Comparative Study of Radio Frequency (RF) & Microwave (MW) Heating of Wood in Compliance with ISPM-15 Phytosanitary Treatment

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Abbreviations

DH	Dielectric Heating: It uses the frequency range from about 5 MHz to 5 GHz either in the form of radio-frequency, RF, (< 100 MHz) or microwaves, MW, (usually 500 MHz to 5 GHz).
D_p	Depth of heating penetration where 63% of the electromagnetic incident energy is absorbed for the corresponding material heating response
HT	Conventional steam or dry kiln heat chamber (56 deg C-30min)
HPRF	High Power Radio Frequency i.e. RF oven operated at the high power settings nearly 3 times than that of LP settings (9.2-10.8 kW)
IR	Infra Red
ISPM	International Standards for Phytosanitary Measure
LPRF	Low Power Radio Frequency i.e. RF oven operated at the power nearly equivalent to that of MW (3.3-3.5 kW)
MB	Methyl Bromide
MW	Microwave
RF	Radio Frequency
t_{60}	Total time when all the temperature probes used in a dielectric heating trial reached 60ºC.
WPM	Wood Packaging Materials

Introduction

- ISPM-15 aims to prevent spread of pests through wood packaging materials used in international trade
- Wood used for international shipments must be debarked and either
  - Fumigated with Methyl Bromide - **MB** "or"
  - Heat-treated either using
    - Conventional steam or dry kiln heat chamber (56 deg C-30min)- **HT** "or"
    - Dielectric Heating using MW or RF (60 deg C-1 min) – **DH**
- There are increasing environmental concerns over use of MB for quarantine and pre-shipment purposes, while conventional heat-treatment is costly & time consuming
- DH can be a viable alternative for MB treatment but its operational feasibility and consistency are the critical issues

Current limitations of ISPM-15 for dielectric heating (DH)

- ISPM-15 states that *WPM **exceeding 20 cm as** measured across the smallest dimension of the piece not currently permitted with dielectric heating.
- 20 cm limit is based on previous data related to characteristic depth of heating of microwaves (higher frequency, thus less depth of penetration)
- *The prescribed temperature (60 deg C) must be reached **within 30 minutes** from the start of the treatment
- * Current ISPM 15 states that ***"Only microwave technology has been proven to date to be capable of achieving the required temperature within the recommended time scale".***
- This study demonstrates RF technology can provide greater heating efficiency and uniformity beyond the 20 cm dimension and it can effectively achieve the required temperature within 30 minutes.

**** ISPM-15 : Last Modified on Nov 2013***

Main Objectives

- Comparisons of RF and MW heating at the similar power settings to demonstrate:
  - Total time to achieve 60ºC throughout the profile of test specimens ($\mathbf{t}_{60}$)
  - Heating pattern and uniformity throughout the cross-section to meet ISPM 15 Phytosanitary requirements for DH treatment
  - Theoretical basis of heat penetration to compare experimentally derived heating uniformity
  - Effect of increased RF power on treatment duration

Experimental methods: Wood specimens

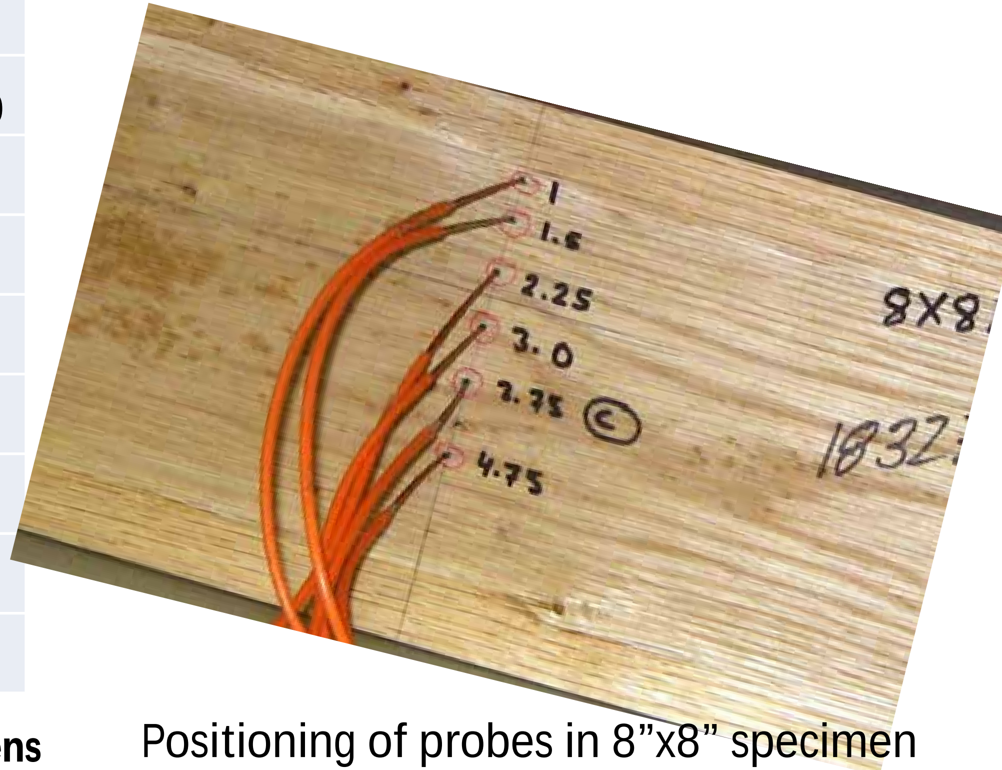
- Freshly processed white oak (*Quercus* spp.) samples were prepared as matched sets with several dimensional (depth) treating classes for equivalent RF and MW heating trials
- Dimensions of test specimens:
  - 19” in overall material length
  - nominal sections of 4”x4”, 5”x5”; 6”x6”, 8”x8” and 10”x10” to evaluate heating at actual depths of 9-cm, 11-cm, 14-cm, 19-cm and 24-cm respectively.
- Specimens double wrapped in polythene bags and stored at 4^{o}C to maintain green moisture conditions
- Conditioned for 72 hrs in environmental chamber at 25^{o}C so that all specimens started at a constant ambient temperature
- Specimens drilled at mid-length and pre-fixed depth from the surface for probes to monitor core temperatures

Positions of fiber optic probes for temperature measurement

Distance of probes from top surface (Inch)

	4x4	5x5	6x6	8x8	10x10
Probe 1	0.50	1.00	1.00	1.00	1.00
Probe 2	1.00	1.50	1.50	1.50	1.75
Probe 3	***1.75**	***2.25**	2.00	2.25	2.50
Probe 4	2.25	2.75	***2.75**	3.00	3.25
Probe 5	x	x	3.25	***3.75**	4.00
Probe 6	x	x	x	4.75	***4.75**
Probe 7	x	x	x	x	5.50

*** center (c) of the specimens**



Positioning of probes in 8”x8” specimen

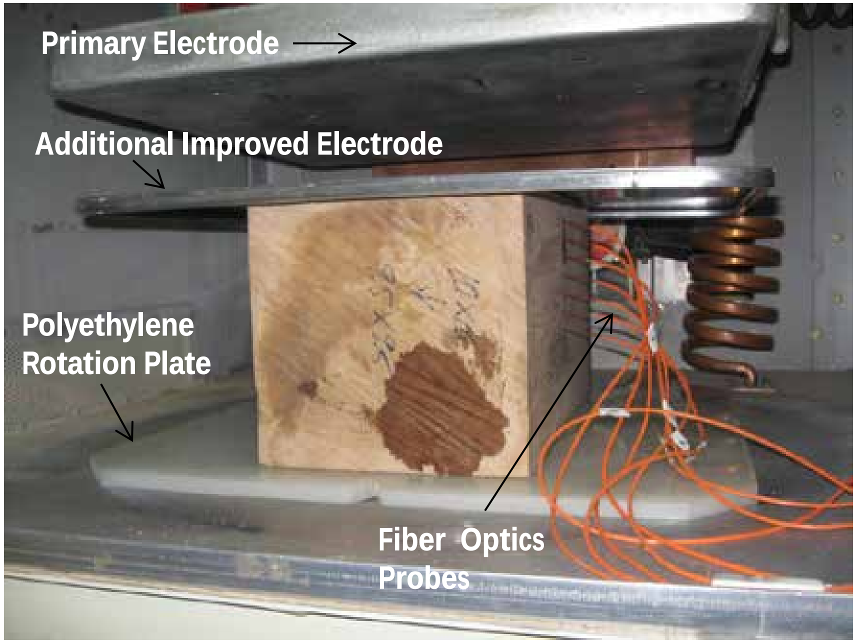
Heating process

- Specimens heated in a RF oven (*PSC, Inc, Model No.PP15L, 15 kW, 19 MHz dielectric oven*) or a MW oven *(Microwave Research Applications Inc. BP-211, 3.4 kW, 2.45 GHz multimode waveguide oven)* till all probes recorded target temperature of **60 degree C**.
- MW run at full power, while RF oven parameters adjusted to achieve equivalent power of **3.4 kW**.
- An improved electrode was developed based on dielectric energy with orthotropic absorption modeling and placed over specimens to facilitate uniform heating in RF oven.
- Two replicates were run for each combination (n=2).
- For reference/comparison, specimens were also heated in RF oven using the high power settings **(9.2-10.8 kW)**, nearly 3X greater power than at low power settings **(3.3-3.5 kW)**.

