Measurements in industrial environments and the laboratory tests reported on here show that the machine casing exhibits an RF voltage during the welding process. This causes stray fields, and furthermore if the operator comes in contact with the metal structure of the machine, RF burns may occur. To avoid direct contact, handles and other control units are made out of insulating material. However, these safety devices do not in any sense lower the RF leakage field strength.

In order to reduce the exposure of the operator, it is absolutely necessary that the RF voltage on the machine casing be reduced. One of the best devices constructed and manufactured for this purpose is the "large capacitive shielding". The best result is achieved if both the welding table and the control panel are properly RF grounded.

Near-field

The isopower density curves for \( S_E \) and \( S_H \) as shown in Fig. 7 to 10 are not identical. This is expected since this is a near-field exposure situation. It is therefore of great importance to measure both the E- and H-field when occupational hazard assessments are done.

Furthermore, it is to be observed that a universal hazardous area (\( S_E \) and/or \( S_H > 250 \text{ W/m}^2 \)) around the machine cannot be given, because the operating conditions often vary for this type of machine. The isopower density curves shown illustrate the hazardous area when
the machine is producing a welding seam on two layers of PVC-fabric with a total weight of 600 g/m², and a welding time of 5.0 s. If any of these parameters are changed the hazardous area will be changed.

**Time dependence of the leakage field strength**

In order to reduce the leakage field strength a lower RF output power in combination with a longer welding time can be used. However, since approximately the same amount of energy is needed to produce a welding seam in the various cases, this procedure does not lower the time averaged exposure level - only the ceiling value is lowered.

In many applications a short welding time in combination with a high RF output power is used. Shorter times than 1 s often cause errors in the measurement because the time constant of commercial RF meters is about 1 s. The readings thus have a tendency to be too low. If a maximum value is wanted, some instruments have a peak hold function, which may be used in these situations.

**AM-modulation**

Induction heaters, short-wave diathermy apparatus and plastic welding machines connected to single phase AC mains often generate leakage fields that are 100% AM-modulated. It is important to observe the type of modulation used: for two reasons the first is from a calibration point of view and the second is biologically related.

Many of the RF meters are equipped with a diode detector, which is peak sensitive. If an AM-modulated field is measured with such an instrument the readings often will be too high. To correct for this,
the meter must be calibrated for the actual type of modulation.

The other reason for observing the AM-modulation is the fact that the biological effects of the RF exposure will not necessarily be the same for CW and AM-modulated signals (Adey, 1981).

Field strength reduction with a "large capacitive shielding"

According to Figs. 9 and 10 the E- and H-field strengths were reduced when the "large capacitive shielding" was connected to the electrode system. Voltage measurements on the machine casing showed that the voltage on the chassis was also reduced. Most unshielded plastic welding machines have a voltage on the machine casing during the welding process, since the electrode system is unshielded and the machine casing is used as a conductor for the return current.

During the welding process the return current from the welding table will be conducted via the casing towards the point of the lowest RF voltage located in the rear part of the machine. Although a good direct coupling between these points prevails, the tool circuit will be inductively and capacitively charged. The voltage on the machine casing is thus directly depending on the voltage on the electrode.

The total impedance of this path depends on resistance of the fabric layers and, hence, the area of the "large capacitive shielding" and the thickness of the layers. Large contact area and thin fabric layers will give a low resistance. The inductance of the strips for return current is low because these are bent only half a turn. In order to increase the capacitive coupling between the welding table and the "large capacitive shielding" the contact area can be increased or the
distance between the welding table and the shielding electrode can be decreased. If the area of the latter is about 4-5 times larger than the area of the welding electrode, no burning or branding of the plastic fabric will result from the return current.

The "large capacitive shielding" is controlled by pneumatic pistons and can easily be fitted to older types of machines. Plastic welding machines manufactured today are often equipped with this type of RF emission suppressing device. The "large capacitive shielding" will work properly if the shielding electrode is placed within a few cm from the welding electrode tool. If the distance is too small shorting by sparks can result, which damage both the electrode and the manufactured product. It is important that the passive electrode is pressed onto the welding table in order to get as high a capacitive coupling as possible. Experiments showed that the coupling decreases very rapidly with increasing distance between the passive electrode and the welding table.

