# Strategy to control the effectiveness of microwave treatment of wood in the framework of the implementation of ISPM 15

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**Abstract**

Wood packaging materials (WPM) are known to be important potential vectors of exotic organisms, some of which turn into major ecological or socio-economic problems in regions where they are introduced. At present, the heating and methyl bromide fumigation of WPM are the only sanitary treatments approved under ISPM15 (FAO 2002). Since both methods present noticeable disadvantages, the use of microwaves for the disinfestation of WPM is a very attractive alternative. Therefore, pallet components (22 mm-thick pine planks) artificially infested with larvae of *Hylotrupes bajulus* (Col., Cerambycidae) were treated in a continuous conveying tunnel design of 4 kW microwave oven. Posttreatment surface and inside temperatures of the planks were strongly correlated. As expected from the literature, all larvae exposed to inside plank temperatures exceeding 55 °C died. Surface temperatures higher than 60 °C guaranteed these lethal conditions inside the wood, whatever its moisture content. Those observations thus suggest that treatment effectiveness could be controlled through the measurement of the planks' surface temperatures. Although further experiments are needed, irradiation of 22 mm-thick pine planks in a continuously supplied 28.8 kW microwave oven confirmed the appeal of this monitoring strategy. If successful treatment control is demonstrated whatever the characteristics of the planks (thickness, basic density, species, MC, . . . ), the proposed monitoring strategy, which can be integrated in an assembly line provided with a tunnel oven, can be a significant step towards the recognition of microwave irradiation as an acceptable treatment for eradication of pests and pathogens in WPM.

Biological invasions rank among major causes of the present worldwide biodiversity decline. From an "ecological point of view" (ecosystem functioning), countless books and scientific papers report the importance of this phenomenon. Beyond this biological effect however, considerable socio-economic consequences are also expected on a long-term and global scale. Regarding forest ecosystems, several authors (Liebhold et al. 1995, Loope and Stone 1996, Krcmar-Nozic et al. 2000, Mack et al. 2000, Allen and Humble 2002) consider biological invasions as a main threat toward maintenance of habitat naturalness and the sustainability of forest exploitation. Unfortunately, as a consequence of growing trade and transport activities, the pace of introduction of alien species into exotic habitats increased over the last decades (Loope and Howarth 2002, Tkacz 2002, Perrings et al. 2005, Work et al. 2005).

Focusing on forest invasive species, wood packaging materials (WPM) rank among the main vectors of exotic organisms (Allen 2001, Bartell et al. 2001, FAO 2002, Labonte et al. 2005, Perrings et al. 2005, Brockerhoff et al. 2006). Important pests such as the pinewood nematode *Bursaphelenchus*

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Forest Prod. J. 58(12):75–81.

*xylophilus* (Steiner and Buhrer) Nickle, lots of Scolytids or the Asian Longhorned Beetle *Anoplophora glabripennis* (Motchulsky), benefited from the transport of WPM to colonize new habitats (see, respectively, Allen 2001, Mudge et al. 2001, Bartell and Nair 2004).

As generally admitted in the scientific community, Kaiser (1999) reports that "preventing an invasive species from getting in is far and away the best and cheapest approach." In particular, since the eradication of an insect is virtually impossible after its settlement in an exotic region (Waring and O'Hara 2005), the phytosanitary treatment of WPM destined for intercontinental transport is the keystone of the prevention of forest species invasions.

Only two treatments are approved in the International Standards for Phytosanitary Measures 15 [ISPM15] (FAO 2002). The first is fumigation with methyl bromide. Because of its detrimental effect on the ozone layer (Singh and Kanakidou 1993, Fields and White 2002), the use of this compound is being phased out (UNEP 2000). The second treatment consists in achieving a wood inside temperature of 56 °C for at least 30 minutes. This process presents several disadvantages:

1. it requires much energy, which generates high amount of $CO_2$ (although energy is sometimes produced by cogeneration) and is expensive. Lallemand (2004) estimates that, for the pallet industry, the cost of the treatment can exceed US$ 2 per unit;
2. it is time-consuming (several hours) and batch processed out of the assembly line;
3. the treatment effectiveness may be spatially heterogeneous and is not always certain in the entire batch;
4. controlling that a particular piece of wood or pallet was efficiently treated is difficult (problem of traceability).