Experimental RF heating

RF oven set up with temperature monitoring system during Trials

Placement of wood specimen (10”x10”) inside oven



RF heating parameters

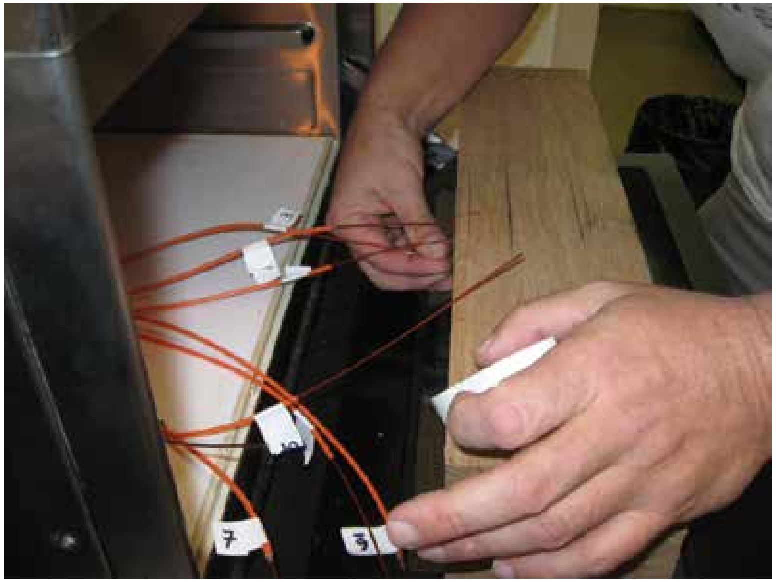
Dimension (inch)	Heating Depth* (cm)	Plate KV (Avg)		Plate Amp (Avg)		Power (kW)		Electrode height (inc)		KV control (%)		Cap. Position (%)		Grid A (Avg)	
		LPRF	HPRF	LPRF	HPRF	LPRF	HPRF	LPRF	HPRF	LPRF	HPRF	LPRF	HPRF	LPRF	HPRF
4x4	**9**	3.5	7.2	1.6	2.4	**3.4**	**10.4**	6.8	7.0	53.0	60.0	52.9	67.5	0.4	0.4
5x5	**11**	3.7	6.8	1.5	2.4	**3.4**	**9.6**	8.8	8.0	54.9	57.0	49.3	68.5	0.4	0.4
6x6	**14**	3.7	6.6	1.5	2.3	**3.3**	**9.2**	9.8	9.3	54.9	55.5	46.1	64.5	0.4	0.3
8x8	**19**	3.0	6.5	1.9	2.6	**3.5**	**10.2**	11.5	11.5	48.6	56.0	52.7	70.2	0.3	0.4
10x10	**24**	3.1	6.9	1.8	2.6	**3.4**	**10.8**	14.0	14.0	49.1	58.0	51.0	65.2	0.3	0.3

LPRF: Low Power Radio Frequency **HPRF**: High Power Radio Frequency

*Total depth of penetration through specimen

MW Heating

MW Oven with Fiber-optics probes



Insertion of Fiber-optics probes into wood specimen

MW heating and recording of temperature of probes in-process

Post-treatment steps

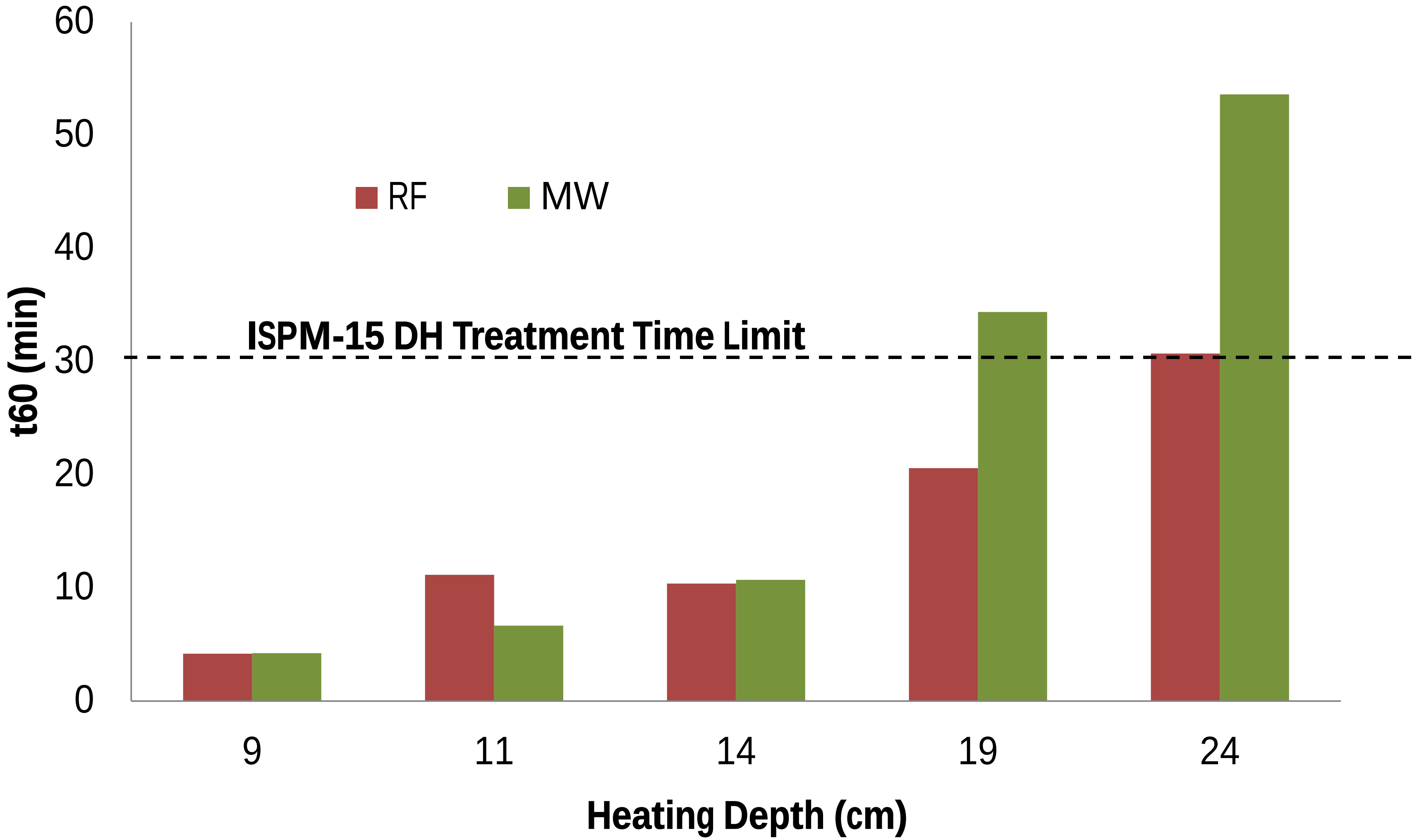
- Specimens kept inside the oven for an additional 2 min to assure compliance with 60ºC for 1 min.
- After 2-6 min of reaching the target temperature of 60ºC, thermal images of all surfaces and cross-sections at mid-length taken using FLIR T-250 Thermacam.
- Specimens weighed for overall moisture loss determination due to DH treatment
- Cross-sections at center of specimens also taken for % moisture content (MC) determination

Results: RF vs MW

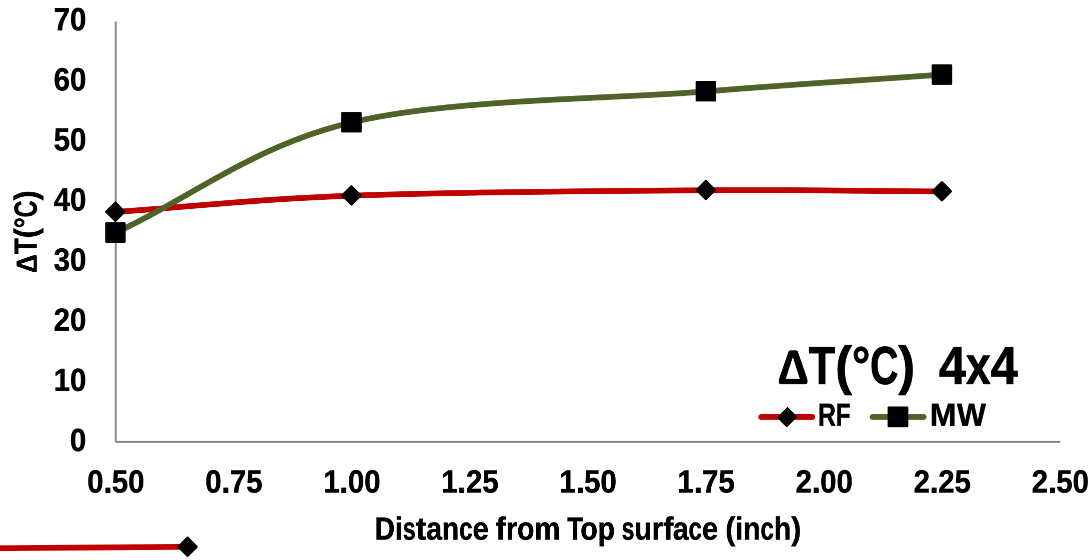
Nominal Dimension (inch)	Heating Depth* (cm)	t_{60} (min)		Initial MC %		Cross sectional MC %		Moisture loss %	
		RF	MW	RF	MW	RF	MW	RF	MW
4x4	**9**	4.2	4.2	62.1	67.5	61.3	64.9	0.5	1.6
5x5	**11**	11.2	6.7	60.7	68.3	59.1	66.4	0.7	1.1
6x6	**14**	10.4	10.7	70.9	63.0	69.5	60.7	0.8	1.5
8x8	**19**	20.6	34.4	67.7	64.3	67.0	54.4	0.5	6.4
10x10	**24**	30.7	53.6	N/A	N/A	62.4	57.5	N/A	N/A

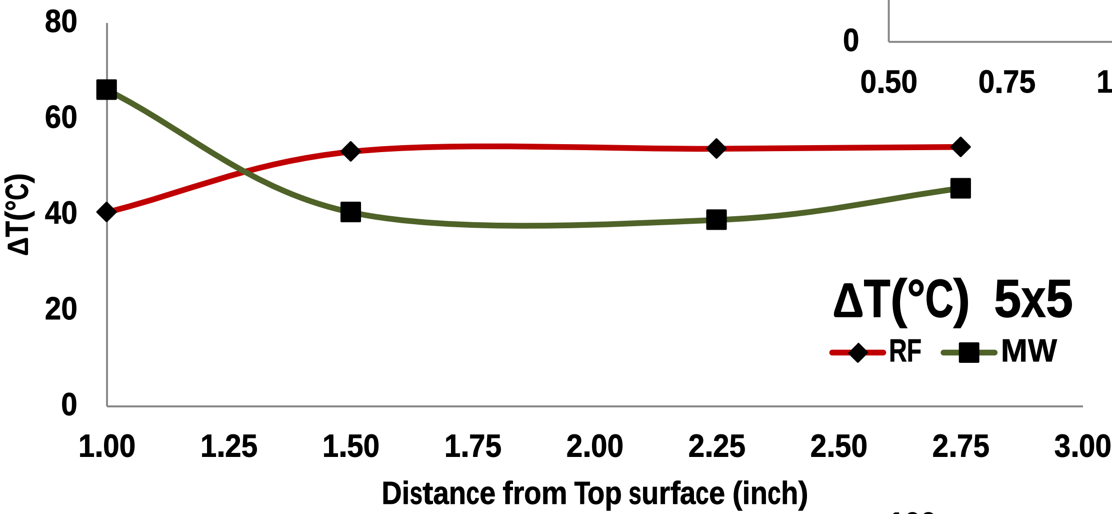
Values reported are an average measure of the test replication

