GUIDELINES FOR THE APPLICATION AND VERIFICATION OF DIELECTRIC HEATING AS A PHYTOSANITARY MEASURE

DRAFT

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CONTENTS

INTRODUCTION

SCOPE

This guideline[1] provides technical guidance on the specific procedures for the application of dielectric radiation (dielectric heating) as a phytosanitary treatment for regulated pests or articles. This does not include treatments used for:

- sanitary treatments (food safety and animal health); or
- the preservation or improvement of commodity quality (e.g. shelf life extension).

REFERENCES

Export certification system, 1997. ISPM No. 7, FAO, Rome.
Guidelines for phytosanitary certificates, 2001. ISPM No. 12, FAO, Rome.
Glossary of phytosanitary terms, 2003. ISPM No. 5, FAO, Rome.
Guidelines for Pest Risk Analysis, 1996. ISPM No. 2, FAO, Rome.
International Plant Protection Convention, 1997. FAO, Rome.
Pest Risk Analysis for quarantine pests including analysis of environmental risks, 2003. ISPM No. 11 Rev. 1, FAO, Rome.
Principles of plant quarantine as related to international trade, 1995. ISPM No. 1, FAO, Rome.
The use of integrated measures in a systems approach for pest risk management, 2002. ISPM No. 14, FAO, Rome.
Others?

DEFINITIONS

Ampere [A]	The unit of electric current in the rationalized meter-kilogram-second system of units. It indicates the electron flow and is equivalent to a flow of charges in a conductor of one Coulomb for second.
Electric field	space region causing a charged body to be attracted to or repelled by other charged bodies.
Electromagnetic field	an electric or magnetic field, or a combination of the two, as in an electromagnetic wave.
Electromagnetic wave	a disturbance which propagates onward from any electric charge which oscillates or is accelerated; far from the charge it consists of vibrating electric or magnetic fields which move at speed of light and are at right angles to each other and to direction of propagation.
Dielectric material	which is an electrical insulator or in which an electric field can be sustained with a minimum dissipation of power.
Dielectric permittivity	the property describing the behavior of materials in an electromagnetic field.
Electromagnetic shielding	the apparatus that prevents the propagation of an electromagnetic signal in a given area.
Frequency [Hertz]	the number of cycles completed by a periodic quantity in a unit time, as example a current.
Gradient	measure the maximum rate of change of a function, in space, in a given direction.
Infrared	Electromagnetic waves having wavelength between 0,75 e 1000 µm (10-6m).
Isotropic material	A material having identical properties in all directions.
Magnetron	The magnetron is a diode-type electron tube which is used to produce the required 2450 MHz of microwave energy.
Microwave (MW)	An electromagnetic wave which has a wavelength between about 0,3 and 30 centimeter, corresponding to frequencies of 1-100 GHz.
Polar molecules	Molecule in which the distribution of the electrons is asymmetrical. In these exist a center for the positive charges and a different center for the negative charges.
Moments of dipole	Measure of the polarity of the molecules
Power [W]	Energy in the unit of time.
Thermocamera	Device for measurement of superficial temperature. It gives a graphic representation.
Thermocouple	Device constituted by two different conductors united to their extremities, the electric voltage developed among the two junctions is proportional to the difference of temperature among the same, so that the device can measure the temperature of a junction.
Watt [W]	Unity of measure of the electric power. It is the power developed in a circuit by a tide of an

[1] Nothing in this guideline shall affect the rights or obligations of contracting parties under other international agreements or national legislation, including those applicable to the dielectric heating (e.g. microwaving) of food.

	ampere that crosses a difference of potential of a volt. It is equal to 1/746 of Horse Vapor (HP).
Watt -hour [Wh]	Unity of measure of energy; it is equal to a Watt for a hour.
Wavelength	The distance between repeating units of a wave patters.

Definitions of phytosanitary terms used in these guidelines can be found in ISPM No. 5 (*Glossary of phytosanitary terms*).

OUTLINE OF GUIDELINES

Treatment with dielectric radiation (dielectric heating) may be used for pest risk management. NPPOs should be assured that the efficacy of the treatment is scientifically demonstrated for the regulated pest(s) of concern and the required response. The NPPO is responsible for ensuring that facilities are appropriately designed for phytosanitary treatments. Procedures should be in place to ensure that the treatment can be conducted properly and commodity lots are handled, stored and identified to ensure that phytosanitary security is maintained.

GUIDELINES FOR THE APPLICATION AND VERIFICATION OF DIELECRTRIC HEATING AS A PHYTOSANITARY MEASURE

1. Authority

The NPPO is responsible for the phytosanitary aspects of evaluation, adoption and use of dielectric heating as a phytosanitary measure. To the extent necessary, it is the NPPO's responsibility to cooperate with other national and international regulatory agencies concerned with the development, approval, safety and application of dielectric heating, or the distribution, use or consumption of dielectrically heated products. Their respective responsibilities should be identified to avoid overlapping, conflicting, inconsistent or unjustified requirements.

2. Treatment Objective

The objective of using dielectric heating as a phytosanitary measure is to prevent the introduction or spread of regulated pests. This may be realized by achieving certain responses in the targeted pest(s) such as:

- mortality;
- preventing successful development (e.g. non-emergence of adults); or
- inactivation.

2.1 Efficacy

The required treatment efficacy should be specifically defined by the NPPO of the importing country. It consists of two distinct components:

- a precise description of required response;
- the statistical level of response required.

It is not sufficient to only specify a response without also describing how this is to be measured.

The choice of a required response is based on the risk as assessed through PRA, considering in particular the biological factors leading to establishment and taking into account the principle of minimal impact. A response such as mortality may be appropriate where the treatment is for the vector of a pathogen, whereas inactivation may be an appropriate response for pest(s) that are not vectors and remain on or in the commodity.

If the required response is mortality, time limits for the effect of the treatment should be established.

Treatments using dielectric heating that have been approved as an international standard will meet the requirements of ISPM 28 or ISPM 15, and be listed under one or both of these ISPMs.

3. Treatment

Dielectric heating may be provided by the application of electromagnetic radiation over a range of wave frequencies, including microwaves or radio waves.

Variables to consider when implementing treatments include the treatment time, temperature, moisture content (of the commodity and/or pest(s)), humidity, ventilation, and modified atmospheres; these should be compatible with treatment effectiveness. Modified atmospheres may reduce treatment efficacy at a prescribed dose.

The intended end use of the product should be considered when conducting irradiation treatments.

Because mortality may not occur during or immediately after treatment application, live target pests may be found on inspection. Where mortality occurs after a lag period, it is preferable that such pest(s) are unable to emerge or escape from the commodity, and are unable to successfully reproduce.

3.1 Application

Dielectric heating can be applied:

- as an integral part of packing operations;
- to bulk unpackaged commodities (such as grain moving over a belt);
- at centralized locations such as the port of embarkation.

When safeguards are adequate and transit movement of the untreated commodity is operationally feasible, treatment may also be performed at:

- the point of entry;

- a designated location in a third country;
- a designated location within the country of final destination.

Treated commodities should be certified and released only after temperature measurements confirm that the minimum required temperature was met over the whole profile of the treated commodity. Where appropriate, re-treatment of consignments may be allowed.

According to the pest risks to be addressed and the available options for pest risk management, dielectric heating can be used as a single treatment or combined with other treatments as part of a systems approach to meet the level of efficacy required (see ISPM No. 14: *The use of integrated measures in a systems approach for pest risk management*).

Methods of applying dielectric heating in trade are described in Appendix 1.

4. Measuring Commodity Temperature

Use of an appropriate temperature measuring system ensures that the required minimum temperature for a particular commodity was delivered to all parts of the consignment. The selection of the measuring system should be such that the temperature range of any sensor covers the entire range of temperatures likely to be received by the product. In addition, the measuring system should be calibrated in accordance with international standards or appropriate national standards (e.g. Standard ISO/ASTM 51261 *Guide for Selection and Calibration of Dosimetry Systems for Radiation Processing*).

