EQUIPMENT SAFETY FOR MICROWAVE AND RADIO FREQUENCY PROCESSING

ABSTRACT

The use microwave technology is increasingly being investigated for existing and new materials processes. Particular advantages and benefits have been identified for applications in ceramics. As progress is made towards commercializing these applications, those who are unfamiliar with the processing equipment will need to be aware of the associated safety issues. This paper reviews the current literature on related health effects, regulatory safety standards, equipment designs practices and guidelines for safe equipment use.

INTRODUCTION

Whenever microwave or radio frequency (RF) technology is considered for a particular industrial process, one of the first concerns to be raised is “Is it safe?” Quite often the answer is “Yes, depending on how you use it.” Admittedly, such a response is hardly comforting to a key decision maker who is new to or unfamiliar with microwave processing. Without a thorough understanding of the issues regarding the safe use of microwave technology, a cautious and slightly skeptical manager might well be reluctant to invest in a new process having unforeseen and potentially costly consequences.

An understanding of a few basic topics relating to the health and safety issues involved in microwave and RF (hereinafter the term “microwave” includes RF frequencies) processing provides confidence that it can be as safe as most conventional heating technologies. The most important topics relate to a) known health effects from working with microwave equipment, b) established regulatory standards and guidelines for safety equipment use, c) design practices of industrial equipment that ensure adherence to safety standards, and d) recommended practices and procedures for safe equipment operation.

The following sections present an overview of these topics, highlighting certain key fundamentals that will help provide a general understanding and working knowledge for ceramists involved in materials research and process development. Certain topics, particularly equipment design, require a much greater degree of study to fully understand all aspects of importance. As specific applications progress towards commercialization, ceramists will prudently seek the advice and involvement of experts in these fields to ensure a successful and safe implementation of their technology.

HEALTH EFFECTS RELATED TO MICROWAVE EQUIPMENT

Public concern over the health and safety issues relating to human exposure to electromagnetic fields has increased dramatically in recent years. Much of this concern is due to the rapid proliferation of cell phone use worldwide, even though electromagnetic fields are emitted by numerous other natural and man-made sources.[1] As a result, numerous studies have been and are being conducted to determine the health effects and risks. Findings covering a broad range of frequencies have been published.

Of particular interest are studies involving the “non-ionizing” microwave frequencies, generally defined as ranging from 3 kHz to 300 GHz, whose energy levels are an extremely small fraction of that required to ionize tissue and disrupt cellular DNA.[2] This is in contrast to Gamma and X-ray frequencies having energy levels sufficient to ionize (displace electrons within the atomic structure of) exposed materials. The primary – and as yet, the only definite, proven - effect in biological materials of microwave radiation exposure is thermal heating[3], which presents a potential health risk due to overheating. However, much of the public concern has been focused on whether any athermal effects exist and pose a health risk.

Cancer Related Effects of Microwave Exposure

Numerous recent epidemiological studies on the relationships between various cancers and exposure to electromagnetic fields have been reviewed by Elwood.[4] Sources of emissions studied included radio and television transmitters, cell phones, radar and occupational environments, while cancer types studied included brain, lung, testicular, lymphatic and hematopoietic cancers, adult and childhood leukemia and Hodgkin's disease. Not all studies gave details of the level of exposure, but those that did indicate exposure levels were within established regulatory or otherwise recommended guidelines where such guidelines exist.

The results of these studies are inconsistent at best and show no statistically significant evidence of a link between incidences of cancer and exposure to electromagnetic fields at microwave frequencies. In most cases the incidence rate showed no significant increase in risk from casual exposure. For example, some studies on broadcast transmitters indicated a marginally increased risk amongst residents near one such emission source but no increased risk near other similar sources. One study on occupational exposure actually showed a decrease in mortality rate that was attributed to a "healthy worker effect".

Non-Cancer Related Effects

Clinical and epidemiological studies of effects on cataracts, sexual function and fertility, spontaneous abortion and birth defects, neurological and cardiovascular disorders, and other non-cancer epidemiological effects have been conducted.[1] As in the cancer related studies, the results are largely inconsistent and, in some cases, subject to scrutiny due to confounding by other causes. For example, inconsistent findings between studies on cell phone use conducted in different countries were suspected to be partly due to cultural influences.