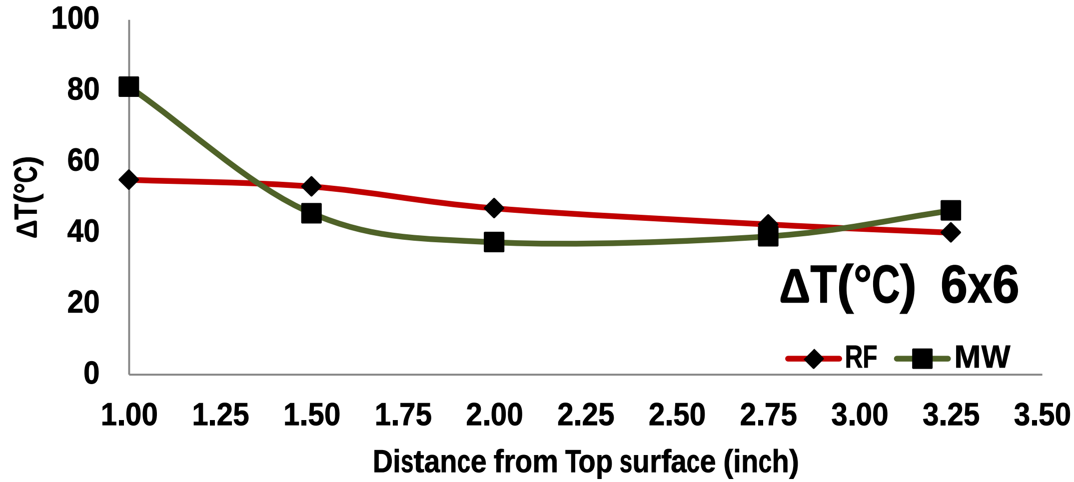
Time to achieve 60˚C (t_{60}) at varying heating depth



Change in Temperature as function of heating depth (1)





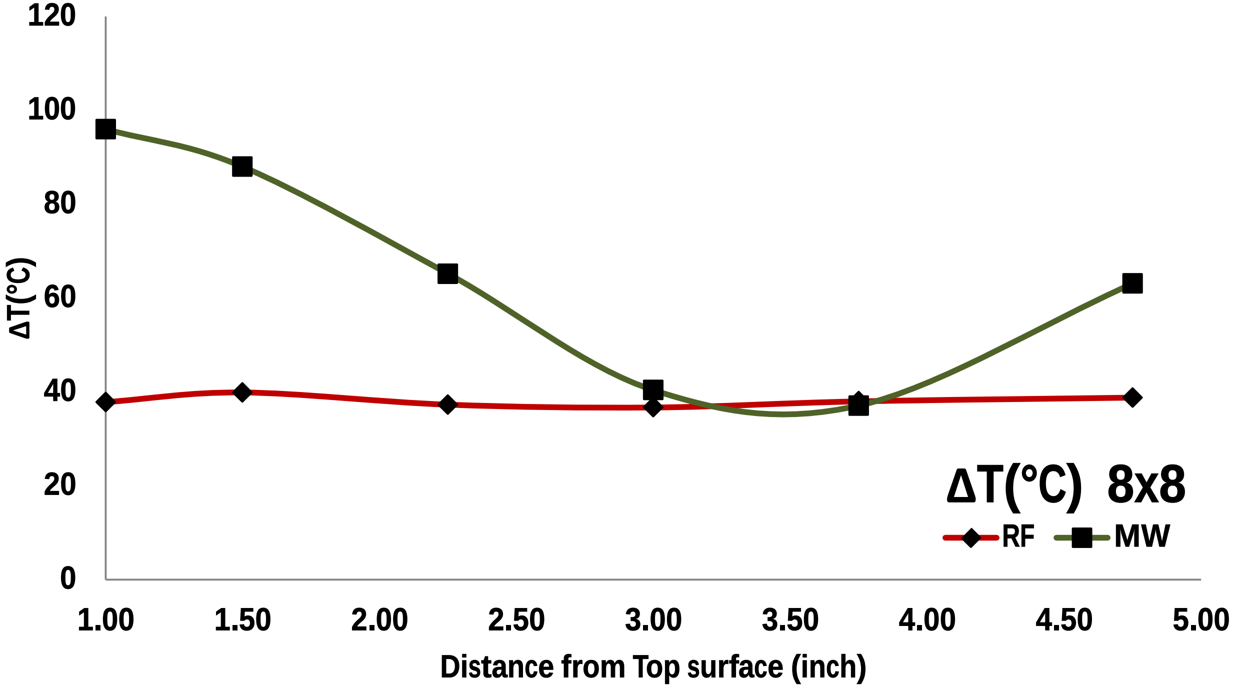


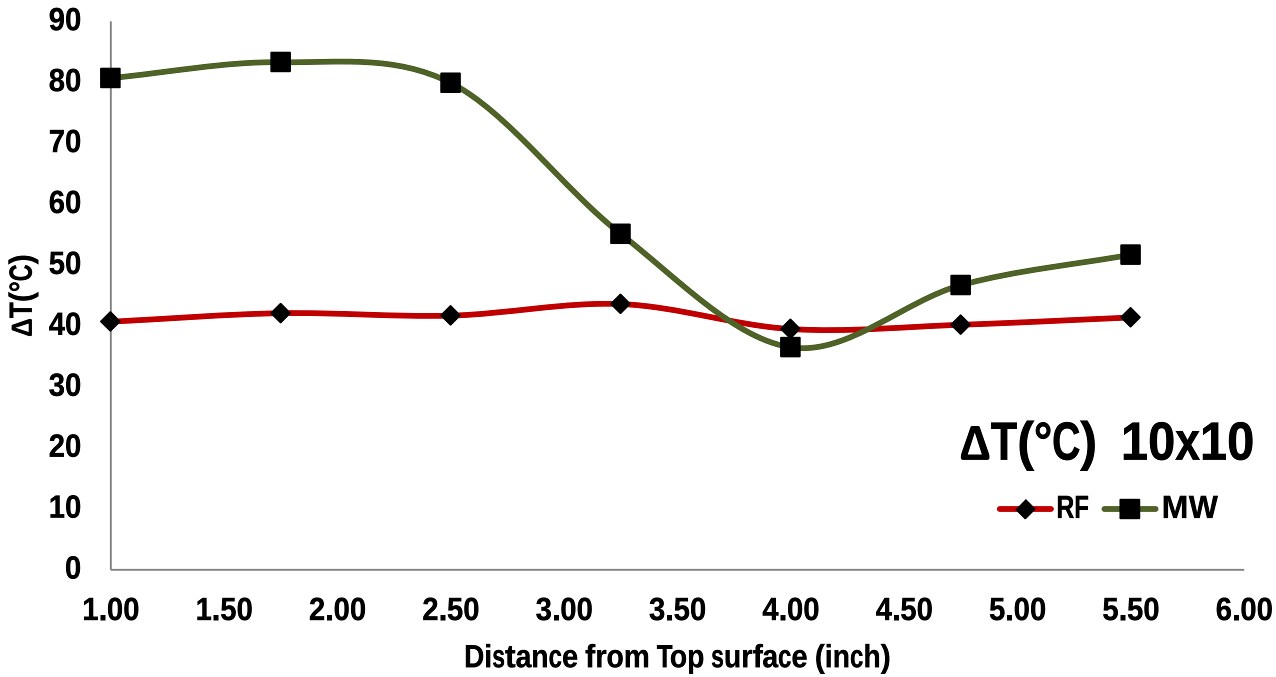
ΔT: Difference between final & initial temperature i.e. T_f-T_i, where,

T_f: Final Temperature i.e. temp of probes when all temperatures reached minimum 60 ° C

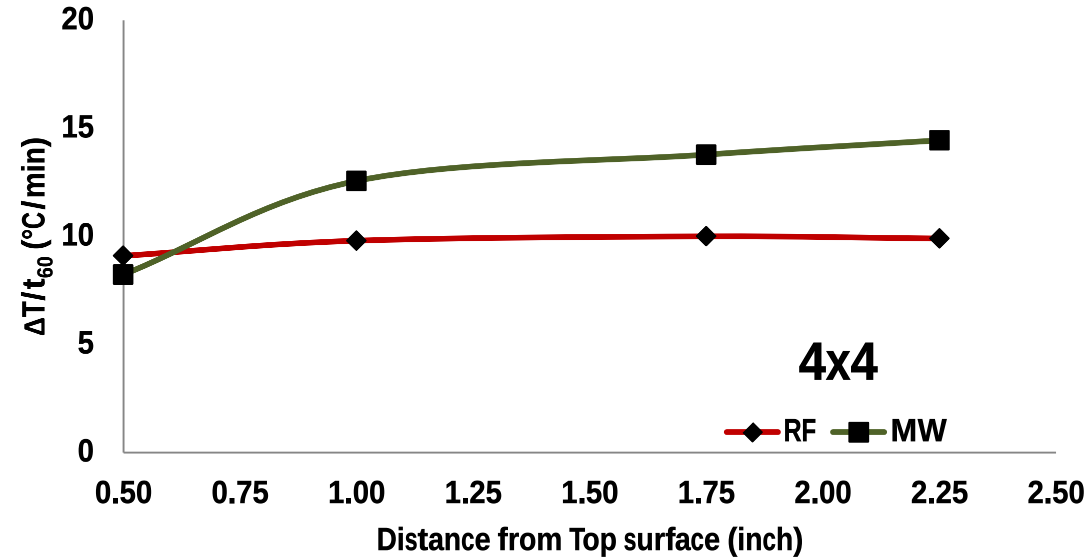
T_i : Initial Temperature at start of run

