OCCUPATIONAL SAFETY 71 AND HEALTH SERIES

SAFETY IN THE USE OF RADIOFREQUENCY DIELECTRIC HEATERS AND SEALERS

A PRACTICAL GUIDE

Prepared by the International Commission on Non-Ionizing
Radiation Protection in collaboration with the International Labour Organization
and the World Health Organization

INTERNATIONAL LABOUR OFFICE · GENEVA

The International Programme for the Improvement of Working Conditions and Environment (PIACT) was launched by the International Labour Organization in 1976 at the request of the International Labour Conference and after extensive consultations with member States.

PIACT is designed to promote or support action by member States to set and attain definite objectives aiming at "making work more human". The Programme is thus concerned with improving the quality of working life in all its aspects: for example, the prevention of occupational accidents and diseases, a wider application of the principles of ergonomics, the arrangement of working time, the improvement of the content and organization of work and of conditions of work in general, and a greater concern for the human element in the transfer of technology. To achieve these aims, PIACT makes use of and coordinates the traditional means of ILO action, including:

- the preparation and revision of international labour standards;
- operational activities, including the dispatch of multidisciplinary teams to assist member States on request;
- tripartite meetings between representatives of governments, employers and workers, including industrial committees to study the problems facing major industries, regional meetings and meetings of experts;
- action-oriented studies and research; and
- clearing-house activities, especially through the International Occupational Safety and Health Information Centre (CIS) and the Clearing-house for the Dissemination of Information on Conditions of Work.

This publication is the outcome of a PIACT project.

Safety in the use
of radiofrequency dielectric
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Preface

This publication is one of a series of practical guides on occupational hazards arising from non-ionizing radiation (NIR) carried out in collaboration with the International Commission on Non-Ionizing Radiation Protection (ICNIRP)[1] as part of the ILO International Programme for the Improvement of Working Conditions and Environment (PIACT).

The purpose of this book is to provide basic guidance on working conditions and procedures that will lead to higher standards of safety for all personnel engaged in the operation and use of radiofrequency (RF) dielectric heaters and sealers. It is intended in particular for the use of competent authorities, employers and workers, and in general all persons in charge of occupational safety and health.

The following topics are covered: RF and electromagnetic radiation, sources, exposure and energy absorption, RF biological effects, occupational RF exposure standards and guidelines, exposure assessment, control technology, work practices and administrative controls, design and installation considerations, and medical surveillance. Emphasis is placed upon protective measures.

The manuscript was prepared by an ICNIRP working group chaired by Mays L. Swicord and including Stuart Allen, Howard Bassen, David Conover and Robert Curtis. Following comments received from ICNIRP members, it was reviewed in detail during the annual meeting of the ICNIRP in Rockville, Maryland, in June 1995.

The book is the result of an ILO/ICNIRP activity in collaboration with the WHO, and is published by the ILO on behalf of the three organizations. The ILO wishes to thank the ICNIRP, and in particular Dr. Swicord and his working group, for their contribution and cooperation in the preparation of this practical guide on safety in the use of RF heaters and sealers.

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[1] The ICNIRP was established in May 1992, and has responsibility for NIR protection in the same way as the international Commission on Radiological Protection (ICRP) has for ionizing radiation.

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Introduction

This document discusses the technical aspects of developing control technology that may be used to limit exposure of workers to emissions of radiofrequency (RF) electric and magnetic fields from dielectric heaters and sealers (hereafter referred to as RF heaters). RF heaters present the most common source of exposure to excessive RF fields. Protective measures can be and have been implemented to minimize such exposure. This guide provides practical methods to install, design or retrofit this type of equipment which will minimize the user's exposure to RF fields.

Workers in many industrial settings have a false sense of security because their exposure to RF energy has not been properly assessed. The relatively high output power of dielectric heaters and use of unshielded electrodes in many of them can produce relatively high-stray RF fields. It was not until the mid-1970s that monitoring instruments were developed to measure RF exposure accurately. With these instruments, worksite studies were done to evaluate the hazards where RF heaters are used. The results of several surveys (Stuchly et al., 1980; Grandolfo et al., 1983; Bini et al., 1986; Joyner and Bangay, 1983, 1986a, 1986b; Stuchly and Mild, 1987; Conover et al., 1980) have shown that RF heaters produce exposure fields exceeding the limits recommended in various countries and by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Some operators were exposed to over 100 times the guideline levels. Surveys in the United States indicated that 60 per cent of 82 devices measured exposed the operators to levels exceeding those recommended. However, shielding of dielectric heaters and other protective measures can reduce worker exposure to acceptable levels.

Absorption of high levels of RF energy from stray fields can cause localized and whole-body heating, which may result in adverse health effects. Certain tissues, such as the lens of the eye and the male reproductive organs, are heat sensitive. RF-induced heat has also been shown to adversely affect the developing foetus. Hazards to operators can also arise indirectly when contact is made with the metallic parts of the heater. This contact can result in RF burns, which are frequently reported as being very painful, deep seated and slow to heal.

Although work practices and administrative controls can and should be used to reduce worker exposure, the use of shielding is emphasized in this book, as it is more effective, dependable and efficient. Because many applications of dielectric heaters are unique, they will require variations in the shielding design. The information required to design, construct and install the shield is provided in Appendix A. This document should provide a basis for understanding the problems that may be encountered and for determining their solutions. Additional background information is given in the appendices.

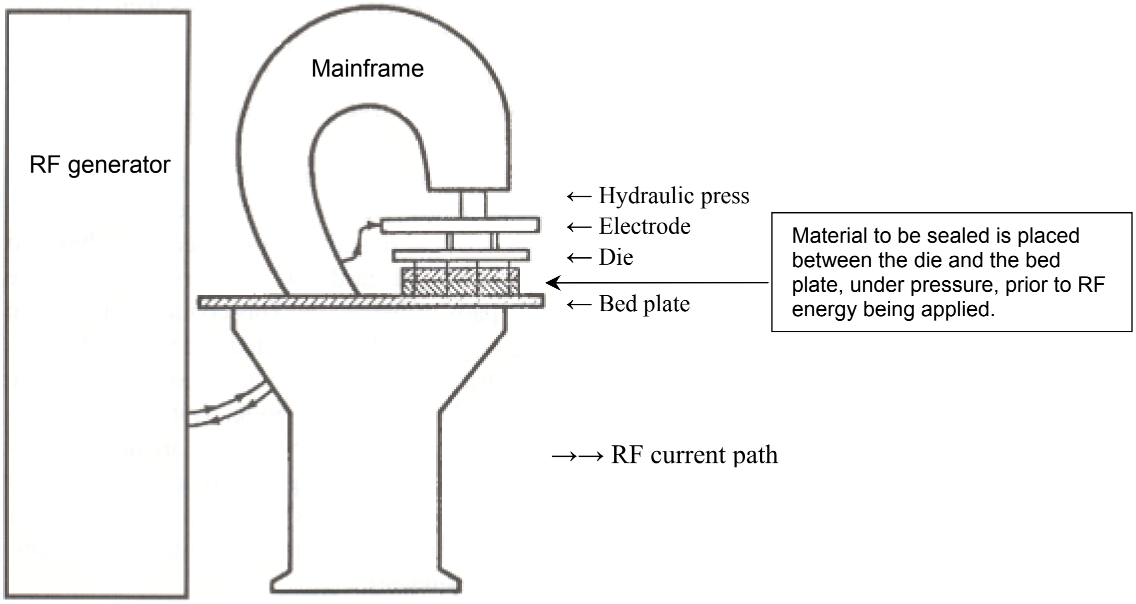
2

Sources

RF heaters are used in many industries to heat, melt or cure dielectric materials. Materials such as plastics, rubber and glue are electrical and thermal insulators; consequently they are difficult to heat using conventional methods. The frequency of operation of RF heaters is in the range 10 MHz to 100 MHz with output powers from less than 1 kW to about 100 kW. This document does not address RF induction heaters that operate at lower frequencies and are used to heat materials which are good conductors of electricity such as metals and crystals.

The most common use of RF heaters is the sealing or welding of polyvinyl chloride (PVC) by applying RF power to PVC materials compressed between two electrodes. The power dissipated per unit volume of dielectric material is proportional to the frequency of the source, the square of the voltage on the electrodes and the dielectric properties of the material. A schematic diagram of an RF sealer is shown in figure 1.

Figure 1. Schematic diagram of a radiofrequency (RF) sealer



Material to be sealed is placed between the die and the bed plate, under pressure, prior to RF energy being applied.

Some examples of the use of RF heaters include:

(a) manufacture of plastic products such as toys, loose-leaf binders, rainwear, waterproof containers, furniture covers and packaging materials;

(b) curing of glue used in the manufacture of wood laminates;

(c) embossing and drying of textiles, paper, plastics and leather; and

(d) curing of materials that include plasticized PVC, wood resins, polyurethane foam, concrete binder materials, rubber tyres and phenolic and other plastic resins.

By international agreement certain frequency bands have been designated for industrial, scientific and medical (ISM) applications (see section 3 for various uses of the electromagnetic spectrum). The frequency restrictions are to prevent interference with communications equipment and do not stem from any considerations related to human exposure to RF fields.

The ISM frequencies often used are:

- 13.56 MHz ± 7 kHz
- 27.12 MHz ± 160 kHz
- 40.68 MHz ± 20 kHz.

The most commonly used frequency for modern equipment is 27.12 MHz but there are many machines in use which operate in the 10-100 MHz bandwidth but outside of the ISM bands. Machines with a nominal ISM operating frequency may also drift outside of the ISM bandwidth during operation. To meet ISM requirements, harmonics of the fundamental frequency must be suppressed and the generator well shielded.

The material processing is accomplished between shaped parallel plate electrodes forming a capacitor. The shape of the applicator electrodes, also called dies, varies with the shape of the product which is being manufactured. Heating of a single load of material is achieved in a relatively short period of time. For instance, 2-3 seconds are typical for a plastic sealing operation, and 1 minute for edge gluing of wood. Dielectric heaters can be divided into two groups on the basis of application (Stuchly et al., 1980):

(1) Devices used in the wood-working industry, referred to as edge glue driers. The edge glue driers have large open frames with long electrodes.

(2) Devices used in the plastics and textile industries. Owing to the differences in general appearance and material feed systems, these devices are further subdivided into four types:

    (a) sewing-machine type: the operators are seated and use independently operated foot or hand controls; the material to be processed is usually loaded manually;

    (b) shuttle tray type: the operators stand in front of and to the side of the weld head; frequently one operator prepares material while the other operator's material is processed;

    (c) turntable type: two or more operators progressively assemble the material to be processed;

    (d) pressure-sealed applicator type: one or two operators stand in front of the unit. There are two trays. The one with the material to be processed is raised to a completely shielded weld head. During this time more material is prepared on the second tray.

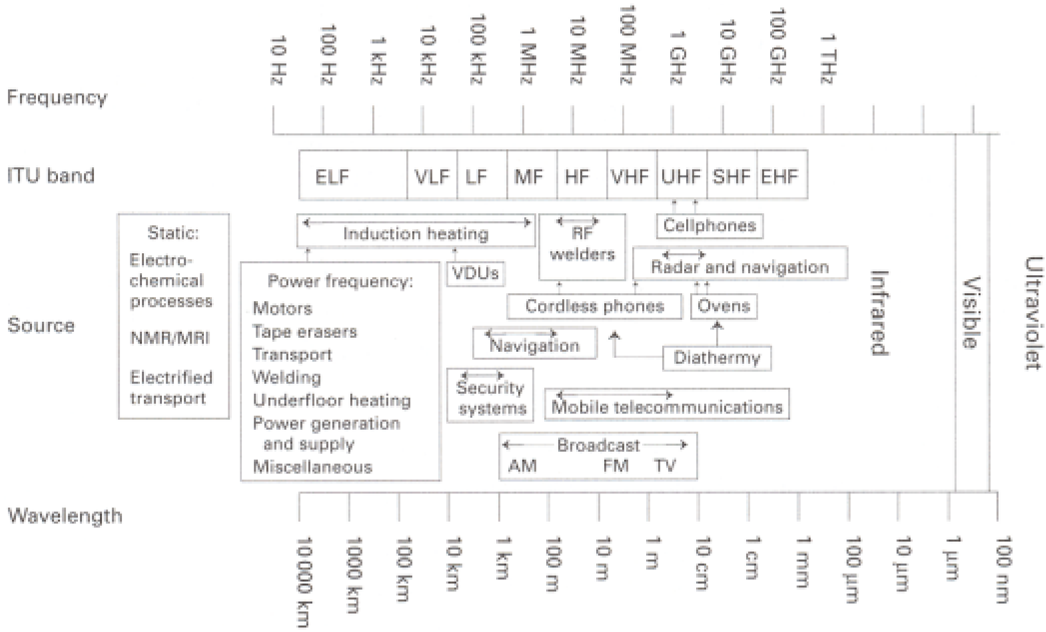
3

Radiofrequency radiation

3.1. Electromagnetic radiation

Electromagnetic radiation (EMR) is the emission of energy in the form of waves transmitted through space as time varying or oscillating electric and magnetic fields. Figure 2 shows the electromagnetic spectrum, with the frequency and location in the spectrum of radiation and field, and typical applications. Radiofrequency radiation is a subset of the electromagnetic spectrum ranging in frequency from 100 kHz to 300 GHz. RF radiation is also often referred to as non-ionizing radiation, although non-ionizing radiation also includes, for example, the infrared and visible spectrums.

Figure 2. The electromagnetic spectrum



The wavelength is the distance between corresponding points of successive waves and the frequency is the number of waves that pass a given point in 1 second. The quantities are related and determine the characteristics of electromagnetic radiation: the shorter the wavelength, the higher the frequency. At a given frequency, the wavelength depends on the velocity of propagation and therefore will also depend on the properties of the medium through which the radiation passes. The wavelength normally quoted is that in a vacuum or air, the difference being insignificant. The linking parameter with frequency is the velocity of light (3×10^8 m/second in air). This relation can be expressed as:

$$\lambda = c/f$$

where: λ = wavelength
c = speed of light
f = frequency.
For example, at 27 MHz the wavelength is 11.1 m.

Electric fields emanate from electric charges and voltages on conductors. Convention dictates that electric fields originate on positive charges and terminate on negative charges. Magnetic fields are generated by moving charges (currents flowing in conducting objects) and encircle the moving charge. The operation of RF heaters will generate both electric and magnetic fields. These primary fields are not technically radiation but are reactive near fields (see EHC 137 for a more complete description of near fields and radiating fields around antennas – UNEP, IRPA and WHO, 1993). However, energy can be coupled from these fields just as energy is coupled from the primary to the secondary winding of a transformer without radiation. These reactive near fields can, in turn, generate radiating fields.

RF heaters are not good antennas because the dimensions of the heater are normally small compared to the wavelength of operation (e.g. 11.1 m at 27 MHz). Therefore, RF heater operators are exposed to the reactive electric and magnetic fields.

Power from RF heaters is generated as a continuous wave (CW) at essentially a single frequency although during the processing cycle the frequency of older machines may change significantly. The electric and magnetic fields oscillate as sine waves and may be amplitude modulated at the power supply frequency.

For any particular RF heater application requiring preparation of the material to be processed, the machine is energized for only part of the total production period. This results in a machine duty factor which is the quotient of the period that the RF power is applied to the total period of a typical operational cycle. The duty factor, D_f, of a machine is given by:

$$D_f = T_e / (T_e + T_o)$$

where: T_e is the period that the machine is energized
and: T_o is the period that the machine is off.

If the machine is energized for 5 seconds followed by a 45-second period with the power off, the duty factor is 5/50 = 0.1. In assessing operator exposure in terms of energy absorption rate (see section 4), the square of the measured electric and magnetic field strengths or the square of the measured induced body current would be multiplied by the duty factor subject to the overriding time averaging restrictions of the exposure guideline.

3.2. Quantities and units of exposure

Electromagnetic radiation has two field components: the electric (*E*) field and the magnetic (*H*) field. The unit of the electric field strength is the volt per metre (V/m), and the unit of magnetic field strength is the ampere per metre (A/m). The magnetic flux density (B) is related to the magnetic field strength by:

$$B = \mu H$$

where μ is the permeability of the medium. The unit of magnetic flux density is the Tesla (T). In non-magnetic materials, which include the human body, μ has the value of $4\pi \times 10^{-7}$ T/(A/m).

At distances greater than a wavelength from the source, the *E*- and *H*-field's have a fixed relationship given by:

$$E/H = Z_o$$

where: E = electric field strength (V/m)
H = magnetic field strength (A/m)
Z_o = impedance of free space, 377 ohms.

This region is called the *far field or radiation field* and the power density (S) or energy flow per unit time through a unit area is determined from the following:

$$S\ (\mathrm{W/m^2=}) = E^2/377 = H^2/377.$$

While power density is often used as the quantity for assessing exposure in the far field, operators of RF heaters are exposed in the near field.

The term *near field* is used to describe the region that is close to the radiation source, generally less than one wavelength. Operator exposures occur well within one wavelength of RF heaters. Thus, heater operators receive near-field exposures. In this region the relative amplitude and direction between the *E*-field and the *H*-field varies with location. Thus a simple measurement of E or H will not determine the power density nor assess the potential hazard. Since the body can couple energy from either of these reactive fields, both E and H must be measured to assess the hazard. Due to the rapid variations of both the electric and magnetic field within the near field zone, the *E*- and *H*-fields must be measured carefully at a number of points in close proximity to the source.

Power density should not be measured to evaluate heater operator exposures. It is not technically correct to use the term power density to describe radiofrequency radiation in the near field of a device. As a result of exposure to fields from RF heaters, currents are induced in the bodies of operators, and measurements of induced currents is a particularly meaningful way of assessing compliance with exposure guidelines. Therefore, a complete assessment of the exposure would be to measure induced currents, as well as electric and magnetic field strengths.

4

Exposure and energy absorption

Unfortunately, no simple relationship exists between exposure fields outside the human body and induced fields within the body which may cause a biological response. Time-varying electric and magnetic fields induce electric fields and corresponding electric currents in people exposed to these fields. The intensities and spatial distribution of induced currents and fields are dependent on various characteristics of the exposure field, the exposure geometry and the exposed person. The exposure field characteristics that play a role include the type of field (electric or magnetic), frequency, polarization, direction and strength. Important characteristics of the exposed person include shape or orientation to the field, and electrical properties of body tissues. Current views are that the biological responses and effects due to exposure to electromagnetic fields depend on the strength of induced currents and fields. Dosimetric techniques have been developed to correlate the induced currents with the external exposure field.

In the 10-100 MHz frequency range, the commonly used dosimetric quantity is the specific absorption rate (SAR). The SAR is defined as "the time derivative of the incremental energy, dW, absorbed by, or dissipated in an incremental mass, dm, contained in a volume element, dV, of a mass density, ρ" (NCRP, 1986). The SAR is most often expressed in units of watts per kilogram (W/kg) and can be averaged over localized regions of tissue or over the whole body mass.

