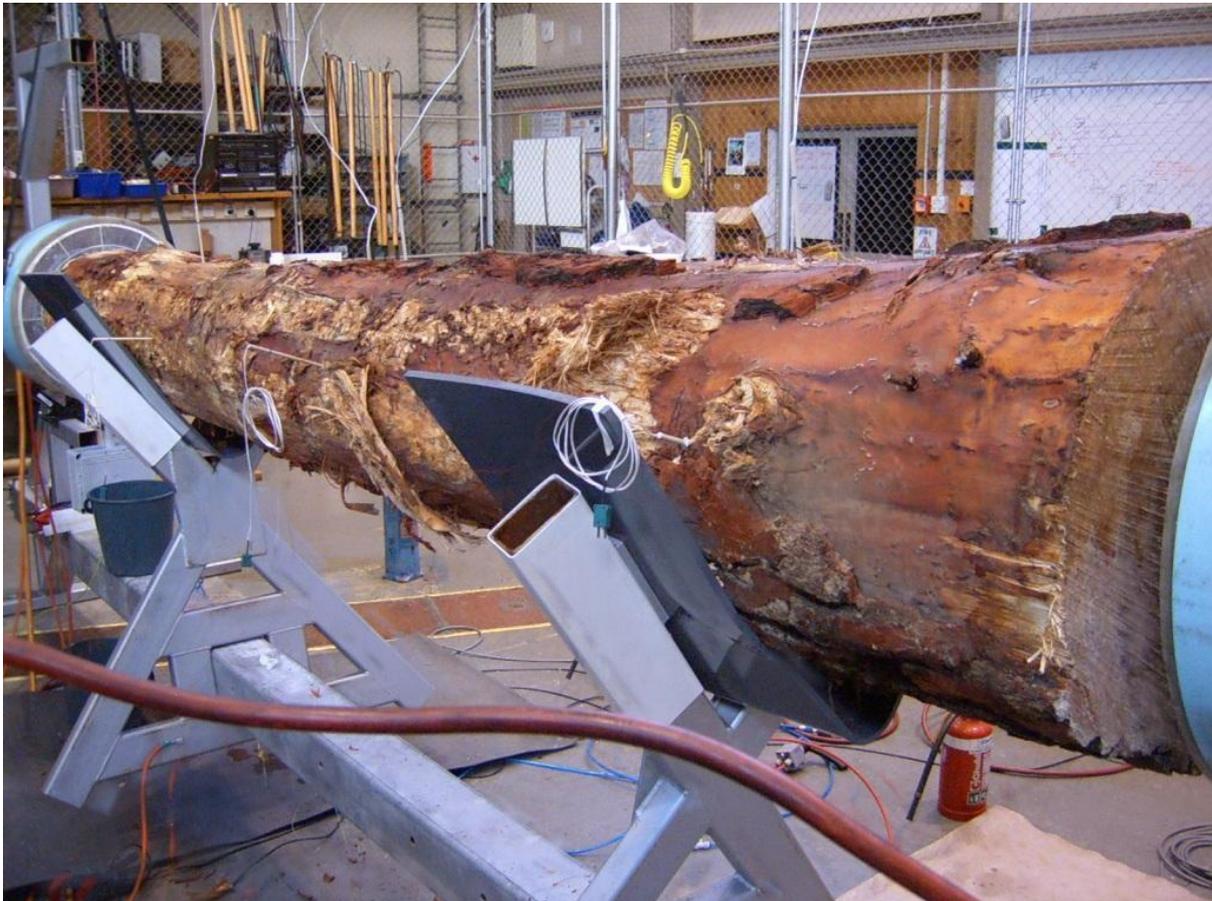


## Practical Application of Joule Heating to the Sterilization of *Pinus radiata* Logs



A research and development study carried out by the EPECentre for the Stakeholders in Methyl Bromide Reduction (STIMBR) Primary Growth Partnership (PGP) in 2012, under project section 1.5.2.

This report contains confidential information concerning concepts and techniques that are the subject of patent applications by the University of Canterbury.

WJB Heffernan, Electric Power Engineering Centre, University of Canterbury, February 2013



## Summary

Following initial feasibility work in 2007 [1] and a MAFBNZ funded project in 2009 [2], the Joule heating concept for log sterilization was incorporated into the STIMBR PGP project as section 1.5.2. This report details the construction, commissioning and testing of the log sterilizing apparatus which had largely been conceived and designed by the EPECentre before the start of this project.

The procedure for sterilizing test logs is described and the results obtained with two such logs are presented and discussed against the objectives of section 1.5.2. Finally suggestions for further work, refinements to the system and tests to fill gaps in current knowledge are proposed, including the author's current impression as to how a wharf-side machine might operate.

Tests on the first log show that after treatment all measured locations in the timber exceed 56°C for over 5 hours. Tests on the second log show that after treatment all measured locations in the timber exceed 56°C for over 8 hours and 70°C for about 3.5 hours. In both cases this includes the geometric centre of the log.

These tests, therefore, show that Joule heat sterilization undoubtedly can work.



Joule heating process (clockwise from top left): Log being lowered into place; Thermocouples inserted into log; Power applied to log (note covers to reduce heat & moisture loss to ambient); Pair of logs after sterilization (note lack of apparent damage to end of logs).

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## 1. Introduction

This work follows on from a brief initial investigation made at the EPECentre in 2007 to the applicability of Joule heating as a log sterilization method, using fence post sized timber [1]. The idea was originally suggested by the Ministry of Agriculture and Forestry Biosecurity New Zealand (MAFBNZ) who subsequently funded an EPECentre project to devise and cost a method for carrying out heating trials on full sized logs [2].

While [2] proposed the use of a three phase 2MVA generator, to enable powers of up to 1MW to be supplied to the log, for the work reported here a scaled down system was designed and implemented using the available single phase 100kVA power source in the High Voltage (HV) Laboratory at University of Canterbury (UC)<sup>1</sup>.

The report begins by outlining the apparatus required for the Joule heating trials, including both purpose designed and built equipment and off-the-shelf products, in section 2. This is followed by details of the equipment testing and calibration carried out, in section 3, prior to describing the sourcing of suitable test logs in section 4. The test procedure followed, along with the rationale behind it, is given in section 5. Section 6 presents and discusses the test results obtained, with a brief investigation into the timber properties after all tests were completed detailed in section 7. In section 8 the overall results achieved are compared with the objectives of the project. Conclusions are drawn in section 9 along with a discussion of the limitations of the work described, suggestions for further work and ideas for future consideration or implementation. The report concludes with a statement of the timeline of IP developments related to the Joule heating implementation technology, acknowledgements and references, in sections 10, 11 and 12 respectively.

The work clearly shows that the requirements of ISPM-15, or similar regimes, can almost certainly be met by this method, for at least some logs. Not yet determined are what effects may be caused to timber quality, particularly if localized overheating is allowed to occur, and what surface temperatures can be achieved in a “hot-box” environment rather than an “open to atmosphere” set-up.

<sup>1</sup> The reason for this order of magnitude power reduction was that the cost of the generator and associated equipment hire was well beyond the available project budget.

## 2. Equipment employed

### a. Available existing equipment

The High Voltage (HV) laboratory at the University of Canterbury (UC) has a 100kVA single phase variable voltage source, known as the Foster Regulator (FR). In fact the voltage is variable from 0 to 400V AC, 50Hz, with a maximum current capability of 500A and a maximum power envelope of 100kVA. (In other words, by way of example, it is not possible to draw more than 250A at 400V for a sustained period).

In addition there are three single phase 200kVA transformers capable of stepping up the voltage from 240V to 11kV, with a maximum HV current of about 18A.

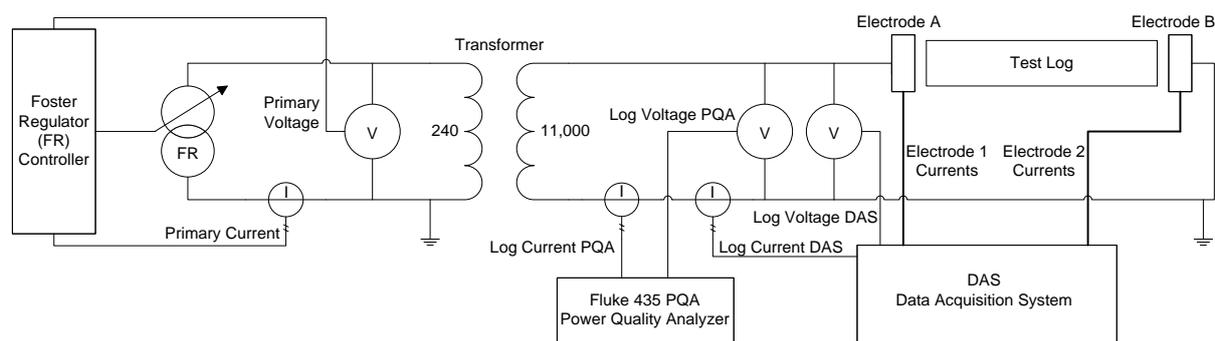
Previous work had indicated that for 1MW of maximum power into a full sized log (6m by 350mm), roughly 33kV at 30A would be required. Thus, with only 100kVA available, roughly 10.5kV at 9.5A would be appropriately scaled figures. This is achievable with a single transformer and was the approach taken for the work reported here.

By reducing the length of the log under test, the voltage gradient (kV/m) could be adjusted to give full current of 30A if required. However this would require at least two transformers with their secondary (HV) windings in parallel (and actually all three transformers with secondaries in parallel and primaries in series to deliver the full 100kVA at 30A). Implementation of such higher current, lower voltage tests across shorter log sections may be carried out in future.

The FR has a manual control console from which the supply voltage can be controlled by the combination of a remote circuit breaker and raise and lower buttons and from which the supply current can be measured.

Equipment suitable for measuring and real-time logging of the applied voltage, total current, power and energy was already available within the EPECentre (Fluke 435 Power Quality Analyzer (PQA)).

The diagram below shows the simplified schematic diagram for the full system.



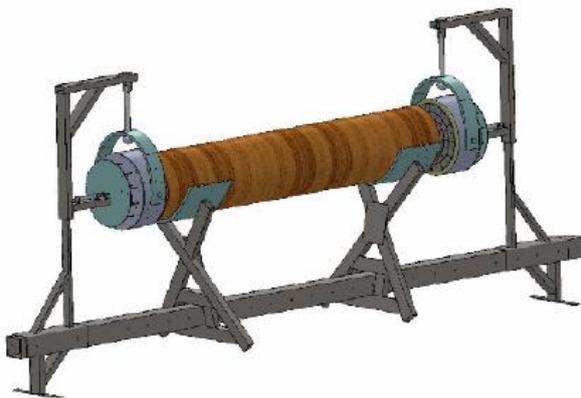
**Simplified system schematic diagram, showing Foster Regulator, Transformer, Electrodes and related instrumentation.**

## b. Equipment designed and built

To enable tests to be carried out a number of pieces of equipment needed to be designed and built, as described below:

### Test fixture to hold logs (insulated from ground).

Due to space constraints in the HV laboratory this was designed to hold logs up to about 3.5m in length, rather than 6m. It could be extended later if necessary. The fixture includes a mounting arrangement for the electrode assemblies and a compressed air driven system for applying the electrodes to the log ends with controlled, adjustable pressure. This fixture was designed by Luke Tough, a 3<sup>rd</sup> professional year student, working under the direction of David Healy (the Department of Electrical Engineering workshop manager) and the author. The fixture is constructed from galvanized steel, with PVC insulated log supports, capable of withstanding 33kV. It incorporates coarse log length adjustment (electrode “gibbets” are movable), height adjustment for electrodes (depending on log diameter) and pneumatic rams to apply the electrodes to the log ends with controllable pressure.



**Adjustable Test Fixture (left to right): Conceptualization; Realization - note PVC insulators, coarse length adjustment, electrode height adjustment and pneumatic rams.**

### Pair of electrode assemblies rated to at least 11kV AC rms<sup>1</sup>.

The assemblies incorporate 30 contact segments and current transformers (CTs) to allow individual segment current monitoring. This helps to provide evidence of a good log contact and some data regarding current distribution at each end of the log. A considerable design and test effort (including a 3<sup>rd</sup> professional year student project by Luke Tough, further input from David Healy and input from Jac Woudberg and Professor Pat Bodger) went into the design of the electrodes and CTs, resulting in a design capable of withstanding in excess of 33kV AC rms, in a laboratory environment. (In a real industrial application a test voltage of around 1.5 to 2 times the rated voltage would be required, but the current electrodes should be reliable with a 33kV centre ground system). Each electrode has 30 equal area segments arranged to monitor current in different sections of the log end and is designed for log diameters up to 500mm.

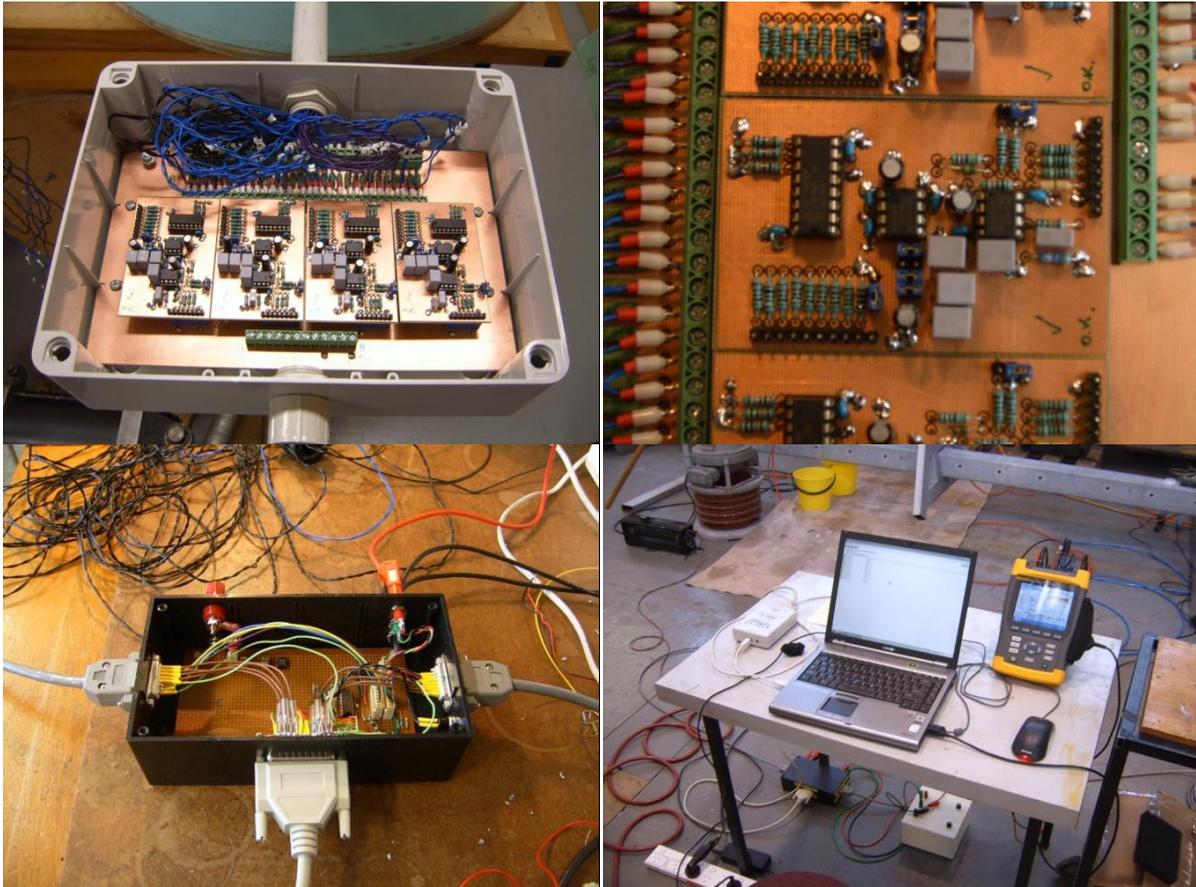
<sup>1</sup> IP in process of being protected by UC



**Electrode assembly (clockwise from top left): Components (note segmented electrodes); Part assembled (note GRP insulators and insulating trays); CTs inserted; insulating spacers fitted, prior to back contact plate attachment.**

#### **Data Acquisition System (DAS) to condition and record CT signals.**

This had to handle inputs from 60 CTs and log the real-time data to a host computer during the tests. The resulting data could then be synchronized with the overall power and energy readings. Each electrode has four amplifier/multiplexer boards, hosted by a mother board. Each amp/mux board takes up to 8 CT inputs and passes a true rms dc representation of the measured current to the address generator/concentrator which passes this and the address data to the analogue to digital converter (ADC). The Full Scale Range (FSR) of the ADC is 2.5V. The CT amplifiers have two gain settings: 1V/A (i.e. FSR is 2.5A) or 0.5V/A (i.e. FSR is 5A). Digital data from the ADC are logged by software running on a host laptop computer. The address generator/concentrator was also fitted with true rms circuits for both total log current and electrode potential difference. The former accepts an input from a 10mV/A Fluke CT, while the latter is fed by the output of an ABB 33kV:110V Potential Transformer (borrowed from Connetics). The current circuit feeds the ADC with a signal of 100mV/A (i.e. FSR of 2.5V represents 25A AC rms of total log current). The voltage circuit feeds the ADC with a signal of 200mV/kV (i.e. FSR of 2.5V represents 12.5kV AC rms across the electrodes).