Available methods of measuring temperatures during dielectric heating are described in Appendix 2.

The applied temperature measuring system should be appropriate for the treatment conditions. Temperature sensors should be evaluated for stability against the effects of variables such as light, humidity, commodity moisture content, commodity type, storage time, and the type and timing of analyses required.

The temperature measuring system should consider variations due to density, moisture content and composition of the material treated, variations in shape and size, variations in orientation of the product, stacking, volume and packaging. Temperature mapping of the product in each geometric packing configuration, arrangement and product density that will be used during routine treatments should be required by the NPPO prior to the approval of a facility for the treatment application. Only the configurations approved by the NPPO should be used for actual treatments.

4.1 Calibration of components of the temperature measurement system

All components of the temperature measuring system should be calibrated according to documented standard operating procedures. An independent organization recognized by the NPPO should assess performance of the temperature measuring system.

4.2 Temperature mapping

Temperature mapping studies should be conducted to fully characterize the temperature distribution within the dielectric heating chambers and commodity, and demonstrate that the treatment consistently meets the prescribed requirements under defined and controlled conditions. Temperature mapping should be done in accordance with documented standard operating procedures. The information from the temperature mapping studies is used in the selection of locations for temperature sensors during routine processing.

Independent temperature mapping for incomplete (partially-filled) as well as first and last process loads is required to determine if the temperature distribution is significantly different from a routine load and to adjust the treatment accordingly.

4.3 Routine temperature measurement

An accurate measurement of temperature of a consignment is critical for determining and monitoring efficacy and is part of the verification process. The required number, location and frequency of these measurements should be prescribed based on the specific equipment, processes, commodities, relevant standards and phytosanitary requirements.

APPENDIX 1

METHODS OF APPLYING DIELECTRIC HEATING

Fundamentals of Dielectric Heating

Microwave (MW) and radiofrequency (RF) heating methods belong to a more general method called dielectric heating (DH). By using this system it is possible to heat a body through the propagation of electromagnetic energy, which is absorbed by a substance and transformed into thermal energy. Because of the interaction effects between the electromagnetic waves and the matter (atoms, dipolar molecules and ions), in specific conditions, it is possible to generate heat directly in various materials. The heating mechanism depends on the frequency of the applied electromagnetic waves and on the chemical-physical characteristics (dielectric properties) of the material.

Electromagnetic waves are generated by the simultaneous and combined action of electric and magnetic fields, whose intensity varies cyclically with a certain oscillation frequency. When a dielectric material is subject to the action of an external electromagnetic field, its molecules undergo a phenomenon called polarization: electric dipoles, the ones induced by the field and the permanent ones, orientate in the applied electric field direction. The cycling frequency causes a vibro-rotational effect in molecules (in particular in dipolar molecules like water). At high frequencies, typically in the field of radiofrequencies or microwaves, where the field polarity is reversed many millions of times per second, the rapid oscillation and the consequent molecular friction provoke an energy dissipation in the form of heat.

Unlike traditional heating techniques, where heat moves from the surface to the internal strata by the phenomena of conduction and convection, MW and RF produce heat directly in the irradiated body ("core"), creating a temperature gradient that propagates with more concentrated heat from the inner part (internal core) to the outer surface of the irradiated material. Thus, heat is generated throughout the material and propagates by convection and conduction from the core of the material outwards, reducing treatment times and consequently lowering energy consumption.

Frequency is in inverse proportion to the wavelength according to the equation: $\mathbf{v = f \lambda}$ where v is the wave speed, f is frequency and λ is the wavelength. The oscillation frequency of the electromagnetic waves is measured in ***Hz*** (cycles per second). Conventionally, the electromagnetic waves ranging between approximately 30 kHz and 300 MHz are called radiofrequencies (RF) and the ones beyond 300 MHz are called microwaves (MW). MW operates over a variety of frequencies. Although classified as an irradiation treatment, these frequency regimes should not be confused with the more extreme electromagnetic spectrum of ionizing radiation. MW and RF are energy sources that produce strictly non-ionizing irradiation relative to safety issues of exposure. Table 1 lists the international MW frequency allocations recognized for industrial, medical and scientific uses.

Two factors influence depth of penetration of electromagnetic energy: (1) dielectric loss, which is a material property and can vary between species and orientation of the wood, and (2) wavelength of the energy. Of the two, wavelength is considerably more influential. Consequently, some disparity in depth of penetration exists between RF and MW treatment. Since depth of penetration increases with longer wavelength (lower frequency), RF ovens may serve as a better system to treat bulk volume consignments as opposed to typical MW oven designs. Dunnage forms of SWPM (e.g. materials with greater thicknesses) may not heat consistently with MW energy because the core is beyond the capable depth of penetration. Thus, RF ovens appear more feasible for this particular consignment type for DH treatment of SWPM.

Table 1. International MW frequency recognized for commercial/industrial, medical and scientific applications

Recognized frequency[1] (MHz)	Frequency tolerance (+/-)	Approval Country or World region
433.92	0-2%	Austria, The Netherlands, Portugal, Germany, Switzerland
896	**10 MHz**	**UK**
915	**13 MHz**	**North and South America**
2375	50 MHz	Albania, Bulgaria, Hungary, Romania, Czechoslovakia, USSR
2450	**50 MHz**	**Worldwide except where 2375 MHz is used**
3390	0-6%	The Netherlands
5800	75 MHz	Worldwide
6780	0-6%	The Netherlands
24150	125 MHz	Worldwide
40680		UK

[1]Bold denotes the more common applied MW frequency relative to range of heating and drying applications and suited to many dielectric property materials. Adapted from Metaxas, A. C and Meredith, R. J. 1993. *Industrial microwave heating*. Institution of Electrical Engineers. Power Engineering Series 4. Peter Peregrinus, LTD.

Investigations of target insect groups and other invasive pests have been extensively investigated applying RF and MW energy at 2450 and to a lesser extent 915 MHz with results that demonstrate Probit 9 levels of mortality. However, MW ovens should not be applied to wood that is thicker than stipulated by the annex of this treatment to ISPM No. 15 (or ISPM No. 28). MW ovens that operate above 2.45 GHz (greater frequency regime and correspondingly shorter wavelengths) are currently viewed as unable to provide sufficient depth of penetration and resultant heating consistency for all typical SWPM thicknesses. It is advisable that further research be performed to ensure that these other recognized MW frequencies satisfy the Probit 9 level of mortality before they are accepted for use in MW heating protocols of SWPM.

Given that dielectric energy primarily heats the water molecules or ionic constituents in a material, and heat transfer is significantly affected by the movement of water at elevated temperatures, heating rates and patterns are influenced by the moisture content (MC) of the SWPM. Treatment involving SWPM composed of dissimilar sapwood (high % MC) and heartwood (lower % MC) volumetric fractions have the potential to impact the resultant heating behavior, affecting effective treatment consistency. Furthermore, at elevated temperatures water movement in the form of evaporation from the free outside surfaces causes a removal of thermal energy, resulting in decreased temperatures at the surface. The phenomenon of evaporational cooling explains the frequently observed pattern of lower extreme surface temperatures compared with higher internal temperature measurements when DH technology is employed.

Often with heterogeneous distributions of moisture within the wood, the potential does exist for overshoot where temperature rise within a portion of the consignment will exceed the heat required for wood sterilization. Successful phytosanitary measures, irrespective of the applied dielectric field and system of application, should recognize this potential outcome and attempt to avoid excessive localized hot zones that may result in thermal decomposition of the treated material. Hot zones may also be observed near wood knots (associated grain distortions and differences of longitudinal fiber orientation) or regions of heavy resinous extractives (wood pitch pockets found in some coniferous species). These consignment conditions that result in heating behavior anomalies should be accounted for through the use of adequate initial temperature measurements. As such, a verification step, i.e. thermal mapping, is essential to examine heating behavior so that minimum threshold temperatures are reached for successful volumetric phytosanitation treatment. Temperature sensor devices are essential for monitoring DH heating to verify that the treatment achieves the prescribed ISPM-15 schedule (60 °C target lethal temperature and 1-minute hold time) (see Appendix 2).

