Practical Application of Joule Heating to the Sterilization of Plantation Grown *Pinus radiata* Logs

WJB Heffernan *[1]

[1] Electric Power Engineering Centre (EPECentre), University of Canterbury (UC)

(Author and Presenter)

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Abstract

Pinus radiata (D. Don) log exports are one of New Zealand's major foreign revenue earners, with 12.8 million cubic metres, valued at nearly NZ$1.7 billion, shipped in 2011. Most trading partners require logs to be treated before shipment from NZ, to prevent the inadvertent import of unwanted pests. This is carried out by the use of the fumigants methyl bromide (MeBr) or phosphine. MeBr is an ozone depleting substance and has been phased out for all but quarantine and phytosanitary purposes. The New Zealand Environmental Protection Agency requires that, by 2020, MeBr used in New Zealand is recaptured after use.

Alternative phytosanitary treatment methods are required, with heat being one option.

Trials using electrical Joule heating were begun at the EPECentre in 2007. Early results indicated that the technique was worthy of deeper investigation. Further EPECentre funded work, with later support from the Stakeholders in Methyl Bromide Reduction and the Ministry for Primary Industries Primary Growth Partnership, has shown that the technique could be used to successfully treat logs in accord with importing country requirements. The work is now funded as part of a six year STIMBR-Ministry of Business, Innovation and Employment co-funded research programme, led by Scion.

A test rig, incorporating novel segmented electrodes and an automated data acquisition and energy control system, has been built and commissioned in the HV laboratory at UC. This rig is powered by a single phase Foster Regulator (FR) which provides 0 to 400V at 0 to 500A, within a 100kVA envelope. The FR output is stepped up by a 200kVA, 240V:11kV transformer, to provide up to 11kV across the log, at up to 11A. The automated energy control system drives the FR to provide maximum power to the log, within the equipment constraints, while integrating the active power supplied until a preset quantity of energy has been injected into the log, to raise its temperature by the desired amount. The rig has successfully been used to treat 3.3m long, 0.5m diameter logs. About 30 to 40kWh of energy per m^3 are required. Thus, on a 16 hour per day, all year round operation, around 400 to 500GWh, from about 80MW of generation, would be required on a nationwide basis (2012 data).

The paper presents and discusses electrical and log temperature data from the rig, along with planned future developments and a sneak preview of how a wharf-located production machine might operate.

1. Introduction

Forest products are the third largest export earner for New Zealand (after dairy and meat products). The export of logs accounts for a large proportion of these earnings, with roughly 13 million cubic metres of logs being shipped per annum [1].

Currently many of these logs are treated with fumigants, such as methyl bromide or phosphine, prior to, or during, shipping, as a means of eliminating the risk of pest infestation. The use of some fumigants, especially methyl bromide, is now under threat, due to the negative environmental impact. Alternative phytosanitary treatments are urgently needed.

One promising technique is Joule heating, in which the logs are heated by passing electrical current through them. This has been shown in the preliminary tests reported on here to be capable of achieving acceptable phytosanitary results. (It should be acknowledged that this idea has already been tried [2], albeit for a different purpose and in a very basic form, a fact of which we were unaware until after the initial tests reported in section 2 of this paper).

However there is a great deal of work still to be done to develop a process that is able to successfully treat all logs, with the minimum expenditure of energy, without adversely affecting any of the timber's mechanical properties or appearance.

There is an international standard applicable to the phytosanitary heat treatment of sawn timber, known as ISPM 15 [3]. Essentially ISPM 15 stipulates that all parts of the timber must simultaneously experience a minimum temperature of 56^{o}C, for a minimum time of 30 minutes. Although ISPM 15 has not currently been adopted for logs, it is likely that a standard with similar requirements will be accepted internationally. For this reason current work is based around a minimum of satisfying ISPM 15.

2. Early small-scale work and results

An approach by the Ministry of Agriculture and Forestry Biosecurity NZ (MAFBNZ), now Ministry of Primary Industries (MPI), in 2007 resulted in initial work into the feasibility of Joule heating of timber. A freshly felled fence-post sized log, with a diameter of about 13cm and a length of about 1m, was energized with a 10kV RMS, 50Hz supply. The power was provided by a single phase, 100kVA, 0 – 400V, variable voltage transformer, known as the Foster Regulator (FR) through a 240V:11kV step-up transformer. Suitable instrumentation was connected to measure applied voltage, current, real power and delivered energy.