**Data Acquisition System (clockwise from top left): CT Amplifiers/Multiplexers in electrode extension housing; single Amplifier/Multiplexer board; Multiplexer Address Generator/Concentrator; Data Acquisition System in situ (ADC to left of laptop)**

### **Foster Regulator (FR) control system.**

Experience with fence post sized timber had shown that manual control of the FR was not ideal and did not allow precise control of applied power, current or total energy. Hence a closed-loop automatic system was devised and implemented in which the maximum power, maximum voltage, maximum current and total energy could be programmed. The operator would then have only to press a button to start off an automated test. The controller measures the FR output voltage using a potential divider and the current using a CT. These signals are fed together into an analogue multiplier, to give a real-time real power signal, and also individually into two true rms circuits to give dc representations of voltage and current level, which are used to control the maximum applied voltage and current. The active power signal is integrated to give a resettable cumulative energy signal, which is used to terminate the test. Due to the limitations of the FR and the HV transformers it drives, the FR controller was set up to use current as the control parameter, but it can be altered to control on constant power instead. In fact control is by the dead-band method, such that when the current reaches the top of the dead-band a solid state relay (SSR) output reduces the FR voltage until the current falls to the bottom of the dead-band. If the current falls below a reset threshold the voltage can again increase.

The various ranges of voltage and current allow maximum real powers between 10kW and 200kW to be catered for. The various integration time constant ranges allow total energies between 0.5kWh and 40kWh to be injected in a single application (of course, multiple consecutive applications allow this to be increased indefinitely).



**Foster regulator controller (left to right):** Close-up showing current and voltage range selectors, voltage, current and energy set-point adjusters, integration time selector etc. Controller in situ with FR (to left) and meters for voltage, current, power and energy.

### Electrode to log interface system.

In order to get a good electrical contact between the aluminium electrodes and the log end-fibres, a conductive pad system employing open cell foam impregnated with an electrically conductive gel (made in-house and referred to as “synthetic sap”) was developed.

Ideally the foam would be conductive in the longitudinal direction only. This will be tried in future tests by segmenting the foam in the same pattern as the electrodes. At this stage though the impregnated foam is equally conductive in all directions, allowing some cross-conduction between segments.



**Conductive Pad system (left to right):** Foam pad in “paddling pool” with “synthetic sap” (not made by Resene!); Pad in situ between electrode and log.

### c. Equipment purchased

It was desired to be able to record the temperature at various locations within the log, both during application of power and in the equilibration and cool down period afterwards. Ideally a wireless system would have been employed to allow real-time viewable data to be captured (each temperature sensor is at a different, hazardous voltage during power application and must therefore be isolated from everything else). In the absence of a budget for this, 10 low-cost USB thermocouple data loggers were purchased, with Type K thermocouples. These were capable of recording time-stamped temperatures every second, enabling the real-time temperature distribution to be reviewed after the fact, but not live during the test. This was a major limitation of the instrumentation. Each logger is powered by its own battery and the thermocouples were inserted in Alumina thermo-wells to insulate the metallic thermocouple from the wood. 20 of these thermo-wells were supplied as free samples from the UK, but are normally around \$90 each. As it proved impossible to retrieve them from the logs after testing a low cost alternative, based on heat forming our own thermo-wells from high temperature thermoplastic tubing, was devised. At this point such thermo-wells have been made but not yet tested.



**Thermocouple Instrumentation (clockwise from top left): 4 of the 10 USB loggers; test log showing thermocouple locations (after successful sterilization); close up of two thermocouples at different depths; arrangement used to keep thermocouples and loggers isolated from each other during testing.**

### 3. Equipment testing and calibration

Each of the 60 CTs (30 in each electrode), their amplifiers, the concentrator and the ADC were bench tested before assembly and an accuracy of better than  $\pm 1\%$  of reading at 1A (and  $\pm 2\%$  of reading at 2.5 and 5A) was achieved, versus a calibrated reference instrument.

The electrodes have been designed to withstand flashover to above 33kV AC rms. Nevertheless it is prudent to test the insulation resistance and leakage current of the whole unit after assembly before putting them into service. Tests at 5kV AC rms showed a leakage current of around 20nA (insulation resistance of about 250G $\Omega$ ).

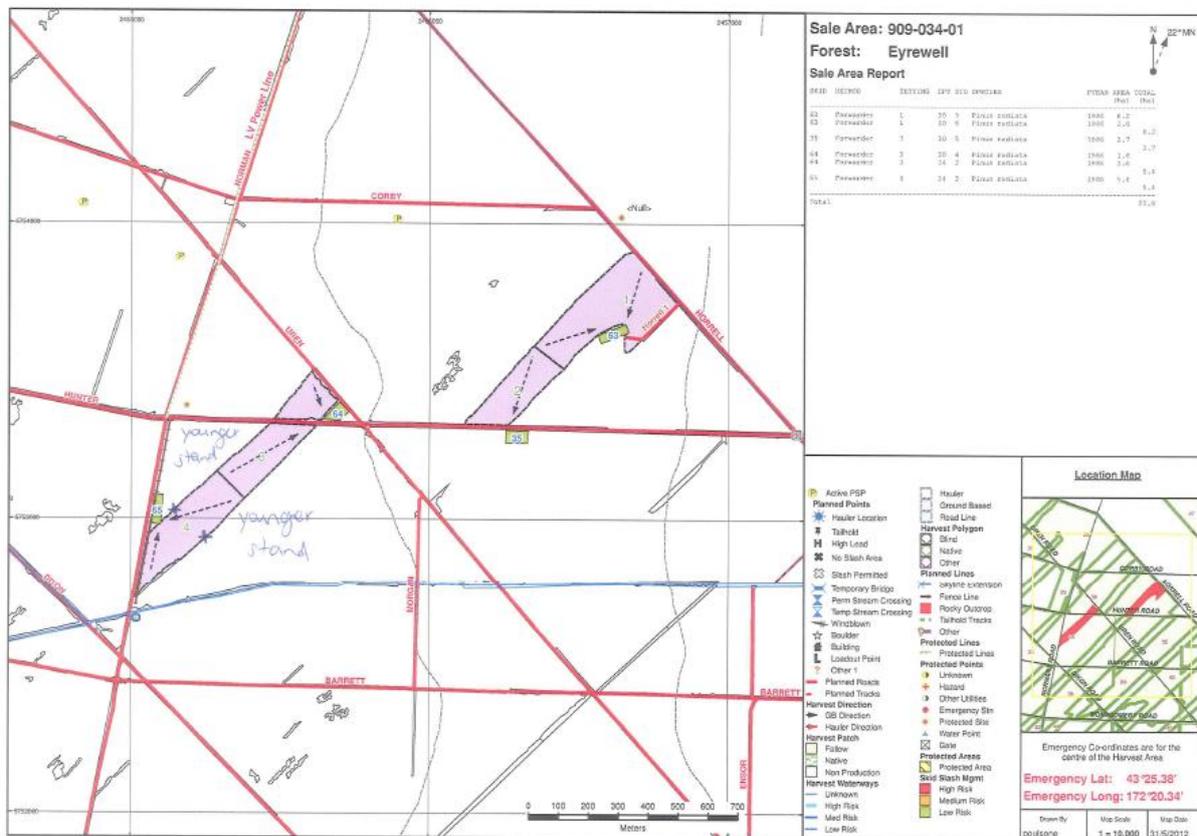
The readings of the total log current sensor and electrode potential sensor in the DAS were measured against the readings from a Fluke 435 Power Quality Meter with independent sensors (Fluke CT and Tektronix 1000:1 'scope probe). This was carried out for electrode potential differences between 1kV and 11kV and for secondary currents between zero and 11A. All results were within  $\pm 2\%$  of reading. The readings from the meters attached to the FR controller were also calibrated against reference primary voltage and current instruments. However their absolute accuracy is not critical to the results, as the HV side measurements (directly applied to the log) are always used, whereas the LV side current measurements include transformer magnetizing current and are just used to set desired test parameters.



**Test & Calibration of instrumentation (clockwise from top left): Bench calibration of CTs and amplifiers at 1A; Hi-Pot testing of electrode assembly at 5kV; Calibration of Fluke 435 versus DAS; Calibration of FR controller**

#### 4. Sourcing of test logs

Test logs were provided from the Eyrewell forest by Rayonier Matariki Forests. A visit was made to the forest, two stems were chosen, felled, limbed and 3.3m butt logs loaded onto a trailer. Since the electrodes had been designed for logs up to 500mm in large end diameter (LED) it was desired to make as full a use as possible of the electrode segments. As most of the trees were rather small this resulted in the choice of two “edge of stand” trees located as shown below. As also shown, the trees were 26 years old. All tests were carried out on these two logs within 17 days of felling (Felled May 14<sup>th</sup>, last test May 31<sup>st</sup>).



#### Provenance of test logs

## 5. Test procedure

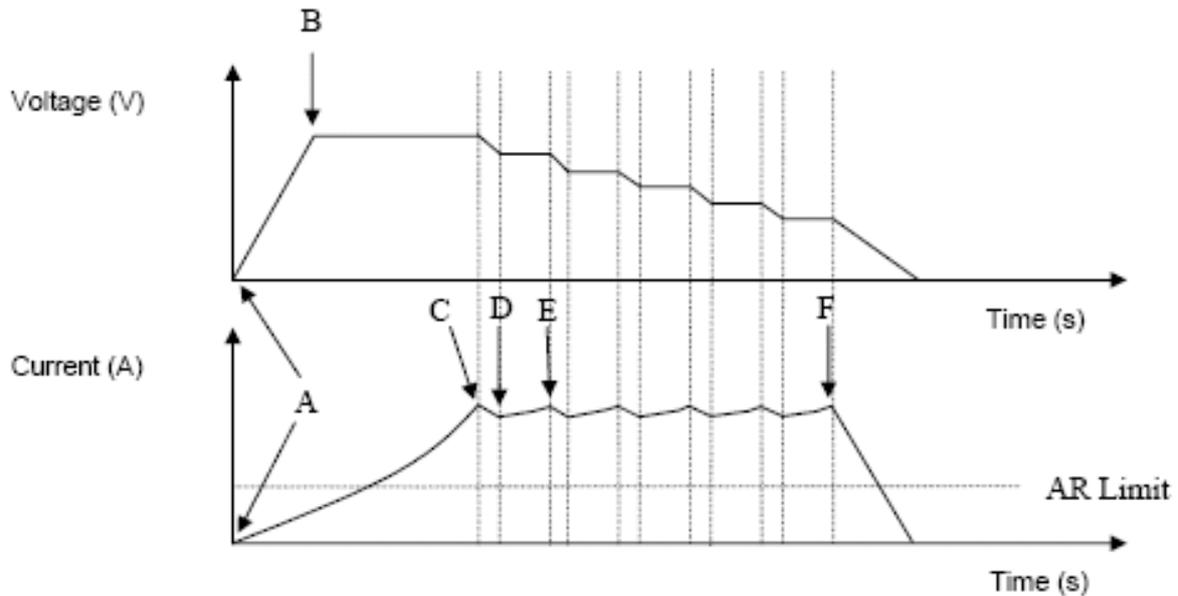
Before testing, each log was drilled in 10 locations, to allow thermocouples to be inserted. In the first log ceramic thermo-wells (which had been obtained as free samples) were inserted to allow the thermocouples to be insulated from the wood (to avoid the possibility of the conductive stainless steel sheath disturbing the current flow). Unfortunately it proved impossible to extract these from the log after testing, as they were glued in with resin and too fragile to exert any significant extraction force on. This, combined with the high cost of replacements, meant that they were not employed in the second log, such that a record of temperature distribution during power-up could not be obtained). A low cost solution, using high temperature thermoplastic tubing has since been found, but not yet tested.

The rest of the procedure was as follows:

- Lower log onto test fixture and fit thermo-wells, thermocouples and temperature data loggers.
- Apply conductive pads to electrodes
- Operate compressed air rams to force electrodes onto log ends
- Set maximum voltage, maximum current, current dead-band and total energy target on FR controller
- Start data logging
- Energize power system
- Start FR controller

The FR controller automatically increases the applied voltage until either the maximum voltage setpoint is reached, or the maximum current setpoint is reached. (With a cold log it is always the voltage limit that is reached first, as the log conductivity and hence current flow increases with rising temperature).

As the log heats up it becomes more conductive and the current increases until it reaches the maximum setpoint. At this point the FR controller automatically reduces the applied voltage until the current reaches the lower setpoint (maximum value minus dead-band). The log continues to heat, current increases again and the cycle repeats, as shown below. All the while the FR controller measures the applied real power and integrates it to keep a tally of the injected energy total. When this reaches the preset value, the FR controller quickly reduces the applied voltage to zero and the test is complete. (Note that the FR controller could be modified to follow a maximum voltage, constant power scheme, rather than the maximum voltage, constant current scheme used, provided the maximum FR current of 500A is not exceeded and the maximum HV winding current of 18A is not exceeded. However in this case, with maximum power of 100kVA, we were up against the 500A FR limit most of the time).



Example Voltage and Current profiles, versus time, for a typical log. Point A: Test begins, with controlled voltage ramp-up; Point B: Voltage reaches maximum setpoint, while current continues to rise; Point C: Current reaches top of dead-band, triggering Voltage ramp-down; Point D: Current reaches bottom of dead-band, halting Voltage ramp-down; Point E: Same as Point C etc.; Point F: Integrated Energy ( $\Sigma V.A.t$ ) reaches preset limit, causing Voltage ramp-down to zero and end of test.

During the test the following data are being logged:

- Actual applied voltage
- Actual applied current
- Actual applied power
- Actual log resistance
- Accumulated energy supplied
- Individual segment currents for each electrode
- Actual temperature at 10 locations throughout the log (only for the first log)

After the power has been removed the temperature continues to be logged for several hours, in the case of the first log. In the case of the second log, the thermocouples are inserted just after power has been removed and temperatures are again logged for several hours.

## 6. Test results

At least two heating runs were carried out on each of the two logs sourced<sup>1</sup>. The test results show that heat sterilization is possible with this method and that no visible damage was caused to the ends of the logs, as specified in the original project scope.

