

Prepared for
Energy Safe Victoria

**Probability of Bushfire Ignition from
Electric Arc Faults**

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by
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At the time of preparing this report Dr Tony Marxsen was engaged by ESV as a member of the ESV secretariat supporting the Powerline Bushfire Safety Taskforce. He was intimately involved in all aspects of the work covered in this report and contributed to design of the test procedure and equipment, determination of electrical conditions for testing that would suitably represent real faults in the Victorian electricity distribution system, the analysis and interpretation of the data and in preparation of this report.

Probability of Bushfire Ignition from Electric Arc Faults

Summary

Energy Safe Victoria and the Powerline Bushfire Safety Taskforce are reviewing protective technologies to reduce the risk of bushfires from faults in electricity distribution powerline networks. This report specifically covers the ignition of fires by electric arcs, typically through contact between a live conductor and either an earthed structure or vegetation.

This report presents results from an 18 day program of tests undertaken by HRL at the TCA High Energy Facility at Lane Cove NSW. Ignition testing was carried out at 12,700 V (the conductor-to-earth voltage of Victoria's 22kV and SWER networks) at realistic fault currents ranging from 4.2 to 1,000 amps, to develop a model to predict the probability of fire ignition from electric arcs in network faults.

The test program was designed to determine worst case ignition probability by combining worst case arc energy release from simulated real network faults with worst case fire weather and fuel conditions. In many real instances, fire risk will be much lower than these test results indicate for a variety of reasons.

Ignition probability was assessed against the arc duration, the arc power and the energy released by the arc to the immediate environment and the effects of wind speed, fuel moisture and ambient temperature were determined.

The action of auto-reclose devices and ground fault neutralisers (GFNs) was simulated so that the effect of these on the risk of ignition could be assessed.

The program of ignition tests has provided valuable insights into the behavior of arcs and conditions for ignition of dried grass and other fuels. Reliable conclusions can be drawn from consideration of the results as a whole. Detailed curves designed to indicate the likelihood of ignition of vegetation have been generated for 50 and 200 amp faults under worst case conditions.

A spreadsheet tool has been developed to predict ignition probability under a wider range of meteorological and electrical conditions, albeit with a higher level of uncertainty.

The key findings from the tests include:

The probability of ignition from electric arcs

- Realistic worst case conditions for an arc at ~0.5 metres height above ground level were determined by tests and analysis to be: wind speed of 10 kph at 45°C air temperature and <20% relative humidity, straw/grass with moisture content ~5%, zero arc-fuel distance.
- Under these worst case conditions, sustained ignition is 50% probable for arc durations around 60ms at 200 amps, 75ms at 50 amps and 155ms at 4.2 amps (though test results for 4.2 amp tests are less certain than for higher currents).

- Based on review of the high speed video records, ignition can occur almost instantaneously (in less than 10ms) when the arc/plasma contacts the fuel, even at low currents. Straw/hay was more flammable than eucalypt leaf litter. Green eucalypt leaves could also be ignited at higher arc energy.
- No instances of ignition from radiation heat flux were observed. Tests indicate that radiation transfers less than 20% of total arc energy to the environment.
- Probability of sustained ignition depends on the following:
 - Arc current and duration
 - Airflow speed – even a light to moderate breeze can extinguish initial ignition
 - Fuel type, fuel moisture content, air temperature and relative humidity.

The probability of sustained ignition was measured against variations in these factors to develop reliable high level conclusions and identify realistic worst case conditions. Results for worst case conditions were plotted against arc duration to produce ignition probability curves at three current levels – 4.2 amps, 50 amps and 200 amps.

- After arc current and duration, airflow is an important determinant of ignition probability:
 - Early extinction of low current arcs with even moderate airflow speeds indicates that low current arcs may not present a major ignition risk at realistic wind speeds, especially if such arcs occur at height where wind speed is greater.
 - Airflow often extinguishes initial ignition, making the probability of sustained ignition much less than the probability of initial ignition. The final outcome of some tests took 30-60 seconds to fully resolve. On occasion, strong airflow extinguished surface flame while sustained ignition continued in the fuel bed shielded from airflow. Post-arc extinction of initial ignition by airflow is a major cause of uncertainty in arc outcomes.

Effect of circuit reclose

- Based on a limited number of tests for a single test condition (200 amps, 45°C air, 20 kph airflow) a single reclose attempt after 5 seconds was found to have significantly higher probability of causing sustained ignition than the initial fault, i.e. the reclose attempt appears to be predisposed towards ignition by the initial fault 5 seconds earlier.
- Tests at an increased reclose delay of 30 seconds (at 35 amps, 45°C air, 10 kph airflow) showed the probability of ignition in the reclose attempt was no higher than in the initial fault, i.e. any residual effects from the initial fault had diminished to a level that did not predispose the reclose attempt towards ignition, so the fault and reclose attempt can be considered independent events.

Effect of Ground Fault Neutraliser (GFN)

- Simulation of phase-to-ground arc faults on GFN-protected powerlines indicated that GFNs may reduce ignition probability to levels close to zero. Ignition was not produced with simulated GFN arcs under conditions designed to be ‘worst case realistic’. Ignition in the GFN simulation only occurred under conditions that were outside the realistic worst case by a factor of two or more.

Probability of Bushfire Ignition from Electric Arc Faults

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1 Introduction

A number of the fires that occurred in Victoria on 7 February 2009 (Black Saturday) are thought to have been caused by faults in the electricity distribution system. The Victorian Bushfires Royal Commission¹ recommended action to dramatically reduce the likelihood that Victoria's electricity distribution networks start catastrophic bushfires. The Victorian government established the Powerline Bushfire Safety Taskforce under the auspices of Energy Safe Victoria (ESV) and commissioned it to undertake a program of work to identify and quantify options to reduce the risk of fires from faults in the electricity distribution powerline network.

A critical component of the Taskforce's program has been development of a quantitative understanding of the probability that a fire will ignite from a powerline fault, depending on the nature and severity of the fault, the condition of the forest or grassland fuel, the meteorological conditions, etc. HRL was contracted by ESV to develop and conduct tests and analysis to address this requirement. ESV defined the ultimate objective of the test program to be:

Development of a series of probability distribution curves that can be used to assess the risk that an electricity-related event will start a bushfire under various circumstances, particularly on days of extreme fire weather conditions.

A literature review² completed by HRL did not identify any research into the prospects of an electric arc starting a fire in forest material or grasses. There was a substantial volume of literature on investigations into the critical parameters that affect the ignition of fuels, relating to the properties of the fuel, the nature and intensity of the heating source, environmental conditions etc. This information was useful in selecting the conditions and design for the testing program.

There has also been substantial work done in Australia on the ignition of fires from hot metal particles emitted by clashing powerline conductors. This has confirmed that emitted particles can cause fires. Since the protective technologies that prevent emission of hot metal particles are already well understood, HRL and the Taskforce developed an approach for a suitable test program focused on ignition of fires by electric arcs.

The test program was specifically designed to determine worst case ignition probability by combining worst case arc energy release from simulated real network faults with worst case fire weather and fuel conditions. The intent has been to define arc conditions such that if these conditions are adequately addressed, there is a material degree of assurance that fire risk will always be low. In many real situations and powerline fault events, fire risk will be much lower than these test results indicate for a variety of reasons.

HRL developed and produced appropriate test equipment and procedures and supervised extensive tests at Testing and Certification Australia's (TCA) high power test facility in Lane Cove, NSW.

¹ 2009 Victorian Bushfires Royal Commission Report The fires and related deaths Final Report Volume 1 July 2010

² Bushfire Ignition from Electrical Faults – A Review of Technical Literature, Dick Coldham HRL Report No HLC/2010/440 March 2011.

This report presents the results of the entire test program, which was carried out over 18 days at TCA finishing on 19 August 2011. It includes the results of additional tests that were not in the Interim Report³. These additional tests, Tranche 4 of the program, were carried out to improve the statistical significance of data at 4.2 and 200 Amp and to obtain sufficient data for 50 Amp probability curves.

In this test program the appropriate electrical conditions that simulated faults in the Victorian electricity distribution system were explored to better understand the energy and power from electrical arcs and the intensity of the resultant heat flux. From this work it was possible to identify appropriate test parameters that were representative of worst-case on days of extreme fire risk. From an extensive test program an improved understanding of the probability of ignition for high, intermediate and low current faults was developed and this is reported in Section 2. Further trials were completed to explore the effects of reclose events on ignition and the prospects that ground fault neutraliser devices could reduce the risk of fires. The results from these trials are presented in Sections 3 and 4.

The tests revealed the importance of wind speed in determining arc stability and ignition and Section 5 sets out the process used to identify worst case wind speed conditions.

The later sections of the report (Sections 6 to 9) provide background information on ignition and combustion and factors that influence these. They also present results from the electrical and heat flux program of testing. Data in these sections was used to support the selection of test conditions and procedures used for the determination of ignition probability.

³ Interim report – Probability of Bushfire Ignition from Electrical Arc Faults. Report No HLC/2010/195-A D.Coldham, A.Czerwinski and T.Marxsen, HRL Technology Pty Ltd July 2011.

2 Ignition probability

- Under relatively still air conditions ignition can be caused by electric arcs of short duration, even at low currents. Dried straw/hay was more flammable than dried leaf litter. Green eucalypt leaves could also be ignited by higher energy arcs.
- Initial ignition appears to be very fast (<30 ms) when the arc 'thread' touches dry fuel. Ignition is most unlikely unless the plasma contacts fuel. No instances of ignition from radiation heat flux were observed.
- Probability of sustained ignition depends on arc current and duration, airflow speed, fuel type, fuel moisture content, air temperature and relative humidity.
- Early extinction of low current arcs under conditions of even moderate airflow speeds indicates that low current arcs may not present a major ignition risk in realistic conditions, particularly at height where wind speed is greater.
- Airflow often extinguishes initial ignition after the arc ceases, i.e. sustained ignition is not achieved. This is a major cause of uncertainty in outcomes of ignition tests.

2.1 Ignition test conditions

The objective of the test program considered in this section was to quantify the probability of ignition from realistic powerline faults under realistic worst-case conditions on days of extreme fire danger.

Extensive exploratory tests and analysis were used to learn more about electric arcs in realistic powerline faults and to define worst case environmental conditions for ignition testing. These exploratory tests informed the experimental design to ensure reproducibility and consistency in the main ignition probability test program. A key finding of the exploratory tests was the necessity to design the test procedure and analysis to account for the chaotic behaviour of arcs. This was compounded by the observed dramatic influence of wind speed on the length and shape of the arc and on self-extinction of the arc (when simulating low current faults).

To achieve reproducible test conditions and ensure tests accurately represented the worst case scenario, the electrodes were partially embedded in the fuel, ensuring an effective arc to fuel distance of zero. This removed the requirement for heat flux measurements in the main ignition test program. A 110 mm maximum arc gap length was also selected so the whole arc was in contact with the fuel for the duration of each test.

Limitation of the test program to just three levels of arc current was judged the best way to meet program time constraints. Distinctive characteristics observed for low and high current arcs led to selection of a low arc current of 4.2 amps to represent tree-contact faults and a high arc current of 200 amps to simulate lower resistance faults, such as those to pole stays, fence posts, etc. An intermediate arc current of 50 amps (representative of phase-to-ground faults typically seen across wide areas of both SWER and 22 kV distribution networks in Victoria) was selected to maximise the applicability of the results.

2.2 Ignition test results

2.2.1 Ignition probability under realistic worst case conditions

Worst case conditions are those that could be reasonably expected on extreme fire weather days, such as those experienced on Black Saturday. In the initial exploratory tests, these were progressively defined as 45°C air temperature at 20% relative humidity, a wind speed of 10 kph and fuel consisting of a loosely packed mix of hay and straw at about 5% moisture content⁴. Under these severe but representative conditions, tests revealed a high probability of ignition from arc durations typical of realistic powerline fault clearance times.

The variation of ignition probability with arc duration is shown in Figure 1 for low, intermediate and high current faults under worst case conditions. The 50 amp and 200 amp curves are each based on a large number of tests and hence the ignition probability prediction has a high level of confidence. The 4.2 amp curve has been developed from fewer tests and provides an indicative rather than a precise estimate of ignition likelihood.

The probability curves confirm that ignition can occur at shorter arc durations in high current faults compared to low current faults; a 50% probability of ignition was indicated for arc durations of ~60ms in 200 amp tests, whereas the same ignition probability required a ~160ms arc at 4.2 amps. At 4.2 amps, arc durations in excess of 200ms could still be insufficient to cause ignition.

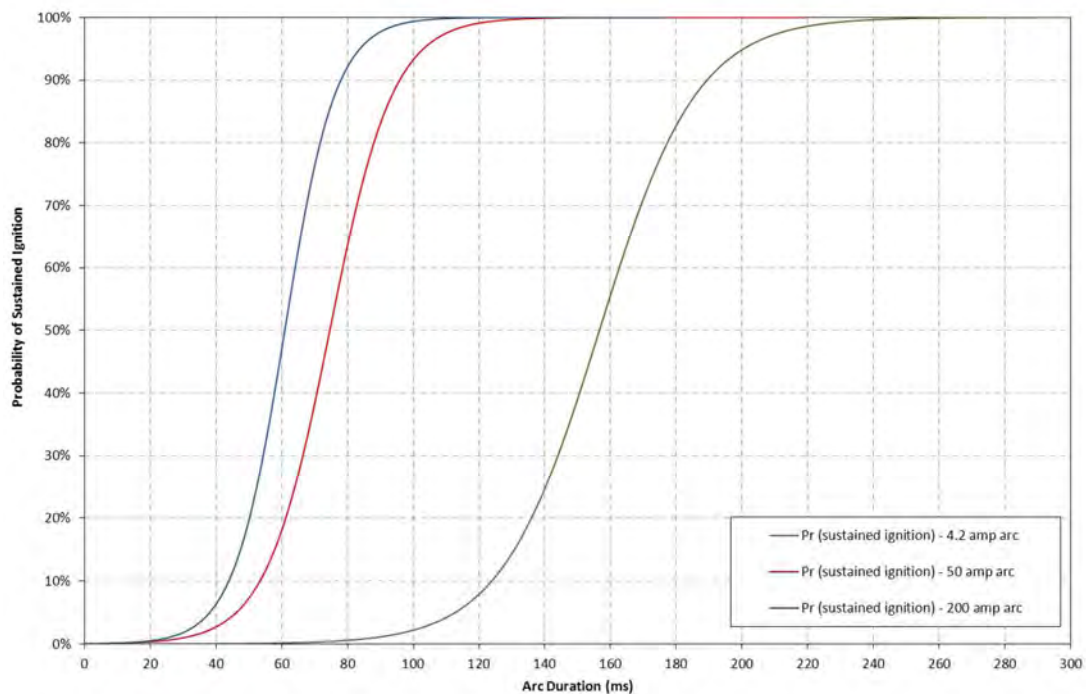


Figure 1. Ignition probability against arc duration for 4.2, 50 and 200 amp arcs at 45°C and 10 kph wind speed for hay/straw at 5% moisture

⁴ Determination of these 'realistic worst case' conditions is outlined in Section 5 of this report and beyond.

Ignition probability (P) curves for faults of duration, t_{arc} in ms, at a given current (I in amps) are described by the following equations. Details of the binomial regression are outlined in Section 2.4.

$$P_I = \frac{1}{1 + e^{-z_I}},$$

where z_I is an environmental factor given by:

$$z_{200A} = -7.85 + 0.129t_{arc}$$

$$z_{50A} = -7.71 + 0.103t_{arc}$$

$$z_{4.2A} = -10.5 + 0.0671t_{arc}$$

The curves shown in Figure 1 are presented in more detail below, including 95% confidence limits. When interpreting these curves, the following should be noted:

1. The solid curve shows the result of binomial regression analysis of 71 ignition tests for 200 amp arcs (Figure 2), 150 tests for 50 amp arcs (Figure 3), and 23 tests for 4.2 amp arcs (Figure 4).
2. The grouped test data points represent the average ignition result of all tests performed at that particular arc duration. The error bars on the grouped test results indicate the 95% confidence interval of that group average result and depend on the number of tests performed to derive it (see Sections 2.4 for details).
3. The 95% confidence limits of ignition probability (dashed curves) represent the fit of the regression to the ungrouped test data. These have been calculated independently of the 95% confidence intervals for grouped test results shown by the error bars.

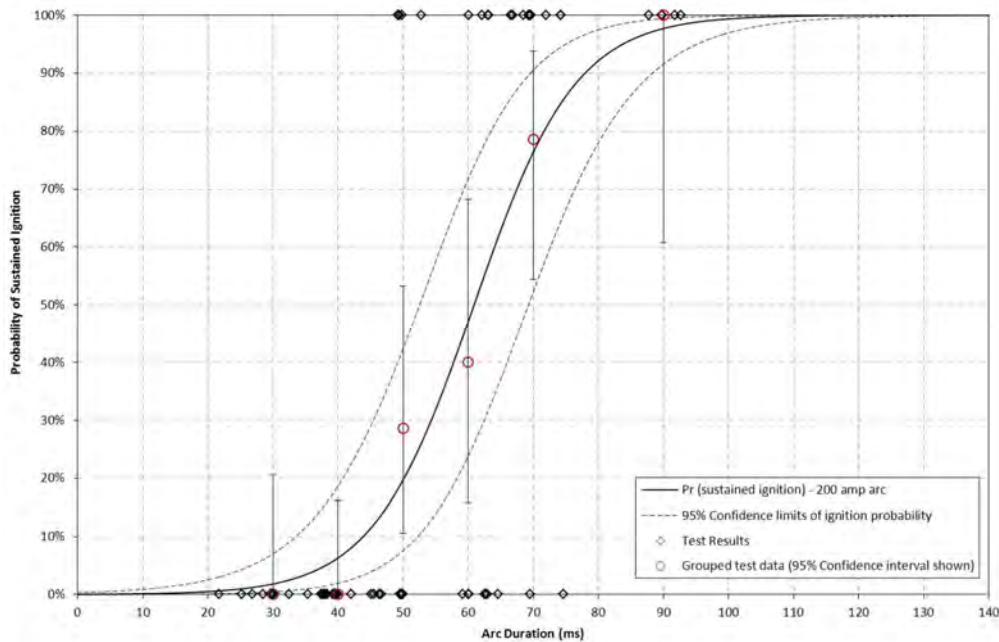


Figure 2. Ignition probability against arc duration for 200 amp arcs at 45°C and 10 kph wind speed for hay/straw at 5% moisture showing 95% confidence limits. Curve is based on regression of 71 tests.

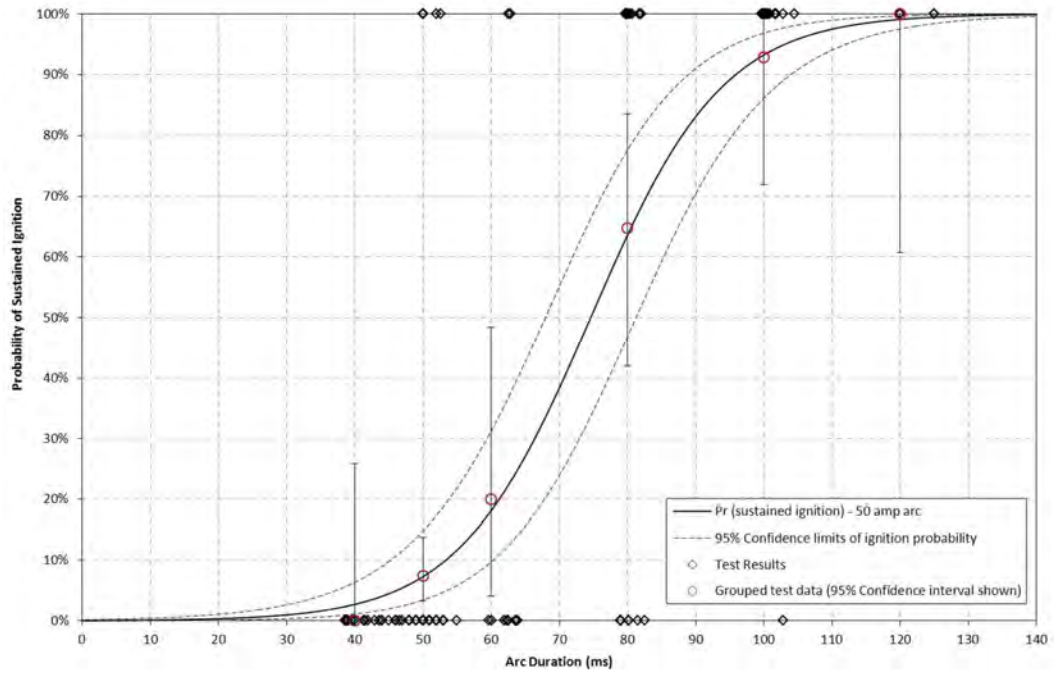


Figure 3. Ignition probability against arc duration for 50 amp arcs at 45°C and 10 kph wind speed for hay/straw at 5% moisture showing 95% confidence limits. Curve is based on regression of 150 tests.

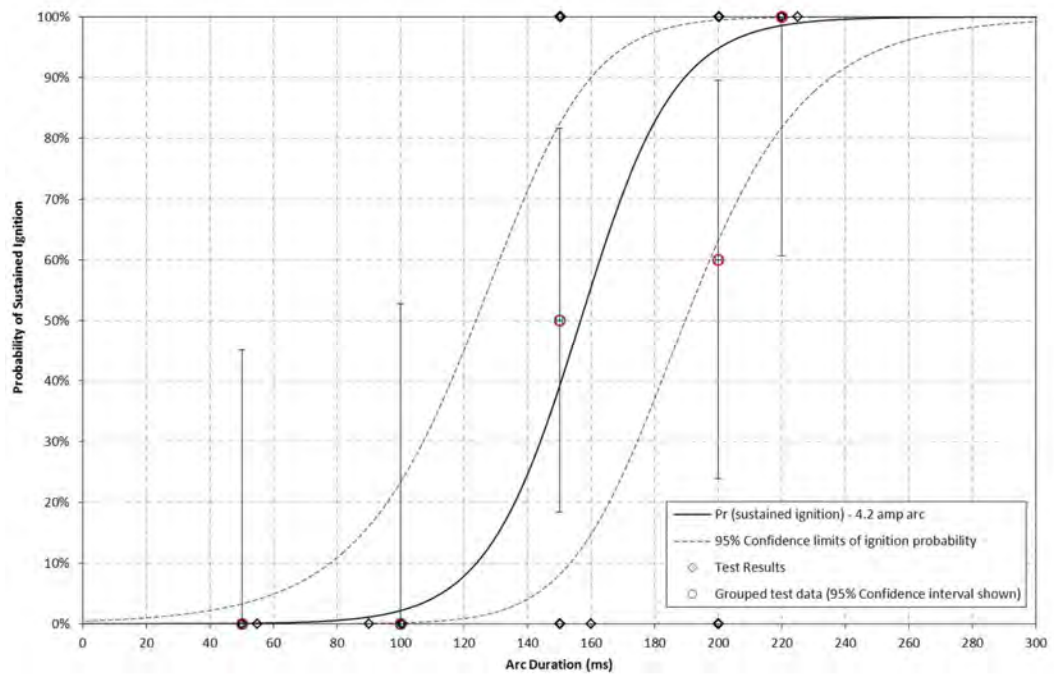


Figure 4. Ignition probability against arc duration for 4.2 amp arcs at 45°C and 10 kph wind speed for hay/straw at 5% moisture showing 95% confidence limits. Curve is based on regression of 23 tests.

2.2.2 Ignition probability under extended conditions

In addition to considering ignition probability for worst case conditions, probability curves were also developed for what might be considered as either ‘less severe’ or ‘unrealistic’ conditions. These curves were developed from tests in both Tranche 3 and 4 of the test program using multivariable regression, the details of which are provided in Section 2.4. The environmental factor, z_I , used to describe ignition probability in these curves is given by:

$$z_{4.2A} = -4.38 + 0.0446t_{arc} - 0.807v_{wind} + 0.199T_{air} - 0.752C_{fuel}$$

$$z_{200A} = -3.83 + 0.0941t_{arc} - 0.693v_{wind} + 0.186T_{air} - 0.717C_{fuel}$$

The primary purpose of this analysis was to illustrate or explore the effect of departures from worst case conditions. One such curve is shown in Figure 5 for 200 Amp arcs but with 20 kph wind speed, and this indicates that significantly longer duration arcs are required for ignition at the higher wind speed. However, in Figure 5 only five series of tests (average of 4 tests in each) were performed at the nominated conditions of 200 amps, 45°C and 20 kph airflow with hay/straw at 5% moisture content. This indicates the uncertainty in such curves, and care must be exercised as they summarise a large amount of data that can reveal overall effects but cannot be used reliably for single-point predictions.