The energy to produce a temperature rise of 50^{o}C in that volume of green timber was calculated at approximately 1.4MJ.

Starting from an ambient temperature of 14^{o}C the log was heated until about 1.2MJ, or 0.33 kWh, had been delivered. It was noted that the log current during the test increased as the log became hotter, with a final value of 6.5A (representing 65kW into the log, being a pure resistive load) after 20 seconds. (6.5A on the HV side corresponds to 300A on the LV side, above which the circuit breaker was set to operate). The test set-up is shown in Figure 1.

Immediately after the removal of power the temperatures at 7 locations throughout the log were measured by thermocouple and recorded. Locations L1 to L5 were drilled to a depth of 30mm and spaced evenly every 200mm along the log, starting with L1 100mm from the left hand (HV) electrode and ending with L5 100mm from the right hand (Ground) electrode. Locations L6 and L7 were drilled to a depth of 65mm (i.e. to the core of the log) and spaced 100mm either side of the geometric centre. The log was then left, in situ, to cool for 70 minutes before a second heating test was carried out. Immediately before commencement of the second test the temperatures at the 7 locations were again measured and recorded.

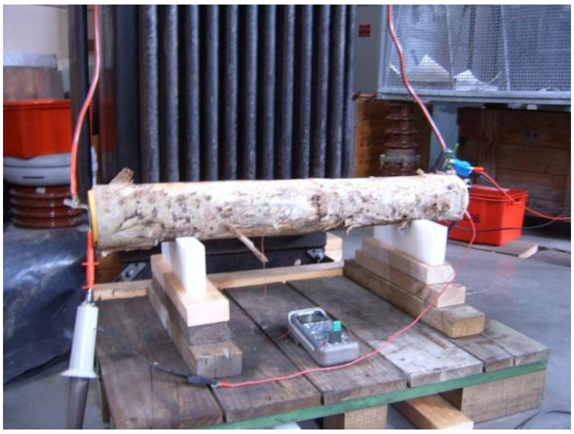

Figure 1. Test set-up for small log heating

For the second test the voltage was reduced to 7kV as it was desired not to exceed 6.5A on the HV side. During the second test the current increased from 4.5A to 6.5A[1] over a 15 second period, at the end of which the power was again removed by operation of the circuit breaker current trip. During this test a further 0.6MJ was delivered to the log.

The log was again left in situ, with the 7 temperature locations monitored and recorded every 5 minutes for half an hour. The temperature results are shown in Table 1.

	Time									
Location	**End Test 1**	**Test 1 +70m**	**End Test 2**	**Test 2 +5 m**	**Test 2 +10 m**	**Test 2 +15 m**	**Test 2 +20 m**	**Test 2 +25 m**	**Test 2 +30m**	**Test 2 +3hr***
L1	82	35	74	65	61	59	57	55	54	30
L2	77	41	73	68	66	64	64	62	61	36
L3	76	42	73	69	66	64	64	62	61	34
L4	74	44	72	68	66	65	64	62	61	36
L5	69	36	71	64	62	60	58	56	55	30
L6	54	47	77	76	75	74	73	71	70	41
L7	54	49	77	79	78	77	75	73	72	41

* Last 2.5 hours with forced air cooling

Table 1. Temperatures in ^{o}C of 7 locations throughout the log

Table 1 clearly shows that after the second test the requirements of ISPM 15 were very nearly met – the exceptions being locations L1 and L5 that just failed to hold up. However this was because the steel electrodes, which acted as a significant heat sink, were still attached and were removing heat from the ends of the log by conduction much faster than the losses by convection and radiation to the air. It was therefore evident that the Joule heating idea had potential!

3. Initial full-scale demonstration design

After presentation of the results, MAFBNZ awarded a small research contract to the EPECentre to investigate how to carry out Joule heating trials on full-sized logs. This was completed in mid-2009.

The earlier work had shown that, in order to inject the necessary heat into a typical 0.6m^3 log in the target time of about 1 minute, roughly 1MW of power at about 33kV would be

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[1] Log conductivity increases with temperature, probably due to increasing mobility of ions in the sap. This phenomenon is now under detailed investigation as part of an ongoing Scion-STIMBR-MBIE programme.

required. Additionally it had shown that control over the supply voltage would be necessary to safely control the rate of log-heating.