The SAR is related to the induced electric field strength in biological tissue by the electrical properties of the tissues through which the current flows. It is possible to obtain a measure of induced current under certain exposure conditions which enables the SAR to be calculated from knowledge of anatomical cross-sections and the conductivity of the relevant tissues. This can be expressed as:

$$\mathrm{SAR} = \sigma E^2/\rho = J^2/\sigma\rho \ \mathrm{(W/kg)}$$

where: J = current density (A/m^2)
σ = conductivity (S/m)
ρ = density (kg/m^3)

SAR is related also to temperature rise; a direct calculation of the expected temperature rise (ΔT Kelvin) in tissue exposed to RF radiation for a time (t seconds) can be made from the equation:

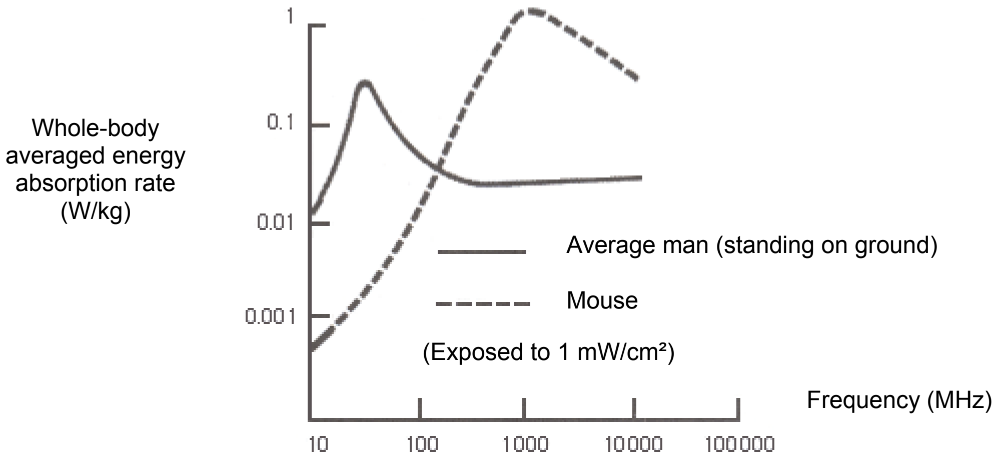
$$\Delta T = (\mathrm{SAR})\ t/\mathrm{C}$$

where C is the heat capacity expressed in J kg^{-1} K^{-1}. This equation, however, does not include terms to account for heat losses via processes such as thermal conduction and convection. The SAR concept has proved to be a useful tool in quantifying the interactions of RF radiation with biological material. It enables comparison of experimentally observed biological effects for various species under various exposure conditions and it provides a means of extrapolating animal data to potential hazards to human beings exposed to RF radiation.

RF dosimetry calculations can be performed for a given configuration approximating the exposed object (an animal, a human being, a part of a human body), and for given exposure conditions. These data have been collected and discussed in the *Radiofrequency Radiation Dosimetry Handbook*, 4th edition (Durney et al., 1978, 1988) and the modelling techniques have subsequently been further developed (Dimbylow, 1988, 1991; Gandhi, 1991).

The absorbed dose rate varies greatly within the body of an exposed person. The concept of wholebody absorption has been developed to express the total quantity of energy deposited in a human being or animal. This wholebody absorption has a maximum value for a given body size and exposure situation, at a certain resonant frequency. Figure 3 illustrates how human and small animal whole-body absorption rates vary with frequency. The whole-body absorption in adult human beings exposed to a uniform RF field is a maximum of 20 to 100 MHz, depending on electrical grounding conditions.

Figure 3. Whole-body averaged energy absorption rate



In contrast to dosimetry results just described for far-field, uniform field exposure conditions, RF heater operators are exposed to near-field non-uniform fields. A limited number of numerical modelling studies have been conducted for RF heater operators receiving near-field exposure that simulates workplace conditions (Allen et al., 1990; Gandhi, 1988; Gandhi and Chen, 1989; Gandhi et al., 1993). A study by Gandhi (1988) shows a strong dependence of ankle and wrist SARs on the operator's hand position relative to the heater. The ankle and wrist SARs were at a minimum with the operator's hands at his or her sides. Ankle and wrist SARs increased as the hands were positioned closer to the heater. Operator ankle SAR increased by 58 per cent at 27.12 MHz and 53 per cent at 40.68 MHz when the operator's hands were extended over the heater applicator plates (compared to when the operator's hands were at his or her sides). Wrist SAR increased 1,472 times at 27.12 MHz and 465 times at 40.68 MHz. Worksite foot and wrist current measurements show the same trends as the numerical modelling data (Allen, 1990; Gandhi, 1988; Williams and Mild, 1991).

Gandhi's data (1988) also show a strong dependence of operator whole-body SAR on operator hand position relative to the heater. Whole-body SAR was at a minimum with the operator's hands at his or her sides. Operator whole-body SAR increased by 57 per cent at 27.12 MHz and 64 per cent at 40.68 MHz when the operator's hands were extended over the heater applicator plates (compared to hands being at the operator's sides). A second modelling study by Chen and Gandhi (1989b) showed the same trends seen in the first study (Gandhi, 1988).

Gandhi et al. (1993) studied the effect of a metallic screen-room enclosure on whole-body and partial-body SARs for an RF heater operator. Heaters and operators are often located inside metallic screen enclosures during heater operation. The screen-room enclosures are used to reduce RF leakage fields which cause interference in RF communication frequency bands used by police and fire-fighters as well as TV and radio stations. In the modelling study (Gandhi et al., 1993), SARs were calculated with and without a metallic screen room enclosing the heater and operator. Operator wholebody SAR increased by 41 per cent at 40.68 MHz when the heater and operator were placed inside a metallic screen room. Operator wrist SAR increased by 162 per cent at 40.68 MHz when heater and operator were placed in the screen room. Likewise, numerous other partial-body SARs increased when the operator and heater were placed inside the screen room. These results are consistent with other numerical modelling research (Kucia-Korniewicz, 1974).

5

Radiofrequency biological effects

The biological effects of exposure to RF and microwave radiation have been studied extensively and have been well reviewed by several national and international bodies (Saunders et al., 1991; UNEP, IRPA and WHO, 1993). The effects are summarized here with reference to data relevant to exposure from RF heaters. Currently, however, there are few data on the effects of exposure to RF in the range of 10 to 100 MHz. Most studies have been carried out using higher frequency radiation.

5.1. Whole-body response

Most of the biological effects of acute exposure to RF electromagnetic fields are consistent with responses to induced heating, resulting either in a body temperature rise of about 1 °C or more, or in a thermoregulatory response. Most responses have been reported at specific absorption rates (SARs) above approximately 1-2 W/kg in different animal species exposed under various environmental conditions. The animal (particularly primate) data indicate the types of response that are likely to occur in humans subjected to a sufficient heat load. However, direct quantitative extrapolation to humans is difficult, given species differences in responses in general, and in thermoregulatory ability in particular.

The most sensitive animal responses to heat loads are thermoregulatory adjustments, such as reduced metabolic heat production and vasodilation, with thresholds ranging between about 0.5 and 5 W/kg, depending on environmental conditions. These reactions form part of the natural repertoire of thermoregulatory responses that serve to maintain normal body temperatures.

Transient effects seen in exposed animals, which are consistent with responses to increases in body temperature of 1 °C or more (and/or SARs in excess of about 2 W/kg in primates and rats), include reduced performance of learned tasks and increased plasma corticosteroid levels. Other heat-related phenomena include effects on the blood-forming and immune systems, possibly due to elevated corticosteroid levels. The most consistent effects observed are reduced levels of circulating lymphocytes, increased levels of neutrophils and altered natural killer cell and macrophage function. An increase in the primary antibody response of B lymphocytes has also been reported. Cardiovascular changes consistent with increased heat load, such as an increased heart rate and cardiac output, have been observed, together with a reduction in the effect of drugs, such as barbiturates, the action of which can be altered by circulatory changes.

There are relatively few studies that directly address exposures of humans to RF fields. When human volunteers are exposed at a frequency of 64 MHz to SARs of 4 W/kg for 15-20 minutes, their average body temperature rises by 0.2 to 0.5 °C, which is quite acceptable in healthy people (Shellock, 1989). The impact that this added thermal load would have on thermoregulatory impaired individuals in environments that minimize the perspiration-based cooling mechanisms is not known.

5.2. Localized responses

5.2.1. Reproductive system

Testicular temperatures are normally several degrees below body temperature, and it has been known for some time that male germ cells are sensitive to elevated testicular temperatures. In humans, it has been reported that repeated heating of the testis by 3 to 5 °C will result in a decreased sperm count persisting for several weeks. Three studies in humans found adverse male reproductive effects for subjects who received microwave exposure: Barron et al. (1959) reported childlessness in male personnel exposed to microwave radiation. Lancranjan et al. (1975) found significant decreases in sperm count and in the number of normal, motile sperms in men who received microwave exposure. Weyandt (1992) reported significantly lower sperm counts for men receiving microwave exposure in artillery and radar groups.

Lebowitz and Johnson (1987) and Berman (1990) have reported transient infertility in rats after chronic exposure at about 6 W/kg, sufficient to raise body temperature by about 1.5 °C and testicular temperatures by about 3.5 °C. This was considered to be the minimum exposure required to cause a slight loss of male fertility in rats. Male fertility is therefore unlikely to be affected by longterm exposure to levels insufficient to raise the temperature of the body and testes.

5.2.2. Teratogenic effects

The embryo and foetus may be particularly sensitive to RF-induced heating since heat loss pathways that are available to adult mammals are denied to the foetus. Heat loss from the foetus to the mother occurs over a temperature gradient of about 0.5 °C. Foetal temperatures may rise more than that of the mother during heat stress severe enough to reduce uterine blood flow (Young, 1990). Heat has been shown to be teratogenic in various animal species, including primates, and has been associated with miscarriages, as well as with central nervous system and facial defects in children whose mothers developed moderate to severe hyperthermia, especially during the first trimester of pregnancy (Cocozza et al., 1960; Hofmann and Dietzel, 1966; Imrie, 1971; Pleet et al., 1981; Marchese, 1953; Minecki, 1964; Rubin and Erdman, 1959). Ouellet-Hellstrom and Stewart (1993) have shown an increased risk of miscarriage among female physical therapists who were exposed to microwave (915 and 2,450 MHz) radiation while operating microwave diathermy units. For female physical therapists operating shortwave (27 MHz) diathermy units, Larsen et al. (1991) found an altered gender ratio (fewer boys) and low birthweight for male newborns. The altered gender ratio showed an exposure-response pattern. This study is particularly relevant here since the shortwave diathermy units operate at a frequency (27 MHz) commonly used by RF heaters.

A number of animal studies have exposed rats to RF and microwave radiation (including 27 MHz radiation sufficient to raise maternal core temperatures by 1 to 2.5 °C and have reported adverse effects, such as growth retardation and postnatal changes in behaviour, with more severe effects such as embryo and foetal death and developmental abnormalities occurring at higher maternal temperatures (Dietzel, 1975; Lary et al., 1982, 1983, 1986; Lary and Conover, 1987; O'Connor, 1980). Most human and animal data, however, indicate that implantation and the development of the embryo and foetus are unlikely to be affected by exposures that increase maternal body temperature by less than 1 °C. In summary, since RF heater operators can have exposures substantially exceeding standards (which may result in appreciable body heating) teratogenic effects may occur in these operators.

5.2.3. Effects on the eye

The lens of the eye is regarded as potentially sensitive to heating because of its lack of a blood supply (and consequent limited cooling ability) and its tendency to accumulate damage and cellular debris. In anaesthetized rabbits, high local temperatures induced by exposure of the head to microwaves have been shown to induce cataracts. The threshold temperature in the lens for cataract induction in rabbits exposed for 2 to 3 hours is between about 41 and 43 °C; the corresponding local SAR was about 100 to 140 W/kg. The threshold for cataract induction resulting from chronic exposure to RF radiation has not been determined. Cataracts were not induced in rabbits exposed at 100 W/m^2 for six months, or in primates exposed at 1.5 kW/m^2 for over three months. The most effective frequencies for acute injury to the eye appear to lie between about 1 and 10 GHz.

A number of studies have investigated the occurrence of cataracts or lens opacities in humans in relation to RF exposure; in most studies it was related to military radar situations. In one of them (Cleary and Pasternack, 1966), a correlation was found between lens opacities and the exposure score. The latter was constructed of several descriptive items of RF exposure, including cutaneous heating. The other studies (Cleary et al., 1965; Siekierzynski et al. 1974; Odland et al., 1973; Shacklett et al., 1975; Appleton et al., 1975) failed to provide indications of an association between cataracts or lens opacities and RF exposure. Exposure to the RF fields of between 10 and 100 MHz associated with RF heaters is considered unlikely to produce cataracts in heater operators.

Eye irritation (conjunctivitis) has been reported for Swedish and Italian heater operators (Kolmodin-Hedman et al., 1988; Bini et al., 1986). Conjunctivitis was confirmed in Swedish heater operators by an ophthalmologist (Kolmodin-Hedman et al., 1988). Eye irritation complaints were highest in Swedish operators receiving the highest RF exposure. However, it was noted that their work situation also included handling materials known to be eye irritants. Deleterious effects of radiofrequency fields on the cornea and retina of monkeys have been reported (Kues and Monahan, 1992). Exposures to 2.45 GHz fields for several hours induced these effects after two days for local close rates of 2.6 W/kg.

5.2.4. *RF burns and operator hand numbness*

RF burns can occur when body tissues come into contact with metallic surfaces of the heater (Kolmodin-Hedman and Mild, 1985; Kolmodin-Hedman et al., 1988; Mild et al., 1987). Local current densities can be sufficiently high to cause localized RF burns which are frequently reported as being very painful, deep seated and slow to heal (Ciano et al., 1981; Kitamaya and Tesukada, 1983; Kolmodin-Hedman et al., 1988). Hand numbness and reduced two-point discrimination (2-PD) ability of heater operators were seen in a Swedish study (Kolmodin-Hedman et al., 1988). There was a dose-response relationship between exposure and numbness. Neurological testing (EEG) was conducted for operators with hand numbness and diminished 2-PD. These tests indicated neurological disturbances (carpal tunnel syndrome and peripheral effects) in some operators. Similar results concerning hand numbness have been reported by Bini et al., 1986.

5.2.5. *Carcinogenesis*

The possibility that exposure to RF fields might influence the process of carcinogenesis is of particular concern. So far, there is no evidence that irradiation does have an effect, but there is a need for further studies. Many experimental data indicate that RF fields are not mutagenic. Thus, exposure is generally considered unlikely to act as an initiator of carcinogenesis.

In vitro studies have revealed enhanced cell transformation rates after RF exposure at levels of 0.1 to 4.4 W/kg. Studies by Balcer-Kubiczek and Harrison (1985, 1989, 1991) found that although 2,450 MHz microwaves alone did not cause malignant transformation in their system, low-level microwave irradiation did increase the amount of transformation caused by TPA, a phorbol ester tumour promoter. The magnitude of this effect increased with increasing microwave power level. It must be noted that the microwaves used in this study were modulated at 120 Hz, raising the question of whether the observed effect could actually be due to the lower frequency component. The implications of this result for human health are not clear. It is clear, however, that studies relevant to carcinogenesis need to be replicated and broadened.

In a study of rats exposed for most of their lifetime to low-level pulsed microwave radiation (Chou et al., 1992), the frequency and site of neoplastic lesions were determined. The exposed group had a significantly higher incidence of primary malignant tumours compared to the control group if the incidence of primary malignant lesions were pooled without regard to site or mode of death; in addition, the primary malignancies appeared to occur earlier in the exposed group. However, no particular type of malignant neoplasm in the exposed group was significantly elevated compared to values reported elsewhere in stock rats of this strain. The data were analysed without taking into account the type and site of the neoplasm, nor was the mode of death incorporated into the analysis. In addition, the incidence of benign neoplasms did not appear to be enhanced in the exposed group compared to controls, although the total number of benign tumours of the adrenal medulla was higher in the exposed group (but not particularly higher than that reported elsewhere for this strain of rat). These data do not provide evidence of an increase in tumour incidence as a result of exposure to microwaves. In other studies (Szmigielski et al., 1982; Szudzinski et al., 1982), the chronic microwave exposure of mice at 2 to 8 W/kg resulted in an SAR-dependent increase in the progression or development of spontaneous mammary tumours or chemically induced skin tumours. Body temperatures were not raised but the authors suggest a possibility of inhomogeneous heating at the highest level of exposure. A further experiment (Szmigielski et al., 1988) showed that exposure at 4 to 5 W/kg followed by the application of a "sub-carcinogenic" dose of a carcinogen to the skin, a procedure repeated daily, eventually resulted in a threefold increase in the numbers of skin tumours appearing.

Some epidemiological studies have investigated groups of adults with RF or assumed RF exposure and cancer incidence or mortality (Lilienfield et al., 1978; Robinette et al., 1980; Milham, 1988; Armstrong et al., 1994; Szmigielski, in press). The results were varied in that in some studies there was no effect, while in other studies associations between RF exposure and various cancers were found. Some of these studies are subject to methodological shortcomings or uncertainties, such as crude exposure assessments, lack of analysis of confounding (except for age), paucity of reported details of analysis, etc. The overall assessment of these studies suggests that certain findings of excess lung cancer in two of them (Robinette et al., 1980; Armstrong et al., 1994) may warrant further investigation, but that uncertainties in exposure assessments currently preclude any conclusions. For other cancer sites, indications of associations were either absent or difficult to evaluate for methodological reasons.

5.3. Conclusion

Although there remains a great deal unknown about the health implications of RF radiation, the potential thermal hazard is understood and should be given serious consideration. The deposition of RF energy in the human body tends to increase the body temperature. During exercise, the metabolic heat production can reach levels of 3 to 5 W/kg. In normal thermal environments, a SAR of 1 to 4 W/kg for 30 minutes produces average body temperature increases of less than 1 °C in healthy adults. Thus, an occupational RF guideline of 0.4 W/kg SAR leaves a margin of protection against complications due to thermally unfavourable environmental conditions.

In conclusion, exposure conditions experienced by some RF heater operators can cause elevated body temperatures. At these elevated temperatures, reproductive and teratogenic effects may occur in heater operators. In addition, eye irritation, RF burns, and neurological problems (hand numbness, diminished two-point discrimination and carpal tunnel syndrome) have been documented for heater operators.

6

Occupational exposure standards and guidelines

Many countries have now established RF health protection standards or guidelines. There have been a number of in-depth reviews of current RF standards (Czerski, 1985; Stuchly, 1987; Sliney, 1988; Repacholi, 1990). Most of the early standards addressed the microwave region only (300 MHz-300 GHz) because of the introduction and proliferation of radar, telecommunications, and radio and TV broadcasting. Later the vastly expanded use of the electromagnetic spectrum was recognized, especially at lower frequencies where concerns were raised about RF exposures from induction heaters, heat sealers and other industrial applications.

RF exposure standards have also been proposed by groups of countries, such as the European Community and the Council for Mutual Economic Assistance. A proposal for a Directive of the Council of the European Communities was published in March 1993. The proposal on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents included electromagnetic fields and waves. Following the advice of the European Parliament, the Commission submitted an amended proposal in July 1994, which was adopted in August 1994. The European Committee for Electrical Standardization (CENELEC) published a prestandard (ENV 50166 part 2) in January 1995, which will be reviewed for adoption as a full standard in three years. The Commission of Mutual Economic Assistance Standard 5801-86, established in 1986, had been incorporated into the regulations of several Eastern European countries in the following years. The maximum exposure levels in the various standards can differ by two orders of magnitude. It is speculated that these differences result from: (a) the physical and biological effects data selected as the basis for the standards; (b) the interpretation of these data; (c) the different purposes to be served by the standards; (d) the compromises made between levels of risk and degrees of conservatism; and (e) the influence of preceding standards in each particular nation. In recent years, an increasing number of countries have adopted limits identical or very close to those recommended by INIRC/IRPA.

6.1. ICNIRP guidelines

The INIRC/IRPA guidelines for frequencies between 100 kHz and 300 GHz were published in 1988 and were based on a whole-body average SAR of 0.4 W/kg (IRPA, 1988). Under conditions where the whole-body average SAR might not exceed the whole-body average limit, several reports (Conover et al., 1992; Dimbylow, 1988; Gandhi et al., 1985, 1986; Chou and Guy, 1985; Stuchly et al., 1985, 1986a, 1986b; Williams and Mild, 1991; Erickson and Mild, 1985) indicate that under certain conditions peak values of local SAR in the extremities (particularly the wrists and ankles) can exceed the whole-body limit value by a factor of 300 at certain frequencies.