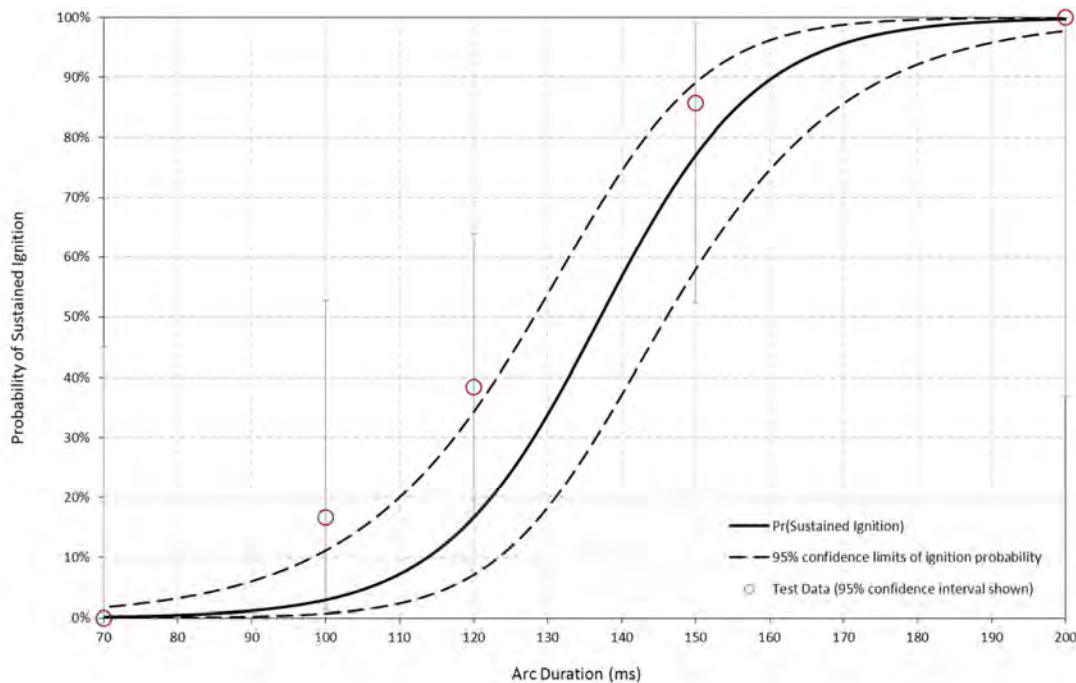


Figure 5. Ignition probability against arc duration for 200 amp arcs at 45°C and 20 kph wind speed for hay/straw at 5% moisture

Probability curves developed on this basis should be taken as indicative rather than accurate. There are a number of points to take note of regarding these curves compared to those presented in Figures 1 through 4 above:

1. The solid curve shows the result of binomial regression analysis of 29 grouped ignition results (arising from 104 individual tests) for 4.2 amp arcs and 38 grouped ignition results (from 184 individual tests) for 200 amp arcs spanning a much wider range of conditions (wind speed, fuel moisture content, air temperature, etc.) than the few test results (indicated by circles) that directly apply to the specific conditions nominated for the chart. Hence the curve may sometimes appear to be a poor fit to the few data points shown.
2. Each grouped test data point is the average result from only 4 tests (on average) performed at a particular condition so uncertainty levels are much higher than for the curves shown in Figures 2 and 3 which have used 18 tests (on average) for each arc duration.
3. The 95% confidence limits of ignition probability (dashed curves) have been calculated independently of the 95% confidence intervals for each grouped test result and represent the fit of the regression to all of the grouped results used in the regression, not just the condition shown.

2.2.3 Relative importance of test variables

Ignition results suggest that, of the variables investigated:

- arc duration and wind speed have the greatest influence on ignition probability
- air temperature, and correspondingly reduced relative humidity, appears to have a lesser effect.

2.2.3.1 Arc duration

Figures 1 to 4 illustrate the profound effect that arc duration has on ignition probability, with near-zero ignition likelihood and near-certain ignition separated by only ~80ms (4 cycles) at 200 amps. Arc duration was identified as the most appropriate test parameter against which to plot an ignition probability curve for a given arc current.

Arc duration is a useful parameter for network engineers as it directly relates to protection system fault clearance time. It is also intimately related to overall arc energy release which clearly has a major bearing on the ignition result.

The relationship between arc energy release and arc duration is illustrated in Figure 6. Lower current arcs behave very differently to higher current arcs (see Section 8.1) and show more variability of energy release. The curves in Figure 6 are shaped by the electrode movement profile used (see Section 2.3.2). A fixed arc gap length would be expected to produce a more linear relationship between arc energy and duration.

2.2.3.2 Wind speed

High wind speeds dramatically reduce ignition probability. This effect is attributed to the dispersion of pyrolysis gases by wind as well as the cooling effect of airflow, even at 45°C. These effects were found to outweigh any intensified burning resulting from an increased supply of oxygen.

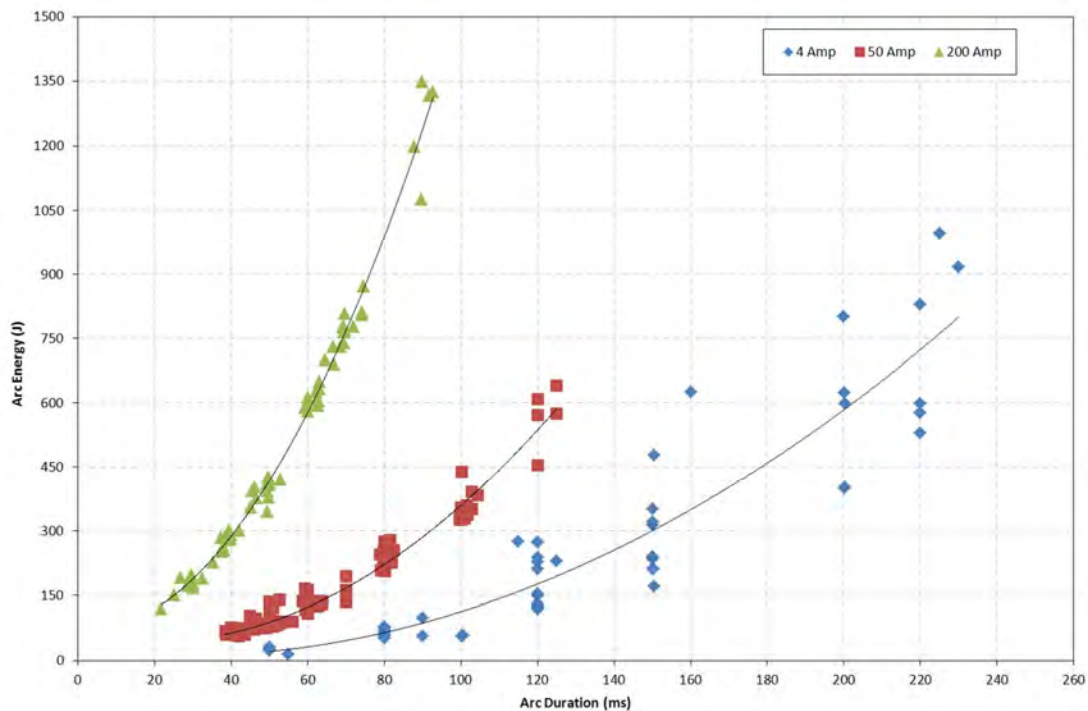


Figure 6. Relationship between arc energy and arc duration for tests performed at 45°C and 10 kph wind speed (worst case ground level conditions)

Figure 7 illustrates the effect of 20 kph wind speed. This value of wind speed is potentially important as it might reasonably be expected based on the analysis set out in Section 5, to be the typical wind speed at a height of 10 metres above ground level, i.e. at the height where trees and powerlines sometimes touch. The increase in wind speed significantly reduces the likelihood of ignition, extending the arc duration required for 50% ignition likelihood from ~60 ms at 10 kph to more than 135 ms at 20 kph.

Airflow was also found to extinguish arcs, particularly at low currents. In five low current tests performed at 20 kph airflow, early arc extinction occurred each time, sometimes after as little as 50 ms in tests intended to last 200 ms. None of these tests resulted in ignition. This is an important finding as it suggests that low current faults may not pose a major risk in moderately windy conditions and almost none in high winds.

Early arc extinction caused by airflow also occurred a number of times in tests with a wind speed of 10 kph and on two occasions at 5 kph.

2.2.3.3 Fuel type

Two fuel types were investigated: straw/hay mix and eucalyptus leaf litter, with most tests done using straw/hay mix once it became clear it is the much more flammable of the two. Difficulty in igniting eucalyptus leaf litter with moisture contents of 5% and 14% led to the conclusion that dry straw/hay mix is a much better simulation of worst case conditions. It also confirmed that conditions for 100% probability of ignition could not always be achieved using eucalypt leaf litter, particularly at low fault currents.

The limited number of tests performed using leaf litter (18 at 4.2 amps and 15 at 200 amps) was deemed sufficient to confirm that this was not a ‘worst case’ fuel, i.e. straw/hay mix was more likely to ignite. It was not sufficient to obtain a quantitative estimate of the difference in ignition probability between the different fuel types.

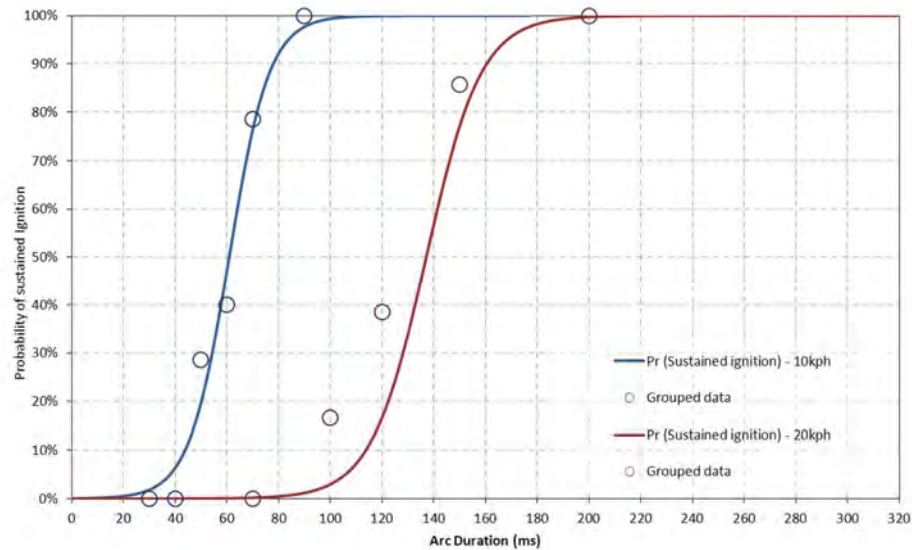


Figure 7. Effect of wind speed on ignition probability (200 amps, 45°C, 5% fuel moisture)

2.2.3.4 Fuel moisture content

The test plan included two levels of fuel moisture content: 5% and 10%. However, analysis of fuel samples after testing indicated the actual range across all tests was from an average of 5.4% to an average of 7.9% (see Section 2.3.3 below).

Figure 8 confirms that higher fuel moisture content reduces ignition probability. However, there was insufficient data to quantify the effect. If quantification of different levels of fuel moisture is required, a more elaborate test rig may be necessary to control moisture content more closely during the testing.

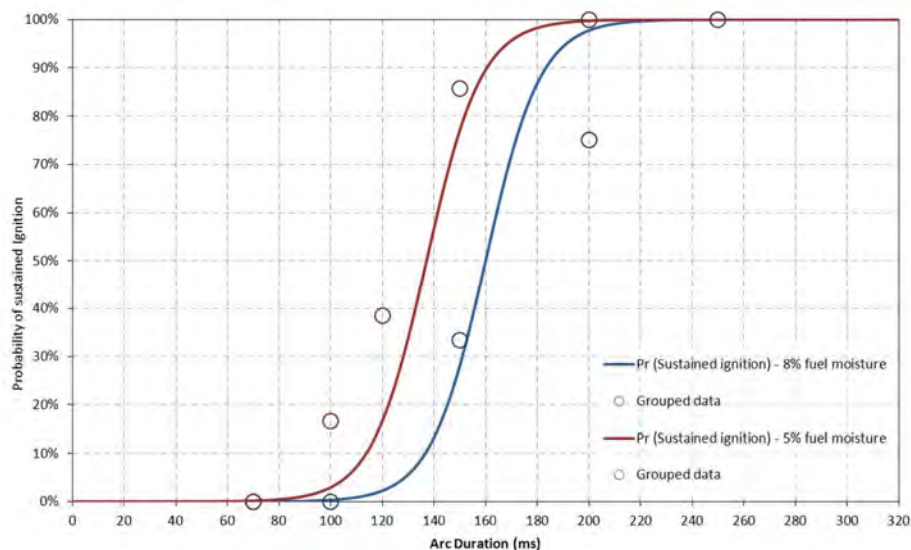


Figure 8. Effect of fuel moisture content on ignition probability (200 amp arc, 20 kph airflow)

2.2.4 Ignition probability tool

A macro-enabled Microsoft Excel tool was developed to generate probability curves for any specific combination of test conditions based on the single and multivariable regressions used to produce the curves shown in Figures 1 and 5. This tool has been separately provided to ESV. A screen shot of the tool is shown in Figure 9.

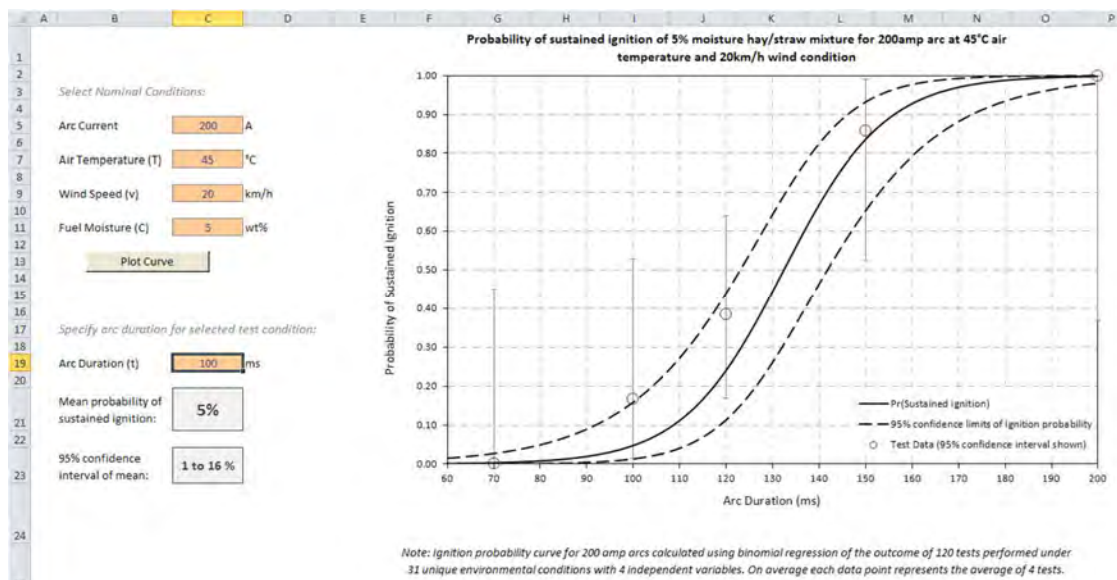


Figure 9. Ignition probability estimation tool

2.3 Experimental design

2.3.1 Ignition criterion

Sustained ignition was defined as flaming that required manual extinction to be contained and this definition was used as the determinant of the outcome of ignition tests. A common result in tests was initial ignition resulting in smouldering and smoking of fuel which was eventually extinguished by airflow, albeit sometimes after more than 40 seconds.

The risk of error associated with the human judgement required to decide if it was necessary to manually extinguish ignited fuel was addressed by allowing tests showing any level of uncertainty to continue until either the entire fuel load was consumed (taken as sustained ignition), ignition escalated to a clearly sustainable level, or the fuel and wind conditions resulted in eventual extinction (no visible flame or smoke, nor crackling sound) though unburned fuel remained (taken as non-sustained ignition). This meant that fuel baskets following tests judged as having a negative ignition outcome often contained significantly charred and burned fuel as well as unburned fuel.

Examples of arcs against dry grass and leaf litter fuel during tests are shown in Figure 10.

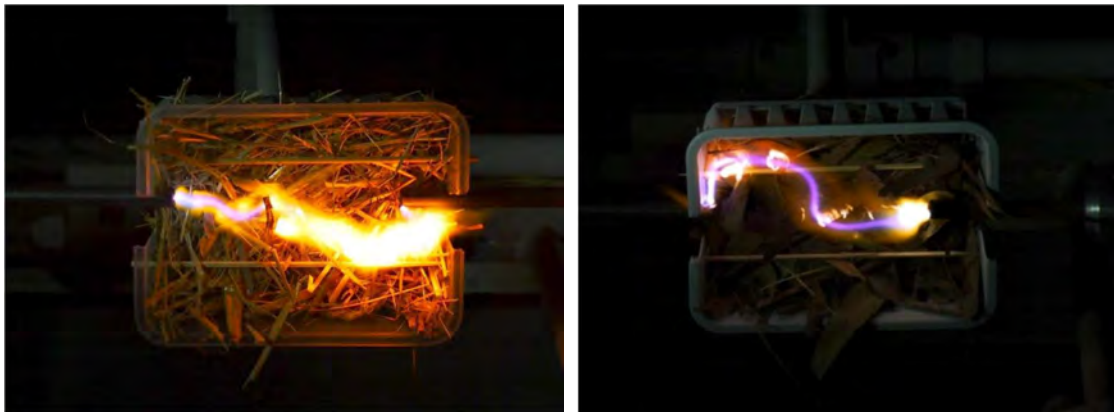


Figure 10. Arc within the fuel basket and subsequent ignition of dried grass (LHS) and leaf litter (RHS). 4.2 amp tests after full arc separation to 110 mm.

2.3.2 Test conditions

Tests were done at high (200 amp), intermediate (50 amp) and low (4.2 amp) arc currents. Exploratory tests were performed at high and low current levels only. These explored the effects of five variables: air temperature (with corresponding relative humidity value), airflow speed, fuel type, fuel moisture content and arc duration. All tests at the intermediate current level were done under worst case conditions, with arc duration as the only variable.

Test conditions used for ignition probability regression analysis are listed in Table 1 which shows the various levels of classification used to categorise test conditions.

Condition ID	Air temperature °C	Wind speed kph	Fuel type	No. of sub-conditions
4.2 amp arcs				
1	23	5	Hay/straw	12
2	45	5	Hay/straw	8
3*	45	10	Hay/straw	9
50 amp arcs				
11*	45	10	Hay/straw	6
200 amp arcs				
6	23	5	Hay/straw	10
7	45	5	Hay/straw	8
8*	45	10	Hay/straw	10
9	45	20	Hay/straw	10

* Used for single variable regression under worst case condition.

Table 1. Test conditions used for probability regression analysis

Further classification was based on the fuel moisture level, 5% and 8% represented by L (low) or M (medium) respectively and the arc duration (to the nearest 10 ms). As an example, a sub-condition of 8L60 indicates a 60 ms duration 200 amp arc ignition test at 45°C air temperature and 10 kph wind speed using 5% moisture straw/hay fuel.

For each of the conditions in Table 1, arc duration was varied to obtain results spanning the full range of ignition probability on the basis of the procedure outlined in the most relevant industry standard⁵. Using the vacuum circuit breaker at TCA it was possible to control arc duration to half a cycle of the 50 Hz power supply (i.e. to 10ms). The arc duration for each test was determined from the arc voltage waveform recorded using TCA's data acquisition system at a 20 kHz sampling rate. Details of all test conditions and results from each test are included in Appendix 4.

When previous test results indicated an expected outcome with high certainty, e.g. consistent ignition because results at shorter arc durations indicated ignition was certain, implied results were assigned and no test was performed. This only applied to a small number of conditions used for the multivariable regression (5 for 4.2 amp faults and 4 for 200 amp faults) where the ignition probability was assumed to be either zero or 100 %. It was assumed that only a single test was performed at each of these conditions. A total of 29 discrete sub-conditions (104 ignition tests) were performed for the 4.2 amp arc current tests and 38 discrete sub-conditions for the 200 amp arc current tests (184 ignition tests).

Realistic worst case conditions were defined as 45°C air temperature, a wind speed of 10 kph and fuel consisting of loosely packed hay and straw with approximately 5% moisture content. This corresponds to condition IDs 3, 8 and 11 in Table 1, where the majority of tests (23, 71 and 150 tests respectively) were performed.

⁵ ASTM F1958/F1958M – 99 (Reapproved 2005) Standard test method for determining the ignitability of non-flame-resistant materials for clothing by electric arc exposure method using mannequins

Tests were carried out with simulated winds between 5 kph and 20 kph. Very high winds (one-minute average of >70 kph with peaks above 90 kph at 10m height) were recorded on Black Saturday and it was reasoned that lower speeds might occur for short periods, particularly closer to the ground. The detailed reasoning and the analysis of Australian Bureau of Meteorology Black Saturday wind speed data is set out in Section 5.

All ignition tests were carried out with mild steel electrodes as preliminary testing indicated the electrode material had insignificant effect on results (see Section 8.5). One of the electrodes was fixed and the other drawn away from it at an acceleration of 9.8 m/s^2 to reach a maximum velocity of 1.2 m/s simulating a live conductor falling away from an earthed structure or vegetation falling away from a live conductor. The electrodes were partially embedded in the fuel, initially in contact with one another before being drawn out to a separation of 110 mm. The arc gap between electrodes was limited to 110 mm in order to confine the arc completely within the length of the fuel basket. The maximum displacement of 110 mm was reached after 170ms as shown in Figure 11.

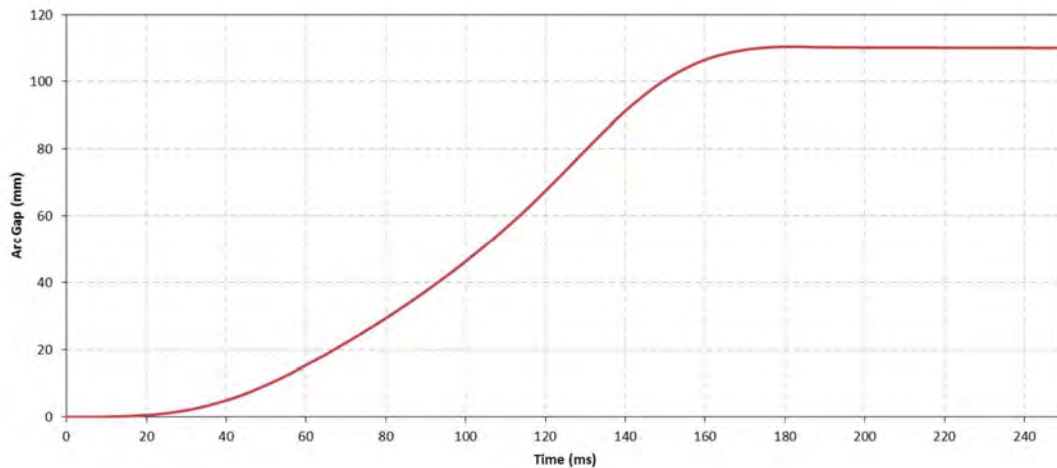


Figure 11. Electrode displacement (arc gap) for ignition tests

2.3.3 Verification

Each variable specified for a particular test condition was verified by direct measurement during the test or (in the case of fuel moisture content) by post-test analysis of samples sealed in plastic bags immediately after the test. Overall, the desired test conditions were verified as successfully achieved.

Measurements of wind speed, temperature and relative humidity during tests are summarised in the tables below. These parameters are considered in Section 7.2.6 and a more detailed analysis of wind speed is provided in Section 5.

Target velocity	Crosswind velocity (kph)		
	25 mm from fuel	Surrounding fuel basket	Uninterrupted (without fuel basket)
5	5±1	6±1	-
10	9±1	10±3	-
20	17±3	19±5	23±2

Table 2. Typical wind speed employed during ignition tests showing 1 S.D.

Condition	Average Temperature (°C)	Average Relative Humidity (%)
Ambient	23±3	59±13
Elevated	45±3	18±5

Table 3. Average air temperature and humidity for ignition tests at ambient and elevated temperatures showing 1 S.D.

Hay/Straw Moisture	As prepared	45°C Tests	20°C Tests
Low	5.2%	5.4%	6.7%
Medium	11.9%	6.4%	7.9%

Table 4. Fuel moisture content measured by post-test analysis of sealed samples.

The fuel baskets were conditioned at controlled humidity and temperature at HRL Mulgrave and sealed in plastic bags. The time between opening of a fuel bag at TCA Lane Cove and initiating the arc was of the order of five minutes. This interval could not be closely controlled due to the many variable factors involved in high voltage safety procedures prior to arc initiation. It is apparent that the hot and windy conditions in the test cell can rapidly dry the fuel. The ambient relative humidity on the test days ranged up to 95% and the maximum ambient temperature was 20°C.

2.4 Probability regression methodology

Two different forms of regression analysis were used, varying only in the degree to which the test data was aggregated before being input to the regression algorithm:

1. Tests at worst case conditions: no aggregation, each individual test entered as a 1 (sustained ignition) or 0 (no sustained ignition)
2. Test at extended conditions: all individual tests for a single condition were averaged and the result (a number in the probability range of 0 to 1) entered for that group of tests.

2.4.1 Tests at worst case conditions

Binomial regression was performed for 50 and 200 amp arcs under worst case conditions. A large number of tests were performed under these conditions, particularly at short arc durations - the low probability region where information is likely to be of greatest value to network engineers.

The result of each individual ignition test was input into a binomial regression analysis algorithm. This approach is consistent with that specified in the ASTM method⁶ for assessing the probability of ignition of clothing from electric arcs, i.e. it is a proven and well understood approach which was considered directly applicable to the test program objectives.

A similar 'high confidence' curve was planned for 4.2 amp arcs. However, the difficulty of achieving consistent test performance at low arc currents prevented collection of the required volume of data within the allocated time in the test program. Consequently, the 4.2 amp curve (Figure 4) has a lower level of confidence than the 50 amp and 200 amp curves.

Post-test analysis also explored the possibility of a single unified curve of ignition probability against arc energy release covering all 4.2, 50 and 200 amp tests done under worst case conditions. However, a poor curve fit was observed, suggesting that arc energy release alone is insufficient to accurately represent ignition probability across a range of arc currents.

2.4.2 Tests at extended conditions

The average result (proportion of sustained ignition outcomes) of each discrete sub-condition was used as input to a single regression calculation covering all such tests for each level of arc current (4.2 amps and 200 amps).

The number of tests performed for any individual condition away from the defined worst case was not large enough to support reliable binomial regression, so a fully aggregated approach was adopted. A single multi-variable regression was based on all tests conducted across the full range of conditions shown in Table 1 for each level of current. The result of this regression analysis was then used to explore the effect of variations from worst case conditions. The confidence level of any single probability estimate derived from this aggregated regression is less than that for the worst case condition predictions.

2.4.3 Regression algorithm

Binomial regression was used to fit the test data to a logistic function of the form

$$P_I = \frac{1}{1 + e^{-z_I}}$$

where P is the probability of ignition, I is the fault current and z is a parameter used to define the test conditions.

⁶ See footnote 5 on page 19.

The resulting logistic function can be used to estimate the ignition probability for a particular test condition. The input values for z can include infinitely large positive or negative numbers. To limit the result to the field of interest, sustained ignition and non-ignition results were assigned z values of ± 6 (corresponding to ignition probabilities of 99.75% and 0.25% respectively).