As part of the new work a log test fixture, suitable electrical and thermal instrumentation and an electrical power circuit were conceived and costed. A log is an inherently single phase load; although an integer multiple of 3 logs could be energized simultaneously, it would be a complex task to control the energy into each. Hence a 1MW single phase 33kV supply, with voltage control, was required. The simplest solution appeared to be to hire a large diesel generator set, with appropriate step-up transformers, disable the alternator’s Automatic Voltage Regulation (AVR) and control the field excitation. Figure 2 shows the schematic diagram for the power circuit.

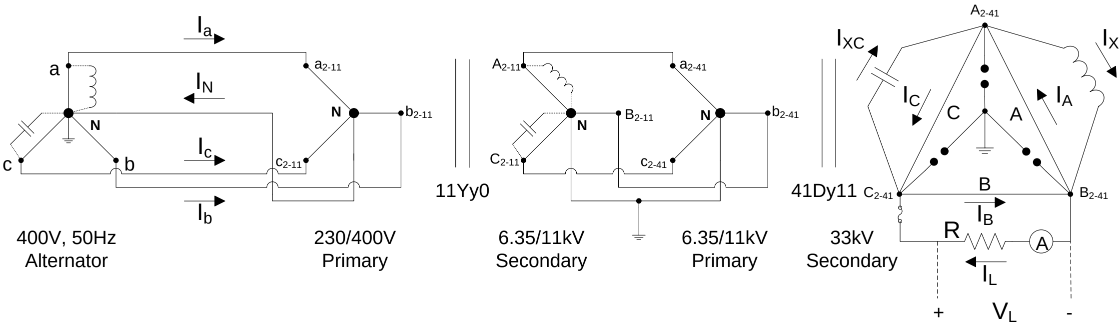

Figure 2. Diesel generator supplied electrical power circuit

With the unbalanced load it is easy to show that, without the balancing reactances in circuit, there is a neutral current equal in magnitude to half the reflected load current. It is also possible to show that the load becomes balanced when $X_C = X_L = R\sqrt{3}$.

Unfortunately the earlier work had shown that the log resistance, R, was likely to fall by roughly one order of magnitude during the heating process, so balance could only be achieved with variable reactances, or at one operating point (e.g. maximum expected power). Additionally the reactive components would be large and expensive. (Figure 2 shows that the reactances could be in any one of three locations (or combination thereof), with the 230V winding probably the best location for the L and the 33kV winding the best for the C).

Phasors for the unbalanced and balanced cases are shown in Figure 3. In the unbalanced case, at full power, on the HV side $|I_A| = |I_B| = |I_C| = 15A$, while on the LV side $|I_a| = |I_b| = |I_c| = |I_N| = 2150A$. Nevertheless, two alternative sources for hire of the generator and both transformers, to be used under the unbalanced conditions with the AVR disabled as described, were identified and costed. In general all units (or combinations thereof) were rated for 2MVA or more, under balanced three phase conditions. (One possible alternative, which could be operated from the mains supply, would be a large three phase motor drive with extra DC link filtering, again operating in an unbalanced condition).

The final report on the contract [4] understandably concluded that the cost for setting up and carrying out the requisite tests would run well into six figures. Further unfunded progress on the project was made within the EPECentre, at a slow pace, until the Stakeholders in Methyl Bromide Reduction (STIMBR) Primary Growth Partnership (PGP) incorporated a small project section to take things further in 2011-2012. In the intervening time the problem of how to measure and control the Joule heating process had been considered in some depth and many new ideas had been conceived, some of them having been implemented.

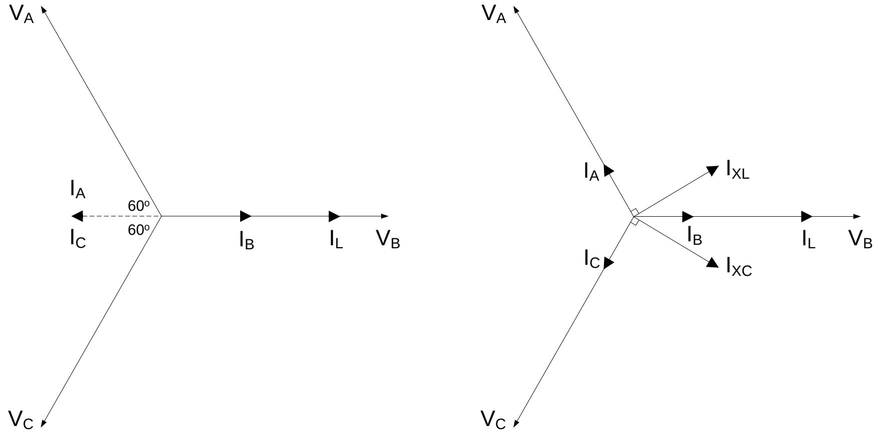

Figure 3. Phasors for unbalanced case (left) and balanced case (right)