Where conclusive evidence of an effect exists, it has mostly been shown to be due to a thermal response of the tissue. An interesting example is the auditory response from high intensity pulse modulation of electromagnetic fields, whereby thermal expansion in soft tissues in the head is conducted to the ear.[5] This annoying effect, however, is not a health risk provided the heat absorption is not sufficient to cause tissue damage. On the other hand, the eyes and testes are considered particularly vulnerable to excessive heating due to their comparative lack of blood flow as a heat dissipation mechanism.

While the above mentioned studies have failed to provide convincing evidence of a strong relationship between exposure and cancer, it should be noted that one cannot conclude from these results that other possible hazards do not exist. Furthermore, most studies generally cover a relatively short time frame, thus no conclusions can be made as to the likelihood or risks of any long term effects.[6]

Thermal Hazards to Microwave Exposure

Thermal injury is a time-temperature phenomenon whereby the rate of tissue cell protein destruction exceeds its rate of self-repair for an amount of time sufficient to terminate cell metabolism.[7] The rate of protein destruction increases with temperature, thus decreasing the time required for thermal injury as illustrated in Figure 1.

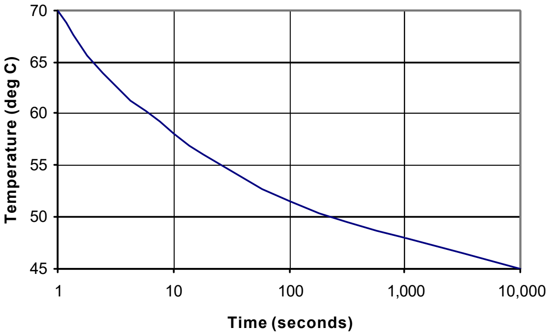

Figure 1. Threshold temperature vs. time at temperature for skin burns.

The rate at which a given volume of tissue is heated by electromagnetic energy varies according to frequency and power density. Higher frequencies have a shorter penetration depth and thus will dissipate heat in a more concentrated volume nearer the skin surface. Similarly, a focused or "contact" source of power concentrates its energy within a smaller volume, resulting in a greater rate of local temperature rise. Therefore, a lower power level is required to cause burns by high frequency and/or focused exposures.[8] As examples, a) a 20 Watt laser can cause a burn within a few seconds whereas a 150 Watt light bulb can make a person feel comfortably warm for hours, and b) a given power level at RF frequencies will cause a lower rate of temperature rise at a given location in a human body than at microwave frequencies due to the difference in penetration depth.

Cardiac Pacemakers

Many electronic devices can be subject to faulty operation if not properly shielded to prevent radio frequency interference (RFI). While some very early pacemakers were designed without RFI shielding, most or all pacemakers manufactured since the mid-1970's include such shielding. A series of studies conducted to determine the maximum threshold of interference for safe operation indicated that newer models could withstand levels well above 1 mW/cm^2.[9] As a result, an editorial was published by the American Medical Association stating that the pacemaker interference issue "does not at this time constitute an important clinical problem."[10]

High Voltage

Although the health effects of electromagnetic exposure seem to generate the most public interest and concern, the hazards associated with high voltage are of equal importance to those working with industrial microwave equipment. Almost all microwave generators contain high voltage circuitry which can be lethal while the equipment is in operation and, in some cases, during non-operation depending on the equipment design. Most microwave generators contain circuitry that stores a high voltage electric charge in one or more capacitors. Although most do, not all designs provide for automatic safe discharge of stored energy, thus creating a potential hazard to service personnel.

Injury or death may result when the human body becomes part of an active electrical circuit having a current capable of overstimulating the nervous system or damaging internal organs.[11] The extent of injury due to exposure to high electrical energy depends on the type (AC or DC) and magnitude of electrical current, the path in which the current flows through the body, and duration of current flow. Direct contact with electrical energy, such as due to a high voltage arc to the body, often results in burns to the skin and internal tissue.

A 50 or 60 Hertz (Hz) alternating current (AC) of 20 milliamps (mA) flowing through the chest area for an extended period can cause death due to respiratory paralysis, whereas a current of 100 mA can cause ventricular fibrillation.[12] Under dry conditions, the body's resistance is approximately 100,000 Ohms, while wet or broken skin can reduce the resistance to 1,000 Ohms. Thus, exposure to common 120 Volts AC mains voltage under dry conditions will produce a current of only 1.2 mA which is barely perceptible, but under wet conditions the resulting 120 mA current can cause death due to ventricular fibrillation. High voltage energy can further reduce the body's overall resistance to 500 Ohms by breaking down the skin layer. This results in extremely high current flow which can cause cardiac arrest and internal organ damage.