ICNIRP is currently revising these RF guidelines as follows: for occupational exposure in the frequency range of 10 to 100 MHz, an SAR of 0.4 W/kg should not be exceeded when averaged over any 6-minute period and over the whole body. In head, neck and trunk, the local SAR should not exceed 10 W/kg averaged over 6 minutes and over any 10-g mass. For other parts of the body, the corresponding local SAR is 20 W/kg averaged over 6 minutes and 10 g.

The field strength limits in table 1 for frequencies between 10 MHz and 100 MHz are derived from the whole-body average SAR value of 0.4 W/kg. A limitation of the body-to-ground current to 100 mA per limb provides a means of complying with the basic restrictions.

Table 1. ICNIRP occupational exposure limits to radiofrequency fields

Frequency range	Unperturbed electric field strength (rms)	Unperturbed magnetic field strength (rms)		Body current to ground through one limb
f (MHz)	*E* (V/m)	*H* (A/m)	*B*(μT)	*I*(mA)
10-100	61	0.16	0.2	100

7

Exposure assessment

Stray fields from RF heaters are complex in nature and dependent upon the machine, the applicator type and the material being treated. Mathematical modelling of a simplified exposure to fields from an RF heater has been carried out (Chen and Gandhi, 1989a) but such modelling of realistic exposures from a wide variety of equipment is not practical. It is necessary therefore to use instrumentation to measure the external fields and to assess induced currents.

The guidelines for restricting exposure of people at work to RF fields are given in Chapter 6. The objectives of any measurement programme are to ensure: (a) that the exposure of machine operators and other people in the vicinity of RF heaters is below the appropriate restrictions; and (b) to assist in evaluating the effectiveness of protection measures such as shielding.

In order to demonstrate full compliance with the guidelines, two types of measurement must be made. The first is to measure both the external electric and magnetic fields, and the second is to obtain a measure of the induced current. The latter is the more reliable method of assessing the potential hazard.

Assessment of the work situation should be made in order to protect against RF burns that may arise due to accidentally touching metal objects in the RF fields.

7.1. Measurement of RF fields

Instruments capable of measuring both *E*- and *H*-field strengths should be used to measure the RF fields in the vicinity of RF heaters. Additional details including an example of an exposure evaluation for an RF heater are given in NCRP (1993).

Field-strength measurements are made in the absence of the operator but at the operator's normal location to demonstrate that the measured value is below the appropriate guideline level. Instrument limitations may prevent measurement closer than 20 cm from the machine. In this case compliance with the guidelines should be established by measurements of induced currents only.

Fields close to RF heaters are highly non-uniform. To evaluate compliance with the exposure guidelines using field-strength instruments, measurements should be made at least 20 cm from the machine in the vertical plane at the position of nearest whole body approach to the applicator.

For accurate measurements the following important factors should be considered.

(1) Measurements should be made at the normal positions of the operator but, if possible, in his or her absence to minimize field perturbations and to standardize procedures.

(2) The instrument probe should be held at arm's length from the surveyor and the meter should also be kept as far as possible from the probe.

(3) If the probe or field-strength meter is not fitted with a suitable insulated handle it should be held in position for the measurement by means of a simple insulating (non-conducting) support at least 30 cm in length.

(4) Normally measurements should be made not closer than 20 cm to any part of the machine.

(5) Dipole, monopole or single-loop antennas used to determine E and H field strengths should be orientated orthogonally to obtain the vector sum of the field.

(6) To avoid overloading or damaging the field-strength meter, the surveyor should begin monitoring at positions remote from the applicator.

7.2. Measurement of induced currents

It is possible to assess the currents induced in the body for comparison with exposure guidelines. These techniques of exposure assessment have been used in the assessment of RF heater exposure (Allen et al., 1990; Conover et al., 1992, 1994; Gandhi et al., 1986; Williams and Mild, 1991).

To obtain meaningful exposure assessments for heater operator, body current (e.g. foot or ankle) must be measured for common hand and upper torso positions (Conover et al., 1994). Otherwise, abnormally low or high body current could be recorded with misleading conclusions. Simultaneous videotaping of current readings (metre face) and operator posture are helpful.

Several references provide useful information on induced current measurement techniques and procedures (Blackwell, 1990; Conover et al., 1992, 1994; Gandhi et al., 1986; Williams and Mild, 1991; IEEE Std C95.3, 1991 a).

For reliable induced current measurements the following procedures should be followed:

(1) Record the nominal heater operating frequency (see name-plate on heater) and measure the operating frequency of the heater.

(2) Measure and record the ankle circumference of the heater operator.

(3) Observe normal heater operation and notice particularly the normal locations of the operator's upper torso and hands relative to the heater.

(4) Measure the current with the operator's upper torso and hands at the closest locations (relative to the heater) observed during normal operation. Record the maximum current and the corresponding locations of the operator's upper torso and hands (relative to the heater).

(5) During current measurements, have the operator assume his/her normal posture (sitting or standing) and wear the type of shoes normally worn during heater operation.

(6) Measure the background current with the sensor in the RF field [at the location(s) used for normal current measurements], *but with the operator absent from the heater surroundings*.

(7) When the concern is source identification, care should be taken to distinguish between current induced by the heater of interest and other heaters. One way this can be done is to energize only the heater of interest during measurements.

(8) Record the maximum root mean square (rms) current (with a 1-second average) observed for at least three (3) product processing cycles with the same exposure conditions for each cycle.

(9) Observe and record the type and thickness of material (if any) between the operator's feet and the floor. Dielectric materials between the operator's feet and the floor can reduce currents (compared to readings without the material).

8

Control technology and radiation protection programme

To minimize the risk of adverse health effects, RF fields as well as induced and contact currents must be in compliance with the applicable guidelines. Reduction and control of exposure can be accomplished through the implementation of appropriate administrative and work practice controls, and/or proper design, construction and installation of RF heaters. RF shielding is emphasized because it is typically both practical and effective (Murray et al., 1992; Ruggera and Schaubert, 1982). Its ease of construction, low cost, versatility, minimal operator involvement, and protective value have been proved through years of experience.

8.1. General obligations and duties

8.1.1. Role of competent authorities

To avoid duplication of effort, there should be cooperation among the competent or regulatory authorities whose scope of function includes protection against potential hazards of RF heaters. These competent authorities should adopt the necessary regulations and establish inspection systems to ensure compliance with applicable safety guidelines.

8.1.2. Responsibility of the employer

It is the responsibility of an employer utilizing RF heaters to implement and enforce, as part of its comprehensive safety and health programme, an RF protection programme which assures the safety of employees from RF hazards. The RF protection programme shall include:

(a) utilization of RF heaters which meet applicable RF and other safety standards when new and during the time of use, including after any modifications made by the employer;

(b) RF hazard identification and periodic surveillance by a competent person (i.e. safety officer) who can effectively assess RF exposures;

(c) implementation of controls to reduce RF exposures to levels in compliance with applicable guidelines, including rules regarding safe work practice procedures;

(d) RF safety and health training to ensure that all employees and supervisors understand the RF hazards to which they may be exposed and the means by which the hazards are controlled;

(e) employee involvement in the structure and operation of the programme and in decisions that affect their safety and health, to make full use of their insight and to encourage their understanding and commitment to the safe work practices established;

(f) implementation of an appropriate medical surveillance programme (see section 8.4);

(g) assignment of responsibilities, including the necessary authority and resources, to implement and enforce all aspects of the RF protection programme; and

(h) periodic (e.g. annual) reviews of the effectiveness of the programme so that deficiencies can be identified and resolved.

8.1.3. Duties of the worker (user)

Workers in charge of the day-to-day operation and maintenance of RF heaters must:

(a) understand the hazards associated with operating the specific equipment assigned to them and the controls used to mitigate those hazards;

(b) be aware of, and follow, normal safe operating practices and procedures;

(c) be able to recognize and report RF sealer malfunctions and maintenance problems, particularly with respect to RF controls (e.g. missing fasteners in the RF shield);

(d) report events which may be germane to medical surveillance (e.g. occurrence of RF burns, implanted medical devices such as a cardiac pacemaker, copper IUD, and hip and knee replacement, etc., sensation of non-routine heating, etc.).

8.1.4. Responsibility of manufacturers

RF heater manufacturers are responsible for making equipment that complies with applicable standards, and for providing information on the hazards of operating and servicing the equipment. The information must be sufficient to alert the owner of the magnitude of the risk and the appropriate precautions that need to be taken. It is recommended that the information include RF survey results obtained prior to shipment of the RF heater, for comparison purposes after installation and periodic maintenance.

Manufacturers will strive to minimize RF exposures through the use of integral engineering controls, particularly RF shielding, to minimize RF exposures. Instructions will encourage users to maintain the controls as designed. Manufacturers will also share applicable information useful in retrofitting RF heaters purchased without shielding.

Manufacturers will incorporate interlocks and physical barriers into the design of RF heaters to prevent contact with the high-voltage components as well as with intense RF emissions. Appropriate labels will be attached to the RF heater to warn operators and maintenance persons of areas of potential electrical shock and RF hazards.

8.2. Work practice controls

Although shielding should comprise the primary control of RF exposures, safe work practices, including proper maintenance procedures, can also significantly reduce exposures.

8.2.1. Maintenance procedures

Appropriate work practices must be followed during the repair and maintenance of RF heaters. Occasionally, cabinet panels must be removed by service personnel to allow access to the interior of the heater for maintenance or repair work. This should be done only by persons who are trained to work on this equipment and who are aware of the potential hazards and how to protect themselves. The electrical power to the heater should be disconnected before proceeding with repair. All parts, including shielding, should be replaced before the power is restored to the heater. Maintenance personnel should understand why all the fasteners, cabinet panels, and interlocks of the panels and doors must be properly reinstalled. Failure to replace a panel may allow high levels of RF radiation to escape and allows direct access to 5,000 volts or more inside the generator. Contact with these high voltages is *deadly*.

RF heaters use interlocks to shut off electrical power when a cabinet panel is removed or a door opened (preventing RF emission or contact with high voltage). The interlocks are vital tools for worker protection. All workers should understand the necessity for interlocks and the need for maintaining them in good working order. Interlocks must not be disabled when a panel is removed or a door opened.

8.2.2. Operator procedures

Heater operator exposure can be reduced by keeping the operator's hands and upper torso as far as practical from the heater (Conover et al., 1994). Thus, administrative controls or physical barriers which maximize the distance between the heater and operator can be effective in reducing exposures. Many of these techniques can be used without decreasing product quality or output.

The operator's control panels for some automated RF heaters are positioned away from the applicator plates, and therefore away from the principal RF source, by using shuttle trays, turning tables or conveyor belts to feed product materials in and out of the RF applicator. These designs were originally introduced to increase efficiency in production, since they allow for loading and unloading at the on position while the other product is being RF heated. However, they often result in reduced exposure due to the increased distance between the operator and the RF applicator. Caution must be exercised so that the shuttle trays or conveyor mechanisms do not become RF energized, thereby increasing operator exposure.

8.2.3. Identification of RF hazard areas

Controlling exposure time and the distance between the RF source and the operator are important in maintaining the workers' exposures below recommended levels. When necessary owing to excessive leakage, "RF hazard areas" must be identified around each heater to alert the workers of areas that are not to be occupied during RF application. The location of the hazard areas must be based on exposure measurements made during maximum field generation and accounting for the highest duty factor (i.e. ratio of RF "on" time during any 6-minute period, assuming intermittent exposure) for which the heater may be used. The RF hazard areas shall be clearly marked with appropriate signs, barricades, floor markings, etc., of sufficient size to be recognizable and readable from a distance of 3 metres. Proper hazard communication is essential, as seen in the box below:

> An example of improper communication is given by Ruggera and Schaurburt, 1982. "During a visit to a user facility a large banner was observed hanging from the ceiling. It was intended to warn the operators not to come within 1 metre of the RF sealer when it was on. This method of exposure control could have been effective, since the "on" and "off" controls of the RF sealer were located on pedestals that had enough connecting cable to allow them to be placed 3 feet from the machine. It was observed, however, that the operators were located approximately 1 foot in front of the unit where exposure fields were higher than the recommended maximum RF field strengths. During the radiation measurements, one of the operators remarked that the investigator should go behind the machine to measure the fields – the sign was hanging above the back of the machine and the operator had assumed that the high fields to be avoided were under the sign (that is, behind the sealer near the AC power lines)."

The evacuation of hazard areas prior to RF application must be strictly enforced. Because of rigid production schedules, some operators are tempted to violate the RF hazard area in front of the RF heater. For example, a procedure which requires the operator to first load the heater, step back 2 metres to get outside the RF hazard area prior to activating the RF energy, and then walk back to unload the heater will be considered an impediment to rapid production. The additional time required and increased operator fatigue will discourage operators from following such procedures, particularly for workers who are paid on a piece-work production basis.

Physical barriers can also be used to ensure that operators and other workers remain outside of the RF hazard areas. To be effective, the barriers must not be easily movable or be electrically conducting. Reactive fields emanating from the RF heater can induce currents in nearby conducting barriers and other objects. Workers' contact with these metal objects can result in shocks or burns. Natural barriers such as walls, tables and fixtures to hold the workload are preferable.

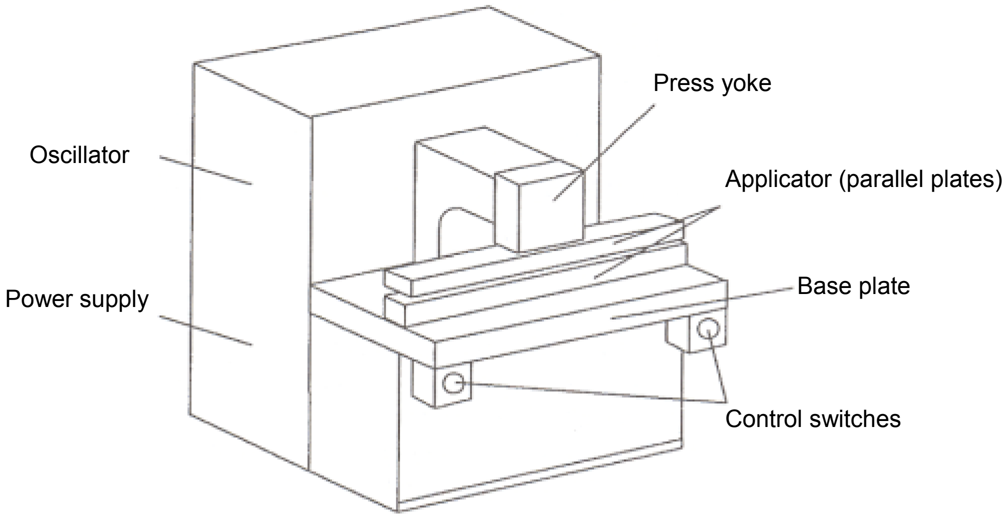
8.3. Design and installation considerations

8.3.1. Shielding

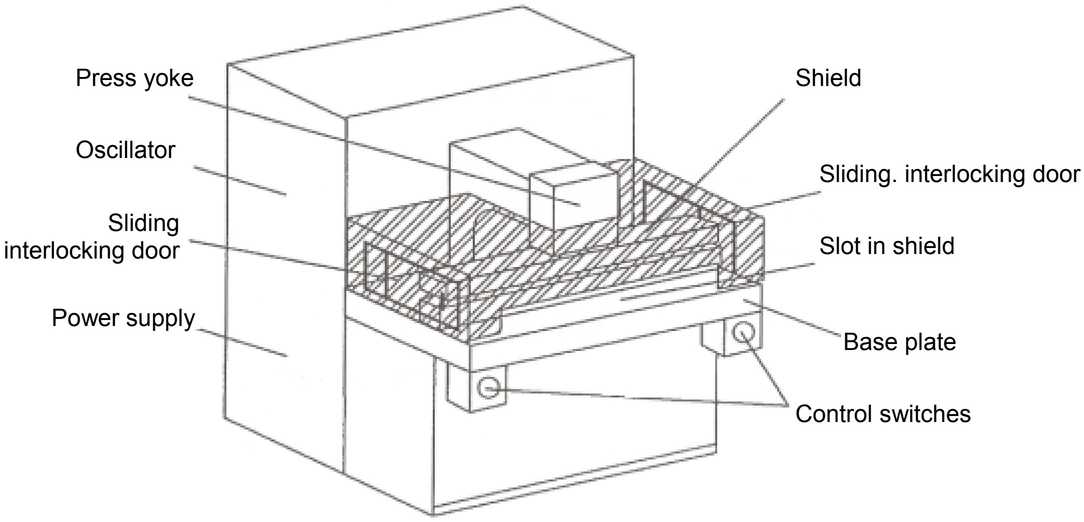
Although work practices and administrative controls can and should be used to reduce worker exposure, the use of shielding is emphasized in this document because it is more effective, dependable and efficient. Because many applications of dielectric heaters are unique, they will require variations in the shielding design. Murray et al. (1992) give additional details concerning effective shielding of an RF heater requiring an innovative design. Additional background information is given in the appendices. The ideal shield will be a complete conducting closure containing the RF applicator (see figure 4).

Figure 4. Unshielded and shielded RF heater used in the study

Unshielded



Shielded



Four basic principles for the successful application of shielding can be summarized as follows:

(1) The shield (including the joints) should have very high conductivity (i.e. low resistance and reactance) for all interior currents that will flow in the walls.

(2) Openings in the cabinet should be as small as possible, consistent with effective machine operation, and the number of openings kept to a minimum. The orientation of the openings to current paths should be selected to minimize worker exposure.

(3) Currents in the shield walls should be minimized by having separate conductors inside the cabinet to carry high currents.

(4) Improperly installed shielding can increase RF energy leakage. Initial and periodic followup RF radiation surveys must be made.

When designing shielding, suggestions from the workers should be considered because of their experience in using the equipment. As long as their ideas do not decrease the effectiveness of the shield, they may be incorporated into the shield design.

Good shielding designs should interfere as little as possible with the normal operating procedures and production requirements.

The necessity of following the principles of shielding RF equipment is demonstrated throughout this document. Omitting "minor" details can result in an ineffective shield. For example, the use of fewer screws decreases conductivity and can allow RF energy to leak through joints.

An effective shield can be easily incorporated into the original design of the RF heater. Retrofitting shielding on older equipment is often necessary. However, modifying existing equipment is sometimes difficult and requires ingenuity to solve the mechanical and electrical problems. An effective retrofitting of shields is described by Murray et al. (1992).

Sometimes mechanical power is used to operate movable parts of the shield, such as a door. Mechanical power can be transmitted by linkages from auxiliary equipment, such as an electric motor, or a pneumatic or hydraulic cylinder. The type of power source used will depend on what is available and easiest to utilize.

Implementation of the four principles of shielding given above has been successful in many installations. *The most critical step is the final one, since a shield's effectiveness can only be judged by measuring the operator's exposure according to the procedures in Chapter 7*. If the exposure is above recommended levels, the points of leakage must be found and corrected. The importance of routine periodic RF surveys is often overlooked. Mechanical and electrical connections often deteriorate over time because of vibration, mechanical stress, heat, etc., resulting in reduced effectiveness of the shield. Also, because a current tends to crowd towards both ends of a slot across the current path, the use of a field strength probe to find leaks can be misleading. Leaks may appear to be near a screw, even if the screw has been tightened. In this case, the spot between screws should be inspected; there is probably poor electrical contact between shield parts. If the screws are spaced too far apart, more screws may have to be added to improve electrical contact between fasteners. Often RF leakage can be reduced by improving contact between shield sections, by adding contacts, or by lengthening vestibules (see figure A-11).

Another form of exposure control in widespread use by RF sealer users is screen-room enclosures. A metal screen-encased room, is used to house (usually older model) RF sealers as well as the operators. This constitutes effective radiation control for the rest of the plant. However, the operators of these screened units may receive a higher dose of RF energy than they would had there been no-screen room (Gandhi et al., 1977; Appendix D).