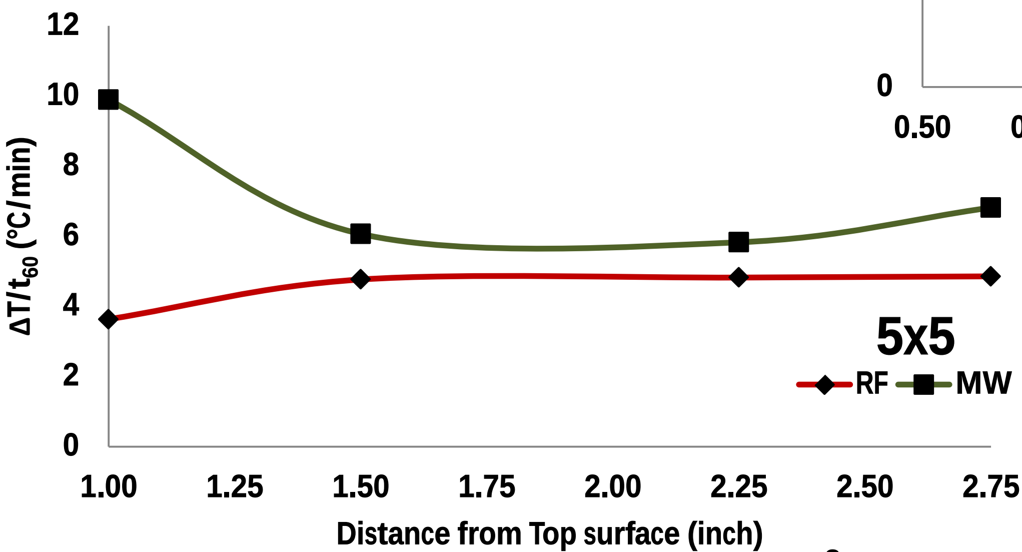
Change in Temperature as a function of heating depth (2)





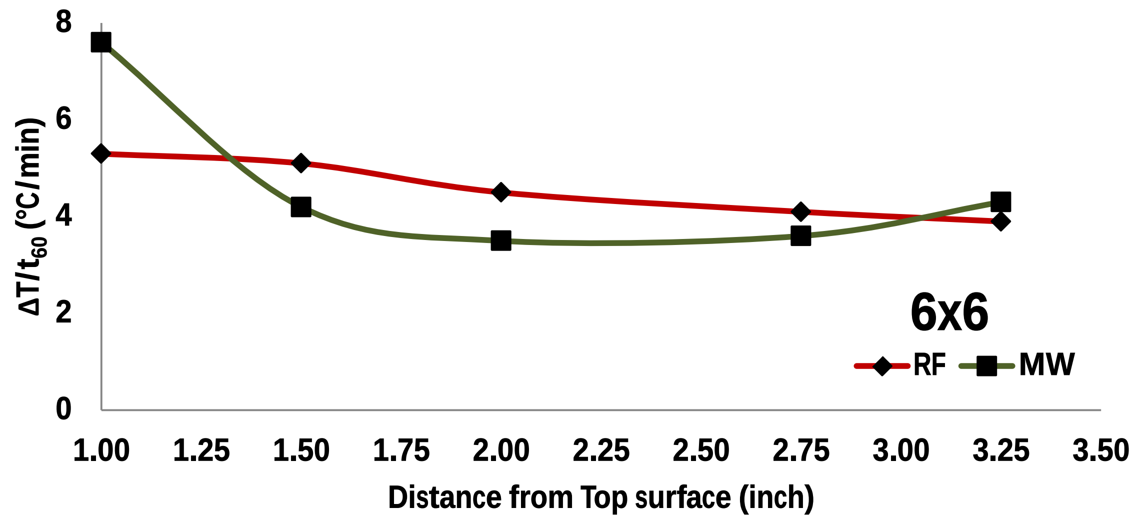
Temperature increase rate ($\Delta T/t_{60}$)at increasing depths with DH energy dissipation (1)



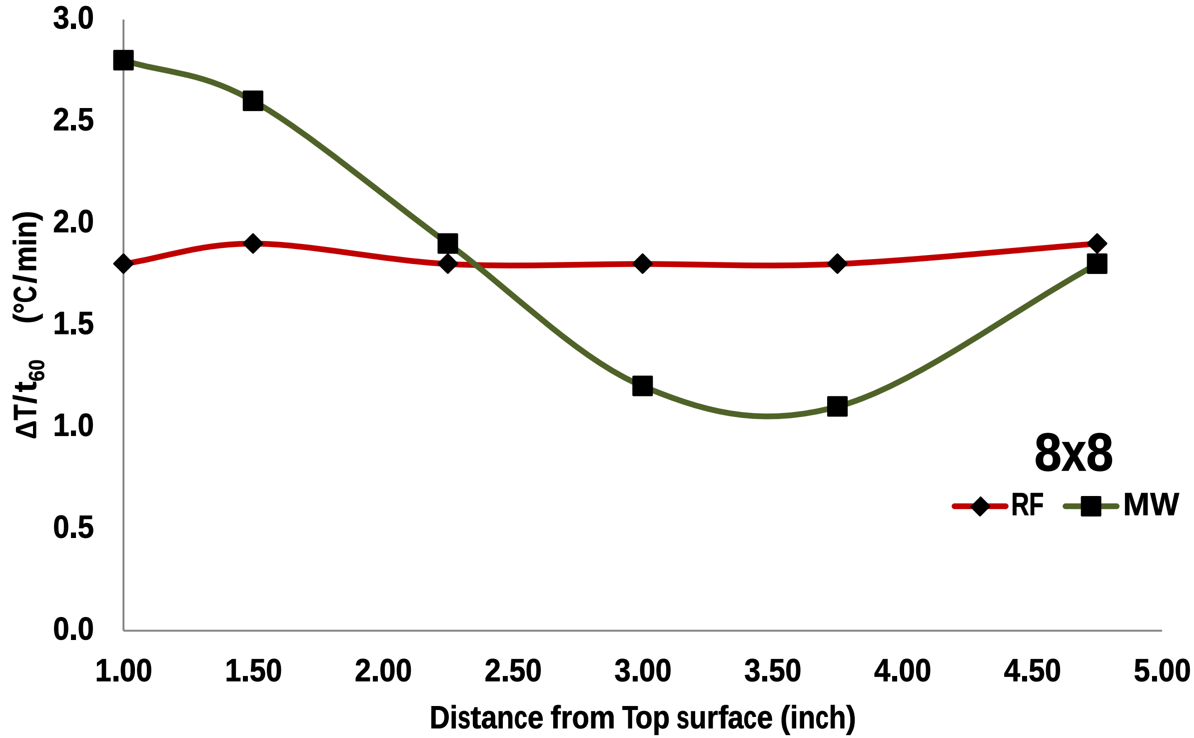


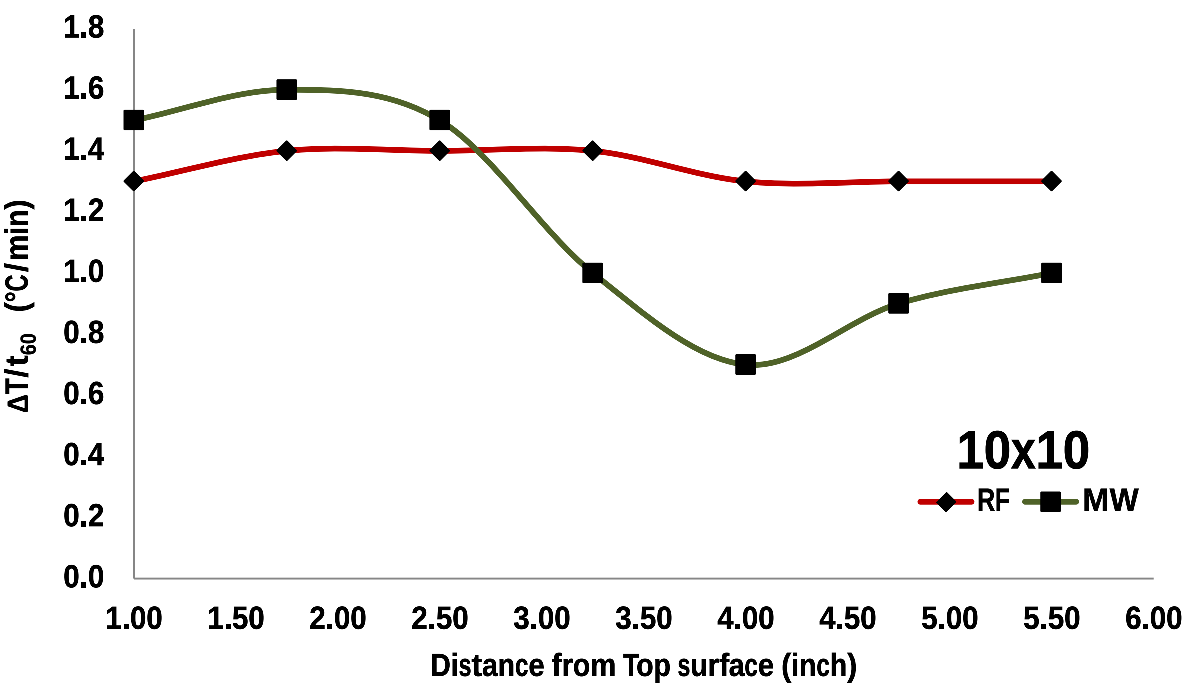
ΔT: Difference between final & initial temperature