Test conditions were described by either

$$z_I = -B_0 + B_1 t_{arc}$$

for the tests performed at worst case conditions or

$$z_I = -B_0 + B_1 t_{arc} + B_2 v_{wind} - B_3 T_{air} + B_4 C_{fuel}$$

for remaining tests at extended conditions.

B_0 in the above formulae is a constant while B_n (where $n = 1$ to 4) are coefficients used to assign a weighting to each of arc duration (t_{arc} , ms), wind speed (v_{wind} , kph), air temperature (T_{air} , °C) and fuel moisture content (C_{fuel} , %).

Regression was performed by using a least squares fit to converge on an optimal solution for each of the coefficients. Uncertainties in the regression were determined for a 95% confidence level by substituting upper and lower limits of z_I :

$$z_{95\%} = z \pm 1.96 SE$$

into the equation for P_I . SE in the above is the standard error calculated according to

$$SE = \sigma \sqrt{\frac{1}{n} + \frac{(z - z_{mean})^2}{SSR}}$$

where σ is the standard deviation, n is the number of tests and SSR is the sum of squared residuals. Parameters for each of the coefficients determined from the regressions are tabulated in Table 5.

Condition	B_0	B_1	B_2	B_3	B_4	n	SSR	Var	SD
50A worst case	-7.708	0.1033	-	-	-	150	2675	17.95	4.2
200A worst case	-7.849	0.1289	-	-	-	71	1419	20.27	4.5
4.2A worst case	-10.50	0.06707	-	-	-	23	442.9	23.31	4.8
4.2A extended	-4.382	0.04458	-0.8071	0.1997	-0.7515	29	126.1	5.045	2.2
200A extended	-3.827	0.09408	-0.6931	0.1861	-0.7171	38	211.5	6.221	2.5

Table 5. Binomial regression parameters for arc-ignition tests.

Regression probability curves showing average ignition results for all test conditions are provided in Figures 12 and 13. Probability curves for specific conditions have been derived from the results of the multivariable regressions.

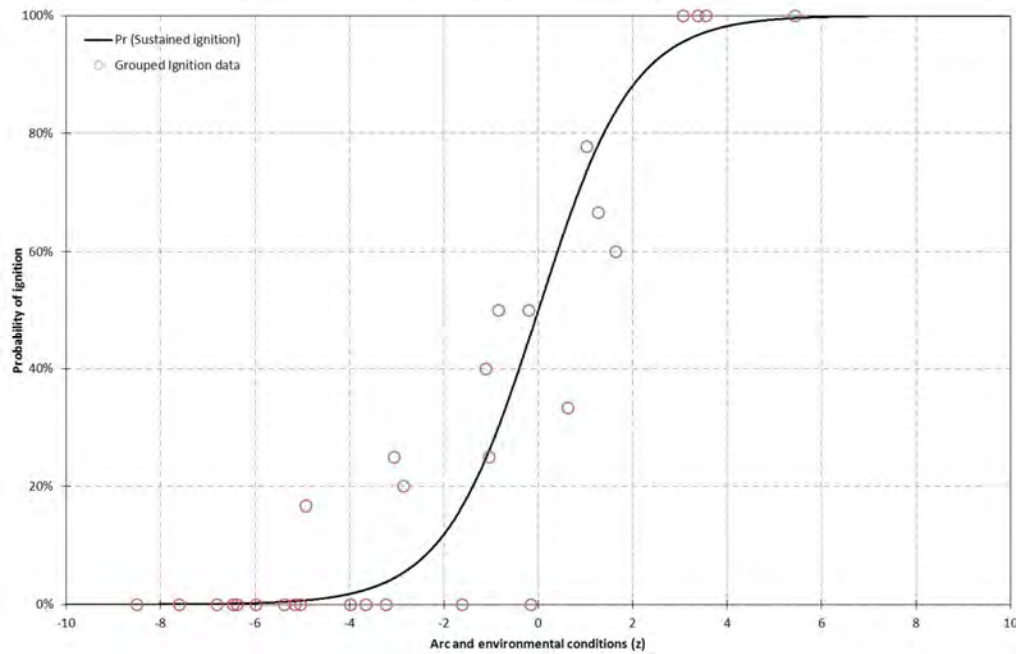


Figure 12. Ignition probability against environmental factor (z) for 4.2 amp arcs (n = 29)

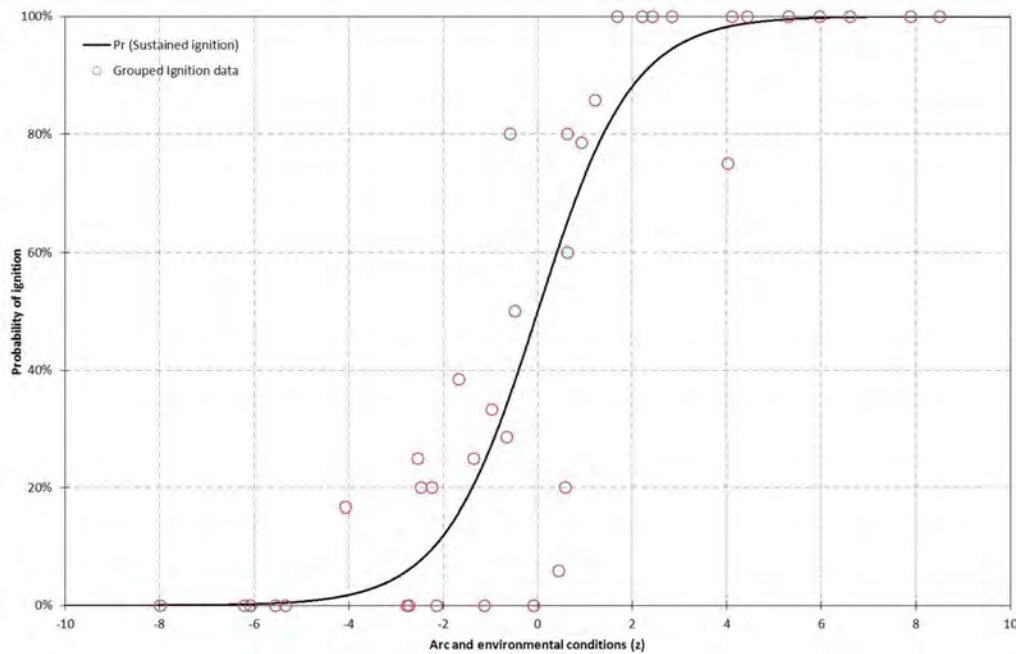


Figure 13. Ignition probability against environmental factor (z) for 200 amp arcs (n = 38)

Confidence intervals for ignition probability at particular test conditions were calculated using an integration of Bayesian posterior (IBP) approach described by Ross⁷. They are indicated through error bars in the ignition probability curves throughout this Chapter.

⁷ Timothy D Ross, *Accurate confidence intervals for binomial proportion and Poisson rate estimation*, Computers in Biology and Medicine 33 (2003) p509-531

3 Reclose simulation tests

Tests indicate that a single reclose attempt will increase ignition risk as it can result in two arc events instead of one. Risk may be further increased for short reclose delay times.

If the reclose delay is long (30 seconds), the initial fault and the reclose attempt each appear to have about the same ignition probability, i.e. they can be treated as independent events and a low level of risk may be doubled if a single reclose attempt is used.

If the reclose delay is short (e.g. 5 seconds - typical of current practice), test results indicate the reclose attempt has a higher ignition probability than the initial fault, i.e. the two events are not independent and a low level of risk may be more than doubled if a single reclose attempt is used.

The tests reported here provide preliminary indications only. They have many limitations and do not directly cover the situation where network settings have already reduced fire risk to a low level.

3.1 Purpose of the tests

The Victorian Bushfires Royal Commission recommended constraints on automatic circuit reclose over the fire season and on days of extreme fire weather. The effects of such constraints on the reliability of customer supply may be substantial. Customers have expressed strong concerns that the constraints may be counter-productive as they could adversely affect community fire preparations.

Ignition probability tests were conducted under simulated automatic reclose conditions. The results reported here provide a preliminary assessment of the effect of a single automatic reclose attempt on ignition probability.

Probability theory states that an independent pair of identical tests, taken together, should have a probability of ignition equal to:

$$P = 2P_1 - (P_1)^2 \text{ where } P_1 \text{ is the probability of ignition in a single test.}$$

If the probability determined by tests is significantly different to this prediction, it indicates that the two tests are not independent, i.e. the first affects the outcome of the second. In the case of ignition testing, this may occur if the second test occurs very quickly after the first, before residual embers are fully extinguished and fuel returns to its original temperature.

Applying this theory to automatic reclose of powerlines following a fault, it implies that:

- The probability of a fire being produced by a fast fault clearance followed by a single reclose attempt and second fast fault clearance can be expected to be somewhat less than twice the probability of a fire with no reclose attempt
- If the first arc (caused by the powerline fault) predisposes the fuel towards ignition by the second arc (caused by the reclose attempt onto a sustained fault) the probability of a fire with reclose may be more than twice the probability of a fire with no reclose attempt.

The purpose of the reclose tests was to conduct a preliminary experimental assessment of these theoretical conclusions for realistic network faults and reclose delay times.

3.2 Test results for 5 second reclose delay

Test results indicate that a 5 second reclose delay may be too short for the two potential ignition events to be fully independent, i.e. overall ignition probability may be heightened by the short delay time.

In Tranche 3 of the test program, 26 tests were performed to assess the effect of a single reclose attempt after a 5 second time delay. The conditions used for the 26 tests were:

Arc current	Arc gap	Arc duration
200 amps	110 mm	100ms
Airflow	Air temperature	Air relative humidity
20 kph	45°C	<20%
Fuel-arc distance	Fuel type, moisture	Reclose delay
Zero	Straw/grass, ~5%	5s

Reclose was simulated by having steel electrodes (which were partially embedded in the fuel) draw apart to a 110 mm gap to produce the first arc. The arc was extinguished by disconnecting the power at the end of the set arc duration. The actuator then moved the electrodes together to their original positions (sometimes, this completely embedded them in the fuel with fuel strands jammed between the electrodes) and the power was re-applied just before they drew apart again to produce the second arc.

This is a very conservative simulation as sustained faults (e.g. fallen powerline conductor on the ground) would usually be characterised by very small arc gap length in the second arc – which would mean low energy release from the second arc. However, it could be seen as representative of a conductor repeatedly touching and swinging away from an earthed structure covered in dry grass.

A total of 26 tests were carried out. 13 tests were performed with no reclose simulation (*TCA File No. 393 – 405*), and 13 tests were performed with a single automatic reclose attempt simulated (*TCA File No. 407 – 419*).

Two different methods of analysis were used and it was concluded that a short 5 second reclose delay may heighten ignition probability because residual effects of the first arc have not fully died away before the second arc occurs. The two analyses are as follows:

3.2.1 ‘Reclose’ versus ‘no reclose’ analysis

In this analysis approach, the two test series were considered as follows:

- No reclose (one shot per test): 5 ignitions in 13 tests - 38% probability of ignition
- Single reclose (two shots per test): 9 ignitions in 13 tests - 69% probability of ignition.

The tests thus suggest that there is an increase in the probability of ignition as a result of a reclose event after 5 seconds. However, if ignition probability of a single test is taken as 38% (the results from the non-reclose tests), the theoretical ignition probability of two successive tests is 62% which is slightly lower than the 69% value observed in the reclose

tests. With only 26 tests in total, significance testing indicates the conclusion that overall ignition probability with reclose is higher than without reclose still has about 6% chance of being incorrect.

3.2.2 'First shot' versus 'second shot' analysis

A different and arguably better analysis approach is to consider the test results in the following two groups:

'First shot' tests: 7 fires resulted from 26 tests with average arc energy release of 2.05kJ per test – 27% ignition probability (95% confidence limits of 13% and 45%).

'Second shot' tests: 7 fires resulted from 11 tests⁸ with average arc energy release of 2.20kJ per test – 64% ignition probability (95% confidence limits of 36% and 86%).

Two fully independent events, each with 27% ignition probability (determined from the 26 'first shot' tests), have a theoretical ignition probability of 47%, i.e. much lower than the 69% observed in the reclose tests. The difference in ignition probability between the first and second shots is illustrated in Figure 14. The low level of overlap between the 95% confidence limits indicates the result has a relatively high level of significance. Significance testing shows less than a 2% chance that the second shot ignition probability is the same or less than the first.

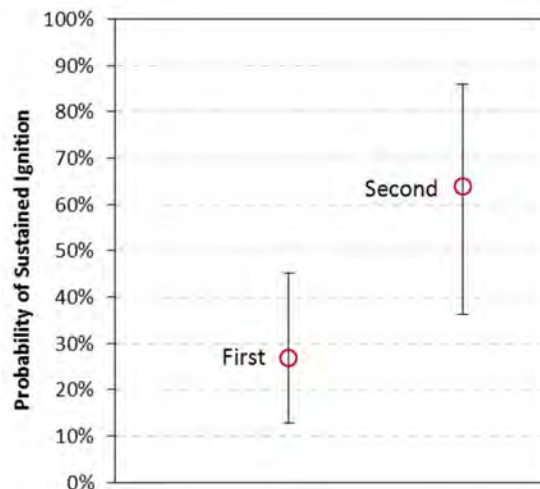


Figure 14. Difference in ignition probability with 5 seconds delay

This is prima facie evidence the two shots are not independent, i.e. residual effects from the first shot predisposes the second shot towards starting a fire.

The measured energy release in second shot tests was 8% higher than in first shot tests and analysis confirmed this was a statistically significant difference. Based on understanding of

⁸ In two of the 13 reclose simulation tests, a fire resulted from the first arc, leaving only 11 'second shot' tests.

the relationships between energy release, arc duration and ignition probability derived from all other ignition tests, this difference was not considered sufficient to account for more than about half the difference in ignition probability between the first and second shots.

3.3 Test results for 30 seconds reclose delay

Tests indicate that with a reclose delay of 30 seconds, the second shot has a probability of ignition no higher than the first. In Tranche 4, a second series of 51 reclose tests were completed. The conditions used for the tests were:

Arc current	Arc gap	Arc duration
35 amps	110 mm	50ms
Airflow	Air temperature	Air relative humidity
10 kph	45°C	<20%
Fuel-arc distance	Fuel type, moisture	Reclose delay
Zero	Straw/grass, ~5%	30s

The arc current level was reduced to 35 amps to produce a mid-range ignition probability by compensating the increase due to the ‘worst case’ airflow speed of 10 kph.

Reclose was simulated in the same way as in the Tranche 3 reclose tests. However, the procedure was modified to make the first and second shots more closely identical. In the Tranche 4 tests, the moving electrode was withdrawn and reclosed (without power applied, i.e. with no arc) prior to the first shot. This meant that conditions for the first shot were closer to those in the second shot: in closing, the electrodes sometimes embedded themselves in the fuel and occasionally closed with fuel jammed between them.

In the Tranche 4 reclose test series, 51 reclose simulations were performed (*TCA file numbers between 679 and 781*). The first shot and second shot results were analysed as two groups:

‘First shot’ tests: 20 fires resulted from 51 tests with average arc energy release of 96J per test – 39% ignition probability (95% confidence limits of 27% and 53%).

‘Second shot’ tests: 9 fires resulted from 30 tests⁹ with average arc energy release of 87J per test – 30% ignition probability (95% confidence limits of 16% and 47%).

The overall probability of ignition in the 51 tests was 29 fires, or 57%. Two fully independent tests, each with 39% ignition probability (as determined from the 51 ‘first shot’ tests), have a theoretical overall ignition probability of 63% which is close to the observed result of 57%. This is illustrated in Figure 15 which shows (by the large overlap of the 95% confidence limits) that the difference in ignition probability between first and second shots is

⁹ In 20 of the 51 reclose simulation tests, a fire resulted from the first arc. In one test, the second shot did not trigger. This left 30 ‘second shot’ tests out of the 51 reclose simulations attempted.

well within the random variation of results for the number of tests done. Significance testing using Cohen's 'effect size' analysis¹⁰ indicates that the effect of reclose on the second shot ignition probability was small ($d < 0.2$).

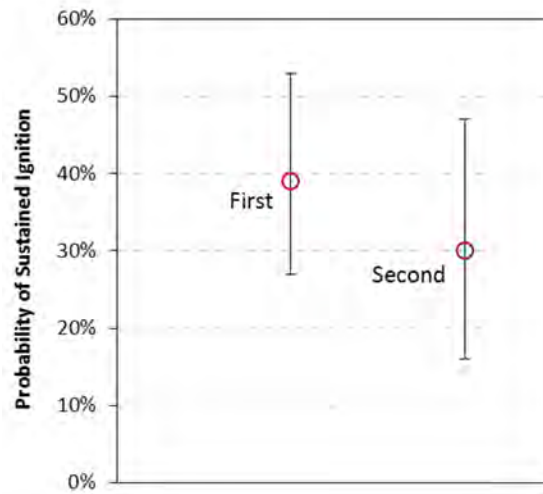


Figure 15. Differences in ignition probability with 30 second reclose delay

The difference in average arc energy release between first and second shot tests (96 joules versus 87 joules over the 51 tests) was found to be significant, with only 1.5% chance that average energy release in the second shot is greater than in the first. Close examination of all test data and video failed to reveal the reason for this difference. This result implies the second-shot arcs were on average of shorter 'thread length' than first-shot arcs. However to minimise test cycle time, high speed video was not used in this test series, so this potential cause could not be confirmed.

Based on the relationships between arc energy release, arc duration and ignition probability revealed in the overall test program, the observed 10% difference in arc energy release can be considered, in itself, a sufficient cause of the observed difference in ignition probability. Recognising this difference in ignition probability is a statistically 'small' effect and is in the opposite direction to the result seen in the 5 second delay tests, it is still valid to conclude that with a 30 second delay, second-shot ignition probability is no higher than first-shot ignition probability. If anything, it is marginally lower – for reasons that remain unclear.

The Tranche 4 reclose tests provide convincing evidence the two shots are effectively independent when reclose delay is 30 seconds, i.e. residual effects from the first shot are unlikely to predispose the second shot towards starting a fire.

Further tests would be required to confirm independence at intermediate values of reclose delay between 5 seconds and 30 seconds.

¹⁰ Cohen, J. (1988) *Statistical power analysis for the behavioural sciences* (2nd ed.). Hillsdale NJ: Lawrence Erlbaum Associates.

3.4 The challenge of testing for differences in ignition probability

The main arc-ignition test program was designed to establish the probability of ignition with sufficient reliability to support the Taskforce's recommendations. Tests for differences, i.e. to determine if reclose events increase ignition probability, are much more challenging and require careful consideration of confidence intervals¹¹ and significance tests. To establish if there is a change in ignition probability due to reclose, enough tests must be done of both the reclose and non-reclose situations that the confidence limits are narrow. Only then can a reliable conclusion be reached about the significance of any difference between the two results.

Confidence limits for binomial distributions are not an exact science and various formulae have been derived over the past 100 years¹². The most common approach is to do enough tests on each condition (reclose and non-reclose) to treat the test results as if they form two normal distributions centred on the two true probabilities for the two different situations under test. The 'rule of thumb'¹³ for the minimum number of tests required to support this approach suggests there must be sufficient tests such that there are at least five ignition results and five non-ignition results.

As the probability of ignition varies so does the number of tests required to achieve this criterion. For example, if the probability of ignition is 50% only ten tests may be needed. However, if there is a 10% or 90% probability, then 50 tests are likely to be necessary. Once this criterion is satisfied, then normal distribution statistics can be used to assess the significance of any difference between observed results for the two different situations.

Analysis of the reclose simulation results used the MATLAB confidence interval estimator¹⁴ for improved significance testing of comparisons of the first and second shot test results.

3.5 Test approach used

In Tranche 3, the effect of a single reclose event was assessed using the following procedure:

- (i) Select a set of conditions known to give an ignition probability near 50%¹⁵ for standard tests, i.e. application of a single period of arc current, with worst case

¹¹ A confidence interval is the range of test results that can result from a limited number of tests being done. For example, if the true probability of ignition is 50% and only ten tests are performed, the observed probability (average occurrence of ignition) may be anywhere between 34% and 66% at a confidence level of 95%, i.e. there is 95% surety that the true value lies somewhere between these two limits.

¹² See footnote 7 on page 24.

¹³ Minimum number of tests must be such that both nP and $n(1 - P)$ are greater than five, where n is the number of tests and P is the proportion of tests that result in ignition.

¹⁴ The MATLAB routines use the Ross approach to confidence interval estimation referred to in Section 2.4.

¹⁵ Hence, the tests reported here only apply to relatively poor fire performance with reclose suppressed. Many more tests would be required to check the effect of reclose when protection settings are more effective at reducing fire risk with no reclose.

environmental conditions and realistic arc duration and current for Victoria's distribution networks.

- (ii) Perform a sufficient number of tests with no reclose to meet the 'normal distribution rule of thumb' based on the average occurrence of ignition in the tests.
- (iii) Using the same test conditions, set up the test rig to provide a single reclose and re-strike of the arc, with a reclose delay at the shorter end of those used in Victoria's distribution networks
- (iv) Perform a sufficient number of tests with one reclose to meet the 'normal distribution rule of thumb' based on the average occurrence of ignition in the tests.

In Tranche 4, a modified test approach was used with the following changes:

- (i) Modify the test procedure to make the first and second shot tests truly identical (do a pre-first shot test without power applied to embed the moving electrode in the fuel).
- (ii) Select arc current and duration to give an ignition probability less than 50% in worst case fire conditions, now specified as 10 kph airflow, not 20 kph. This required reduced current of 35 amps and short arc duration of 50ms.
- (iii) Perform as many full reclose simulation tests as possible in a single day to minimise the confidence interval of the ignition probability results. In the event, 50 tests proved feasible on the day.
- (iv) Use a much longer reclose delay: 30 seconds was selected as a mid-range value among the range suggested by stakeholders.
- (v) Analyse the 'first shot' and 'second shot' results separately to represent the non-reclose situation and the reclose attempt respectively.

4 Ground fault neutraliser simulation

Initial test results indicate the anticipated fire risk reduction benefits of GFNs are real – no ignition was achieved in nine tests at estimated worst case conditions for GFN arcs. Twelve further tests indicate ignition can only occur with a GFN if either or both arc gap length and wind speed are outside realistic worst case conditions by at least a factor of two.

In January 2011, a workshop of technical experts sponsored by the Taskforce identified the ground fault neutraliser (GFN) as a protective technology with potential to substantially reduce powerline fire risk in Victoria's rural distribution networks. To properly evaluate the benefits of GFNs, testing was required to estimate the ignition probability for phase-to-ground faults on powerlines emanating from a zone substation fitted with a GFN. There is only one GFN installed in Australia - at Frankston South, a zone substation that supplies some tens of thousands of customers - and it is not available for use in arc-ignition tests.

Arc-ignition tests for traditional powerlines require only 50Hz arc currents. Tests for GFN-protected powerlines require simulation of the much more complex fault currents that flow when a GFN acts to limit fault energy. Test configurations at the TCA facility were developed to simulate GFN operation using two different methods.

4.1 Test results – realistic worst case

Tests used realistic worst case conditions:

- Zero arc-fuel distance – electrodes partially embedded in loose fuel
- Fuel: dry straw/grass mix with a moisture content of ~5%
- Airflow of 5 kph¹⁶ and 10 kph with air temperature 45°C and RH <20%
- Fixed arc gap of 5 mm with arc initiation by very fine fuse wire

Two different simulations of GFN fault currents were used (described in Section 4.6) and the conditions and outcomes are included in Table 6 and Table 7.

4.1.1 Single loop current pulse simulation

Arc energy release (Joules)	Peak current (Amps)	Gap (mm)	Airflow (kph)	Ignition result	TCA file number
82	320	5	10	None (small scorch mark)	447
131	440	5	10	None (small scorch mark)	448
135	440	5	5	None (small charred area)	449

Table 6. Ignition test results for GFN (single loop current pulse)

¹⁶ The lower airflow speed of 5kph is worse than the realistic worst case defined for other tests (10kph). It was seen as potentially applicable to the case of a fallen live conductor on the ground.

The single loop current pulse tests indicate that phase-to-ground faults on powerlines protected by a GFN will not start fires in worst case conditions, even with arc energy ten times that calculated for a typical network (12 joules).

4.1.2 RC discharge current pulse simulation

Arc energy release (Joules)	Peak current (Amps)	Gap (mm)	Airflow (kph)	Ignition result	TCA file number
~11	230	5	5	None	453
11	230	5	5	None	454
12	230	5	5	None (same fuel)	455
10	230	5	5	None (same fuel)	456
12	230	5	5	None (same fuel)	457
11	230	5	5	None (same fuel)	458

Table 7. Ignition tests with RC discharge current pulse

In the RC discharge current pulse tests, ignition could not be achieved under realistic worst case conditions even with repeated tests on the same fuel. Six tests were performed, four of them without fuel change, i.e. the same fuel was exposed five times to the arc energy of the fast current pulse with no ignition.

4.2 Tests with non-realistic conditions

An additional ten tests were carried out using the single loop current pulse under conditions beyond realistic worst case to better understand the ignition process for very short (8ms) arc durations. The ten tests and their ignition results are recorded in Table 8. These tests do not reflect realistic arc faults for a GFN and should not be taken as an indication of the fire risk performance of GFN-protected powerlines.

These single loop current pulse tests indicate that the only conditions that produce ignition include unrealistically long arc gap length at minimum airflow speed.

Two further tests were carried out using the RC discharge current pulse with an unrealistic 30 mm gap length to increase energy delivery into the fuel. The test results are included in Table 8. The larger arc gap length produced a 30 Joule energy release, which is 2.5 times the energy release for the worst case gap length of 5 mm. The result of the first test was no ignition and the second test (with the arc applied twice to the same fuel) led to ignition.

The RC discharge pulse tests tended to confirm that a GFN protected powerline could only produce ignition under conditions well outside the range of circumstances in real distribution networks.

Consideration of the results shown in Table 8 indicates that the primary finding that GFNs substantially reduce powerline fire risk is sound:

- No ignition was achieved at wind speeds at or above 10 kph even with an unrealistic 30 mm arc gap

- No ignition was achieved at arc gap lengths at or below 10 mm.

The 12 test results for non-realistic conditions could be taken to imply a factor of perhaps two between conditions involving potential GFN ignition outcomes and realistic network conditions.

