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JOULIA

Electrification of industrial processes using induction and microwaves technologies

D4.3

Health and Safety Requirements

ISQ, K-FLEX and ARTIGO

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Project Information

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PROJECT OVERVIEW	The JOULIA project is focused on **transforming energy-intensive industries by replacing traditional fossil fuel-based heating methods with advanced electric technologies**. These industries rely on **high-heat processes**, which are critical for manufacturing products like **rubber, ceramics, and plastics**. By focusing on specific, high-heat applications, JOULIA seeks to **showcase the potential of electrification to decarbonise operations, enhance efficiency, and drive sustainable industrial transformation.**

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0.4	03/12/2025	Final version of the Deliverable	ISQ, CIRCE

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Abbreviations

ALs	Action levels
BR	Basic restrictions
EMF	Electromagnetic fields
ELVs	Exposure limit values
GHz	Gigahertz
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IGBTs	Insulated Gate Bipolar Transistor
kHz	Kilohertz
MRI	Magnetic Resonance Imaging
PPE	Personal Protective Equipment
RF	Radiofrequency
RL	Reference levels
SDS	Safety Data Sheet
SAR	Specific absorption rate

Executive Summary

Joulia project (ID 101138325) aims to demonstrate advanced electric heating solutions to promote industrial decarbonisation through the design and development of induction- and microwave-based heating systems. This campaign will validate their technical feasibility and assess their environmental, health, safety and economic impacts. The demonstration and upscaling will focus in two industrial processes, *i.e.*, rubber flooring vulcanisation and adhesive gluing.

This deliverable ***D4.3 – Health and Safety Requirements – Preliminary report*** of JOULIA project (WP4: T4.3) aims to identify the health and safety (H&S) requirements for the induction and microwave heating systems, based on the analysis of standards, regulations and guidelines; H&S good practices for safe design, installation, operation and maintenance of the equipment; as well as H&S challenges/critical factors, perceptions and needs on the adoption of the innovative technologies. Therefore, each heating technology was first analysed in terms of how it works, and the hazards and risks were identified, as well as potential prevention measures to mitigate the risks identified. In a second phase, standards and regulations were analysed, namely in terms of electromagnetic fields, which are associated with both heating technologies. Finally, the guidelines and recommendations to mitigate the risks identified for both heating technologies were analysed.

This analysis will be updated in M18 with *D4.5 – Health and Safety Requirements* and the conceptual and design of the induction and microwave heating systems in the two demonstrators will also be analysed, considering the technical specifications of both technologies under development in JOULIA project to deliver the final health and safety requirements for the rubber flooring vulcanisation and adhesive gluing case studies.

The submission of this deliverable is done in accordance with the description in the Grant Agreement Annex 1 Part A with no time and no content deviation from the original planning.

1 Introduction

The efficient transfer and control of thermal energy are essential in a wide range of engineering applications, particularly in materials processing, manufacturing and thermal treatment. Traditional heating methods, which often rely on conduction and convection, can be energy-intensive and limited in terms of precision and speed. As a result, alternative technologies such as induction and microwave heating have gained significant attention in both research and industrial contexts due to their enhanced efficiency, controllability and energy utilization.

Induction heating is based on the principle of electromagnetic induction, wherein alternating currents generate eddy currents within a conductive material, producing heat due to the material's electrical resistance. This method is widely used for localized heating in processes such as hardening, brazing and metal forming. On the other hand, microwave heating involves the interaction of high-frequency electromagnetic waves with dielectric materials, causing molecular agitation and internal heat generation. This technique is increasingly employed in areas such as drying, polymer curing and chemical synthesis.

Both induction and microwave heating systems rely on electromagnetic fields (EMFs) to transfer energy to materials. Although EMFs are confined within applicators or coils, leakage might occur, leading to potential occupational exposure if systems are not properly shielded or maintained.

This deliverable provides a comprehensive overview of the physical aspects supporting induction and microwave heating systems and the advantages and limitations of each technology. The aim is to offer a clear understanding of these technologies and their relevance in modern engineering practices.

Additionally, the associated hazards and risks that these technologies can present for operators in industrial applications are described and discussed, as well as potential prevention measures, based on a literature review.

The standards and regulations that apply for electromagnetic fields (EMFs) exposure of workers in industrial applications are analysed, such as: Directive 2013/35/EU [1], ICNIRP guidelines [2] and standard IECC C95.1-2019 [3].

Finally, guidelines and recommendations in terms of operating principles, system components and engineering considerations associated with induction and microwave heating systems are analysed based on a literature review.

2 Induction heating systems

2.1 Induction heating and how it works

Induction is a flame-free and contactless heating method that heats a conductive metallic component through the generation of an alternating magnetic field, which induces electric currents within the material and causes it to heat up. In induction heating, an alternating current is passed through a coil, generating an alternating electromagnetic field around it. Note that the induction coil is connected to an alternating current power supply, and it is the main emitter of the magnetic field [4]. When an electrically conductive (ferromagnetic) material is placed within this field, electrical currents are induced within the material (also called eddy currents). The resistance of the material to these eddy currents generates heat due to the Joule effect, resulting in the heating of the component, as shown in Figure 2.1 [5].

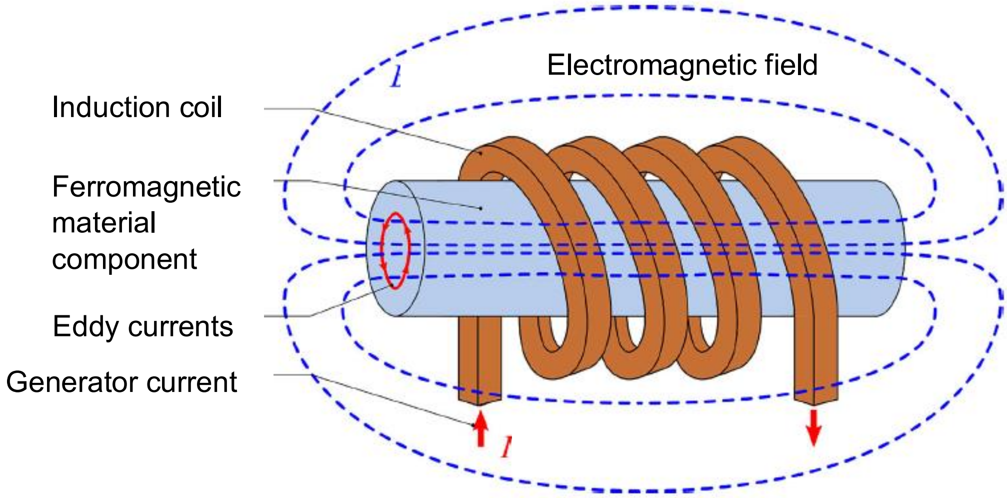


Figure 2.1 Principle of induction heating (adapted [5]).

In ferromagnetic materials, magnetic hysteresis also contributes to heat generation; however, its influence is generally minor compared to that of eddy currents [6]. Due to the skin effect, the induced current density and consequently the resulting heat generation, diminish exponentially from the surface of the workpiece toward its interior. The area at which approximately 86% of the total induced energy is dissipated as heat is defined as the penetration depth (δ), which relates with frequency (*f*), the magnetic permeability (*μ*), and the electrical conductivity of the component (*σ*), according to **Equation 2.1** [5].

$$\boldsymbol{\delta} = (\sqrt{\boldsymbol{\pi}} \cdot \boldsymbol{f} \cdot \boldsymbol{\mu} \cdot \boldsymbol{\sigma})^{-1} \qquad \text{Equation 2.1}$$

Equation 2.1 shows that the penetration depth (δ) increases at lower frequencies and decreases at higher frequencies (*f*), as the magnetic permeability (*μ*) and electrical conductivity (*σ*) are intrinsic material properties. The typical operating frequencies of induction heating systems range from line frequency (*e.g.,* industrial and high-power applications) to several megahertz (*e.g.,* medical systems) [7]. Temperature rise during the heating process also influences variation in the penetration depth (δ), as since these material properties are temperature-dependent (*i.e.,* magnetic permeability (*μ)* and electrical conductivity (*σ*)) [5]. Therefore, both the frequency (*f*) of the current and the temperature rise determine the depth of penetration (δ) for the heating process.

Induction heating technology shows several advantages comparatively with conventional heating techniques, which are key features needed for the automation of the industrial processes, *i.e.,* ([5], [7])

- **Faster heating rates**, as it directly heats the induction target, reducing wasted heat and heating times.
- **Controlled heating**, as the power applied by the induction heating system and the location can be accurately controlled through an appropriate design and control of the coil and the power converter.
- **Higher efficiency**, due to the modern efficient designs of the coil and the power converter. In fact, 95% of the electrical energy in induction heating systems are reported to be converted to heat [8].
- **Higher quality and productivity of the process and good reproducibility**, due to induction heating consistency and repeatability.

However, there are several limitations in the application of induction heating across industry sectors, such as [9]:

- **Cost**: induction heating equipment can be expensive to purchase and maintain, which may reduce its cost-effectiveness for certain applications.
- **Material limitations**: induction heating is effective only for electrically conductive and/or magnetic materials, limiting its applicability for non-metallic or non-magnetic materials.
- **Size limitations**: the method is generally less suitable for heating large or bulky components due to limitations in coil design and energy transfer efficiency.
- **Heating depth**: induction heating is often restricted to surface or near-surface regions, as the heat penetration decreases with depth, potentially leading to uneven heating in thicker materials.

Extensive research on induction heating systems has expanded their applications across a wide range of industrial manufacturing processes, such as hardening, tempering, brazing, bonding, welding, annealing, pre- and post- heating, forging, melting, straightening, shrink-fitting, and surface treatment (Table 2.1). There are several commercially available induction heating systems specifically designed for each one of the industrial manufacturing processes. Note that although induction heating also has medical and domestic applications, this study is only focused on the industrial applications.

Table 2.1 Types of induction heating applications in industrial manufacturing processes (this table does not represent an exhaustive list. Adapted from [10], [11].

Applications of induction heating systems in industrial manufacturing processes	
Induction hardening	It uses induced heat and rapid cooling (quenching) to increase the hardness and durability of steel
Induction tempering	It is a heating process that optimizes mechanical properties such as toughness and ductility in workpieces that have already been hardened
Induction brazing	Brazing is a materials joining process that uses a filler metal (and usually an anti-oxidizing solvent called flux) to join two pieces of close-fitting metal together without melting the base materials. Instead, induced heat melts the filler, which is then drawn into the base materials by capillary action
Induction bonding	It uses induction heating to cure bonding adhesives
Induction welding	The heat is electromagnetically induced in the workpiece
Induction annealing/ normalizing	This process heats metals that have already undergone significant processing. Induction annealing reduces hardness, improves ductility and relieves internal stresses
Induction pre-heating	It is a process where materials or workpieces are heated by induction prior to further processing
Induction post-heating	Any process where induction is used to heat workpieces or materials that have already undergone significant processing
Induction forging	It uses induction to heat metal parts before they are shaped or deformed by presses or hammers
Induction melting	It is a process where metal is melted into liquid form in an induction furnace crucible. The molten metal is then poured from the crucible, usually into a cast
Induction straightening	It uses a coil to generate localized heat in pre-defined heating zones. As these zones cool, they contract, pulling the metal into a flatter condition
Induction shrink-fitting	It uses thermal expansion to fit or remove parts made of metal. By employing controlled heating, this method takes advantage of the expansion and contraction of materials, ensuring a precise and secure assembly or disassembly process
Surface treatment	Coating, drying or cleaning by generating the heat in the component, where the top layer dries from the component surface, and the surface of the coating remains moist for the longest time

Industrial manufacturing applications typically demand higher output power and greater reliability, which imposes constraints on the selection of power converter topologies. Moreover, due to their intensive use in production lines, these systems must support assembly-line integration and feature enhanced user interfaces. Additionally, the inductor design must be adaptable to various geometries of the target component, such as shafts, gears, and other components, while ensuring the desired heat distribution profile is achieved [7].

Depending on the specific application and the material being heated, the operating frequency of the power converter can vary significantly, *i.e.,* from a few hertz in high-power systems used for metal melting, to several hundred kilohertz in surface heat treatment processes. The semiconductors commonly used in industrial heating converters include the following [7]:

- **Thyristors** for operating at frequencies up to 3 kHz, for power ratings of several MWs.
- **Insulated Gate Bipolar Transistor (IGBTs)** for operating at frequencies up to 150 kHz for power ratings up to 3 MW.
- **Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFETs)** for higher frequencies, up to several hundreds of kHz and output powers lower than 500 kW.