The identification of alternative methods of phytosanitary treatment of WPM is thus particularly urgent (Fields and White 2002, Batchelor and Alfarroba 2004) and many different approaches are currently tested or proposed. Among the latter are chemical treatments (e.g., Barak et al. 2006), vacuum achievement (Chen et al. 2006), hot water bath treatment (Slahor et al. 2005) or use of reconstituted wood (Brockerhoff et al. 2006), for instance.

In this framework, microwave treatment has been proposed as an alternative treatment method for wood packaging. In recent decades, many studies of microwave energy for the disinfestation of wood have been conducted (Thomas and White 1959, Andreuccetti et al. 1994, Lewis and Haverty 1996, Bini et al. 1997, Fleming et al. 2003, Fleming et al. 2004, Nzokou et al. 2008). Several portable devices using microwaves for wood disinfestation were recently patented in the United States. Despite its main disadvantage, which is the need for electrical energy to achieve the microwave treatment (Fleurat-Lessard, 2000, Lewandowski 2000), this technology presents numerous advantages such as:

1. the disinfestation of green wood is currently achieved in a few tens of seconds (Lewis et al. 2000, Fleming et al. 2003) and could be reduced to a few seconds (F. Fleurat-Lessard, personal communication 2006), which is already the case for dry wood (Fleming et al. 2003);
2. it is nonselective, which means all forest pests can be destroyed with microwave energy if adequate power is applied;
3. no resistance could be developed towards this treatment;
4. the treatment is not toxic (advantage for the workers) and leaves no residue (advantage for the intermediary handlers and for the final consumer);
5. each treated component could be easily labeled if an automatic marker is coupled with the online microwave oven.

*Table 1. — Characteristics of the ovens.*

| Oven | Experiment | Max power (kW) | Magnetrons (no.) | Length (cm) | Width (cm) |
|---|---|---|---|---|---|
| A | 1 & 2 | 4 | 2 | 108 | 45 |
| B | 3 & 4 | 28.8 | 16 | 400 | 45 |

However, in spite of all those promising elements, a standardized methodology for wood treatment with microwaves is still lacking. Several issues remain to be addressed before microwave treatment of WPM could be applied on an industrial scale. Among those problems are the facts that:

1. experimental evidence of the range of pests killed (including insects, fungi and nematodes) and statistically valid efficacy data are still needed;
2. an easily measurable physical parameter, which enables a reliable monitoring of treatment effectiveness, should still be identified;
3. since the profit margin on WPM is very low, the duration of the treatment and the input power must be perfectly tuned in order to avoid energy overconsumption (as well as associated risks of wood damaging).

In this context, focusing our study on the pallet industry, we present and discuss the results of preliminary experiments that were performed with the purpose of:

1. assessing the effectiveness of microwave treatment for wood disinfestation in nearly industrial conditions;
2. identifying a way to easily monitor treatment effectiveness in an industrial environment.

Based on our results, a strategy to enable industrial applications of microwave sanitary treatment of wood is proposed.

## Materials and methods

### Oven characteristics

Two industrial 2.45 GHz microwave ovens designed by Microwave Energy Applications Company (MEAC.) were used for this study. The ovens are provided with a conveyor belt that enables continuous supply of wood. Conveyor speed can be controlled by the operator. Three infrared sensors spread out above the conveyor enable continuous measurement of wood surface temperature, with an accuracy of 0.1 °C. At both openings of the ovens, filters absorb reflected radiations. Other technical characteristics of the ovens are provided in **Table 1**.

The two 2 kW magnetrons of oven A work together: both are switched on or off together. Conversely, all 1.8 kW magnetrons of oven B are controlled individually. In oven B, low power thus corresponds to lower energy density, as described in Fleming et al. (2004). It should be noted that in this case, when not all magnetrons are working (as in experiments 3 and 4), treatment duration cannot be accurately characterized.