Operational Oven Designs

MW and RF ovens acceptable for phytosanitary treatment include equipment designs that operate either through a static batch consignment unit treatment or dynamic continuous system for heating: 1) individual components of SWPM or 2) a constructed shipment commodity unit, e.g., assembled wooden pallets. Dielectric oven designs may include a hybrid approach that combines rapid internal heat development (irradiation heating mechanism) with a conventional thermal process segment (heated air or other conductive surface source mechanism) to complete the desired treatment protocol schedule. Hybrid technology could also be used that may provide the certified treatment facility the advantage of using initial rapid heating (DH), followed by conventional heat (HT) to maintain target temperature during a hold cycle, resulting in lower overall energy consumption for the total treatment schedule. The illustration below (Figure 1) provides a schematic diagram of a dielectric system design applying both a dielectric irradiation cavity followed by conventional heating equipment to achieve temperature uniformity of the SWPM consignment.

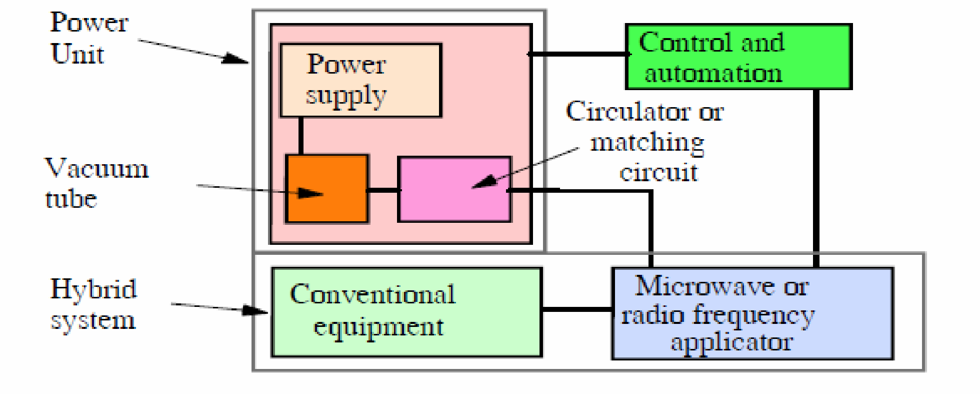

Figure 1: Generalized representation of the DH method (hybrid system design) shown as an option for phytosanitary wood treatment.

Figure 1 depicts a simplified view of the three major components of a typical industrial DH system: 1) Power Unit where MW or RF electromagnetic waves are generated at a given frequency regime; 2) Delivery Unit or the equipment design component that forms the applicator cavity where the dielectric material is subjected to the irradiation field; and 3) Equipment Control and Automation component for optimization (control or regulation) of the overall performance of the microwave or RF equipment with or without optional conventional oven heater. Magnetron or klystron tubes are used to generate microwaves as the electromagnetic field from a steady state electrical power supply for the heating operation.

Many other DH design adaptations are possible, which may exclude addition of a conventional heat application, instead relying exclusively on MW and/or RF frequency heating to accomplish the complete sterilization treatment.

Microwave systems

A microwave system is composed of three parts:

- The microwave energy generation system, which includes the magnetron and its supply unit;
- The waveguide, which is a metallic pipe where the microwave energy is propagated and conveyed from the generator to the process area (applicator);
- The applicator is a cavity or tunnel made of a material that reflects microwaves (generally stainless steel) having a geometry and size suitable to the specific object/product heating procedure.

The microwave energy generation system converts electric energy derived from the grid into microwave power. The most commonly used generator in industrial applications is the magnetron, which generates the electromagnetic field that is put into a waveguide through an opportune antenna. The waveguide consists of a conductive metal pipe, typically with a rectangular section, that carries microwaves from the generator to the applicator by means of a mechanism of multiple reflections from its walls. The applicator is a fundamental element of the microwave system, which provides continuous or batch treatment. There are two categories of applicators: single-mode and multi-mode. For single-mode applicators, one of the dimensions is the same as the wavelength (12.25 cm at the frequency of 2.45 GHz typically used). The generated field is well determined (mode) and has limited influence on the material being processed. Some advantages of single-mode applicators are:

- high and well-defined fields are possible;
- fields can be matched to product geometry;
- heating a wide range of materials is possible, including both low-loss and high-loss materials;
- the applicators are compatible with continuous product flow systems;
- high energetic efficiency is possible (in terms of ratio between heat generated in the material to the electromagnetic energy in the applicator).

Multi-mode applicators, in their simplest configuration, take the form of a box with dimensions larger than the operating wavelength enclosed in metal walls. This structure is a resonant cavity where unlike what occurs in single-mode cavities, there are many different modes resonating at frequencies very near to the operating frequency. For this reason these modes are excited with a significant intensity. Key features of multimode applicators include:

- better suitability for treating bulky objects;
- flexibility since their dimensions are often determined by material dimensions;

- high efficiency;
- adaptability to batch or continuous product flow;
- less sensitive to product position or geometry;
- good heating uniformity; and
- ability to handle irregular workloads.

A particular type of multi-modal applicator is the reverberation chamber. A reverberation chamber (RC) is a large metallic cavity or box that encloses an electromagnetic environment field, which is homogeneous, isotropic, incoherent and randomly polarized. Thus, the electromagnetic field is the same in all directions (isotropic) and evenly distributed within the chamber (homogeneous). This is achieved through one or more electromagnetic modal agitators called stirrers that are composed of continuously rotating conductive material. Stirrers are easily recognizable as a simple metal fan mounted inside the enclosure that rotates slowly during oven operation. The RC walls are generally made of conductive material such as aluminum and copper, while the metal shield is composed of stainless steel. Despite a higher electrical resistivity with respect to aluminum and copper, it offers better mechanical performance, good resistance to corrosion, and low costs. The box structure serves to isolate electromagnetic emissions to prevent the release of irradiation to the surrounding environment. It should be noted that the load itself serve as a mode stirrer if it is placed in translational motion, so that it distributes the electromagnetic field. Heating homogeneity is greatly improved with the use of an RC, thus its use is highly recommended. Furthermore, the RC improves efficiency as it attains a high-powered electromagnetic field with only moderate input power.

Radio Frequency Oven Designs

A radiofrequency heating system is composed of four main sections: the generator, applicator, coaxial RF transmission line, and impedance adapter as represented in Figure 2.

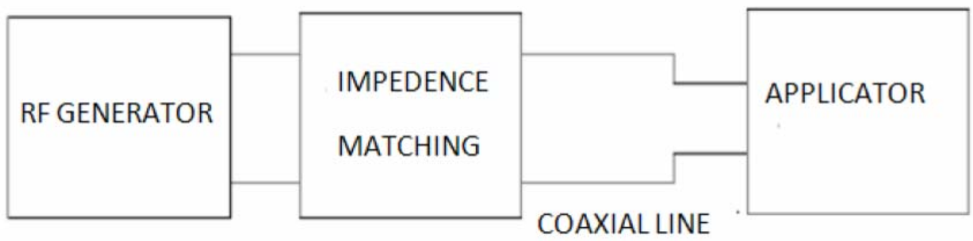

Figure 2: Layout of a radio frequency heating system

The generator, supplied with the electric power from the grid, produces and makes available an electromagnetic field, oscillating typically at a frequency of 27 MHz. The radiofrequency generator is composed of one or more triodes and for each one there is a heating system of the filament, a half-wave rectifier, a controlled oscillator, and a cooling system. The maximum power is 600 kW and the overall system’s efficiency is 60%. The applicator is a device useful for exposing the product to be heated to the alternating electromagnetic field. It is composed of two opposite electrodes that can be considered as two plates of a condenser. There are different architectures for the applicators depending on the nature and thickness of the product to be treated and on the shape of the desired magnetic field lines. Electrodes may be in the form of flat plates, or grids with parallel interconnected bars or other possible configuration. Finally, electrodes at a fixed height (with predetermined automatic positioning) or variable height can be used, depending on the application. The simplest and most common applicator is composed of flat parallel electrodes supplied by a radiofrequency generator. The product to be treated is placed between the electrodes without making contact with them, as shown in Figure 3.