Therefore, several factors that can behave synergistically can affect the efficiency and performance of an induction heating system, *i.e.,* [9]:

- **Operating frequency**: it determines the penetration depth of the electromagnetic field within the component (as observed in Equation **2**.**1**). Higher frequencies result in a more superficial penetration, while lower frequencies allow for deeper heat penetration. Additionally, frequency is closely linked to the efficiency of the heating process, *i.e.*, in general, higher frequencies can improve efficiency, particularly in applications requiring rapid surface heating.
- **Power supply**: it must be capable of delivering sufficient power to the work induction coil to achieve the desired heating rate. Moreover, it should maintain a stable output despite variations in the load presented by the work induction coil.
- **Inductor design**: the inductor plays a critical role in generating the electromagnetic field, making its design essential for the optimal performance of an induction heating system. A well-designed inductor must provide the required field strength and distribution while ensuring high efficiency and operational reliability.
- **Work coil design**: it is responsible for conducting current and inducing heat within the component. Its design is critical to optimizing overall system performance. The coil must be carefully engineered to deliver the required heating rate and achieve uniform heat distribution, while maximizing efficiency and ensuring long-term reliability.

2.2 Types of hazards and risks and prevention measures for induction heating

The human body is continuously subjected to a complex mixture of weak electric and magnetic fields (EMFs), originating from both internal and external sources across residential and occupational settings. The human body naturally generates weak electrical currents due to chemical reactions to support fundamental biological functions [12].

External stimuli and alterations in the environment are known to trigger various biological effects within the human organism, many of which are part of normal life and are typically well-regulated by the body's adaptive systems [12]. While these biological effects are generally non-hazardous, they can lead to adverse health outcomes should the intensity or chronicity of the exposure be unusually strong or prolonged, respectively [12].

The impact of EMF on human health depends on several factors, such as frequency, strength of the magnetic field, workplace design, duration of exposure, as well as the distance from the EMF source [12]. Additionally, certain groups of workers are at risk from EMF exposure, such as workers wearing active implanted medical devices, passive implanted medical devices containing metal, and wearing body-worn medical devices, as well as pregnant workers (Table 2.2).

For low frequency fields (<100 kHz), the stimulation of the nervous system and the resulting sensory responses is the primary biological effect of EMF. Very strong EMF can induce internal electric fields within the human body. These induced electric fields are capable of interfering with normal nerve excitation processes and can, under certain conditions, precipitate phenomena such as visual magneto phosphenes, *i.e.* flashes of light perceived when exposed to changing magnetic fields, such as those encountered during a Magnetic Resonance Imaging (MRI) scan [12].

However, the EU-OSHA [12] mention that there is no scientific evidence that magneto phosphenes cause any adverse health effects. Indeed, the effects of EMF at low frequencies (<100 kHz) are typically acute and will cease immediately once the source of exposure is removed [12].

Operators of induction furnaces and heaters are reported to be highly exposed, as at 1 m from a 1-10 kHz heating equipment, flux densities typically range from 0.03 to 0.5 mT, and it may reach 5 mT at 10 cm [13]. Similarly, devices working at a frequency of 50 Hz, may produce 5 mT fields at 20 cm, and over 0.1 mT at several meters, and the guidelines recommended by [2] are exceeded manifold during work procedures close to furnace (*i.e.*, 27 μT for 3 kHz -to 10 MHz and 1 mT for 50 Hz) [13].

Although the human body is exposed to both electric and magnetic fields, it seems that scientists are most concerned with the magnetic field component [14] rather than the electric field component due to two major physical mechanisms, *i.e.*, penetration capability and current induction. The strength of the magnetic field depends on equipment design and current flow, not on equipment size, complexity or voltage [14]. Table 2.2 shows a list of prevention measures that can be applied to mitigate the hazards and risks associated with the EMFs generated by induction heating systems.

Besides the occupational risk of exposure to EMFs in industrial applications where induction heating systems are used, workers can also suffer an electrical shock or burn if the operator touches an energized electrode (*i.e.* the power is on a metal part which touches the energized electrode) (Table 2.2). Several risk control measures are proposed for installation, maintenance, personal protective equipment (PPE) and for electrode holders, to mitigate the risk of electrical shock (Table 2.2). Additionally, touching live electrical parts can also cause fatal shocks or severe burns. Therefore, an operator dealing with an induction heating system has the risk of burning, when he touches a hot part, and there is also the risk of fire or explosion, when parts are overheated or when the atmosphere contains flammable dust, gas or liquid vapours (*e.g.,* gasoline). Table 2.2 also lists risk control measures to mitigate these risks.

Finally, fumes, gases and airborne particulate can also be produced from an induction heating system of metallic parts when in contact with coatings, adhesives or fluxes, which can harm the operator health. Additionally, fumes and gases from heating can displace air and lower the oxygen level causing injury or death. Table 2.2 shows recommendations to prevent these risks.

Table 2.2 Types of hazards and prevention and control measures of induction heating systems in industrial workplaces (adapted from [14], [15], [16]).

Induction heating system hazards and risks and how to avoid them		
	Hazards and risks	**Prevention and control measures**
Fumes and gases	Induction heating of metallic parts that are in contact with certain materials (e.g. coatings, adhesives, or fluxes) can produce fumes, airborne particulate, and gases (airborne contaminants). Breathing these fumes and gases can be hazardous to the operator health	- Keep your head out of the fumes and do not breathe the fumes. - If inside, ventilate the area and/or use local forced ventilation to remove airborne contaminants. The recommended way to determine adequate ventilation is to sample for the composition and quantity of fumes and gases to which personnel are exposed. - If ventilation is poor, wear an approved air-supplied respirator. - Read and understand the Safety Data Sheets (SDSs) and the manufacturer's instructions for adhesives, coatings, cleaners, consumables, coolants, degreasers, fluxes, metals, etc. - Work in a confined space only if you are properly trained and the space is well ventilated, or while wearing an air-supplied respirator. Always have a trained watchperson nearby.
	Fumes and gases from heating can displace air and lower the oxygen level causing injury or death. Be sure the breathing air is safe	- Do not heat in locations near degreasing, cleaning, or spraying operations. The heat can react with vapours to form highly toxic and irritating gases. - Do not heat coated metals, such as galvanized, lead or cadmium- plated steel. When heating a coated metal, remove the coating from the area to be heated, ensure the area is well ventilated and wear an air-supplied respirator. The coatings and any metals containing these elements can give off toxic fumes when heated. See coating SDS for temperature information.
Fire or explosion		- Do not overheat parts. - Watch for fire and keep the extinguisher nearby. - Keep flammables away from work area. - Do not operate where the atmosphere contains flammable dust, gas, or liquid vapours (such as gasoline). - Ensure parts are adequately pre-heated to ensure removal of trapped liquids.
Hot parts	Induction heating of parts can cause burns	- Do not touch hot parts bare-handed. - Allow cooling period before handling parts or equipment Do not touch or handle induction head/coil during operation unless the equipment is designed and intended to be used in this manner as specified in the owner's manual.

Induction heating system hazards and risks and how to avoid them			
	Hazards and risks		**Prevention and control measures**
			- Keep metal jewellery and other metal personal items away from head/coil during operation. They also can become heated by the process. - To handle hot parts, use proper tools and/or wear appropriate hand protection and clothing to prevent burns.
	Touching live electrical parts can cause fatal shocks or severe burns, such as bus bars and coolant fittings that are not insulated or protected from unintentional contact by persons		- Enclose any connecting bus bars and coolant fittings to prevent unintentional contact. - Use only nonconductive coolant hoses and coolant to provide isolation.
Electrical shock	When the power is "on" and metal parts touch the energized electrode, they can cause fatal shocks or severe burns when touched by the operator	**Installation**	- Read all instructions, labels, and installation manuals before installing, operating, or servicing the equipment. - Have all installation, operation, maintenance, and repair work performed only by qualified people. - Properly install and ground the equipment in accordance with the instruction manual and national, state, and local codes. - Disconnect the input power or stop the engine before installing or servicing the equipment. Lock the input disconnect switch in the “open” (Off) position, or remove the fuses, so that power cannot be turned on accidentally.
		Maintenance	- Frequently inspect input power cord for damage or bare wiring – replace cord immediately if damaged – bare wiring can kill. - Keep all covers and panels securely in place.
		PPE	- Wear dry, hole-free, insulating gloves in good condition and protective clothing. Do not touch the energized electrode with a bare hand. - Insulate yourself from the workpiece and ground using dry insulating mats or covers big enough to prevent any physical contact with the work or ground or wear properly designed and approved rubber-soled boots in good condition. - Wear a safety harness to prevent falling if working above floor level.
		Electrode holders	- Use fully insulated electrode holders. Never dip the holder into water to cool it or lay it on conductive surfaces or the work surface. - Do not touch two electrode holders, connected to two separate welding machines, at the same time since double open-circuit voltage can be present. - Do not allow the electrode holder or electrode contact with a person or any grounded object.

Induction heating system hazards and risks and how to avoid them		
	Hazards and risks	**Prevention and control measures**
		- Do not touch an energized electrode while you are in contact with the work circuit.
		- Do not use worn, damaged, undersized, or poorly spliced cables, or torch cables. Make sure all connections are tight, clean, and dry. - Do not wrap cables carrying electric current around any part of your body. - Do not touch live electrical parts. - Do not work alone where there are electrically hazardous conditions.
Electromagnetic fields (EMF)	The induction heating circuit and parts being heated create an EMF and it can affect implanted medical devices. For example, the technology of heart pacemakers and other electronic devices changes frequently, and this may change the way these devices are affected by other electrical devices	- Wearers of pacemakers and other implanted medical devices should keep away. - Implanted medical device wearers should consult their doctor and the device manufacturer before going near induction heating operations. - Observe the EMF data and minimum approach distances provided by the induction heating equipment manufacturer. - Keep cables close together by twisting or taping them or using a cable cover. Do not place your body between cables. Arrange cables to one side and away from the operator. Do not coil or drape cables around your body. - Keep metal jewellery and other metal personal items away from heating circuit during operation. - Keep head and trunk as far away from the heating circuit as possible. - Do not work next to, sit or lean on the induction heating power source.
	Workplace design and worker distance and exposure time to the EMF source can affect their exposure during work shift	- Inform workers and employers about possible hazards of magnetic elds. - Increase the worker's distance from the EMF source. Since magnetic elds often drop o dramatically within about 30.48 cm (3 feet) of the source, workers can stand back from electrical equipment, and workstations can be moved out of the 30.48 cm (3 feet) range of stronger EMF sources. - Use low-EMF designs wherever possible (*e.g.*, for the layout of power supplies). - Reduce EMF exposure times. No action should be taken to reduce EMF exposure if it increases the risk of a known safety or health hazard such as electrocution.

3 Microwave heating systems

3.1 Microwave heating and how it works

All electromagnetic (EM) radiations, namely gamma rays, x rays, ultraviolet rays, infrared rays and radio waves, are used in a wide range of industrial and scientific applications. Among these, microwaves, with wavelengths between approximately 1 mm and 1 m, are increasingly applied not only in traditional technologies but also in advanced industrial processes [17].

Microwaves are a form of nonionizing EM radiation with frequencies typically between 300 MHz (0.3 GHz) and 300 GHz [18]. Like all electromagnetic waves, they consist of oscillating electric and magnetic fields that propagate through space at the speed of light ($C = 3\ x\ 10^8$ m/s). The relationship between wavelength (λ), frequency (f), and the speed of light is expressed by the fundamental equation:

$$\boldsymbol{\lambda} = \frac{\boldsymbol{C}}{\boldsymbol{f}} \qquad \text{Equation 3.1}$$

Equation **3.1** shows that wavelength is inversely proportional to frequency: as frequency increases, wavelength decreases. The electromagnetic spectrum is divided into regions based on frequency and wavelength. Radiations with frequencies between 10 kHz and 300 GHz are termed radio waves, within which microwaves occupy the range from 0.3 to 300 GHz, positioned between radio waves and infrared radiation. Table 3.1 summarizes the frequency ranges and corresponding wavelengths of these three spectral regions, and Figure **3.1** presents their relative positions within the electromagnetic spectrum.

Table 3.1 Frequency ranges and corresponding wavelengths of radio, microwave and infrared electromagnetic radiations.