Arc energy release (Joules)	Peak current (Amps)	Airflow (kph)	Arc gap length (mm)	Ignition result	TCA file number
119	200	5	30	Ignition	437
94	200	5	30	Ignition	438
135	200	5	30	Ignition	439
83	200	5	15	Ignition	440
58	200	5	10	None	441
61	200	5	10	None (brief smoke)	442
63	200	5	10	None	443
110	200	10	30	None	444
96	200	10	30	None	445
112	200	10	30	None	446
30	230	5	30	None	459
36	230	5	30	Ignition (same fuel)	460

Table 8. Non-realistic tests carried out with single loop current pulse (File no. 437-446) and RC discharge current pulse (File no. 459-460)

4.3 Fault (arc) currents with a GFN

A GFN greatly reduces energy released from phase-to-ground faults, but not much data has been published on the fault currents that flow in such circumstance in distribution networks like Victoria's. Network simulation using event records from the GFN installation at Frankston South zone substation indicated that phase-to-ground fault currents with a GFN exhibit the following properties:

- An initial transient current reflecting the sudden change in the energy stored in the electric field that exists between each powerline conductor supplied by the zone substation and ground¹⁷. This current is a single pulse that lasts about 2 milliseconds.
- The initial pulse is followed by a small (less than 5 amps) 50Hz alternating current due to the imbalance (caused by the fault) of the network capacitive currents on the whole distribution network supplied by the zone substation. This small current exists for about 60 milliseconds.
- When the GFN's Residual Current Compensator (RCC) acts after 60 milliseconds, the fault current goes to zero and remains at zero until operator intervention.

¹⁷ These electric fields are supported by a capacitive current on the powerline conductors. When a fault occurs the voltage of each powerline conductor with respect to ground suddenly changes and currents that flow on the conductors establish new stored energy levels commensurate with the new voltages.

Theoretical modelling of faults using published GFN design details also predicts these features.

The arc-ignition tests for GFNs focused on the initial high current pulse and relied to some extent on an assumption that the small 50Hz current that exists for 60ms after the initial current pulse (until the RCC eliminates it) is insufficient to create or sustain an arc, i.e. the only potential cause of ignition is the initial current pulse. This assumption is generally aligned with broader arc-ignition tests that demonstrate that low current arcs do not produce ignition under realistic wind speeds, especially at small arc gap lengths. However, it must be recognised that the results presented here are yet to be confirmed by tests on an actual GFN.

4.4 Arc geometry considerations

In non-GFN ignition tests, the arc configuration reflects the reality of a conductor falling onto an earthed structure and then falling away drawing an arc as it does so (or equivalently, an earthed item such as a tree falling against a conductor and then falling away drawing an arc). In short, faults occur when things touch, arcs occur as they then draw apart. Typical arc gap configurations used in arc-ignition tests for such faults comprise an arc drawn out at 1-2m/s to a gap length of 120-420 mm with typical arc durations of 50-250ms.

The reality of faults in a GFN protected system is quite different. The current pulse in GFN faults is so fast that its 2ms duration effectively constrains the range of conductor movement that can create an arc. With a GFN, if a conductor falls onto an earthed structure or onto the ground, an arc is created by spontaneous flashover as the gap between the live conductor and the earth or earthed item closes to less than 5 mm¹⁸. If the conductor is moving at 2m/s, it will move only 4 mm in the 2ms period of the fast current pulse, so typical arc gap lengths are constrained to less than 5 mm.

If a conductor fell free from a height of 5m, its speed could be much higher - approaching 10m/s and it would move 20 mm in 2ms. However, it is difficult to envisage how this faster movement could produce a longer arc gap, because the conductor would first have to get within 3-4 mm of an earthed structure or the ground to create an arc by flashover and yet continue to move at high speed. The close approach required for flashover would most likely immediately precede the conductor striking the earth or earthed structure. If so, its motion would be at least momentarily interrupted and the arc gap during the 2ms of arc duration would be quite small.

Pending the identification of other scenarios capable of generating longer arc gaps, a conductor falling to ground or onto an earthed structure was adopted as the basis for consideration of arc gap length.

Since arc power increases with gap length, it is conservative to test for ignition with a fixed 5 mm arc gap since any smaller (perhaps more realistic) arc gap will release less energy to

¹⁸ AS 60053-2005 states that the flashover distance for 12.7 kV is 3-4mm with spherical electrodes. More realistic electrode shapes may increase this distance slightly.

the environment¹⁹. The test results show no ignition for an arc gap of 30 mm, giving unrealistically high levels of total arc energy, provided airflow speed is 10 kph or more.

4.5 Energy delivery considerations

The network response to a phase-to-ground fault on a GFN-protected powerline, has three characteristic features:

- A fast current pulse that changes the stored energy in network-to-ground electric fields
- A shift in the system neutral voltage from zero to near 12.7kV (enabled by the GFN)
- A fall in the voltage on the faulted conductor at the fault location to a level close to zero²⁰.

The change in stored energy can be calculated and used to calculate the current pulse. A realistic 22kV rural network of ten feeders of average length of 60km and no high voltage underground cable, has a total capacitance²¹ of 4 μ F between each phase and ground, i.e. 12 μ F in all. In such a network, the largest possible change in stored energy that can occur with a phase-to-ground fault is of the order of 1 kJ. The current in a 2ms pulse that could deliver this change in energy is about 80 amps.

Modelling based on field records from the Frankston South GFN indicated that phase-to-ground fault current pulses there may peak at around 200 amps. Full modelling and analysis of the distribution network was beyond the scope of these initial tests. For the purposes of the tests, it was conservatively decided to use a peak current of 200 amps or higher.

The energy released into the environment by the arc at the fault location is only a very small part (perhaps less than 2%) of the total change in the network's stored energy. The arc energy can be calculated using the arc current and an appropriate arc voltage. Since arc voltage depends on both the arc current and the arc gap length, a value for arc gap length must be assigned. In design of the test simulations, a 5 mm gap length was assumed for this calculation in accordance with the considerations on arc geometry set out in the preceding section.

One other arc-ignition test done at 5 mm arc gap length had shown that the arc voltage at 320 amps arc current is about 35 volts. The arc voltage will be slightly less for a 200 amp current, so a figure of 30 volts has been used as more realistic while still remaining conservative.

At 30 volts arc voltage and 200 amps arc current, the arc power is 6kW and the energy delivered in 2ms is only 12 joules. This was close to the 11.6 joules of arc energy measured in the RC discharge tests.

¹⁹ Non-realistic tests described in Section 4.2 showed ignition could occur with a gap length of 15 mm or more.

²⁰ When the RCC acts after 60 milliseconds, this voltage goes completely to zero.

²¹ The capacitance is the measure of energy stored in the electric field for a given voltage.

4.6 Selection of test conditions

In simulating GFN effects on ignition, it proved challenging to achieve all four target requirements at the same time: short (5 mm) arc gap, high (200 amp) peak current, short (2ms) current duration and high delivered arc energy (100 joules). The tests revealed that the 5 mm/200A/ 2ms combination would only deliver energy close to the calculated 12 joules. Unrealistic conditions (30 mm gap length, peak currents up to 440 amps) would produce higher arc energy release (e.g. 120 joules).

Airflow is another critical determinant of ignition probability. Lower wind speeds give higher ignition risk, so ignition tests were carried out at 5 kph and 10 kph airflow at 45°C air temperature and low (<20%) air relative humidity.

4.6.1 Single loop current pulse

This simulation method used a single half cycle pulse derived from a normal 50Hz waveform, i.e. supply voltage was applied for 10ms from one waveform zero-crossing to the next. The 200 amp current was sufficient to explode the fuse wire in the first 1-2ms and give an arc duration close to 8ms. Peak current was selected for an energy release of around 100 Joules and ranged up to 440 amps.

The current waveform for single loop current tests is shown in Figure 16.

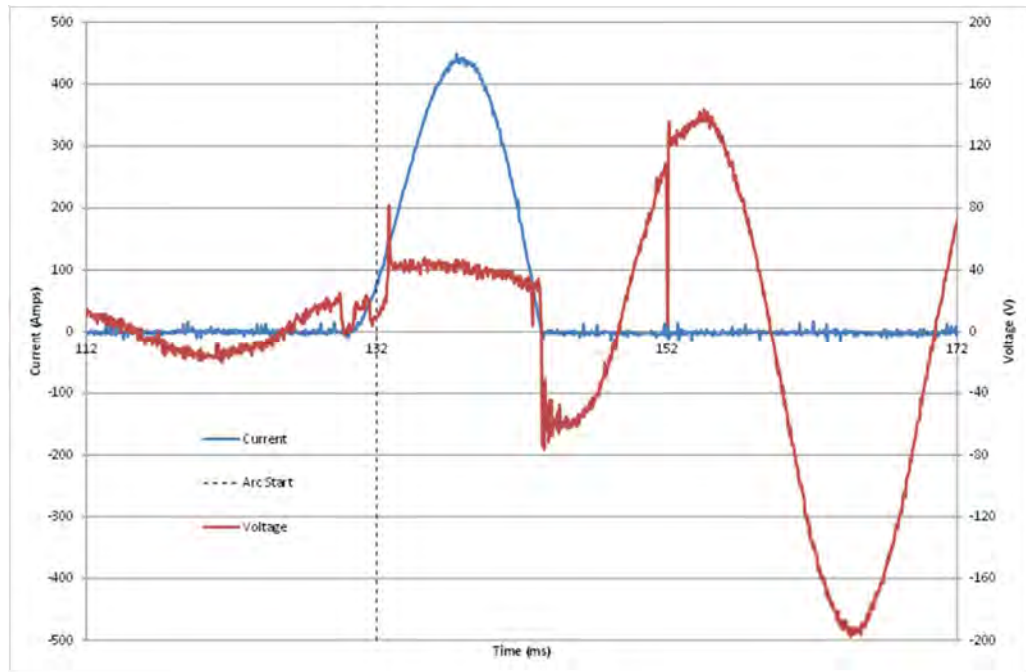


Figure 16. Current and voltage waveforms in single loop current pulse tests

4.6.2 RC discharge current pulse

The second technique produced a fast current pulse by discharging a capacitor (C) through a resistor (R) to give a fast initial rate of rise of current followed by an exponential decay to zero over a few milliseconds. A 25 μ F capacitor was charged to around 18kV, then

discharged through a resistor selected to approximate the target of 200amps and 2ms. In the test, the results followed the theoretical calculations exactly – an exponential current decay giving a total arc duration of 6-8ms (much of which was the low current ‘tail’). This delivered arc energy of 12 joules. The current waveform for RC discharge tests is shown in Figure 17.

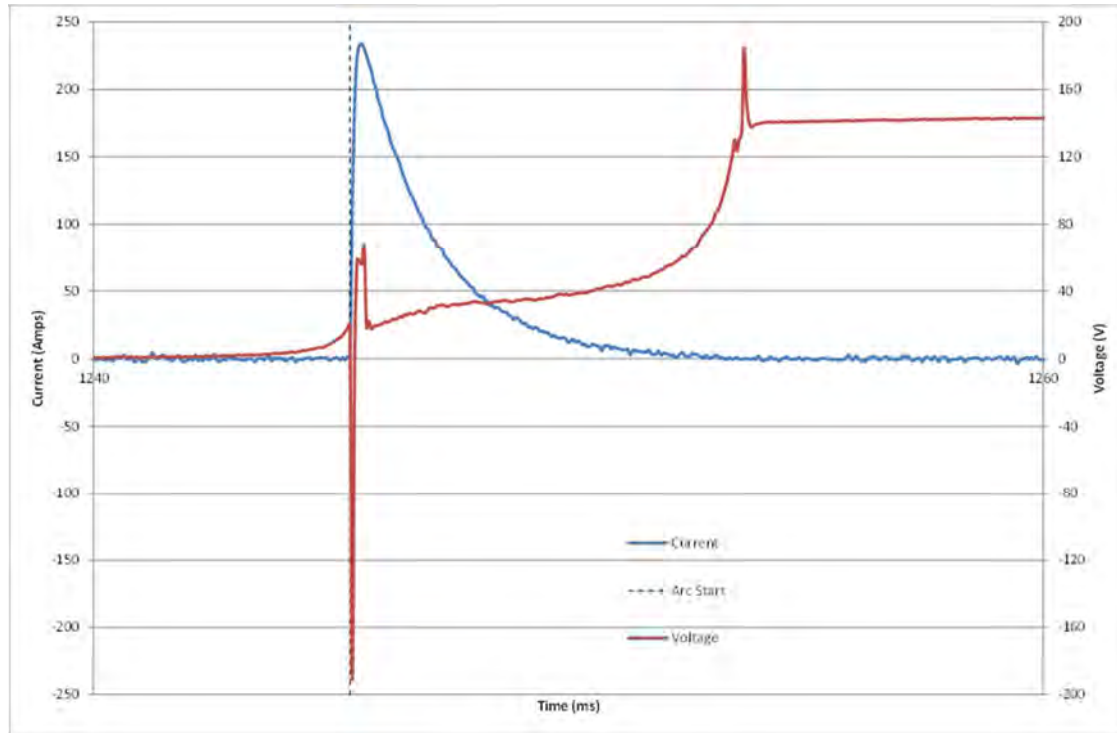


Figure 17. Fast current pulse in RC discharge tests

In both Figure 16 and 17, the value of post-arc voltage is random. Once the arc has extinguished the ‘live’ electrode is left isolated and assumes a voltage level determined by various stray capacitances and resistances and the (very high) impedance of the voltage measurement system which was different in the two simulations (capacitive voltage divider for single loop current pulse tests and resistive voltage divider for RC discharge tests).

5 Identification of worst case wind speed

Air flow can move and distort electric arcs and at sufficiently high air speeds the arc can be rapidly extinguished; wind speed of 5 kph can extinguish a 4.2 amp arc. Wind can also extinguish combustion after the arc is removed. Winds on Black Saturday were approaching gale force and would greatly reduce the probability of ignition from arcs. However, statistically there are brief, quiescent periods when wind speed is low, particularly near ground level. Analysis of BOM data for Black Saturday supports the conclusion that a light breeze of 10 kph would be representative of realistic worst case wind conditions for bushfire ignition from arc faults on extreme fire risk days.

5.1 Effect of air flow on arcs and ignition

Air movement is an important determinant of arc behaviour. Some arcs self-extinguished very early with light to a moderate breeze from a fan blowing on the arc gap. Others exhibited less chaotic behaviour than normal with air movement on the arc gap. Some of the variability in the power curves in Section 8.5.1 is probably a result of changes in ambient air speed. This varied from ~7 to 14 kph during these tests.

The effects of air movement induced by a fan should be very similar to that caused by air heating from the arc and consequential convective movement. Depending on the 'wind' direction the arc could be blown sideways or downwards (both these behaviours were observed in tests and are illustrated in Figure 18), opposing the normal tendency of the arc and plasma to rise vertically in still air.

Low current arcs were much more prone to being extinguished by airflow than high current arcs. In tests conducted with a simulated 20 kph crosswind, 4.2 amp arcs blew out at a gap length of approximately 40mm. Even 5 kph wind could prematurely extinguish arcs in the ignition tests, e.g. in less than 0.2s with an arc gap around 100 mm. However, 200 amp arcs did not extinguish even at the maximum 425 mm gap, though they extended well away from the arc gap. In 200 amp tests airflow tended to extend the high current arc by 'untangling' the typically convoluted, vortex-like thread structure. In some instances, this led to the arc billowing out sideways from the rig for a distance of up to 1 m.

Ignition tests showed that at very low wind speed, under effectively still air conditions, there was almost certain ignition of the dried grass fuel in most cases. Airflow can extinguish fires started by arcs, even those ignited by repeated striking of the fuel by a high current arc. If tests were done at high wind speeds, simulating the severe conditions on extreme fire days, it is considered likely that arcs would extinguish rapidly and there would be a low probability of ignition. However, this is not realistic - even on days such as Black Saturday there are brief periods of lower wind speed, particularly near the ground. The ignition tests were done with wind speeds of 5, 10 and 20 kph, a range that spanned high to low airflow effect on ignition probability.

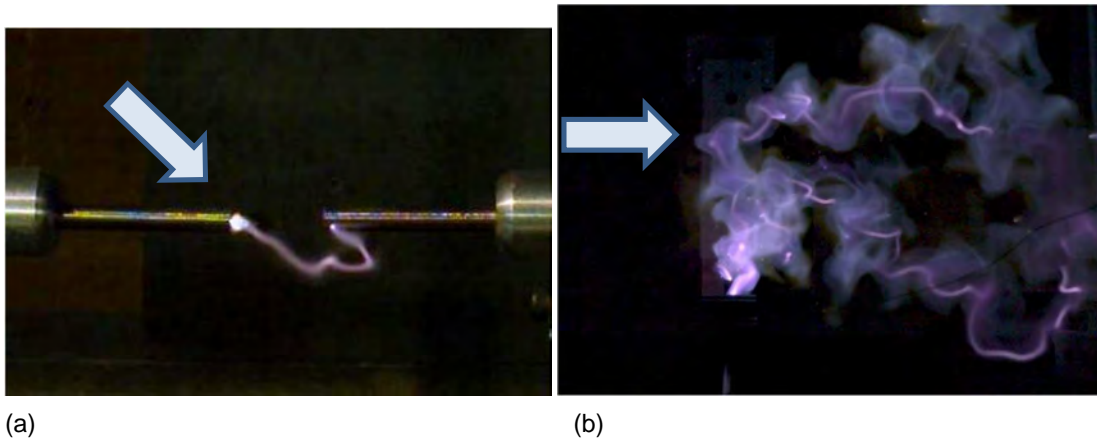


Figure 18. Photographs from high speed video showing the effect of air flow on the arc (a) at 4.2 amps (Test #028) and (b) at 200 amps (Test #118)

5.2 Ground level wind speed on Black Saturday

Data were obtained from the Bureau of Meteorology on the temperature and wind speed for the 24 hour period of Black Saturday. One minute data were available for a number of monitoring stations, including Kilmore Gap, Eildon, Ballarat Airport and Melbourne Airport. The records provided the average and maximum wind speed and standard deviation in (the usually 60) readings over the previous minute as well as air temperature and wind direction.

The wind speed record for Kilmore Gap is presented in Figure 19 showing the maximum and average wind speeds over Black Saturday. It is noted that during the most severe period of that day the 1 minute average wind speed does not drop below 40 kph.

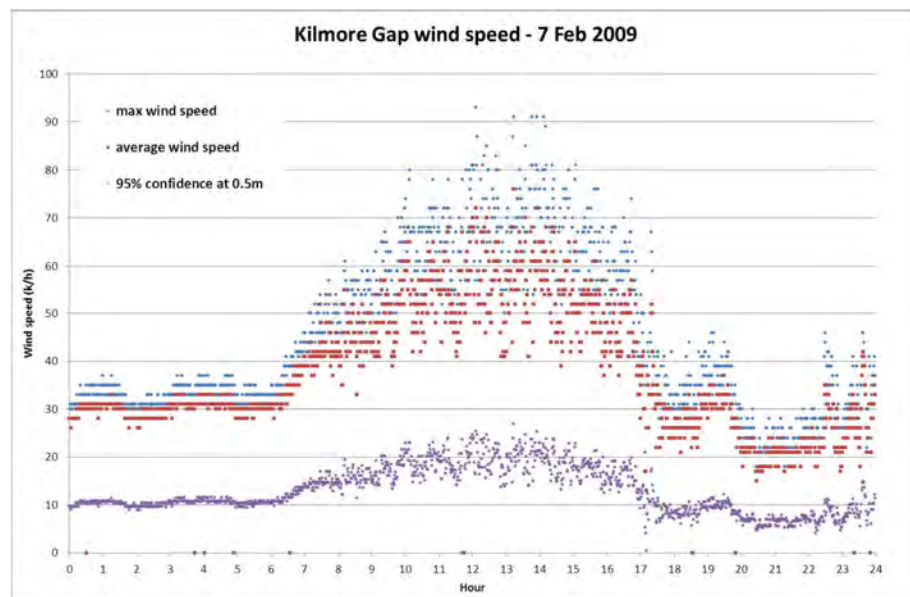


Figure 19 Wind speed data for Kilmore Gap wether station from Black Saturday (2009) showing the relatively low wind speeds that could be expected for some time (95% confidence at 0.5m) at close proximity to the ground.

From the 1 minute data of wind speed the lower 95% confidence limit was determined – i.e. 95% of recorded wind speeds over the past minute are expected to be greater than this value, or conversely and more pertinent to this work, wind speeds less than this would be anticipated for 5% of the time. This was estimated assuming a *t distribution*, which is reasonable with 60 readings per sample.

The wind speed increases with height above the ground. At height h above the ground the velocity (V_h) can be estimated from the measured data at 10m level (V_{10}) from the following relationship:

$$V_h = V_{10} \times (h/h_{10})^\alpha$$

where α is a factor determined by the terrain.

This formula has been used in a variety of applications (wind farm design, wind loads on structures, noise propagation) and is considered potentially applicable in interpreting BOM 10m wind speed data to derive worst case wind speeds for realistic powerline fault conditions.

In work on wind turbines α is referred to as the Hellman exponent²² and it depends upon the coastal location, the local terrain, and the stability of the air. Examples of values for the Hellman exponent are given in the table below:

Location	α
Unstable air above open water surface:	0.06
Neutral air above open water surface:	0.10
Neutral air above flat open coast:	0.16
Unstable air above flat open coast:	0.11
Stable air above open water surface:	0.27
Unstable air above human inhabited areas:	0.27
Neutral air above human inhabited areas:	0.34
Stable air above flat open coast:	0.40
Stable air above human inhabited areas:	0.60

In the case of wind turbines it is the increase in wind speed above the 10 m sampling height that is important. However, this approach can also be used to estimate the decrease in wind speed closer to the ground. Ground level wind speeds for use in assessing noise monitoring have been estimated using the same formula as above²³. This work draws on the Australian

²² Renewable energy: technology, economics, and environment by Martin Kaltschmitt, Wolfgang Streicher, Andreas Wiese, (Springer, 2007.), page 55

²³ Converting Bureau of Meteorology wind speed data to local wind speeds at 1.5 m above ground level. T Gowan, P Karantonis and T Rofail. Proceedings of Acoustics 3-5 November 2004, Gold Coast Australia

Standard²⁴ relating to wind load on buildings, so the examples provided are more relevant to build up areas rather than open terrain, but the general methodology is validated

The plot in Figure 20 shows the calculated decrease in velocity at heights less than the standard height of measurement at 10 m. With the higher value of the terrain factor α there is a greater decrease in wind speed as the height decreases. Clearly a higher value of α will lead to a lower wind speed close at the ground and will produce a more demanding target arc duration if fire starts are to be prevented, i.e. selection of a high value is conservative.

The relationship has been used to estimate the wind speed at a height of 0.5 m, and assuming a terrain factor of 0.34 – i.e. using a mid-range factor applicable to urban terrain, recognising the relatively hilly and sparsely forested region where bushfires might sometimes start. This value is reasonably consistent with AS1170.2.

This provides an estimate of the lower (95% confidence limit) wind speeds that might be expected over the course of the day at each BOM measurement site. This limit is included in the graphs of data for Kilmore Gap in Figure 19. Similar plots for all stations considered and included in Appendix 2.

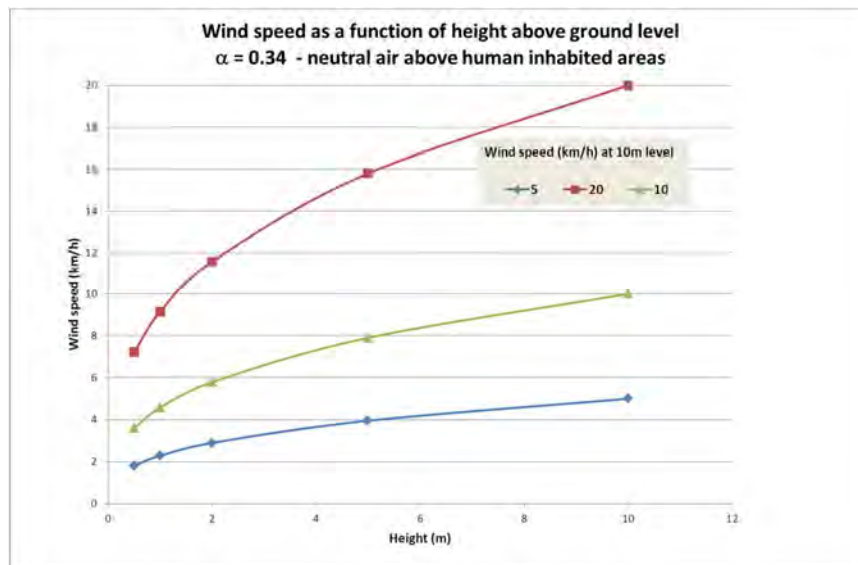


Figure 20. Calculated reduction of wind speed with height above ground level, based on the measured wind speed at 10m height.

5.3 Worst-case wind speed for test program

The Black Saturday data for Kilmore Gap shows that statistically, the wind speed at 0.5m above the ground will be greater than 10 kph for more than 95% of the time.

²⁴ AS1170.2 – 2002 Structural Design Actions – Part 2: Wind Actions Standards Australia.

The tests have confirmed that ignition is more likely at lower wind speed and under the very severe conditions where the arc is in contact with the fuel, ignition was practically assured in the absence of any air movement. This is certainly a worst case condition, but from the analysis of wind data, zero wind speed is not considered to be realistic. It is considered reasonable to concentrate tests around a wind speed of 10 kph as representative of realistic worst case wind conditions at a height of 0.5 m. At a height of 10 m this realistic worst case figure would translate to around 20 kph.

All the airflow speeds used in tests should be regarded as typical of relatively mild conditions. The Beaufort wind scale describes various wind speeds as:

5 kph	Light air	Smoke drift indicates wind direction
10 kph	Light breeze	Leaves rustle
15 kph	Gentle breeze	Leaves and small twigs constantly moving
20 kph	Moderate breeze	Small branches begin to move.