4. Implementation of medium-scale laboratory design

Under the STIMBR PGP around 20% of the estimated budget for the full-sized log tests was made available, although the requirement was still to prove that full-sized logs could be successfully Joule-heated. The hire of large equipment was out of the question and the instrumentation budget was severely restricted. Nevertheless a log test fixture, a pair of electrodes, an electronic controller for automating the HV laboratory's FR, and some novel current instrumentation had been designed and part-constructed in the meantime and were able to be completed during the PGP. The intended wireless temperature sensor network was beyond the restricted budget and battery-powered low-cost thermocouple data loggers were employed as a substitute.

The two major drawbacks to this approach were the FR power limit of 100kVA (i.e. an order of magnitude down on that estimated) and the inability to view the temperature at various log locations in real-time during live tests. A simplified schematic diagram of the test set-up constructed is shown in Figure 4. The transformer is rated at 200kVA, while the FR can operate within the maximum output constraints of 100kVA, 400V, 500A.

As a result of the reduction in the available power, the maximum excitation was dropped from 33kV to about 11kV, with the expected maximum log current dropping from about 30A to about 10A. The log test fixture is capable of heating logs with Large End Diameter (LED) up to 500mm and lengths up to 3.5m (extendable in the future), and is shown in Figure 5.

The purpose built Data Acquisition System (DAS) recorded relevant current and voltage data throughout the tests, with a Fluke 435 Power Quality Analyzer (PQA) providing a second independent set of measurements and energy totalization.

The FR Controller was set to raise energization potential to the adjustable desired start level and then automatically control the primary current between adjustable upper and lower limits (by varying the primary voltage), while measuring the real power and total energy supplied to the primary of the transformer. In this way, the maximum possible power could be supplied to the log without exceeding the transformer's rated voltage or current, or the FR's rated current or power. When a pre-settable energy total was reached the controller would automatically lower the voltage to zero and terminate the test. (Note that although *P. radiata* logs have been found to be purely resistive (at 50Hz), the real, rather than apparent power measurement carried out by the FR controller allows for transformer magnetizing current).

Test logs were sourced from a Canterbury forest and brought to the HV laboratory where they were Joule-heated within a few days of felling.

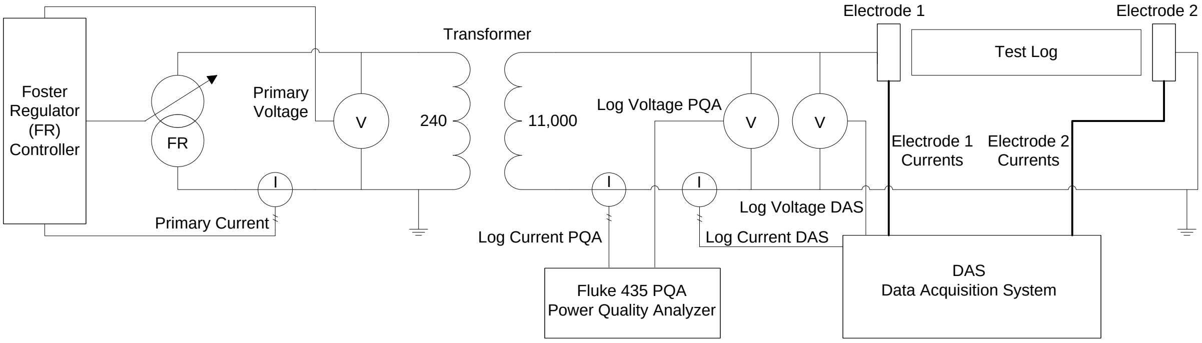

Figure 4. Simplified system schematic diagram, showing Foster Regulator, Transformer, Electrodes and related instrumentation.

Figure 5. Log test fixture in HV laboratory

5. Results from medium-scale laboratory design

Test logs were pre-drilled with 10 thermocouple temperature sensing locations, arranged as shown in Figure 6. The first sensor is at the geometric centre of the log, with the other nine sensors distributed in three 120^{o} rings, 100mm below the surface. Electrical and thermal measurements from a two stage test on a typical 0.5m^{3} log are shown in Figures 7 - 10. In the first stage of the test (Figs. 7 & 8), 22kWh is supplied over 19 minutes, with all the temperatures rising from the initial 16^{o}C ambient during the application of power.