### Log #1 Data:

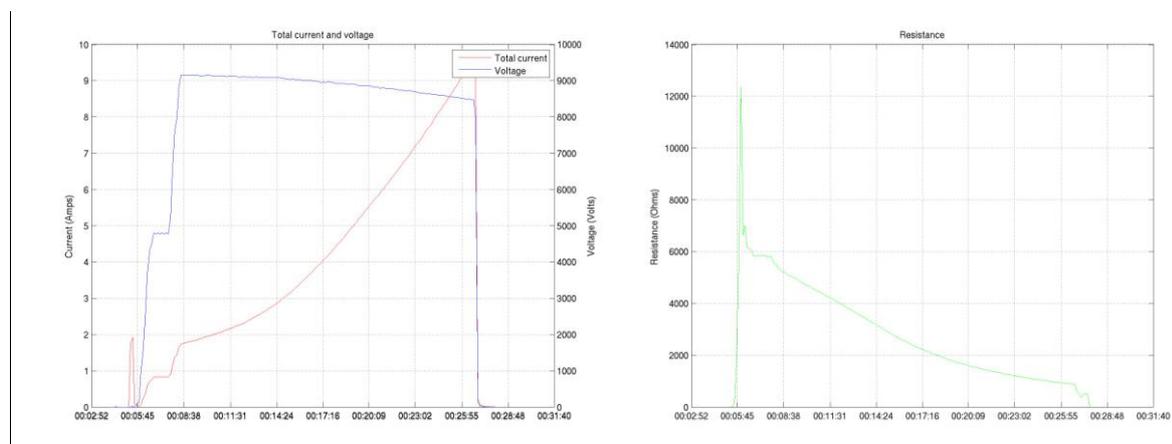
Large end diameter (LED):	approximately 500mm
Small end diameter (SED):	approximately 380mm
Length:	3.3m
Estimated volume:	approximately 0.5m <sup>3</sup>
Estimated energy injection needed for 50°C rise:	approximately 15kWh

### Log #1, Initial test:

An initial test was carried out on Thursday 24<sup>th</sup> May 2012 to validate the test set-up. The following parameters were set on the FR Controller:

V <sub>set</sub> :	200V on primary (approx 9.3kV on secondary)
I <sub>h</sub> :	485A on primary (approx 10.6A on secondary)
I <sub>i</sub> :	475A on primary (approx 10.4A on secondary)
I <sub>rst</sub> :	250A on primary (approx 5.5A on secondary)
E <sub>set</sub> :	15kWh

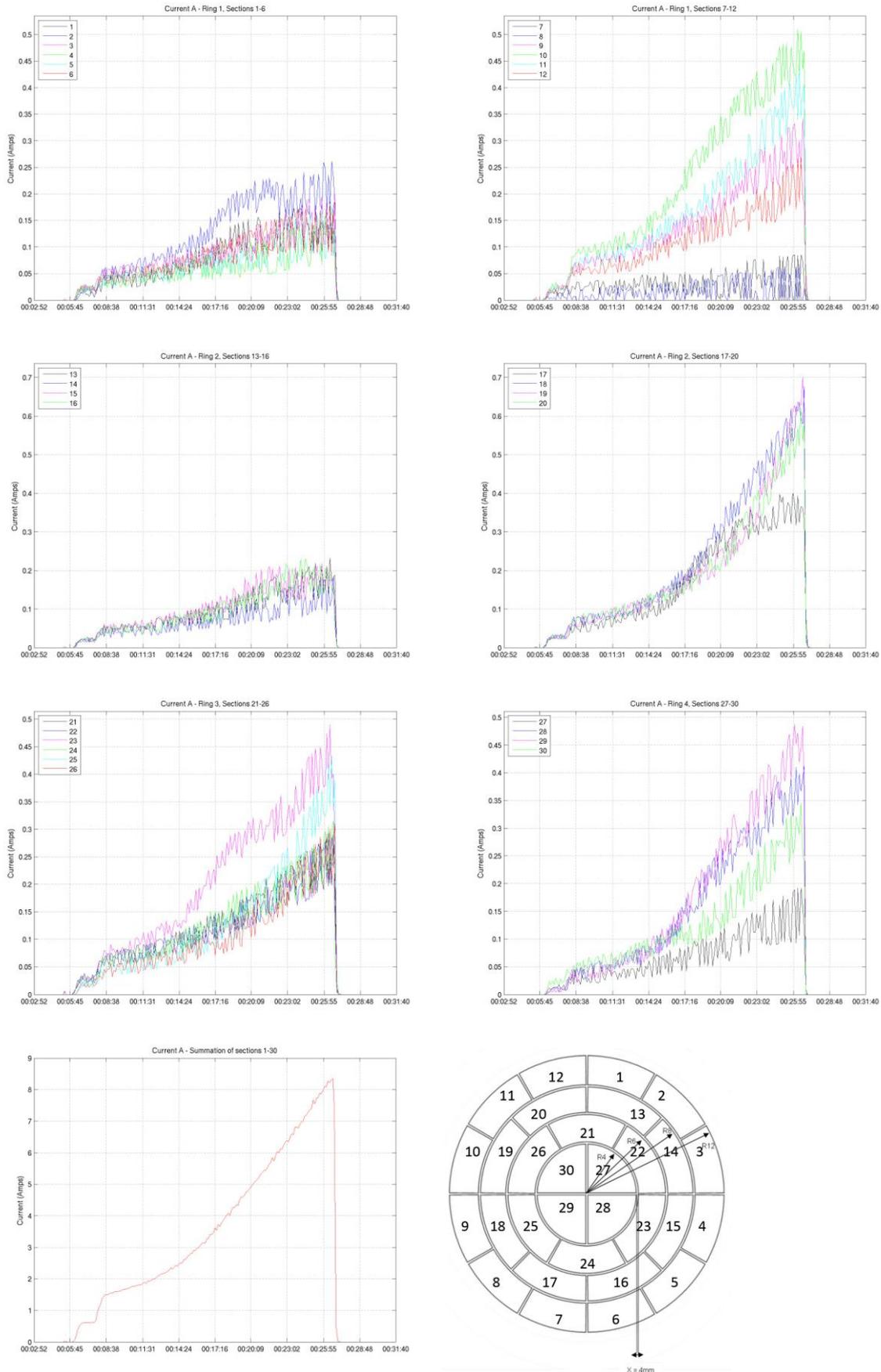
Initial log voltage was about 9.3kV – a step at about 5kV is seen in the DAS results, due to the operator checking that all was well at the lower voltage before enabling full voltage. Once full voltage was established, initial log current was about 2A, rising to about 10A after about 20 minutes. The power being delivered increased from about 20kW to 90kW over the same period. The log voltage fell to about 8.5kV as the current increased, due to increasing voltage drop across the transformer and cable impedances at higher currents. After 20 minutes about 14kWh had been delivered to the log and the test was terminated, although the current set point had not yet been reached. Had more energy been supplied to the log, current control would have kicked in. The reason for the increase in current and hence power delivered, over time, is that the log's resistance falls as it heats. In this case, once the voltage has reached its full value, the resistance falls from about 6kΩ to about 1kΩ. These measurements from the DAS are shown in the graphs below.



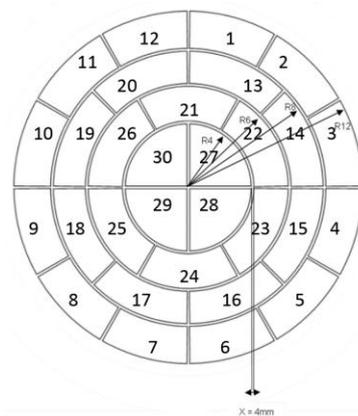
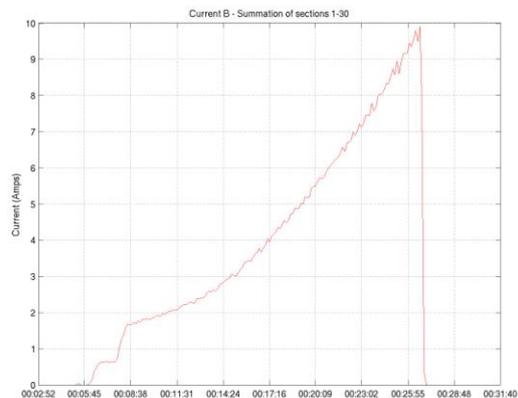
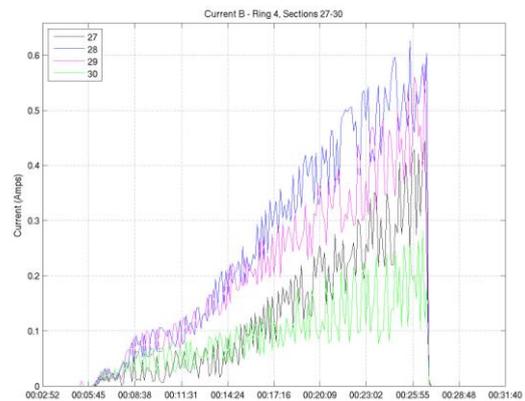
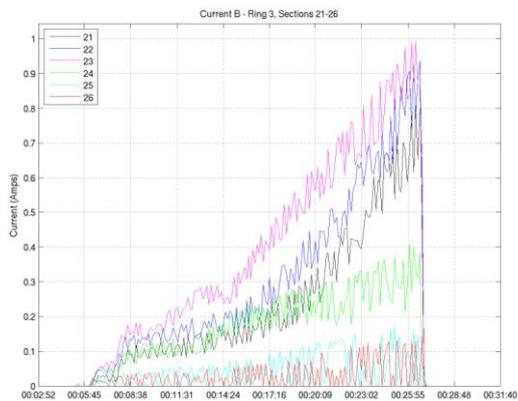
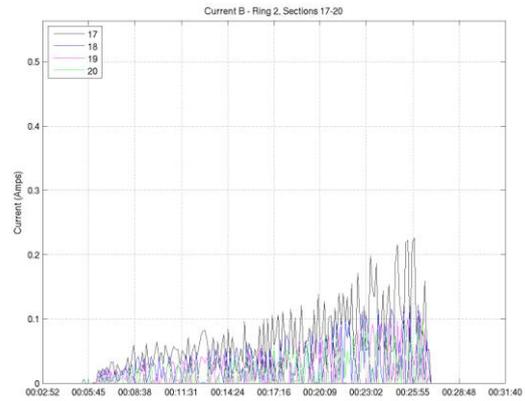
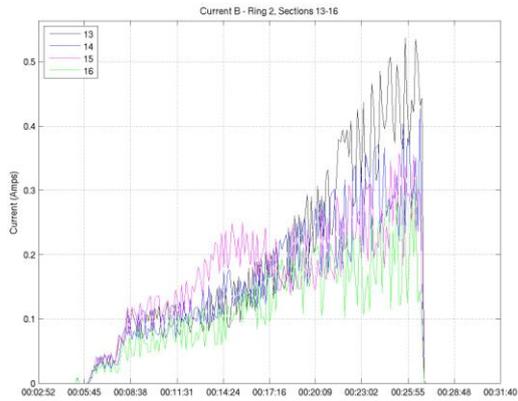
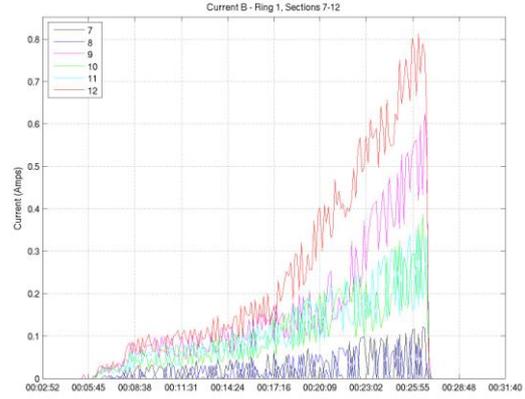
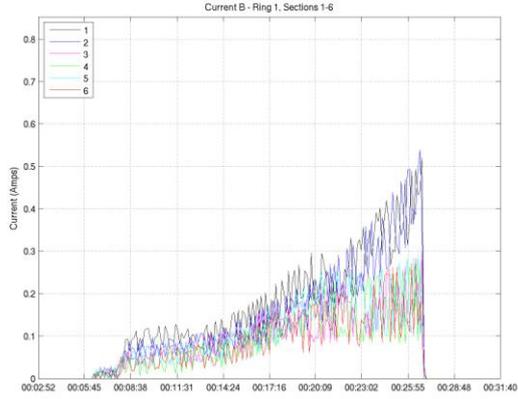
Log Voltage, Total Current and Resistance versus time, plotted from DAS measurements, Log 1 initial test

<sup>1</sup> Although not strictly within the scope of the project, attempts to assess timber quality and verify what effect, if any, the treatment has on these, indicated that a far greater quantity of timber, with untreated control logs for comparison, would need to be sterilized to provide statistically useful results.

The individual currents for each of the 30 segments of Electrode A (HV) and Electrode B (Ground), together with a summation are shown below, along with the segment numbering scheme.



**Individual Segment Currents for Electrode A (HV), with summation & numbering scheme, Log 1 initial test**



**Individual Segment Currents for Electrode B (Ground), with summation & numbering scheme, Log 1 initial test**

The segments in each electrode are numbered from 1 to 30 and are arranged in concentric rings as shown. The numbering is as viewed from the log (front) side. If the electrodes are pushed together the current flows directly between Electrode A segment 1 and Electrode B segment 12 and so on.

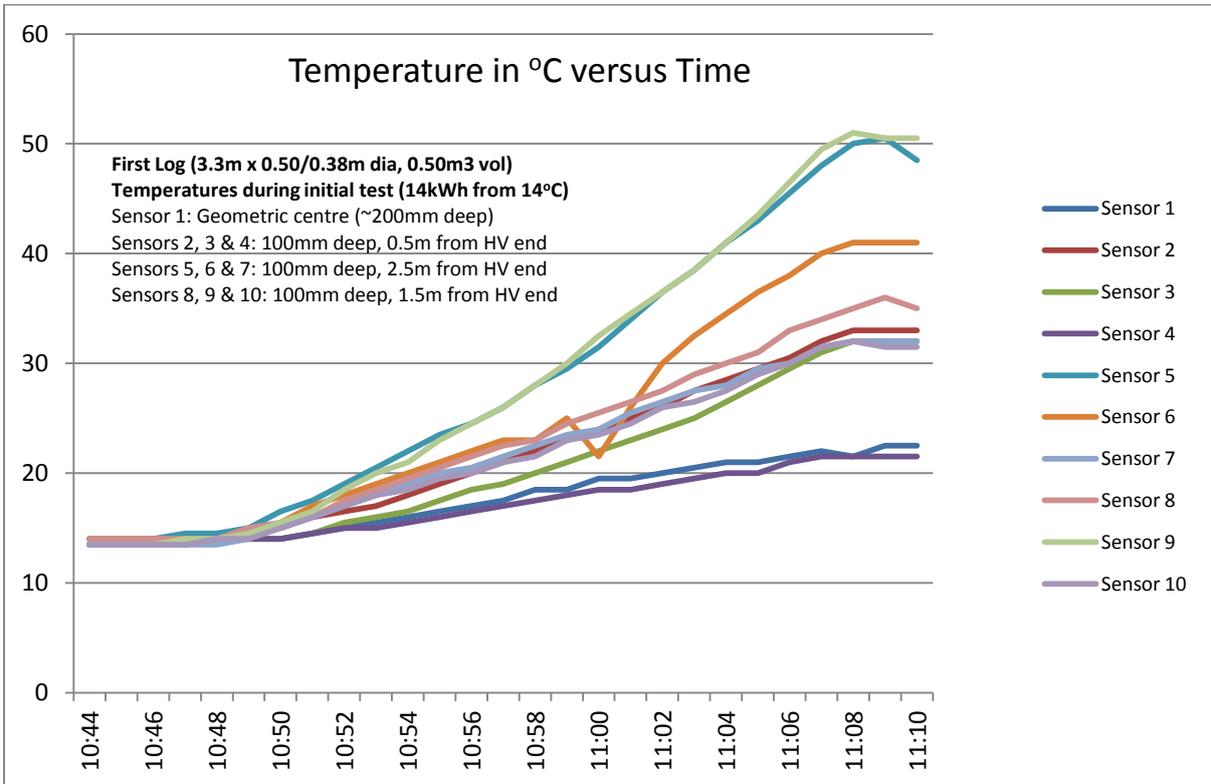
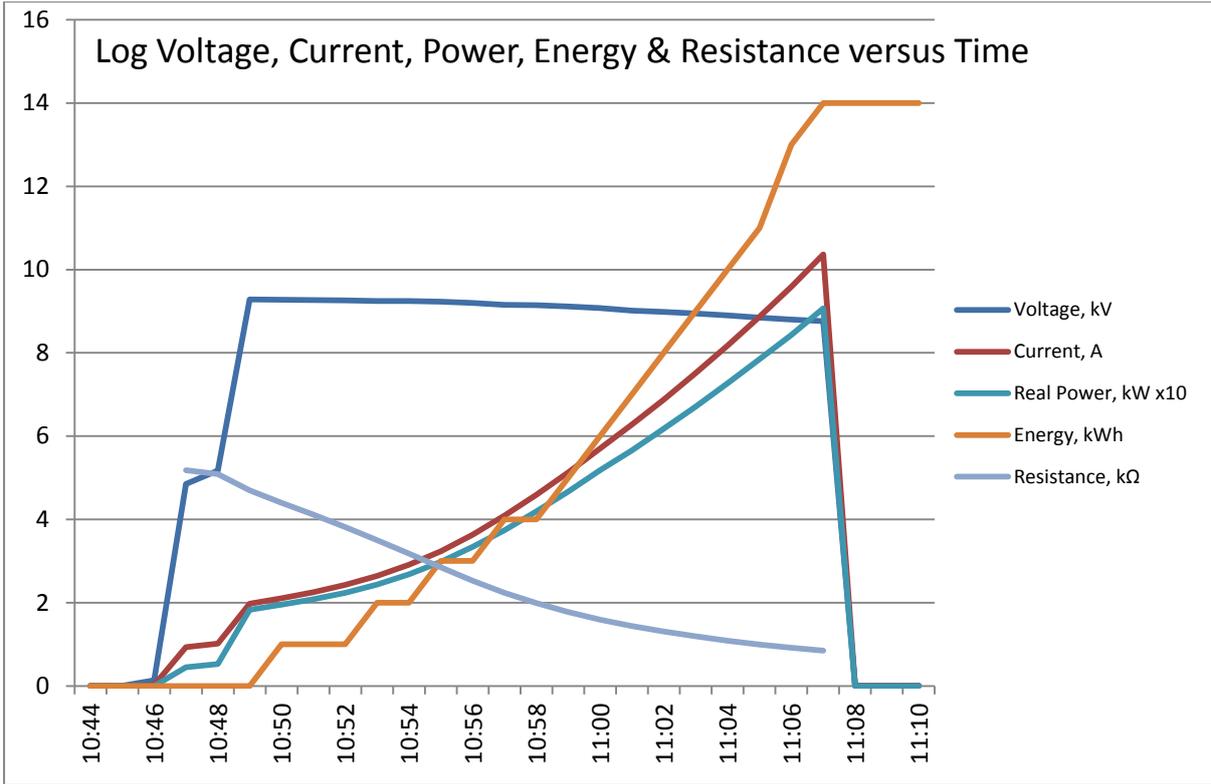
The CTs in each electrode are arranged such that conventional current flow from HV to Ground is regarded as positive. (This is of little concern at this stage as only the rms current value is presently being used, with the log appearing as a pure resistance; if dc and Hall Effect sensors are used at a later stage, or phase information proves to be of interest, this convention will be important).