6 Considerations in testing for ignition by electric arcs

The ignition of solid fuel requires pyrolysis, i.e. the formation and release of flammable gases from the fuel as a result of heating. This can occur in very short times with an intense heat source and high heat flux, such as in flash pyrolysis systems. Conditions with an electric arc are likely to be similar to these, thus ignition may be possible even with short duration arcs. The effects of both arc energy and arc power must be considered.

The literature review²⁵ provided quantitative data on critical parameters that influence the ignition of fires. However, there appeared to be no research on the probability of fire ignition from electric arcs. Many of the findings from the review have contributed to the design of the test program and the interpretation of test data. The following commentary draws together significant points from the review and other sources and outlines specific issues that have contributed to the test program design.

6.1 Pyrolysis and ignition and flaming

How does solid fuel ignite when heat is applied to it? How fast does it occur?
What are the factors that influence ignition and how?

For the purposes of the test program, ignition was regarded as self-sustained flaming from the fuel, which continued after cessation of the arc. Other definitions have been used in other studies. For instance, smouldering of the fuel could be regarded as ignition, or the development of flames regardless of whether or not the flaming is sustained. Some of these alternatives might be more conservative than the sustained existence of flaming. In the test program, the behaviour of the fuel during the test was examined using high-speed video and it was possible to definitively state whether or not flaming was sustained, or if smouldering occurred. These various conditions were noted in the test results, but only the sustained flaming condition was used in the ignition probability analysis.

Flaming is the end result of pyrolysis of the fuel – where pyrolysis is the formation and emission of flammable, gaseous compounds as the fuel is heated. As the temperature of the fuel increases, gases such as CO and H₂ plus water vapour, are emitted at increasing rates. The flammable gases mix with air and if the gas concentration falls within the range of flammability, i.e. exceeds the lower flammability limit, and there is a suitable energy source to ignite the gas, a flame will be produced. The flame will be sustained until the concentration of volatile gases falls below the lower limit of flammability, either because pyrolysis has slowed due to cooling of the fuel or the volatiles in the fuel are exhausted.

The rate at which pyrolysis generates flammable gases around the fuel to support initial ignition is essentially determined by the physical processes of thermal conduction of heat through the fuel, diffusion of the pyrolysis gases to the surface and boundary film, and their entrainment in air movement. Pyrolysis can therefore occur extremely rapidly, particularly

²⁵ See footnote 2 on page 7.

for thin or fine grained fuel material, where reactions can start almost instantly on the surface and there is little time delay for heat and mass transfer processes. Work on flash pyrolysis of wheat straw has been carried out at heating rates of 10,000°C/s. This is probably consistent with heating of the fuel close to an electric arc.

In the case of heating of fuel by an electric arc, the heat transfer will occur by radiation and convection. The radiative process is well understood and it is anticipated that pyrolysis will occur more rapidly for higher radiative heat flux. Research into flash pyrolysis at heat fluxes of 10^4 to 10^5 kW/m² has shown that the pyrolysis process and ignition can occur within 20ms. Similar ignition times have been attained in the pyrolysis of coal with a heating rate of 10^7 °C/s. We did not attempt to measure the arc temperature (though others have measured arc temperatures of 15,000-20,000°C for arc power in the MW range²⁶), but it would seem that heating rates of this order would be achieved in the early stages of the arc. The heat flux in close proximity to the arc is likely to be at least of the order used in the flash pyrolysis (10^5 kW/m²) in tests where heat was supplied from a high power xenon light source. Thus it seems reasonable to expect that under intense power conditions in the vicinity of an electric arc, pyrolysis and ignition of fine fuel could occur in a very short time, of the order of 20 ms.

Convective heat transfer processes are more complex in terms of defining the effect on probability of ignition because the heat transfer rate is related to the velocity of the surrounding gas. At low gas velocity the heat transfer rate is lower, but there will be more time for the pyrolysed gas concentration to exceed the lower flammability limit. As the gas velocity increases the heat transfer increases but there is greater dilution of the pyrolysis product, and thus the time to ignition is likely to pass through a minimum at some intermediate value of gas velocity.

Observation of arc and plasma behaviour in the test program has confirmed that the arc can move at very high velocity, although the motion is not continuous or predictable. The testing has shown that the arc must effectively be in contact with the fuel to cause near-instantaneous ignition. The random and rapid motion of the arc within and across the fuel may reduce the probability of ignition under some conditions by limiting the opportunity for such contact.

The above considerations apply to situations where the arc-fuel distance is close to zero. If the fuel is not close to the arc gap, there is an additional time period required for the arc to move from its original position to contact the fuel. However, to determine the worst case probability of ignition, a zero arc-fuel distance eliminates this random additional component of arc duration required for ignition and maximises the heat flux into the fuel.

²⁶ Measurement of electron temperature in the arcing period of a high voltage fuse. M. A. Saqib et al. Available: [www.physics.usyd.edu.au/~falconer/Fuse Electron Temp/SaibETempMay03.pdf](http://www.physics.usyd.edu.au/~falconer/Fuse%20Electron%20Temp/SaibETempMay03.pdf)

6.2 Energy and power for ignition

Can ignition of solid fuels by electric arcs be characterised by a 'critical heat flux' or a 'critical ignition energy'?

There is a concept of a critical ignition energy for gaseous fuels, i.e. the relatively low energy input required to ignite gases that are at a concentration above the flammability limit. However, researchers in this area do not appear to believe there is a critical ignition energy for solid fuels because of the complexity of the transfer processes involved. If the energy input occurs over a relatively long period (perhaps minutes) then it is likely that the pyrolysis activity will not occur at a sufficiently high rate for the gas concentration to reach the lower flammability limit. Research has also confirmed that the ignition energy decreases by several orders of magnitude as the heat flux increases – i.e. at higher power and higher rates of heat input the energy flux required for ignition decreases. Tests on insulating cellulosic fibreboard (0.27 g/cm^3) showed the minimum energy flux for ignition decreased from approximately 5000 kJ/m^2 at a heat flux of 10 kW/m^2 to approach 200 kJ/m^2 at $>80 \text{ kW/m}^2$. In this work the 'ignition energy flux' did appear to be approaching a limit at very high heat flux, in excess of 100 kW/m^2 , thus it is possible that in tests with electric arcs a critical ignition energy might exist for solid fuels.

It is also noted that at the higher heat fluxes both the ignition temperature and the time to ignition decrease, possibly towards limiting values for particular fuel conditions. The concept of a critical heat flux for ignition is thus more acceptable. In the tests noted above, the minimum time to ignition was of the order of 1 second, which is a relatively long time in terms of electrical arcing. Thus it is again possible that in tests with high power electric arcs these temperature and time limits might be approached, making heat flux more relevant.

In standard pyrolysis testing it is difficult to determine the net energy flux into the fuel from the heat source. Depending on the fuel surface condition some of the energy will be reflected (typically 25%), some of the absorbed heat energy will be re-radiated from the surface and heat will also be lost through convection and conduction. Laboratory tests have not been able to fully quantify the energy balance during fuel ignition, and hence to determine the net energy uptake. However, in the very short durations of electric arc tests there will be limited time for heat loss processes, other than reflection, and the process is expected to approach adiabatic conditions. Under these conditions it is expected that the concept of a critical heat flux or a critical energy flux for ignition would become equally applicable.

6.3 Energy and power from arcs

How do heat flux levels likely in arc-ignition tests compare with those used in other solid fuel ignition tests?

The heat flux used in conventional ignition research appears to be typically in the range 10 to 60 kW/m^2 . The heat flux from electrical arcs will depend on the distance from the arc to the fuel, but for tests where the arc is discharged within the fuel, and thus arc-fuel distances

are of the order of a few millimetres then very intense heat flux conditions would be anticipated. The results from the arc tests discussed in Section 8 show average arc power of the order of 5 to 100 kW for 4.2 amp and 200 amp tests, with the power generally increasing as the arc gap increases. If the arc was 500 mm long the heat flux at a radial distance of 5 mm from the arc would be around 300 kW/m² in the 4 amp test and approach 10,000 kW/m² in the high current testing. Thus the heat flux conditions in the arc-ignition tests are well above those typically used in solid fuel ignition tests, and are in line with heat fluxes used in flash pyrolysis studies.

6.4 Arc power versus arc gap

What does previous research reveal about likely arc power levels and their relationship with arc gap length?

Stokes et al²⁷ have undertaken extensive tests of high power arcs and from this work they developed an empirical relationship between the arc gap length and the arc power. They defined two regimes separated by a transition value of arc current:

$$I_T = (10 + 0.2x)$$

where x is the arc gap (mm).

Arcs at currents less than the transition current tend to be influenced most by air convection. At current levels above the transition current, they are more influenced by magnetic forces.

The investigations were mostly focused on current levels above the transition current, when the arc produces plasma jets under the intense electromagnetic forces. In this case the arc power, P was given by:

$$P_I = (20 + 0.534x) I^{1.12}$$

where I is the arc current (amps).

Thus for a steady current this work suggests a linear increase in power with arc gap. It should be noted that much of Stokes work was focused on high currents – generally multiple kilo amps – as part of an investigation into clashing conductors.

The work of Stokes and others was for fixed arc gaps, whereas real network faults can produce arcs ‘drawn’ by moving conductors. The test program was designed to reflect this.

For 110 mm arc gap (the gap length used in most of the arc-ignition tests reported here), the transition current is 32 amps. At 200 amps, the arc power calculated according to Stokes’ formula is 30kW. Typical values measured in the current test program were around 30 – 50 kW with moving electrodes and 50 – 70 kW for a fixed electrode gap of 100 mm.

²⁷ Stokes and Oppenlander, *Electric arcs in open air*, 1991, J, Phys. D: Appl. Phys. 24, p 26-35.

6.5 Fuel type and fuel moisture

What fuel moisture content level is appropriate to represent worst case fire risk conditions for test purposes?

The review confirmed that the moisture content of the fuel is one of the key determinants of ignition. Drier fuels ignite at lower temperature and with less heat flux input. The transition in the ignition probability curve with moisture is also quite abrupt, and in some fuels an increase in moisture content from 15% to 20% would be sufficient to transition from certain to very unlikely ignition. It is suggested that with grasses it is very difficult to achieve ignition at moisture contents above 20%.

The moisture content of growing vegetation is high and usually reasonably constant, and also relatively independent of the atmospheric conditions. Once the plant has stopped growing, dies off and is fully cured, the moisture content is determined by ambient air temperature and humidity. Thin material such as grasses will rapidly equilibrate with atmospheric conditions, and Sullivan²⁸ reports that even after rain grass will dry back to its equilibrium condition in less than 2 hours. Sullivan offers a correlation to estimate the moisture content of fuel (M_f , %) based on ambient temperature (T , °C) and relative humidity (RH , %) as:

$$M_f = 9.58 - 0.205 \times T + 0.138 \times RH$$

Data for the estimated moisture content of fully cured fuel are shown in Figure 21. In preparation of the hay/straw fuel for the ignition tests the fuel was conditioned at 45°C, with a background humidity around 20%. This is consistent with a fuel moisture of less than 5%.

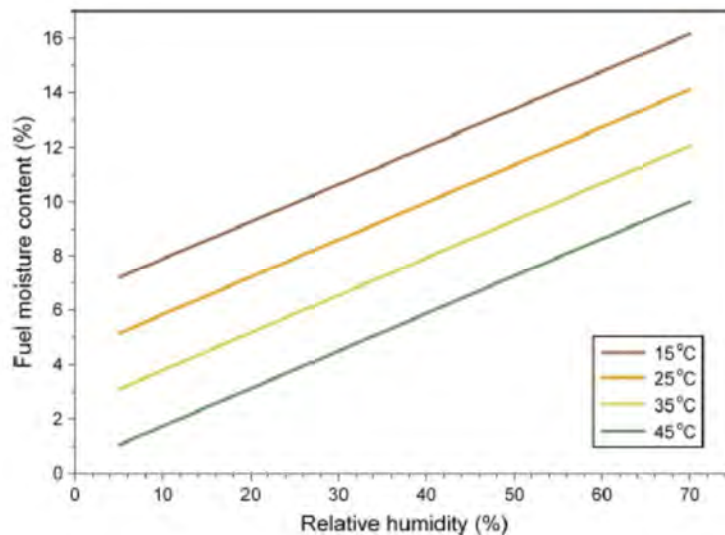


Figure 21. Predicted fuel moisture content of fully cured fuel at equilibrium at a given temperature and humidity²⁸

²⁸ A. L. Sullivan, Grassland fire management in future climate, Advances in Agronomy Vol 106 pp 173 – 208 D L Sparks (Ed.) Burlington: Academic Press 2010

6.6 Wind speed

What effect does air flow have on ignition?

CSIRO has studied the effects of wind speed on the spread of bushfires and, stated simplistically, has confirmed that stronger winds cause faster propagation. In the ignition of fires the situation is different and less predictable – the presence of wind can promote ignition or prevent ignition, depending on the wind speed, fuel type and the test conditions. The wind can increase the supply of oxygen, and if there is smouldering ignition within the fuel bed this might promote flaming. If the wind speed is too high then it will tend to disperse and dilute the pyrolysis gas products and may reduce the gas concentrations to levels below the flammability limit, thereby preventing ignition. The air flow will also tend to remove heat from the fuel – i.e. heat absorbed from the arc energy – and this will reduce fuel temperatures and reduce the rate of production of pyrolysis products.

6.7 Particles from clashing conductors

Are electric arcs used in ignition tests likely to produce hot metal particles and if so, could these play a significant role in arc-ignition results?

Tests carried out in 1977 by SECV researchers²⁹ found particles were formed when two aluminium conductors came into momentary contact at potentials of 240V and 415 V and fault currents of 100, 200 and 500 Amps. The number of particles greater than 1 mm diameter increased in the higher current and higher voltage tests. About 5% of the particles formed were in this range, typically around 60 to 80 particles per test. Around 80% to 90% of the particles produced were < 0.5 mm diameter and unlikely to produce ignition.

Stokes et al³⁰ continued this work and in tests at 240V and 60A produced 50 to 200 particles greater than 2.0 mm diameter per test with both steel and aluminium electrodes. He found a high probability of ignition for barley grass from the particulates formed by arcing³¹. These results indicate that in conventional arc-ignition tests there might be a requirement to consider whether the emission of particles from the arc contributes to the ignition process. However, in the ignition probability test program the electrodes were partially embedded in the fuel, and the effects of arc energy and emitted particles are coincident, and this would seem to be representative of worst case conditions.

²⁹ G E Pleasance Emission of particles from clashing conductors SECV R&D Report No FM-1 May 1977

³⁰ Stokes A Fire ignition of electrically produced incandescent particles Journal of Electrical and Electronics Engineering Australia 10(3):175-187 1990

³¹ Rowntree G and Stokes A Fire ignition by aluminium particles of controlled size Journal of Electrical and Electronics Engineering Australia 14(2):117-123 1994

7 Test program

A test rig was developed to simulate the physical conditions of electric arcs that might occur when a falling powerline conductor contacts earthed metal or when vegetation contacts a live conductor. The test program was segmented to converge from exploratory investigations to repeated and consistent ignition tests under defined worst case conditions. Procedures for simulating the fuel and weather conditions of extreme fire risk days were identified and incorporated into the rig design and test procedure

The scope of work to be undertaken in the test program was developed jointly by the Taskforce and HRL³². The objective of the work was summarised as -

“to establish the minimum fault conditions necessary to start fires, such that the efficacy of various technological and operational options to prevent fires can be evaluated. The critical output from the ignition testing will be data on the probability of bushfire ignition for increasing arc duration for both high and low current faults and for both steel and aluminium conductors under conditions simulating extreme fire danger days.

It is important to emphasise here that the focus of the testing is on the ignition of fires, not the propagation and development of wildfires.”

The program of tests was divided into four separated Tranches to ensure that the ignition probability testing would be completed efficiently with confidence it represented real electrical fault conditions that could be expected in the field.

- Tranche 1:** Initial tests carried out from 19th to 21st April 2011 at TCA. These explored arc behaviour under various realistic electrical conditions and the effect of arc gap on arc power at current levels from 2 amps to 1000 amps.
- Tranche 2:** Subsequent tests carried out on 12th and 13th May 2011 investigated the relationship between the calculated arc power and the measured heat flux from the arc. The effect of fuel-arc distance and orientation were also considered. Repeatability and the effect of electrode material were resolved.
- Tranche 3-1:** The main program of ignition tests was carried out from 31st May 2011 to 3rd June 2011.
- Tranche 3-2:** Remaining ignition tests were completed from 8th to 10th June 2011, including tests on reclose and GFN effects on ignition.
- Tranche 4:** Additional ignition tests designed to improve confidence intervals under worst case conditions and better understand reclose effects on ignition. Performed from 15th to 19th of August 2011.

³² Arc and Ignition Testing Program prepared for the Powerline Bushfire Safety Taskforce by Dick Coldham
HRL Technology 25 February 2011

A rig was designed to simulate the arcing that might occur when a live conductor falls across an earthed structure. The rig was set up in the TCA high energy test facility and over 860 tests were carried out covering a wide range of variables. Details of the equipment and procedure used and of the parameters that were varied and controlled are presented in Appendix 1. Sufficient information is listed such that the work could effectively be repeated by a suitably expert independent third party. Pertinent information regarding the testing and test variables is summarised in the following sections.

7.1 Test equipment and test procedure

Arc-ignition testing was done using a rig which had a moveable electrode driven by an actuator controlled by a programmable logic controller (PLC). The arc could be automatically initiated and was drawn out to a specific distance at a set rate, simulating the behaviour of a falling conductor, by moving one electrode. The moving and fixed electrodes are connected into a 12.7kV test circuit and tests were carried out at currents from 2 amps to 1,000 amps using a range of values of reactance and resistance defined by ESV to best simulate real fault conditions. The test rig is shown schematically in Figure 22.

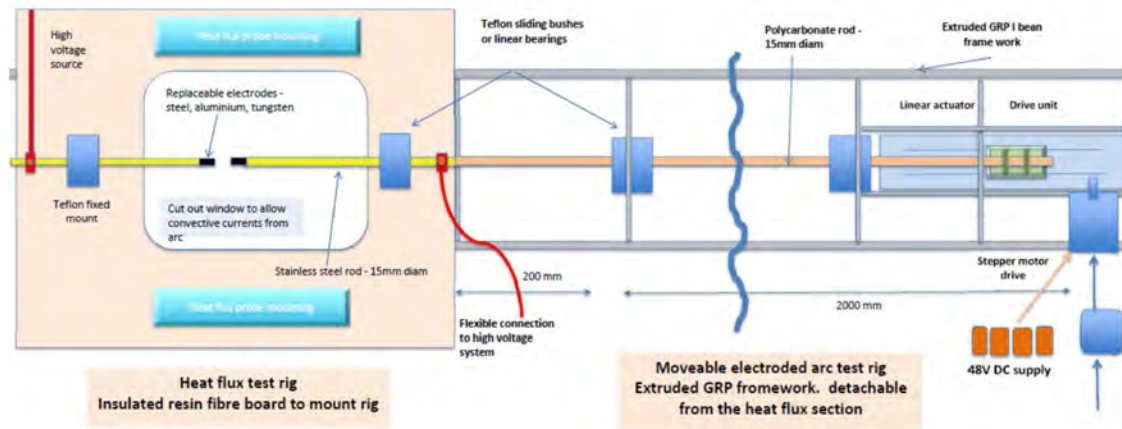


Figure 22. Schematic of the arc test rig showing the actuator drive and electrode arrangements.

During each test the arc voltage and current were monitored through the TCA 20kHz data acquisition system. Voltage measurement points were close to the HV connections to the arc test rig, rather than near the tips of the electrodes themselves. Transducer bandwidths and measurement noise levels were checked and confirmed to be satisfactory.

7.2 Test parameters

7.2.1 Voltage

The Victorian electricity distribution network is predominantly 22kV (12.7kV phase to neutral) and 12.7 kV SWER, therefore testing was undertaken using a 12.7kV 50Hz power source.

7.2.2 Current

Preliminary tests were conducted to simulate high current metal-to-metal arc faults, at 1000, 200 and 50 A, and at lower currents of 4.2 and 10 A to simulate high resistance faults. Note that some of the initial tests were conducted at the lower limit of the TCA capability of 2A.

Full probability assessments were completed at 4.2, 50 and 200 A.

7.2.3 Source impedance

Five test conditions covering two classes of faults were considered:

- The three test conditions simulating high current metal-to-metal arcs that might occur when a live conductor contacts an earthed structure were carried out at source impedances determined by network parameters plus a nominal 10 ohm earth resistance at the fault (typical of pole stay or other metal structure mounted on simple foundations). The source impedance in these tests was a mix of air-cored reactance and resistance reflecting the electrical supply system impedance and the fault path resistance.
- The two test conditions for low current high resistance faults typical of vegetation contact where current is primarily determined by the tree 'resistance' were carried out with a source impedance with minimum reactance and relatively large resistance values. A single 3,000 ohm resistor was used in the 4.2 amp ignition tests.

The test conditions used are shown in the following table.

Reference	Nominal current (Amps)	Source reactance (Ohms)	Source resistance (Ohms)
A	1000	6.5	11.3
B	200	62	20
C	50	115	96
D	10	152	1240
E	2	220	6300

Ignition probability data was developed at high (200 amp), intermediate (50 amp) and low (4.2 amp) arc currents. The tests at high and low current levels explored the effects of air temperature (with corresponding relative humidity value), airflow speed, fuel type, fuel moisture content and arc duration. All tests at the intermediate current level were done under worst case conditions, with arc duration as the only variable. For the majority of ignition tests, the following conditions were used:

- 200 amp tests: source impedance of 63 ohms with lag angle of 55 degrees
- 50 amp tests: source impedance of 250 ohms with lag angle of 22 degrees
- 4.2 amp tests: source impedance of 3,000 ohms with lag angle close to zero

7.2.4 Velocity at which arc gap extends

The arc gap was increased at an acceleration of 9.8 m/s^2 to a maximum speed of 1.2 m/s. In ignition tests, the arc gap reached 50 mm in 100ms, 110 mm in 180ms. In exploratory tests, a higher speed was used (2m/s) and it reached the 425 mm limit of actuator travel in 320ms.

7.2.5 Electrode material

Mild steel, galvanised steel, aluminium and tungsten electrode materials were used in tests. The electrodes were manufactured from 10 mm diameter rod with either a square or minimally chamfered end, simulating a break. For the galvanised material a fresh area of galvanised surface was exposed for each test.

As the electrode material did not appear to have any measureable effect on the arc energy or the ignition of fuels all the ignition probability tests were done with mild steel electrodes.

A few tests were done to assess the effect of electrode diameter by reducing the steel rod to approximately 2.7 mm diameter, roughly equivalent to the diameter of a single wire from a SWER line.

To determine the current-voltage behaviour when an arc occurs through contact with timber, a few tests were carried out with electrodes fabricated from a green tree branch and from dried timber.

7.2.6 Ambient temperature and wind speed

For the ignition probability tests, the air temperature in the test cell was adjusted using a high power electric fan heater. The equipment did not offer fine control of the temperature, but temperature and relative humidity around the arc-fuel interaction area were continually monitored. Tests were done at either the uncontrolled ambient temperature, typically around 20°C, or with air heating to close to 45°C.

Air temperature was monitored using two thermocouples (in heat flux probes) positioned ~200 mm behind the fuel basket, sampled at 5 minute intervals. Air humidity was also recorded at 5 minute intervals using two humidity/temperature sensors positioned ~50 mm to the side of, and ~350 mm in front of, the fuel basket respectively. The average air temperature and humidity across all of the ignition tests are presented in Section 2.3.2.

The variability of the temperature and humidity on typical test days is shown below in Figure 23. In the 2nd June 2011 test program, the test cell temperature was initially maintained at ambient (no heating) then various heating modes were implemented to attain temperatures of 40°, 45° and 50°C. The effect of temperature increase on the relative humidity can be seen in Figure 23, decreasing to levels around 20%. On 3rd June 2011, the test cell conditions were maintained at a consistently high temperature ranging from 45°C to 55°C. The ambient humidity on 2nd and 3rd of June was 93% and 95% respectively, whereas after the test cell was heated it dropped to around 10-20% as estimated. Further data on ambient conditions during Tranche 3 test dates is included in Table 9, taken from the Bureau of Meteorology.

Control of the wind speed was limited to either changing the fan speed or the distance of the fan from the arc rig. The wind speed in the vicinity of the fuel basket was measured with a portable anemometer and recorded. Airflow was generated from either one or two fans, operating in series with the electric heater, and directed at the fuel basket using a 300 mm diameter duct.