### Insects

Treatment effectiveness was assessed on old house borer larvae (*Hylotrupes bajulus* L.) bred in the facilities of the Walloon Research Center for Nature, Forests and Wood

*Table 2. — Number of slats for all the tested combinations MC-treatment duration.*

| | Treatment duration | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | (minutes) | | | | | | |
| Slat MC | 1 | 2 | 4 | 5 | 5.5 | 6.5 | |
| Dry | 6 | 6 | – | – | 6 | – | 18 |
| Humid | 6 | 6 | 6 | 6 | 12 | 6 | 42 |

*Table 3. — Number of planks treated, for all the tested combinations MC-microwave power.*

| | Mean MC | Microwave power | | | |
|---|---|---|---|---|---|
| | | (kW) | | | |
| | (percent) | 5.4 | 9 | 12.6 | 16.2 |
| Dry planks | 14 | 10 | 10 | 10 | – |
| Humid planks | 75 | – | 10 | 10 | 10 |

(CRNFB). The insects were bred on Scots pine (*Pinus sylvestris* L.) samples maintained in conditioned atmosphere (temperature 22 °C and relative humidity 70%). Larvae used for this study were classified into two mass categories: type A larvae weighed 40 to 109 mg; type B larvae weighed 110 to 189 mg. According to European Standard EN22 (1974), vigorousness of all larvae was assessed before the experiments and nonreactive or unhealthy specimens were thrust aside.

*Experiment 1: Microwave treatment of infested wood (4 kW oven).* — In order to achieve the first objective of this study, *H. bajulus* larvae were placed in 60 Scots pine (*Pinus sylvestris* L.) slats 150 mm long, 60 mm wide and 22 mm thick. One larva was placed at both ends of each wood slat, into a 40-mm-deep hole drilled halfway up. At one end, a type A larva was placed in a 3-mm-diameter hole; at the other end, a type B larva was placed in a 5-mm-diameter hole. After larva introduction, holes were plugged with cotton. A total of 120 larvae were thus irradiated in this experiment. In order to assess the effect of wood moisture content (MC) on treatment effectiveness, slats were classified into two categories: 42 humid slats contained between 37 and 125 percent of water (average = 81%), while MC of the 18 dry slats was between 12.6 and 14.7 percent (average = 13.5%). **Table 2** presents the number of irradiated slats, according to their MC and to the treatment duration.

Larvae were taken out their cavity and examined just after the treatment. Some larvae that survived might have died if they had been left for a longer period in their cavity (because of the slow heat loss in inner wood). All temperatures were measured with an infrared thermometer (Fluke 123 ScopeMeter). Inner temperatures were measured at the bottom of the holes.

*Experiment 2: Relationship between inside and surface temperatures of the wood (4 kW oven).* — Experiment 2 assessed the relationship between the internal and the surface temperatures of the wood. This experiment was performed on the abovementioned slats, as well as on *P. sylvestris* planks 1400 mm long, 150 mm wide, and 22 mm thick. A total of 36 planks were treated: 20 humid planks (MC between 30 and 40%; average MC = 35%) and 16 dry planks (MC between 16 and 20%; average MC = 18%). Four humid and four dry planks were irradiated during 1, 2, 4.4, and 7.3 minutes; four additional humid planks were treated for 4.4 minutes. Two 11-mm-deep holes were drilled in each plank to permit the measurement of inside temperature. Temperatures were measured with the same thermometer as for the first experiment, and were assessed as in experiment 1 (at the bottom of the hole and on wood surface).