It can be seen that the summation for the HV end is a little lower than that for the Ground end, which agrees well with the total current sensor measurement. This is thought to probably be due mainly to common-mode displacement current flowing capacitively to the grounded galvanically isolated side of the HV electrode CT amp/mux mother board. This effect is not seen on the Ground end, as there is no voltage present to drive displacement current. This will be investigated further in future, although the effect does not appear to be too serious.

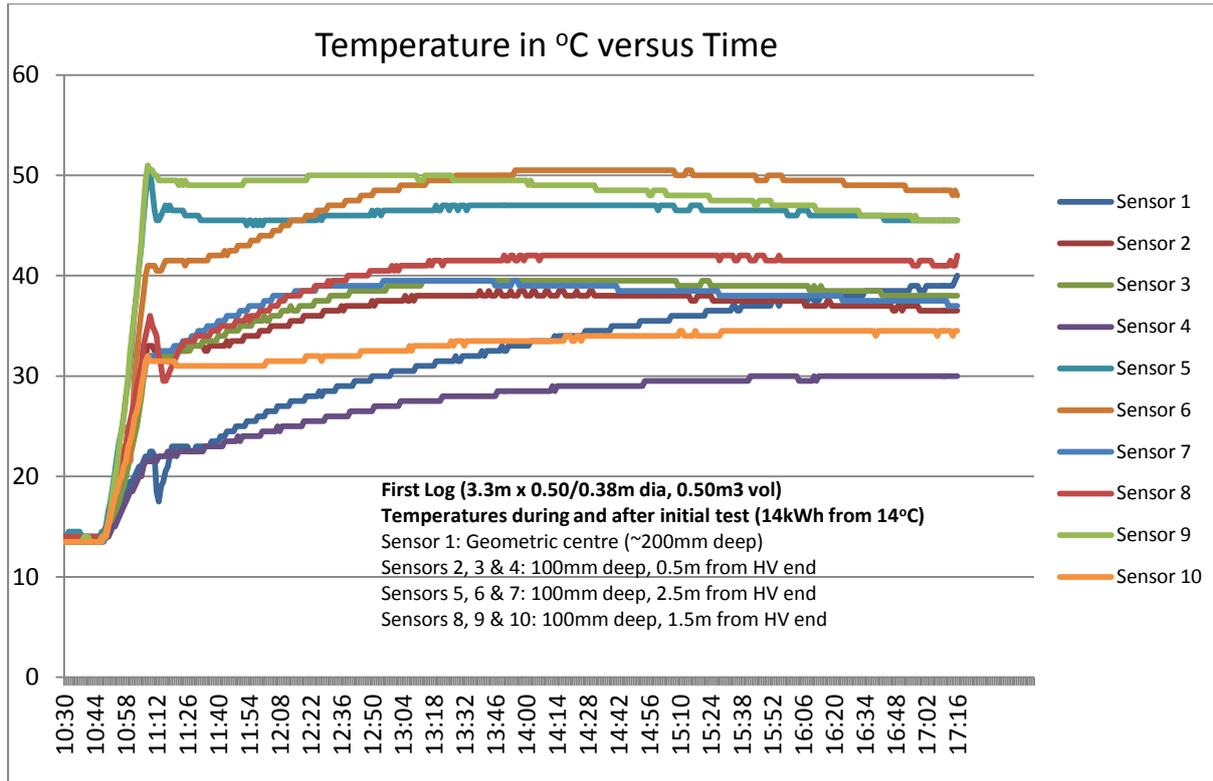
Clearly the current is not evenly distributed in the segments, although it does generally rise in all segments (albeit with some noise present) as the overall log resistance falls and total current increases. At this stage this system gives a good indication of satisfactory contact across the log ends, but more analysis work is needed to obtain the full benefits of the data. Additionally the cross-conduction between segments in the conductive pad system needs further consideration, as discussed earlier.

Voltage, current, power and energy data were logged simultaneously by the PQA, with real-time stamping. They show good agreement with the DAS measurements above. Results for the initial Log 1 test are shown below. The actual temperatures at 10 locations throughout the log were also recorded with real-time stamping and are shown directly below the corresponding electrical measurements.

The temperature logging continued for about 6 hours after the removal of power, the overall temperature results also being shown below.



PQA measured Voltage, Current, Power, Energy & calculated Resistance, with corresponding temperature readings, during Log 1 initial test



#### Temperature readings during and after Log 1 initial test

These results demonstrate several points:

- The DAS and the PQA are in relatively good agreement, giving reasonable confidence in the instrumentation.
- Temperature measurements can be made with the log energized, despite the high voltage, although they would be more useful if visible in real-time rather than after the fact.
- All temperatures begin to rise fairly soon after injection of the first kWh or so of energy and generally continue to do so while energy supply continues (although sensor 6 deviates).
- Some temperatures rise faster than others.
- Some temperatures begin to fall after the removal of power, but may rise again later.
- Some temperatures continue to rise after removal of power.

These findings are in agreement with the theory that heat builds up faster in certain, more conductive parts of the log, during energization, and then soaks into cooler parts of the log. The time constant of this heat soak appears to be in the order of 2 to 5 hours.

Clearly the temperature rise of approaching 50°C expected with the injected energy of 14kWh has not been achieved – average temperature rise is more like 25°C, with the centre only experiencing a 16°C rise. However the calculated energy does not take into account the large convection and radiation losses and the moisture losses occurring from the log, into the cold ambient air, during the 20 minutes of the test and the 5 hour equilibration period. In the previous, fence-post sized tests, the power to volume ratio was at least an order of magnitude higher, such that heating occurred in about 1 minute, resulting in far lower losses. This is a feature of being restricted in power level (about 100kW, rather than the 1MW calculated in the earlier MAFBNZ report [2]) by the available equipment. In subsequent tests an attempt to alleviate the problem was made by covering the logs with duvets, but this was only partially successful. Earlier, using a length of suitably sized plastic sewer pipe cut in half longitudinally as a thermal casing had been considered, but was not implemented due to cost considerations<sup>1</sup>. Nevertheless, despite these limitations, the general trend of temperature rise is encouraging.

<sup>1</sup> 5m of 600mm PVC pipe at a cost of about \$2K

### Log #1, Sterilization attempt:

A sterilization test was carried out on the same log on Monday 28<sup>th</sup> May 2012. By this time the log's temperature had decayed back to ambient.

The following parameters were set on the FR Controller:

$V_{set}$ : 240V on primary (approx 11kV on secondary)  
 $I_h$ : 400A on primary (approx 8.7A on secondary)  
 $I_l$ : 390A on primary (approx 8.5A on secondary)  
 $I_{rst}$ : 250A on primary (approx 5.5A on secondary)  
 $E_{set}$ : 22kWh

This was to provide the maximum possible power to the log within the equipment constraints:

Maximum transformer primary Voltage: 240V  
 Maximum FR output Power: 100kW

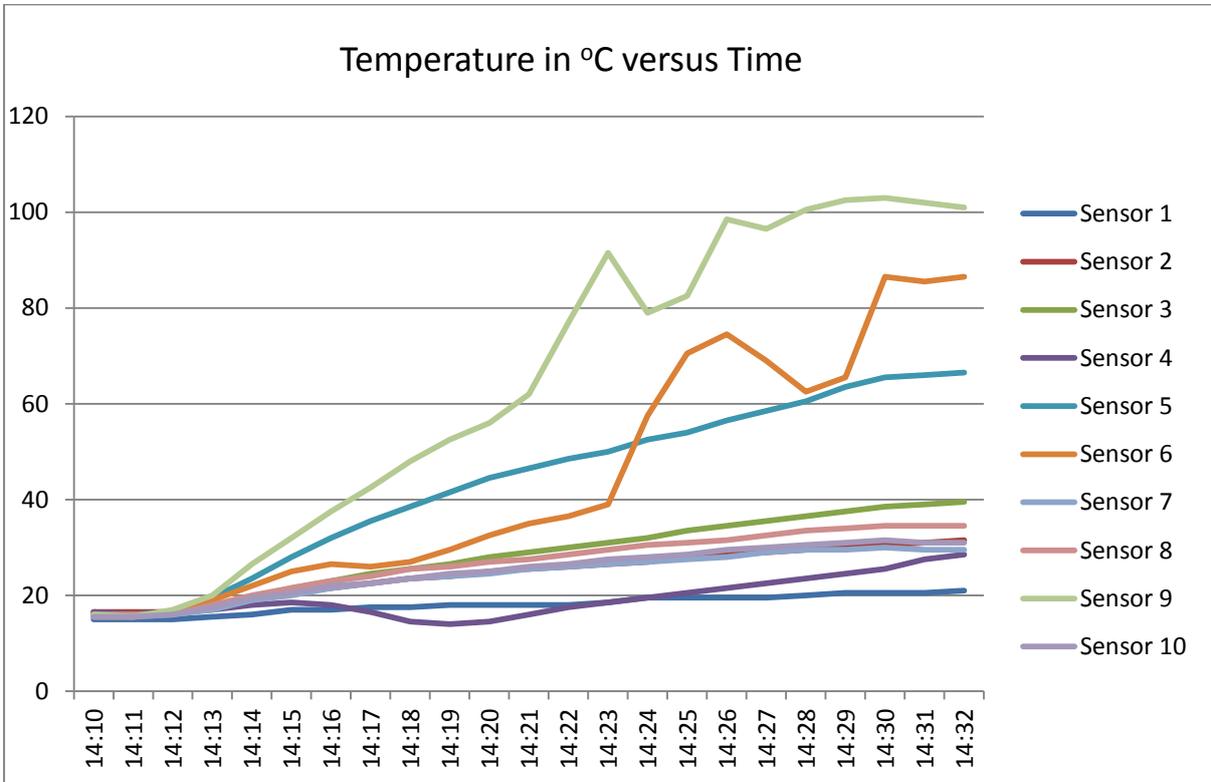
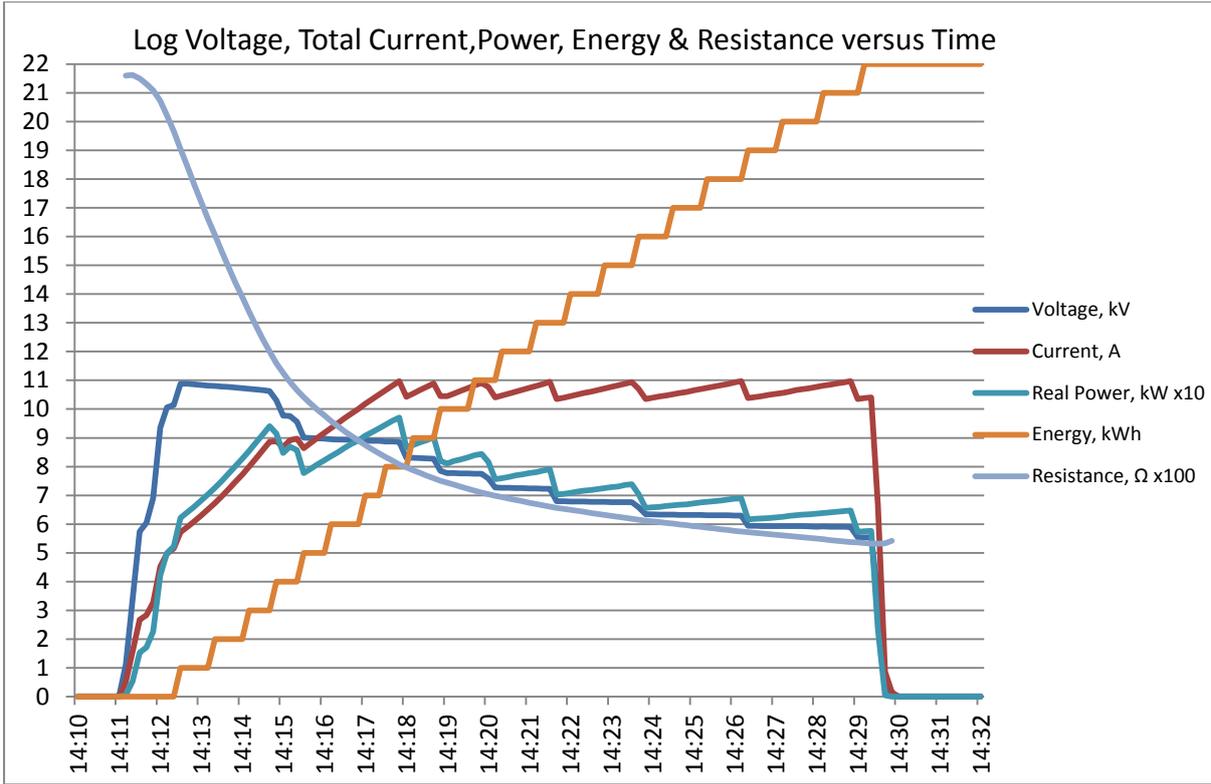
It soon became clear that the log resistance was falling quickly, reducing the voltage necessary to drive 400A and thus the current setpoint could be increased and the maximum voltage be reduced as follows:

$V_{set}$ : 200V on primary (approx 9.2kV on secondary)  
 $I_h$ : 500A on primary (approx 10.9A on secondary)  
 $I_l$ : 490A on primary (approx 10.7A on secondary)  
 $I_{rst}$ : 250A on primary (approx 5.5A on secondary)  
 $E_{set}$ : 22kWh

This continued to provide the maximum possible power to the log within the equipment constraints:

Maximum FR output Current: 500A  
 Maximum FR output Power: 100kW

The results from the PQA, shown below, clearly demonstrate the action of the current dead-band control and its effect on the log voltage and power. As discussed above, the initial limiting factor is the maximum transformer secondary voltage of 11kV (corresponding to 240V on the primary), followed by the maximum FR current rating of 500A (corresponding to 10.9A on the secondary). Although the log power does not quite reach the 100kW power limit, the equipment is nevertheless being used at its voltage and then current limits, demonstrating its limitations.



**PQA measured Voltage, Current, Power, Energy & calculated Resistance, with corresponding temperature readings, during first energy injection stage of Log 1 sterilization test**

Over a period of about 19 minutes 22kWh of energy is injected into the log, which this time is wrapped in duvets to attempt to reduce heat and moisture loss. The 22kWh figure was an estimate based on the temperature rise results of the initial 14kWh test and the anticipated effect of the duvet lagging. Over the duration of the test, log resistance falls from just over 2k $\Omega$  to just over 500 $\Omega$ . It is interesting to note that this is lower than in the initial test, even though the log is only about 2 $^{\circ}$ C hotter at the start this time (16 $^{\circ}$ C versus 14 $^{\circ}$ C)<sup>1</sup>.

During the application of power, the temperature sensors were logging temperature every second. As soon as power was removed (test automatically terminated on integration of 22kWh total, at 14:30) the temperature loggers (but not the thermocouples) were removed and readings were taken from the thermocouples with a digital thermometer. The readings indicated that insufficient energy had been injected. Therefore the loggers were replaced and the decision was taken to inject a further amount of energy<sup>2</sup>.