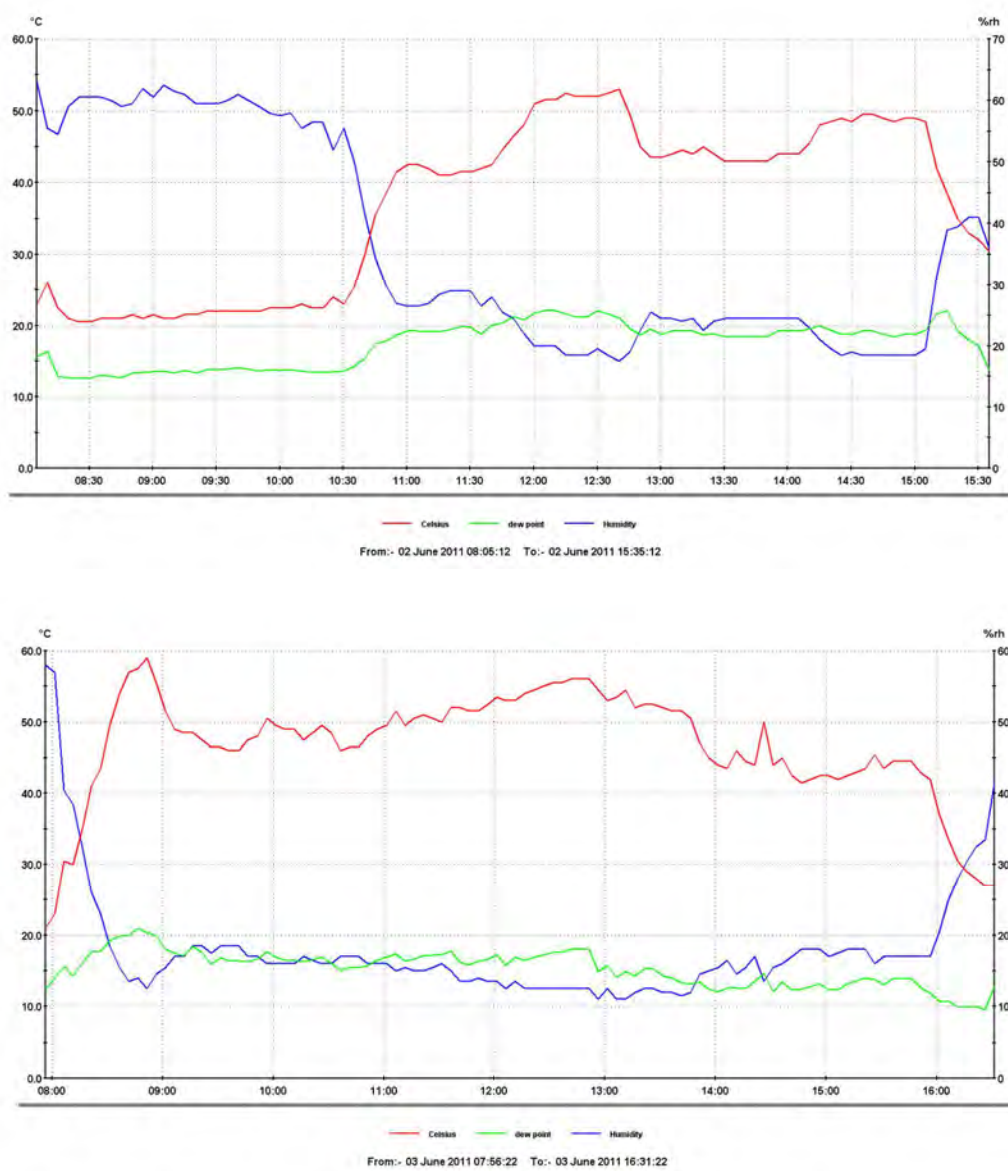


Figure 23. Temperature and relative humidity trends during tests on 2 – 3 June 2011 at TCA

Day	Date	Temperature		Rain mm	9:00 AM		Estimated RH @ 45°C %
		Minimum	Maximum		Temp	RH	
		°C	°C		°C	%	
Monday	May-30	10.3	18.5	19.1	13	94	13
Tuesday	May-31	12.8	19.4	29.7	17.6	82	16
Wednesday	Jun-01	15.2	19.7	4.6	18.1	58	13
Thursday	Jun-02	11.5	19	1.6	14.5	93	16
Friday	Jun-03	8.9	20.3	0.4	11.5	95	13
Wednesday	Jun-08	6	13.9	0	8.2	57	7
Thursday	Jun-09	5.6	16.2	0	8.9	65	8
Friday	Jun-10	6.5	16	0	10.7	67	9
Monday	Aug-15		17.2				
Tuesday	Aug-16	8.2	18.1	0.6	12	94	14
Wednesday	Aug-17	7.4	14.9	0	12.1	96	14
Thursday	Aug-18	9.8	17.9	6.4	12	78	11
Friday	Aug-19	6.2	16.4	1	8.5	96	11

Table 9. Bureau of Meteorology data from Lane Cove monitoring station for period of ignition tests showing the temperature and humidity, and from this the estimated humidity in the test cell at 45°C.

7.3 Fuel characteristics – types, size, moisture, calorific value

The ignition tests were done using dried grasses as the fuel, as research work by others had previously shown this to be typical of the more flammable bushfire fuels. Preliminary tests were carried out to assess various grasses. A reasonably consistent fuel was developed from a mix of relatively coarse straw and finer hay. The moisture content from various trials in Table 10 showed similarity in behaviour, with a reduction in moisture content of the mix dried at low humidity at 45°C to ~5%. Sullivan²⁸ suggests that at this level, ignition and conduction behaviour is extreme and erratic. The calorific value of the mix was typically 18.3 MJ/kg (gross dry). Some tests were also completed using dried eucalypt leaf litter and a few with green eucalypt leaves (after two days off the tree).

Fuel type	Fuel moisture content (wt %)	
	Ambient ~20°C	45°C @ RH=17%
Phalaris grass	10.4	5.1
Paspalum grass (sl green)	10.2	
Hay/straw mix	11.8 - 12.0	4.3 – 4.6
Eucalypt leaf litter	14.2	5.1
Green Eucalypt leaves	15.1	

Table 10. Moisture content of grasses and leaf litter as received and dried condition.

The fuel baskets were nominally 150 x 120 x 50 mm and approximately 16 g of the hay/straw mix was loosely packed into each basket. The appearance of the fuel is shown in Figure 24. From the scale the coarser straw material appears to have flat fibres typically 1 mm wide x 0.2 mm thick and the finer hay material to have stems around 0.2 mm diameter.



Figure 24. Appearance of the hay/straw fuel mix in the fuel baskets. Scale labelled in cm (largest divisions), mm (intermediate divisions) and 0.1 mm (smallest divisions).

8 Characteristics of realistic powerline arcs

Exploratory tests to refine the design of the arc-ignition test program revealed many features of electric arcs that are likely to be exhibited in powerline faults:

- Real electric arcs can be large, very complex and very dynamic, even at low current levels. In still air, stable electric arcs could be maintained over an arc gap of greater than 400 mm for periods in excess of 1 second at all current levels tested. However, with any significant airflow low current arcs are not stable.
- The arc power (rate of energy released into the environment) for realistic faults ranged from 6kW at 4.2 amps, 170kW at 200 amps to 600kW at 1000 amps fault current.
- Realistic electric arcs exhibit four features when viewed using high speed video:
 - o A pink plasma 'thread' the thickness and brightness of which pulses with each half cycle of arc current
 - o A blue sheath of high temperature plasma surrounding the central 'thread'
 - o Turbulent orange plumes of cooling plasma shed from the arc, but still hot enough for a short time to ignite fuel
 - o Emitted metal particles that burn in the plasma.
- For realistic network faults, arc voltage varies as arc 'thread' length. However, it usually remains below 5% of the 12.7kV source voltage, so arc current is relatively constant and is set by network impedance and fault resistance parameters.
- In still air, low current arcs rapidly extend upwards – increasing arc 'thread' length and power – until they self-extinguish or repeated chaotic short circuits of the plasma 'thread' limit the overall physical size and power of the arc. Higher current arcs rarely self-extinguish but can be limited by repeated chaotic short circuits.
- Arcs are strongly influenced by airflow at realistic wind speeds. Airflow can very quickly extinguish low current arcs, limiting their size and energy release. It can also greatly extend the physical size and power of high current arcs.
- Variation in arc power or energy release with different electrode materials or different source impedance angles does not materially exceed the random variation observed from one arc test to another under identical conditions.

Prior to commencing the arc-ignition probability test program it was important to have reliable information on the behaviour of arcs under the different electrical conditions that simulate real powerline faults. The dynamics of the arc and plasma, the duration of the arc, the power and energy released and the electrode materials used could all, potentially, influence ignition.

Tests conducted at TCA from 18th to 20th April 2011 and from 12th to 13th May 2011 provided information on the physical features and behaviour of arcs. Details of the effects of test conditions on arc energy release are set out in the following paragraphs. Conditions for each test are listed in Appendix 4. Arc appearance and behaviour were studied using very high speed video records provided by MACS Camera Film and Television Supplies contracted for the purpose by TCA.

8.1 Arc and plasma appearance

Arcs produced under various simulated powerline fault conditions were large, often extending up to a metre in height, and they exhibited very complex and semi-chaotic behaviour. Typically, as the electrodes draw apart, the arc extends and almost immediately starts to rise into the air and adopt a constantly moving tortuous convoluted structure well above the electrodes.

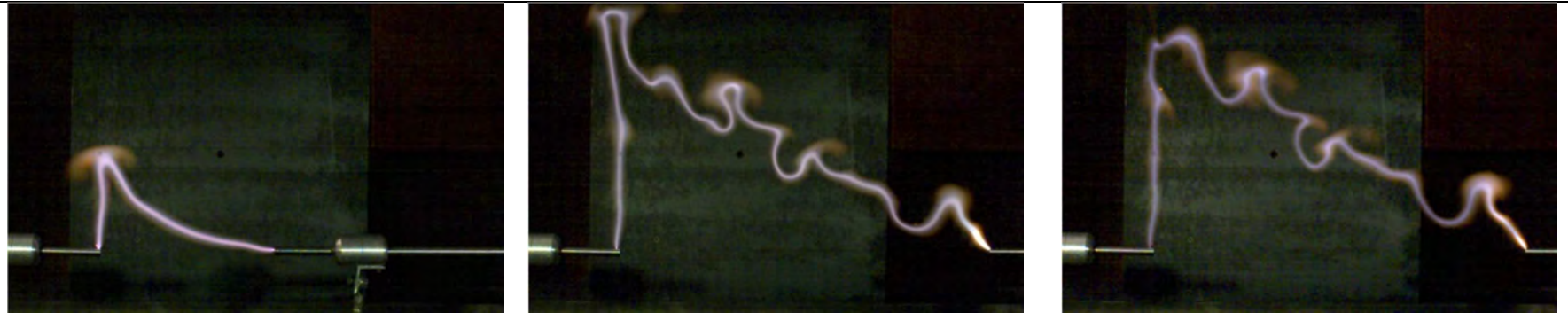
At low currents (4.2 amp), the arc exists as a relatively thin (5-10 mm diameter) pulsing (100Hz) pink thread running through a broader slightly fuzzy glowing blue tube of plasma. The length of the arc thread increases as it rises and curls upon itself in a random manner similar to smoke rising in still air. The arc rises close to vertically above the stationary electrode due to convection, at a speed of 0.5 m/s after 0.2 seconds and at more than 0.8 m/s at 0.3 seconds when the full arc gap was reached.

At times, two parts of the 'arc thread' will come close enough to short circuit through the intervening plasma, thereby suddenly reducing the total arc length somewhat. Photographs of arcs in 4.2 amp tests at increasing times in Figure 25 illustrate this dynamic behaviour. Whenever such a short circuit occurs, the arc power drops suddenly before resuming its upward trend. As the glowing mass of the twisted arc rises, these short circuit events become more frequent until they effectively constrain the total arc power to a plateau level around which it varies randomly.

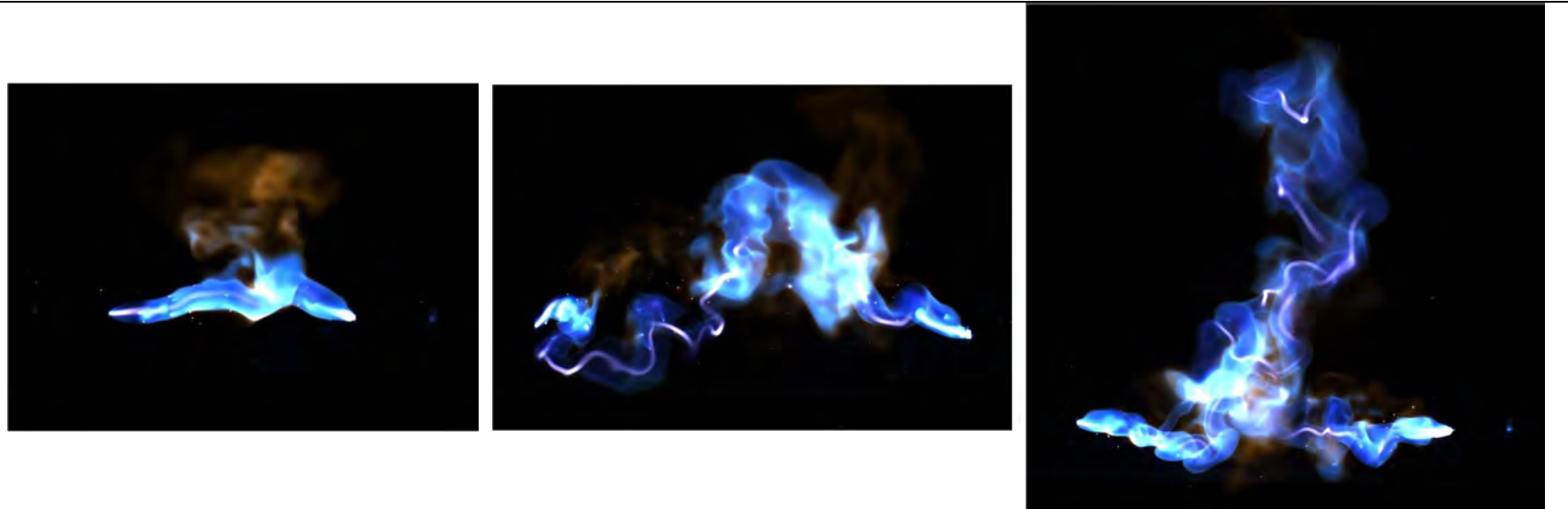
At higher currents, the behaviour is similarly complex but the arc and plasma tend to be somewhat more constrained to the region between the electrodes. Increased detail from the high speed videos revealed that the morphology of high current arcs is significantly different to low current arcs. Rather than the rapidly rising arc thread seen with 4.2 amp arcs, the 200 amp arcs very quickly form a tangled, vortex-like structure above the arc gap, presumably due to electromagnetic forces. The convoluted, tangled thread is enveloped within a large diffuse cloud of plasma, which rises at a much slower rate than the thread of low current arcs. The thread of the arc continually short-circuits as it re-strikes within the plasma cloud and moves so quickly that it is difficult to track, even at 1000 frames per second. The tangled nature of the thread within the cloud makes the actual length very difficult to estimate. The photographs in Figure 25 also show a 200 amp arc – the area of the arc and plasma is brighter and whiter than in the 4.2 amp arcs, probably reflecting higher temperatures and there is a much broader plasma cloud.

From the test program it was not possible to determine a maximum stable arc length or an effective maximum arc gap. The tests were usually done with the arc gap increasing to a maximum length of 425 mm as one electrode moved, and at this gap length, a stable arc was maintained, seemingly indefinitely though the maximum allowed duration was around 1-2 seconds to protect the test equipment.

This was also the case for a fixed arc gap with the arc initiated with a fuse wire; there was no problem sustaining an arc for at least 1 second at all current levels. The presence of wind upset the arc – the arc durability applies only to relatively still air conditions.



Test ET7, 4.2A (TCA ID 024) – Arc at 4.2 amps with tungsten electrodes accelerating to 2m/s at 9.8m/s^2 . First image at 200 ms after the start of arcing, second image at 425 mm separation and third image 21ms after 2nd image, after short circuit



TCA Test 293 – Arc at 200 amps with tungsten electrodes accelerating to 2m/s at 9.8m/s^2 . First image at 200ms, second image after 350 ms and third image at full separation. Note the visible emission of particles.

Figure 25. Appearance of arcs developed with 4.2 amps (top) and 200 amps (bottom) current as the electrode gap increases with time.

8.2 Arc current & voltage characteristics

The bulk of 200 amp tests were completed with a source impedance lag angle of 55° . The current and voltage waveforms (Figure 26) for a 200 amp test shows:

- Full current flow with electrodes in contact with low (nominally zero) voltage
- A slight rapidly decaying DC offset in the current in the first cycle
- Increase in arc voltage as the electrodes separate and the arc is drawn
- Peak in arc voltage just prior to each re-strike of the arc every 10ms
- Severe voltage clipping, i.e. the arc voltage is not at all sinusoidal
- Increasing voltage with subsequent cycles as the arc gap is increased
- Extinction of the arc after approximately 2.5 cycles, whereupon the arc current drops to zero and the voltage across the arc gap adopts a random value³³.

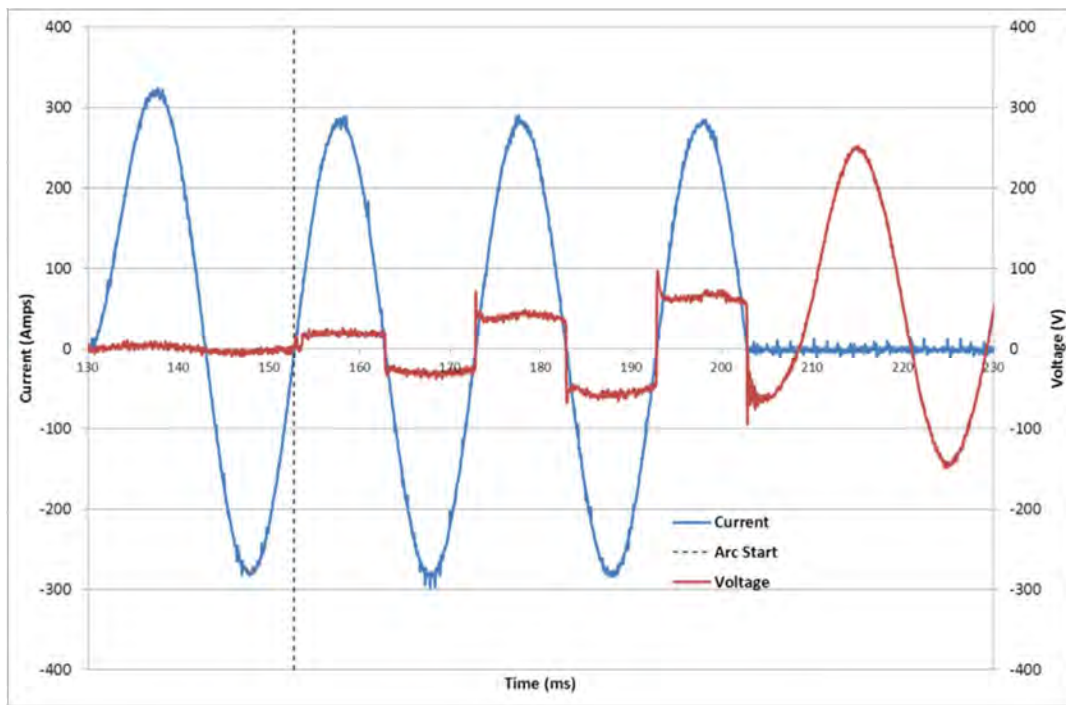


Figure 26. Voltage-current characteristics in a typical 200 amp test (TCA file #299) from the ignition probability trials

In the 4.2 amp test for which the traces are plotted in Figure 27 a similar behaviour occurs, although the arc duration is longer. Conditions at the start and conclusion of the arc are illustrated. The increase in voltage with progressive cycles is more apparent, as is the strike voltage peak, particularly towards the end of arcing. This behaviour suggests the arc may have been about to self-extinguish.

³³ In all tests where the arc is extinguished by removing the power, the 'live' electrode is left floating after the circuit breaker opens and it then assumes some random voltage (always less than 12.7kV) depending on the stray capacitance between it and the live parts of the system and between it and earth.

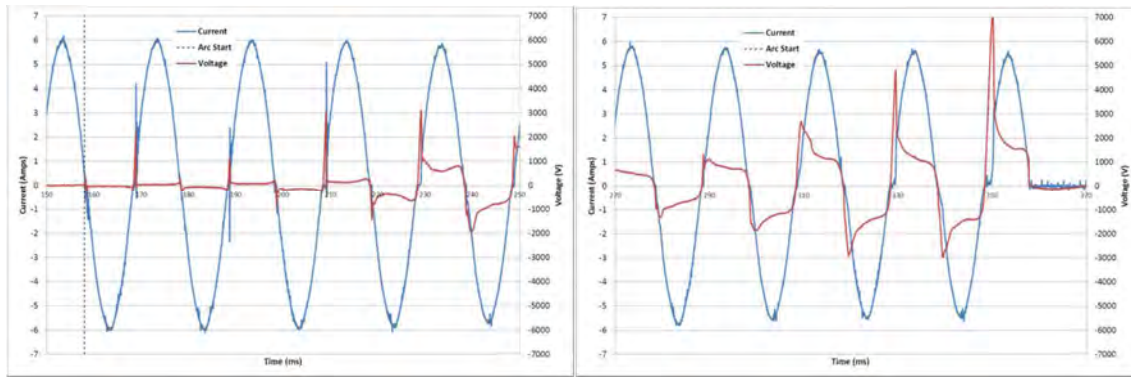


Figure 27. Voltage-current characteristics in a 4.2 amp test (TCA file #190 – start and finish) from the ignition trials

8.3 Calculation of arc energy and power

From the 20 kHz current and voltage data for each test the arc energy and arc power were calculated:

$$\text{Arc energy (J)} = \text{instantaneous current} \times \text{voltage} \times \Delta \text{time}$$

$$\text{Arc power (W)} = \text{instantaneous current} \times \text{voltage}$$

The cumulative energy as a function of time from arc start was calculated and plotted together with arc power averaged over the past 20ms, i.e. the last full 50Hz cycle.

8.4 Effect of arc gap on arc power

Stokes had noted that the arc power increases with arc gap and fitted a correlation formula to his data that applied to conditions where the test current was greater than the transitional current when the arc is more strongly influenced by magnetic forces than by air convection. His relationship for the arc power (P_I) was:

$$P_I = (20 + 0.534x) I^{1.12}$$

for an arc gap x (mm) and current I (A). The arc behaviour in the Tranche 1 tests was extremely dynamic and unpredictable and the arc gap bore little relationship to the actual length of the arc, particularly at longer durations. Stokes acknowledges this but does not account for it in his correlation. For this reason the formula developed by Stokes did not appear appropriate; arc power would be expected to be more closely related to the total arc thread length.

A plot of arc power per unit length of arc thread, as estimated from high speed video footage, is shown in Figure 28. This appears to be a more suitable basis for developing a correlation between arc power and current, though is admittedly not as convenient as simply using arc gap. The plot shows a linear relationship across the range of currents investigated. This implies a constant voltage per length of arc thread of 0.5 V/mm. This is only a preliminary investigation based on a limited number of measurements (74 power and length

readings from 28 tests) and has been developed by applying a fixed scaling factor of 1.5 to the measured arc length to allow for the out-of-plane arc thread excursions not captured by the video.

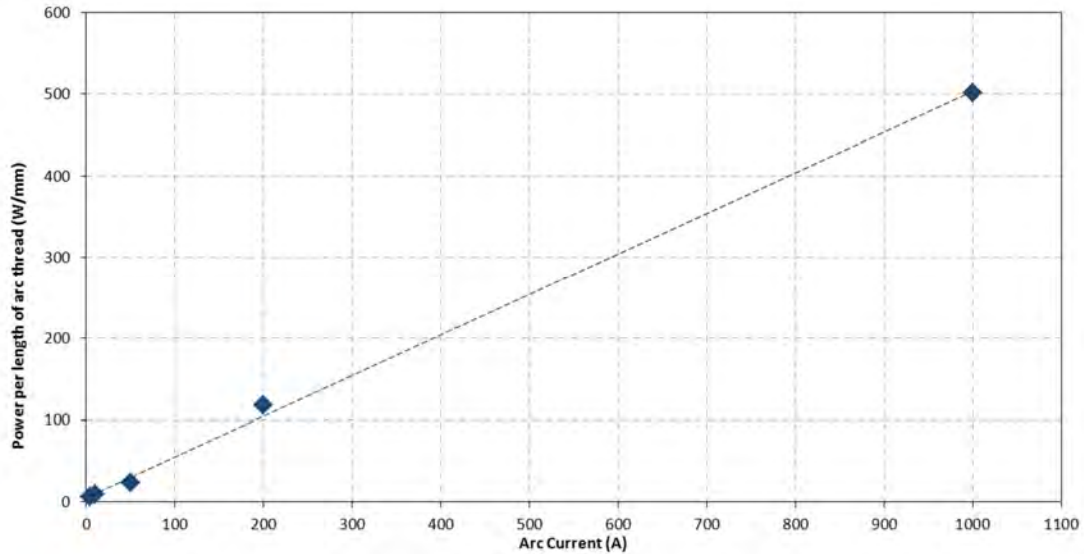


Figure 28. Arc power per length of thread for the five current levels investigated.

As the arc gap is increased by the movement of one electrode, the arc power increases relatively smoothly before the random fluctuations due to the semi-chaotic movement and short circuiting of the arc thread become prominent causing the arc power to plateau. At 4.2 amps, arc power plateaued at levels around 7kW. At 10 amps this had risen to nearly 20kW. At 50 amps, it was 55kW and at 200 amps, it was 190kW (Table 11).

The arc power increased as the electrodes separated, but also continued to increase (because of the arc dynamics, which extended the arc thread length) even after the electrode gap had reached the maximum separation of 425 mm and the electrodes were stationary.

Current (amps)	Arc power plateau at 425 mm gap (kW)	Arc power at 300 mm gap (approx.) (kW)
4.2	7 - 8	4
10	15 - 20	7
50	40 - 70	17
200	160 - 220	70
1000	600	405

Table 11. Typical arc power characteristics for the different test conditions.

Initiating the arc at various points along the AC cycle by varying the timing of the linear actuator trigger pulse did not appear to have any influence on arc stability or power.

8.5 Effects of test variables on arc behaviour

Data from both of the preliminary test stages is considered in this section and summarised with the use of graphical plots against time from arc start of the 20ms-average arc power and/or the cumulative arc energy.

8.5.1 Reproducibility

Tests indicated that the key characteristics of arcs that determine ignition probability are reasonably reproducible from test to test.

Several tests under identical conditions were completed to assess repeatability for 4.2 amp and 200 amp currents and the results (Figure 29) show the extent of random variation in the power curve. In the 4.2 amp trial the power varies considerably between tests; in the test that gave the highest power curve (the green curve in Figure 29) the arc power as the arc gap increases is twice the power of the lowest power test (the orange curve). However, the maximum arc power reached in all tests is reasonably consistent. In general there is reasonable overlap, but there is obviously significant random variability. This appeared to be related to the looping and short circuiting behaviour of the arc. Local air movement probably causes this variability.

The 4.2 amp plots (Figure 29) indicate that there is reasonable consistency in arc power at smaller gaps, at the start of arcing. As ignition tests were done with the electrodes embedded in the fuel and the gap restricted to 110 mm the arc is expected to be relatively stable, and this should improve the level of consistency between tests.