Type	Frequency Range	Wavelength
Radio	< 300 MHz	> 1 m
Microwave	0.3 – 300 GHz	1 mm – 1 m
Infrared	> 300 GHz	< 1 mm

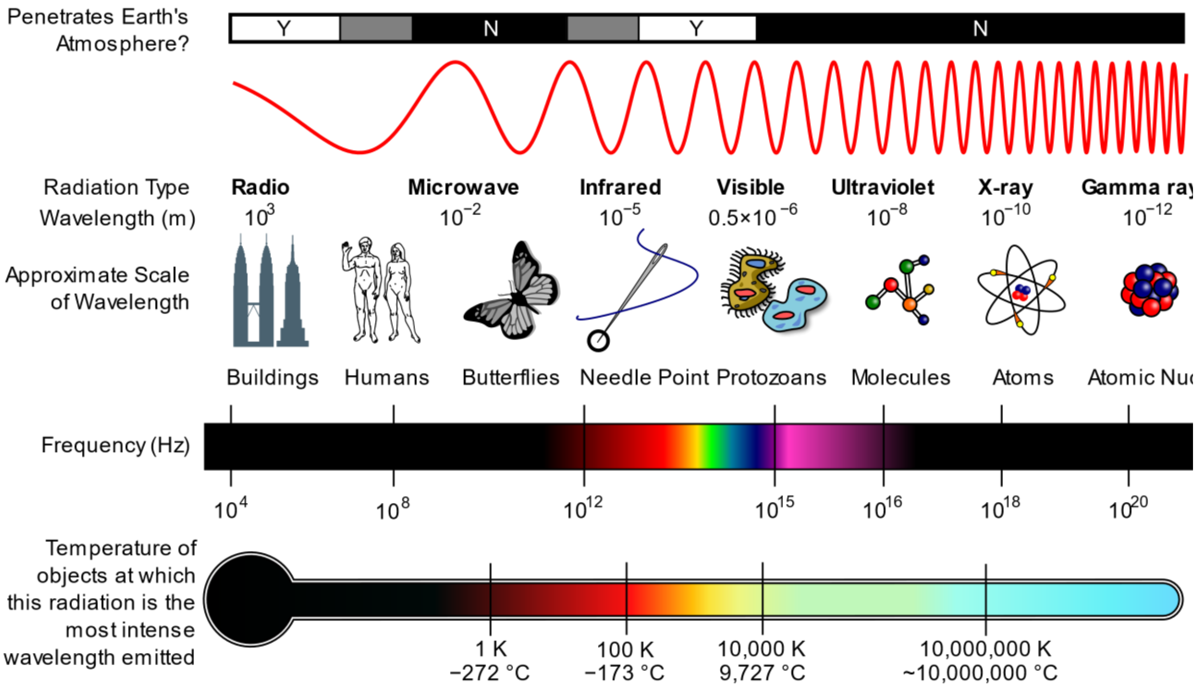


Figure 3.1 A diagram of the electromagnetic spectrum [19].

Microwave behaviour is primarily determined by frequency, wavelength, and power density, which influence how energy interacts with materials and how deeply it penetrates them. In industrial systems, microwaves are typically generated using magnetrons, klystrons, or solid-state oscillators, and transmitted through waveguides or coaxial systems to ensure impedance matching and minimize reflection [20]. When microwaves interact with matter, energy is absorbed mainly through dielectric heating, the oscillating electric field causes polar molecules (such as water) to realign rapidly, generating heat through molecular friction [21]. This mechanism enables efficient and uniform heating, which is exploited in processes such as drying, curing, vulcanization, sintering, and sterilization. The penetration depth of microwaves decreases with increasing frequency and with the electrical conductivity of the material, an important parameter in process design.

The efficiency of microwave heating depends on the dielectric properties of the material, specifically the dielectric constant (ε′), which determines energy storage, and the dielectric loss factor (ε″), which governs how much energy is converted to heat. Materials with high ε″ values, such as water and polar solvents, absorb microwave energy efficiently, while low-loss materials (*e.g.*, Teflon, quartz) remain transparent to microwaves [22].

Microwave radiation is nonionizing, meaning that its photon energy is insufficient to remove electrons from atoms or molecules. The primary established effect on biological tissue is thermal heating, which can pose health risks only at high exposure levels. Therefore, occupational use of microwave-based technologies, such as in polymer curing, rubber processing, and composite fabrication, must comply with recognized exposure standards, including the [23] and the Directive 2013/35/EU [1]on worker exposure to electromagnetic fields.

Microwave heating is a dielectric heating process in which electromagnetic energy (commonly at 915 MHz or 2.45 GHz) interacts with materials to generate volumetric heat [21]. Unlike conventional conduction, convection, or infrared heating, microwaves penetrate the material, achieving rapid and uniform temperature rise. These frequencies (915 MHz and 2.45 GHz) correspond to RECOMMENDATION ITU-R SM.1056-1 designated industrial, scientific and medical (ISM) bands, globally allocated for industrial and scientific applications to avoid interference with telecommunications systems ([24], [25]).

A typical microwave system includes three essential components [17]:

- Transmitter: generates the microwave signal using oscillators such as magnetrons, klystrons, or solid-state devices.
- Transmission line: conveys the generated microwaves, often via rectangular waveguides or coaxial cables, ensuring minimal loss.
- Antenna or applicator: delivers energy efficiently to the target material.

For low-power applications, gallium arsenide (GaAs)-based transistor transmitters (1–10 W) are common, while high-power systems employ devices such as travelling-wave tube amplifiers, crossed-field amplifiers, magnetron oscillators, klystrons, gyrotrons, or twystron amplifiers [17]. These components together ensure controlled, efficient energy transfer for heating, drying, and processing in industrial environments.

Microwave heating is based on the interaction between the electromagnetic field and polar molecules within the material, resulting in volumetric heating due to molecular dipole rotation and ionic conduction. This allows rapid and efficient heat generation throughout the product volume rather than by surface conduction. To improve heating uniformity, industrial microwave systems often use mechanical or electronic mode stirrers, rotating platforms, or moving conveyors to redistribute standing wave patterns within the cavity and minimise hot or cold spots.

Advantages of microwave heating include faster processing times, reduced energy losses, selective heating of materials, and compact equipment design, which make this technology attractive for various industrial applications such as drying, sintering, and curing. Typical industrial uses include food processing, materials processing (*i.e.*, ceramics, sintering, composites), chemical synthesis and processing, drying and moisture removal, mineral processing and rock breakage, waste treatment and biomass conversion, sterilisation and pasteurisation, polymer processing and vulcanisation, and specialised manufacturing (*e.g.*, adhesives curing, continuous-flow chemical reactors). In

Table 3.2 are listed some of common manufacturing industry applications for microwave heating systems.

Table 3.2 Applications of microwave heating systems in manufacturing industry (this table does not represent an exhaustive list).

Application	Use
Food Industry [26]	Used for cooking, tempering, thawing, drying, blanching, baking, pasteurization, sterilization, moisture control and microwave-assisted extraction. The rapid volumetric heating shortens process time, improves throughput and can preserve quality compared with conventional heating in some processes.
Industrial drying [27]	It can be used for drying of wood, paper, textiles, sludges and other wet materials; vacuum and freeze-drying hybrids; microwave-assisted drying to reduce cycle times.
Materials processing (ceramics, sintering, composites, metals) [28]	Microwave sintering and densification of ceramics and composites; rapid sintering of metal and ceramic powders; microwave-assisted firing; production/processing of advanced ceramics and composites; microwave-assisted coating or glaze processing. Very rapid heating rates and reduced processing times can be attained, and sometimes unique microstructures or enhanced properties versus conventional heating.
Polymer processing, curing and vulcanization [28]	Can be used for polymer synthesis (microwave-assisted polymerization), curing of thermosets and composites, rubber vulcanization, crosslinking, adhesive curing and surface treatments. Microwaves can lead to faster reaction/curing times, and there is potential for improved control and energy efficiency in some processes.
Chemical synthesis and continuous-flow processing [28]	Microwave-assisted organic/inorganic synthesis, accelerated chemical reactions, continuous-flow microwave reactors for scale-up, solvent-free synthesis, catalytic processes.
Mineral processing and rock breakage [29]	Microwave-assisted rock weakening and fracture to aid comminution, ore beneficiation, pre-treatment of ores, selective heating for mineral liberation. Microwaves are used due to the selective absorption in mineral phases that can create internal stresses and cracks, lowering energy needed for mechanical comminution.
Waste treatment, sludge drying and biomass conversion [27]	Used in drying of sewage sludge and industrial slurries, microwave-assisted pyrolysis/torrefaction of biomass to produce biochar, microwave-assisted waste remediation and detoxification.
Sterilization, pasteurization and decontamination (medical/industrial) [30]	Used for the sterilization of medical instruments, decontamination of packaging, microbial reduction in food and some pharmaceutical processes.
Electronics and semiconductor processing [31]	Rapid annealing, sintering of conductive inks, drying of printed electronics, materials activation, some sintering of ceramic dielectric layers.
Adhesive bonding, coatings and surface treatments [32]	Curing of adhesives and coatings, microwave-assisted surface modification, solvent removal and curing of thermal spray targets.

To improve heating uniformity, industrial microwave systems often use mechanical or electronic mode stirrers, rotating platforms, or moving conveyors to redistribute standing wave patterns within the cavity.

Given this wide range of applications and the unique physical mechanisms involved, it is essential to evaluate both the benefits and limitations of microwave heating systems. Microwave heating offers several advantages that make it a compelling alternative to conventional thermal processing methods in industrial applications. Some of the advantages are the following [33]:

- **Volumetric heating**: Microwaves penetrate dielectric materials and generate heat internally, enabling faster and more uniform temperature distribution compared to surface-based heating methods.
- **Rapid heating rates**: The direct interaction of microwaves with polar molecules leads to efficient energy transfer and significantly reduced processing times.
- **Selective heating**: Materials with different dielectric properties absorb microwave energy at different rates, allowing for targeted heating of specific components or phases within a composite material.
- **Energy efficiency**: Microwave systems minimize heat losses to the environment by focusing energy directly on the material, which can result in higher overall energy efficiency.
- **Compact equipment footprint**: Microwave systems often require less physical space than conventional furnaces or ovens, facilitating integration into modern production lines.
- **Clean and controllable process**: The flameless and contactless nature of microwave heating reduces contamination risks and allows precise control through frequency and power modulation.

However, as in all technologies, the use of microwave heating systems also presents some limitations, some of these are the following:

- **Non-uniform heating in heterogeneous materials**: Variations in dielectric properties within a material can led to uneven heating, hot spots, or thermal runaways, especially in complex geometries.
- **Limited penetration depth at high frequencies**: Higher frequencies result in shallower penetration depths, which can limit effectiveness in thick or dense materials.
- **Material compatibility**: Effective heating is limited to materials with sufficient dielectric loss. Metals, which reflect microwaves, require special design considerations or hybrid systems.
- **High initial investment**: Industrial microwave systems with high power ratings and necessary safety features (e.g., shielding, interlocks) can be expensive to acquire and maintain.

- **Electromagnetic interference (EMI)**: Without proper shielding, microwave systems can interfere with nearby electronic equipment, necessitating careful electromagnetic compatibility (EMC) design.
- **Safety concerns**: Although non-ionizing, microwave radiation can cause thermal injuries or interfere with medical implants if exposure limits are exceeded. Compliance with safety standards (*e.g.*, IEC 60519-6 [34], Directive 2013/35/EU [1]) is essential.

In summary, microwave heating represents a versatile and efficient thermal processing technology based on the interaction of electromagnetic fields with dielectric materials. Its ability to provide volumetric, selective, and rapid heating offers significant advantages over conventional methods, enabling higher energy efficiency, shorter process times, and enhanced product quality across diverse industrial applications. However, the implementation of microwave-based systems also demands a comprehensive understanding of the electromagnetic behaviour, material dielectric properties, and compliance with applicable safety and technical standards such as IEC 60519-6:2022 [34] and Directive 2013/35/EU [1]. These aspects are crucial not only for process optimisation but also for ensuring safe operation and worker protection. The following section examines in greater detail the types of hazards and risks associated with microwave heating systems and the corresponding preventive and control measures to ensure their safe industrial deployment.

3.2 Types of hazards and risks and prevention measures for microwave heating

Microwave heating systems, while offering significant industrial advantages, also present a range of occupational hazards that must be carefully managed. Concern regarding the health and safety implications of human exposure to EMFs has increased substantially in recent years. This heightened awareness largely stems from the widespread adoption of mobile communications and the rapid development of advanced wireless technologies, although EMFs are also emitted by many natural and anthropogenic sources. Consequently, extensive research has been undertaken to evaluate the potential health effects and associated risks across a wide range of frequencies. Particular attention has been given to the non-ionising region of the spectrum, typically defined between 3 kHz and 300 GHz, where energy levels are far below those required to ionise atoms or damage cellular DNA. This distinguishes such radiation from ionising forms, such as X-rays and gamma rays, which possess sufficient energy to displace electrons within atomic structures.