*Experiment 3: Microwave treatment of infested wood (28.8 kW oven).* — Experiment 3 aimed at verifying that the observations realized in the frame of experiments 1 and 2 enable to parameterize a lethal treatment. This experiment was performed on 60 *P. sylvestris* planks 800 mm long, 150 mm wide, and 22 mm thick. In total, 30 humid planks and 30 dry planks were treated. Along both edges of the planks (at 10, 200, and 400 mm from the end), three 40-mm-deep holes were drilled halfway up. Three type A and three type B larvae were placed in the 6 holes, which afterward were plugged with cotton. Three microwave powers were applied to both dry and humid planks (**Table 3**). For each combination MC-microwave power, 15 planks were introduced in the oven in single file, nearly end to end. Only the 5 middle planks (6th to 10th) contained larvae, whereas the 10 remaining planks enabled maintenance of a constant energy density in the oven while the middle planks were passing. Each trial was repeated twice: In the first trial, planks were kept piled up during 1 hour after the treatment, to assess the impact of this practice on insect mortality rates; the planks of the second trial were left isolated from each other. Moreover, 30 larvae respectively placed in five untreated humid and in five untreated dry planks were used as control.

The speed of the conveyor belt was 2.2 m/min. Surface temperature of the 5 central planks was measured with the same thermometer as for experiment 1, at the upper side of the planks, above each hole (6 records per plank). Examination of larvae was performed the day after the treatment.

*Experiment 4: Control of wood surface temperature in simulated industrial conditions (28.8 kW oven).* — The aim of this experiment was to illustrate how surface temperature measurement can be used to lead an efficient treatment. Therefore, we present and discuss the temperature records corresponding to one of the trials of 15 planks mentioned in experiment 3. Note that a distance between 10 and 15 cm was left between consecutive planks, to enable their individual identification on the temperature graphs (the conveyor belt does not heat like wood and those spaces are thus identifiable because of the drop they create on the temperature graph). Each sensor measures the temperature every 0.5 second and data are displayed in real time on the screen.

## Results and discussion

*Experiment 1: Microwave treatment of infested wood (4 kW oven).* — **Figure 1** presents the mortality of larvae obtained for different treatment durations, according to two MC classes (dry or humid) and two larvae mass categories (A and B). As shown on **Figure 1**, very high mortality rates are achieved for inner temperature exceeding 50 °C. Two type A larvae survived in dry slats irradiated for 2 minutes where final inside temperature reached 53 °C and 55 °C respectively. These larvae were completely amorphous after the treatment and, because of the slow heat loss inside the slats, they very likely would have died if they had not been taken out for examination. Regardless of MC, inside temperatures higher than 55 °C warrant 100 percent efficacy of the treatment. Mortality is

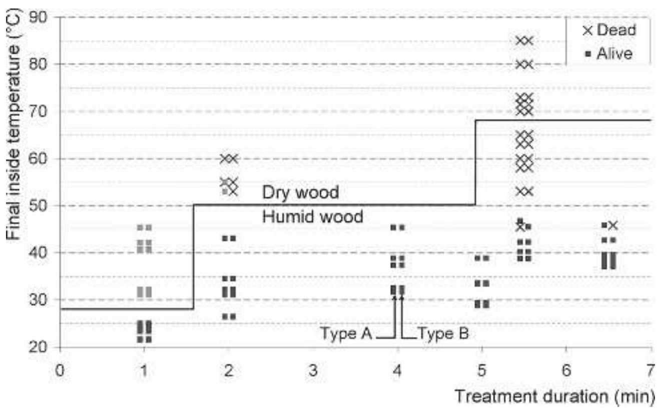


*Figure 1. — Mortality of larvae, according to treatment duration and final inside temperature of wood. The inconsistency of the final temperature reached for the 5 and 6.5 minutes treatments is due to a misuse of the microwave oven (unintentionally, full power was not applied).*

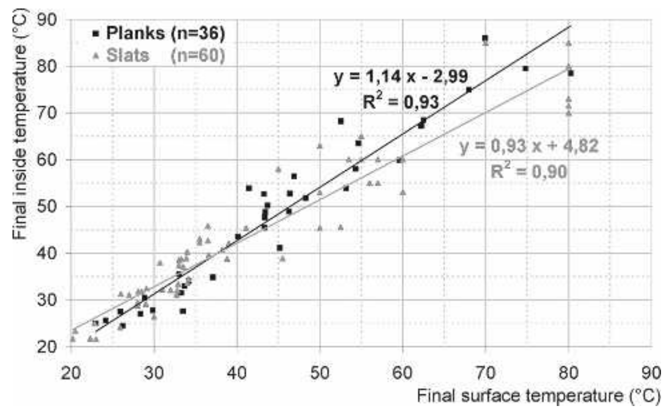


*Figure 2. — Relationship between inside and surface temperatures of the wood.*

even observed below 50 °C for the long treatments (more than 5 min).