t_{60}: Total time at when all probes recorded temperature of 60°C

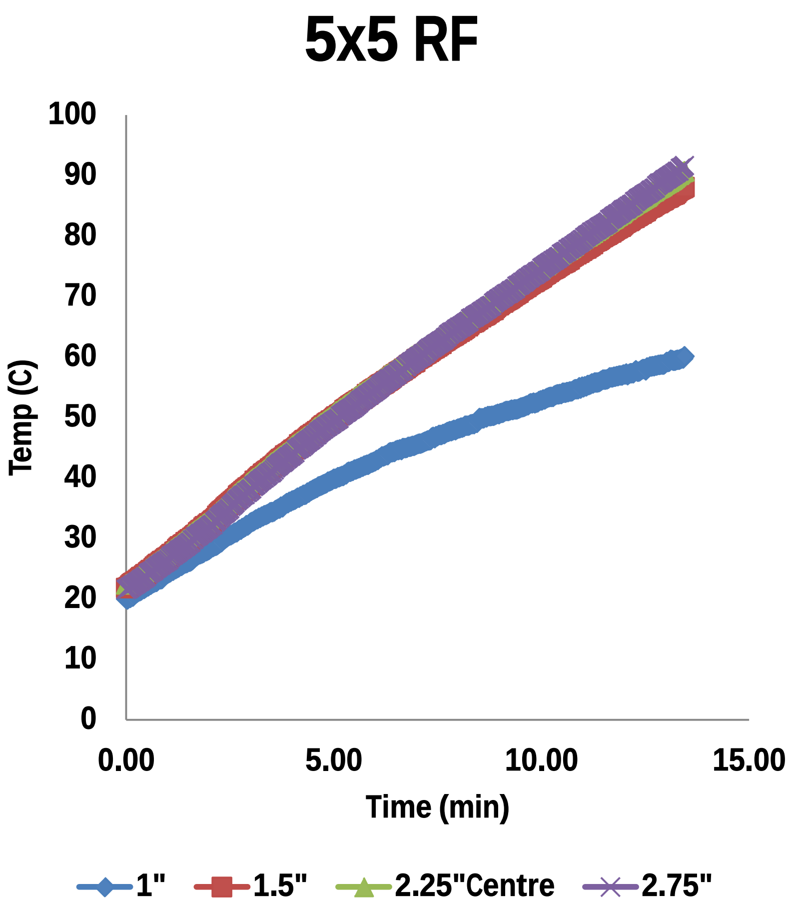


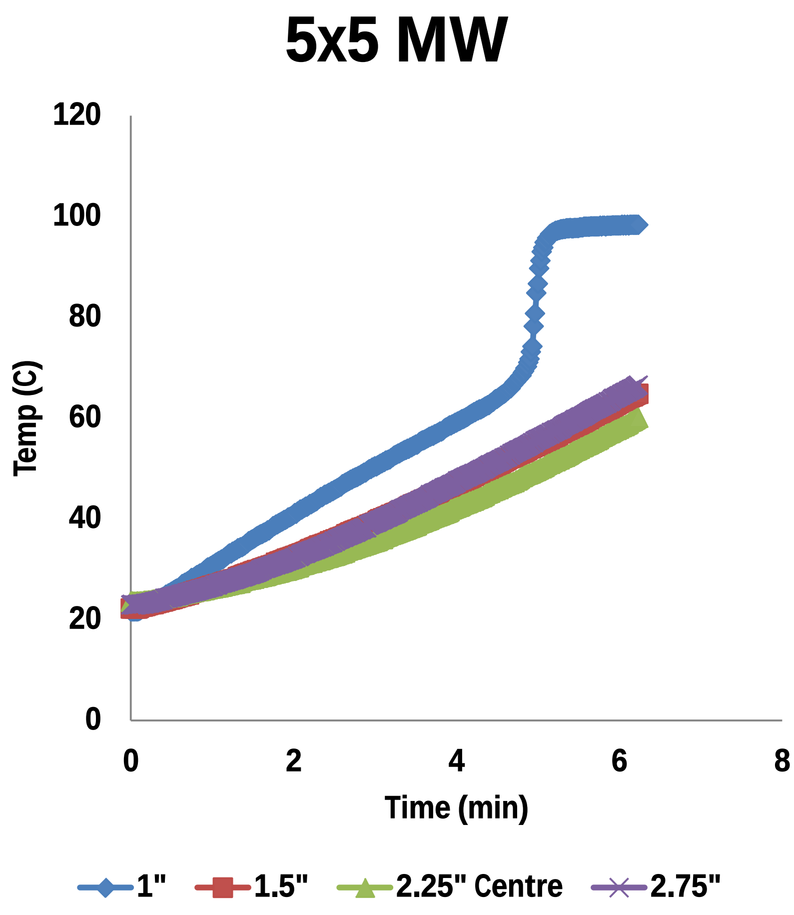
Temperature increase rate ($\Delta T/t_{60}$)at increasing depths with DH energy dissipation (2)



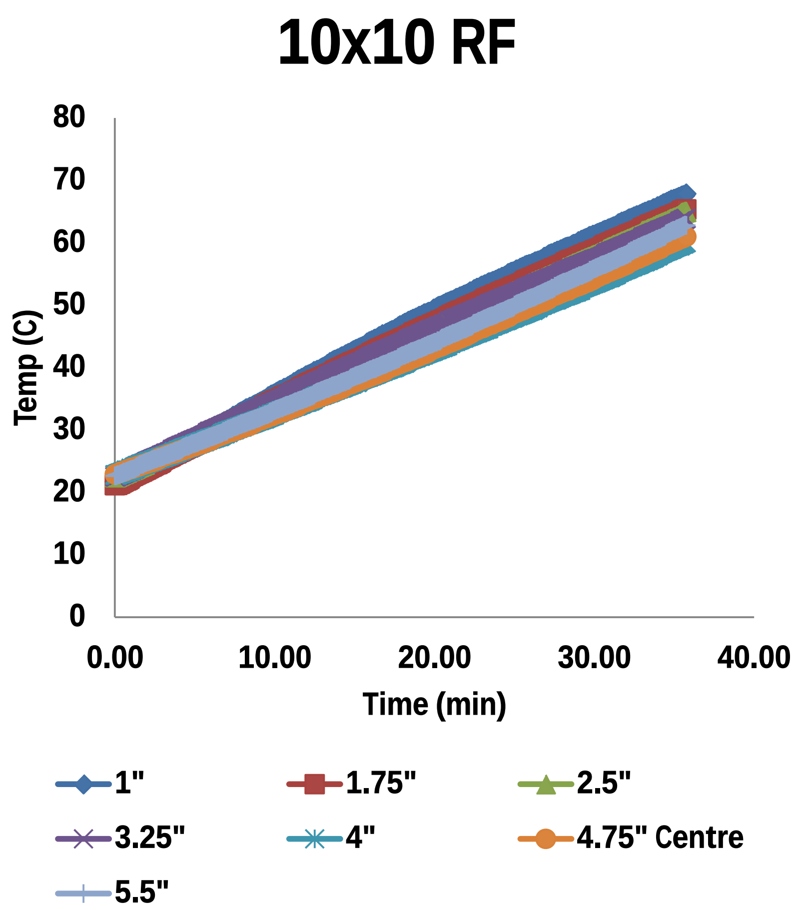


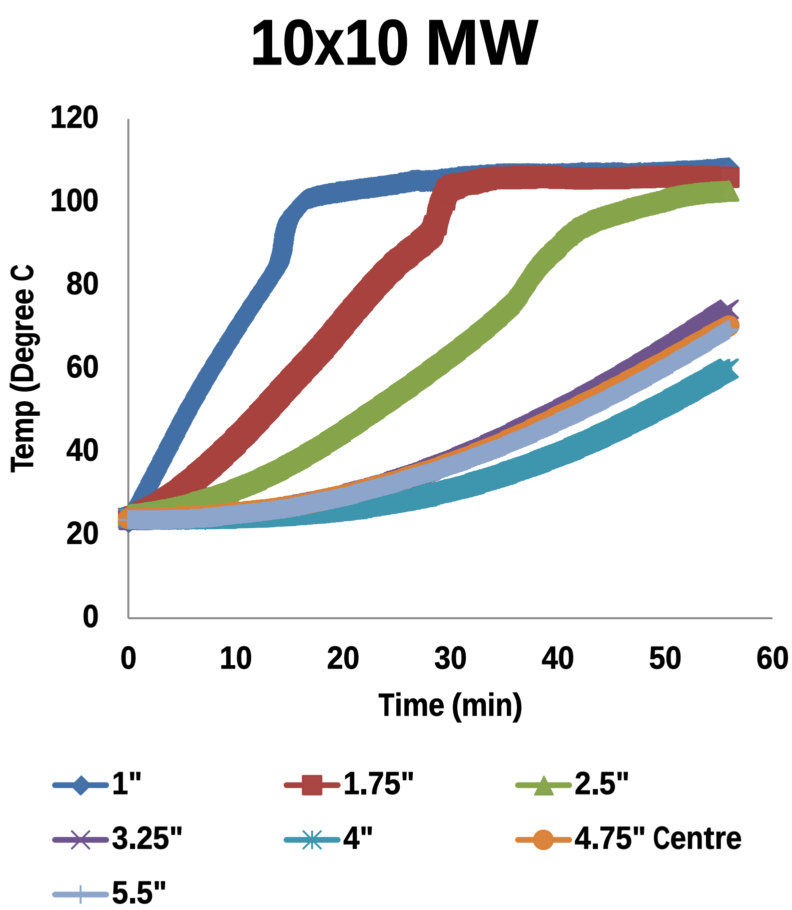
Temperature versus DH treating time (1)



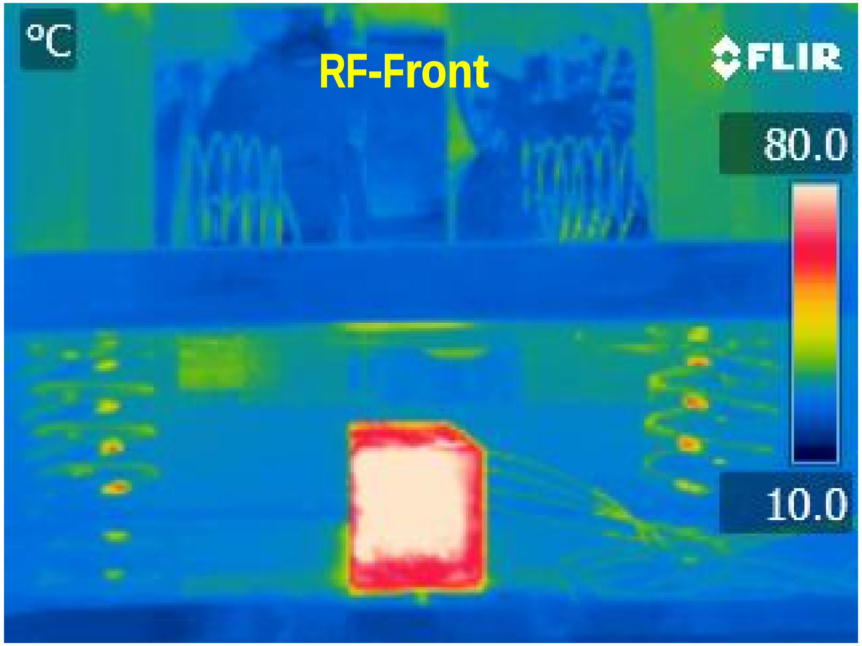


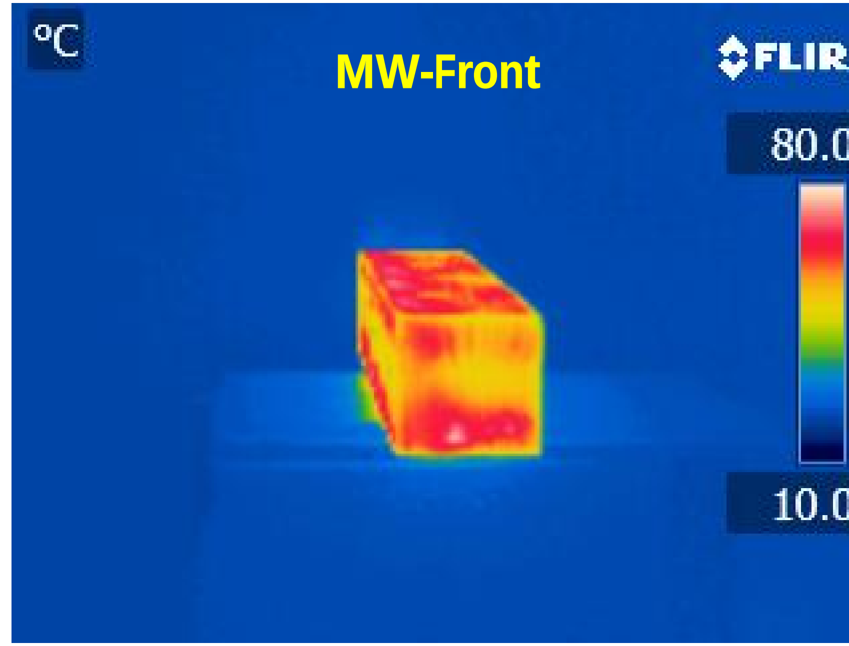
Temperature versus DH treating time (2)