To date, the only scientifically established biological effect of microwave-frequency radiation is thermal heating, which may pose a health risk if excessive tissue heating occurs. Nonetheless, public debate continues to focus on the possibility of non-thermal (athermal) effects and their potential implications for human health [35]. Research has explored possible health and safety implications from the microwave exposure beyond thermal effects, as outlined below:

- <u>Cancer related effects</u>: epidemiological reviews, such as those by Elwood [36], have examined potential associations between exposure to EMFs and various cancers,

including brain, lung, testicular, lymphatic, and hematopoietic types, as well as adult and childhood leukaemia and Hodgkin's disease. The studies have assessed exposures from radio and television transmitters, mobile phones, radar, and occupational sources. Reported exposure levels were generally within existing regulatory or recommended limits. Overall, the findings were inconsistent and provided no statistically significant evidence linking microwave-frequency EMF exposure with increased cancer incidence. In most cases, no elevated risk was observed from casual or occupational exposure.
Recent systematic reviews and meta-analyses, including a WHO-commissioned review led by ARPANSA [37], similarly concluded that is no consistent evidence associating RF/microwave exposure from mobile phones or environmental transmitters with brain or other common cancers.

- Non-cancer related effects and non-thermal mechanisms: Clinical and epidemiological studies have examined cataracts, reproduction, neurological and cardiovascular outcomes, and other endpoints. Results are heterogeneous and often confounded, while confirmed adverse effects remain thermal in nature (*e.g.*, localized heating, auditory perception from high-intensity pulses). Research on possible non-thermal mechanisms is ongoing but currently does not yield conclusive evidence of population-level health risk. In occupational contexts, precautionary controls focus on preventing excessive heating and electrical interference rather than hypothetical non-thermal effects ([23], [38]).

- Thermal Hazards: Thermal injury occurs when tissue heating exceeds the rate of cellular repair for a sufficient duration to disrupt normal metabolism. The rate of protein denaturation increases rapidly with temperature, reducing the exposure time required to cause damage, as illustrated in Figure 3.2.
Heating depth and rate depend on frequency, power density and material properties: higher frequencies deposit energy closer to the surface (shorter penetration depth), and focused sources concentrate heating in small tissue volumes. Exposure prevention therefore requires limiting local power density, controlling exposure time, and ensuring applicator design minimises leakage.

- Cardiac implantable electronic devices (CIEDs): early reports of pacemaker interference remain historically significant, but modern pacemakers and defibrillators are designed and tested for electromagnetic compatibility (EMC). ISO 14117 (2019) defines EMC test protocols for active implantable cardiac devices. Systematic reviews show that most contemporary CIEDs exhibit substantial immunity; however, specific high-power or novel sources (*e.g.*, wireless power transfer, industrial induction systems) can still present EMI risks and should be evaluated on a case-by-case basis. Risk management combines device-specific guidance, controlled access and clearance distances, and appropriate signage for workers with CIEDs [39].

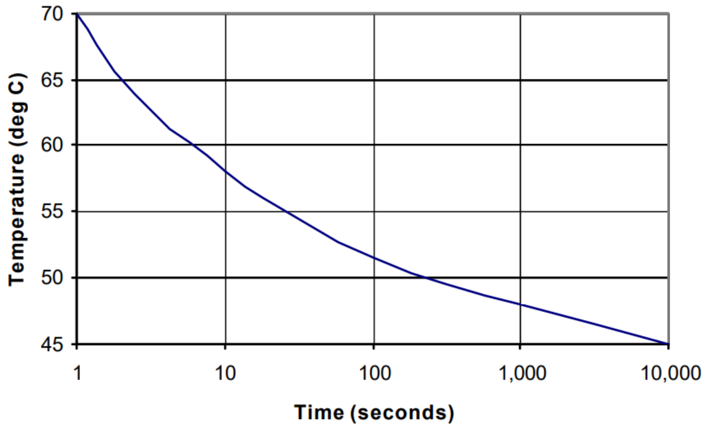


Figure 3.2 Threshold temperature vs. time at temperature for skin burns.

Overall, occupational hazards associated with the microwave heating systems arise primarily from exposure to EMFs, thermal effects, electrical risks, and the potential for fire or explosion due to material processing.

Regarding standards, practical guidance for ensuring worker H&S, as established in the Framework Directive 89/391/EEC), applies when working with electromagnetic fields and in ensuring equipment safety. Industrial microwave heating systems must comply with the IEC 60519 series (*i.e.*, IEC 60519-6:2022 [34], Directive 2013/35/EU [1] and the ICNRP guidelines [23] for limiting exposure to EMFs. These documents specify safety requirements for high-frequency and microwave heating installations and address essential aspects such as system design, shielding, interlocks, and measurement methods to protect workers from EMF exposure and accidental/incidental emissions. Also, best practices are defined for achieving the safest possible working environments. Particularly, employers must implement the actions and preventive measures summarised in Table 3.3.

Table 3.3 Action and measures to be implemented when using microwave heating systems in manufacturing industry.

Measures/Action	Description
Design and engineering controls (first priority)	Select equipment with low leakage design and good shielding; prefer units complying with IEC 60519-6 and with manufacturer leakage test data. Use fixed enclosures, waveguide seals and RF gaskets, and interlocked access panels so the microwave cavity is not energized when opened. Incorporate automatic interlocks and fail-safe shutdowns (door interlocks, emergency stops) to prevent accidental exposure. Design process layout to minimize time people spend near to high-power applicators (use conveyors, automated loading/unloading, robotic manipulators). This reduces exposure by distance and time.
Administrative and operational controls	Perform an initial risk assessment (identify sources, worst-case scenarios) and, where indicated, exposure measurements against action levels and Exposure Limit Values (ELVs) from Directive 2013/35/EU and ICNIRP guidance. Use the EU non-binding guide for methodology. Establish controlled (restricted) zones around equipment where access is limited to trained personnel; mark these with signage and floor markings. Set work schedules to limit individual exposure time in higher field areas and rotate tasks where appropriate. Implement safe work procedures for maintenance (isolation/lock-out, verification of zero-field before opening enclosures), and require a permit-to-work for any work that exposes technicians to potential leakage.
Measurement, verification and monitoring	Carry out commissioning field measurements after installation and periodic checks, thereafter, using calibrated RF survey meters and techniques compatible with ICNIRP/ITU/IEC guidance. Document results and corrective actions. Apply action levels and ELVs from Directive 2013/35/EU (which reference ICNIRP) to determine whether further controls are required (engineering, administrative, or exclusion zones).

Measures/Action	Description
Training, signage and worker information	Provide specific training for operators and maintenance staff on EMF hazards, safe distances, how to use PPE (see note below), and emergency procedures. Inform workers of any personal restrictions (*e.g.*, presence of implantable medical devices). Use clear signage indicating controlled areas, relevant action levels, and PPE/permit requirements. Maintain accessible records of measurements and risk assessments.
Personal protective equipment (PPE) and medical considerations	PPE is of limited effectiveness for RF/microwave fields and is not usually relied upon as a primary control; however, RF-protective clothing can reduce surface power density in some niche maintenance tasks (need to consult specialists). Prioritize engineering and administrative controls over PPE. Identify workers with cardiac implantable electronic devices (CIEDs) or other medical implants; provide bespoke risk assessment and access restrictions; follow ISO 14117 guidance for EMC of active implantable devices.
Maintenance, testing and documentation	Include periodic verification of shielding integrity, interlocks and leakage levels in preventive maintenance schedules, record tests and remedial actions. Retain a log of EMF surveys, incident reports, maintenance and risk assessments to demonstrate ongoing compliance with Directive 2013/35/EU requirements.
Emergency planning	Define emergency procedures for accidental exposure events or shielding failure (evacuation, medical assessment, isolation of the source), and practice them during safety drills.

In addition to the general preventive actions and organisational measures required from employers, it is essential to address the specific hazards inherent to microwave heating systems through targeted control strategies. In Table 3.4 is presented an overview of the main safety domains relevant to industrial microwave applications, *i.e.*, electrical, thermal, electromagnetic, and process-related (fumes, fire, and explosion), and summarises recommended prevention and control measures. These measures, adapted from recognised standards and safety guidelines ([1], [34], [40]), support the practical implementation of health and safety requirements for safe system operation, maintenance, and worker protection.

Table 3.4 Types of hazards and prevention and control measures related with microwave heating systems in industrial workplaces (based on [1], [34], [40]).

Microwave heating system hazards and how to avoid them		
Safety Domain	**Hazards**	**Prevention and control measures**
Electrical	Electrical hazards: Shock, arc, or short circuit from high-voltage components in magnetrons/klystrons.	- Lock-out/tag-out procedures.
		- Isolate power before service.
		- Provide training for authorised personnel only.
		- Use insulated tools and PPE.
Fumes	Fumes, gases and vapours can be released during polymer curing, composite bonding, adhesive drying, paint/coating curing, rubber vulcanisation, waste treatment, food processing, and sterilisation of organic materials.	- Provide forced ventilation or extraction at the applicator outlet and chamber.
		- Install gas sensors (VOC, O□ depletion, CO) to detect fume build-up.
		- Use inert gas atmospheres (N□, Ar) if process requires prevention of oxidation or ignition.
		- Include temperature monitoring and automatic shutdown if material overheating occurs.
		- Ensure chamber design includes fume exhaust ports
		- Perform a process hazard analysis (PHA) for any new or modified material.
		- Review safety data sheets (SDS) to identify decomposition or flammability hazards.
		- Train operators in safe start-up, shutdown, and ventilation checks.
		- Implement lockout and purging procedures before maintenance.
		- Provide respiratory protection when ventilation is insufficient during inspection or cleaning.
		- Use heat-resistant gloves, eye protection, and flame-retardant PPE where high-temperature residues are handled.
Fire, ignition or explosion	Fire, ignition or explosion effects can be heating of flammable materials or arcing due to metal contamination.	- Do not put metallic objects, plastic containers, sponges or dishcloths inside the microwave as they can catch fire.
		- Fit temperature sensors and automatic shutdown.
		- Keep all vents clear and avoid storing objects on top of the appliance.
		- Maintain cleanliness of applicator and microwave to avoid the build-up of flammable grease and dirt.
		- Do not leave the microwave unattended whilst in use.
		- Do not use an extension cord to power your microwave.
Th er ma l		- Maintain safe distances and use barriers

Microwave heating system hazards and how to avoid them		
Safety Domain	**Hazards**	**Prevention and control measures**
	Thermal burns (contact or radiant): effects can be Localised skin or eye heating due to high field strength or hot components.	- Provide thermal insulation on hot surfaces
		- Train workers on safe handling and lock-out procedures
EMF/Radiation	Equipment malfunction / EMF leakage due to poor maintenance	- Preventive maintenance including seal replacement and leakage testing.
		- Maintain calibration and records of EMF surveys.
	Exposure during maintenance or setup	- Ensure interlocks cannot be bypassed without key control.
		- Use permit-to-work and supervision.
		- Provide emergency stop devices within reach.

Organizations and scientific literature support the use of ALARA (As Low As Reasonably Achievable) to non-ionizing EMFs, including those generated from radio and microwaves. This approach is particularly relevant given the divergent risk assessments surrounding technologies such as wireless devices and industrial microwave systems. The ALARA principle requires that any activity involving non-ionising radiation must be subject to risk-benefit analysis, considering both human health and environmental impacts. The primary responsibility for conducting this assessment lies with those initiating or overseeing work involving non-ionising radiation [41].

In practice, the ALARA principle entails implementing the most effective protective measures considered deemed "reasonable", regardless of whether the exposure levels remain below regulatory limits. Its application involves balancing the resources devoted to protection against the degree of risk reduction achieved, to ensure optimal safety within prevailing economic and social conditions [42].

Since 1980, the ALARA principle has formed part of the European Basic Safety Standards and has been progressively incorporated into national regulatory frameworks. In the Euratom Directive 96/29, ALARA was reaffirmed as a cornerstone of the radiological protection system. During the 1980s and early 1990s, ALARA became an integral component of many organisations' radiation protection programmes. In 1996, the European Commission established the European ALARA Network (EAN)[1] to promote targeted research on optimisation of radiation protection and to facilitate the dissemination of best ALARA practices across European industrial, research, and medical sectors [43].

In summary, ensuring the safe use of microwave heating systems in industrial environments requires a holistic approach that integrates engineering controls, administrative procedures, and adherence to recognised international standards. Beyond compliance, fostering a safety

[1] https://www.eu-alara.net/images/stories/EANdocuments/Presentations/EAN_Strategic_Agenda_2021-2026_V3.pdf

culture that prioritises continuous monitoring, preventive maintenance, and worker training is essential to reduce both direct and indirect risks. Applying the ALARA principle further reinforces this preventive mindset by promoting the optimisation of exposure control and protection strategies, even when operating within regulatory limits. Altogether, these measures contribute to the sustainable and safe deployment of microwave technologies, supporting both productivity and worker well-being.