It was decided to inject a further 22kWh of energy, with the limitation again being the 500A FR output current limit. This is clearly shown in the results from the PQA below. During the approximately 50 minutes between power applications the resistance has increased slightly to just under 600 $\Omega$ , falling to just over 330 $\Omega$  by the end of the 30 minute period. This period is longer than the first due to the reduced power that can be delivered to the log whilst up against the maximum current, rather than power, limit.

Again, once the test, including the equilibration and cool down phase was completed (roughly 8 hours later), it was possible to line up the temperature sensor readings with the PQA electrical data as shown below.

Finally, the complete temperature data are presented for this two stage sterilization test.

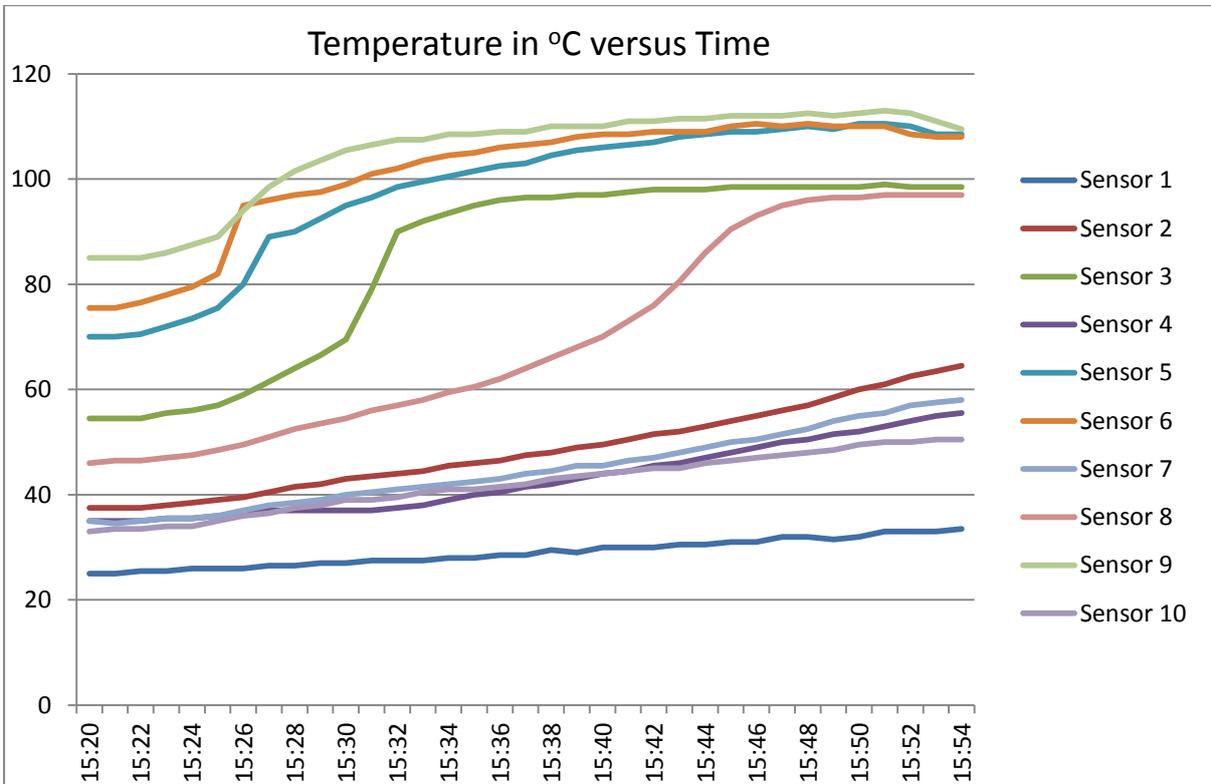
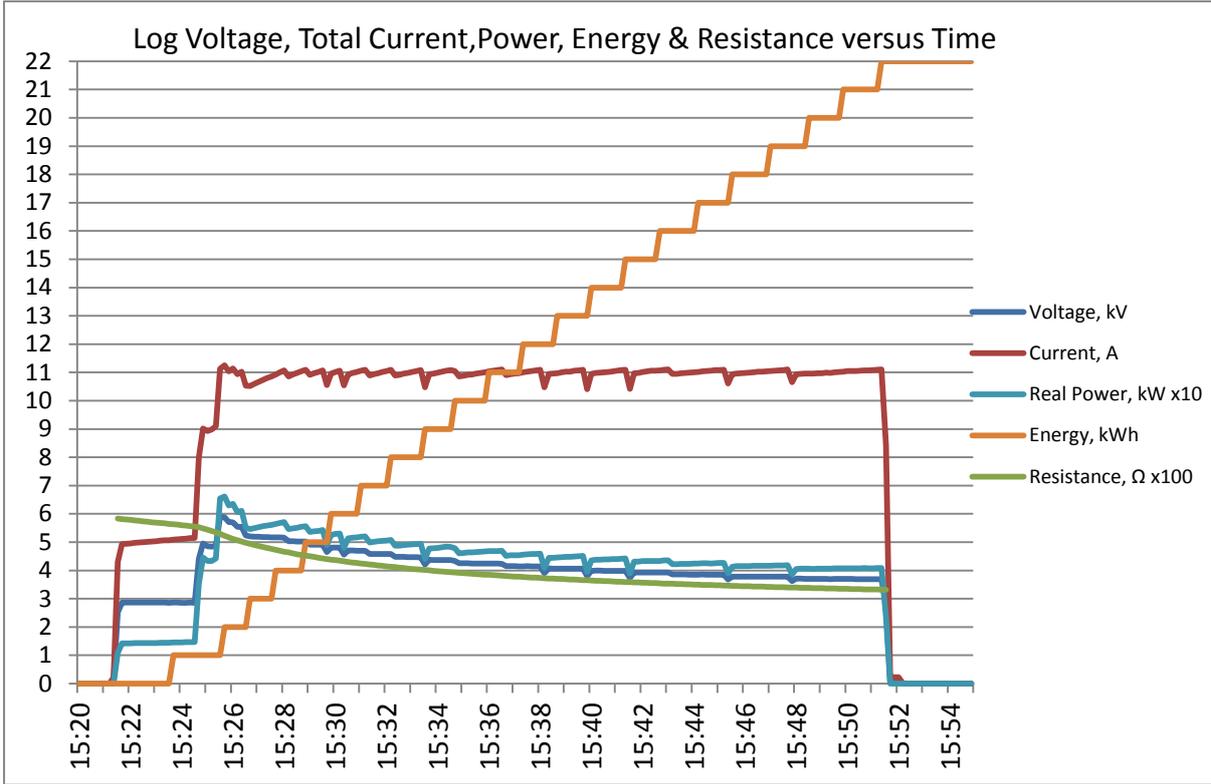
It is clear that the sterilization has been somewhat overdone! However, at the time, it was hard to tell, due largely to the unavailability of real-time temperature data. Furthermore, the amount of loss to ambient in the form of radiation, convection and evaporation during the long test periods was not properly accounted for. It would have been good to be able to weigh the log before and after each stage of the testing to determine moisture loss and hence latent heat of vaporization lost. In the future this would be possible by fitting the HV lab ceiling crane with a load cell. It might also be possible to fit load cells into the test rig, providing real-time moisture loss data. And, of course, as stated earlier, some form of insulating enclosure, superior to a few duvets, should be investigated.

After the first heating stage all the sensor locations appear to be continuing to heat up, except for sensor 9 (and briefly sensors 5 & 6). This is again indicative of heat soak from hotter locations within the log<sup>3</sup>. Sensors 9, 6 and 5 appear to heat faster than the others and this is consistent with the results of the initial test. In fact sensor 9 briefly exceeds 100 $^{\circ}$ C, which is likely to be undesirable.

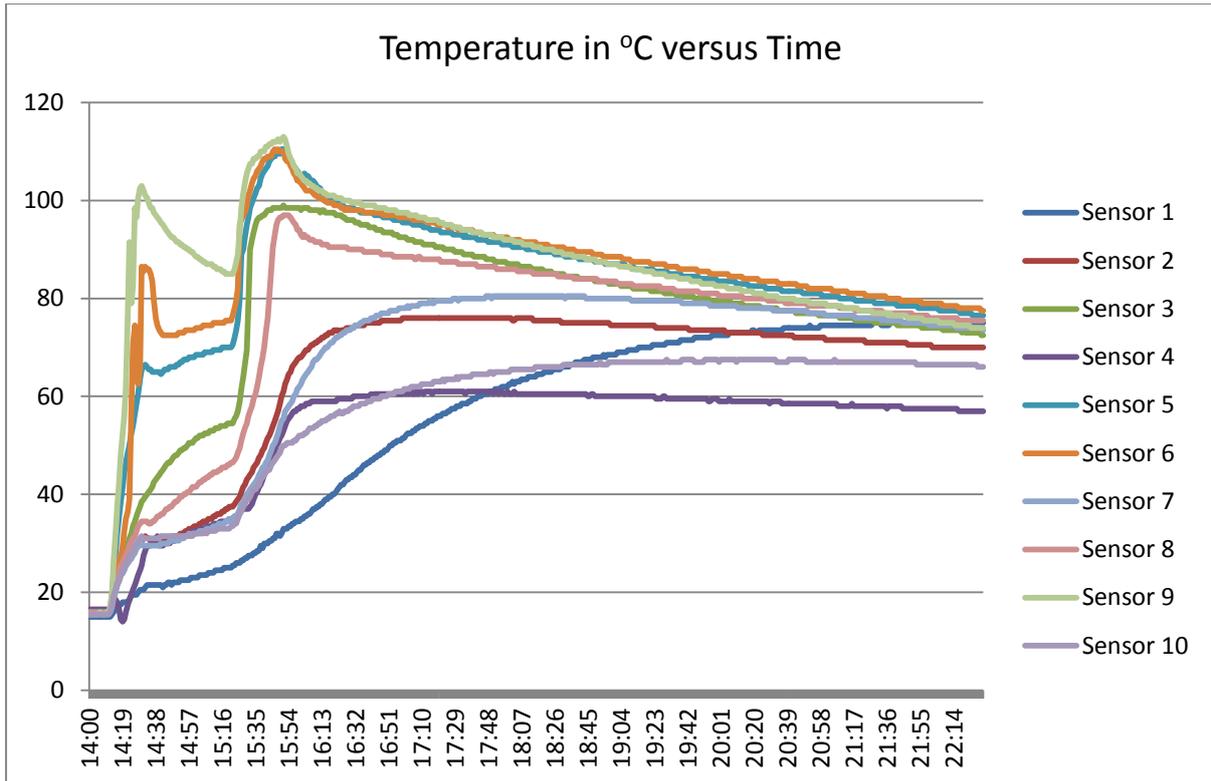
<sup>1</sup> This may be due to better penetration of the synthetic sap into the log ends after the initial test, or due to some real change to the log's conductivity caused by the initial test. Further investigation is needed here.

<sup>2</sup> Again, the fact that the temperatures could not be read in real time either during the test, or immediately after the test (without stopping the logging), was a major drawback which had already been envisaged, as can clearly be seen from the initial equipment budget for the project, but could not be avoided, due to the level of funding actually available. After the whole sterilization test was completed it was then possible to line up the electrical and temperature data to see what had happened, as shown above. At the time, however, we were running blind.

<sup>3</sup> It is also possible that the presence of the thermo-well holes themselves may cause some extra issues.



**PQA measured Voltage, Current, Power, Energy & calculated Resistance, with corresponding temperature readings, during second energy injection stage of Log 1 sterilization test**



#### Temperature readings during and after Log 1 sterilization test

The second heating stage causes the hottest 5 sensor locations to reach excessive temperatures (especially 9, 6 & 5 again) with all but the very centre of the log being within reach of meeting ISPM-15 conditions by the end of the application of power. The temperatures recorded as above 100°C are regarded with concern, as such a condition would require either localized superheating or a pressure increase to around 1.5 atmospheres. Further investigation is needed.

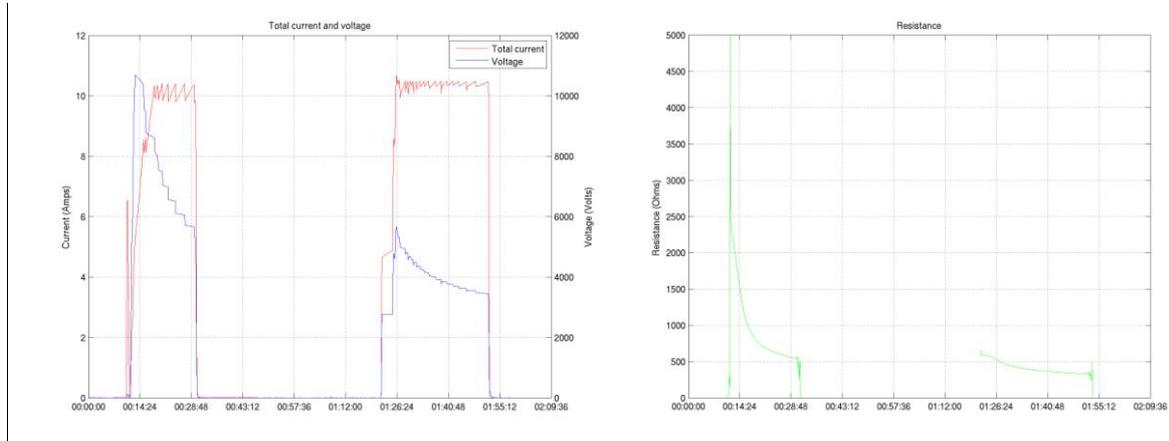
After removal of power for the second time the hottest 5 locations cool, while the others continue to warm up, with all locations exceeding 56°C between 17:21 and 22:27 (i.e. for over 5 hours).

This test, therefore, shows that Joule heat sterilization undoubtedly can work. After the test the log appeared to the naked eye to be unchanged and the ends appeared exactly as before, which was the criterion specified in the initial project scope. Photographs of the large (HV) and small (Ground) ends are shown below. (Photographs of both logs after all testing are shown on the summary page at the front of this report and of the whole of Log 1 after sterilization, under “Equipment purchased”).



**Log 1 ends after sterilization (left to right): Large (HV) end; small (Ground) end**

For completeness' sake, the data logged by the DAS during the Log#1 sterilization test are also presented.