Fields and White (2002) reported that exposure times of 5, 1, and 0.5 minutes at temperatures of 50, 55, and 60 °C, respectively, were sufficient to ensure 100 percent mortality of stored-product insects. Andreuccetti et al. (1994) reported lethal temperature of ca 55 °C for *Hylotrupes bajulus* L. larvae, without specifying a time-temperature schedule, and Fleming et al. (2005) observed 100 percent mortality of cerambycid larvae heated up to 62 °C. Fleurat-Lessard (2000) stated more generally that no insects survive above ca 60 °C. Our observations are thus consistent with previous work.

Andreuccetti et al. (1994) demonstrated that the temperature reached by insect larvae contained in irradiated dry wood (MC ca. 10%) may be more than 10 °C higher than wood temperature. This relies on the fact that if the water content of a substrate is much less than the water content of an organism present in it, microwave energy is preferentially absorbed by the organism. Conversely, the same authors estimate that *H. bajulus* larvae present in Douglas-fir wood do not undergo preferential heating when wood MC exceeds 15 percent, except for thin larvae (length/max. diameter reaching 8) which may heat faster than wood even when wood MC exceeds 30 percent.

No preferential heating of larvae occurred in the MC conditions of our experiments. This means that, for the MC characteristics of the elements assembled in pallet manufactures, preferential heating could virtually never be expected as assembly lines are generally designed for humid wood. Wood inside temperature is thus a reliable indicator of treatment effectiveness. Nevertheless, as the measure of this temperature is very difficult, a surrogate measure should be identified to enable industrial control of treatment effectiveness. We therefore examined the relationship between inside and surface wood temperatures after MW treatment.

*Experiment 2: Relationship between inside and surface temperatures of the wood (4 kW oven).* — **Figure 2** presents the relationship between inside and surface temperatures of the slats and of the planks, without regard to treatment duration and sample MC. Whether measured on planks or slats, the correlation between inside and surface temperatures is very high ($r^2 > 0.9$) and reveals a strong relationship between these parameters. However, a paired t-test evidenced that inside temperature is significantly higher than surface temperature ($p < 0.001$). The higher inside temperatures are probably due to the slower rate of heat loss in the well-insulated inner wood, whereas cooling is much faster in the outer wood layers. These observations confirm, as already suggested by Bini et al. (1997), that surface temperature of wood could be used to guarantee lethal conditions inside the MW-treated wood. **Figure 2** shows that under the conditions of our experiment surface temperatures higher than 60 °C warrant inner temperatures in excess of 65 °C.

*Experiment 3: Microwave treatment of infested wood (28.8 kW oven).* — **Table 4** shows that the set-up of the treatment according to experiment 1 and 2 results was successful. Indeed, surface temperatures exceeding 60 °C guarantee mortality rates of 100 percent, whatever the plank's MC. On humid planks, the 12.6 kW treatment even resulted in 100 percent mortality rates although surface temperature only reached ca. 55 °C. This latter observation is in fact not very surprising. In the frame of experiment 2, all surface temperatures higher than 55 °C corresponded (except in one case) to inside temperature higher than this threshold, which appeared critical in experiment 1.

As highlighted by Fleming et al. (2004), wood MC is of prime importance regarding irradiation effectiveness. Hence, Fleming et al. (2005) suggest sorting the elements that are to be treated according to their MC (identifying wide classes of wood MC).