4 Standards, regulations and guidelines for induction and microwave heating systems

Several standards were consulted to provide guidelines for the safe design, installation, operation, and maintenance of equipment, as well as for protecting workers from potential hazards (particularly electromagnetic fields, electrical safety and thermal effects) associated with the induction and microwave technologies. Based on the literature review, the ISQ aim to ensure worker safety, prevent accidents, and promote compliance with regulatory standards; minimizing hazards associated with electromagnetic equipment while maintaining efficient process performance.

4.1 EMF – Electric and magnetic fields/ Electromagnetic field

Electromagnetic radiation consists of electric and magnetic waves that travel together through space at the speed of light, forming what is known as the electromagnetic spectrum. A portion of this spectrum includes radio waves and microwaves, which are types of electromagnetic energy emitted by transmitting antennas and collectively referred to as radiofrequency (RF) energy or radiation. RF energy is generally defined within the frequency range of 3 kilohertz (kHz) to 300 gigahertz (GHz), while microwaves represent a specific category of RF energy, typically ranging from about 1 GHz to 30 GHz. These forms of energy are often referred to as electromagnetic or RF fields, indicating their presence in the environment.

It is widely accepted that electromagnetic fields (EMF) above certain thresholds can produce biological effects. Studies involving healthy volunteers show that short-term exposure to levels commonly found in the environment or homes does not appear to cause harmful effects. However, exposure to higher levels that could be dangerous is regulated by national and international standards. The ongoing discussion focuses on whether long-term exposure to low levels might trigger biological changes and impact overall well-being [44].

In the case of workers exposed to higher levels of EMFs for extended periods, who are often positioned much closer to the source and exposed to more complex EMF modulations (frequency compositions) [12], it is essential to carefully assess the risks associated with their workplace. These types of workplaces should conduct an exposure assessment to ascertain that the workers' exposure is below the recommended limits.

For this reason, many standards and guidelines have been created that address the limits of exposure to electromagnetic fields. To provide a structured overview, Table 4.1 presents the key standards regulating EMF exposure in occupational settings, which are further elaborated in the following subsections.

Table 4.1 Summary of Key Standards Regulating Occupational EMF Exposure, Including Limits for Induction and Microwave Frequencies.

Standard / Guideline	Issuing Body	Scope of Application	Frequency Range	Exposure Limit (Occupational)	Notes
Directive 2013/35/EU	**European Union**	Workers in EU member states	**Induction:** ~10 kHz – 1 MHz **Microwave:** 915 MHz, 2.45 GHz	**Induction:** Action Level for magnetic field ~27 A/m at 100 kHz **Microwave:** SAR limit of 0.4 W/kg (whole body), 10 W/kg (localized)	Legally binding; requires risk assessment and preventive measures
ICNIRP Guidelines (2020)	**International Commission on Non-Ionizing Radiation Protection**	General public and occupational exposure	100 kHz – 300 GHz	**Induction:** Internal electric field limit ~1.1 V/m at 100 kHz **Microwave:** SAR limit of 0.4 W/kg (whole body), 10 W/kg (localized)	Scientific basis for EU Directive and many national regulations
IEEE C95.1-2019	**IEEE (Institute of Electrical and Electronics Engineers)**	Occupational exposure in industrial and research environments	0 Hz – 300 GHz	**Induction:** In situ electric field limit ~1.1 V/m at 100 kHz **Microwave:** SAR limit of 0.4 W/kg (whole body), 10 W/kg (localized)	Widely used in North America and by technical institutions globally

Notes:

- **SAR (Specific Absorption Rate)** is the key metric for microwave exposure, reflecting energy absorbed per unit mass.
- **Induction heating** typically operates in the 10 kHz to 1 MHz range, where magnetic field strength and internal electric fields are critical.
- **Industrial microwave ovens** often use 915 MHz or 2.45 GHz, where thermal effects dominate, and SAR becomes the primary concern.

4.1.1 Directive 2013/35/EU

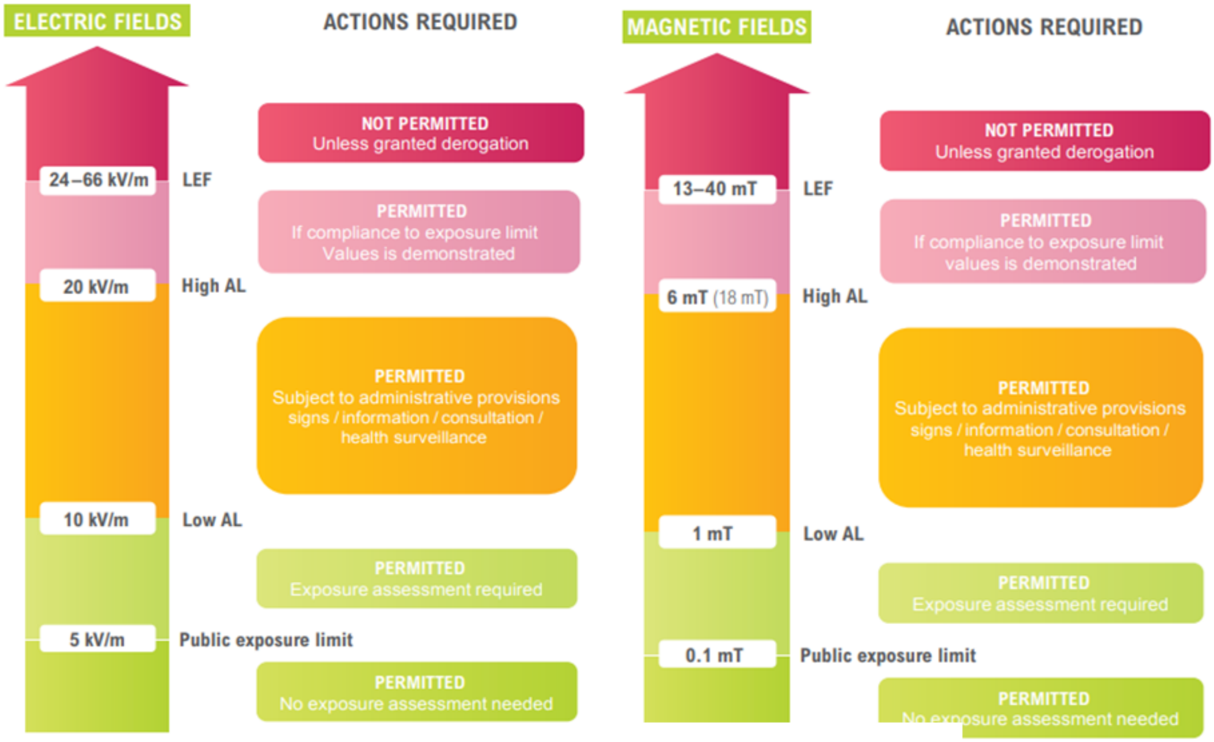
In 2013 the EMF Directive [1] was adopted, repealing the previous one [45], that addresses the protection of workers exposed in all sectors to electromagnetic fields from 0 to 300 GHz and the carrying out of effective and efficient risk assessments, proportional to the situation encountered at the workplace.

Within this EU Directive, exposure limit values (ELVs) and action levels (ALs) are clearly defined to manage worker safety. Action levels are measurable physical quantities designed to simplify the process of ensuring compliance with the exposure limit values. The ELVs themselves are based on well-established scientific evidence, focusing on short-term, acute effects such as thermal effects and electrical stimulation of body tissues.

Both the ELVs and ALs vary depending on the frequency of the electromagnetic fields and include two distinct levels. The first level is set to protect against temporary sensory disturbances and minor brain function changes (sensory effects ELV). The second level is more stringent and aims to prevent more serious adverse health effects, including tissue heating and nerve or muscle stimulation (health effects ELV).

In practice, risk and exposure assessments typically rely on the action levels because ELVs relate to induced electric fields inside the body, which are difficult to measure directly. These occupational exposure limits include a significant safety margin to ensure that if they are followed, harmful health effects are avoided.

In Figure 4.1 is an overview of the ALs and Exposure-Limit-Equivalent-Fields explained in the Directive 2013/35/EU [1] and summarize also the actions required at these different levels. It is important to note that employers are obligated to assess and, if needed, measure or calculate the EMF exposure levels to which workers are subjected. If exposure exceeds the defined action levels, employers must either take steps to reduce exposure or further evaluate whether the legal ELVs are exceeded. This assessment must be done by qualified personnel and should be properly documented, even when no further action is needed. Measurements should follow established IEC standards and be taken at 1 meter above ground, avoiding proximity to metal structures (minimum 20 cm distance). Harmonics are to be ignored, and only broadband or 50 Hz-specific measurements are required. Even in scenarios where direct measurement of electric fields is difficult, measuring contact currents can be used as an alternative method to estimate electric field exposure.



3.6 LIMITS FOR STATIC FIELDS

	ELVs	ALs
Normal working conditions, sensory effects	2 T	
Localised limb exposure, sensory effects	8 T	
Controlled exposure, health effects	8 T	
Workers with active implanted medical devices		500 μT
Attraction and projectile risk in the fringe field of highfield strength sources (> 100 mT)		3 mT

Figure 4.1 Action Levels (Als) and Exposure-Limit-Equivalent-Fields (ELVs) overview explained in the Directive 2013/35/EU [1] (ENTSO-E – EMF report, 2016).

4.1.2 Guideline developed by International Commission on Non-Ionizing Radiation Protection (ICNIRP)

The ICNIRP addresses guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz – 100 kHz) [2]. The main aim of these guidelines is protecting humans from potential health effects caused by exposure to low-frequency (1 Hz to 100 kHz) electric and magnetic fields (EMFs).

These guidelines are based on scientific evidence concerning short-term, transient effects on the nervous system, as long-term health effects have not been conclusively proven. Above 100 kHz, thermal effects become more significant, and separate ICNIRP guidelines address those frequencies. However, due to overlapping effects in the 100 kHz to 10 MHz range, this document also provides partial guidance for nervous system effects up to 10 MHz. The primary concern in this frequency range is the stimulation of the peripheral and central nervous systems, including sensations like retinal phosphenes and possible short-term effects on brain function. While these are not considered harmful, they can be disturbing in occupational settings and are therefore addressed. Exposure limits are designed to prevent the induction of electric fields in the brain and retina above 50 mV/m at certain frequencies, particularly from 10 Hz to 25 Hz.

For occupational exposure (see Table 4.2), especially in controlled environments where workers are informed of potential effects, higher thresholds are permitted, but safety margins are still applied. For example, to prevent peripheral nerve stimulation, the induced electric field should stay below 800 mV/m, incorporating a safety factor of 5 from the established 4 V/m stimulation threshold. These limits increase with frequency, especially above 3 kHz, where the risk of nerve stimulation becomes more prominent.

The guidelines replace the 1998 ICNIRP low-frequency standards and are part of an ongoing effort to update exposure recommendations based on the latest scientific understanding. Separate publications address static magnetic fields and exposures below 1 Hz, as well as the high-frequency range above 100 kHz. The goal of ICNIRP remains to provide science-based exposure limits that prevent known health effects while allowing for safe use of technologies involving electromagnetic fields.

Table 4.2 Reference levels for occupational exposure to time-varying electric and magnetic fields [2].

Frequency range	E-field strength E ($kV.m^{-1}$)	Magnetic field strength H ($A.m^{-1}$)	Magnetic flux density B (T)
1 Hz−8 Hz	20	1.63×10^5 /f^2	0.2 /f^2
8 Hz−25 Hz	20	2×10^4 /f	2.5×10^{-2} /f

25 Hz−300 Hz	5×10^{2} /f	8×10^{2}	1×10^{-3}
300 Hz−3 kHz	5×10^{2} /f	2.4×10^{5} /f	0.3/f
3 kHz−10 MHz	1.7×10^{-1}	80	1×10^{-4}

4.1.3 Standard IECC C95.1-2019

The Standard IECC C95.1-2019 [46] developed by the International Committee on Electromagnetic Safety, stipulates exposure criteria and limits to protect against established adverse health effects in humans associated with exposure to electric, magnetic, and electromagnetic fields in the frequency range of 0 Hz to 300 GHz. The aim of this standard is not guarantee or ensure safety, security, health, or environmental protection, or even ensure against interference with or from other devices or networks, but to express the exposure limits to persons permitted in restricted environments and to the public in unrestricted environments.

This standard defines two distinct tiers of human exposure limits [3]:

1. **Occupational Exposure (Controlled Environment)**: Applied to adults who are aware of and trained regarding potential EMF exposures in their work environment, so higher exposure levels are permitted because:
    - Individuals are informed about risks.
    - Exposure is anticipated and controlled.
    - Safety programs and protective measures are in place.
2. **General Public Exposure (Uncontrolled Environment)**: Applied to the public, including people of all ages and health conditions. More conservative limits are used because:
    - People are not expected to have knowledge of or control over their exposure.
    - Vulnerable populations (*e.g.,* children, elderly, chronically ill) are included.
    - Safety factors are increased to account for uncertainties.