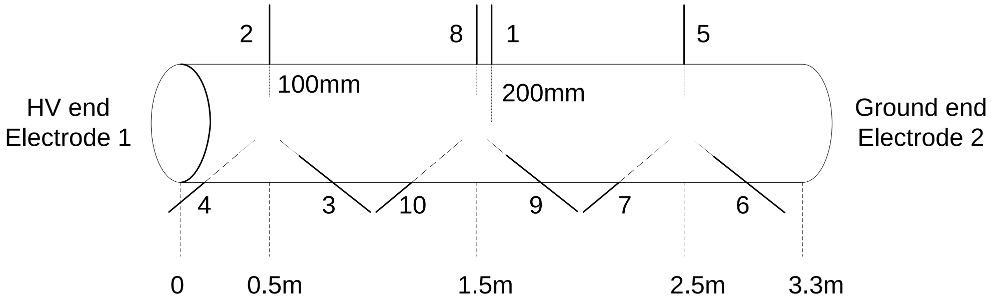

Figure 6. Temperature sensing locations in 3.3m long logs

The FR controller initially ramps the applied voltage up to 11kV (HV side). The current begins to rise as the log starts to heat and its resistance falls, until the HV current reaches the upper set-point of 9A (corresponding to about 95kW). The FR controller then reduces the applied voltage to 9kV, at which point the current upper set-point is raised to 11A and the power can rise to about 98kW. Thus the controller gets the maximum possible power out of the FR into the log without overloading any equipment. It can be seen that the FR current limit of 500A (about 11A on the HV side) eventually limits the power that can be supplied to the falling resistance of the log (initially over 2kΩ, falling to about 530Ω).

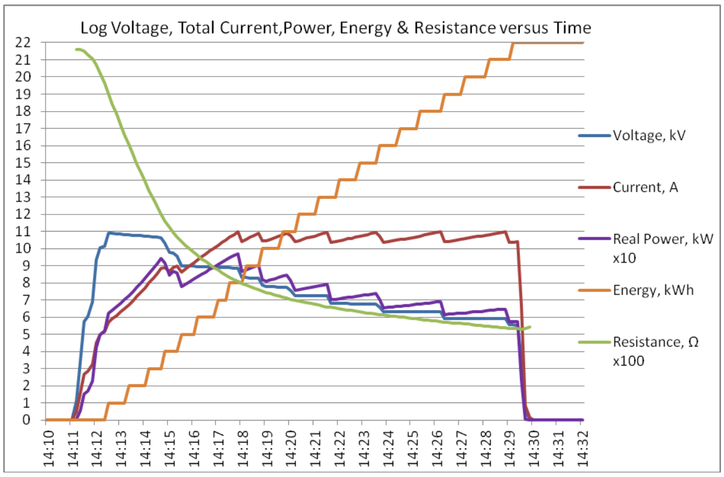

Figure 7. Electrical Data, Stage 1

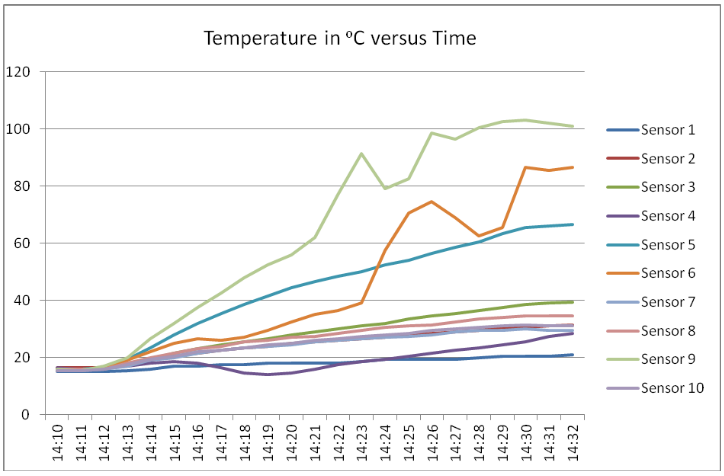

Figure 8. Temperatures, Stage 1

50 minutes after the end of Stage 1, temperatures ranged from about 25^{o}C at Sensor 1, to between 33 and 85^{o}C at the other 9 locations. A second injection of 22kWh was then initiated. This test took about 30 minutes, as the FR current limit into the still-falling log resistance restricted the power level to less than 65kW, as shown in Figure 9. The resistance had climbed back to about 580Ω during the rest period, subsequently falling to about 330Ω by the end of Stage 2, by which time all temperatures were close to reaching ISPM 15 levels, with the exception of the geometric centre of the log, which was still slowly warming.