Just as the screen room may enhance exposure to operators, improper shielding by untrained or uninformed individuals may create more serious exposure problems. Portions of a formerly well-shielded machine could also be rendered ineffective and cause more radiation by simple misuse or partial removal of the shield. In order to determine the effectiveness of the shield, it is essential that both the electric and the magnetic fields and induced current be measured (Murray et al., 1992). In a shielding evaluation experiment, Ruggera and Schaubert (1982) have shown that some attempts at shielding may reduce the electric field strength to quite a low level, but the corresponding magnetic field strength can be increased or vice versa.

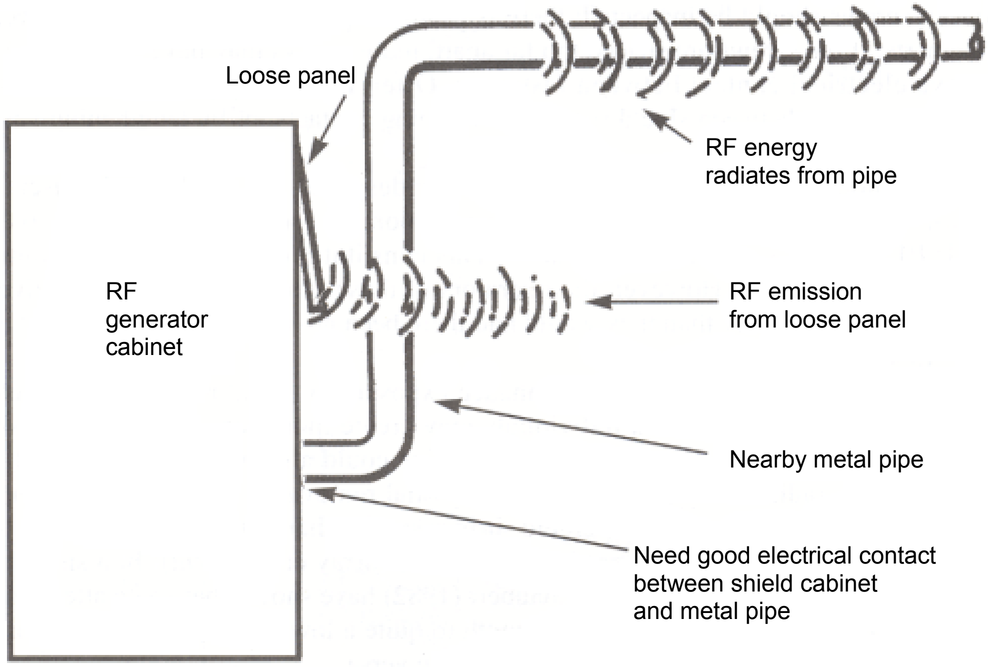
8.3.2. Installation details

8.3.2.1. Installations near pipes

Excessive radiation in unexpected locations in a plant can occur when RF energy leaking from a dielectric heater couples to a nearby pipe. The pipe or other metal object can act as a good antenna for high frequencies. If the pipe is the right length (e.g. equal to an integral multiple of quarter wavelengths), it will resonate (couple maximum RF energy) at the fundamental operating frequency or at one of its harmonics.

Figure 5 illustrates how RF energy couples to pipes and how it can be radiated at other locations as it follows the pipe. The best solution, after shielding the generator cabinet as well as possible, is to move the pipes away from the RF generating equipment, especially away from potential openings in the cabinet shielding. Radiation can leak from joints in panels, output lead locations and ventilation openings. Where possible, any pipes carrying power to the heater should be located underground and brought up through the floor directly into the bottom of the heater. This minimizes RF leakage into the work area. Generator pipes that are perpendicular to the cabinet surface are best, because they leave the equipment as directly as possible and thus minimize the amount of pipe to which RF energy can couple.

Figure 5. RF energy coupling to pipes



Power lines, water lines, and aircooling ducts connected to the generator may also have RF energy coupled to them. Figure 6 illustrates a method that successfully prevents the coupling of RF radiation to pipes. A pipe flange that threads onto the outside of the pipe and is bolted to the unpainted surface of the cabinet gives the best electrical contact. This construction will keep all cabinet currents inside the shield since currents will not flow very far down the inside of the pipe unless the pipe's diameter is one-half the RF wavelength or greater. For example, currents above 1,475 MHz would flow down a 10-cm (4-inch) diameter pipe. For currents to flow down smaller pipes, the RF frequency must be even higher (wavelength even smaller). The current flow will occur in a pipe only when the cut-off frequency is exceeded (see Appendix A on vestibules).

If the use of a pipe flange is not desirable, a clamp can be installed around the pipe and connected to the cabinet (figure 7). This connection should be as short and wide as possible. Also, the hole in the metal shield through which the pipe enters should be as small in diameter as is practical. This avoids large slot-type openings where RF energy may escape.

Figure 6. Method to prevent the coupling of RF radiation to pipes

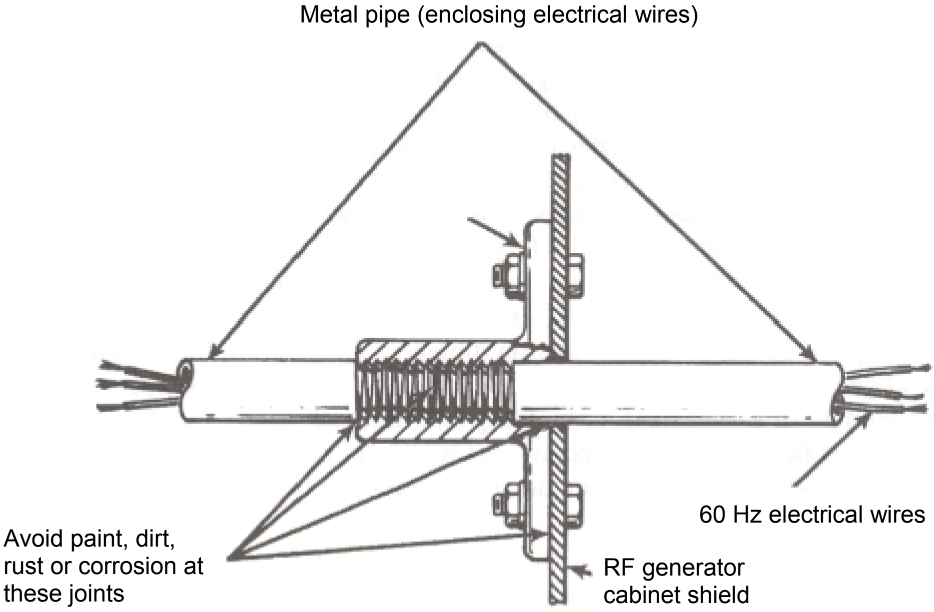
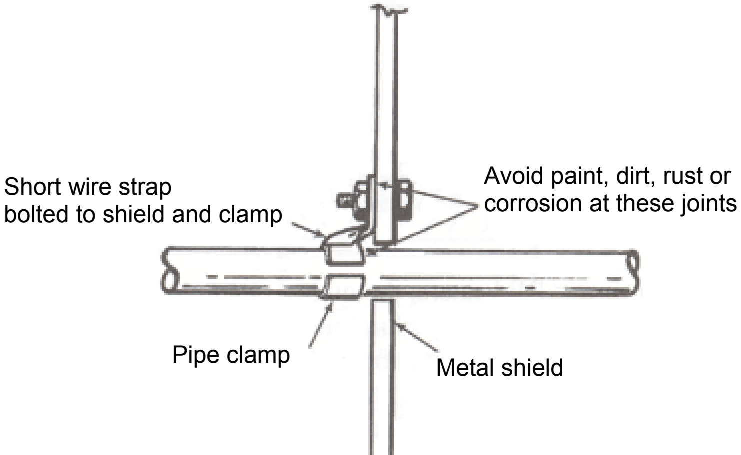


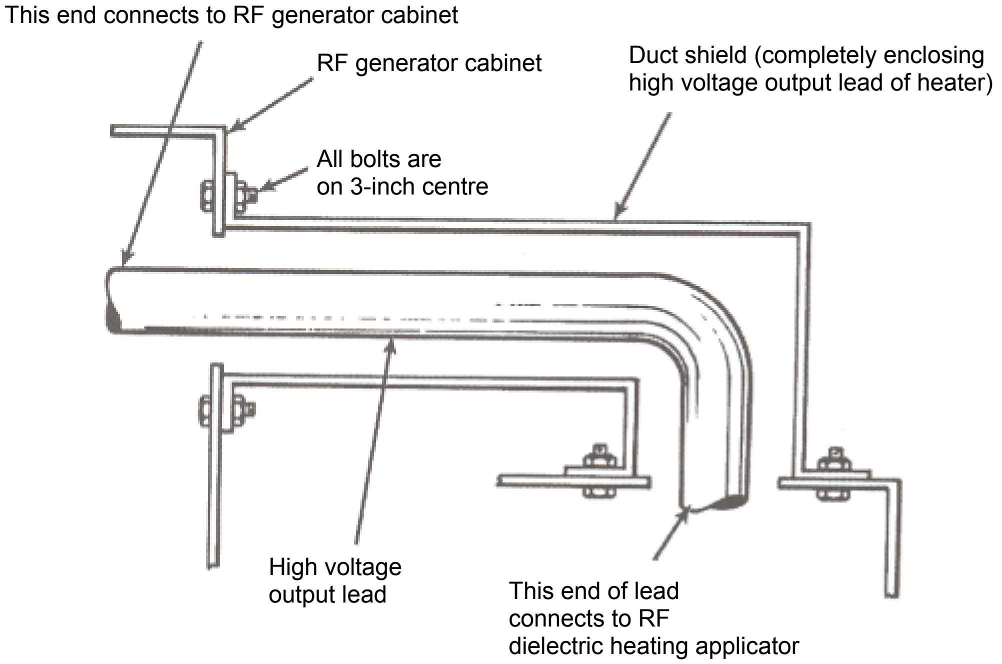
Figure 7. Clamp installed around pipe and connected to the cabinet to inhibit current



Non-metallic pipes should be used wherever possible because they cannot pick up RF energy and reradiate it. However, any electrical wiring connected to RF heaters must be enclosed in metallic pipes or conduits. This is necessary because these wires will carry unwanted RF energy away from the heater. Using metallic pipes to enclose these RF-carrying wires is the only way to keep the RF energy on them from being radiated. In extreme cases, where sensitive instrumentation is employed, it may be necessary to include an RF filtering device in series with each wire leading from the RF heater to the instrument. Often it is sufficient to install a large (e.g. 0.005 microfarad) capacitor with the shortest possible leads between each wire and ground. Where high field intensities are present, a special RF filter, including several capacitors and an inductor, may be required to prevent interference with very sensitive instruments. The capacitors should be rated for at least 100 volts.

Many RF power output cables on dielectric heaters are high current conductors, and generally cannot be installed without at least one slot or opening in the generator cabinet. To assure proper shielding and meet RF safety requirements, the output cable must be inside a metal conduit of high conductivity (figure 8). In lower power RF heater installations, aluminum downspout pipe has been used successfully.

Figure 8. Square copper duct



In large, higher power RF heaters, the output pipe may be 30 to 45 cm (12 to 18 inches) in diameter and made of heavy aluminum for rigidity. The inner surface of this pipe is used to carry the ground currents from the applicator back to the generator. Forward currents from the generator to the applicator are usually carried on another conductor that is coaxial to the outer one. Usually, copper water pipe is used, although specially fabricated aluminum tubing may be used in larger equipment. Aluminum irrigation tubing also is often used.

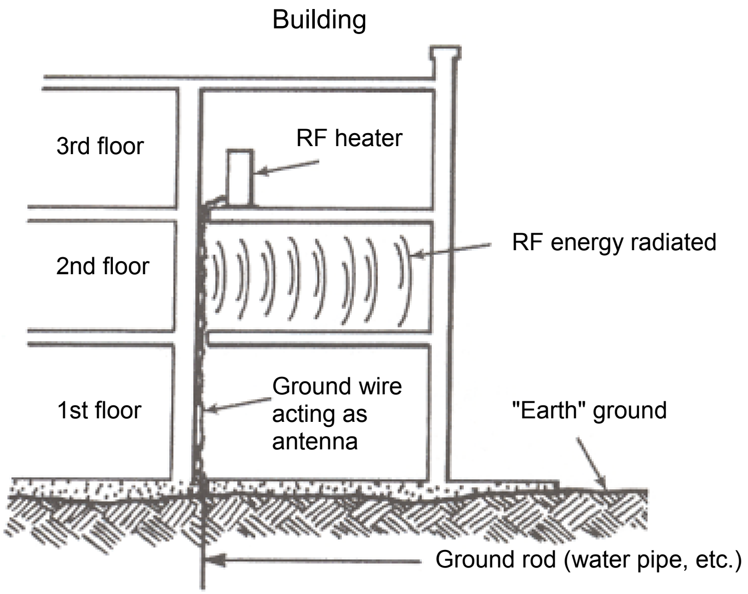
In very small heaters with low RF power, a standard, commercially available, RF coaxial cable (e.g. RG-9) is sometimes used. The cable must carry considerably more current in this situation than it does for normal communications services. Thus, except for very low-power generators, using commercially available coaxial line with insulation made of polyethylene or similar material is usually not practical. The potential difference across the inner and outer conductors of the coaxial cable should not exceed 1,000 to 1,400 V depending on the type of cable used.

8.3.2.2. Grounding

Most national electric codes require that all equipment connected to an AC power line must have the metal cabinet frame grounded to prevent any human contact with the electrical energy. In RF heaters, the ground wire required by electric codes should be enclosed inside the same pipe as the power lines. As described in the preceding section, conduit pipes should enter at carefully selected locations in the generator cabinet shield so that an RF leak will not be coupled to a pipe and radiated in the plant.

A ground wire is basically like any metal connected to the shield; if RF energy gets onto the ground wire, this energy will follow the ground wire and be radiated at other locations in a plant. The RF energy must not be allowed to couple to these conductors, particularly if the RF heater is above the ground floor and the conductor is raised above the ground floor (see figure 9). A ground wire that is elevated above ground level can act like a transmitting antenna. This can be prevented by locating ground wires inside a metallic pipe so RF energy cannot be efficiently radiated. The metallic pipe (conduit) must be electrically insulated from the wires in it and it must be grounded.

Figure 9. RF energy leak



Ground wires penetrating the shield and connected to metal parts inside the equipment cabinet are more likely to couple RF energy than a pipe that is entirely external to the shield and not near a potential point of RF leakage.

8.4. Medical surveillance

Medical surveillance of RF workers serves the following purposes:

1. Assessment of the health status of the worker before starting work involving RF exposure (pre-employment), during the period involving RF exposure, and at the end of occupational RF exposure. Longitudinal records of this type allow detection of contraindications and assure protection of the worker and safe RF use.
2. Detection and early prevention and treatment of any adverse exposure effects that might not have been anticipated in exposure guidelines.
3. Collection of precise individual data on RF exposures and adequate medical records that can be used in future epidemiological studies.

8.4.1 Normal conditions

In many countries the initial and periodic examinations of workers are a legal requirement; in other countries industrial employers and governmental agencies may require similar pre-employment examinations and periodic check-ups.

Contraindications to employment with RF exposure should be considered. Persons with cardiac pacemakers, or with surgically implanted metallic appliances may be especially sensitive to the effect of an RF field. Although exposure guidelines with their safety margins provide considerable protection against thermal overload due to absorption of RF radiation, persons with limited cardiovascular reserves who may work at an elevated workplace temperature may need additional medical surveillance.

8.4.2 Abnormal conditions

When overexposure occurs, depending on the circumstances and the severity of the exposure, a medical examination may be required. So far no unique syndrome requiring highly specialized treatment has been identified. Treatment can be expected to be symptomatic and deal with local or systemic thermal excursions.

Appendix A – Shield theory, design and construction

1. Basic principles

Before attempting to shield a radiofrequency (RF) heater, one must have a basic understanding of the concepts and theories used in RF shielding. The applications of RF heating and the types of equipment are so numerous and varied that not every case can be discussed individually.

Basic principles, as discussed later, can be used to design shields for specific applications. Detailed instructions for applying these principles are included in section A2. Because an understanding of static DC field concepts is basic, these are described and then extended to the AC field concepts used in RF heating.

In static fields, an electric field can exist without a magnetic field and vice versa. With alternating fields, both the electric and magnetic fields exist, but the relationship between them may vary. Thus both fields need to be evaluated in terms of biological interaction.

If a static electric field exists in a volume in space, certain effects can be detected (see Appendix B). The electric field effects can be detected by observing the action of a free electron inside the volume. For example, between the two parallel plates of a capacitor, an electron near the centre of the plates would be repelled from the negative plate and attracted to the positive plate. The path of motion would be a straight line that starts perpendicular to the negative plate and ends perpendicular to the positive plate. Near the edges of the two plates, an electron still leaves in a direction perpendicular to the surface of the negative plate. This path of motion is called a "line of force" because there is a force on the electron causing it to move.

The directions of lines of force depend on the size and shape of the conductors that set up the field. Near the conductor, the lines of force are always perpendicular to the conductor, regardless of the size or shape of the conductor.

To gain a better understanding of the lines of force, current flow and electric fields, consider the following theoretical example and how these parameters change under different conditions. Assume that a metal conductor is completely surrounded by a rectangular metal box (figure A-1). This "shielding cabinet" (metal box) has no openings. All electric and magnetic fields are confined within its interior. The rectangular metal plate is similar to the top of a thick metal table on wooden legs, with the edges of the top rounded.