Experiments showed that the device worked satisfactory for a total thickness of material less than 2 mm. When tarpaulins and truck covers manufactured with 2-3 layers of PVC-fabric are welded, the "large capacitive shielding" works properly and causes no obstacle to the working process.

**Coupling between the operator and the leakage field**

Even if measurements of leakage field strength from two different types of plastic welding machines would give the same readings, this does not mean that the absorbed RF energy by the two operators will be the same. The specific absorption rate (SAR) depends among other
things on the field direction and grounding of the operator. Gandhi (1980) showed that the resonance frequency for an ungrounded person is 70-80 MHz for a plane wave incident with the E-field component parallel to the body. If the operator is grounded the resonance frequency is lowered to approximately 30 MHz.

Grønhaug and Busmundrud (1982) showed that the RF current in the legs is 9 mA per V/m for a grounded person exposed to a 27 MHz E-field parallel to the body. A field strength of 300 V/m (the Swedish ceiling value) at resonance frequency will thus give rise to an RF current in the leg of the operator of 2.7 A.

In order to reduce the effect of the RF exposure the work place should be designed such that only a minor part of the body is parallel to the field direction. Furthermore it is very important that the operator not be RF grounded during the welding process. This can be provided by an insulating boarding with a height of 0.1-0.2 m placed on an RF conducting floor or a floor holding reinforcing irons in the concrete.

Tables for material storage and other outfits should be constructed from nonconducting material. Steel constructions will have raised RF voltages because these will serve as antennas to the E-field. The potential hazard of local burn injuries then exists when the operator touches such equipment.

The H-field component of the RF near-field is mainly generated by the current loop formed by the RF power strip, the electrode, the welding table and the generator wall. The coupling factor depends on how large the part of the body is that is oriented perpendicular to the field. A large area will give a high coupling factor, thereby inducing strong
currents in the exposed part of the body. The H-field induces eddy currents in metal objects, which is still another reason that the outfit constructions ought to be made of nonconducting material.

**Accident risks**

Ciano et al. (1981) report on an accident with grave consequences. An operator accidently got her hand tightly squeezed between the welding table and the electrode, which was subsequently activated with 15 kW output RF power during 2 s. When visiting a physician the operator complained of pains in her hand. A closer examination showed that the injuries were of such proportions that an amputation was necessary. Similar cases has recently occurred in Norway and in Japan.

**Final comments**

The measurements done in this study show that it is a very complex task to properly survey the RF leakage fields from plastic welding machines from an occupational hazard point of view. Considerations must be taken as to the size of the electrode, the duty cycle of the welding process, the force acting on the electrode, the number of fabric layers, the output power, etc. Furthermore, consideration must be given to the location of the machine in the factory, the nearness to other machines, and if there are RF grounded floors or reinforced concrete walls. The way the operator works during the welding process is also of great importance.

In order to do proper measurements a standardized practice is desirable. This procedure would also be of interest to the machine manufacturers when doing control measurements before delivery.
REFERENCES


Food and Drug Administration (FDA) (1984) "Guideline for Exposure of
Personal to Stray Emissions from Radiofrequency (RF) Dielectric Sealers and Heaters. Federal Register 49, no 198, p. 39992-39993.


LEGENDS

Figure 1. Electrical diagram of a plastic welding machine, which illustrates how the three main parts, the power unit, the RF generator and the inductively coupled tool circuit, are interconnected.

Figure 2. Electrical diagram, which illustrates how the "large capacitive shielding" is connected to the electrode system. The impedance of the shield, $Z_{sh}$, is lower than the impedance between A and B, $Z_1$. Thus, B has a lower voltage than A.

Figure 3. The resonance frequency of the tool circuit as a function of the tuning of plastic fabric (total weight 600 g/m$^2$), 2 and 6 layers, respectively. Welding seams of the best quality are produced when using tuning marked with asterisk. The dashed line marks the generator frequency 27.12 MHz. The length of the electrode is 29 cm.