The human body can tolerate up to five times the level of direct current (DC) than AC.[13] Typical power supplies used in microwave ovens generate approximately –4,000 Volts which can result in a body current of 8 Amps. Industrial microwave generators typically generate much higher voltages. Thus, even with the higher tolerance threshold, exposure to these voltages can quickly cause death due to cardiac arrest.

REGULATORY STANDARDS FOR SAFETY

Electromagnetic Exposure

An important parameter used in establishing guidelines for reducing the risk of injury due to exposure to electromagnetic field is the "specific absorption rate" (SAR) which is usually expressed in units of Watts per kilogram (W/kg).[14] Numerous studies have determined the minimum SAR at which a risk of thermal injury exists, and various international government agencies have adopted standards to limit exposure such that the maximum safe SAR is not exceeded.[1,3,8]

Most European countries have adopted guidelines established by the International Committee on Non-Ionizing Radiation Protection (ICNIRP) for maximum safe occupational and general public exposure levels for whole-body average SAR and localized SAR.[15] These guidelines give rise to reference levels for plane wave power densities as given in Table 1 for frequency ranges of interest.

Table 1. ICNIRP recommended exposure reference levels for plane wave power densities (mW/cm^2).

Frequency Range	Occupational	General Public
10-400 MHz	1	0.2
400-2000 MHz	f/400	f/2000
2-300 GHz	5	1

The International Electrotechnical Commission (IEC) has specified a standard for industrial microwave heating equipment which defines maximum exposure levels for equipment operating under "normal conditions" (as the equipment was designed or intended) and "abnormal conditions" (such as with an empty cavity).[16] Under this standard, which is applicable to equipment operating in the frequency range from 300 MHz to 300 GHz, the power density is measured at least 5 cm from any accessible location on the equipment and limited to 5 mW/cm^2 during "normal" operation and 10 mW/cm^2 during "abnormal" operation.

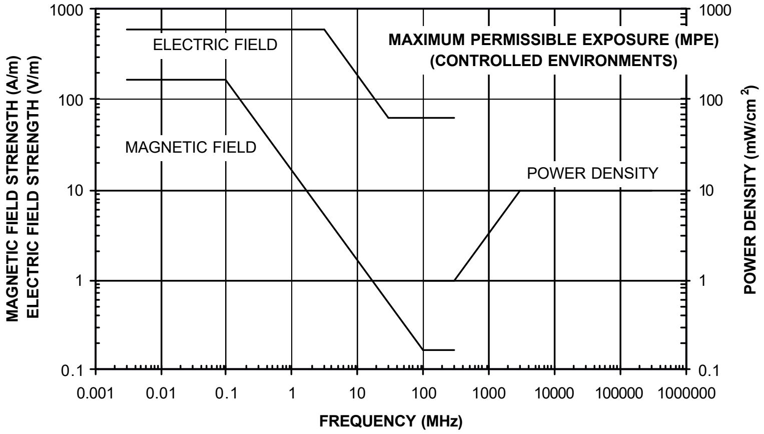

Figure 2. ANSI/IEEE recommended maximum permissible exposure (MPE) for controlled environments per standard C95.1-1999.

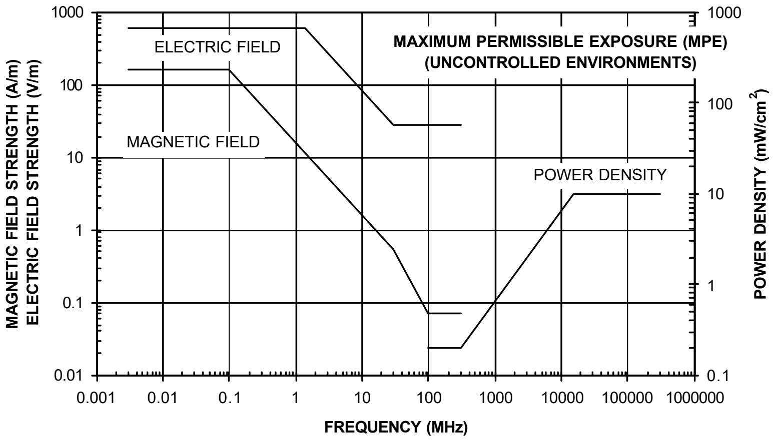

Figure 3. IEEE recommended maximum permissible exposure (MPE) for uncontrolled environments per standard C95.1-1999.