It is important to note that although all the electrical data were visible in real-time, the temperature readings were not available from the data loggers until after all logging was complete. The data shown in Figures 8 & 10 have been aligned with those in Figures 7 & 9 after the fact, due to all instrumentation being equipped with synchronized real-time clocks. Finally the complete temperature data, including over six hours of cool-down period, are given in Figure 11. The first and second heating periods can clearly be seen, as can the elevated temperatures experienced by sensors 5, 6 & 9. The long time constant of sensor 1 (geometric centre) can also be seen, but all ten sensors exceed ISPM 15 temperatures simultaneously for over 5 hours.

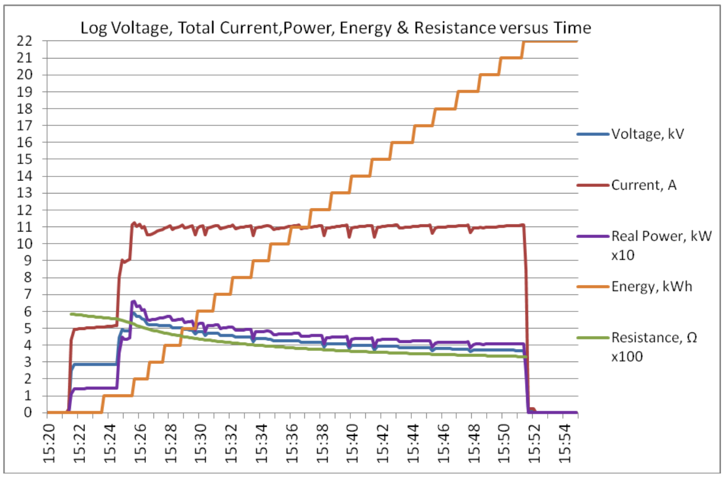

Figure 9. Electrical Data, Stage 2

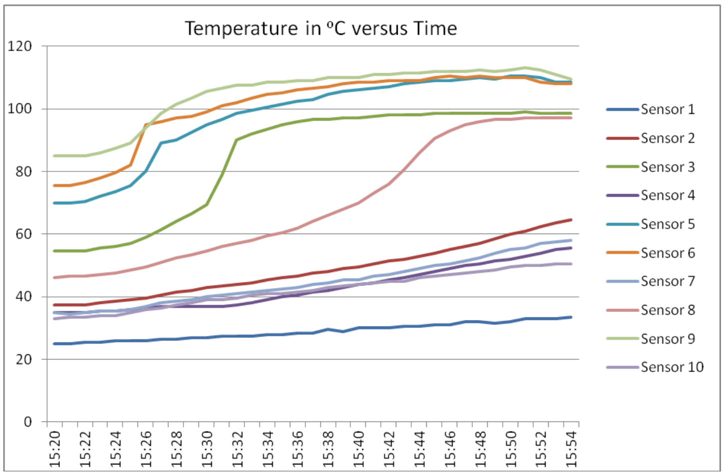

Figure 10. Temperatures, Stage 2

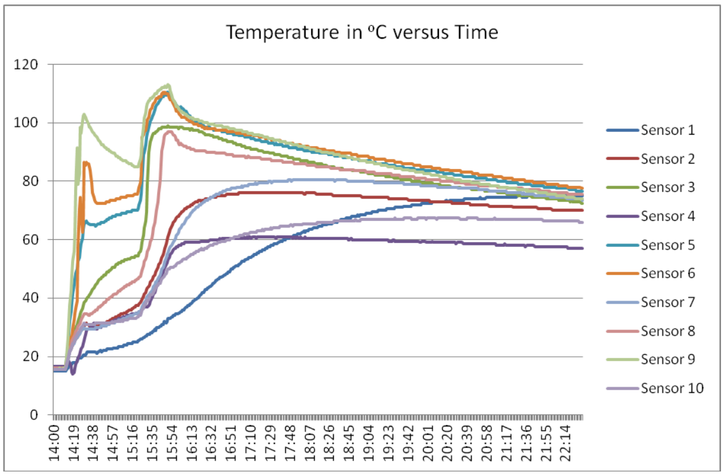

Figure 11. Temperatures, Overall

6. Further technological challenges

The energy injected into the typical test log described was about twice that calculated to be necessary to raise the log temperature by 50^{o}C. Calculations based on various timber densities and moisture contents have been made and have also been compared with the recorded data from tests described in section 2. These calculations lead to the belief that the use of insufficient power (100kW vs. 1MW) results in a great deal of additional convection, radiation and evaporation losses to ambient due to the greatly extended test duration. Two solutions are possible: Increase power by an order of magnitude, as originally mooted; build an insulated, humid, “hot-box” environment to reduce losses (or both).