Each tier includes:

- Basic Restrictions (BR), based on direct biological effects (*e.g.,* tissue heating, nerve stimulation). Expressed in terms like Specific Absorption Rate (SAR), induced electric field, or current density.
- Reference Levels (RL), derived from BR to facilitate practical exposure assessments. Expressed in measurable quantities like electric field strength (V/m), magnetic field strength (A/m), or power density (W/m²).

In resume, the IEEE Standard C95.1™-2019 [3] defines exposure limits for electric and magnetic fields, power density, and specific absorption rate (SAR) to ensure safety for both occupational and public exposure. For frequencies between 3 kHz and 30 MHz, electric field strength limits are set at 614 V/m for occupational exposure, while for the public, the limit decreases linearly with frequency. Magnetic field strength limits in this range are 1.63 A/m for workers, also decreasing for the public. At higher frequencies, from 30 MHz to 300 GHz, the standard sets power density limits, with occupational exposure allowed up to 50 W/m² (30–300 MHz) and 10 W/m² (300 MHz–300 GHz), and lower limits for the public, 10 W/m² and 2 W/m² respectively.

Additionally, the standard specifies limits on the Specific Absorption Rate (SAR), which measures the rate of energy absorption in body tissue. For whole-body exposure, occupational SAR is limited to 0.4 W/kg, while for the public, it is 0.08 W/kg. Localized SAR limits, relevant for areas like the head and trunk, are higher—10 W/kg for workers and 2 W/kg for the public. All these limits are averaged over a six-minute period to account for exposure duration, aiming to protect against potential health risks from electromagnetic fields across a wide frequency spectrum.

4.1.4 Other Standards

Unlike standards that define specific exposure limits to electromagnetic fields, such as the ICNIRP Guidelines [2], Directive 2013/35/EU [1], or IEEE C95.1 [3] described above, IEC 62311:2019 [46] and IEC TS 62997:2017 [47] serve a different but complementary purpose. These standards do not prescribe threshold values; but they provide methodologies for evaluating and demonstrating compliance with existing exposure limits. IEC 62311 [46] focuses on assessing EMF exposure from electrical and electronic equipment across a broad frequency range, while IEC TS 62997 [47] offers specialized tools for characterizing magnetic nearfields and calculating induced effects in the human body, particularly in industrial electroheating contexts. Together, they form the technical backbone that enables manufacturers to verify whether their equipment meets the safety criteria established by regulatory and scientific bodies.

4.1.4.1 Standard IEC 62311:2019

IEC 62311:2019 standard [46] provides a framework for assessing human exposure to electromagnetic fields (EMF) from electronic and electrical equipment, focusing on ensuring safety across a wide frequency range from 0 Hz to 300 GHz. It is especially relevant for devices that do not fall under specific product standards, including many industrial systems.

The standard does not define exposure limits itself but requires that equipment be evaluated against internationally recognized thresholds, such as those from the ICNIRP. It outlines methods for determining whether a product complies with these limits, considering both intentional radiators and unintentional sources, which are defined as:

- Intentional radiators: devices designed to emit electromagnetic energy, such as RF transmitters, wireless communication systems, or industrial microwave generators.
- Unintentional radiators: Equipment that emits EMF as a byproduct of its operation, like leakage from microwave heating systems, induction heaters, or power electronics.

This distinction is crucial because intentional radiators are typically well-characterized and regulated, while unintentional emissions may vary depending on shielding, design flaws, or installation conditions.

The assessment includes evaluating electric and magnetic field strengths, power density, and proximity to human operators, ensuring that exposure remains below harmful levels, according with a structured evaluation process, which combines:

- Field strength measurements: quantification of the electric field (E) and magnetic field (H) intensities at various points around the equipment, especially where human access is possible.
- Power density calculations: for frequencies above 10 MHz (including microwave range), exposure is often assessed in terms of power density (W/m²), which reflects the energy absorbed per unit area.
- Spatial proximity analysis: the standard emphasizes evaluating exposure at realistic distances (for example, 5 cm, 20 cm, or 1 m from the equipment), depending on how close operators or bystanders may be during normal use or maintenance.
- Time-weighted exposure: in some cases, exposure duration is factored in, especially for intermittent or pulsed sources.

If measurements or simulations show that EMF levels exceed safe thresholds, IEC 62311 [46] requires manufacturers to implement mitigation strategies, such as:

- Physical shielding (metal enclosures, waveguides).
- Access restrictions (interlocks, warning signs).
- Design modifications (reducing leakage, rerouting cables).
- Documentation and labelling to inform users of potential risks.

The goal is to ensure that no part of the equipment exposes users to EMF levels above the recommended limits, whether during operation, maintenance, or accidental access.

In resume, IEC 62311 [46] emphasizes the importance of risk management in design and installation. It requires manufacturers to identify potential EMF hazards, apply shielding or distance-based mitigation strategies, and document compliance through technical reports. This is critical for industrial microwave equipment, where high-frequency energy can pose risks such as tissue heating or nerve stimulation if not properly contained. By following IEC 62311, manufacturers help ensure that their equipment does not exceed safe exposure thresholds, protecting both workers and the public.

4.1.4.2 Standard IEC TS 62997:2017

The IEC TS 62997:2017 [47] is a technical specification from the International Electrotechnical Commission that provides methods for evaluating the hazards of magnetic nearfields (the magnetic fields that exist close to current) from industrial electroheating and electromagnetic processing equipment. It specifies how to characterize external magnetic fields and calculate the induced electric fields in the human body to assess risks like induced electric shock and local skin overheating. The standard is applicable for frequencies between 1 Hz and 6 MHz and includes considerations for nerve stimulation, muscle response, and thermal effects, with limits on touch currents.

The standard aims to provide **quantitative methods** to assess these risks and determine whether equipment design and operation are within safe exposure thresholds, providing a multi-step approach to hazard evaluation:

- Characterization of magnetic fields
  - Measurement or simulation of the magnetic field strength (H-field) in the nearfield region around the equipment.
  - Consideration of field gradients and spatial distribution, especially near accessible surfaces.
- Calculation of Induced Electric Fields
  - Using anatomical models or simplified geometries, the standard provides methods to estimate the electric field induced in body tissues by time-varying magnetic fields.
  - These calculations are essential for evaluating compliance with basic restrictions from ICNIRP or IEEE standards.
- Assessment of Physiological Effects
  - The standard includes thresholds for nerve and muscle stimulation, based on frequency and exposure duration.
  - It also considers specific absorption rate (SAR) and temperature rise in tissues, which are critical for evaluating thermal hazards.
- Touch Current Limits
  - IEC TS 62997 [47] sets limits on permissible touch currents, which are currents that may flow through a person upon contact with conductive parts exposed to magnetic fields.
  - These limits are frequency-dependent and are designed to prevent discomfort or injury.

By applying IEC TS 62997:2017 [47], manufacturers can ensure that their equipment does not pose undue risk to operators or maintenance personnel, even in close-contact scenarios.

4.1.4.3 Standard IEC 60519-1

IEC 60519-1 is the foundational standard that outlines the general safety requirements for industrial electroheating equipment and installations. It establishes the essential principles for protecting personnel and equipment from electrical, thermal, and mechanical hazards associated with electroheat technologies, including induction and microwave systems. This standard applies to both new and existing installations and serves as a baseline for evaluating conformity and implementing risk mitigation strategies in industrial environments.

The standard emphasizes the importance of proper design, installation, operation, and maintenance practices to ensure safe functioning. It covers aspects such as insulation coordination, protection against electric shock, thermal hazards, electromagnetic compatibility (EMC), and emergency shutdown procedures. IEC 60519-1 is intended to be used in conjunction with more specific standards—such as IEC 60519-3 [48] for induction and conduction heating—to address the unique risks posed by technologies.

In the context of occupational safety, IEC 60519-1 complements regulatory frameworks like Directive 2013/35/EU [1], ICNIRP guidelines [2], and IEEE C95.1-2019 [3] by providing the technical foundation for managing exposure to electromagnetic fields (EMF) in industrial settings. Together, these documents support a comprehensive approach to safeguarding workers from both immediate and long-term hazards associated with high-frequency energy systems.

4.2 Guidelines, Recommendations and contributions of key organizations

The health and safety good practices and recommendations for safe design, installation, operation and maintenance of the equipment of induction and microwave heating systems are discussed in the following subsections, as induction and microwave heating operators and other personnel coming near to these systems may be exposed to several hazards, as observed in Table 2.2 and Table 3.4.

4.2.1 Induction Heating

Induction heating operations can cause short-term health impacts, such as stimulation of nerve and muscle tissue [49], when workers are exposed to EMFs. These effects are limited to the duration of exposure and cease or diminish once exposure ends. To date, there is no scientific evidence of long-term impacts from exposure to electromagnetic fields from induction heating operations.

According to the literature [49], in the case of industrial induction heaters, one-third of the maximum flux densities reported, measured in the workplace, exceed the high action level established in the revised directive [45]. It is important to note that the specific characteristics of industrial and professional induction heating equipment and its use only cover the frequency range up to 30 MHz, and the strength of the magnetic field depends on the power of system (*i.e.,* the level of current passing through the cables and coil) [50].

Koppel *et al.* [51] analysed workers exposure to the magnetic fields from induction ovens that are used in production to melt aluminium in otherwise iron containing units. Electromagnetic field measurements were performed across the working area where the induction heater was positioned through spatial, spectrum, and expositmetry means. Additionally, visual observations based on video recordings of worker movements during work procedures and questionings of workers and supervisors were also conducted. The authors proposed risk mitigation procedures to lower exposure during induction heating, such as workplace rearrangement, work procedure redesign, and other measures. Moreover, time-weighted average exposure to the magnetic field could be lowered from 2.57 μT (maximum observed procedure) to 0.12 μT (recommended procedure after interventions), based on a simulation of an alternative procedure. Finally, the authors mentioned that suitable qualification and training programs should be planned for employers, workers, and work environment specialists.

Therefore, surrounding objects in the workstation of the induction heating system can affect the propagation of the electromagnetic wave, *i.e.,* peripherical devices, the building structure, and the materials used [51]. Additionally, the workstation design may also affect the electromagnetic field's exposure scenarios [51].

In Figure 4.2, it is possible to see a representative view of occupational exposure in a case study workstation of induction heating. As it can be observed in Figure 4.2 it is important to examine the distribution of the magnetic field in the work areas and assess the possible exposure scenarios during the operation of the induction heating process.

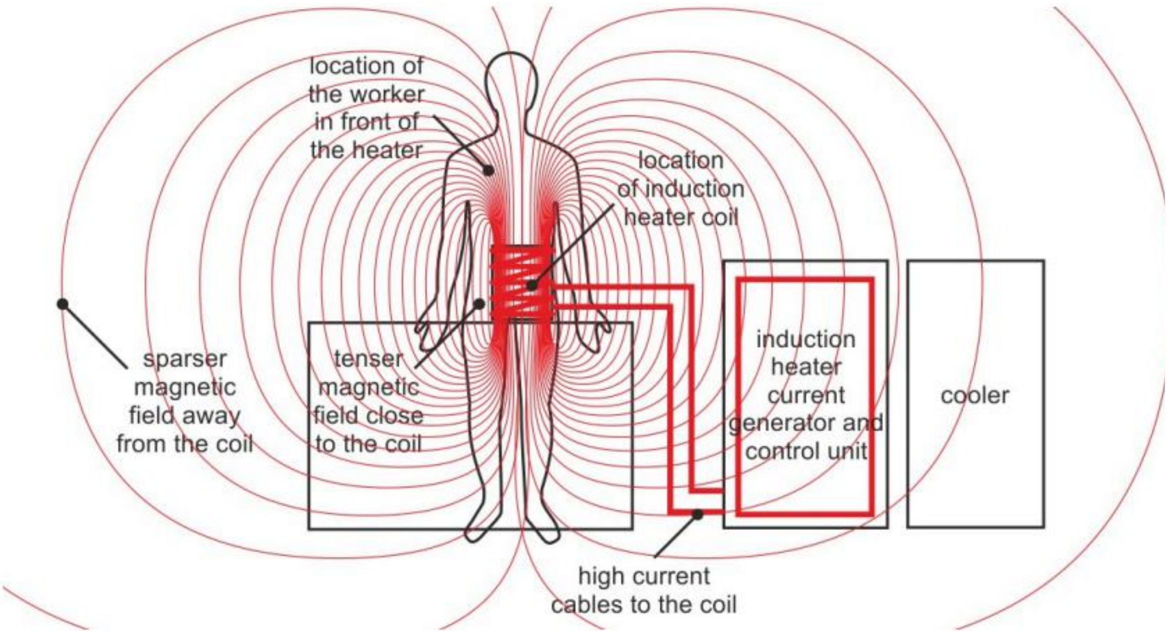


Figure 4.2 Perception of the industrial induction heating occupational exposure, whereas red areas represent the magnetic field or its source [51].