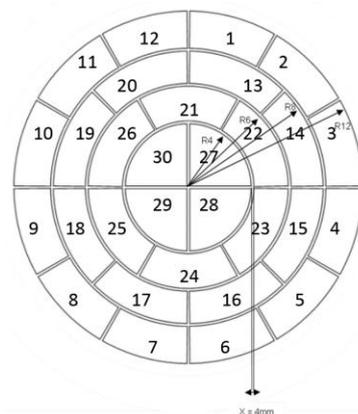
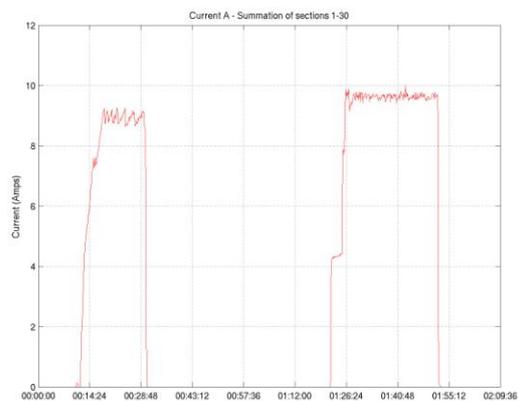
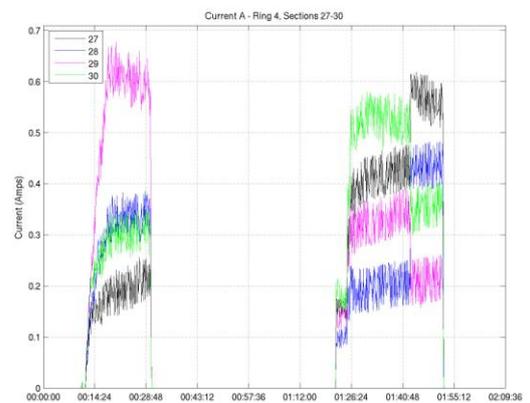
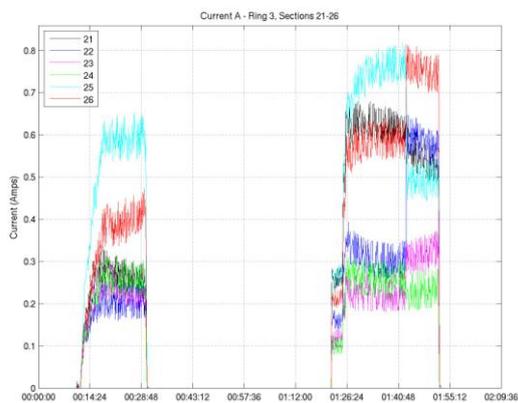
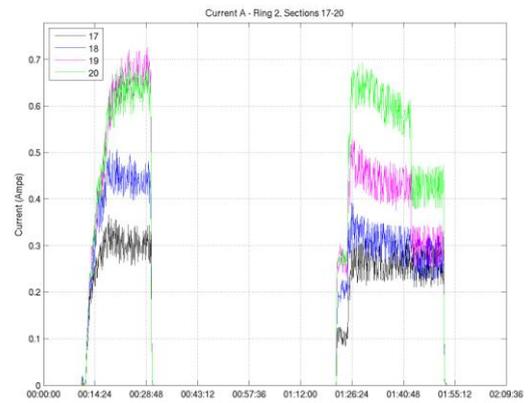
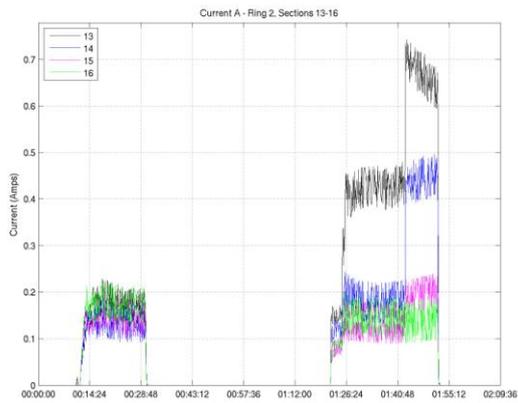
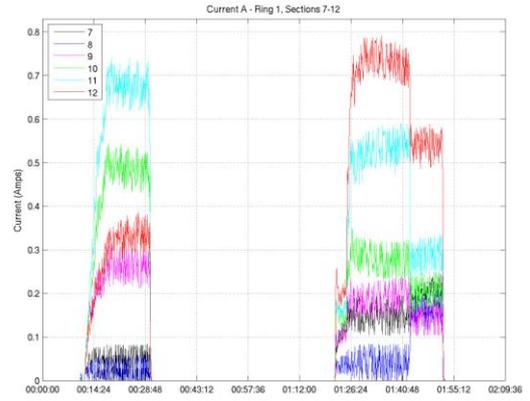
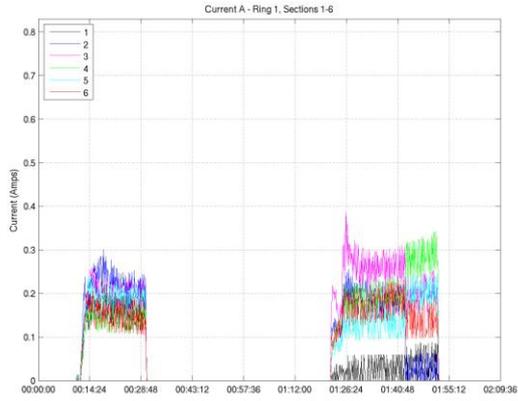


**Log Voltage, Total Current and Resistance versus time, plotted from DAS measurements**

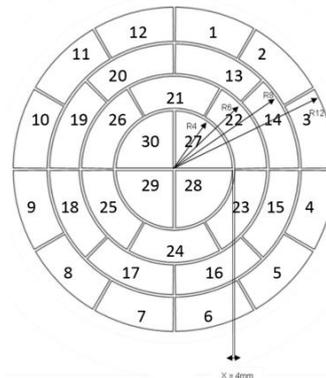
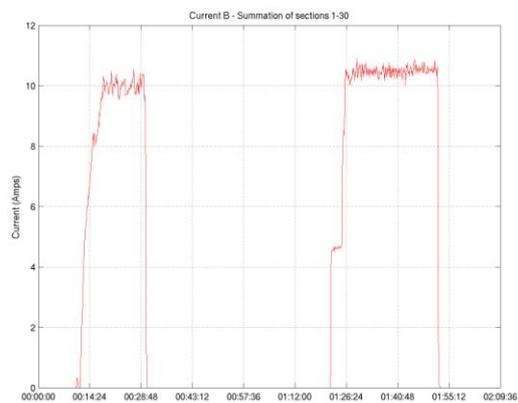
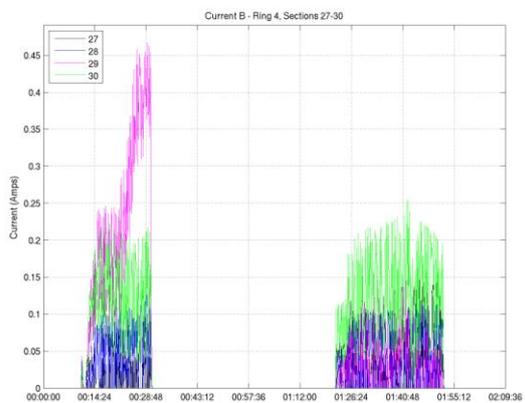
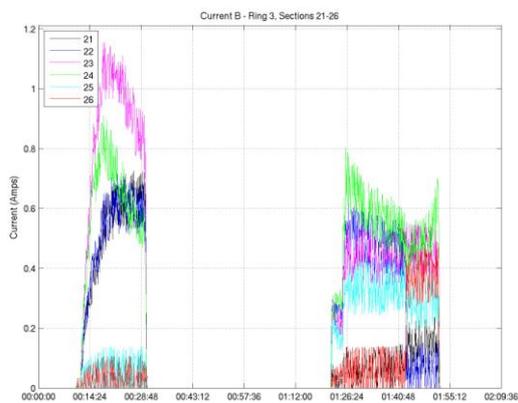
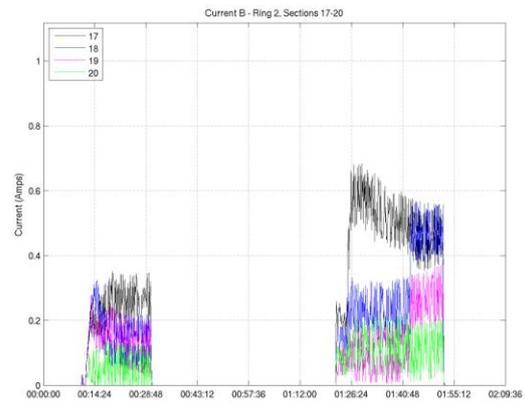
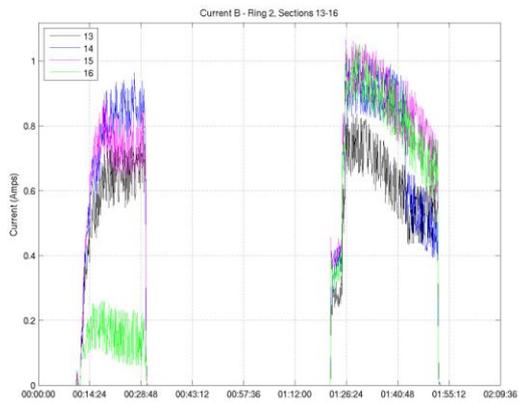
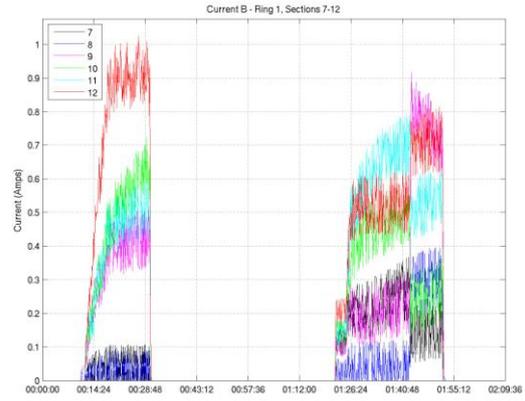
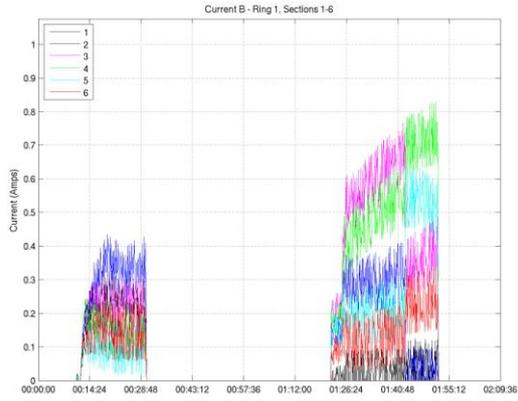
The DAS results for both stages of the test are plotted on a common time axis, and show good agreement with the PQA data<sup>1</sup>.

The 30 segment currents for each electrode were again logged and are presented below, along with their summation. Again the summation at the HV end is a little low, with the effect more noticeable when the voltage is higher during the first heating stage. This tends to support the displacement current theory described earlier. Nonetheless the results are still reasonably accurate and are interesting and worthy of further analysis. In particular, a sudden, major current redistribution occurs about two thirds of the way through the second heating stage. This is thought to be linked to the onset of boiling at many locations throughout the log and appears to correspond with the rapid temperature rise experienced by sensor 8. Further work is required.

<sup>1</sup> The current spike seen on the left of the DAS data is due to initially forgetting to remove the earth wand from the HV electrode, leading to high current with virtually zero voltage - this forms no part of the test and has been edited out of the PQA results presented earlier. Additionally the extrapolation of resistance value when the excitation voltage is near zero leads to false results – this has also been edited out of the PQA results.



**Individual Segment Currents for Electrode A (HV), with summation & numbering scheme, Log 1 sterilization test**



**Individual Segment Currents for Electrode B (Ground), with summation & numbering scheme, Log 1 sterilization test**

**Log #2 Data:**

Large end diameter (LED):	approximately 450mm
Small end diameter (SED):	approximately 360mm
Length:	3.3m
Estimated volume:	approximately 0.43m <sup>3</sup>
Estimated energy injection needed for 50°C rise:	approximately 13kWh

**Log #2, Sterilization attempt:**

A sterilization test was carried out on the second log on Wednesday 30<sup>th</sup> May 2012.

The following parameters were set on the FR Controller:

V <sub>set</sub> :	240V on primary (approx 11kV on secondary)
I <sub>h</sub> :	400A on primary (approx 8.7A on secondary)
I <sub>i</sub> :	380A on primary (approx 8.3A on secondary)
I <sub>rst</sub> :	250A on primary (approx 5.5A on secondary)
E <sub>set</sub> :	27kWh

When the applied voltage had fallen to 220V, the current set-points were moved up to 450/430A and when it had fallen to 200V, to 500/480A. This was again to provide the maximum possible power to the log within the equipment constraints:

Maximum transformer primary Voltage:	240V
Maximum FR output Power:	100kW
Maximum FR output Current:	500A

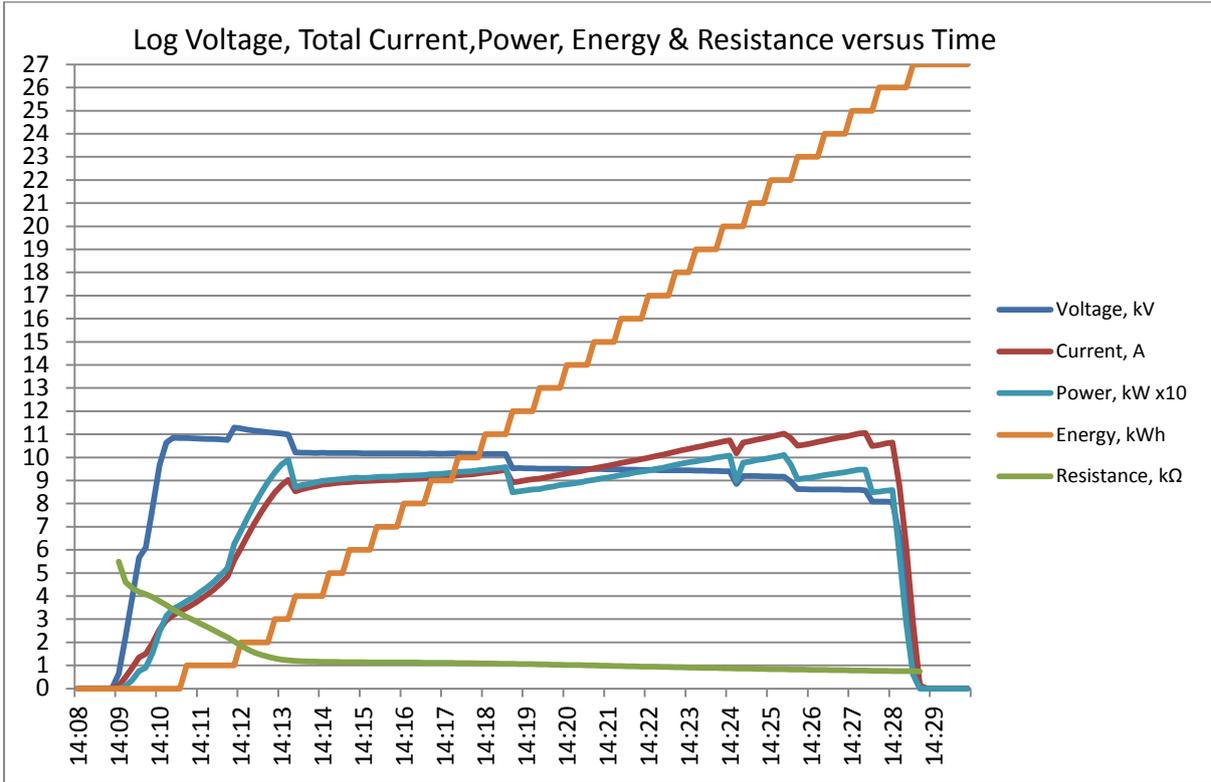
As stated earlier, it had proved impossible to retrieve the ceramic thermo-wells from Log#1 and, at this stage of the tests, no low cost alternative had been found<sup>1</sup>. Hence the test was carried out without any thermocouples in situ and there are no temperature data during the heating phase. Thermocouples were inserted, in similar locations to the first log, after power had been removed and the temperatures logged for the subsequent 9 hours, as shown below. Before application of power the sensor locations in the log had been drilled and the starting temperature measured. The lowest reading was 14.1°C, the highest being 15.4°C, and the mean being 15.0°C.

The energy was set to about twice the required level (calculated assuming no losses) and the log was wrapped in duvets throughout the approximately 19 minute test duration, was unwrapped immediately afterwards to insert the thermocouples, and was left wrapped up again after the thermocouples had been inserted. The traces start with each thermocouple being inserted to the log from an ambient air temperature of about 20°C.

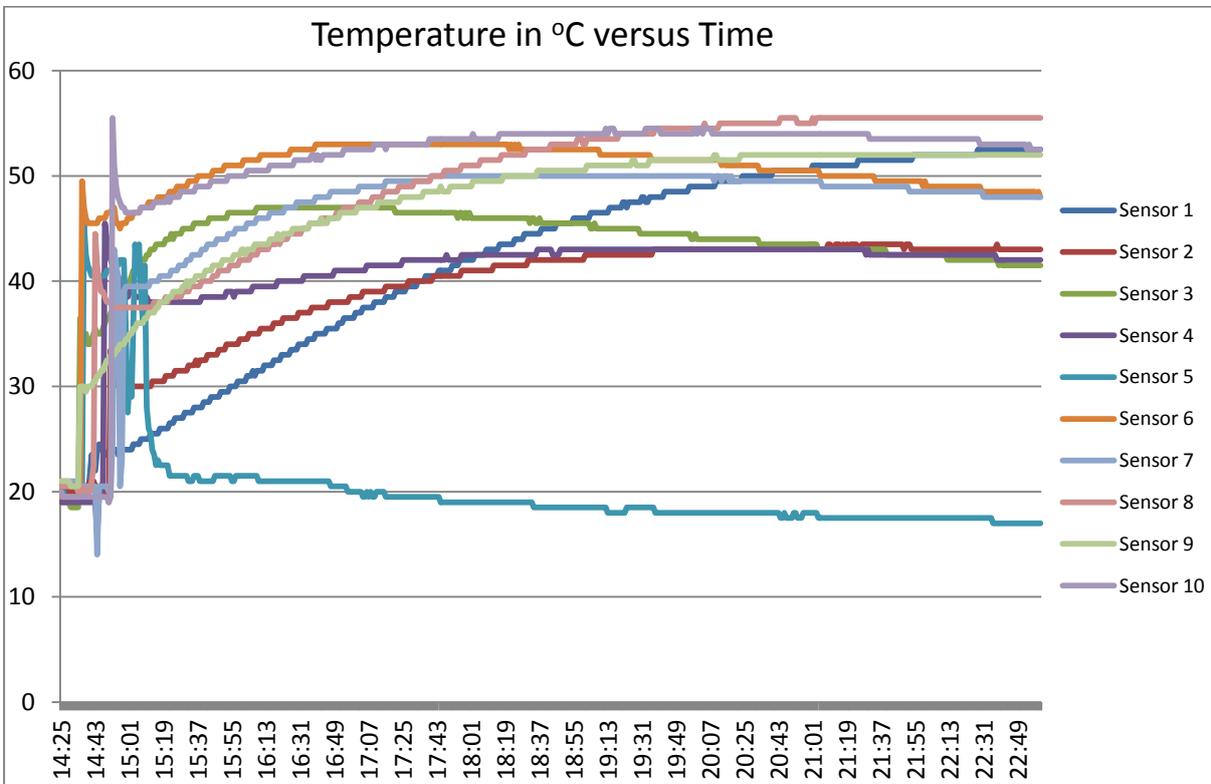
Thermocouple sensor 5 was subsequently found to be giving false readings, due to its connector being soaked in sap-filled water – after cleaning and drying out it again became functional – so these readings should be ignored. The other 9 temperatures eventually reach an average of about 48°C for about 5 hours or so, with actual peak temperatures ranging from 43°C to 56°C. As expected, the longest time constant for heat soak is for the centre of the log which is of the order of 5 hours.