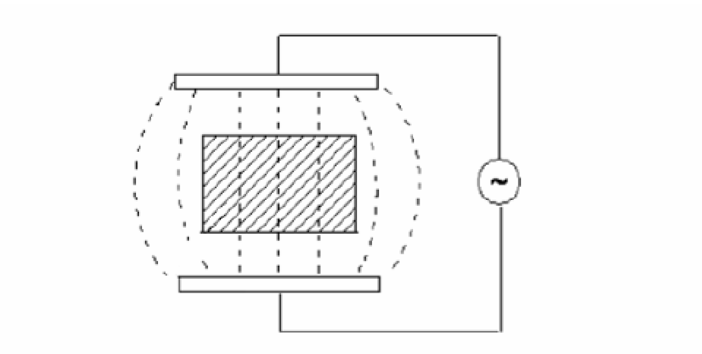

Figure 3: Lay-out of the "parallel plate" configuration

The coaxial line transfers power from the generator to the adapter/load group with a common technology called the "50 W technology," which provides operation under optimal conditions without reflection phenomena (stand waves) in the line. The impedance adapter is useful to adapt the load impedance (which is supposed to be variable) to the generator so that it can produce the maximum power with good efficiency. There is a compensation that occurs between the capacitive reactance of the load by means of inductances and variable capacitors.

RF ovens allow for very rapid heating, approaching rates of approximately 1°C/sec, but achieving field uniformity can be more challenging in comparison to a reverberation chamber. In many processes the geometry of the product to be treated represents another layer of complexity, as the oven must be designed in a particular way to achieve optimal electromagnetic penetration, providing the highest energy efficiency.

RF volumetric heating of a wood consignment can be manipulated by two principal control methods: Method one is accomplished by changing the distance of the electrode to the workload; Method 2 involves changing the Plate kV from the adjustable oven controller panel. Method 2 tends to provide the greatest overall power density relative to heating rate adjustments and is preferable over manipulations of the plate electrodes. The first method is typically used more discretely to fine tune the RF unit to achieve or reach the final heating rate.

Description of Dynamic DH Heating for Phytosanitary SWPM Treatment

More specialized tunnel applicators are suitable for dynamic (continuous) processing of SWPM consignments. These commercial processes can provide higher overall processed volume capacity for the commercial HD treatment facility (certified phytosanitary treater) as recognized by the relevant NPPO. Tunnel or modular designs are equipped with a mechanical belt or other conveyor transport mechanism to facilitate transport of the SWPM load through the treatment process. Examples of both continuous MW and RF systems are shown in Figure 4 and Figure 5.

Continuous high frequency systems are more prone to leakage than static batch treatment oven units, because the conveying system must have entry and exit ports to enable the continuous consignment flow. Environmental leakage of electromagnetic energy can be minimized by using protective control devices, which include absorbing loads or reflective devices located at the in-line flow ports. Industrial heating units are inherently designed for minimum environmental leakage for safety and reduce waste of dielectric power for optimum operational cost and efficiency. Modular microwave systems consist of multiple oven units adjoined in sequence with the consignment feed conveyer, rather than one large oven unit. This arrangement potentially reduces energy consumption without sacrificing heating performance.

Dynamic heating with a "tunnel" design for continuous oven heating may involve only a single capacity high frequency generator where the system is coupled with a special waveguide(s) to deliver the electromagnetic energy to multiple locations within the cavity. Horn applicators are a prime example, which split magnetron produced energy into a sequence of divisions to provide four equal intensity electromagnetic fields to the tunnel. These oven systems are known to work effectively for partial or deeply (well below 0 ºC) frozen blocks of food (e.g., bulk meats or butter). This type of system operation provides a unique opportunity to treat partially or completely frozen SWPM consignments.

Whether the system uses RF or MW heating, power input for oven operation must be properly matched to achieve maximum cost benefit. Additionally, this is important to avoid thermal induced decomposition (losses of material integrity) and excessive heating energy that might induce material ignition. Spontaneous combustion or wood ignition can result from undersized loads compared to the total applied heat energy. Electromagnetic field collapse (arcing) from extraneous metals that enter the oven cavity is another more serious source of fires. Many oven designs can include or incorporate element devices in the form of spark detection, fire sensor technology, and belt conveyer cleaners for industrial process fire safety. Other fire safety precaution measures include the installation of metal sensing devices affixed to the cavity or tunnel entrance to control problematic electrical arcs that may ignite the consignment and cause internal oven damage. Softwood SWPM (coniferous species with heavy oleoresin contents) may require that the consignment feed systems are routinely inspected and cleaned free from depositions of these flammable compounds.

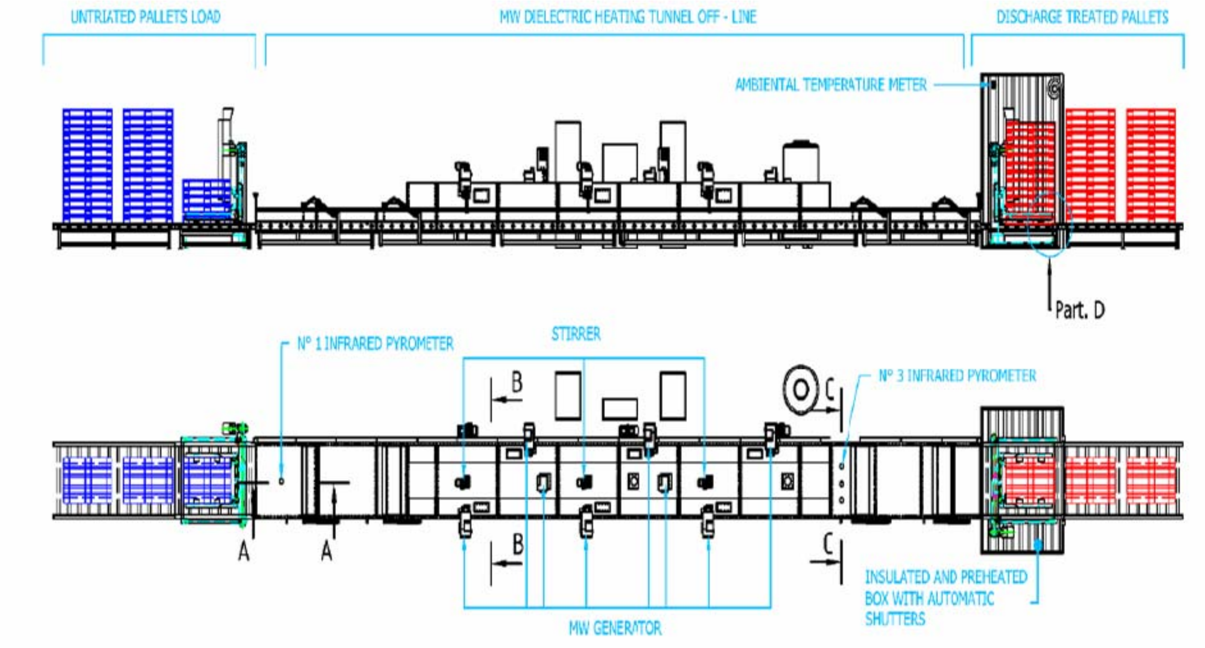

Figure 4: Schematic of a dynamic (continuous) MW oven design for commodity unit phytosanitary treatment of shipping pallets.