Figure A-1. General principle of shielding

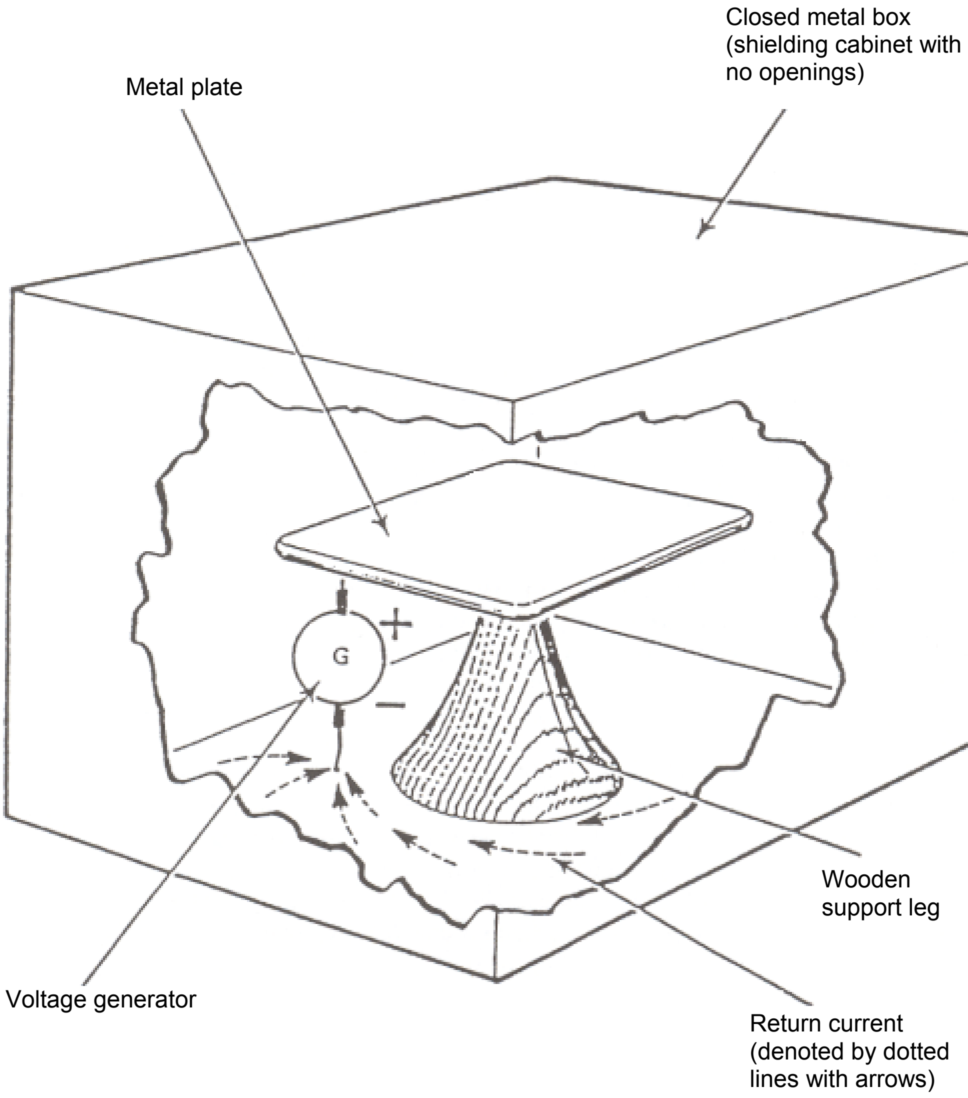
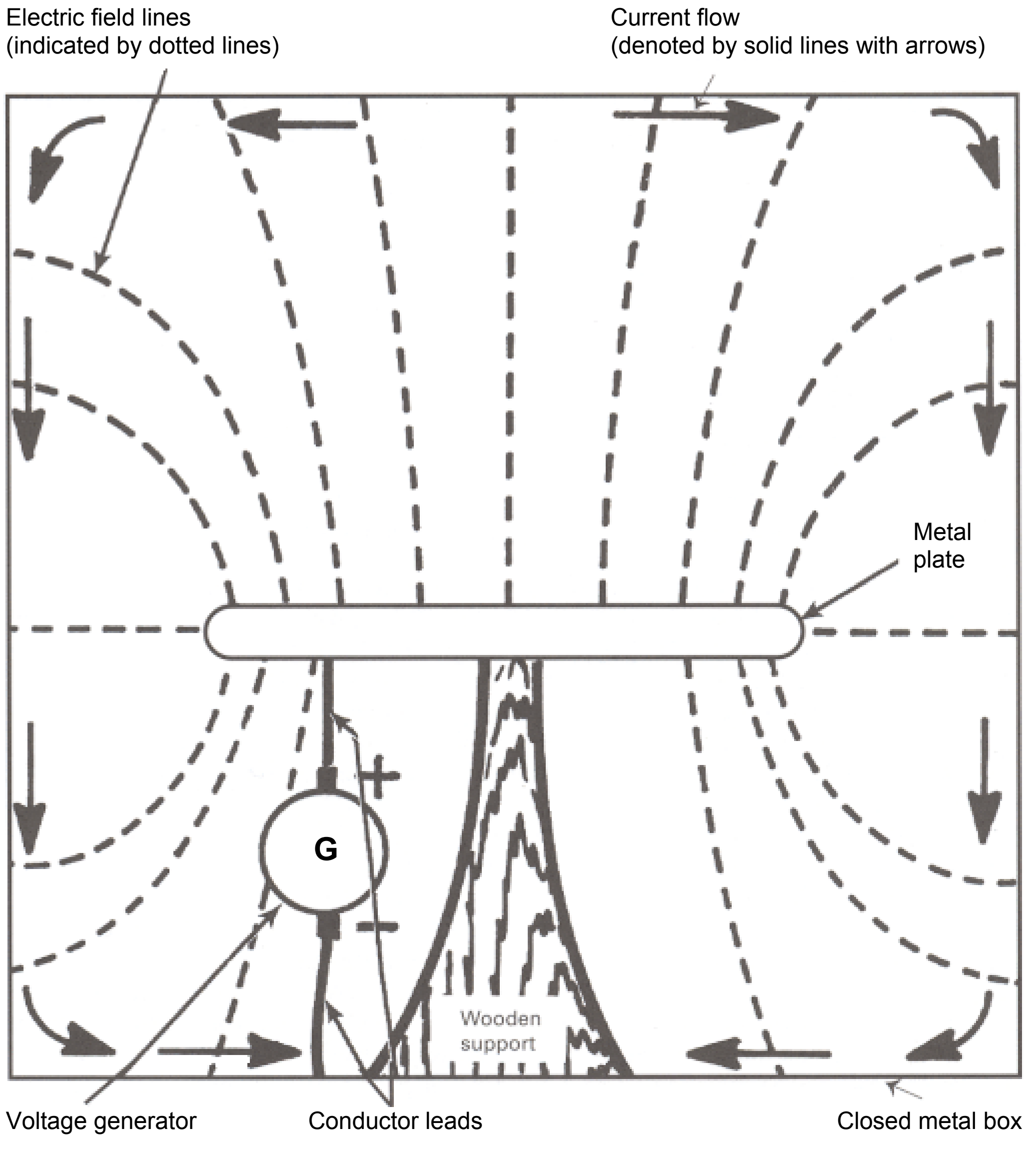


Figure A-2 shows a cross-section of the metal box with the thick metal plate in the centre. In the centre of the box, under the plate, a source of DC voltage is connected between the floor and the underside of the plate.

Figure A-2. Cross-section of the shielding cabinet



The electrical parameters change in a step-by-step manner under the following circumstances:

(1) Assume that the voltage generator has not been connected between the plate and the metal box. No voltage exists between the plate and the surrounding box. Therefore, no electric field exists inside the box and no current flows in any part of the box.

(2) Now assume that the voltage source is connected to the metal plate and the box. At the instant the positive terminal of the voltage source is connected to the metal plate, free electrons are moved from the plate and distributed on the inside surface of the box. This movement of the electrons is called *current flow* or *electrical current*. The force causing this movement comes from the voltage source, and only lasts for a fraction of a second. The magnitude of the small current flow depends on the magnitude of the voltage and the amount of capacitance or capacitive reactance between the metal plate and the interior surfaces of the box. Because of the current flow, a magnetic field exists for a very short period of time.

(3) After the current flow ceases, the voltage difference between the metal plate and the box is the same as the voltage of the voltage source. Often the interior of the box is arbitrarily designated as zero voltage and the metal plate as a positive voltage. At this instant, the lines of force appear as they are shown in figure A-2. Their strength increases as soon as the source is connected, but their shape is not altered appreciably as the voltage increases.

(4) When the polarity of the voltage source is reversed, free electrons are removed from inside the box (leaving it with a positive charge) and they are moved by the voltage to the metal plate. This motion of the electrons creates a current flow, of which the duration is very short. The shape of the field remains essentially as shown, but its strength decreases to zero and then increases in the opposite polarity. The metal plate then passes from a positive to a negative voltage with respect to the interior of the box.

(5) After the current flow ceases, the reverse charging cycle (making the metal plate negative with respect to the box interior) is complete. All current flow in the box ceases. The strength of the field between the plate and the box is at its maximum; it has the same magnitude as when current flow ceases in stage (3) but has the opposite polarity.

During stages (2) and (4), a current flowed in the box for a short time. This current flow occurs each time the polarity of the voltage source is changed. A current flow will also occur when the magnitude of the voltage source is changed. The current flow will continue until the voltage difference between the box and the metal plate is equal to that of the voltage source.

The electric field lines of force are closer together (or stronger) at the edges of the metal plate, but are widely spaced (or weaker) on the top of the metal plate. Because one connection point for the voltage source is on the metal box, any current flow must find a path back through this voltage source.

Electrical laws state that the current path will be the one of least resistance (DC) or impedance (AC). For discussion purposes, the current path is assumed to be the shortest path back to the voltage source because the conductivity of all portions of the metal box is uniform.

Also, in this discussion, the charges are assumed always to have sufficient time to be distributed throughout the box. Although electrons move at high speed, their speed is finite. With a voltage source that alternates at a sufficiently high frequency, some electrons may not move fast enough to reach the voltage source before the polarity of the voltage source reverses. The charges on the interior of the box are not completely redistributed. Consequently, the fields are different from those shown in figure A-2, and the shape and intensity of the fields depend on the instant of time being considered. This phenomenon depends on the size of the box (enclosure) and the RF frequency of the voltage source.

Thus when the box is larger than the wavelength at the RF frequency of the voltage source, a high voltage difference can exist inside the box.

Current paths

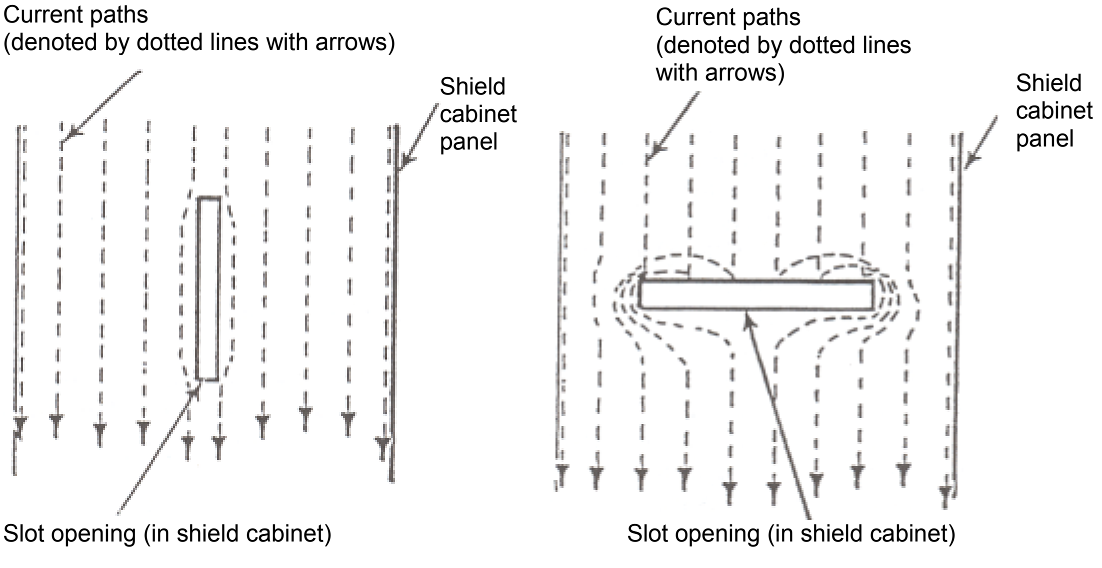
Understanding and visualizing current paths is essential for the proper design and construction of the shielding. If a slot (a rectangular opening) is required in the shielding enclosure (e.g. to permit air to enter), the placement of this slot with respect to the current paths determines how much RF energy is radiated or escapes the enclosure. A slot parallel to current paths will result in a much lower radiated field than if it is perpendicular to current paths.

In a cylindrical enclosure of uniform conductivity, the current paths radiate towards, or away from, the centre of the floor where the voltage source is connected. Because the walls are the same distance from the centre of the floor, the shortest path for all the currents is the same and the current density is uniform.

In contrast, the density of currents in the floor is not uniform in a box enclosure with a rectangular floor. The distance from the voltage source – located in the centre of the floor – to the walls varies, depending on which point on the wall is being considered. The distance from the voltage source to a corner is always longer than the distance to a side. Because the current takes the path of least impedance (the path with the lowest voltage drop), the path tends to be the shortest route from side to centre. However, in most practical situations where there is more than one voltage source, the current density is not uniform and the currents may not be exactly radial at all points in the floor.

Currents flowing in the enclosure may change slightly if a slot is cut in the enclosure. In figure A-3, the slot is narrow and the long dimension is parallel to the current paths. Some elements of current may have to take a slight detour around the slot, but with little disturbance. Only those current elements that would have normally passed through the space occupied by the narrow slot will be disturbed.

Figure A-3. Effects on current distribution of different orientation of openings



More current paths are affected if a slot is cut in the enclosure with its long dimension perpendicular to the current flow paths, also shown in figure A-3. Much of the current has to detour around the slot and much more current is affected than with a parallel slot. This adds greatly to the impedance of the path and causes the current to concentrate around the ends of the slot. The added impedance in the current path causes the top of the slot to be a different voltage from the bottom. The voltage difference results in an escape of RF energy to the environment (i.e. the slot radiates and can increase worker exposures).

A varying magnetic field induces currents in any conductor located in that field. Thus the current flowing in a conductor designed to provide a return path can induce a similar current with the opposite instantaneous polarity in a nearby or adjacent shield wall. This induced current will follow the general routing of the shield wall rather than return to the RF generator more directly. When trying to visualize possible current paths and design effective shielding, this fact must be considered.

The shield wall must be included as a path for the current returning to the generator. If return currents in the shield wall are neglected, openings in the shield wall (such as slots) can radiate RF energy to the environment and increase worker exposures. Current flowing from a generator to a two-electrode field applicator system (usually one electrode is grounded) must return to the generator. The forward currents flow from the generator to the applicator electrodes. The return currents flow from the applicator electrodes back to the generator, sometimes through the shield. In this case, the forward and return currents will get as close to each other as possible. The return current from the applicator electrodes is usually directly under the conductor carrying the forward current. In these cases, the path of least reactance is the one in which the forward and return currents are as close as possible.

Resistance

The resistance of the metal carrying the currents is important. Resistance depends on the material in the conductor, its length, width and RF frequency. The thickness of the conductor is also a factor, but at high frequencies the thickness of the current path will be much less than the thickness of any practical conductor.

The actual resistance of a conductor can be determined by equation A1:

$$R = L / (\sigma \mathrm{WS}) \tag{A1}$$

where: R is the resistance of the conductor in ohms
L is the length of the conductor in metres
σ is the conductivity in S/m
W is the width of the conductor in metres
S is the thickness of the current path in metres
(for high frequencies, it is the effective skin depth of the current in metres).

DC situations will cause a uniform current throughout the material, but for alternate currents (at RF heater frequencies) the current flows near the surface of the conductor. Indeed, at the frequencies normally used in dielectric heating, the depth of the current is very small, measured in fractions of one millimetre.

Equation A2 relates the skin depth (δ) to frequency (f), conductivity (σ), and permeability (μ).

$$\delta = (66 / f^{1/2})\, k_1 \tag{A2}$$

where: δ is the skin depth in mm
f is the frequency in hertz
$k_1 = [(1 / \mu_r)(\sigma_c / \sigma_m)]^{1/2}$
μ_r is the relative permeability of a metal with respect to air (dimensionless)
σ_c is the conductivity of copper in mho/metre
σ_m is the conductivity of another metal in mho/metre.

Table 2 gives data on skin depth and conductivity for several common metals and for metals used in plating to prevent corrosion length or width. These characteristics and shielding design and construction are discussed in the sections that follow.

Table 2. Conductivity, skin depth and resistance per unit surface area of materials

Material	Conductivity[*] (mho/m)	Skin depth (mm)		Resistance per unit surface area at 3 MHz (ohms)
		at 3 MHz	at 30 MHz	
Silver	6.139×10^{7}	0.03556	0.0117348	4.393×10^{-4}
Copper	5.8×10^{7}	0.0381	0.012065	4.525×10^{-4}
Gold	3.367×10^{7}	0.050038	0.015875	5.935×10^{-4}
Aluminium alloy (6063)	3.067×10^{7}	0.052578	0.0165862	6.201×10^{-4}
Brass	1.563×10^{7}	0.073406	0.023241	8.716×10^{-4}
Nickel ($\mu_r = 5$)	1.461×10^{7}	0.034036	0.0107442	2.011×10^{-3}
Zinc	1.429×10^{7}	0.076962	0.0243586	9.093×10^{-4}
Cadmium	1.3263×10^{7}	0.079756	0.0252222	9.454×10^{-4}
Steel ($\mu_r = 600$)	0.602×10^{7}	?	?	3.435×10^{-2}
Tin	0.550×10^{7}	0.122682	0.039116	1.467×10^{-3}
Stainless steel	0.1351×10^{7}	0.249936	0.078994	2.962×10^{-3}

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[*] Conductivity data are available in many references, such as the *Handbook of Chemistry and Physics,* 52nd edition, p. E-72, 1972, and *Reference Data for Radio Engineers*, 5th edition, pp. 4-21 to 4-22, 1969. Resistivity (the reciprocal of conductivity) is sometimes listed.

Note: $\mu_r = 1$ for all metals in table 2 except nickel and steel.

This table illustrates how much more conductive silver or copper is than aluminium, iron, or other conducting materials. Skin depth is given for two frequencies to show its dependence on frequency. Note that the relative permeability (μ_r) is 1 for all materials in table 2 except nickel and steel. The thickness of the conductor is assumed to be several (perhaps at least three) times the skin depth.

The "resistance per square" expression refers to the resistance of a material with unit length and width, and at least a skin depth thickness. This value is the same regardless of the use of metric or English units (see table 2). Equation A3 relates "resistance per square" (R_{sq}) to frequency (f), material conductivity (σ_m) and material relative permeability (μ_r).

$$R_{sq} = (2.60 \times 10^{-7})\, f^{\,½}\, k_2 \qquad \text{(A3)}$$

where: R_{sq} is the resistance per unit surface area in ohms
and: $k_2 = (\mu_r\, \sigma_c / \sigma_m)^{½}$.

The results are tabulated (table 2) for a frequency of 3 MHz. The resistance per surface unit area can be used to calculate the actual resistance of a square (or rectangular) conductor at 3 MHz with equation A4.

$$R_{3\text{MHz}} = (\text{resistance per unit surface area, from table 2})\ (L)/W \qquad \text{(A4)}$$

where: L is the conductor length
and: W is the conductor width, both in the same units of length.

The resistance at other frequencies in MHz is obtained by multiplying the calculated actual resistance from equation A4 by the square root of the ratio of the two frequencies, as shown below in equation A5.

$$R\ (\text{at new frequency}) = R\ (\text{at 3 MHz}) \times [f_{\text{new}}/3]^{½} \qquad \text{(A5)}$$

where: f_{new} is the" new" frequency (in MHz).

2. Shielding design and construction

When designing shielding, several questions must be considered: What type of material should be used for construction? How can materials be efficiently processed by dielectric heaters while still maintaining effective shielding? Are ventilation openings needed? How should the cabinet be constructed and installed? This section will provide answers which result in both efficient processing of dielectric materials and an effective shield.

Characteristics and selection of shielding materials

One of the primary considerations in shield design is the selection of the materials to be used in constructing the shield. There is some flexibility in what can be done, depending on the materials and the means of fabrication available.

All parts of the shield must have excellent electrical conductivity; currents should flow in their natural paths without hindrance from openings or poorly conducting paths. This requires a metal that will not corrode or rust during its normal lifetime and prevents the use of paints or other non-conducting coatings. Metal plating is acceptable if the plating has good conductivity and is thick enough compared to the skin depth for the RF current involved (compare table 2).

The effect of cabinet wall conductivity was tested by a dielectric heater manufacturer in a cost-saving experiment using 1-kW generators. The manufacturer compared an aluminium cabinet with three similar cabinets made from other metals. One was made from cold-rolled steel, another from galvanized steel and the third from aluminium-coated steel. When tested, the generator in the aluminium cabinet delivered the 1,000 watts; the generators in the all-steel and the galvanized steel cabinets only delivered about 700-850 watts. The generator in the aluminium-coated steel cabinet delivered the 1,000 watts, but more RF power was dissipated in this cabinet than was dissipated in the normal aluminium cabinet. The less expensive and somewhat easier to use cabinet materials caused severe reductions in power output (i.e. more power was dissipated in the cabinet materials) even when the equipment was new and joints were clean.

Cold-rolled steel and other ferrous materials are subject to rust which causes joints to have poor electrical conductivity. In addition, steel's high magnetic permeability causes RF power (heating) losses that make it very poor for RF-current-carrying applications. Thus in a high intensity magnetic field, ferrous materials can be heated readily, representing an RF power loss that should be avoided. The heat in the shield can burn human skin. In some rare cases, the steel has become red hot; however, this is unusual in commercial equipment. Occasionally steel is used in some lower frequency equipment, primarily because of its low cost and ease of fabrication. How well these cabinets continue to shield after ageing is not completely known.