Clearly the amount of energy absorbed by the log was insufficient to meet ISPM-15 requirements, largely due to the significant losses occurring to ambient despite the duvet lagging. Again, without real-time temperature monitoring, it was not possible to determine this until after the fact. Nevertheless the 9 valid temperature traces provide some encouragement that by increasing the energy absorption of the log, either by further injection, or preferably by improved heat/moisture loss control, by about 40%, ISPM-15 could be satisfied. The log resistance fell from about 5.5kΩ to about 750Ω during the test.

<sup>1</sup> a high temperature thermoplastic alternative solution has subsequently been found, though not yet tested.

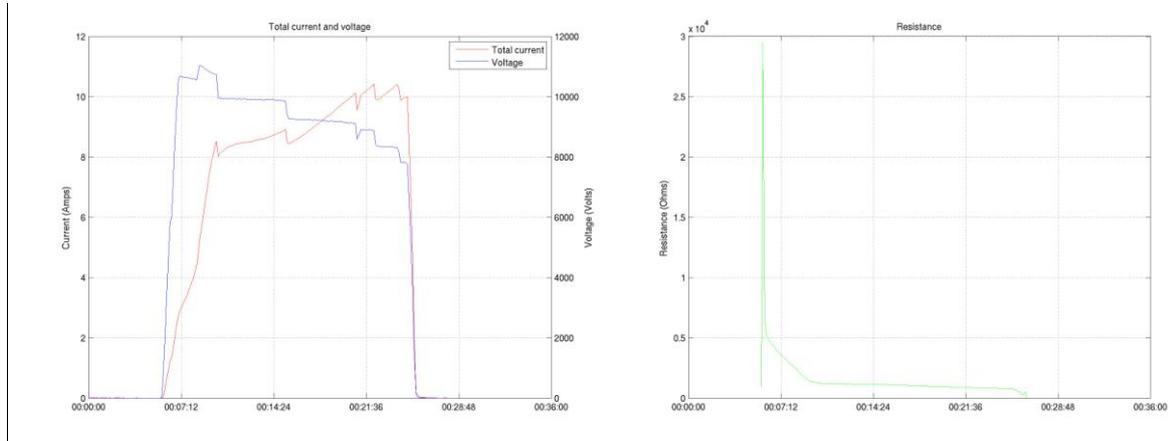


PQA measured Voltage, Current, Power, Energy & calculated Resistance during Log 2 sterilization test



Temperatures logged from immediately after removal of power, following Log 2 sterilization test

For completeness' sake, the data logged by the DAS during the Log#2 sterilization test are also presented.

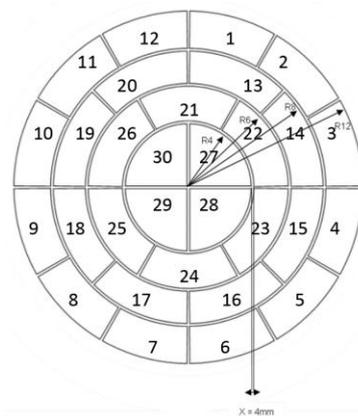
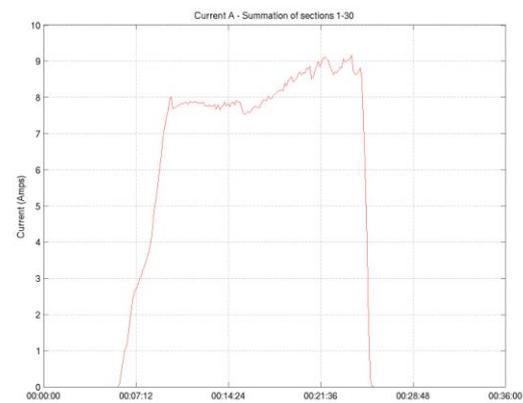
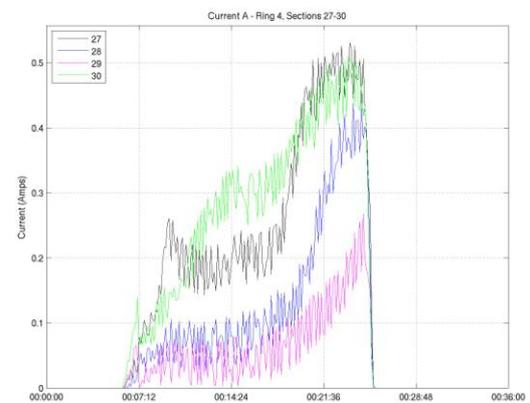
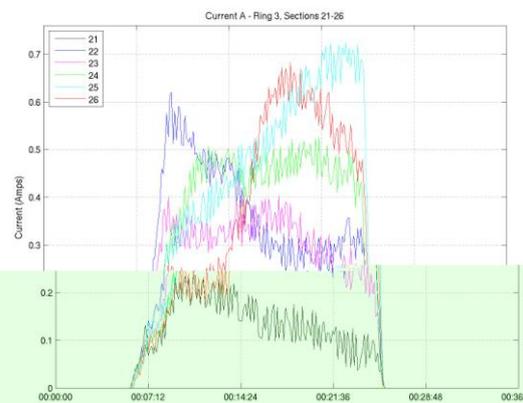
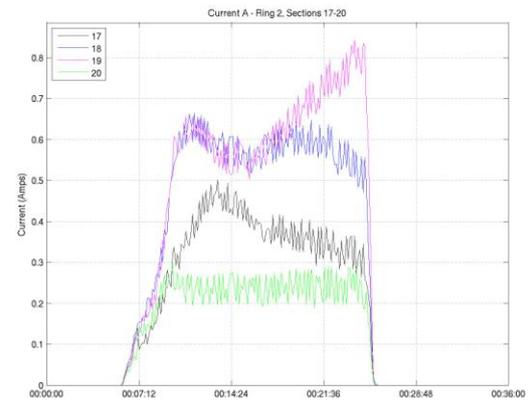
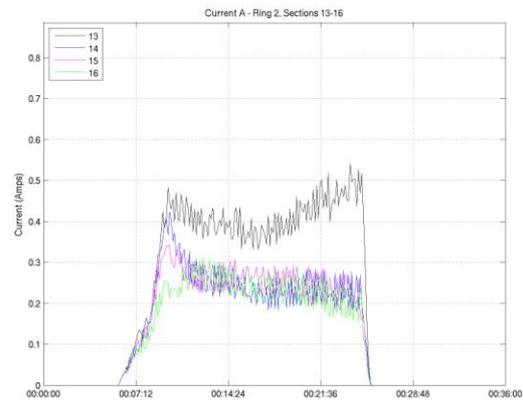
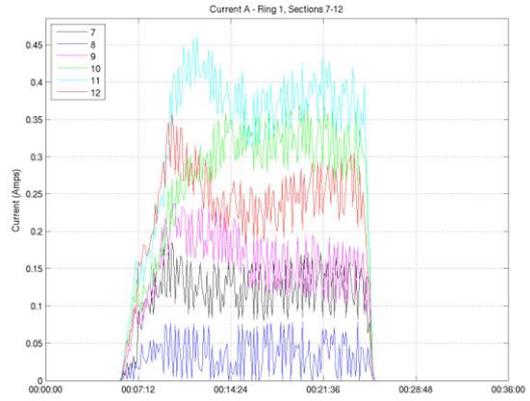
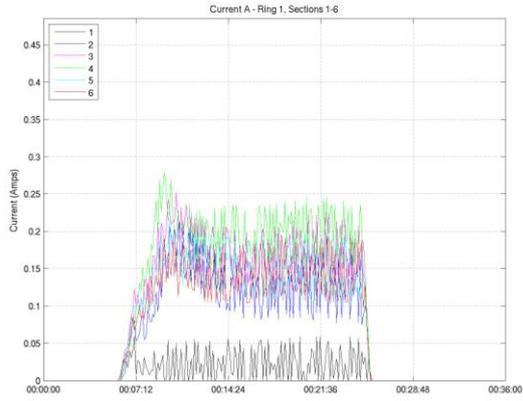


**Log Voltage, Total Current and Resistance versus time, plotted from DAS measurements, Log 2 sterilization test**

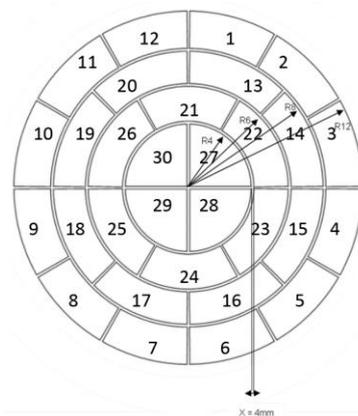
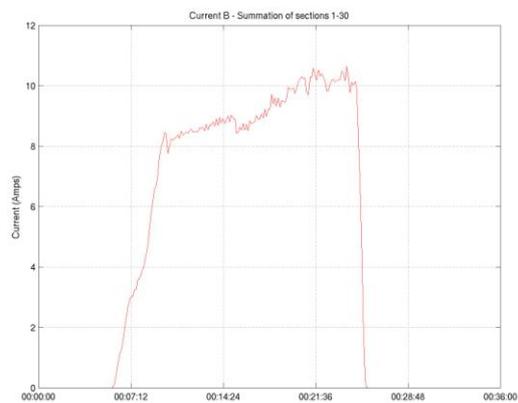
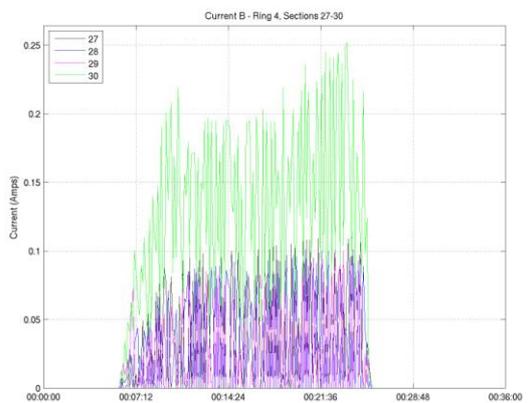
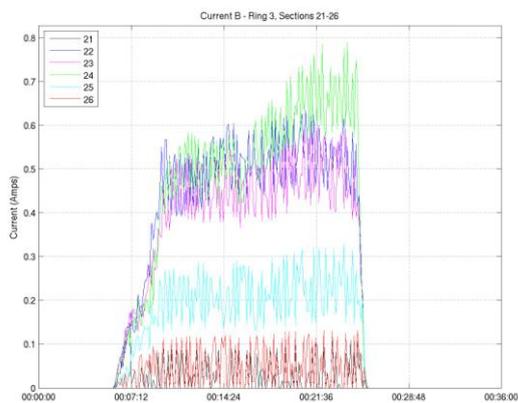
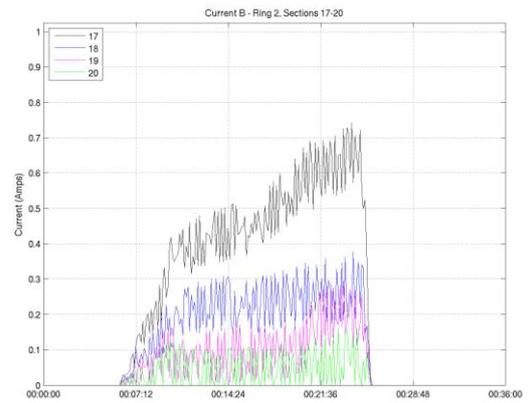
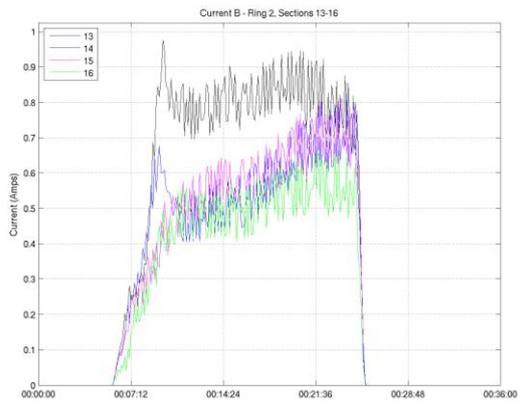
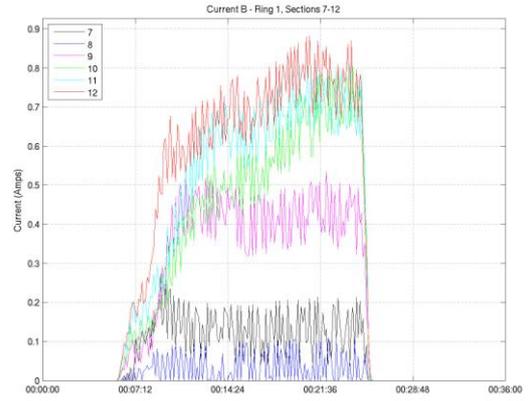
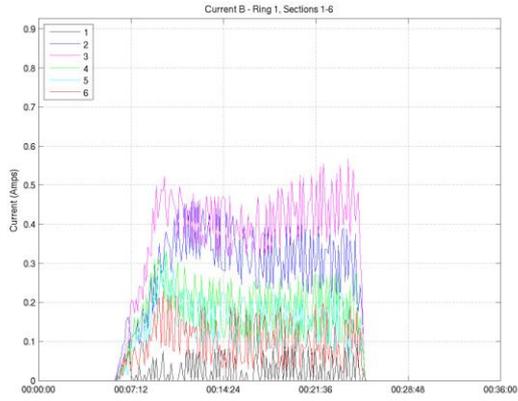
The DAS results for the test again show good agreement with the PQA data<sup>1</sup>.

The 30 segment currents for each electrode were again logged and are presented below, along with their summation. Again the summation at the HV end is a little low, as discussed previously.

<sup>1</sup> Again the extrapolation of resistance value when the excitation voltage is near zero leads to false results – this has again been edited out of the PQA results.



**Individual Segment Currents for Electrode A (HV), with summation & numbering scheme, Log 2 sterilization test**



**Individual Segment Currents for Electrode B (Ground), with summation & numbering scheme, Log 2 sterilization test**

## Log #2, Reheating attempt:

A reheating test was carried out on the second log on Thursday 31<sup>st</sup> May 2012. This was primarily to enable filming of the process to be carried out for record and publicity purposes, because the log was still at elevated temperature from the previous day's testing.

The 10 thermocouple temperatures were measured with a digital thermometer immediately before the test and found to range between 34°C and 47°C (with 43°C in the centre) and a mean of 40.6°C. (i.e. the duvet-covered log had only cooled by about 8°C over the 10 hours between 11 at night and 9 the next morning).

The thermocouples were removed, the duvets replaced and a test carried out as follows:

$V_{set}$ : 240V on primary (approx 11kV on secondary)  
 $I_h$ : 400A on primary (approx 8.7A on secondary)  
 $I_i$ : 380A on primary (approx 8.3A on secondary)  
 $I_{rst}$ : 250A on primary (approx 5.5A on secondary)  
 $E_{set}$ : 22kWh

Since the current reached 400A with the primary voltage still below 200V, it was possible to immediately increase the upper current set point to 500A (approx 11A on secondary), again to provide the maximum possible power to the log within the equipment constraints:

Maximum transformer primary Voltage: 240V  
 Maximum FR output Power: 100kW  
 Maximum FR output Current: 500A

The log resistance had increased back up to just over 1k $\Omega$ , from 750 $\Omega$ , during the cool down period following the sterilization attempt. It fell to 430 $\Omega$  during the reheating test.