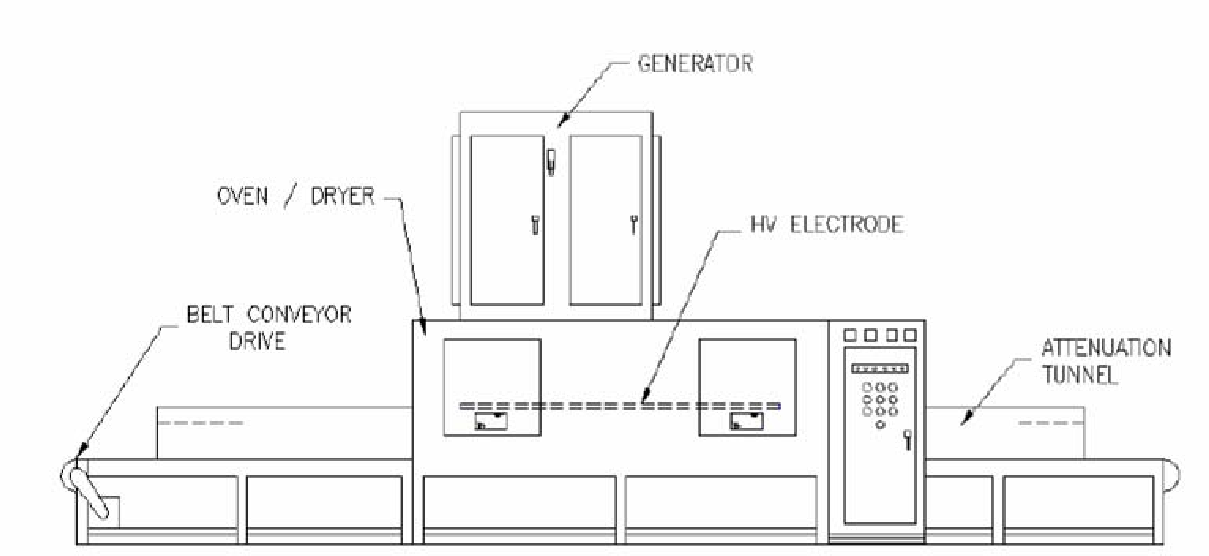

Figure 5: Schematic of a dynamic (continuous) RF heating oven design for SWPM consignment treatment.

APPENDIX 2

METHODS OF MEASURING TEMPERATURES DURING DIELECTRIC HEATING

OVERVIEW

This appendix describes the devices and methodology for determining temperature during dielectric heating of SWPM consignments to ensure that proper phytosanitary treatment is attained.

DEFINITIONS

Emissivity (ε) - ability of a material surface to emit energy through radiation. The property is quantified by taking the ratio of energy emitted by a material to energy radiated by a black body at identical temperature. While a true black body possesses an $\varepsilon = 1$, all real objects have an $\varepsilon < 1$. Materials with high emissivity (ε close to 1) tend to be dark in color and dull in appearance, where low emissivity materials (ε close to 0) are lighter and more reflective. Surface finishing can affect emissivity, so it can be different for the same material depending on the finish.

MEASUREMENT DEVICES

Fiber optic probes – Light transmitting sensors that use changes in light properties to measure temperature variation. The capabilities of fiber optic temperature sensors are variable given the available probe designs. Sensor diameter varies depending on fabricated construction, but sizes from 0.5 mm to a few mm are typical from the device manufacturer. The two most prevalent methods to monitor temperature with fiber optic sensing devices are fluorescent and radiation thermometry, with precisions of 0.1 to 1.0 °C, again depending on the type and specific manufacturer. Sensors are composed of two layers, a silica or plastic filament that transmits and measures the reflected light signal, and an outer cladding layer for protection of the more delicate inner cable. The tip of the fiber is most critical to function, and the use of a high strength polymer such as a polyamide coating is recommended for sustained durability. An example of a typical cladded fiber optic sensor with cable length probe is shown in Figure 6. Continuous cycles of heating and cooling tend to thermally fatigue the transmission filament and can introduce signal reading disruption and eventual complete failure of the sensor. Once temperature anomalies are observed, the sensor should be replaced to avoid defective measurements by the failing fiber optic device. Periodic calibration checks are highly advisable to assure proper sensor device operation as per specifications from the device manufacturer.

Thermocouples – Sensors that rely on a junction of dissimilar metals, which upon heating or cooling, create a change in voltage. This change in voltage measure is correlated to a change in temperature. Size varies based on applicator type and gauge of wire for probe design from approximately 8 to 0.07 mm. Different types exist, based on metal type combinations and calibration, but the four most common are E, J, K, and T. Error limits range from approximately 0.5 to 2.0°C in the range of temperatures pertinent to dielectric heating of SWPM for phytosanitation purposes. Exact values of error are specific to the type, size, and manufacturer of the thermocouple. Thermocouples generally cannot be used in electromagnetic environments, and should be used for post-process temperature readings only. New technologies are emerging that enable usage in electromagnetic environments that would allow for use during treatment. The newer thermocouple sensors are shielded by a reflective material coating or wrap that permits active temperature readings inside the oven reverberation chamber.

Examples of thermocouples are shown in Figure 7, where they are integrated with a handheld device for easy portability, but integration with a PC is also possible. The thermocouple wire is useful for internal measurements, while the handheld device is applicable to surface measurement. Proper application of the surface measurement device is shown in Figure 8. The face of the applicator should be placed flush with the surface of the wood material. It should be noted that the surface sensor is in contact with a specific length of material (in this specific case approximately 2.5 cm), so the measured temperature is the average temperature measured over the length of the sensor.

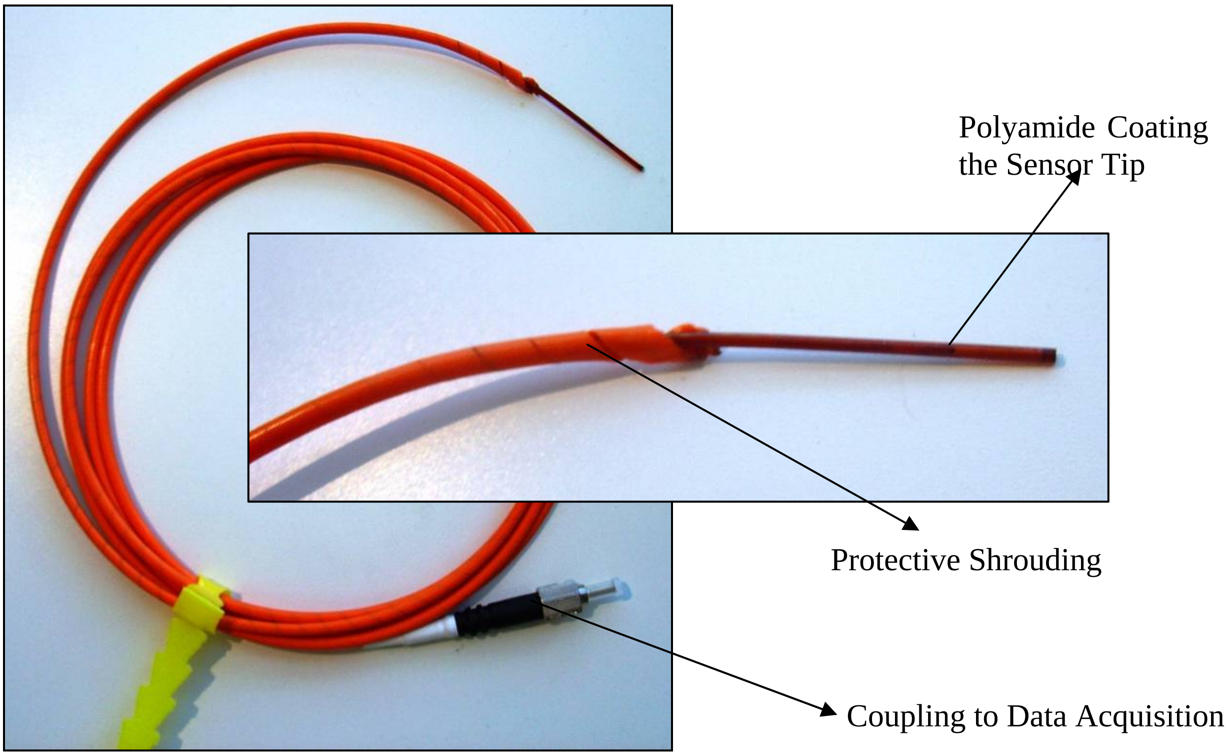

Figure 6: Typical fiber-optic probe most useful for internal temperature measurement during dielectric heating the phytosanitary consignment treatment.