Figure 4. The squared electric field strength ($E^2$) as a function of the tuning for 2, 3 and 4 layers of plastic fabric (total weight 600 g/m$^2$), respectively. The point of measurement is 10 cm above the welding table and 30 cm in front of a 29 cm long bar electrode. Welding seams of the best quality are produced when using tuning marked with asterisk.

Figure 5. The time dependence of the squared electric field strength ($E^2$) for two combinations of welding time and tuning when producing welding seams of the same quality.
A) Tuning 7.5, welding time 2.0 s.
B) Tuning 6.6, welding time 5.0 s.
The area beneath each curve is approximately equal, which means that the same amount of energy is needed to produce the welding seams.

**Figure 6.** The squared H- and E-field as a function of the distance from the electrode for three different tunings measured in front of the machine at the welding table level. The welding time is 5 s. The length of the electrode is 29 cm.

\[ H^2 \]
\[ E^2 \]

**Figure 7.** Isopower density curves for \( S_E = 250 \text{ W/m}^2 \) and \( S_H = 250 \text{ W/m}^2 \). Strips for return current excluded.
Length of the electrode 29 cm. Welding time 5 s, tuning 7.0.

**Figure 8.** Isopower density curves for \( S_E = 250 \text{ W/m}^2 \) and \( S_H = 250 \text{ W/m}^2 \).
Strips for return current included.
Length of the electrode 29 cm. Welding time 5 s, tuning 7.0.

**Figure 9.** Isopower density curves for \( S_E = 250 \text{ W/m}^2 \) and \( S_H = 250 \text{ W/m}^2 \).
Strips for return current included.
Length of the electrode 29 cm. Welding time 5 s, tuning 7.0. The "large capacitive shielding" attached in front of the electrode (5.0, 7.0)

**Figure 10.** Isopower density curves for \( S_E = 250 \text{ W/m}^2 \) and \( S_H = 250 \text{ W/m}^2 \).
Strips for return current included.
Length of the electrode 29 cm. Welding time 5 s, tuning 7.0.
The "large capacitive shielding" attached behind the electrode.

**Figure 11.** The relative strength and the direction of the E-field in front of the electrode. The width of the arrows corresponds to the relative field strength.

A = Support for electrode heater
B = Electrode
C = Welding table
TABLE 1

<table>
<thead>
<tr>
<th>PVC-coated fabric</th>
<th>Tuning</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trade mark: Almedahls</td>
<td></td>
<td></td>
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</tbody>
</table>

**Quality index figure 50004.**

Total weight 600 g/m², basic fabric 8.4 900 V
940 dtex polyamid - weight 190 g/m²
(Special weave). Coated with softened PVC, standard.

**Quality index figure 51100.**

Total weight 700 g/m², basic fabric 8.4 1280 V
1100 dtex polyamid - weight 210 g/m²
(Special weave). Coated with softened PVC, standard.
The front side lacquered with acrylate.

**Quality index figure 52221.**

Total weight 1350 g/m², basic fabric 9.3 2100 V*
1670 dtex polyester-weight 525 g/m²
(3/3 panama weave).
Coated with softened PVC, flame-resistant.

Trademark: DURATEX A/S

**Quality index figure 0607907.**

Total weight 500 g/m², basic fabric 8.3 920 V
940 dtex nylon - weight 175 g/m² (plain cord cloth texture) Coated with softened PVC.
Quality index figure 0608307.
Total weight 700 g/m², basic fabric 8.3 800 V
40 denier nylon -weight 185 g/m² (1/2 panama weave)
Coated with softened PVC.

Quality index figure 0709007.
Total weight 600 g/m², basic fabric 8.6 1200 V
1100 denier polyester weight 200 g/m² (plain cord cloth texture) Coated with softened PVC.

Trade mark: BECKER LAY-TECH

Galorex DG O60 ----- 8.3 870 V
634550H DG 313 ----- 8.6 1320 V

*) Welding time 5.5 s.
Fig 3

- Tuning
- Frequency (MHz)
- 27.12 MHz
- 6 layers
- 2 layers

- 1 2 3 4 5 6 7 8 9 10
Fig 4

![Graph showing $E^2$ vs. Tuning for 2, 3, and 4 layers.](image)

Fig 5

![Graph showing $E^2$ vs. Time for points A and B.](image)
Fig 6