Although temperature measurement (unless by non-invasive means, such as IR thermometry, which has been extensively tested, but is of limited use) will not be possible in production, real-time visible measurements during testing are essential, as also originally mooted. Additional instrumentation has already been designed, constructed and partially tested, to enable correlation of other physical parameters, measurable non-invasively, to temperature rise. Further instrumentation is also under development and applied research on the electrical and thermal conduction mechanisms in timber is ongoing. This is not reported here.

Although ISPM 15 requirements have clearly been met, questions remain as to the effect on timber properties that may be caused by Joule heating. Studies are also ongoing in this area.

7. Envisaged wharf-based machine

Evidently any production Joule heating system would need to be designed to have the lowest possible electricity costs and the minimum of log-handling. Preferably the electricity source would also be demonstrably carbon-neutral. At electricity costs of around $0.08/kWh the process appears to be commercially viable, although a full study of machine cost has not yet been carried out.

Current thinking is that a likely electrical solution will involve a high power factor rectifier supplying a well-filtered DC bus, from which multiple single phase inverters simultaneously control the power into multiple logs in such a way as to provide a constant load factor (e.g. incoming log power ramps up as outgoing log power tapers off, replicated multiple times, with varying phase). This common DC bus could be at LV, with modified motor-drive inverters used to excite multiple single phase transformers (necessitating approximately sinusoidal modulation). A simplified electrical circuit for such a solution, in which pairs of three phase IGBT bridges are controlled as three single phase inverters, with 120^o phase shift between each, all fed from a 12-pulse rectifier-supplied DC bus, is given in Figure 12.

Alternatively an HV common DC bus could be used, in which case multi-level, or two-level, square wave modulation could be used. In either case, using a centre ground on the HV side would be a good standard to adopt, to minimize the absolute potentials in the system.

Many other solutions are possible, including multiple phase-controlled three phase thyristor bridge rectifiers which could provide reversible DC excitation.

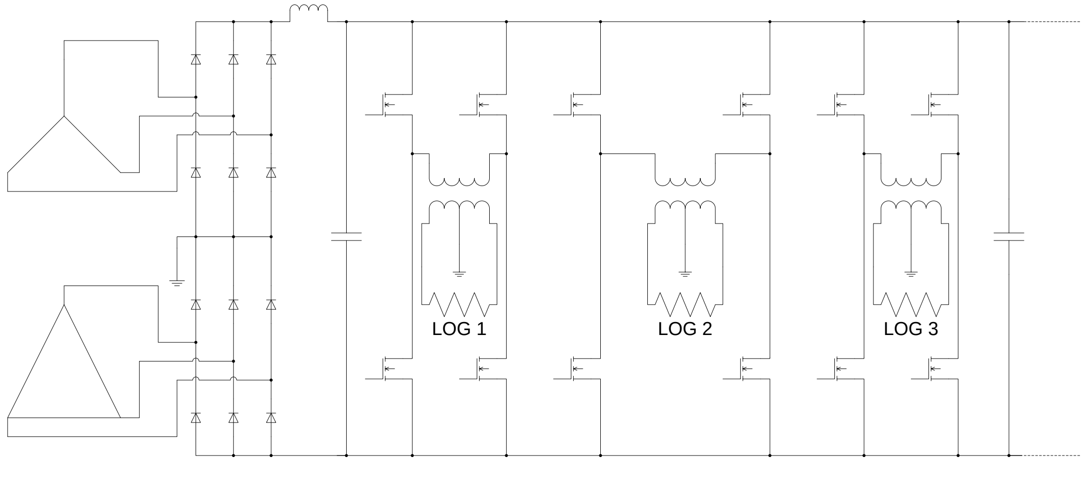

Figure 12. Simplified example of electrical power circuit for multiples of three logs

From a log-handling viewpoint an **n**MW machine would be capable of a throughput of about 210**n** typical logs (~0.6m^3) every 3.5 hours. (This is to ensure that the centre of each log has reached the required temperature before emerging from the machine).