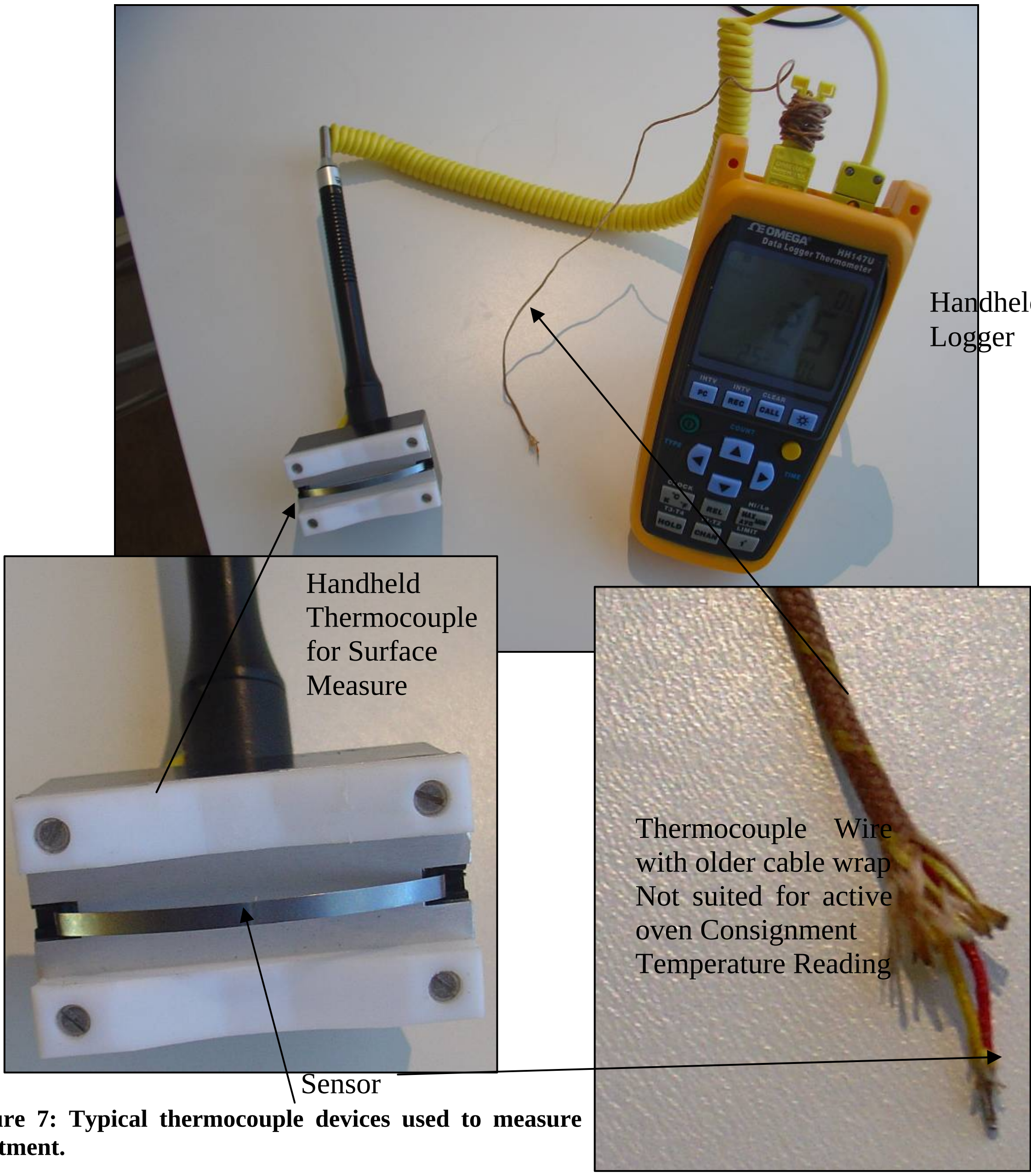

Figure 7: Typical thermocouple devices used to measure dielectric treatment.

Figure 8: Illustration of proper application of handheld thermocouple useful as an auxillary measure to verify surface temperature of the SWPM after dielectric heating.

Infrared (IR) cameras – IR cameras measure temperature using IR thermography, which measures radiation in the IR range of the electromagnetic spectrum. The key to using an IR camera is determining the emissivity of the object that is being measured, which has a predominant effect on temperature determination. Another important consideration when using an IR camera is reflectivity, as radiation from surrounding objects can be reflected onto the measured object. Substantial reflectivity can be determined by placing an IR blocker between the object of interest and a suspected source of reflectivity. If the temperature measured by the IR camera changes significantly when the blocker is removed, then the source of reflectivity must be eliminated to achieve accurate temperature readings. Also, a calibrated temperature sensor can be used to measure the surface temperature and verify that no artifacts are created by reflectivity.

Additionally, the ambient temperature affects the temperature reading made by the camera and input to the camera settings. Ambient temperature should be minimized wherever possible to improve contrast between it and the measured object. For a properly calibrated IR camera, thermal measurement error should be in the range of ± 1°C.

MAIN CONCEPTS

Dielectric heat treatment can be performed on individual packaging components, i.e. stringers, eith singularly or in a bulk form, simultaneously. Alternatively, a consignment may consist of an entire wood packaging unit, i.e. pallets, or a bulk treatment of multiple pallets, providing that proper treatment can be verified throughout the profile of the consignment. Thermocouple wires and fiber optics provide reliable temperature information for finite locations of a treated consignment; therefore, multiple sensors of these kinds should be placed in particular locations as determined through the temperature mapping procedure.

Anatomical anomalies such as knots, pitch pockets, etc. should be avoided when locating temperature sensors, as they tend to heat more rapidly in comparison to typical wood material. Thermocouples and fiber optics should be mounted internally by drilling a pilot hole to the point of interest, as shown in Figure 9. The diameter of the hole should be sufficient for sensor insertion but not oversized such that intimate contact between the sensor and wood material is lost. Surface temperatures may be taken with specialized thermocouples designed for surface measurement, or probe sensors may be taped to the surface using a Kapton tape, which is thermally and dielectrically neutral.

An IR camera can be used to monitor temperature on the surface of the treated consignment. This method provides a macroscopic view so that locations of inadequate treatment may be identified, but is limited to the surface. Depending on the consignment being treated, the surface temperature can be a good control measure to determine proper treatment, as the state of evaporational cooling causes the surface to be cooler than the internal volume of the material, as shown in Figure 10. The extent of evaporational cooling should be determined during the temperature mapping process.

Figure 11 provides an example of how IR imaging can be used to identify improper treatment. In this case, the consignment consists of individual SWPM components. Sample (A) shows that 60 °C was achieved throughout the region not affected by significant evaporational cooling, where Sample (B) shows an area, or cold spot, where the prescribed temperature was not attained. The same methodology may be applied to wood packaging units rather than components, but requires more comprehensive temperature measurement. An example of such a methodology is shown in Figure 12.