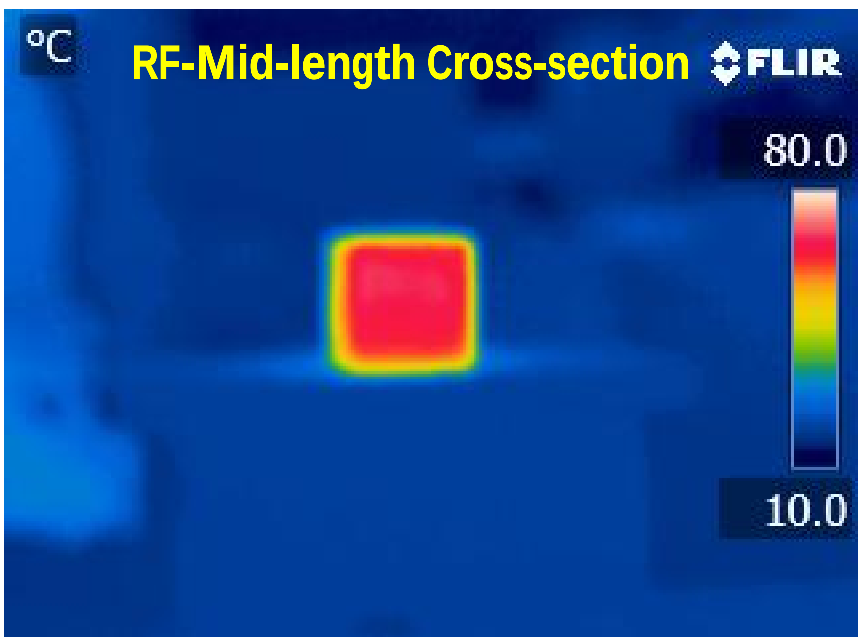


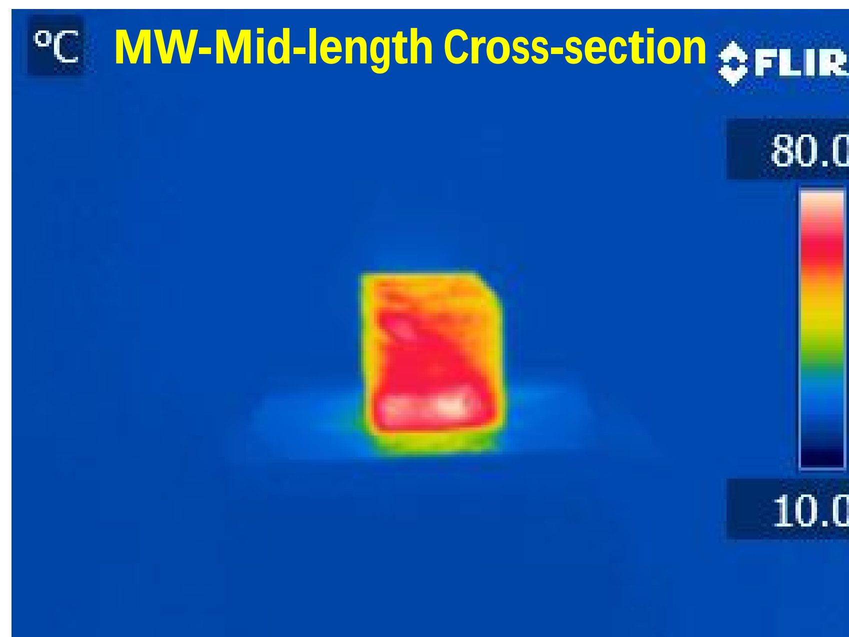


Infra Red (IR) Images: 4”x4”

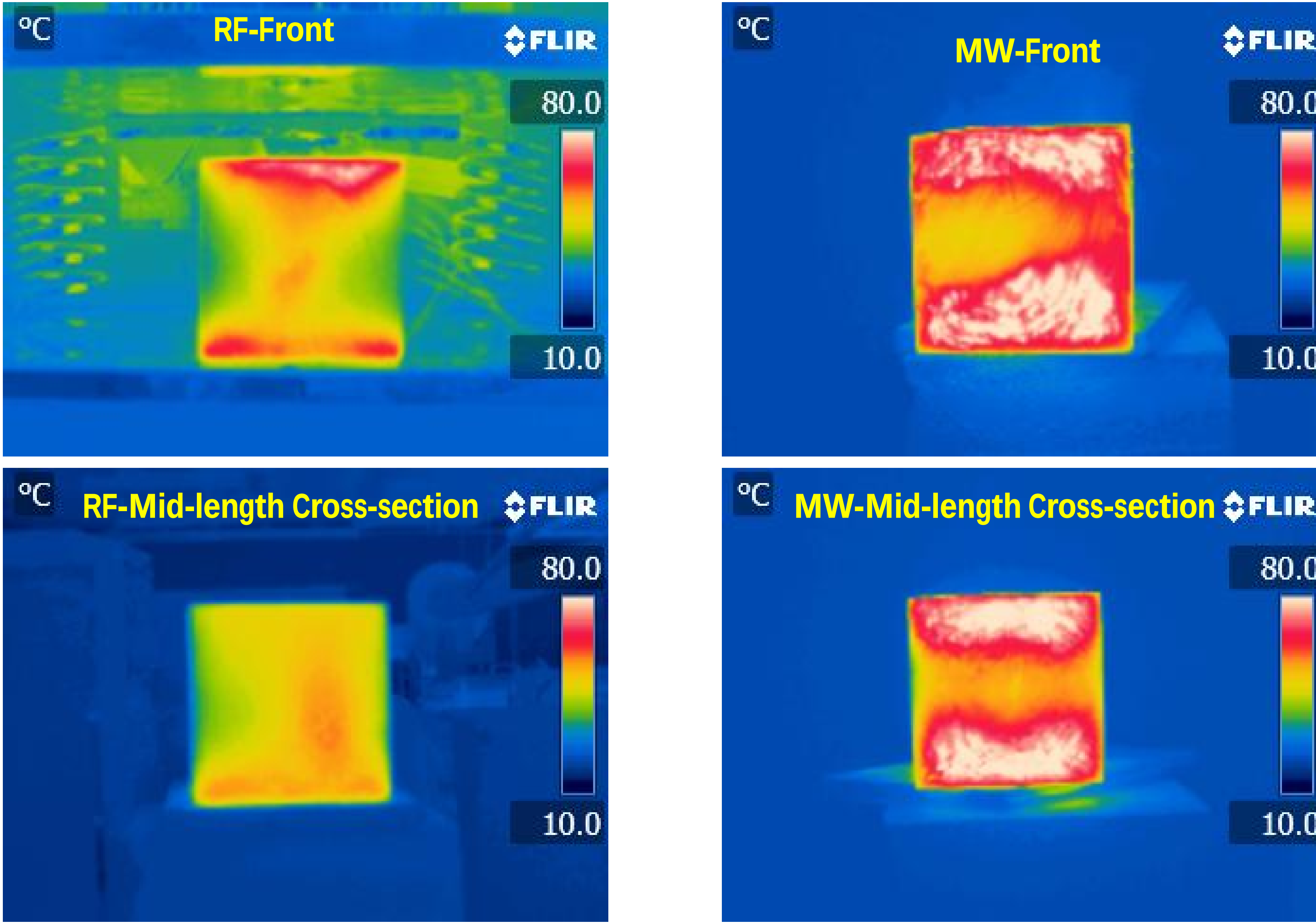






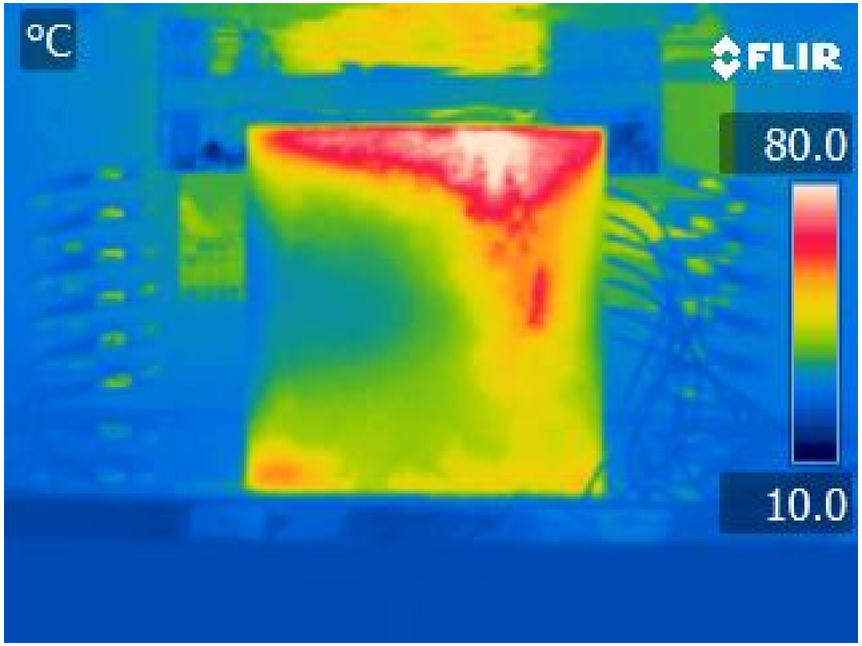


IR Images: 8”x8”