After steel, aluminium cabinets cost the least to construct. They have good conductivity at high frequencies and good resistance to corrosion. The oxide that forms almost immediately on aluminium is very thin and, once formed, does not get progressively thicker. Salt atmospheres are deleterious to it. Aluminium is more difficult to weld than steel because it requires an inert gas atmosphere and will often warp when overheated. In spite of these disadvantages, aluminium is undoubtedly the best material for shield construction.

Silver and copper have the best electrical conductivity of all metals, and silver oxide is also a good conductor. However, these metals are too expensive to be practical. Most other metals have poorer conductivity than pure aluminium, which has about 58 per cent of the conductivity of pure copper. Aluminium alloy 6063 seems to have the best conductivity except for pure aluminium; other alloys have conductivities that range down to those of some brasses. Aluminium suppliers publish engineering data books that provide electrical conductivity information.

According to table 2, silver and copper are nearly alike in resistance per square metre, and the aluminium alloy has 37 per cent more resistance per unit surface area than copper at any frequency. The resistance per unit surface area of steel (normal cold-rolled sheet) is about 76 times that of copper and over 55 times that of aluminium for a sheet without any joints. Joints in the steel sheet can increase its resistance per unit surface area, particularly if there is rust or paint in these joints.

The implications of these data for RF power dissipation and shielding can be illustrated by assuming that a steel and a copper strap of the same dimension (30 by 2.5 cm) are used to connect the same two points. If 50 amperes of 3 MHz current are flowing in each strap, the steel strap will dissipate 1,030 watts, whereas the copper strap will dissipate only 13.6 watts. Equation A4 and data on resistance per unit surface area in table 2 can be used for these calculations. This is why copper is used to carry high currents in dielectric heaters. Stainless steel resists corrosion from most atmospheres and is sometimes used in shielding under unusual circumstances. Although steel and stainless steel are both made of iron, stainless steel has less than one-tenth the resistance per unit surface area of cold-rolled steel (table 2). Therefore, a stainless steel strap that is 30.5 by 2.5 cm with 50 amperes of 3 MHz current flowing in it will dissipate 88.9 watts. Because shields must often carry high currents, they must have high electrical conductivity (i.e. low resistivity).

If a steel shield is plated to prevent corrosion and increase the conductivity of steel, the plating must be thick enough to ensure that most of the current flows in the plating metal rather than in the parent metal. This thickness can be determined by using table 2 for "skin depth", which is the depth at which the current density has decreased to about 37 per cent of the current density at the surface. Currents at lower frequencies will have more of their flow at greater depths. Therefore, the plating should be at least as thick as the skin depth for the plating metal and frequency involved (see table 2). For example, in cadmium-plated steel, the cadmium plating must be at least 0.08 mm thick at 3 MHz to minimize losses; at 30 MHz, the thickness should be at least 0.025 mm.

Joints

Joints between adjacent portions of any cabinet used for shielding must have very good electrical conductivity so that the current paths will not be interrupted (see section Al). As mentioned above, selection of the construction materials to ensure good metal-to-metal contact (and good electrical conductivity) is very important. Furthermore, the shield cabinet should contain a minimum number of joints. For example, in a panel and frame construction, panels are often bolted to a frame so that they are adjacent to each other. However, if the panels are overlapped instead, the number of joints the current must flow across is reduced and the resistance is minimized. The overlapping panels make transferring the current from panel to frame and back to the next panel unnecessary. Also, if the frame is painted, as in a steel frame, the current path is not interrupted by the paint (e.g. when using aluminium panels over a steel frame). In this case, it is sometimes necessary to wrap aluminium over the steel frame at points where high currents or magnetic fields exist. This results in reduced RF power dissipation in the shield because of the lower resistance per square metre of aluminium compared to steel.

If at all possible, all joints between sheets of metal should be welded, thereby avoiding any slots or openings. However, if rivets or bolts are used, they should be spaced close together – much closer than required merely to hold the panels onto the frame. Not more than 7.5-cm spacing should be considered. Although a large number of fasteners may seem unnecessary and excessive because it requires time and labour to remove and replace them, it must be recognized that the use of a minimal number of fasteners greatly reduces the conductivity of a cabinet, causing increased RF energy leakage and reduced shielding effectiveness.

Ports or slot openings in shielding

Ports are often necessary for viewing materials inside the shield and for ventilation of the shield interior. Where the current paths can be readily determined and wide openings are not required, it may be possible to use narrow (as feasible) slot openings parallel to the current paths in the shield. Constructing slots parallel to current paths in dielectric heater shielding (see figure A-4) has proved successful in laboratory trials. Where the openings in the shield must be wide, they should be covered with a perforated metal sheet having good electrical conductivity (see figures A-5 and A-6). This perforated metal sheet must be securely fastened around the periphery of the opening so that the currents in the perforated metal can transfer easily to the shield frame (see figure A-5). There should be an uninterrupted current path from one side of the opening to the other that provides a low impedance path for shield currents across the opening. The low impedance path will reduce RF energy leakage and worker exposure from the shield.

Figure A-4. Slot openings parallel to current paths improve shielding compared to non-parallel slots

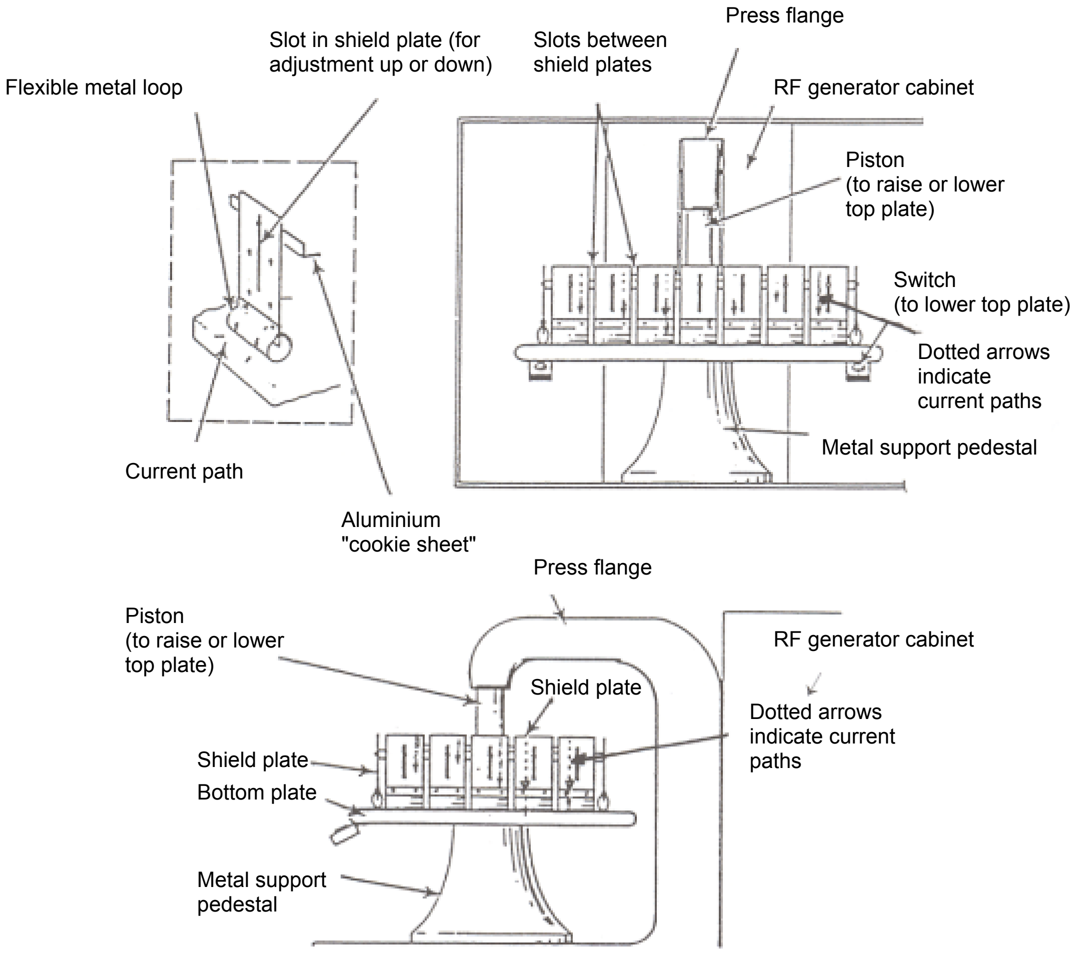


Figure A-5. Perforated metal plate across wide opening as part of shielding

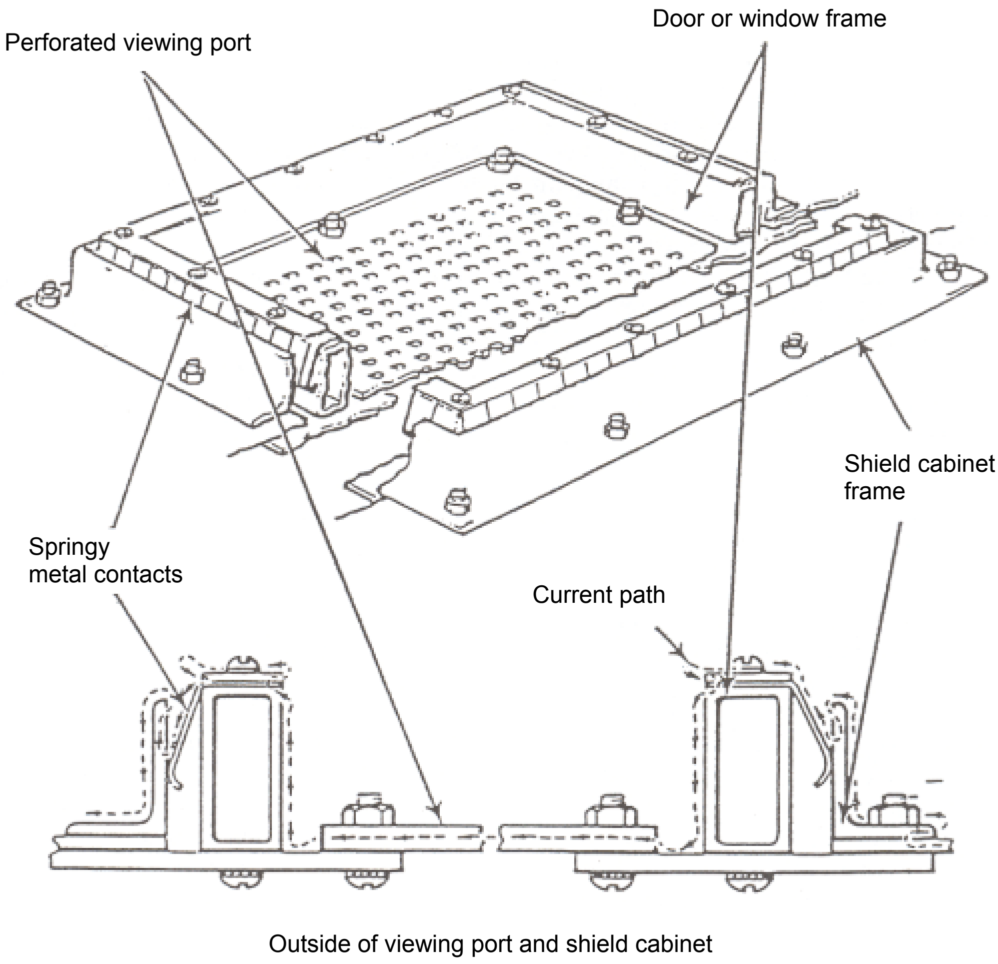
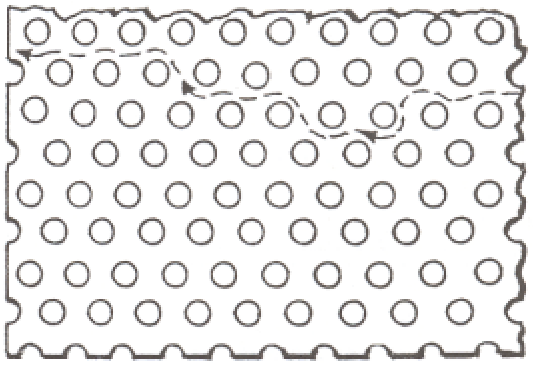


Figure A-6. Current paths across a perforated metal sheet



Some hardware stores sell thin, perforated, aluminium sheet metal, with a pattern resembling a cane-bottomed chair that has proved very satisfactory for ports (figure A-6). For example, patterns with 3-mm diameter holes on 6-mm centres, or 6-mm holes on 9-mm centres, provide good shielding. At 30 MHz, a sheet with 15-mm square holes on 25-mm centres is not as effective a shield as other patterns mentioned, probably because of the large holes.

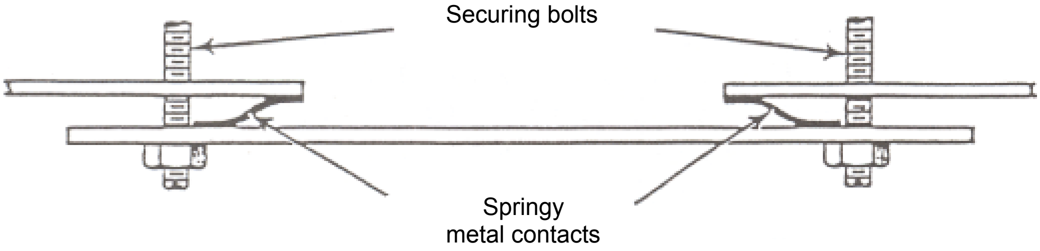
Woven wire screen, even if made of aluminium or bronze, is not a preferred shielding material for dielectric heaters. Apparently, only occasional and poor electrical contact occurs between wires in the screen as they cross each other. Currents that must flow diagonally across the woven screen must pass over many joints with low electrical conductivity. Thus a single layer of perforated aluminium is a more effective shield than two layers of bronze screen isolated from each other to provide a double shield.

To reduce reflection from room lighting and improve viewing, the outer surface can be painted flat black. If a window is desired for viewing the interior of the shield, the outer surface of the perforated metal can be painted flat black, being careful to avoid painting surfaces where contact must be made. Illumination within the cabinet will also be helpful for viewers. Often sufficient RF fields exist within the cabinet to light a fluorescent lamp tube without its being connected to the AC power line.

Doors and removable panels

Access to the shield interior is required for insertion and removal of the material to be heated, as well as for servicing and cleaning the shield. Doors and removable panels to accommodate servicing and cleaning must be opened and shut frequently. Good electrical conductivity must be present around the contact edges (disconnect joints) between the doors and panels and the associated frames whenever the RF is turned on. It is imperative that good current paths (i.e. high electrical conductivity) be restored when the door is closed or the removable panel is repositioned against its frame. To assure high electrical conductivity at the disconnect joints, springy material is installed around the contact edges of the door. A convenient material is metallic "weather stripping" that is usually made of a springy bronze material (e.g. beryllium copper). If the door frame or the door is slightly warped or curved, the weather stripping should be serrated at frequent intervals to assure good contact. The serrations are usually made by cutting the material perpendicular to the edge*, but only part way through*, making finger-like contacts that can follow wavy surfaces and yet provide frequent contacts. Often it is best to use a thin, fine-toothed saw blade to cut a narrow slot in the "weather stripping". The design shown in figure A-5, although it may be more expensive at first, requires less maintenance and will last longer than the design in figure A-7.

Figure A-7. Contact strips between removable panel and fixed part of the cabinet



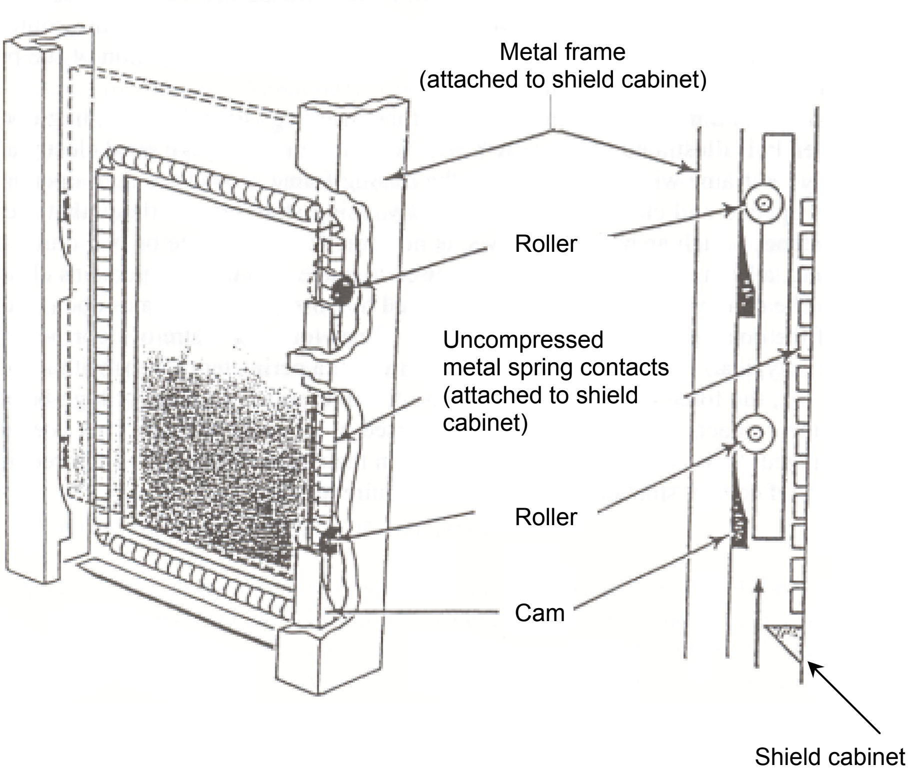
One disconnect joint method uses contact strips between the removable panel and the fixed part of the cabinet frame (figure A-7). This method is often used when the panel or door is infrequently removed (e.g. monthly, quarterly, or yearly). The number of screws needed to mount the panel or door has to be sufficient to hold it closed against the force of the contact strips. Care must be exercised when the panel is removed to ensure that the contacts are not deformed. To prevent unbalanced pressure on the contacts and deformation of the panel, all of the screws must be used, and they must be tight.

A second method of using the "weather stripping" for a large, sliding door which is open frequently is illustrated in figure A-8. The force required to make good electrical contact is provided by the frame within the door and the mating frame around the door opening. Because the door is opened and closed many times a day, using shielding methods that require many manual fasteners, such as bolts or screws, is not practical. Only one or two quick disconnect fasteners (e.g. a latch or clamp) are normally used to make sure the door remains closed.

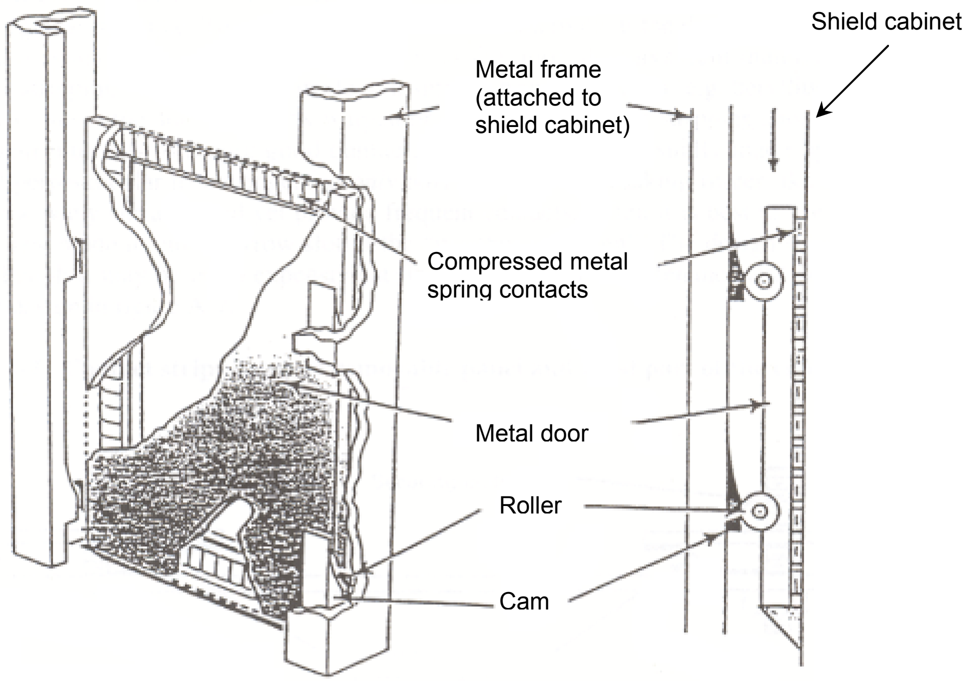
The contacts increase the force required to close (and sometimes open) the door, particularly if the door is large. A contact force of 60 newtons per metre of door perimeter linear centimetre is typical. For a door 2 m high by 1 m wide (a perimeter of 6 m) with a coefficient of friction of 0.2, the force needed is 72 newtons. A value of 0.2 is probably high because it presumes all the contacts are compressed and released at the same instant. This does not usually happen. Hinged doors, with "weather stripping" on their contact edges will not require as much force either. Of course, smaller doors or panels require less force.