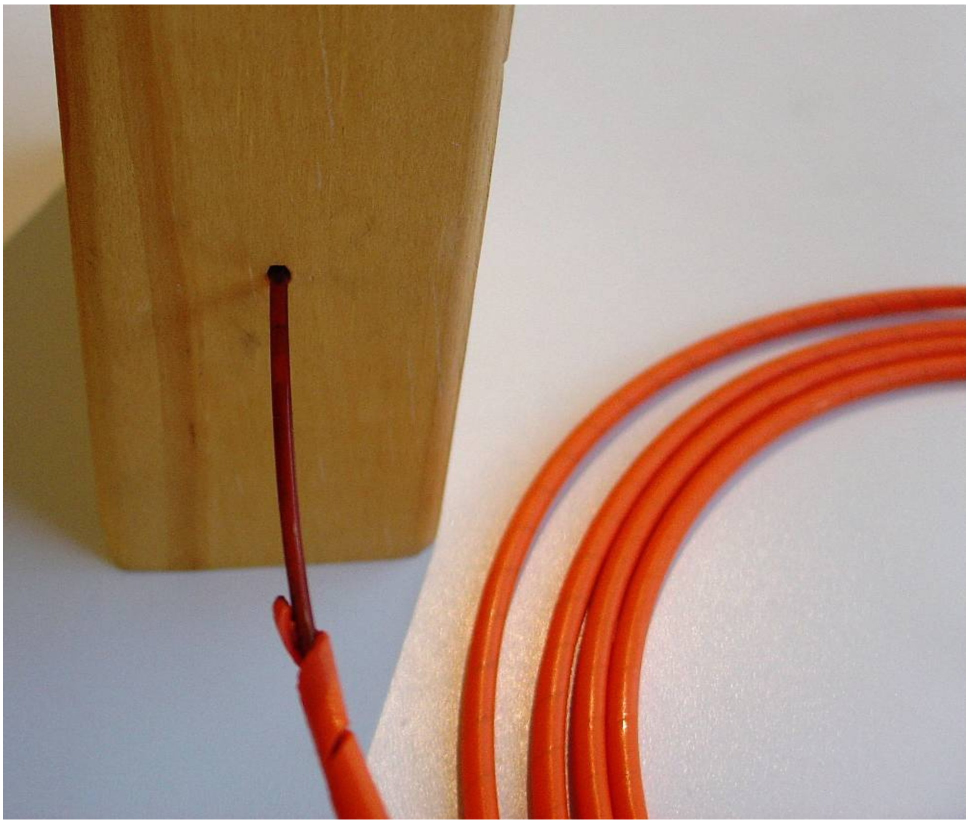

Figure 9: Illustration of proper insertion of a fiber-optic probe for internal temperature measurement during dielectric heating (Note: holes drilled into SWPM to allow probe placements should not be excessively oversized).

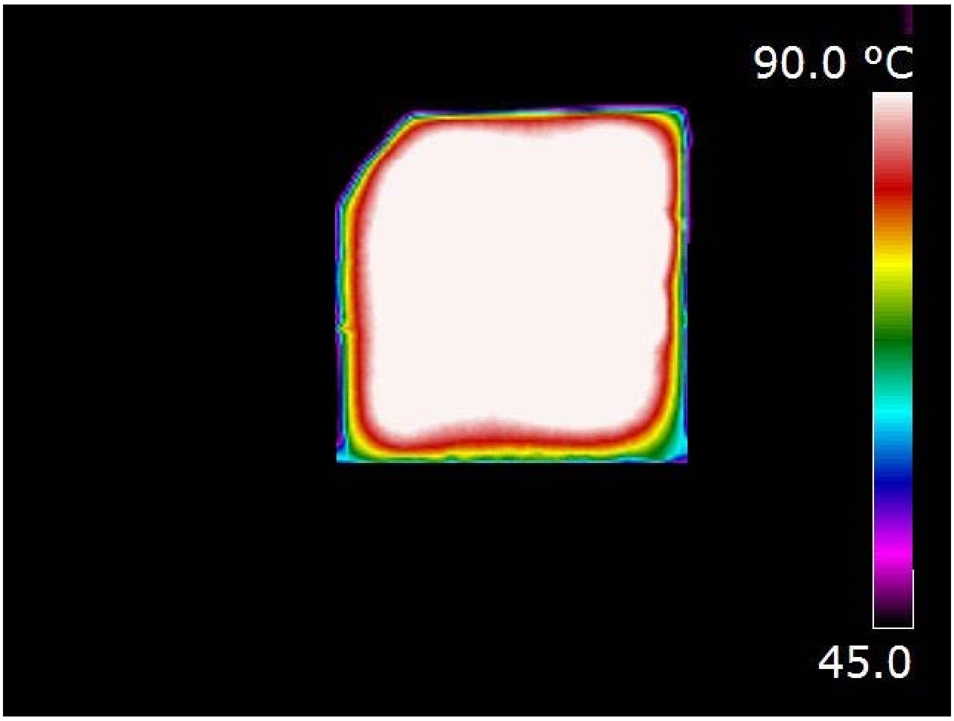

Figure 10: IR thermographic image showing the cross sectional end of a heated bolster component, which exhibits the effect of evaporational cooling at the surface of the material.

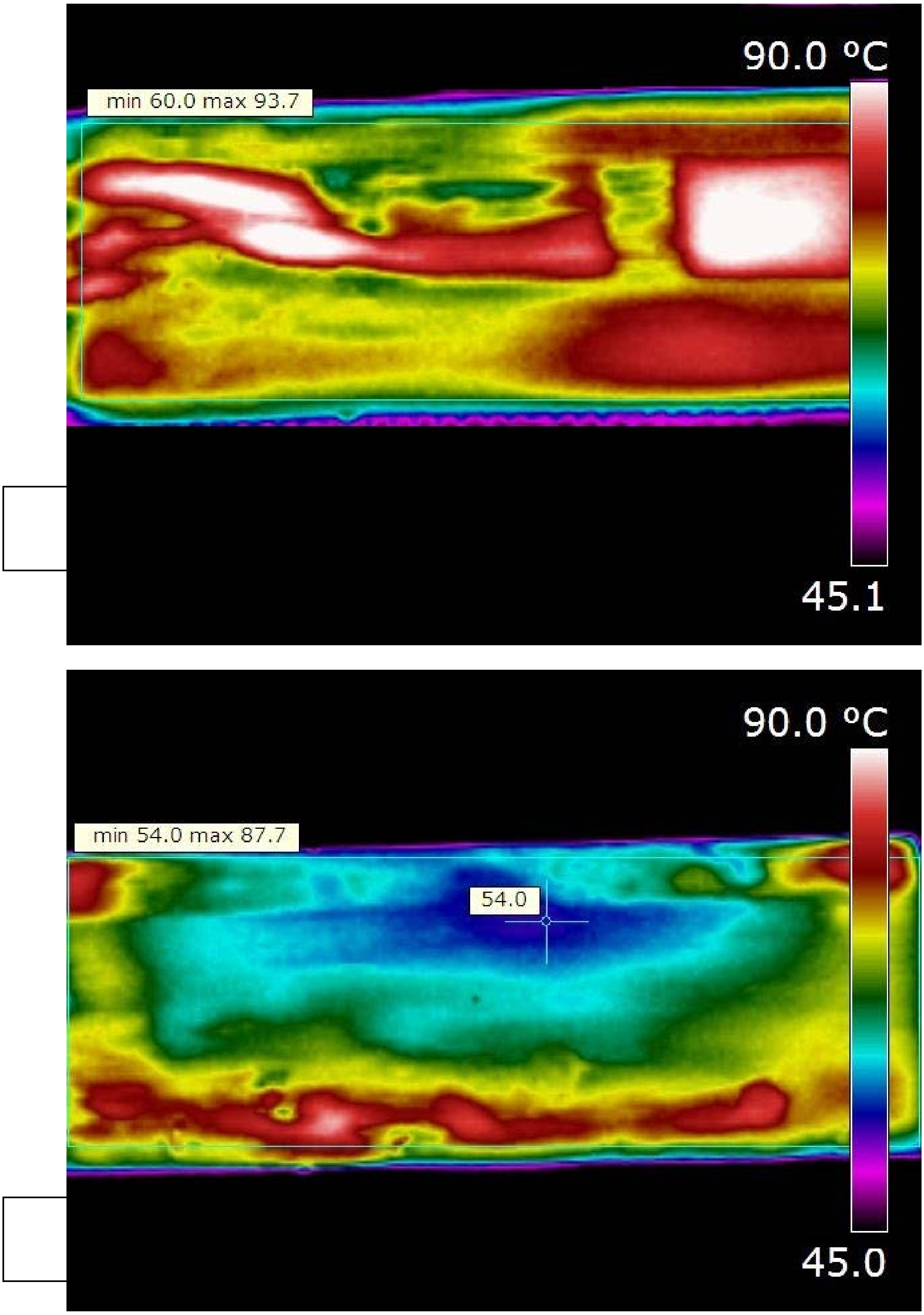

Figure 11: IR thermographic images depicting (A) a successful treatment in which no areas outside the significant evaporational cooling zone are below the designated 60 °C treatment temperature and (B) a failed treatment with a cold spot below the 60 °C benchmark.