As an example, a 1MW machine could be housed in an insulated enclosure approximately 20m long, by 8m wide, by 6m high. This would be scaled up for machines greater than 1MW.

n logs would be loaded into the machine every minute and have a cycle time inside the enclosure of 3.5 hours. i.e. 3.5 hours after the first log is loaded, logs emerge continuously at the rate of **n** logs per minute.

In the case of a 1MW machine, 7 horizontal conveyors would be stacked one above the other, with logs fed in at the top left of the machine, as shown in Figure 13 below.

The top, 3rd and 5th conveyor down would move logs from left to right and would drop them onto the 2nd, 4th and 6th conveyors (which move logs from right to left) respectively.

The 6th conveyor would drop the logs onto the 7th (bottom) conveyor which would move them from left to right and deliver them fully treated from the bottom right of the machine.

When full the 1MW machine enclosure would hold 210 logs, with 30 on each of the 7 conveyors.

At the 10th position from left on the top, 3rd and 5th conveyors down, energy would be applied to each log, as it passes that point. In this way the log has 1 hour between the first and second and between the second and third heat injections, and a further 1 hour and 20 minutes before leaving the machine. This would allow ample time for heat-soak to occur throughout the log between injections, avoiding excessive hot-spots during any injection and ensuring internal ISPM 15, or similar phytosanitary regime, compliance for all the timber.

The conveyors could be arranged to roll the logs as they travel, ensuring even convection, while the enclosure would be thermally insulated with recirculation fans and humidity control (RH just below condensation to minimize evaporation). The losses from the first few logs would probably be sufficient to "prime" the heat and humidity requirements (e.g. air temp 60 to 65°C, RH 90 – 95%).

This would ensure that the bark/outside of the log meets ISPM 15, or similar, requirements.

Condensate removed by dehumidification could be used for some other co-located process and/or, after leaving the enclosure, the logs could be used as the input source to a heat exchanger for a co-located process (e.g. milk processing).

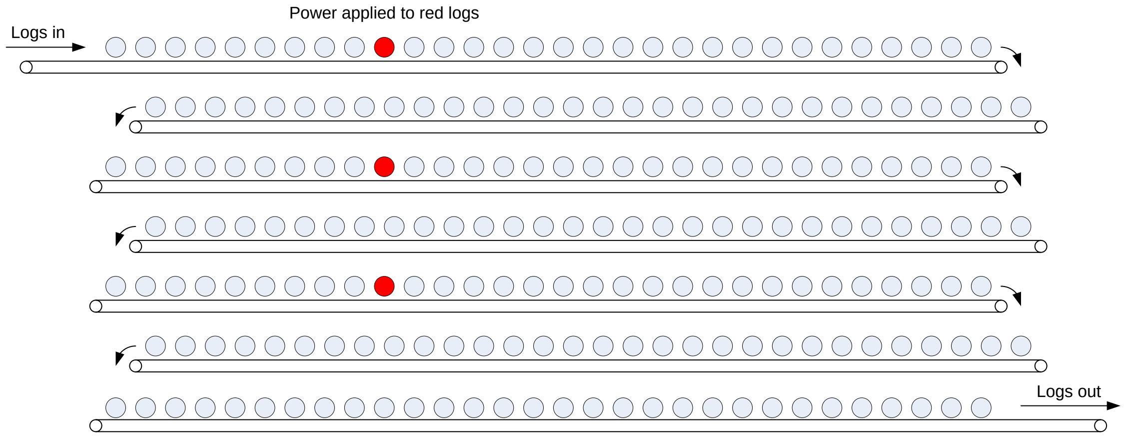

Figure 13. Conceptual diagram of a 1MW system, holding 210 logs on 7 conveyors, with a throughput of 1 log per minute

9. Conclusions

Joule heating of *P. radiata* timber has been shown to have merit as a potential sterilization method for export logs. Laboratory tests show that phytosanitary standards can be met for full-sized logs, at a reasonable electricity cost. Novel instrumentation to improve process control has been constructed, with further instrumentation and control techniques under development. A great deal has already been done with very little funding. Work on improved understanding of the relevant timber physical properties is underway as part of an ongoing Scion-STIMBR-MBIE programme. Interest from electricity generators and electrical equipment/machinery manufacturers will be welcomed.

10. Acknowledgements

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The author would also like to acknowledge MAFBNZ (now MPI), Stakeholders in Methyl Bromide Reduction and the Primary Growth Partnership for supporting this work during the various phases.

11. References

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