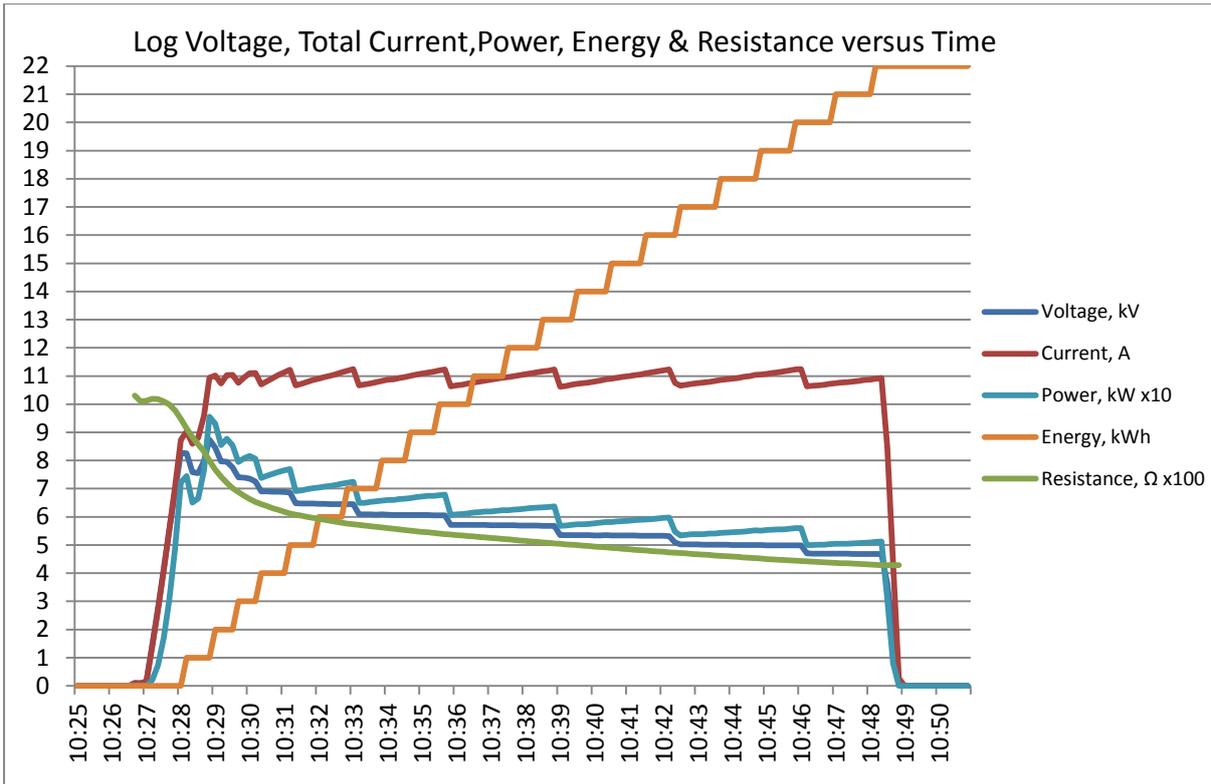
Immediately after the reheating test, the duvets were stripped back, the thermocouples replaced and the duvets then replaced. At 6pm the duvets were removed (1 hour before the end of temperature logging).

The electrical data from the PQA during the application of power, along with the complete 9 hours of temperature data logged following the test, are shown below.

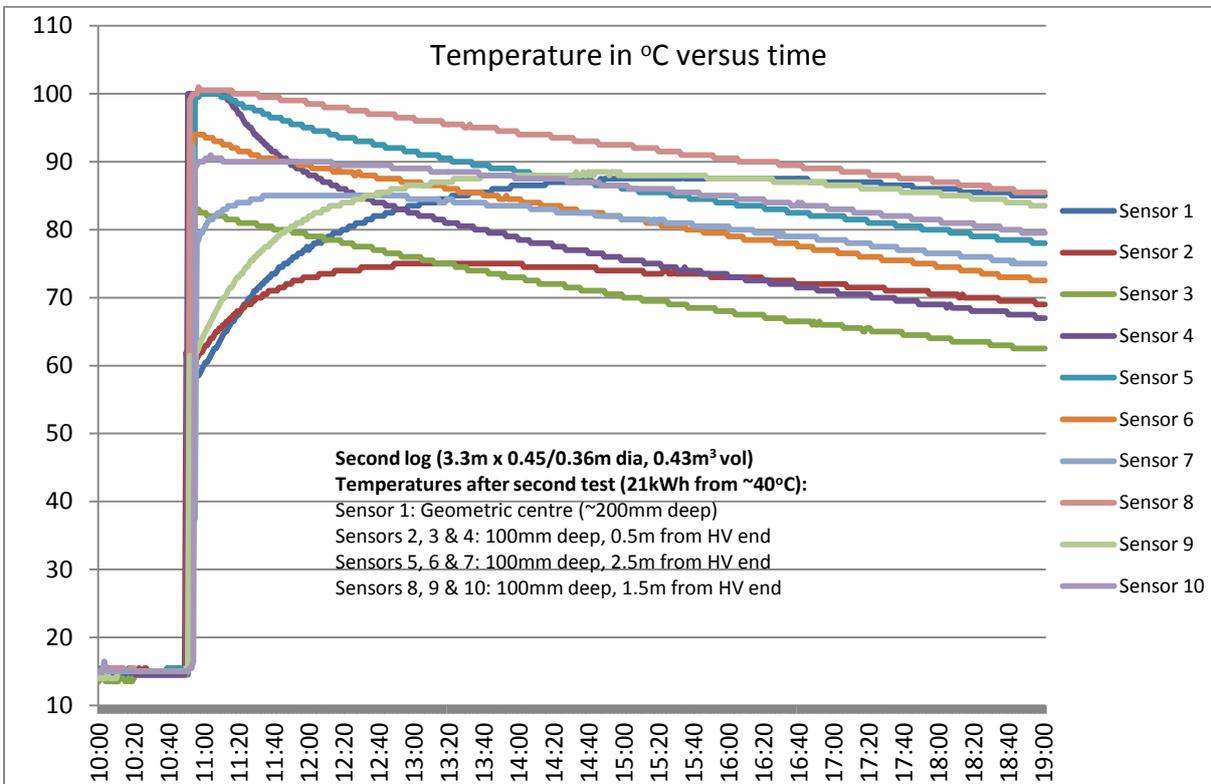
Sensors 8, 5 & 4 have been subjected to boiling temperatures, indicating that the energy input has been a little overdone again. Nevertheless, all 10 sensors exceed 56°C for at least the 8 hours of data recorded and simultaneously exceed 70°C for about 3.5 hours<sup>1</sup>. Interestingly, the time constant for heat soak for the centre of the log, from the elevated starting temperature, is now less than 3 hours, compared with 5 hours from ambient starting temperature previously seen. This may be due to improved thermal conductivity, as well as electrical conductivity, at higher temperatures. Again, more work is needed.

Photographs of both ends of Log 2 after the final reheating test, along with the whole log under the duvets after all testing and a dead beetle retrieved from the bark after the test are shown below.

<sup>1</sup> By 10:15 the following morning (i.e. over 16 hours after removal of duvets) the 10 sensors ranged between 41 °C and 49°C, with a mean of 43.5 °C.



PQA measured Voltage, Current, Power, Energy & calculated Resistance during Log 2 reheating test



Temperatures logged from immediately after removal of power, following Log 2 reheating test



Log 2 after completion of all tests (clockwise from top left): Large (HV) end; Small (Ground) end; log under duvets; dead beetle from bark

## 7. Brief investigation of timber after completion of all tests

Although beyond the initial project objectives, a brief look at the timber structure after the tests described above was attempted. Each of the two logs was cut into three 1.1m sections. One section of each log was cut into 50mm rounds, one slabbed into 50mm planks and the final one left as a log for future reference. The ends of all logs showed no apparent damage. However, some of the rounds and slabs showed evidence of checking. Unfortunately, without untreated control logs and many more samples to test it is hard to confirm the cause of the checking – checking can occur naturally, particularly in edge of stand trees, such as those from which both of these butt logs came.

A number of photographs of the samples are shown below.

It is likely, but beyond the scope here, that localized boiling of parts of the log caused some or all of this checking. Further work, with far more samples will be able to determine this. Additionally more samples, improved instrumentation and real-time temperature monitoring should reduce or eliminate the chances of localized boiling.



Timber samples milled after completion of all tests (clockwise from top left): Log 1 section close up part way through showing checking; Log 2 crosscut at 1.1m, showing checking; Log 2 slabbing, showing checking



Timber samples milled after completion of all tests (clockwise from top left): Log 1 rounds; Log 2 rounds; slabs; Log 2 small end after removal of initial 25mm

## 8. Comparison of results with project objectives

1. *Determine how successfully a controlled variable rate of heating can be used to ensure acceptable temperature distribution throughout the timber during the heating and post-heating phases, with a representative range of export grade logs;*

The results show that it is probably possible to achieve acceptable temperature distribution. However both improved temperature instrumentation and testing of a much larger number of samples is required to state this categorically.

2. *Determine if a time/temperature profile, encompassing the heating and post-heating phases, can satisfy the International Plant Protection Convention (IPPC) International Standards For Phytosanitary Measures No. 15 requirements and what limitations exist regarding the applicability of the technique to a representative range of export grade logs;*

Again the results show that satisfying ISPM-15 is certainly achievable, but further samples would need to be heated to define the full range of applicability.

3. *Determine if the bark meets the time/temperature profile under various different heating and post-heating conditions, with a representative range of export grade logs;*

It is almost certain that in a production machine the heating and subsequent equilibration should take place in a “hot-box” environment, as it would be impossible to guarantee the surface temperature of an irregular convecting and radiating body sitting in cold ambient air. There was insufficient funding to make such a “hot-box” for the work reported. However surface measurements with the logs covered in duvets, in ambient air, showed the bark to reach satisfactory temperatures, except on the uncovered underside of the log.

4. *Determine if the high voltages and moderate currents required can damage the ends of the log and how to avoid this eventuality;*

It has been clearly demonstrated that the present electrode design and electrical parameters used cause no visible damage to the ends of the logs treated. Further work, with improved instrumentation, is needed to assess the effects of excessive temperature rise on wood properties.

5. *Evaluate the cost of energy per log and estimate a proposed cost assuming a “major user” electricity discount.*

Due to the available power being an order of magnitude below that estimated to be required [1, 2], the heating time has proved to be greatly increased, especially without a “hot-box” environment, leading to significant heat loss to ambient in the form of radiated heat, convected heat and latent heat of vaporisation. Without mass measurement of the logs before and after testing it is impossible to gauge the relative contributions.

Based on the present work we can say that 44kWh, over two applications, was excessive for the 0.5 cubic metre Log#1 and that 27kWh in one application was insufficient for the 0.43 cubic metre Log#2, under these conditions.

Based on the early fence-post work [1], it is still believed that roughly 30 to 40kWh per cubic metre of timber is about right, when losses are properly controlled and the high power source is available. Using indicative figures from Meridian Energy, Variable Volume 100% price schedule, from 2011, average kWh price is just under 11c per kWh. At 40kWh per cubic metre, this equates to \$4.40 per cubic metre. Electricity prices do of course change, but this schedule is not based on a particularly high usage. If all 12 million cubic metres of logs were heat sterilized this way, 480GWh would be needed. If this was evenly spread over a year, with machines running 16 hours a day, about 80MW of capacity would be required (i.e. just under 12% of Manapouri’s output).

## 9. Conclusions, further work and implementation ideas

The work reported shows that the Joule heating technique can satisfy the requirements of ISPM-15, or similar heat sterilization regimes. However the logs need to be insulated from ambient atmosphere after heating and preferably during heating also, by constructing a “hot-box”, to ensure bark is held at or above the required minimum temperature and energy use is minimized.

An electrode, foam and conductive gel system has been developed that ensures good contact and no damage to log ends.

Improved real-time instrumentation (temperature, current distribution, mass), with real-time visibility, is needed to improve the process control.

Multiple fast injections of energy, with heat-soak equilibration intervals, are likely to yield better temperature uniformity (with the whole process in a temperature/humidity controlled “hot-box”).

The power source available is not sufficiently large to allow optimum heating of full-sized logs, especially in the absence of a “hot-box”. Even in a “hot-box” the likely total energization time required will be an order of magnitude larger than that proposed in [2].

Further testing is needed to prove the new instrumentation and “hot-box”, followed by extensive further testing to ascertain the variability of logs and extensive controlled testing to evaluate any changes to timber properties caused by the process. The latter is likely to involve detailed analysis of timber structure properties, before and after/with and without testing, with multiple logs from the same tree, or at least from the same provenance.

Work to determine the electrical and thermal conductivity of timber from different parts of the same range of logs and, in particular, their temperature dependence is likely to yield useful results which should aid in process control and understanding.

At the present stage the author’s current impression as to how a wharf-side machine might operate, based on all the work to date, is as follows:

An nMW machine would be capable of a throughput of about 180n typical logs ( $\sim 0.6\text{m}^3$ ) every 3.5 hours.

By way of example, a 1MW machine would be housed in an insulated enclosure approximately 20m long, by 8m wide, by 6m high. This would be scaled up for machines > 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.

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

The 6<sup>th</sup> conveyor would drop the logs onto the 7<sup>th</sup> (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 10<sup>th</sup> position from left on the top, 3<sup>rd</sup> and 5<sup>th</sup> 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 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).

## 10. Statement of IP position and IP timeline

As is hopefully evident from this report, a great deal of work has been carried out to enable the completion of this project and certainly very much more than might be indicated by the level of funding provided for the project per se. This is because a great deal of the equipment and process planning and much of the equipment design and production had already taken place before the commencement of the present project. It is important for all concerned parties to be aware of this - the EPECentre has already stated its claim to ownership of the initial IP, before the commencement of the project, as it is the EPECentre and the author at UC who have taken the majority of the initial development risk. The previous work carried out for MAFBNZ [2] saw the IP retained by the EPECentre.

Of particular note are the following ideas and their auditable conception or reporting dates, which predate the present project by a considerable margin. This comprises background IP to be carried into the new Scion project funded by MBIE and STIMBR:

- |     |  |                    |
|-----|--|--------------------|
| 1.  | Synthetic sap contact system (originally with sharp metal electrodes): | December 2007      |
| 2.  | Energy injection by multiple small bursts, rather than all at once:    | December 2007      |
| 3.  | Absorbent electrode pad interface (originally felt, later foam):       | March/July 2009    |
| 4.  | Hydraulic/pneumatic rams for applying force to electrodes:             | Dec 2007/Apr 2010  |
| 5.  | Hydraulic injection of synthetic sap to electrode pads (grease-gun):   | December 2007      |
| 6.  | Segmented electrodes with multiple current sensing for log ends:       | October 2009       |
| 7.  | System for sensing current distribution along a log:                   | April 2010         |
| 8.  | Current distribution/log resistance tomography from above sensing:     | April 2010         |
| 9.  | Correlation of current distribution with temperature rise:             | April 2010         |
| 10. | Design of controller for Foster Regulator:                             | April 2010         |
| 11. | Wireless real-time temperature measurement network:                    | April 2010         |
| 12. | Estimation of approx. log temperature by resistance drop from cold:    | March 2009         |
| 13. | Non-contact timber temperature measurement by IR thermometry:          | March 2009         |
| 14. | As above with plastic insulating window (e.g. polyethylene):           | July 2011          |
| 15. | In situ mass measurement to determine moisture loss:                   | March 2009         |
| 16. | Controlled environment to reduce heat and moisture loss:               | July 2009/May 2010 |
| 17. | Consideration of excitation source: DC vs. AC vs. frequency:           | July 2009          |
| 18. | Recapture of heat energy to power another process:                     | July 2009          |

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## 12. References

- [1] Heffernan, WJB (2007) *Joule Heating of P. radiata logs. Internal EPECentre report 20-12-2007*
- [2] Heffernan, B. and Lawrence, J. (2009) *Joule Heating of Export Logs: An Investigation of Joule heating of Pinus radiata export logs as an alternative to Methyl Bromide fumigation. Stage I Final Report (0810757). MAF Biosecurity NZ. 49pp.*