Figure A-8. Contact strips for frequently used sliding door

Door partially open



Door closed



Vestibules (shielding tunnels)

Previously, the design of ports and doors was discussed in some detail. The size and placement of slots in the shield were shown to be critical with regard to leakage of radiation. Slots that are parallel to current paths and have a narrow width will minimize operator exposure. An extension of this slot principle is illustrated by equipment that uses conveyor belts to move dielectric material into and out of the RF field for processing. Usually the shield opening cannot be a slot at all, but it is a rectangle with a height and width that do not greatly differ. However, a shield opening with approximately equal height and width will have larger RF energy leakage than a narrow slot parallel to current paths. Consequently, other methods are needed to reduce RF leakage from shield openings with approximately equal height and width. The vestibule method can often be used to do this. A vestibule is a metal tunnel that the dielectric material to be heated traverses while it passes into and out of the RF field. One end of the tunnel encloses the shield opening (slot) and the other end allows insertion and removal of the dielectric material. For reasons discussed below, a vestibule which is properly designed can greatly reduce RF leakage, and its use is illustrated in figure A-9. Current flow in a shield cabinet is contrasted in figure A-9 (vestibule) and figure A-10 (no vestibule). Vestibules are also useful in reducing the energy that escapes from a large ventilation duct.

Figure A-9. Current flow in a shield opening with a vestibule

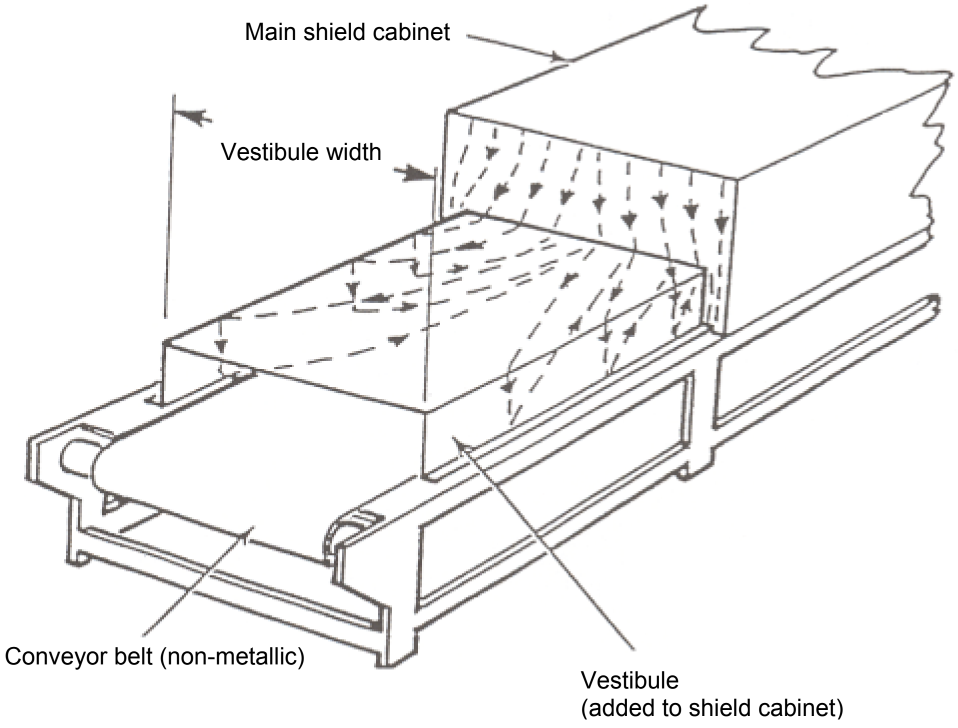
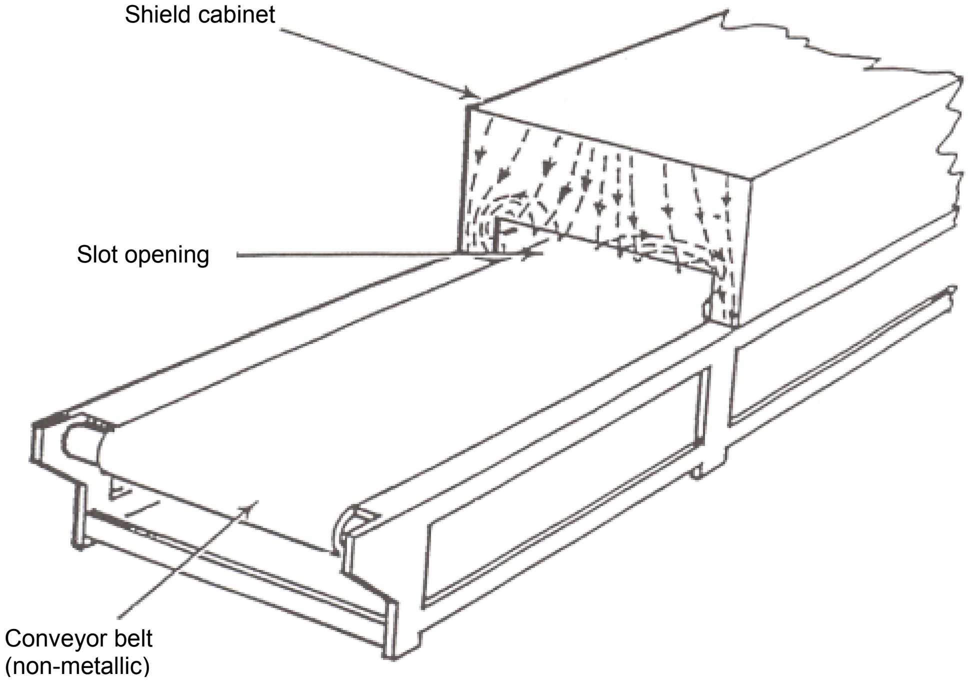


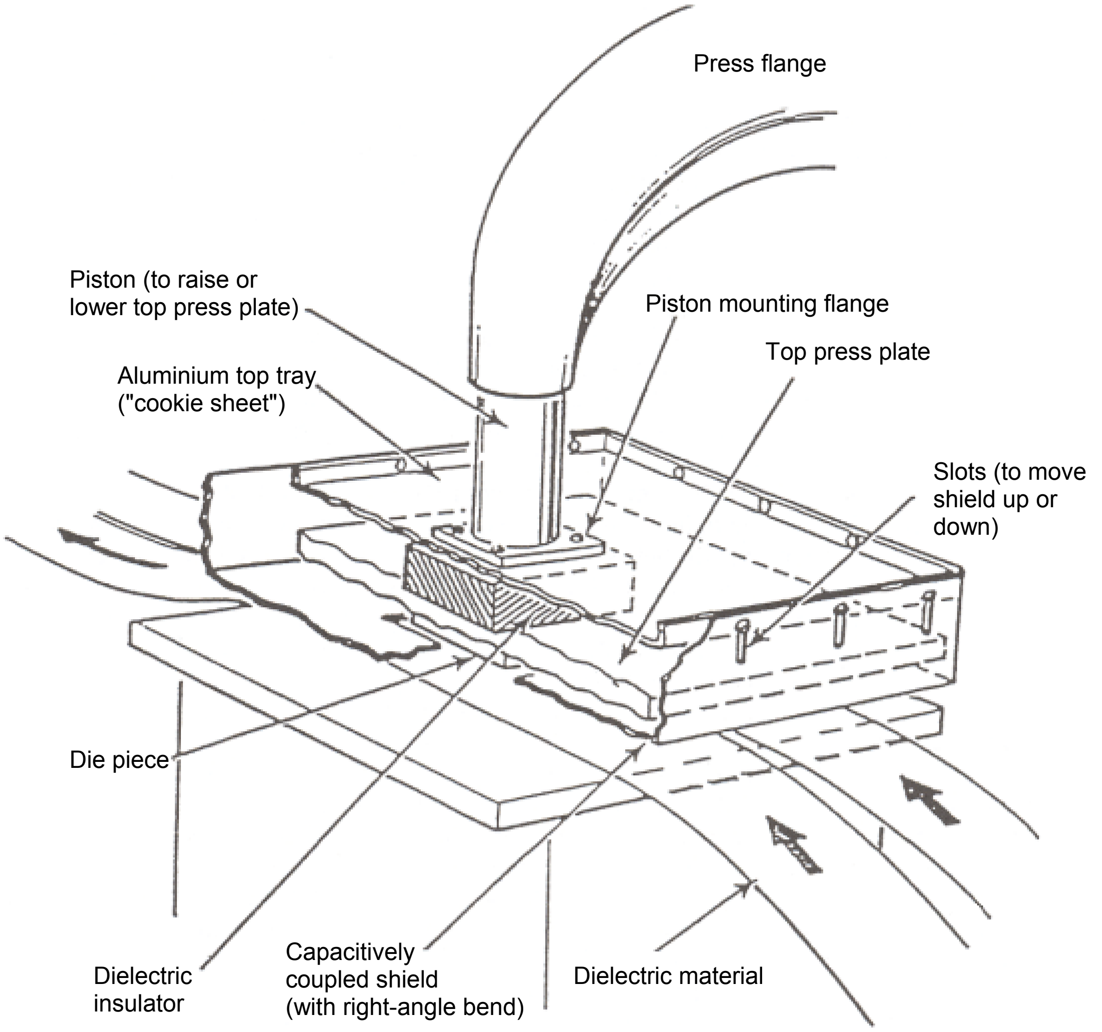
Figure A-10. Current flow in a shield opening without a vestibule



For very thin materials used in dielectric heating applications, a slot may be used for the entrance and exit of materials. However, these slots are wide and are perpendicular to the current paths.

Alternatively, a "short vestibule" can be used. A short vestibule can be formed by having its top and bottom very close; to be effective, it must be of sufficient length to act as a capacitor through which the normal shield currents can flow across the slot (figure A-11).

Figure A-11. Principle of a "short vestibule"



Alternating currents flow into and out of this capacitor and the higher the frequency the greater the current. These currents can be large even though the capacitance is small (see Appendix B). Conversely, the greater the capacitance, the lower the voltage needed to drive a given current through it. This is illustrated by the capacitance vestibule of figure A-11 described above, where the top and bottom are close. The dielectric material to be heated increases the capacitance between the press plates forming the short vestibule. Because the currents can pass through the shield without an appreciable voltage across the capacitor (press plates), the energy radiated through the opening where the material passes will be minimized.

Sometimes the upper plate of the capacitor (short vestibule) is too close to allow the material to pass through it easily. However, once the material is loaded, the upper plate can be lowered to the desired position before the RF energy is applied. Then the upper plate can be raised when the press opens or when new material is loaded. The upper capacitor plate is moved by an independent power source. The upper plate must be lowered to ensure proper shielding whenever the RF energy is on.

This type of short vestibule was tested in the laboratory for engineering modelling purposes. The opening was 3 mm high and the re-entrance port was 25 cm long. A 12.5-cm long vestibule was also tested but then the leakage exceeded recommended levels. This type of shield would be very practical for operations that seal large areas of material such as truck covers or tents.

For thicker materials, where the capacitance of this short vestibule is not sufficient to keep the voltage low across the capacitor, other means must be used. A tunnel-like vestibule can be used to reduce the amount of energy escaping (figure A-9). If properly constructed, it can reduce emissions to recommended levels. Tunnel vestibules are often used for heaters with conveyor belts.

The width and height of a vestibule should be kept to a minimum. The size limitation plays a role in harmonic emissions. Harmonics which are multiples of the operating frequency, sometimes extend to multiples of 20 and above. At high frequencies, a vestibule can pass emissions of RF energy unattenuated (see Appendix C). The narrower the vestibule, the fewer harmonics will be able to pass.

The length of a vestibule required to reduce RF leakage to levels at or below recommended levels is difficult to determine. Although a number of factors influence the length needed, experience has shown that the RF field's orientation to the vestibule is very important. This information can be determined with the help of the manufacturer or dielectric heating consultant. If the RF electric field in the enclosure is at right angles to the height of the vestibule, more energy will be coupled into the vestibule than if the electric field is parallel to the vestibule's length. Vestibules should be about twice as long when their width is at right angles to the field as when their length is parallel to it. Where the field is across the vestibule (i.e. parallel to width), and it is high, the length is often twice the width.

The orientation and distribution of the electric field changes along the length of the vestibule. Some vestibules, which have been constructed with the length and width equal for similar field configurations, have been successful. With equal length and width, electric field attenuation towards the end of the vestibule has approached 50 dB if the cut-off frequency (see Appendix C) is much higher (i.e. about 300 times higher) than the frequency being considered. However, the voltage difference induced on the vestibule by the RF field is not known, nor is the exact attenuation which depends on the vestibule length.

Electrical safety is another important factor in determining the minimum length. The vestibule should be long enough to prevent an operator from reaching into the vestibule and touching the high voltage electrode(s). Safety considerations alone dictate that vestibules be at least 75 cm.

Attenuation panels attached to the inside of vestibules are needed if the harmonics of the generator's fundamental frequency are above the cut-off frequency of the vestibule, as is often the case. A lossy material that readily absorbs RF radiation may have to be included in the vestibule to reduce the RF leakage to desired levels.

The lossy material is often placed in the upper portion of the vestibule; the higher the percentage of this material that occupies the entire height, the greater the attenuation. Water, or special tiles, is often used. The resistance of the material must be sufficient to provide the required attenuation. Caution should be exercised to avoid the possibility of fires when materials such as carbon-loaded foam or other flammable absorbing materials are used.

The amount of attenuation needed from vestibules is also affected by the amount of stray radiation emitted by other parts of the equipment. Doors or windows in the shield walls may allow radiation to escape, adding to the total amount emitted by the dielectric heater. Vestibule design should provide enough attenuation that the escape of RF energy from other parts of the dielectric heater does not result in exposing the workers to RF levels exceeding recommended levels.

Air ducts can act as good vestibules provided they are properly connected to the shielding on the main heater chassis. The length of the air duct should be equal to twice its diameter or greatest cross-sectional dimension. The duct should be made of a material with good electrical conductivity and connected to the shield with a minimum of slots between fasteners. To ensure high conductivity and to avoid corrosion, at least the first length of the duct closest to the dielectric heater should be made of aluminium. However, some air ducts have become coated with a flammable material that can catch fire and burn the aluminium ducts. To prevent fire damage in these cases, the first length of the duct closest to the dielectric heater should be made of stainless steel and cleaned frequently. No paint should be used because it will impede current conduction and it is flammable. Stainless steel has a sufficiently high melting point that it will not be destroyed by a fire. If the air duct is used, little need exists for a screen over the opening in the shield where the duct is connected. In very wide ducts, connecting straps across (perpendicular to) the narrow dimension of the shield opening is sometimes desirable to shorten long current paths. This will decrease leakage and other undesirable effects such as a voltage variation in an electrode system.

Although vestibules made of a very lossy material would seem to reduce the need for further attenuation, this was not supported by experimental results; perhaps the wall currents were not sufficient for this to occur. Also, the product being heated will cause some attenuation when it extends into the vestibule. However, if the material's resistance is sufficient for it to be heated with an RF field, its resistance will be too high for it to act as an effective attenuator for vestibules.

High frequency power connections

Metallic conductors run between the generator and the applicator of a dielectric heater and carry high currents in most cases. These ungrounded conductors usually have a high voltage as well as a high current. They can also be sources of intense RF leakage unless shielded which involves enclosing them in a duct (see figure A-8). The enclosing duct must have high conductivity contacts with both the generator cabinet shield and the applicator housing. Fasteners used to connect the duct to the generator cabinet and the applicator housing must be closely spaced because any slot between them is perpendicular to the normal current path and will emit radiation. On high-powered heating equipment, a staggered, double row of bolts is sometimes necessary to provide a higher conductive connection and reduce RF leakage to an acceptable level.

The power output conductors (cables, straps, wires, etc.) often have bends to reach between the desired positions of the generator and the applicator. Such bends may create gaps in the conductors that are across the current path and are parallel to the inner conductor of the connecting system. Therefore, connections to bends such as elbows must also have high electrical conductivity. Joints in the conductors should be soldered to such bends. A well-soldered joint eliminates the possibility of gaps across current paths.

Any shielded enclosing ducts with inner, high-power conductors should be as short as possible. They should be well under one-fourth the wavelength unless special electrical circuitry is used to ensure proper energy transfer.

For small heaters, metallic heating (flue) pipes or gutter downspouts are a good outer conductor. The joints, which are made like stove-pipe joints, make high conductivity connections between sections, with minimal RF energy leakage. However, these joints must be tightly pushed together and maintained in this condition to reduce RF leakage over the lifetime of the heater.

3. Summary of control technology

Several methods for reducing exposure around RF heaters have been investigated that are presently used by both the manufacturers and the users of such RF equipment. Some exposure controls, such as moving the operator away from the applicator electrodes during sealer operation, can be effective, but they can also be ignored by the operator. Another exposure control – the use of shuttle trays – can reduce operator exposure by increasing the source-operator separation distance. This method can increase the machine's productivity simultaneously because one tray can be loaded while the other is being processed.

Exposure controls consist primarily of proper grounding and shielding (box enclosures and vestibules). Grounding can sometimes be very effective in reducing RF exposures. Box shields that completely enclose the RF applicator electrodes can reduce the RF energy significantly and can be used on both new and existing equipment. The RF heaters can also be effectively shielded using other principles given in this publication (such as vestibules and tunnels). Screen rooms (a room totally surrounded by metal) enclosing dielectric heaters can be used to reduce RF interference with communications equipment outside the screen rooms. However, operators inside screen rooms can receive greatly increased exposures from the heaters enclosed within such rooms.

The electric and magnetic field exposures of dielectric heater operators can change dramatically when the shielded equipment's configuration or use is altered. Such changes include alterations in heater shielding and grounding.

Appendix B – Radiofrequency characteristics of capacitors and inductors and implications for shielding

Understanding the electrical characteristics of capacitors and inductors and their reactances at radiofrequency (RF) frequencies is essential to shield RF heaters successfully. These characteristics will be compared at the powerline frequency (50/60 Hz) and at a typical RF heating frequency (27 MHz). The comparisons will emphasize the dramatic differences in these characteristics between these frequencies and their important implications for successful shielding of RF heaters. Failure to account for these differences in designing heater shielding and assuming that familiar 50/60 Hz or DC electrical characteristics apply can result in unsuccessful attempts at shielding which may increase operator exposure.

Capacitors

Any two conductors that are completely electrically insulated from each other by air or some non-conductor, such as wood, porcelain, or plastic, can store a small amount of electrical charge between them. Electrons can be removed from one conductor (plate) and carried to the other conductor. If this is done, a small voltage difference will be present between the two conductors generating an electric field between the plates. The two conductors form a "capacitor".