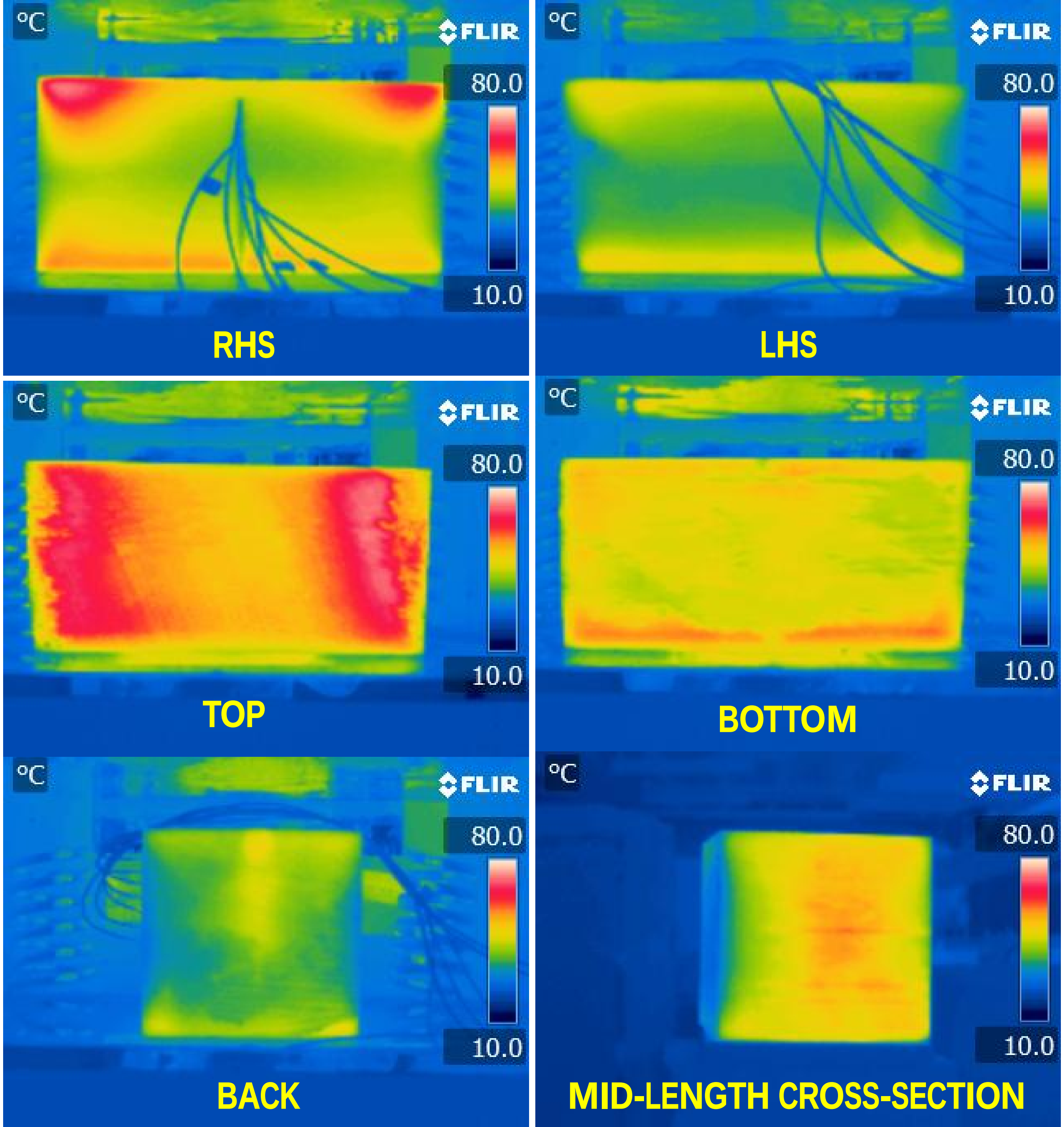
RF-10”x10” : 360° Images

Front Digital



Front IR

360^{o} **IR images 10”x10” RF**



Note: All the thermal images in this study were taken **after 2-6 minutes** of achieving the target temperature of 60 ° C

Theoretical Depth of Penetration "D_p" for white oak

- Depth of heating penetration (D_p) denotes where 63% of the electromagnetic incident energy is absorbed for the corresponding material heating response
- i.e., 63% of initial transmitted power has been transformed into heat as the EM wave propagates to the computed depth (D_p)
- We can quantify D_p with RF & MW irradiation frequency of the DH treatment and avoid heating disparities of batch volume consignments of wood.
- Depth of penetration (D_p) for low loss type of dielectric materials where $\varepsilon''/\varepsilon' \ll 1$, such as wood, can be given by following formula

$$\mathbf{D_p = 0.1592\,[\lambda_o'(\varepsilon')^{0.5}]/\,\varepsilon''}$$

where,

- λ_o' : free space wavelength, equals c (3×10^8 m/s) divided by specific electromagnetic frequency value (*f*).
- ε' : Dielectric constant
- ε'': Dielectric loss factor, equals dielectric constant (ε') multiplied by loss tangent ($\tan\delta$)

Computed values of “Dp” (depth of penetration) for white oak

Frequency	Dielectric Heating	ε′	tan δ	Dp (cm)
10 MHz	RF	*7.3	*0.21	800.42
50 MHz	RF	*6.6	*0.16	200.32
2.45 GHz	MW	**4.9	**0.2	4.0 (=1.73”)

* Tangential grain direction as test material conditioned at 90% RH (~24% wood EMC) and 25^{o}C (James, 1975)

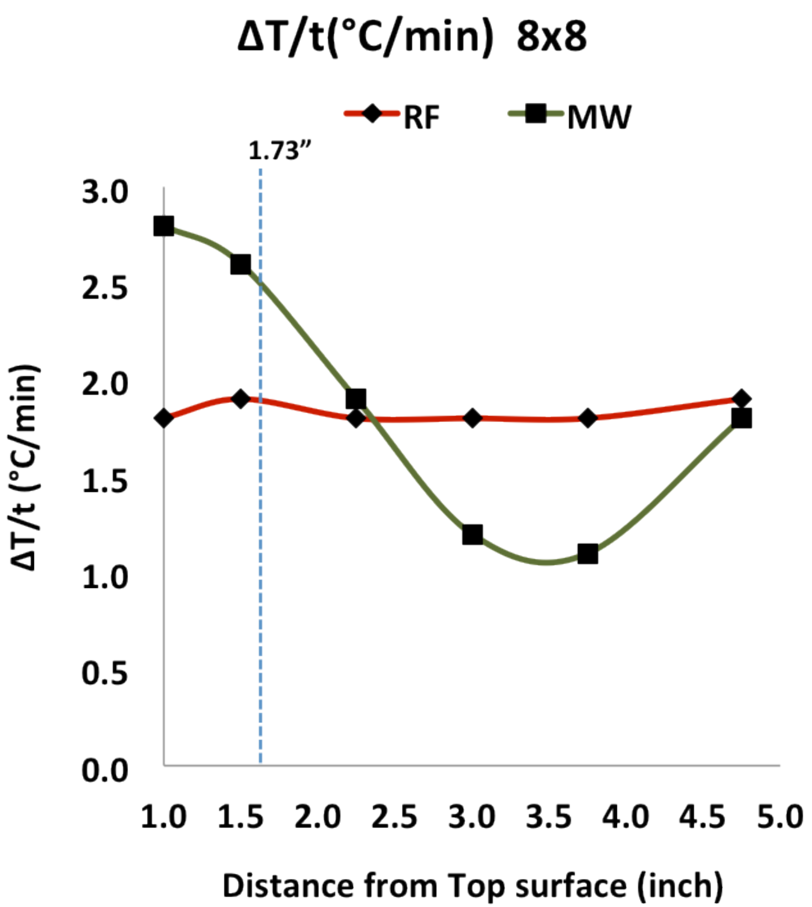
** For 25% moisture content and 25^{o}C measurement temperature (Olmi, *et* al. 2000)

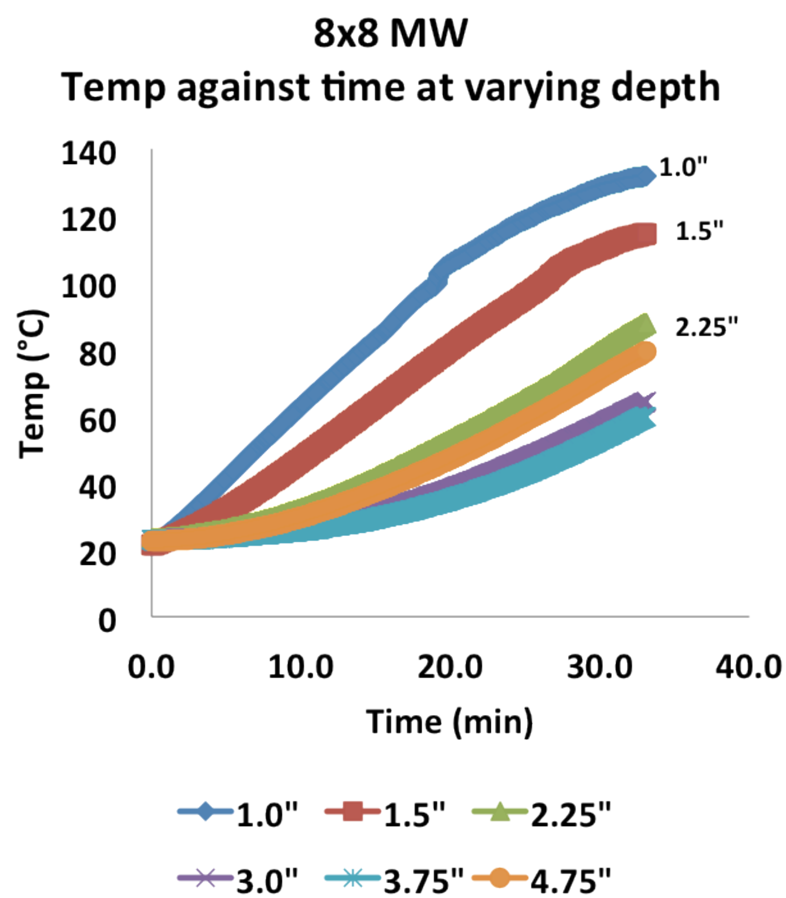
Theoretical & experimental “D_p” (1)