In the USA, the Federal Communications Commission (FCC) has adopted standards based on recommendations developed by the American National Standards Institute (ANSI) and Institute of Electrical and Electronics Engineers (IEEE) as defined under IEEE standard C95.1.[17] This standard defines the maximum permissible exposure (MPE) averaged over a period of six minutes for "controlled environments" (where persons exposed generally are either cognizant of the potential for exposure or simply passing through the environment) and "uncontrolled environments" (where persons exposed have no knowledge or control over their exposure) as summarized in Figures 2 and 3. Table 2 highlights MPE values for specific industrial, scientific and medical (ISM) frequencies commonly used in materials processing applications.

Table 2. IEEE recommended maximum permissible exposure (MPE) for plane wave power densities (mW/cm^2) at ISM microwave frequencies.

Frequency	Controlled Environments	Uncontrolled Environments
915/896 MHz	3	0.6
2.45 GHz	8.2	1.6
5.8 GHz	19	3.9

The Occupational Safety and Health Administration (OSHA) has established a regulation applicable to frequencies from 10 MHz to 100 GHz whereby exposure is limited to no more than 10 mW/cm^2 measured at 5 cm from the emission source and averaged over a 0.1 hour period.[18] OSHA further establishes regulations for hazard labeling of equipment.

High Voltage and Equipment Safety

Safety guidelines have been established for voltages used with and generated by microwave equipment. Although the National Electrical Code (NEC) defines high voltage as greater than 600 Volts AC[19], various safety requirements for electrical wiring apply to all voltages. These requirements, applicable in the United States, include circuit overload and ground fault protection devices, wire sizes and materials, conduits and shielding, enclosures and workspace clearances. Specific requirements apply to industrial machinery which includes most microwave processing equipment. Similar standards and requirements have been established internationally by British Standards (BS), European Committee for Electrotechnical

Standardization (CENELEC), International Electrotechnical Commission (IEC), and Japanese Industrial Standards (JIS).

Microwave generators, power supplies and other components that make up industrial processing systems are governed under various standards established for product safety. Underwriters Laboratory (UL) and American National Standards Institute (ANSI) standards generally apply to products used in the United States, compliance to which is evaluated and certified by a Nationally Recognized Testing Laboratory (NRTL). Similarly, products used internationally must also comply with safety standards established within the countries where used, including those by Standards Council of Canada (SCC), the European Union "Low Voltage"[20] and Machinery[21] directives (CE Mark) and, to a limited extent, the Chinese Compulsory Certification (CCC Mark). Certain industry groups also have specific requirements for equipment, such as the SEMI S2 Environmental, Health, and Safety Guideline for Semiconductor Manufacturing Equipment.[22]

EQUIPMENT DESIGN FOR SAFETY

Microwave processing systems generally consist of three main elements: a microwave power generator, power delivery (waveguide) components and a process cavity (applicator). Systems can be as small and simple as a typical residential microwave oven or as large and complex as a industrial food processing conveyor. Many different types of generators and waveguide components are available and can be configured in a variety of ways depending on the process characteristics.[23] However, they all perform essentially the same function: to safely and reliably generate and deliver microwave power to the process cavity.

The process cavity itself can also be configured in many ways, but its primary function is to effectively "couple" the delivered microwave energy to the material being heated in such a manner as to meet the requirements of the heating process. Process cavities are generally designed for either "batch" or "continuous" material processing, while some are designed for semi-continuous flow.

Many common design practices for safety apply to all types of commercial and industrial equipment used in materials processing as defined in the standards mentioned above. In addition to these commonalities, microwave processing systems utilize several features that are uniquely necessary to ensure reliable and safe operation. Most pertain to suppression of emissions, or "microwave leakage," while others may be specific to certain materials processes.