The 5.4 kW treatment performed on dry wood showed that piling up can induce higher mortality rates compared to nonpiled planks. Obviously, the mortality increase is due to the fact that high temperatures are maintained much longer when planks are piled up. For example, it was observed on dry planks that, 1 hour after the 9 kW treatment, temperature loss was around 10 °C when planks were piled up, whereas it exceeded 30 °C for nonpiled wood (room temperature was 20 °C). Regarding the same MC-microwave power combination, a surface temperature of 55 °C was maintained during 22 minutes in piled planks, instead of 6 minutes when not piled. The similarity of both mortality rates observed after the 9 kW treatment of humid planks (47% and 50% for piled and nonpiled planks, respectively) could be due to the fact that high temperatures are more harmful for larvae when undergone in a dry environment.

Table 4. — *Mortality rates (average surface temperature in °C) obtained for different powers. Each mortality rate is calculated from 30 larvae.*

| | | Microwave power (kW) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 5.4 | | 9 | | 12.6 | | 16.2 | |
| Dry planks | Piled up | 73 percent | *(48)* | 100 percent | *(63)* | 100 percent | *(82)* | – | – |
| | Nonpiled up | 27 percent | *(43)* | 100 percent | *(66)* | 100 percent | *(77)* | – | – |
| Humid planks | Piled up | – | | 47 percent | *(46)* | 100 percent | *(54)* | 100 percent | *(62)* |
| | Nonpiled up | – | | 50 percent | *(48)* | 100 percent | *(57)* | 100 percent | *(60)* |

All control larvae maintained in untreated humid and dry planks during 24 hours survived and resumed normal activity when replaced in the breeding room.

*Experiment 4: Control of wood surface temperature in simulated industrial conditions (28.8 kW oven).* — In the conditions of the previous experiments, wood surface temperatures exceeding 60 °C warrant efficient microwave treatment (i.e., mortality rates of 100%). Consequently, a strategy to optimize the disinfestation of planks on a production line could be to link the functioning of magnetrons to the continuous surface temperature records. In order to illustrate the feasibility of this strategy, **Figure 3** presents the results of the continuous measurement of surface temperature recorded by the three temperature sensors on 15 planks, for dry wood submitted to a 9 kW treatment.

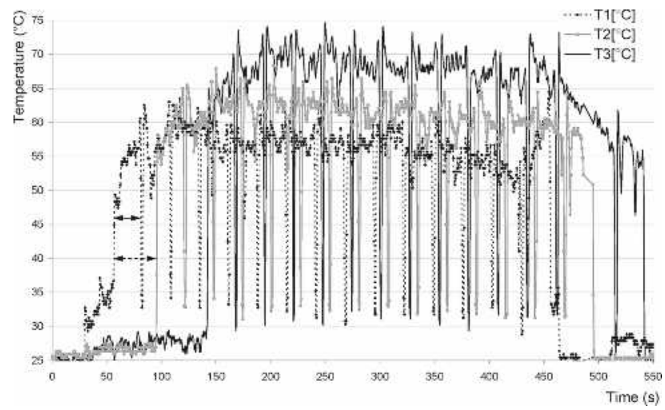


*Figure 3. — Temperature recorded by 3 sensors in the oven vs. time (15 dry planks; 9 kW). The continuous arrow corresponds to the passing of a plank under the sensor. The dotted arrow represents the time lag between the passing of a plank under sensor 1 (S1) and sensor 2 (S2).*

On the three lines, the temperature drops correspond to the space between two successive planks. The temperature spike recorded after 56 seconds (T1) corresponds to the arrival of the first plank beneath the first temperature sensor (S1). This plank reaches the second temperature sensor (S2) after 96 seconds (first T2 spike) and the third sensor (S3) after 142 seconds (first T3 spike).

In order to analyze more accurately the evolution of temperature at plank level, **Figure 4** presents the temperature measured on the fifth, sixth, and seventh planks after synchronization of temperature records (i.e., getting the temperatures recorded by the 3 sensors to coincide).