- Theoretically computed D_p values for RF heating are significantly greater (**8.4 m** at 10 MHz and **2.3 m** at 50 MHz) than that of MW heating (**4.0 cm or 1.73”** at 2.45 GHz)

- This is also reflected in the experimental findings and IR images for MW heating, which shows that rate of temperature increase should began to decrease >1.73 inch depth from the surface (i.e., heating rate tends to decline)

Theoretical & experimental "D_p" (2)



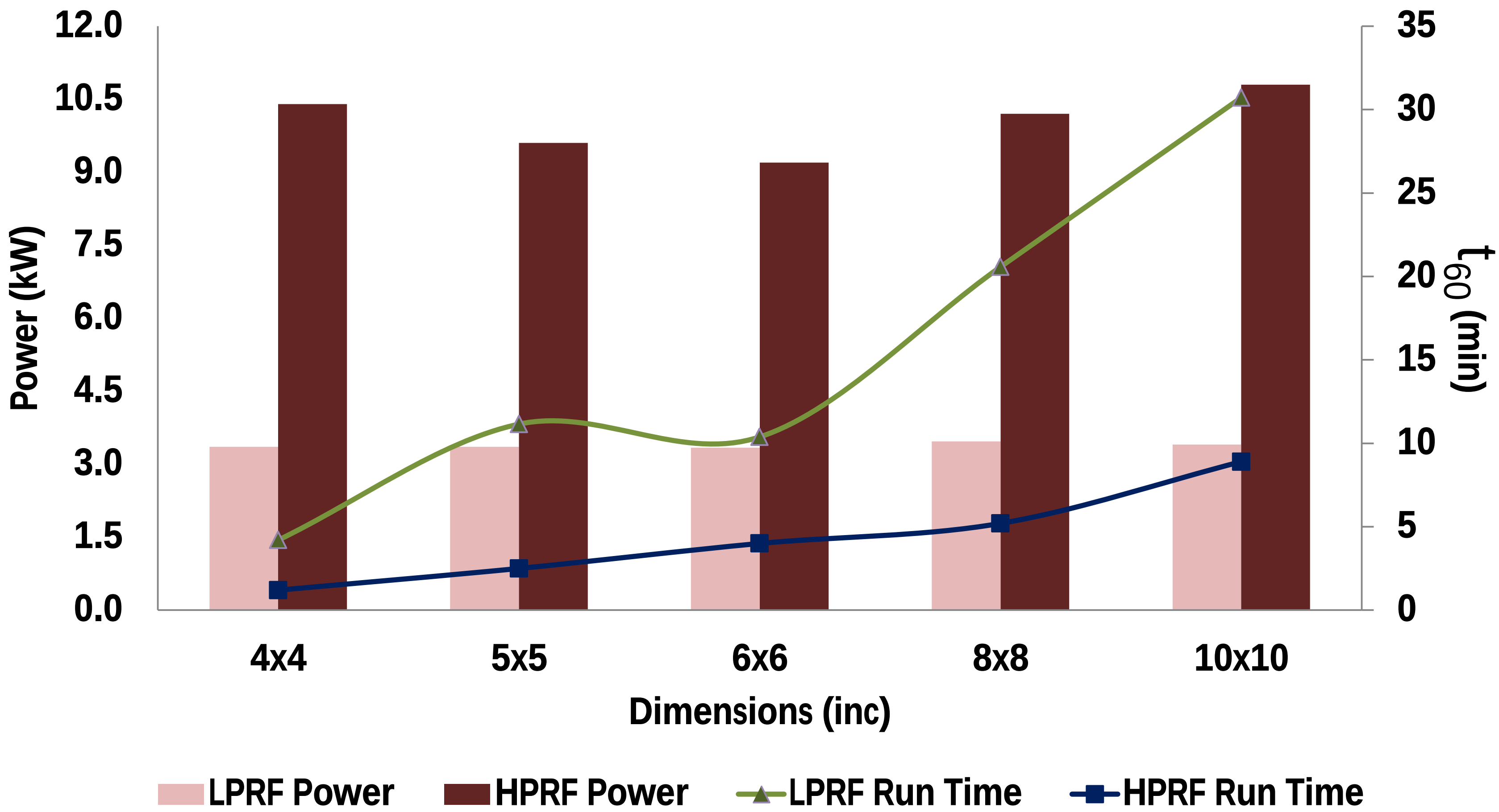


RF Heating at High Power Settings

Dimension (inch)	Power (kW)		t_{60} (min)			Initial MC %		Cross section MC %		Moisture loss %	
	LPRF	HPRF	LPRF	HPRF	% Differ.	LPRF	HPRF	LPRF	HPRF	LPRF	HPRF
4x4	3.4	10.4	4.2	1.2	71.4	62.1	64.8	61.3	63.5	0.5	0.8
5x5	3.4	9.6	11.2	2.5	77.6	60.7	66.2	59.1	65.3	0.7	0.5
6x6	3.3	9.2	10.4	4.0	61.5	70.9	62.3	69.5	61.3	0.8	0.6
8x8	3.5	10.2	20.6	5.2	74.7	67.7	65.9	67.0	65.5	0.5	0.2
10x10	3.4	10.8	30.7	8.9	71.0	N/A	N/A	62.4	68.5	N/A	N/A

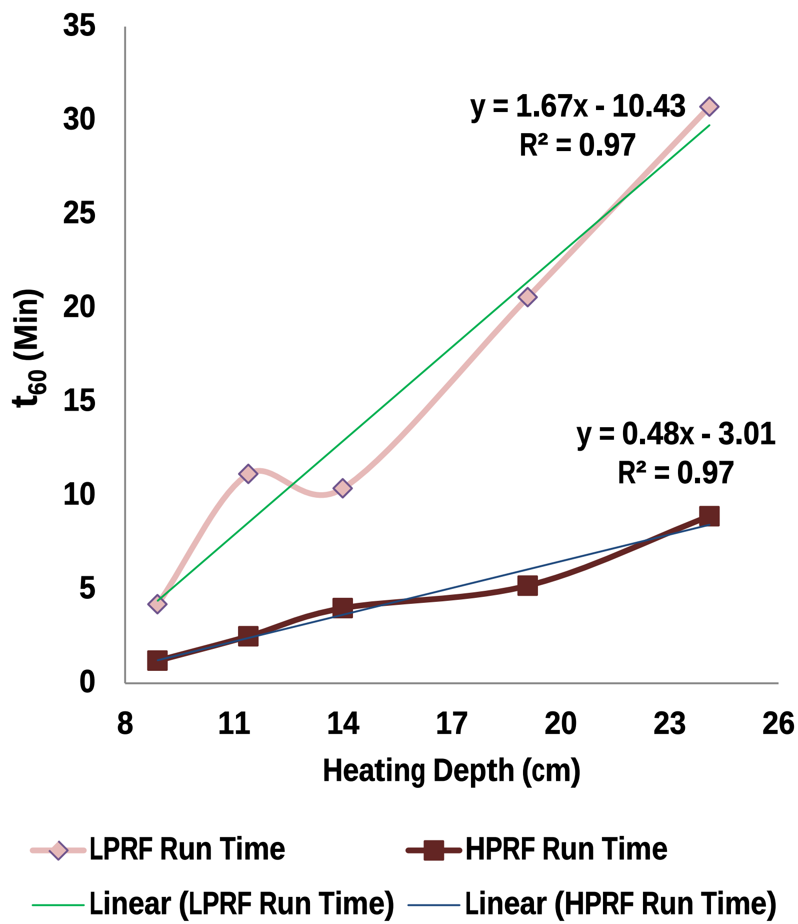
LPRF: Low Power Radio Frequency **HPRF**: High Power Radio Frequency

RF Heating at High Power Settings



- Nearly, 3 fold increase in RF heating power resulted in shortening of total run time (t_{60}) by 62-78%

Run Time (t_{60}) versus Heating Depth



Dimension	Heating Depth	Predicted Run Time (t_{60}) (min)	
(inch)	(cm)	LPRF	HPRF
12x12	29.2	**38.2**	10.9
16x16	39.4	**55.2**	15.7
20x20	49.5	**72.1**	20.5
24x24	59.7	**89.1**	25.4
28x28	69.9	**106.1**	**30.2**
*48x48	121.9	**503.9**	**143.7**

Data in bold is beyond the time limit of 30 min

* Typical commercial stack size (4'x4')

Conclusions

- RF can effectively penetrate beyond the 20 cm limit in the recently approved ISPM-15 standard.
- RF heating is more uniform, consistent and faster than MW heating, especially for dimensions greater than 6"x6".
- For larger dimensions (8"x8" & 10"x10") MW heating, temperature at the surfaces were significantly higher than in the core.
- The results also indicate that MW (2.45GHz) cannot effectively penetrate beyond a depth of 1.73" (4.4 cm)
- Increasing RF power by 3-fold significantly reduced run time (t_{60}) by up to 78%.
- **RF heating meets ISPM requirement of achieving 60˚C within 30 min and can be used as an approved treatment**
- However, the 30 min time limit for DH treatment is unrealistic and commercially non-viable for treating larger material or bulk volumes.

Future Directions

- This study provides a basis for developing commercial treatment schedules with RF technology
  - for heating large volumetric workloads, and
  - for wood species commonly used for WPM
- However, to establish RF as viable alternative for MBT, this study ***strongly advocates appropriate modifications in the language of current ISPM-15 regarding***
  - ***RF can achieve ISPM-15 requirements***
  - ***ability of RF to treat beyond the depth of 20 cm, and***
  - ***Removal of 30 minutes time restrictions for DH treatment***

Work in Progress (1)

- Commercial Trials on stacks of 2’, 3’ and 4’ height
- Site: Ben Aaron Lumber Co., Forestville, NY
- RF vacuum drying oven (4.6 MHz; 150kW Generator)

Work in Progress(2): Experimental

- Species: Mixed white oak; mixed red oak and mixed ash
- Green, Average MC 50-60%
- Selected cants kerf cut, weighed and pre-drilled for temperature probes
- Multichannel fiber optic temperature monitoring system: OFX-USB OmniFlex system used to monitor the core temperature of cants during RF heating

Work in Progress(**3**)

Acknowledgements

(Research Support and Collaborations)

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Thank you..........