Microwave Leakage Suppression

Once high power microwave energy is generated, it must be contained almost entirely within the processing system in order to comply with regulatory standards for safety and interference. The term "Faraday cage" (British physicist Michael Faraday, 1791-1867) has often been used to describe a microwave cavity in that it is an enclosure capable of blocking the entry or exit of electromagnetic waves. The ideal Faraday cage is a metallic enclosure with no holes, broken seams or openings of any kind. For all practical purposes, the term also applies to microwave generators and waveguide components. But for obvious reasons, no practical microwave processing system can be a completely continuous metallic enclosure as it must, as a minimum, allow access to its interior for entry and exit of the material to be heated. In most cases it must also have seams or openings suitable for assembly, viewing, ventilation, sensor insertion and other process related necessities.

Material Entry/Exit for Batch Processing: The most common type of opening in a microwave heating system is the door of a household microwave oven. One can easily see that the door does not make complete contact with the oven cavity, leaving the casual observer to wonder what is preventing the microwave energy from radiating out of the oven. The door is designed with a nondissipative "reactive" ¼-wave choke along the opening perimeter that effectively blocks the transmission of energy at a specific frequency.[24] Most industrial systems having batch cavities utilize such door seals, although some employ a direct contact seal using a woven metal mesh gasket or springy beryllium copper fingerstock. In either case, the door seal design is robust and capable of withstanding repeated openings without degradation in performance throughout the life of the equipment.

Material Entry/Exit for Continuous Processing: Continuous flow process systems require openings that allow for material entry and exit on a continuous basis, such as for conveyorized and/or extruded product. Depending on the size and geometry of these openings as required for the process material, the means for suppressing microwave leakage is either reactive, as in the case described above for door seals, or dissipative whereby microwave energy is actively absorbed within the structure of the opening, or a combination of both.[25] In either case, microwave energy is attenuated at some rate as it passes through the opening. The rate of attenuation through these openings depends on the opening size and attenuation method used. Thus, the opening typically has some length in order to attenuate the energy to sufficiently safe regulatory levels, with larger openings generally having a lower attenuation rate and requiring greater length. The term "tunnel" is often applied to openings for continuous flow processing.

Cavity Ventilation and Viewing Ports: Almost all microwave ovens have a window in the cavity door through which the cooking process can be observed. Close inspection of this window reveals the presence of a screen made of tiny perforations in thin metal. Each hole in the screen acts as a high-pass filter that effectively blocks the transmission of electromagnetic energy at microwave frequencies yet allows transmission of visible light. Other openings in the oven cavity, such as for ventilation and illumination, are perforations in the cavity wall that function in a similar manner.

As microwave energy propagates through a waveguide or other restricted path, it is attenuated exponentially as a function of wavelength and the size of the path according to

$$P_1 = P_0 e^{-2\alpha x} \tag{1}$$

where P_1 and P_0 are the power densities at the path exit and entrance, x is the path length and α is the rate of attenuation in dB/unit length as energy propagates along the path.[26] Figure 4 illustrates the rates of attenuation through a circular waveguide as functions of the inside diameter for various ISM frequencies. The diameter at which the attenuation rate approaches zero is the "cut-off" diameter for the respective frequency, and waveguides smaller than this dimension are said to be below or beyond cut-off. These curves are used to determine the minimum screen thickness, or hole "length," that provides the necessary total attenuation for a given perforation hole diameter and power density.

For example, suppose the highest internal power density at a cavity opening is determined to be 1 kW/cm^2 and the regulatory limit to be met outside the cavity is 1 mW/cm^2. Using equation 1, the minimum attenuation constant, α, required for a 0.020" thick screen is 345 dB/inch. Figure 4 then yields a maximum perforation hole diameter of roughly 0.08".