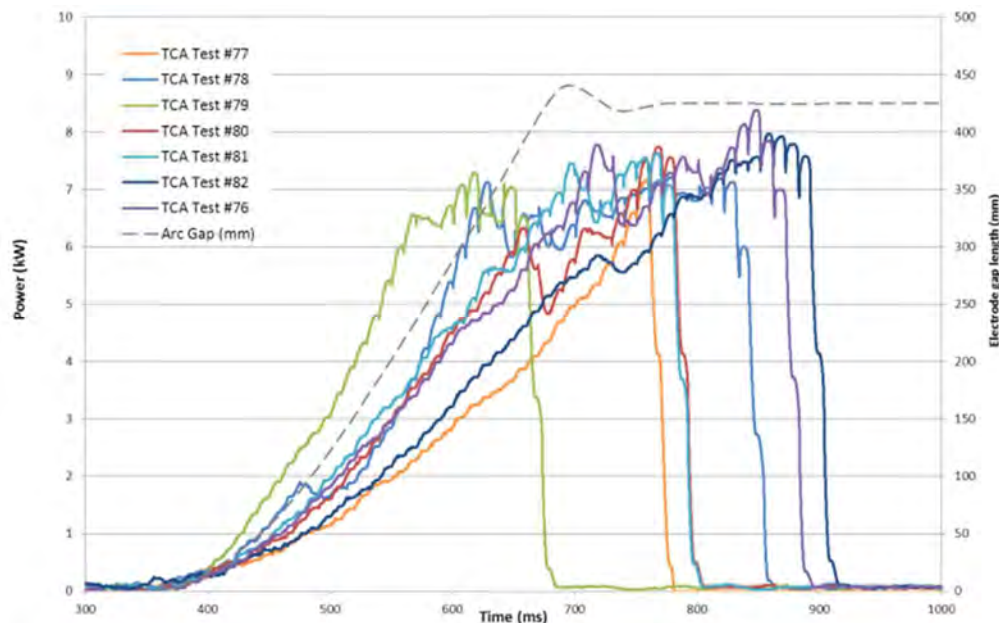


Figure 29. Variability of arc power in several tests at 4.2 amps with tungsten electrodes with an electrode speed of 2m/s

Repeatability tests at 200 amps generally showed greater consistency between tests (Figure 31) than in the 4.2 amp trials. The arc power curve showed considerable fluctuation, particularly as the arc gap increased towards the maximum. As above, at arc gaps of the order of 100 mm there was good reproducibility in the power curves.

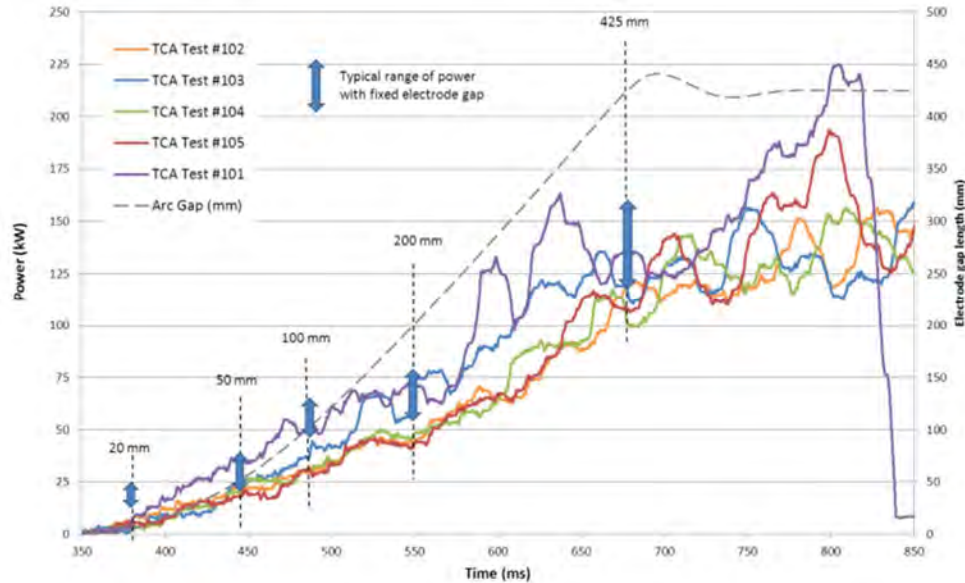


Figure 30. Variability of arc power in several tests at 200 amps with tungsten electrodes with an electrode speed of 2 m/s

The plots of cumulative energy release as a function of arc duration tend to be smoother than the power curves. However, there is still considerable variability between tests, as shown in Figure 31. The energy released by a 200 amp arc in the first ~ 450 ms varied from 33 to 47.5 kJ, with most of the readings clustered around the average of 38 kJ.

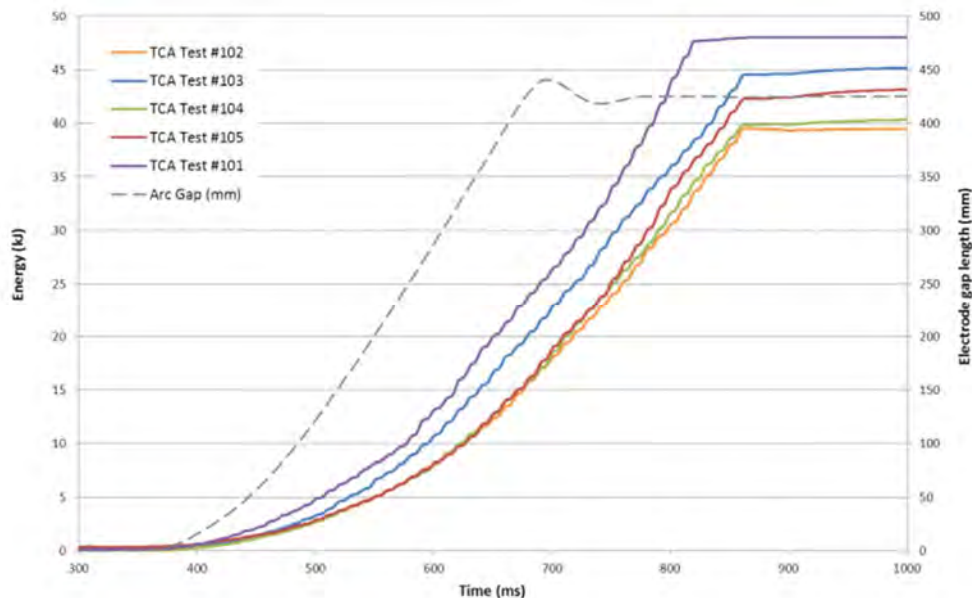


Figure 31. Variability of arc energy in several tests at 200 amps with tungsten electrodes with an electrode speed of 2m/s

8.5.2 Fixed vs moving electrode

Though a moving electrode was used to 'draw' an arc in the ignition tests to mimic what happens in real powerline faults, tests indicated the specific means of producing the arc was unlikely to have a strong influence on ignition probability.

Exploratory tests were done at several fixed electrode gaps with a thin fuse wire used to start the arc. This is a standard method for arc testing though it is not realistic for powerline faults as the flashover distance for 12.7kV is less than 5 mm and longer arcs must be 'drawn out' from an initial small arc. Although the arc power fluctuated widely in some tests (Figure 32) there was no consistent increase in power with time – the arc power remained reasonably constant as the arc continued. For longer arc gaps lengths the arc still tended to loop upwards from convective action, and this tended to produce random fluctuations in arc power (rather than any sustained increase in power).

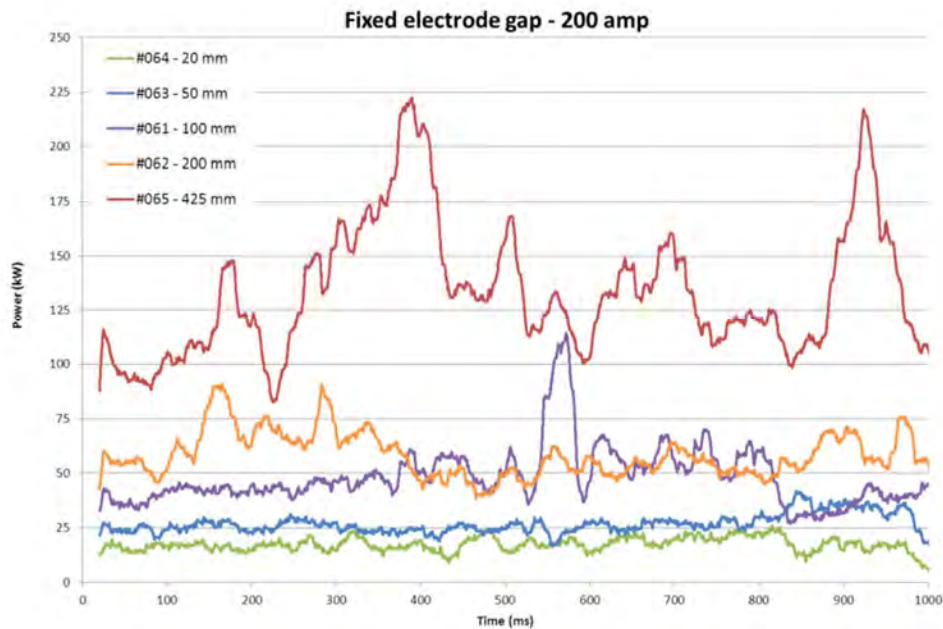


Figure 32. Arc power in several tests at 200 amps with tungsten electrodes at fixed gap

The range in arc power for each of the fixed arc gaps has been superimposed on the arc power curve at 200 amps with the moving electrode in Figure 30. These tests confirmed that there was similar power output with fixed or moving electrodes, any differences observed lay within the bounds of random test-to-test fluctuations.

There were considerable operational benefits in using the moving electrode for ignition tests – principally related to the turn-around time between tests – and this approach was adopted.

8.5.3 *Electrode materials*

The test program assessed the effect of electrode material on arc energy but found there was no major difference across the range of materials commonly found in distribution networks

Tests were completed at all test currents with pairs of tungsten, steel, aluminium and galvanised steel electrodes. All were manufactured from 10 mm diameter rod (or galvanised bolts) and had the same arrangements for electrical connection. The objective was to determine if the power output from the arc was influenced by electrode material. The thermal stability of these materials is quite varied, and one (or more) might be more prone to emit hot particles or show unexpected behaviour. If all showed similar performance then it would be reasonable to streamline the ignition tests by using one material only. In the earlier exploratory tests tungsten was used. It was regarded as the most inert of the electrode materials selected and therefore expected to be less likely to emit hot particulate material during arcs.

Comparison of the average arc power curves during tests with each material is shown in Figure 33 on the next page for tests at 4.3, 10, 50 and 200 amps. Where there were results from several tests using tungsten (as was the case for some reproducibility tests) an averaged result is plotted.

There is considerable variability between tests, but this appears to be random variation rather than to indicate any consistent difference in the performance of electrode materials. In the 200 amp tests the power released with tungsten electrodes (an average of five tests) showed the same trend as with other materials. However this is not a consistent finding. In the case of the 10 amp tests it appeared that the highest power release was with galvanised steel electrodes – at 3 to 4 times the power release with steel electrodes. As it is likely that early in the arc of galvanised electrodes the zinc coating will be rapidly penetrated and then the arc will be to the steel substrate, it therefore seems probable that the observed differences are indicative of the variability of the arc test itself, rather than a difference caused by the change in material.

It is considered that there is no significant (i.e. consistent and material) difference in the power released in arcs with the various electrode materials, and tungsten was therefore used as the default material in exploratory tests. However, most ignition tests were carried out with steel electrodes because tungsten was harder to return to original condition between tests.

8.5.4 *Tests with wood ‘electrodes’*

Some tests were done using green and dried wood covers on the metal electrodes to simulate contact between a tree branch and a live conductor. The electrodes were machined to approximately 25 mm diameter, with a 10 mm diameter central hole such that the wood could slide over the fixed metal electrode tip. The depth of the central hole was varied such that the distance from the end of the fixed metal electrode to the exposed end of the timber was either 10 mm or 50 mm. Tests were carried out at 10 amps.

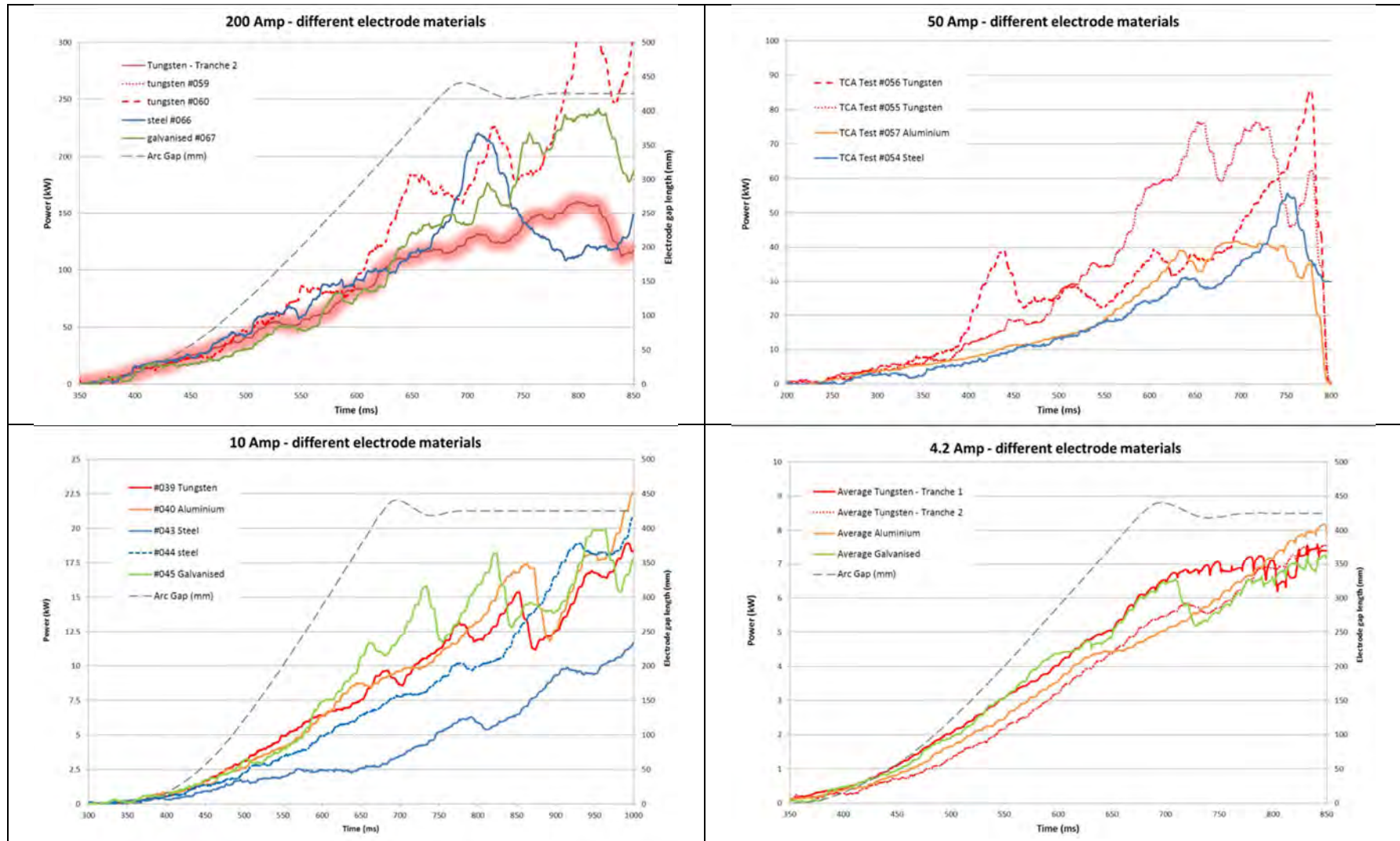


Figure 33. Increase in arc power with arc duration for various electrode materials – electrode separation at 2 m/s to 425 mm

The moving electrode was placed in contact with the end of the timber in each test and moved away at 0.01 m/s after the test initiated. With the dried timber and the short (10 mm) distance to the moving electrode there was obvious conduction through the timber and it was severely charred though not ignited. An arc developed but did not appear to be associated with the wood. With the larger 50 mm through-wood distance in the arc path, no arc or activity occurred.

With the green wood electrode it appeared that electrical connection developed through the wood to the extent necessary to initiate arcing. The arc tracked back along the side of the wood to the metallic part of the fixed electrode, and subsequently the arc was effectively between the two metal electrodes, bridging across the green wood cover on one of them.

8.5.5 Source impedance lag angle

Though care was taken to faithfully represent realistic powerline network parameters in the test rig power source, tests indicated this was not a critical factor in ignition probability.

Most 200 amp arc-ignition probability tests were conducted with a source impedance having a lag angle of 55° . Some additional exploratory tests were done to determine the power and energy characteristics under conditions with a near-pure resistance load (lag angle of 8°), and with a near-pure reactance load (lag angle of 88°). Plots from two series of tests in Figure 34 show no consistent effect of source impedance lag angle on the power curve.

Even though this result is derived from less than a dozen tests, it indicates the test rig used to produce the arc need not mimic a real distribution powerline network as closely as was done in this test program. Valid results may still perhaps be generated without an exact simulation of a realistic power source.

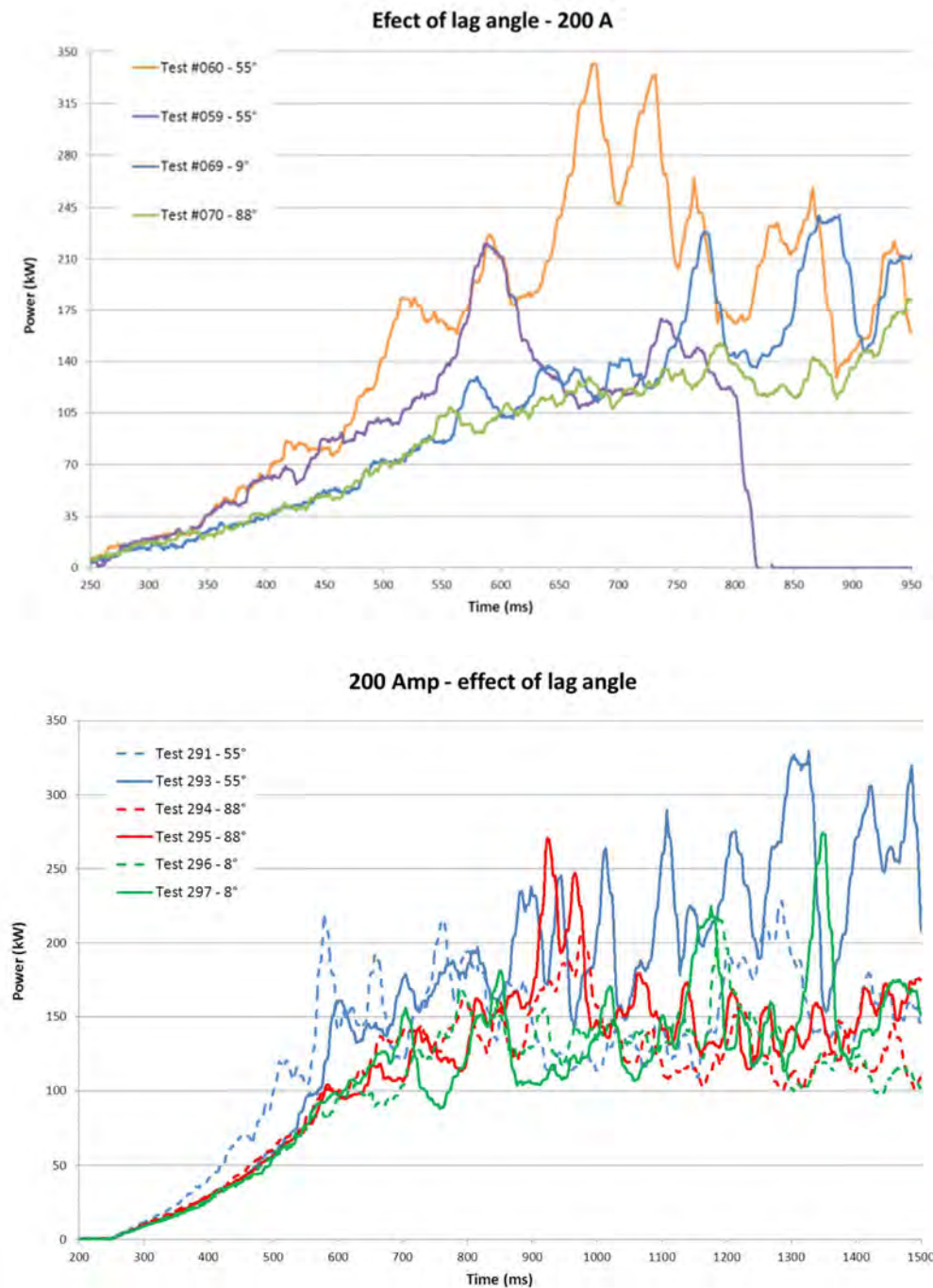


Figure 34. Effect of lag angle on arc power output as a function of arc duration at 200 amp. [Tests were done of two occasions]

8.5.6 *Effect of electrode separation speed*

Tests indicated that the speed at which the arc was 'drawn' did not have a major effect on arc energy release other than slower speeds allowed time for arcs to develop more, i.e. increase their physical size and power at a given arc gap length.

Actuator acceleration, given the overall mass of electrode assembly, was limited by stepper motor power and tests were done with a default acceleration of 9.8 m/s^2 to a velocity of 2 m/s in about 0.15 seconds after which this velocity was maintained until the set arc gap limit was reached. Some tests were carried out at lower speed to determine if this changed the arc power release or arc conditions. Some of the 10 amp tests using aluminium and galvanised electrodes were done at a maximum separation speed of just 0.25 m/s. The power output increased fairly steadily to a maximum of approximately 24 kW in the slower electrode speed tests, although the arc appeared to have self-extinguished before the full 425 mm arc gap had been reached. The maximum velocity attained during ignition testing, during which the actuator displacement was restricted to 110 mm in order to confine the arc within the boundaries of the fuel basket, was 1.2 m/s.

In tests conducted under the default (2m/s electrode speed) conditions the average arc power increased with electrode gap, reaching a value of 10-12 kW when the maximum separation was reached within 340ms of the arc starting. However, arc power increased further as the arc continued with electrode separation constant at 425 mm, and the average power levelled off at around 24 kW, i.e. the same figure as with the lower electrode velocity.

The energy output with slower electrode movement would be greater because the arc has time to extend and grow as the gap increases over a significantly longer period – approaching 1.75 seconds for the slow speed compared to 0.3 seconds for the high speed separation.

8.5.7 *Incandescent particles*

Attempts were made to collect metal particles emitted from higher current arcs. None were collected though many were visible in high speed video records. The adoption of a zero arc-fuel configuration in the ignition tests incorporated the effect of hot particles in the results.

It is known that an arc between two metal electrodes can lead to the melting of the electrodes and the expulsion of particles of molten (and sometimes burning) metal. The extensive work by Stokes et al into hot metal particles emitted by clashing conductors showed that particles up to 3 mm diameter could be produced, and particles were produced with aluminium, copper and steel electrodes.

In the current program of tests the video record often showed signs of hot, possibly molten metal being emitted. If there were significant numbers of relatively large particles produced these might materially increase the likelihood of ignition. In several tests, attempts were made to collect particulates using a water bath beneath the arc area. No particles were collected in any of the tests regardless of the electrode material selected.

In some tests the electrode tips (both fixed and moving) were weighed before and after arcing. If there was significant generation and emission of particles some weight loss was

expected. In most of the tests the electrodes gained weight, presumably due to oxidation in the high temperature arc. From very limited tests with steel electrodes, the weight increase seemed to be greater in higher current tests, viz:

0.12 and 0.46 g	at 200 amp
0.01 g	at 10 amp
Less than 0.01 g	at 4.2 amp

From review of the video records it appeared that tungsten electrodes were at least as likely to produce particles as other electrode materials. However, as no particles were collected it seems reasonable to conclude that the original particles from these tests were small, and probably significantly smaller than those collected in Stokes' testing.

With the electrodes partially embedded in the fuel in the ignition probability tests, any particles emitted would contribute to the heating and ignition of the fuel. This would be a fair simulation of an arc in the field and it seemed reasonable under these conditions to not attempt to differentiate between the contribution of emitted hot or incandescent particles and the overall heat flux from the plasma through conduction, convection and radiation.

8.5.8 Transient recovery voltage (TRV)

A conservative approach was taken to TRV settings for the test rig, i.e. TRV was managed in a way that would maximise arc duration and power.

A high level of TRV promotes re-strike of the arc and inhibits arc extinction. In all high power arc tests of circuit breaker operation, TRV is carefully specified and set to ensure test results are conservative. However, in powerline faults, often the main current being carried by the conductor is not being broken by the fault, e.g. a conductor loose and swinging against a pole or other earthed structure. Only in the case of conductor breakage is the circuit current interrupted in a similar way to its interruption by a circuit breaker. For this reason, it is difficult to directly apply the extensive body of TRV knowledge to arc-ignition tests.

In consultation with TCA, the TRV settings for the arc-ignition tests were selected to maximise TRV while staying within the bounds of equipment safety (excessive TRV can generate flash-overs in the high voltage equipment supplying the test rig). This use of the lightest possible TRV suppression settings ensured the arc-ignition tests were conservative as the test configuration provided maximum support for arc continuation rather than early extinction.

8.5.9 Issues for subsequent ignition testing

The semi-chaotic and convection driven behaviour of arcs was the most significant challenge for the arc and ignition testing program. The convective nature of the arc and plasma cloud made it apparent that the heat flux above a horizontal arc is significantly greater than that beside or below it. It remains unclear how best to model arc geometry during the semi-chaotic, convection driven period of development or high current arc conditions, but this did not appear to be an essential input for ignition tests.

9 Heat flux from arcs

Heat flux measurements in exploratory arc tests confirmed that only a small proportion of total arc energy transferred to the environment by radiation. The heat flux measurements generally aligned with those in other ignition research once allowance was made for the special character of arc tests. Heat flux measurements were not used in the arc-ignition tests due to high risk of damage to equipment. The choice of zero arc-fuel distance as the worst case condition removed the requirement for more sophisticated models of heat flux

Established ignition test methods cover a very broad range of heat flux. Conventional ignition tests of solid fuels are often carried out using heat flux in the range 10-100kW/m². At these levels, extended periods of exposure, perhaps from 20 seconds to several minutes, might be required for ignition. Standard tests to assess the flammability and performance of heat resistant clothing use very high power arcs and peak heat flux levels of 25,000kW/m². Although the key outcome from the current arc-ignition test program is to quantify the probability of ignition, it was valuable to confirm that the heat flux delivered to the fuel by the arc was consistent with expectations. Heat flux was measured during a number of the exploratory tests carried out in May 2011. More details on the methods used are included in Appendix 3.