The Standard EN50519 [52], which is no longer active (as of about 2017), can be used as technical reference to evaluate workers' exposure in workplace. This standard divide induction heating devices into three groups, as field distributions differ by geometry, *i.e.*:

- Cylindrical coils in horizontal orientation.
- Cylindrical coils in vertical orientation.
- Non-cylindrical or complex geometry devices.

According to the assessment procedure described in EN50519 [52], it is necessary to apply several steps:

- **Preparation and planning**: define worst-case operating conditions, determine measurement points, ensure safety, etc.
- **Initial field topology scan**: map the spatial distribution of fields to locate maxima or critical zones.
- **Final detailed measurement**: at selected points, measure relevant E (Electric Field Strength – V/m), H (Magnetic Field Strength – A/m), B (Magnetic Flux Density or Induction - µT), induced currents, contact currents (if applicable) to compare with action values.
- **Documentation and reporting**: Record measurement methods, results, uncertainties, operating conditions, diagrams, etc.

Note that in some cases, electric or contact currents only need measuring if field strengths approach action values (especially above ~1 MHz).

The classification of devices according to coil orientation and geometry is particularly relevant, as the distribution and intensity of magnetic fields can vary significantly depending on these factors. Understanding these differences is essential to accurately model the exposure scenarios and implement appropriate protective measures. Workers may be positioned at different distances and angles relative to the coils during normal operation, maintenance, or setup procedures, each potentially involving different levels of exposure. Therefore, it is not sufficient to rely solely on general exposure limits; rather, a scenario-based approach, supported by standards such as EN 50519 [52], can provide more realistic and precise assessments.

To assess workers' exposure, it is important to consider not only the field strength and frequency, but also the duration of the exposure, and the nature of the exposure, including how it is distributed across the worker's body and within the workspace volume.

In the IEC 60519-3 standard ([48]) is presented the safety requirements for induction and conduction heating and melting installations, ensuring the protection of both equipment and personnel. The IEC 60519-3 [48] is part of the broader IEC 60519 series, which addresses safety in electroheat installations. It applies to equipment operating at low, mains, medium, and high frequencies, and includes systems used for heating solids or melting, holding, and superheating liquid metals. The standard also covers relevant parts of conveying or handling equipment that fall within the influence of the electroheat process.

Key provisions include protection against electric shock, thermal hazards, and mechanical risks, as well as requirements for control systems, interlocks, and emergency stops. It emphasizes the importance of proper shielding, cooling systems, and monitoring of critical parameters like temperature and current. In detail:

- Protection against electric shock
  - Proper insulation of conductive components and use of physical barriers to prevent accidental contact.

  - Effective grounding of metallic structures and exposed conductive parts.
  - Residual current devices (RCDs) or differential protection systems to detect insulation faults and disconnect power.
- Thermal and mechanical hazards
  - Hot surface protection using shields, warning signs, and insulating materials.
  - Burn and fire prevention through temperature control and thermal sensors.
  - Mechanical safety measures to guard against moving parts, vibration, and impact forces.
- Control systems and safety functions
  - Safety interlocks that prevent operation when access doors or protective covers are open.
  - Emergency stop systems with easily accessible buttons that immediately shut down the equipment.
  - Continuous monitoring of critical parameters such as temperature, current, voltage, and coolant flow.
- Shielding and cooling systems
  - Electromagnetic shielding to limit exposure to high-frequency fields.
  - Cooling systems (water or air) to dissipate heat from coils and components.
  - Alarms and auto-shutdown in case of cooling failure or overheating.

To ensure safe operation of induction and conduction heating installations, IEC 60519-3 outlines a comprehensive set of safety requirements. The flowchart (in Figure 4.4) summarizes the logical sequence of safety checks and system conditions that must be met before and during operation. It serves as a visual aid to understand how protective measures, such as grounding, interlocks, cooling systems, and emergency stops, interact to maintain operational safety and prevent hazards.

[Start]
↓
[Power Supply Activated]
↓
[Check Grounding & Insulation]
↓
[Enable Control System]
↓
[Safety Interlocks Engaged?] → No → [Block Operation]
↓ Yes
[Cooling System Operational?] → No → [Trigger Alarm & Shutdown]
↓ Yes
[Monitor Parameters: Temp, Current, Voltage]
↓
[Emergency Stop Available]
↓
[Safe Operation Continues]

Figure 4.3 Safety checks and system conditions that must be met before and during operation based on the procedures described in IEC 60519-3 [48].

The standard is intended to be used in conjunction with IEC 60519-1, which provides general safety principles for electroheat installations, while IEC 60519-3 [48] adds the specific technical and operational safeguards necessary for induction and conduction technologies.

Additionally, it is important to consult the **Directive 2013/35/EU (2013)** [1]**, ICNIRP (2010) guidelines** [2] and **standard IECC C95.1-2019** [3] to address the assessment and limitation of workers' exposure to electromagnetic fields (EMF), particularly in environments where induction and microwave technologies are employed. These references provide thresholds for exposure, risk evaluation procedures, and protective measures to ensure compliance with occupational safety requirements, especially in high-frequency and high-intensity field scenarios.

4.2.2 Microwave Heating

Currently, domestic microwave ovens are subject to an emission limit of 50 W/m² at 2450 MHz, as defined in IEC 60335-2-25 [53] (formerly IEC 335-2-25:1988). However, there is no specific emission standard for industrial microwave ovens in Europe; instead, general safety requirements are addressed in IEC 60519-6 [34] which refers to broader electromagnetic exposure guidelines. In specific, the standard IEC 60519-6:2022 is an international safety standard that addresses industrial equipment used for dielectric heating, particularly in the microwave and high-frequency range (3 MHz to 300 GHz). It provides comprehensive safety requirements for systems that apply electromagnetic energy to heat insulating materials, including microwave ovens, generators, and hybrid heating systems. The standard ensures that equipment design, installation, and operation minimize risks associated with electromagnetic radiation, electrical hazards, and thermal exposure.

As microwave heating is one of the main focuses of this standard, specific safety measures for microwave systems are described, including shielding to prevent radiation leakage, interlocks to disable operation when access doors are open, and monitoring systems to control power levels and field strength. It also requires emergency shutdown capabilities to protect operators and equipment. The key safety requirements described are:

- Electromagnetic field limits: exposure levels must comply with internationally recognized thresholds, such as those defined by the ICNIRP Guidelines, and be assessed using methodologies outlined in IEC 62311,
- Protective enclosures and interlocks: equipment must prevent access to active microwave zones during operation.
- Monitoring and control systems shall include fail-safes for power supply, temperature, and field strength.
- Emergency shutdown protocols: systems must allow rapid deactivation in case of malfunction.

On the other hand, in Canada, Health Canada established Radiation Emitting Devices Regulations [54], where Part III is dedicated to Microwave Ovens, specifying the following limits for the leakage radiation at 5 cm from the surface of the microwave oven:

- 1.0 mW/cm^2 with test load (*i.e.,* microwave with load, representing actual use)-
- 5.0 mW/cm^2 without test load.

The values published are based on scientific studies, including both internal and external authoritative reviews of the scientific literature, as well as Health Canada's own research.

In general, the microwave oven is considered a useful and safe technology. For this reason, the Health Physics Society (HPS) [55] recommends implementing one or more of the following practices instead of testing every unit for radiation leakage:

- Maintain a basic inventory of all microwave ovens, including details such as model, year of manufacture, serial number, wattage, responsible contact person, and location.
- Post a one-page microwave safety guideline near each oven. Simply doing this can help prevent many unsafe behaviours that often result in leakage.
- Perform visual checks on ovens suspected of leaking—usually identified through staff complaints. If the oven shows visible damage (*e.g.,* loose doors, broken switches, or holes in the casing), it should be repaired or disposed of (cutting off the power cord is recommended);
- Only if properly calibrated radiation measurement equipment is available, test the ovens suspected of leaking and record the results. Any oven that fails to meet safety standards should be repaired or discarded.

Occupational exposure data related to industrial microwave ovens remains limited and is not extensively documented in the scientific literature. Nevertheless, some case studies offer valuable insights. For example, the study published by Plets *et al.* (2016) [56] examined exposure levels associated with 11 different types of microwave ovens under various load conditions and power settings, as a function of distance (within 1 meter) from the source. This study included a comparative analysis of the measured electric field strengths against the reference levels established by ICNIRP [2] and IEC-335-2-25 (1988) [53] standards. The authors concluded that, across all measurement points, the field strengths remained within ICNIRP [2] reference limits for both occupational exposure and the public. The highest levels were recorded at the closest measurement distance, which was 5 cm (see Figure 4.4).

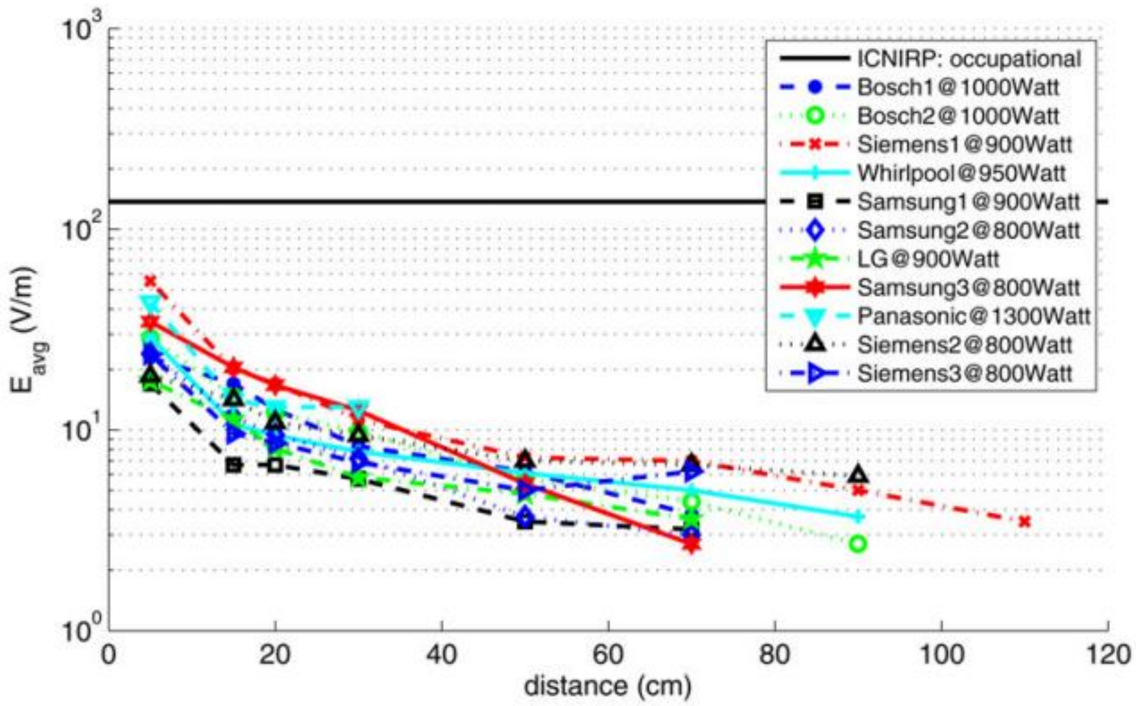


Figure 4.4 Electric-field values as a function of distance for the 10 different microwave ovens for occupational exposure [56].

Based on the empirical data, a predictive model of electric field intensity as a function of distance was developed by Plets *et al.* [56]. This model facilitates more accurate assessments of occupational exposure and enables comparison with regulatory exposure limits for workers (Figure 4.5).

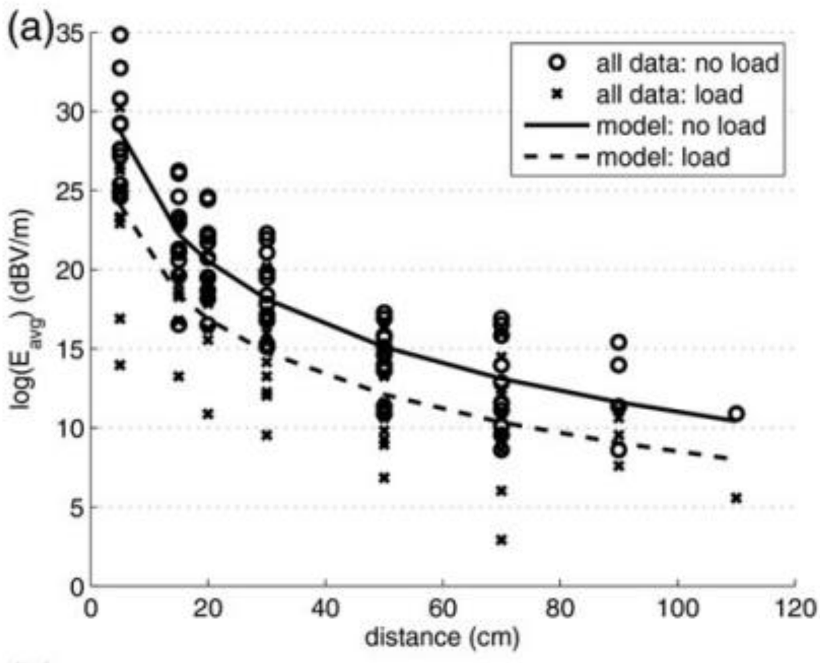


Figure 4.5 Electric-field strength of all microwave ovens and fitted models without and with oven load for occupational exposure [56].