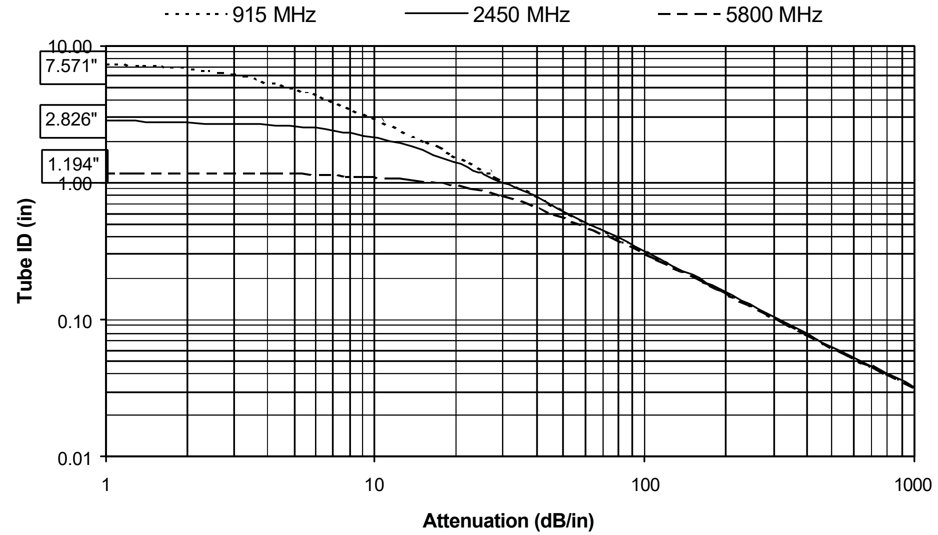

Figure 4. Attenuation curves for circular waveguide at three ISM frequencies.

Cut-off Tubes: The waveguide below cut-off principle is also commonly used for larger unobstructed openings, referred to as "cut-off tubes," such as for optical thermometry, fluid flow, etc. However, the curves in Figure 4 apply only to unfilled tubes. When filled with a dielectric material, the effective inside diameter is increased by a factor equal to the square root of the material's dielectric constant. This lowers the effective attenuation rate and increases the minimum tube length, although it will be counteracted somewhat for high dielectric loss materials that absorb energy propagating through the tube. The analysis is further complicated when the tube is filled only partially or with multiple materials of various dielectric properties, such as when flowing water in Teflon tubing through the cut-off tube.

Feed-thru Openings: Inserting a metallic object, such as a thermocouple probe or wire, through a cavity opening can be extremely dangerous by causing excessive microwave leakage. Unless it is in intimate contact with the opening wall, the metal object in conjunction with the metallic opening wall will have a coaxial transmission line effect, thus allowing microwave energy to propagate freely through the opening and radiate from its end. Materials having a high dielectric constant can also create a similar effect when inserted through a cavity opening, such as passing a small column of water passing through a comparatively large cut-off tube. Electrical wires passing through a cavity opening require special techniques such as capacitive filtering to prevent leakage and other forms electrical interference in the external circuitry. Given the complexities involved with proper feed-thru design, professional advice and assistance should be sought whenever installing feed-thru devices in microwave cavities.

Safety Interlock Devices

Interlock devices are typically defined as mechanical and/or electrical components or sub-systems that prohibit the operation or functioning of other components or sub-systems if certain conditions are not satisfied. In the case of microwave processing systems, this usually applies to the devices that prohibit the operation of the microwave generator if a condition exists that might cause excessive microwave emissions.

Cavity Access: Regulatory standards require interlock devices at all locations where the microwave cavity can be opened without the use of tools. Of course, the most common access point is the cavity door, although many industrial systems have other features that require periodic opening for maintenance or other such purposes. Interlock devices prevent the microwave generator from operating if the opening is not closed, and they are typically designed such that a failure of the interlock device leaves the system in a safe non-operative mode. US government standards applicable to residential and commercial microwave ovens require redundant interlock devices that are concealed and inaccessible, at least one device of which having a means of fail-safe monitoring.[27] IEC standards also require redundant and concealed interlock devices at all cavity access locations, as well as interlocks for the presence and/or flow of material through the cavity if necessary to maintain emissions within the guidelines.[16]

Waveguide Flanges: An often neglected location for microwave leakage due to inadvertent carelessness during equipment maintenance is a waveguide flange connection. Many systems are designed to allow easy disconnection of a waveguide component for routine maintenance, some even without the use of tools. In such cases an interlocking device is required to ensure proper re-assembly before bringing the system back on-line. In fact, literal interpretation of the IEC standards would require interlock devices at all waveguide flange connections, although this practice is rarely found or deemed necessary in industrial equipment.

High Voltage: As described earlier, microwave generators contain high voltage circuitry that can be lethal when contacted inadvertently during operation. For this reason, interlock devices on enclosure access covers are typical of most contemporary equipment designs and required by almost all regulatory standards. These safeguards are generally sufficient to protect service personnel from exposure to stored high voltage energy hazards. Most circuit designs provide for safe electrical discharge within the time required to remove safety covers and gain access the internal circuitry.