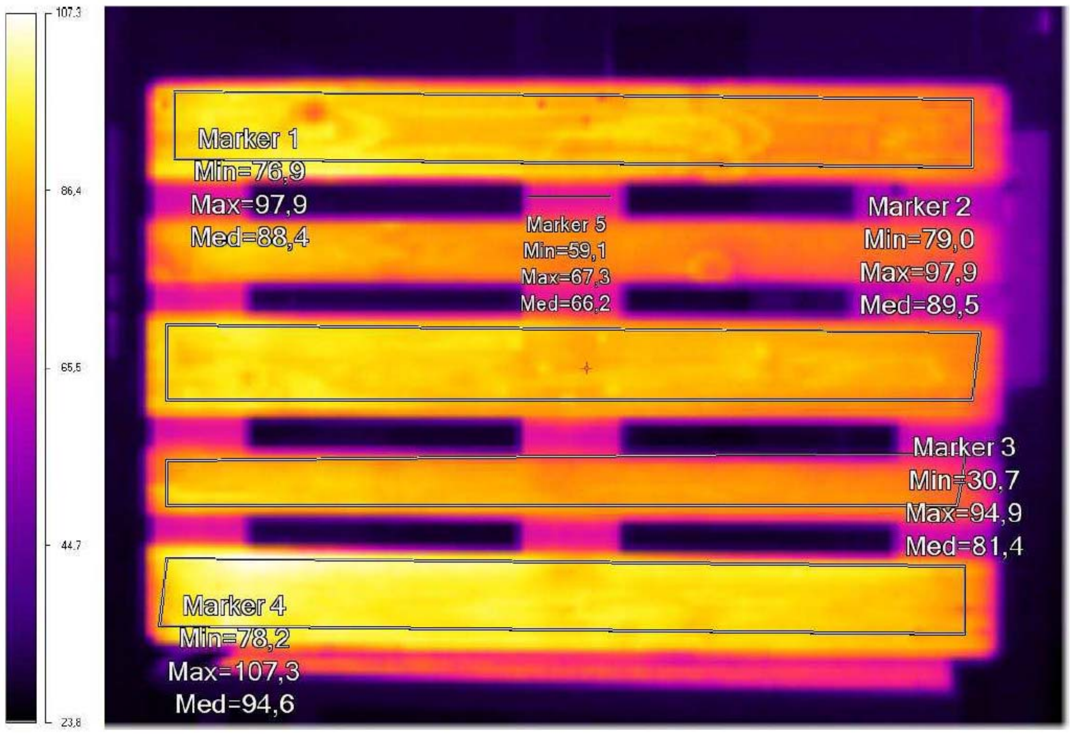

Figure 12: Example of how IR thermagraphic imaging can be used to monitor the temperature development of an entire wood packaging unit rather than pallet components.

Figure 13 shows how a consignment of SWPM, rather than individual components, may be monitored over time with an IR imaging camera. The preferable method is to use the IR camera for a comprehensive depiction of the heated consignment, where any locations of insufficient treatment may be identified. The aforementioned sensors can then be used to measure the temperature at the location of insufficient treatment as a quality assurance measure.

Temperature can be monitored in-situ continuously using fiber optics as well as specialized thermocouples designed for exposure to electromagnetic environments. IR cameras can be mounted internally to measure temperature change during heating, although the treatment chamber may introduce reflectivity and a variable ambient temperature that requires accounting for proper temperature determination (See devise description for IR cameras). Figure 13 depicts how an IR camera can be used during a treatment cycle.

For process control purposes, both types of sensors and the IR camera are typically compatible with personal computers and possess software to monitor and log temperature change during treatment. This information provides a database to ensure that proper treatment has been achieved on a consistent basis. If any part of the consignment does not reach the specified temperature for the proper duration, it should be retreated.

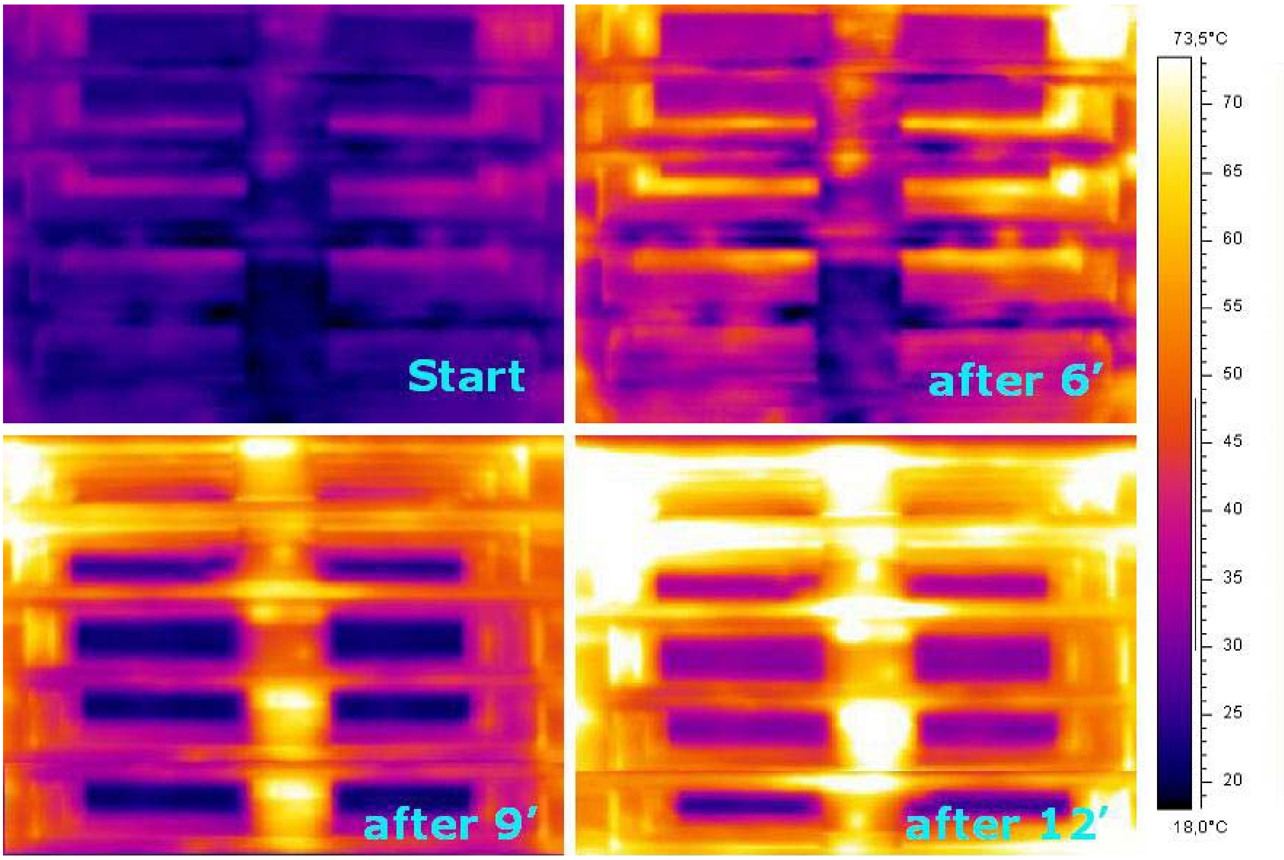

Figure 13: Thermographic images of a consignment of pallets taken with an IR camera over several treatment periods. Image captions are minutes of MW irradiation treatment (915 MHz heating frequency).