On the other hand, there are some studies showing that the workers should avoid staying at shorter distances from the microwave oven while it is operating, due to the high levels of EMF, which may pose potential health risks (such as cataracts, infertility, among others [57]. In the study of Xiang and Xiang [57] the power density and strength of EMF) were measured at different distances and directions in front of a microwave oven (Figure 4.6), to evaluate if “one arm’s length” (~61 cm) from microwave oven was a safe distance. The findings from the power density and EMF measurements in this study indicate that a minimum distance of 91 cm is needed for the power density to drop to 0.05 mW/cm² or less, and 122 centimetres are necessary for EMF levels to fall to 25 mG or lower [57].

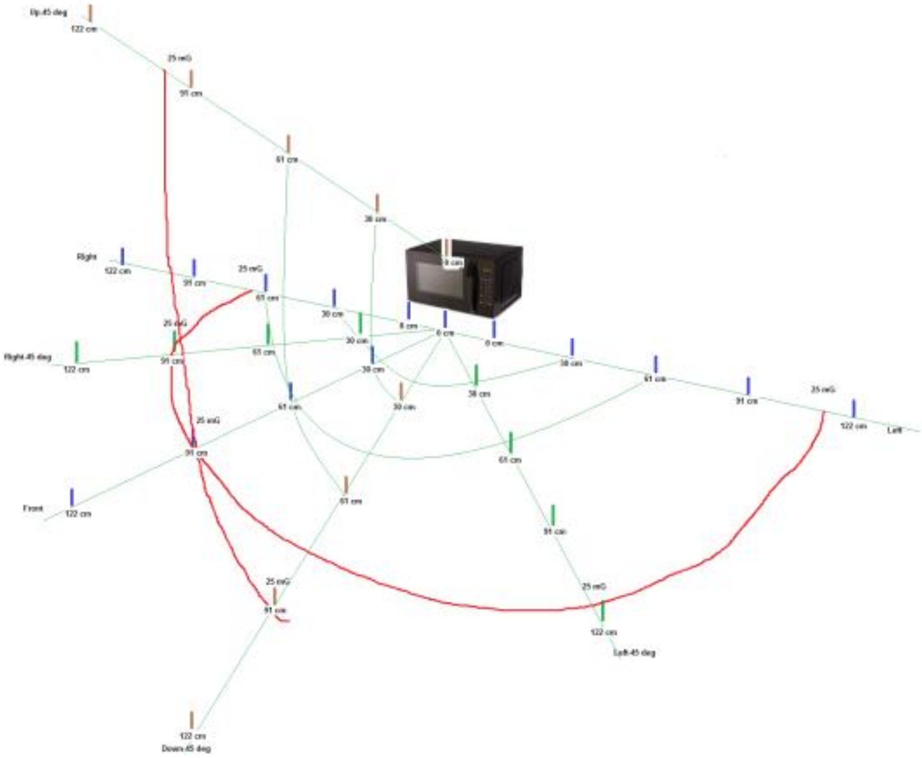


Figure 4.6 Illustration of the EMF distribution in front of microwave oven. Green lines and curves represent approximate distances (in centimetres) in different directions and the red lines represent the EMF threshold of 25mG [57].

Considering the studies mentioned, the risks associated with the use of microwaves in industrial settings remain unclear, therefore further research is important.

5 Conclusions

This deliverable ***D4.3 – Health and Safety Requirements – Preliminary report*** of JOULIA project provides a comprehensive literature review and analysis of induction and microwave heating systems for industrial applications, detailing the underlying physical principles and assessing the distinct advantages and inherent limitations of each technology. The objective is to establish a clear foundation to analyse the associated occupational hazards and risks posed by these technologies in industrial applications, as well as risk control measures. Applicable standards, regulations, guidelines and recommendations were also analysed based on a literature review.

For induction heating systems, several physical parameters are critical, most notably the frequency of the electrical current, power density and resulting temperature gradient, which determine the penetration depth of the induced currents (and electromagnetic field) into the materials during the heating process. In microwave heating systems, the analysis performed in the present report underscores their growing industrial relevance as efficient, clean and controllable alternatives to conventional thermal processes. Their operation is based on dielectric heating, in which electromagnetic energy, typically at 915 MHz or 2.45 GHz, interacts with polar molecules within the processed material, generating volumetric heat through dipole rotation and ionic conduction. This mechanism enables rapid and relatively uniform temperature distribution throughout the product volume. Nevertheless, the effectiveness of microwave heating strongly depends on the dielectric properties of the material (dielectric constant and loss factor), as well as on process design and power configuration, which must be carefully optimised to avoid non-uniform heating, localised hot spots, and process instabilities.

The electrification of industrial activities based on induction and microwave heating systems can play a crucial role in the energy transition across various industrial applications, offering higher thermal efficiency, precise process control, faster heating rates, and improved product quality across multiple industrial sectors. For example, induction systems can achieve efficiencies above 90–95% in converting electrical energy to heat [8]. However, these technologies also present limitations: high capital and maintenance costs, restricted penetration depth for large or dense materials, and material constraints, since induction heating is applicable only to electrically conductive and/or ferromagnetic materials, while microwave absorption depends on the dielectric properties of the medium. These factors must be balanced against performance, safety, and economic considerations when selecting and designing electrified thermal systems for industrial applications.

Additionally, these heating technologies can create several **occupational hazards and risks**, such as ([14], [12], [15], [16]):

- **Electromagnetic fields (EMF) exposure**, which can impact human health depending on the frequency, strength of the magnetic field (it depends on equipment design and current flow, not on equipment size, complexity or voltage), workplace design, duration of exposure and the distance from the EMF source of the induction heating system to the operator.

- **Fatal electrical shock and/ or severe burn**, when the operator touches a hot part, live electrical parts, or an energized electrode (*i.e.,* the power is on a metal part which touches the energized electrode), which is part of the induction technology system.
- **Fire or explosion**, when parts of the induction and microwave heating systems are overheated or when the atmosphere contains flammable dust, gas or liquid vapours.
- **Fumes, gases and airborne particulate exposure**, as they can be produced from the induction and microwave heating systems of metallic parts when in contact with coatings, adhesives or fluxes (*i.e.,* a substance used in smelting and metal joining to help remove impurities and to prevent oxidation); and they can displace air and lower the oxygen level, causing injury or death.

Although a **health and safety risk assessment following a case-by-case basis is required for adequate risk mitigation of induction and microwave heating systems**, general prevention measures are well-known. A revision of these general prevention measures was performed for both heating technologies.

The revision and analysis of **standards, regulations and guidelines** for occupational health and safety and to promote compliance with regulatory standards associated with induction and microwave heating technologies was performed and the main conclusions are listed below:

- **Worker' exposure limits to EMF** are established by several standards and guidelines, such as Directive 2013/35/EU (2013)n [1], ICNIRP [23] guidelines and IEEE C95.1-2019 [3], and they depend on the specific frequencies involved and the scope of application (*i.e.,* public or occupational exposure).
- **Occupational exposure limits to EMF of microwave systems** are the same for the standards and guidelines analysed, *i.e.* Specific Absorption Rate (SAR) limit of 0.4 W/kg (whole body), 10 W/kg (localized) ([1], [2], [3]). Note that industrial microwave ovens often use 915 MHz or 2.45 GHz, where thermal effects dominate, and SAR becomes the primary concern (SAR is established as the key metric for microwave exposure, reflecting energy absorbed per unit mass).
- **Occupational exposure limits to EMF of induction systems** depend on the standards and guidelines used, *i.e.* the IEEE [3] and ICNIRP [2] focus on the electric field component (internal electric field limit approximately 1.1 V/m at 100 kHz), while the Directive 2013/35/EU [1] focuses on the magnetic field component (action Level for magnetic field approximately 27 A/m at 100 kHz). Note that induction heating typically operates in the 10 kHz to 1 MHz range, where magnetic field strength and internal electric fields are critical.
- **Standards and guidelines are focused on the short-term effect of EMF**, *i.e.* acute effects such as thermal effects and electrical stimulation of body tissues ([1]) and transient effects on the nervous system ([23]), as long-term health effects have not been conclusively proven ([49]). Note that above 100 kHz, ICNIRP [2] guideline mention that thermal effects become more significant. These effects are limited to the duration of exposure and cease or diminish once exposure ends ([49]).
- **Although there are no exposure limit standards dedicated exclusively to induction heating or microwave technologies,** occupational exposure can be

assessed using general frameworks such as Directive 2013/35/EU, the ICNIRP Guidelines, and IEEE C95.1-2019. Additionally, process-specific safety requirements are addressed in standards like IEC 60519-3 (for induction heating) and IEC 60519-6 (for microwave heating).

IEC 60519-1, IEC TS 62997:2017, and IEC 62311:2019 reinforce the practical implementation of EU directives and ICNIRP guidelines by providing a solid technical basis for assessing and controlling EMF exposure in both industrial and non-industrial environments. Together, they support an integrated approach to protecting workers from acute and chronic risks associated with high-frequency systems.

The **health and safety good practices and recommendations** related with induction and microwave heating systems were also analysed and the **key aspects** are summarized below, *i.e.*

- **Specific characteristics and use of industrial induction heating equipment**: only cover the frequency range up to 30 MHz, and the strength of the magnetic field depends on the power of system, *i.e.* the level of current passing through the cables and coil ([50]).
- **The assessment of workers' exposure to EMF** should consider not only the field strength and frequency, but also to pay special attention to the duration of the exposure, and the nature of the exposure, including how it is distributed across the worker's body and within the workspace volume.
- **EMF measurements** should be performed across the working area where the heater is positioned through spatial, spectrum and exposimetry means; visual observations based on video recordings of worker movements during work procedures and questionings of workers and supervisors should also be conducted ([51]).
- **Workstation design of induction and microwave heating systems and surrounding objects** can affect the EMF exposure scenarios (*i.e.* peripherical devices, the building structure and the materials used. Therefore, it is crucial to examine the distribution of the magnetic field in the work areas and assess the possible exposure scenarios during the operation of the induction heating process ([51]).
- **Risk mitigation procedures for EMF worker exposure from an heater** could include to lower exposure during heating, such as workplace rearrangement, work procedure redesign and other measures; to lower the time-weighted average exposure to the magnetic field based on a simulation of an alternative procedure; to plan suitable qualification and training programs for employers, workers and work environment specialists ([51]).
- **Workers' exposure assessment methodology for induction heating systems**: preparation and planning, initial field topology scan, final detailed measurement and documentation and reporting. The heating devices are classified depending on the orientation and geometry, as the distribution and intensity of magnetic fields can vary significantly depending on these factors (*i.e.* cylindrical coils in horizontal or vertical orientation, and non-cylindrical or complex geometry devices). Additionally, workers

may be positioned at different distances and angles relative to the coils during normal operation, maintenance or setup procedures, each potentially involving different levels of exposure ([52].

- **Limited evidence exists in the literature regarding the effects of occupational exposure to industrial microwave ovens**, with most studies being conducted on domestic microwaves and yielding inconclusive results. While research on **the effects of occupational exposure to induction technology exists for the industrial context.**

Therefore, it is not enough to rely only on general exposure limits. Rather, **understanding and analysing the key aspects related to the occupational health and safety of induction and microwave heating technologies is essential:**

- **To accurately model the exposure scenarios (by following a scenario-based approach).**
- **To provide more realistic and precise assessments.**
- **To implement appropriate protective measures.**

The final deliver of JOULIA project (WP4: T4.3), *D4.5 – Health and Safety Requirements*, aims to provide a concise analysis of the standards, regulations, guidelines and recommendations for the health and safety requirements for both induction and microwave heating systems. Additionally, a qualitative exposure assessment of the demonstrators involved in JOULIA project will be performed and analysed, to understand the risks to which workers are exposed at each demonstration site, and the necessary health and safety requirements (*i.e.* rubber flooring production line at ARTIGO S.P.A. and glue activation and multilayer pipes production line at K-FLEX Polska Spolka Ograniczona Odpowiezialnoscia).

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