Although not required by regulatory standards, many equipment designs also incorporate interlock wiring into electrical connectors associated with inter-modular high voltage circuitry, thus disabling the high voltage circuits whenever these connectors are not properly mated. However, even when the equipment is designed with such protection, quickly disconnecting an electrical cable and exposing its contacts may not allow sufficient time for stored energy to be discharged. Thus, caution must be exercised ANY time an electrical cable is disconnected.

Warning Labels and Visual Indicators

Many regulatory standards require various labels and indicators alerting the equipment operator of a potentially hazardous condition.[3,16,20,22,27] Warning labels are required for both electrical shock and electromagnetic radiation hazards and must indicate briefly a) the nature of the hazard, b) the potential consequences of exposure to the hazard, and c) necessary actions to prevent exposure. Special labels are required for cavity doors and other openings to warn against allowing foreign objects to interfere with the door seals.

Visual indicators are required to alert nearby personnel that the equipment is in operation. These indicators must be plainly visible during normal operating conditions or where personnel might typically be present.

System Architecture and Process Safety

Fire and explosion prevention is particularly challenging as it combines the volatile characteristics of certain materials processes with the unique propensity for ignition in a microwave system.[28] Inert gas purging is commonly used to remove oxygen from the cavity atmosphere, and regular cleaning of interior surfaces helps to reduce the sources of fuel. But these practices may not be practical for or applicable to all processes. The system developer must have a thorough understanding of both the materials process and microwave technology. Recognizing that such hazards often are not completely avoidable, the design must minimize the hazard potential and effectively deal with a hazard event.

There are many other aspects of the overall system design that are considered when minimizing the risks and hazards associated with microwave processing, including walk-in cavity access, high temperatures, automated mechanisms and moving parts.[29] A thorough review of these considerations is well beyond the scope of this paper, so materials process developers are encouraged to seek the advice of equipment experts having experience in similar processes.

GUIDELINES FOR SAFE EQUIPMENT OPERATION

Common sense plays an important role in the safe operation of any product regardless of the magnitude of its associated hazards. Apart from that, a few basic practices and habits should be institutionalized when operating microwave equipment.

Safety Training: Basic first aid treatment and emergency rescue procedures should be a part of a formal safety training program. Many hazards, particularly those associated with high voltage, can be prevented from becoming lethal if immediate rescue action is taken. For example, electrocutions resulting in ventricular fibrillation do not necessarily cause immediate death[11], thus emergency cardiopulmonary resuscitation (CPR) can be administered to potentially save the life of the victim.

Equipment Training: All personnel engaged in operating and/or maintaining industrial microwave equipment should receive proper training to be aware of the hazards associated with their respective tasks. As a minimum, all product user manuals and other documentation provided by the equipment manufacturer should be read and thoroughly understood before attempting operation or service. Safety training should emphasize awareness and recognition of both microwave radiation and high voltage hazards and appropriate responses when identified. In addition, service personnel should be knowledgeable and competent with regard to safe troubleshooting and repair of high voltage circuitry.

Buddy System: Never operate or perform maintenance on industrial microwave equipment while alone. In the event of hazard exposure, the victim may be incapacitated and need immediate medical attention for survival.

Leakage Detection: Every user of an industrial microwave heating system should have on hand or ready access to a high quality microwave leakage detector, also referred to as a microwave survey meter.

Leakage should be checked on a periodic basis and always after any maintenance has been performed on the equipment. Upon detecting excess emissions, the equipment should be immediately shut down and the cause of emissions investigated and corrected before restarting. Also, the leakage detector should be calibrated at least annually to ensure proper operation.

Periodic Maintenance: Many hazards result from inadequate or improper equipment maintenance practices. A formal program of periodic inspection and maintenance should be implemented that addresses all potential hazards and hazard sources. The program should include not only the microwave equipment itself but also any other tools or equipment required for the maintenance tasks. The most basic tasks to be included are a) to inspect for microwave leakage, b) clean the cavity interior and all internal waveguide surfaces, and c) replace damaged or broken electrical connectors even if still functional.

CONCLUSION

While there are indeed many hazards associated with industrial microwave and RF processing equipment, the risks associated with them are no greater than with conventional equipment when proper safeguards have been implemented. Microwave heating technology has been a vital component of industrial production since the 1940’s and will continue to be applied as new materials processes are developed. Newcomers to this technology can develop a sense of security with its use by learning and understanding the basic concepts about health effects, regulatory standards, design safeguards and operational guidelines presented here.

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