For DC, the voltage scene will be a battery. At power-line frequencies, the voltage changes direction (or polarity) 50/60 times per second. At 27 MHz, it reverses polarity 27,000,000 times each second. Due to the rapid oscillation at the higher frequencies, the current will be less inhibited (less time to charge the capacitor). Thus the current is more likely to be larger at the higher frequency.

Ohm's law mathematically relates the amount of current flow in a circuit to the amount of voltage in the source. Equation B1 shows how the law is normally written for DC sources:

$$I = V / R \qquad \text{(B1)}$$

where: I is the current in amperes
V is the voltage in volts
R is the resistance in ohms.

This law is similar for AC circuits:

$$I = V / X \qquad \text{(B2)}$$

This reactance is composed of two components, the resistance (R) and a second part due to capacitive and/or inductive reactance. These latter do not cause a power loss (heating) from current flow, while the resistance (R) does.

The value of capacitive reactance may be calculated from equation B3:

$$X_c = \tfrac{1}{2}\, \pi f C \qquad \text{(B3)}$$

where: X_c is the capacitive reactance in ohms
f is the frequency in Hz
C is the capacitance in farads.

At RF heating frequencies it is more practical to express frequency in terms of MHz and capacitance in terms of either microfarads (10^{-6} farads) or picofarads (10^{-12} farads).

Note that raising the frequency reduces the capacitive reactance and that reducing the reactance increases the current (as shown in equation B2).

Capacitors come in various sizes and shapes. A common configuration is two plates electrically insulated from each other by an air gap or dielectric material. In the case where the thickness of the dielectric material equals the distance between the plates, the capacitance between the plates may be calculated from equation 134:

$$C = A\,e/d \tag{B4}$$

where: C is the capacitance
A is the total area of one plate
e is the relative dielectric constant of the material between the plates with respect to vacuum,
and: d is the spacing between the two plates.

The dielectric material usually occupies the entire space between the two plates. However, capacitance can be inadvertently created by parts of an electrical circuit. Gaps between separated wires, plates, an open switch or partial metallic parts of an RF heater can result in a "stray" capacitance. Thus there is no such thing as a complicity open circuit.

Inductors

Any conductor carrying AC current has associated with it a magnetic field that alternates in direction and magnitude with the AC current that produces it. It is also true that any magnetic field that is alternating in direction and magnitude induces a voltage in any other conductor near it. Thus the magnetic field surrounding the current-carrying conductor causes a voltage to be induced in the conductor itself that acts to reduce the original current. It opposes the original current and is therefore known as "inductance". This inductance also has an associated reactance. More rapid field variating results in a higher induced voltage. The higher the speed of growth and decay of the RF field, the higher the voltage induced in a conductor by the magnetic field. Thus the inductive reactance increases with RF frequency. The current in an inductor decreases as the RF frequency increases.

The equations for finding the inductance of a conductor are complex and need not be considered here. However, a few "rules of thumb" will be given. A small diameter round conductor has much more inductance than a large diameter round conductor, or a wide flat conductor with a large area. A long conductor has more inductance than one that is short. The introduction of materials having appreciable magnetic permeability, such as iron, into a conductor changes its inductance. More important, the magnetic materials add to the conductor's resistance and to the power dissipated in it. These general statements are true for any conductor. An equation for a specific conductor is complex, and depends greatly on the location of the current in the conductor.

Equation B5 relates inductive reactance with frequency and inductance:

$$X_L = 2\pi f\,L \tag{B5}$$

where: X_L is the inductive reactance in ohms
π is the mathematical constant 3.14159
f is the frequency in Hz
and: L is the inductance in henries (H).

In RF heating, the frequency is usually specified in MHz and the inductance in microhenries (µH) ($1\ \mu H = 1 \times 10^{-6}$ H).

The variation of conductor inductive reactance with frequency has many practical and important implications (especially at 60 Hz and 27 MHz). At 60 Hz, a floor lamp can be conveniently connected to a wall socket with a few feet of insulated wire. At 60 Hz, the reactance of this extension cord is not important, but its resistance may be. The conductor must have a low enough resistance that it can carry the current without creating excessive heating and voltage drops. Like capacitance, inductance has a reactance associated with it. At 60 Hz, a wire several feet long has a negligible reactance. At 27 MHz, it is 450,000 times as great and can be very important in affecting the voltage drops and current flow through the wire.

Inductances of greatest interest for RF heating applications are those made from coils of wire. Equation B6 can be used to find the inductance of a single layer solenoid coil (i.e. a single layer of wire wrapped around a right circular cylinder):

$$L = (r^2n^2)/(23r + 25b) \qquad \text{(B6)}$$

(English units)

where: L is the inductance in microhenries
r is the coil radius in cm
n is the number of turns of wire in the coil
b is the length of the coil from one end turn to the other end turn (cm).

The application and implications of equations B6 and B5 are illustrated by the following example. Assume a round coil of ten turns, with a radius of 2.5 cm and a length of 5 cm (two turns per cm). Such a coil could be used as an RF choke coil in an RF heater generator. Using equation B6 above, this coil has an inductance of 3.41 μH. At 27 MHz, the inductive reactance is 582 ohms; at 60 Hz, it is 0.0013 ohms. At 10,000 volts, the current in the coil at 27 MHz will be 17.2 A (see equation B2). However, at 60 Hz, the current will be about 7,692,000 A (assuming there is enough power to supply this current and voltage). The ratio of the two currents is about 450,000:1, as expected.

These equations illustrate that electrical laws apply at high frequencies just as they do at power-line frequencies. The major reason that capacitor and inductor characteristics are so different at high frequencies is because they are frequency dependent. This dependence is proportional to the ratio of the two frequencies involved – 450,000:1 in these illustrations. Since the frequency range used in dielectric heating is about 2 to 120 MHz, the ratio of the power-line frequency (50/60 Hz) to dielectric heating frequencies can range from about 33,000:1 to 2,000,000:1.

Particularly at the high frequencies used in RF heaters, current does flow across what appears to be an open circuit in a DC analysis. The reactance of even small capacitances is never very high at high frequencies (1 picofarad has a reactance of only about 15,915 ohms at 10 MHz and about 1,592 ohms at 100 MHz; a 1 picofarad capacitor has parallel plates about 5 cm (2 inches) square with a 2.5 cm (1 inch) air spacing between them). Thus at dielectric heating frequencies, significant currents flow between conductors lying close to each other (i.e. within a few centimetres), or conductors lying close to the walls of a shielded enclosure.

Similarly, at dielectric heating frequencies, two points connected by a strap conductor (i.e. an inductor) may not be at the same voltage with respect to another point in the circuit even though the two points are connected by a strap conductor that would provide a good DC short circuit.

The voltage difference can also be large where the RF current flowing through the strap is large. For example, an RF current of 1,500 amperes in a strap 20 cm (8 inches) wide and only

25 cm (10 inches) long had a voltage drop of 5,000 V at 22 MHz. In this example, the inductive reactance of the strap was calculated to be about 3.33 ohms and the inductance was about 0.024 mH, which is small, but certainly not negligible in terms of its effect on RF voltage and current.

Appendix C – Resonant conductors and waveguides: Applications to shielding

All alternating currents and voltages can produce energy that radiates into space. At low frequencies (e.g. 50/60 Hz), the wavelength is so long (5×10^6 m) that an efficiently radiating antenna cannot be made. However, very good antennas can be made easily (and inadvertently) at radiofrequency (RF) heating frequencies. Unintended antennas such as metal pipes, light fixtures, and other metal objects can couple RF energy from nearby RF heaters and add significantly to worker exposure. Thus a good understanding of antenna operation versus wavelength is needed to minimize the RF energy coupled to these conductors which can increase worker exposure near a leaking heater and at remote locations.

Resonant conductors

At certain lengths, sometimes called resonant lengths, conductors will both absorb and radiate RF energy very readily. These lengths are related to the wavelength (or the frequency) of the RF radiation. The resonance phenomenon occurs if the length of a conductor acting as an antenna is one-fourth the wavelength or an integral multiple of a one-fourth wavelength. Under resonance conditions, an electrical conductor will absorb and radiate the most RF energy. For example, a 2.8 m (9.1 ft) long metallic conductor one-fourth the wavelength at 27 MHz) will *most efficiently* absorb and reradiate RF energy from a nearby 27 MHz dielectric heater. The RF energy reradiated from this metallic object can add to operator exposure or that of other workers. At twice the 27-MHz fundamental frequency (i.e. the second harmonic), the length of the metallic conductor need be only 1.4 m (4.6 ft); at three times the frequency, it need be only 0.9 m (3 ft) long, etc. This is important because many dielectric heaters radiate considerable RF energy at harmonic frequencies in addition to the fundamental or operating frequency.

The most effective way to minimize this reradiation from metal objects is to minimize the RF energy leakage reaching the conductor which can act like an antenna. Changing the conductor length may be helpful in reducing reradiated RF energy, but a resonant length must not exist over the entire frequency range (including the fundamental and harmonic frequencies) at which the generator will operate. When harmonic frequencies (integral multiples of the fundamental operating frequency) exist, eliminating all RF energy absorption and reradiation for a conductor can be very difficult, if not impossible. For example, if the RF heater generator operates with a range of fundamental frequencies of 25-30 MHz, the harmonic ranges are:

2nd harmonic 50 to 60 MHz

3rd harmonic 75 to 90 MHz

4th harmonic 100 to 120 MHz

5th harmonic 125 to 150 MHz

6th harmonic 150 to 180 MHz

7th harmonic 175 to 210 MHz

8th harmonic 200 to 240 MHz

... etc.

Because the harmonic frequency ranges overlap at frequencies above the 5th harmonic, the frequency and conductor length cannot be adjusted to avoid RF energy absorption and reradiation. Also, in many plants containing RF heaters, the conductors are much longer than 3 m (9.11 ft), making it more difficult to minimize RF energy absorption and reradiation. Consequently, the only sure way to reduce reradiation of RF energy from a nearby conductor and potentially higher worker exposures is to reduce the RF energy leakage reaching that conductor.

Waveguides

A waveguide is a hollow pipe, tube or duct, made of electrically conducting material, that is sufficiently large for an RF field to exist in it and pass through it readily. An understanding of waveguide concepts is necessary for proper design of dielectric heater shielding. Vestibules (i. e. waveguides below cut-off) are used where material must be carried into and out of the dielectric heating field with minimal RF energy leakage. In this case, the shield must have an opening for passage of materials. As seen in Appendix A, "Shield theory, design and construction", an opening in any shield will permit RF energy to be emitted from the opening. The purpose of the shield, of course, is to minimize RF radiation leakage.

A waveguide transmits electromagnetic energy only above a certain frequency, called the cut-off frequency. Below this frequency, RF radiation is not transmitted, but is attenuated as the length of the waveguide is increased.

The cut-off frequency of a waveguide or vestibule is:

$$F_c = 150 / 2w$$

where: F_c is the cut-off frequency in MHz
and: w is the width of the waveguide or vestibule in metres (feet).

With a 12 m (4 ft) wide waveguide, the cut-off frequency is 125 MHz which is well above the common dielectric heating frequency of 27 MHz. This cut-off frequency is between the 4th and the 5th harmonic of 27 MHz (108 MHz and 135 MHz). Consequently, all the frequencies above the 4th harmonic will pass through the 1.2 m (4 ft) wide vestibule without significant energy loss.

If the RF frequency is at or very near the cut-off frequency, experience indicates that the coupling from the waveguide to the space beyond it is very good. The waveguide acts as an efficient antenna and radiates RF energy from its opening. However, the attenuation built into the waveguide reduces this effect.

If the waveguide walls have high resistance or attenuation, most of the RF energy coupled into the input will be lost as it passes through the waveguide. In this case, it is converted to heat in the lossy waveguide walls. The energy that leaves the waveguide is weaker than when it entered, which is desirable for shielding.

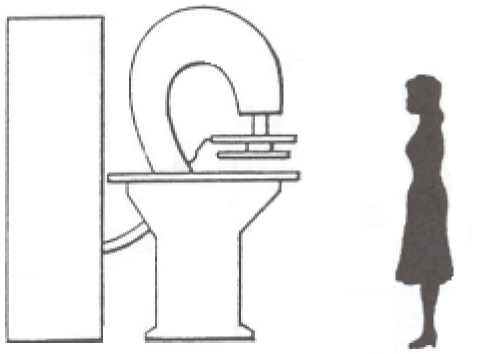
Appendix D – Effects of ground planes and reflectors on operator exposures

Simple models can be used to assess the effects of large nearby metallic objects on the exposure of operators and other personnel. In particular, the effect of metallic walls and floors (as in a shielded room) can be analysed to give exposure information. Radiofrequency (RF) heaters are often placed inside shielded rooms to reduce RF interference with communication sources for compliance with national FCC regulations, such as the FCC in the United States.

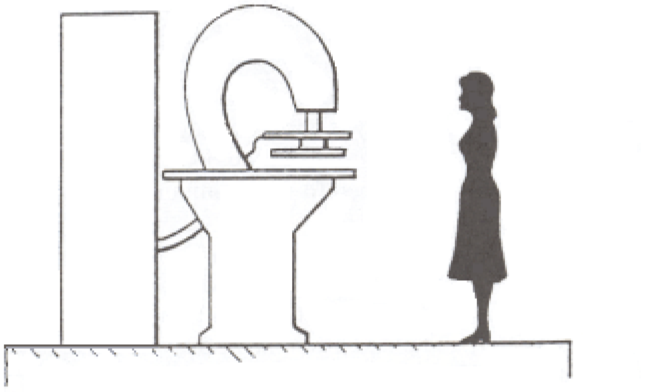
A simple analogy to antenna theory is useful for estimating the increase in absorbed power due to the energy reflected from the conducting walls and floor of the shielded room. At RF frequencies, the human body absorbs energy from an incident electromagnetic field in much the same way that a simple dipole antenna does. That is, the incident electromagnetic field causes currents to flow in the body. Because the human body is a lossy conductor, these currents heat the tissues. The amount of heat deposited in a particular part of the body is proportional to the square of the current density in that part of the body. Therefore, maximum heat is produced where a maximum current density exists.

Figure D1 depicts three workplace exposure situations that may occur when using RF heaters and may affect worker exposures. In figure D-1a, an RF heater and an operator are in an unshielded room with no metallic objects and no metal floor or buried pipes. Figure D-1b depicts a room with a metal floor that acts as a ground plane. Both the heater and the operator's feet are grounded to the floor; the effect of a metal floor may also be created by the steel reinforcement used in concrete floors. Figure D-1c shows a heater and operator in a room with a metallic wall that is not in contact with the operator or the heater. In some situations, such as in a shielded room, the operator is exposed to the combined effects of a metallic floor and wall.

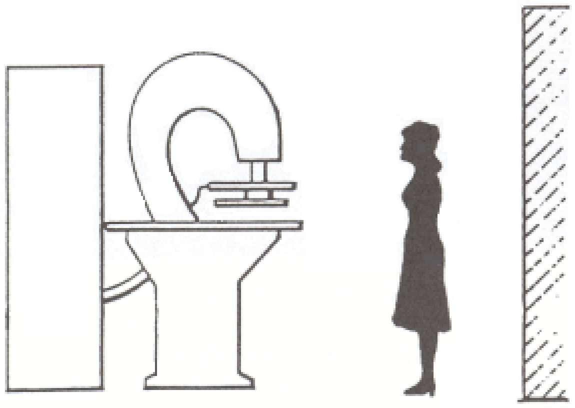
Figure D-1. Workplace exposure situations when using RF heaters



a) Free space exposure



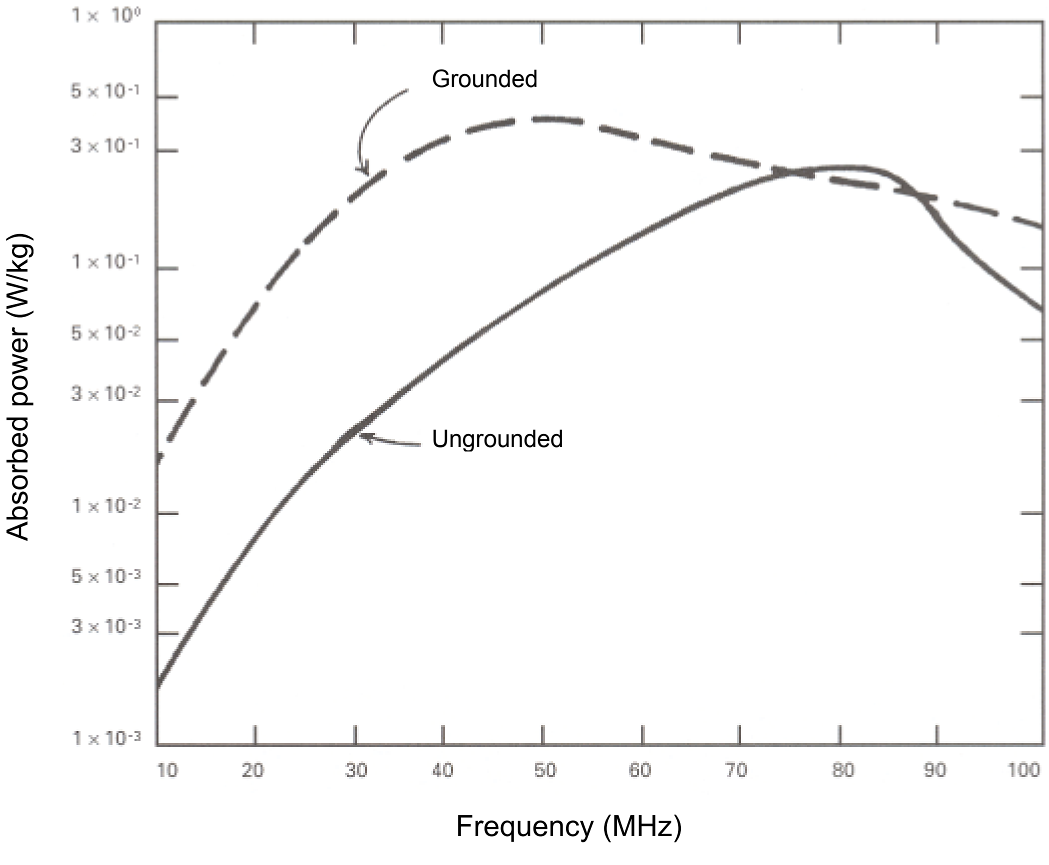
b) Exposure with ground plane



c) Exposure with reflector

The operator's body and a resonant length conductor (see Appendix C) are used to predict the frequency dependence of the absorbed power in the operator. This frequency dependence is associated with the whole-body resonant absorption (i.e. maximum RF energy absorption) by the operator's body. Figure D-2 shows that the maximum RF absorption occurs at 70 to 80 MHz for the ungrounded operators shown in figures D-1a and D-1c. The peak absorption shifts downward to 40 to 50 MHz for the grounded operator shown in figure D-1b. Because of the distribution of current within the operator's body, the grounded operator will absorb more RF energy in the ankle and lower leg than the ungrounded operator. Detailed calculations (Gandhi et al., 1979) for a 27-MHz field have shown that a grounded individual will absorb five to seven times the power absorbed by an ungrounded individual. The operator in front of the reflecting wall (figure D-1c) could absorb five times more power than without the reflecting wall (Gandhi et al., 1979).

Figure D-2. RF absorption for grounded and ungrounded operators



The presence of ground planes and reflectors may also reduce the total RF power absorbed by workers. This can occur when the reflected and incident radiation interact and create a minimum of the dominant exposure field at the operator's location.

Likewise, if the operator is very close to the radiating source (the usual case for RF heaters), the effects of the reflector behind the operator may be lessened. However, the operator's exposure could be higher if he/she is closer to the RF heater and the higher RF fields present there. Each situation is unique and these examples must be considered only as guides. Operator exposures depend on the workplace conditions and each situation must be evaluated individually. Because so many factors can affect the worker's exposure, the only reliable method for assessing these exposures is through periodic radiation measurements.

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