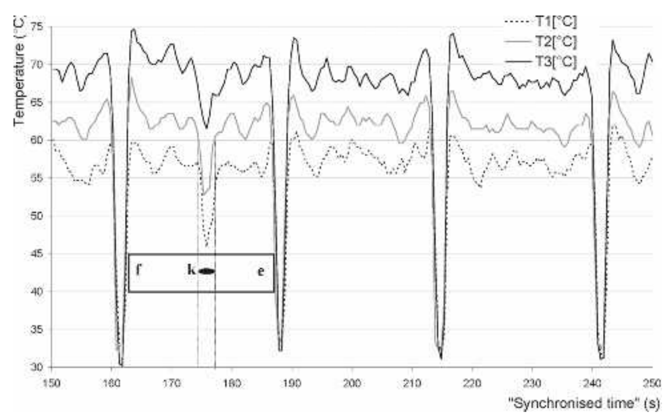


*Figure 4. — Focus on the temperature recorded on the fifth, sixth, and seventh planks. Plank 5 is schematized on the graph (f = front part, which first entered in the oven; e = the end; k = knot).*

As observed in **Figure 4**, passing of each plank corresponds to a 22-second period (60 seconds × 0.8 m/2.2 m/min = 22 s). The average surface temperature recorded by the three sensors on a plank increases as the latter progresses in the oven. Nearly all along the 3 planks represented on **Figure 4**, surface temperature reached or exceeded 60 °C when passing under the second sensor (S2). Only the central part of plank 5 did not met those temperature conditions, due to the presence of a knot. Other variations of surface temperature correspond to local heterogeneities of MC or basic density of the wood. The lower temperature recorded on the knot is however not problematic since they are avoided by insect larvae and other pests. Furthermore, if the temperature measured in the oven does not locally reach the treatment requirements, later heat transfer will make this zone reach 60 °C, especially if wood is kept piled up. Based on the speed of the conveyor belt and on the distance between S2 and the next magnetron, it is easy to program automatically the latter to continue the treatment if necessary. As visible on **Figure 4**, all magnetrons located after S3 on the treatment line could be switched off since S3 recorded lethal temperatures. Planks 5, 6, and 7 could thus leave the line with a quality label which guarantees that, all along each plank, temperature requirements for efficient treatment were met.

It is noticeable that all planks show maximum temperature values at both extremities. Those temperature peaks became more marked as planks progressed in the oven. The peaks could be due to variation of local energy density when planks arrived beneath magnetrons. They could also be the result of faster water evaporation (and thus wood drying) at both ends of the planks.

## Conclusion

In conclusion, the experiments confirmed that lethal temperatures for old house borer larvae can be reached very rapidly on 22-mm-thick pine planks. Surface temperatures higher than 60 °C ensure mortality rates of 100 percent. These observations corroborate those of Fleming et al. (2005). Our preliminary results suggest that, for microwave treatments, several measurements of wood surface temperature should suffice to assess the phytosanitary treatment efficacy. As it is easy and rapid, the measurement of surface temperature can be performed on all treated planks, which enables individual monitoring of treatment effectiveness. This is a significant advantage compared with conventional treatments.

Despite our encouraging results, efforts must now be devoted to a comprehensive assessment of treatment efficiency when plank thickness and MC, wood basic density, microwave power, oven load and conveyor speed vary in a broader range. In other words, it should be assessed which surface temperature guarantees 100 percent mortality rates whatever the planks' and oven characteristics.

Microwave irradiation has the advantage of enabling individual processing of the planks to be treated. The treatment effectiveness can be more homogenous compared to fumigation or heat treatment, and energy consumption could thus be optimized. Furthermore, this fast treatment allows its integration in a pallet production line provided with a continuously supplied tunnel oven.

Among the final steps of microwave treatment implementation, the profitability of this process should be assessed (Fleurat-Lessard 2000). If treatment profitability is proved, we hope the proposed strategy will facilitate the implementation of industrial applications of microwave wood disinfestation, and more specifically the recognition (by the FAO or the International Plant Protection Convention) of microwave irradiation as an acceptable treatment for eradication of pests and pathogens in WPM.

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