9.1 Results from testing

9.1.1 Fixed arc gap

Heat flux measurements for fixed arc gap tests indicate that less than about 15% of total arc energy is transferred to the local environment by heat radiation.

Initial heat flux measurements were undertaken during tests at 200 amps with a fixed arc gap, using a fuse wire for arc initiation. The arc gaps used were 20, 50, 200 and 425 mm and in each test, the heat flux assembly with three copper discs was arranged beside and parallel to the arc at approximately 250 mm lateral distance from the centreline of the electrodes. The size and dynamic nature of the arc made choice of location of the copper discs difficult. If the arc rose vertically over the arc duration, the distance between arc and calorimeter probes would increase. If the discs were too close to the arc they would be damaged.

The results in Table 12 show there is significant variation in the heat flux measured from adjacent copper discs, but in general the heat flux increases as the arc power increases with each larger arc gap. The heat flux at a distance of 250 mm from the arc increased from around 5kW/m² for a 20 mm gap to approach 30kW/m² at the largest (425 mm) gap. Literature suggest that with this level of heat flux, ignition of a timber fuel would be possible after perhaps 20 seconds exposure, thus much higher heat flux would be expected to be necessary to cause ignition within the arc duration. This would be the case at positions closer to the arc.

The heat flux will be inversely proportional to the distance to the probe. Thus for the 200 amp tests the heat flux at a distance of 25 mm from the arc should be of the order of 50-300 kW/m². One of the 200 amp tests had the probe only 110 mm from the arc (for the 425 mm gap test) and this gave a proportionately higher heat flux within 10% of the ‘inverse distance’ prediction.

TCA Test:	Test # 064			Test #063			#062	Test #065		
arc gap (mm)	20			50			200	425		
Average power (kW)	15			25			60	140±40		
Cumulative energy (kJ)	17			28			60	135		
Thermocouple	TC1	TC3	TC4	TC1	TC3	TC4	TC4	TC1	TC3	TC4*
Temperature rise (°C)	0.9	0.9	4.8	1.5	1.6	2.5	5.5	3.4	3.9	9.3
Heat energy (J/cm ²)	0.47	0.47	2.51	0.79	0.83	1.31	2.88	1.78	2.02	4.87
Heat flux (kW/m ²)	4.9	4.8	26.1	8.0	8.4	13.3	29.7	17.8	20.2	48.7
Ratio – measured/total	1.0%	1.0%	5.5%	2.5%	2.6%	4.2%	15.6%	8.5%	9.6%	10.2%

Table 12. Measurement of energy and heat flux from probes at a distance of 250 mm from the arc, with arc duration of approximately 1 second. * TC 4 in 425 tests was at a distance of 110 mm.

From the average arc power in the fixed electrode tests the total heat flux in all directions at a distance of 250 mm has been calculated, assuming that:

- the arc is cylindrical with length equal to the arc gap, i.e. an approximation ignoring the convective rise and complex extension of the arc.
- the average arc power is evenly dissipated along the arc gap length, and the heat flux is uniformly distributed radially.

The ratio of the measured heat flux to the estimated total heat flux at a distance of 250 mm is included in Table 12. Measured heat flux accounts for typically <5% and up to 15% of the measured arc power in the 200 amp tests. At best this should be regarded as a rough approximation.

This suggests that for the test conditions the radiated power is a relatively minor proportion of the total power. Stokes and Sweeting³⁴ had commented that in their view the radiated heat loss from the arc was only a small fraction of the total, less than 10%, with the bulk of the heat, and the highest risk of arc burns, from convective transfer in the plasma. Their work related to the conditions used in assessing thermal performance of clothing materials, i.e. tests at high currents when electro-magnetic effects may produce plasma jets. It would appear that at the lower currents used in the arc-ignition test program this is also the case.

³⁴ Stokes A and Sweeting D Electric arcing burn hazards IEEE Transactions on Industry Applications 42(1) page 134 Jan/Feb 2006

9.1.2 Moving electrodes

Heat flux measurements for 'drawn' arcs indicate that less than about 5% of total arc energy is transferred to the local environment by heat radiation. Much higher heat flux is recorded vertically above the arc.

Heat flux was also measured during the 200 amp repeatability tests. In these tests one probe (with two calorimeter discs) was positioned beside the arc (parallel to the electrodes) at a distance of 250 mm from the electrodes (horizontal probe as above), and a second probe was positioned about 95 mm behind the end of the fixed electrode (vertical probe). The calorimeter discs in the vertical probe were approximately 70 and 120 mm above the centreline of the electrodes. The electrodes separated at 2 m/s speed to the maximum gap of 425 mm. Conditions in all tests were kept constant and there is reasonable consistency in the measured values of heat flux, as shown in Table 13. With the horizontal probe beside the arc the heat flux was around 20 kW/m², i.e. in the same range as with a fixed electrode gap of 425 mm. With the vertical probe the heat flux was similar but the upper probe (further from the arc) had a lower heat flux, as expected.

	Heat flux calculated from heat calorimeters (kW/m ²)				Max power (kW)	Cumulative Energy (kJ)
	Horizontal probe - 250 mm		Vertical probe - 95 mm			
	TC 1	TC 3	TC 12	TC 11		
Test #101	17.2	13.5	19.3	14.6	225	47
Test #102	14.6	13.5	17.2	10.4	155	39
Test #103	23.4	18.8	20.3	11.5	155	44
Test #104	28.7	24.0	17.2	10.4	155	40
Test #105	16.7	13.0	24.5	14.6	190	42
Test #106	14.6	13.0	28.1	17.7		
Average	19.2	16.0	21.1	13.2		
Std Dev	5.7	4.5	4.4	2.9		
Total heat flux	374.5	374.5	420.8	420.8		
Ratio*	5.1%	4.3%	5.0%	3.1%		

Table 13. Heat flux (kW/m²) from 200 amp repeatability tests with arc duration of 0.4 to 0.5 seconds. TC1 & TC3 horizontal probe @ 250 mm. TC12 & TC11 vertical probe with TC12 @ 70 mm and TC11 @ 120 mm. *Ratio is based on a (low estimate of) power of 125 kW.

To estimate the proportion of heat energy absorbed by the probes it is necessary to estimate the area over which the total arc energy is dissipated. The cylindrical model (above) is reasonable for the horizontal probe. For the vertical probes a spherical model was used, with the sphere radius equal to (95 mm + half arc gap). The maximum power used for this estimate was 125 kW – i.e. on the low side of the values from the tests. These models are

rudimentary, but again suggest the heat flux picked up by the probes accounts for only a small proportion of the total heat flux, i.e. 3 to 5%.

An additional test at 4.2 amps was carried out with the probes only 50m from the arc. This was done with a moving electrode and the heat flux (Table 14 – Test #77) was ~7 kW/m². The arc plasma was observed to hit the second disc in this probe assembly leading to the very high heat flux of 128 kW/m² and destroying that calorimeter.

	4.2 Amp		4.2 Amp	200 Amp	
TCA Test Number:	77		89/90	110	
Thermocouple number	TC12	TC11	TC1	TC1	TC3
arc gap (mm)	Increased to 425		Inc 425	Increased to 425	
arc duration (sec)	0.403	0.403	0.414	0.309	0.309
Average power (kW)	↑ 6.5	↑ 6.6			
Cumulative energy (kJ)	1.1	2.1			
Temperature rise (°C)	0.5	10.0	0.6	3.0	5.7
Heat energy (J/cm2)	0.3	5.2	0.3	1.6	3.0
Heat flux (kW/m2)	6.5	128.4	7.6	50.9	95.5
Distance from arc to probe (mm)	50	50	220	200	200

Table 14. Heat flux from probes close to the arc and above the arc

The two tests in the table identified as 89/90 and 110 had the heat flux probes in a horizontal orientation above the arc, and these show relatively high heat flux readings. In a 200 amp tests the flux was around 95 kW/m² at a distance of 200 mm above the arc. However, the arc plasma rises convectively towards the probe so this distance will effectively decrease as arcing continues. This is clearly visible in Figure 35 where the distance has shrunk to zero due to arc movement.

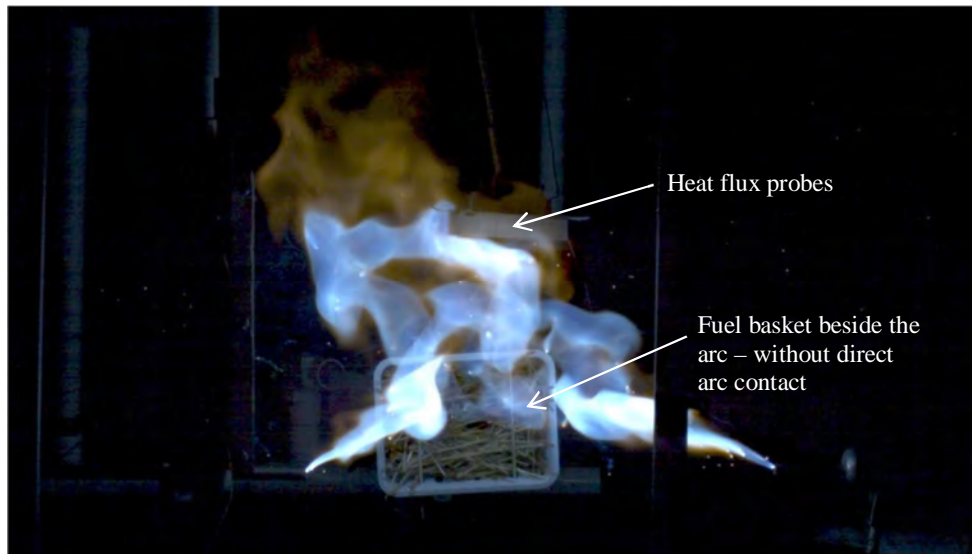


Figure 35. TCA Test # 110 at 200 amps – Plasma passing across heat flux probes positioned above the arc.

9.2 Implications for ignition probability tests

The heat flux measured at a distance of 250 mm from a 200 amp arc is of an order sufficient to lead to the piloted ignition of solid fuels after exposure for perhaps 20 seconds. At positions closer to the arc, and at positions above the arc the measured heat fluxes can be significantly higher and thus more likely to lead to ignition. Heat fluxes in the range 50 to 100 kW/m² were recorded vertically above 200 amp arcs with the arc gap increasing to 425 mm.

High heat fluxes were measured as the arc plasma approached and contacted the probe. This damaged the probe and it was considered undesirable to monitor heat flux routinely in the ignition probability test program.

In preliminary tests, ignition was seen to be almost instantaneous (under extreme conditions) when the arc plasma actually contacted the fuel. This is seen as a worst case condition, and also a possible condition in real powerline faults. It was therefore decided that rather than further exploring the effect on heat flux of distance from the arc and to include this as a variable in the ignition test program, tests would be done with the electrodes partially embedded in the fuel. This meant that a maximally severe test would be done, but that the arc-fuel distance would be reliably consistent.

Appendix 1 – Procedure for ignition testing

This appendix describes the approach adopted for the ignition tests used to generate the ignition probability curves described in Section 2. This is presented at a level of detail considered sufficient to reproduce the experiments. Some information is reproduced from the body of this report.

Test equipment

Arc-ignition testing was performed using a rig which had a moveable electrode driven by an actuator controlled by a programmable logic controller (PLC) that could be programmed using a laptop computer. The arc was automatically initiated and could be drawn out to a specific distance at a set rate, simulating the behaviour of a falling conductor, by moving one electrode. The moving and fixed electrodes are connected into a test circuit using a 12.7kV source and tests were carried out at currents of 4.2, 50 and 200 amps using a range of values of reactance and resistance defined by ESV to best simulate real fault conditions.

The test rig is shown schematically in Figure 36. A labelled photo of the setup surrounding the fuel basket prior to an ignition tests is included in Figure 37. The test rig includes the following features:

- Belt driven linear actuator (Festo EGC-70-TB) with a 500 mm working stroke and 48V DC battery powered stepper motor (Festo EMMS-ST-87-S-SE).
- PLC stepper motor controller (Festo CMMS-ST-C8-7) programmed using Festo Configuration Tool software (V1.2.0) installed on a laptop computer.
- Connection from actuator to the moving electrode through polycarbonate rod.
- Replaceable mild steel electrode tips – with bolted electrical connections.
- Actuator frame fabricated from non-conducting precision extruded GRP to ensure stability and alignment.
- Heavy aluminium electrostatic and eddy-current shielding for actuator and PLC
- PVC frame to hold fuel baskets, humidity sensors and disk calorimeters (not shown)
- Polypropylene (no toxic fire products) fuel baskets attached with Velcro strips.

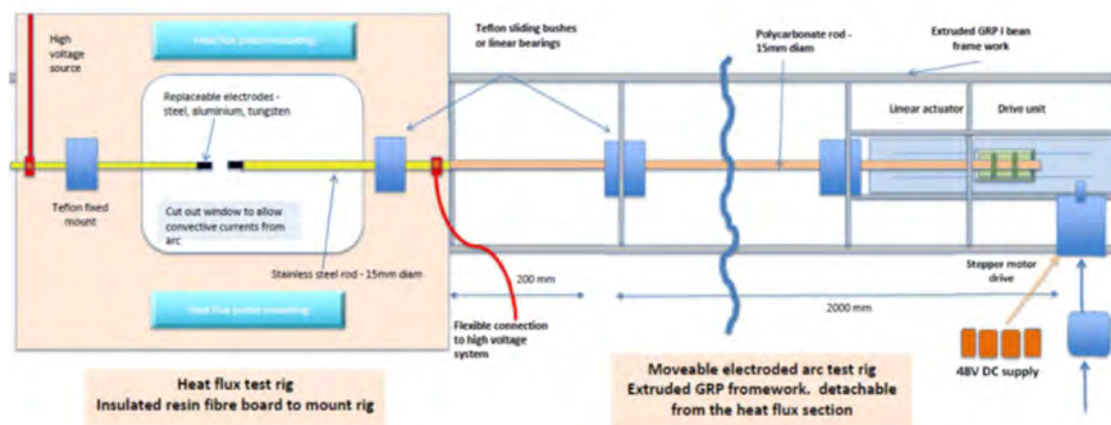


Figure 36. Schematic of the arc test rig showing the actuator drive and electrode arrangements

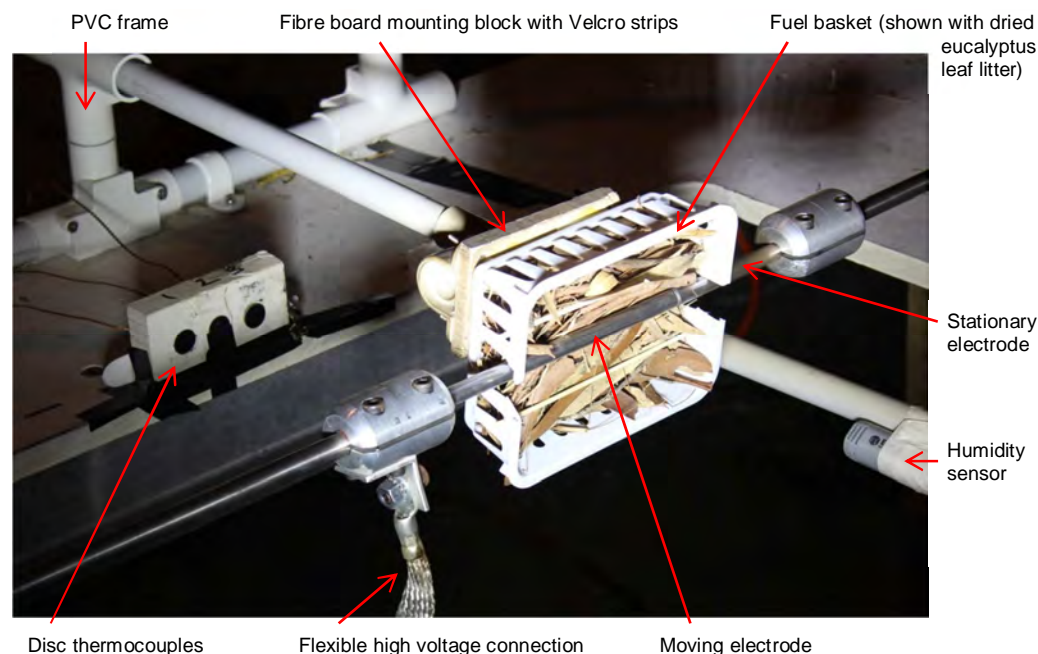


Figure 37. Test rig showing fuel basket/arcing site

Electrical conditions

Testing was undertaken using a 12.7kV, 50Hz power source representative of the Victorian electricity distribution network which is predominantly 22kV (12.7kV phase to neutral) and 12.7 kV SWER. Tests were performed at high (200 amp), intermediate (50 amp) and low (4.2 amp) arc currents. Tests at high and low current levels explored the effects of five variables: air temperature (with corresponding relative humidity value), airflow speed, fuel type, fuel moisture content and arc duration. All tests at the intermediate current level were done under worst case conditions, with arc duration as the only variable. Tests were performed at source impedances determined by network parameters plus a nominal 10 ohm earth resistance at the fault (typical of pole stay or other metal structure mounted on simple foundations). The source impedance in these tests was a mix of air-cored reactance and resistance reflecting the electrical supply system impedance and the fault path resistance. Circuit diagrams for the tests performed at TCA are shown in Figure 38.

For the majority of ignition tests, the following conditions were used:

- 200 amp tests: source impedance of 63 ohms with lag angle of 55 degrees
- 50 amp tests: source impedance of 250 ohms with lag angle of 22 degrees
- 4.2 amp tests: source impedance of 3,000 ohms with lag angle close to zero

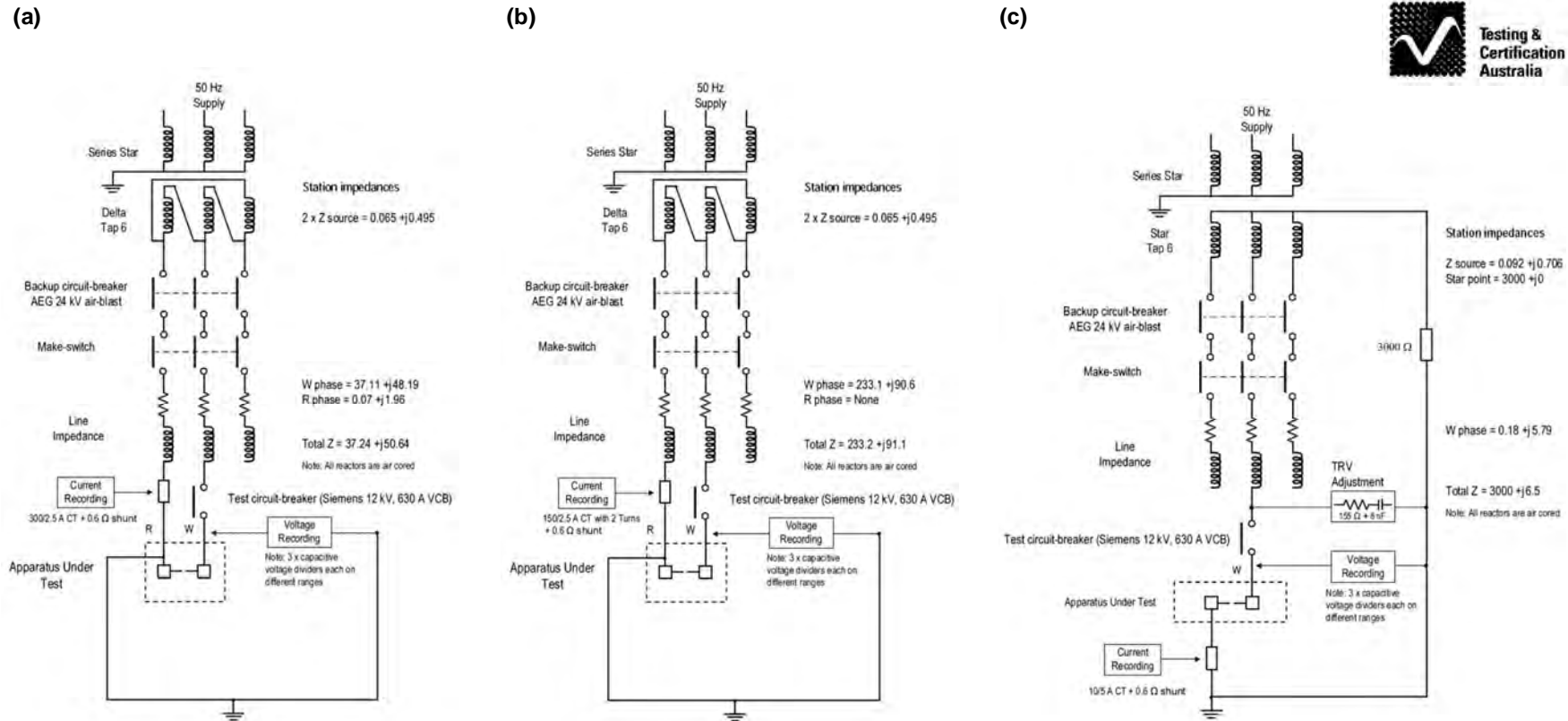


Figure 38. Test circuit diagram: (a) 200 A at 12.7 kV, 0.57 pf lag (b) 50 A at 12.7 kV, 0.93 pf lag (c) 4.2 A at 12.7 kV, unity pf.³⁵

³⁵ Laboratory Reference No. 102947, Testing & Certification Australia

In each test the arc was initiated through the TCA control system and the arc voltage and current were monitored through TCA's 20 kHz data acquisition system. Voltage measurement points were close to the HV connections to the arc test rig, rather than near the tips of the electrodes themselves. Measurement noise levels were checked and confirmed to be satisfactory. Arc duration was regulated by a vacuum circuit breaker, which made it possible to control arc durations to half a cycle of the 50 Hz power supply (i.e. to 10 ms). The duration of each arc was determined from the plotted current waveforms, either using TCA's dedicated software or in Microsoft Excel.

Ambient temperature and wind speed

For the ignition probability tests, the air temperature in the enclosed test cell was adjusted using a high power electric fan heater. The equipment did not offer precise fine control of the temperature, but temperature and relative humidity around the arc-fuel interaction area were continuously monitored and recorded. Tests were done at either the uncontrolled ambient temperature, typically around 20°C, or with air heated to close to 45°C.

Air temperature was monitored and recorded using two K-type thermocouples (in copper disc heat flux probes as described in Appendix 3) positioned 50 mm apart and ~200 mm behind the fuel basket connected to handheld loggers with digital readouts. Readings were sampled at 5 minute intervals and checked regularly between tests.

Air relative humidity was also recorded using two USB logging devices with an accuracy of $\pm 3.5\%$ for humidity measurements between 20 and 80 %. The devices were positioned ~50 mm to the side of, and ~350 mm in front of, the fuel basket respectively.

Both the temperature and humidity sensors were in the path of the fan directing either heated or ambient air across the test cell. The average of the two temperature and humidity measurements taken at the nearest 5 minute interval to each test was recorded for each test. The average air temperature and humidity across all of the ignition tests are presented in Section 2.3.3.

Tests were carried out with "wind speeds" of 5, 10 and 20 kph. Airflow was generated from either one or two fans, operating in series with the electric heater, and directed at the fuel basket using a 300 mm diameter duct. Control of the wind speed was limited to either changing the fan speed or the distance of the duct outlet from the arc rig. The wind speed in the vicinity of the fuel basket was measured with a portable anemometer and recorded roughly once per hour of testing or whenever test conditions were changed. The average of six readings taken ~25 mm in front of the fuel basket and four readings taken ~25 mm above, below and to either side of the fuel basket were recorded each time.

Fuel characteristics

The ignition tests were done using dried grasses. A reasonably consistent fuel was developed from an equal mix of relatively coarse straw and finer hay purchased from a farm animal food retailer. The fuel baskets were nominally 150 x 120 x 50 mm and

approximately 16 g of the hay/straw mix was loosely packed into each polypropylene basket. The appearance of the fuel is shown in Figure 39. From the scale the coarser straw material appears to have flat fibres typically 1 mm wide x 0.2 mm thick and the finer hay material to have stems around 0.2 mm diameter.

The moisture content in Table 15 shows a reduction in moisture content of the mix dried at low humidity at 45°C. The calorific value of the mix was typically 18.3 MJ/kg (gross dry). Some tests were also completed using dried eucalypt leaf litter collected in urban areas of Melbourne and a few with green eucalypt leaves (after two days off the tree) taken from a tree growing at TCA in Sydney.



Figure 39. Appearance of the hay/straw fuel mix in the fuel baskets. Scale labelled in cm (largest divisions), mm (intermediate divisions) and 0.1 mm (smallest divisions).

Fuel type	Fuel moisture content (wt %)	
	Ambient ~20°C	45°C @ RH=17%
Hay/straw mix	11.8 - 12.0	4.3 – 4.6
Eucalypt leaf litter	14.2	5.1
Green eucalypt leaves	15.1	

Table 15. Moisture content of grasses and leaf litter as received and dried condition.

Electrode material and separation velocity

Mild steel electrodes were used for all ignition probability tests. The electrodes were manufactured from 10 mm diameter rod with either a square or minimally chamfered end. One of the electrodes was fixed and the other drawn away from it at an acceleration of 9.8 m/s² to reach a maximum velocity of 1.2 m/s simulating a live conductor falling away from an earthed structure or vegetation falling away from a live conductor. The electrodes

were partially embedded in the fuel, initially in contact with one another before being drawn out to a separation of 110 mm. The arc gap between electrodes was limited to 110 mm in order to confine the arc completely within the length of the fuel basket. The maximum displacement of 110 mm was reached after ~170ms as shown in Figure 40. In exploratory tests, a higher speed was used (2m/s) and it reached the 425 mm limit of actuator travel in 320ms.

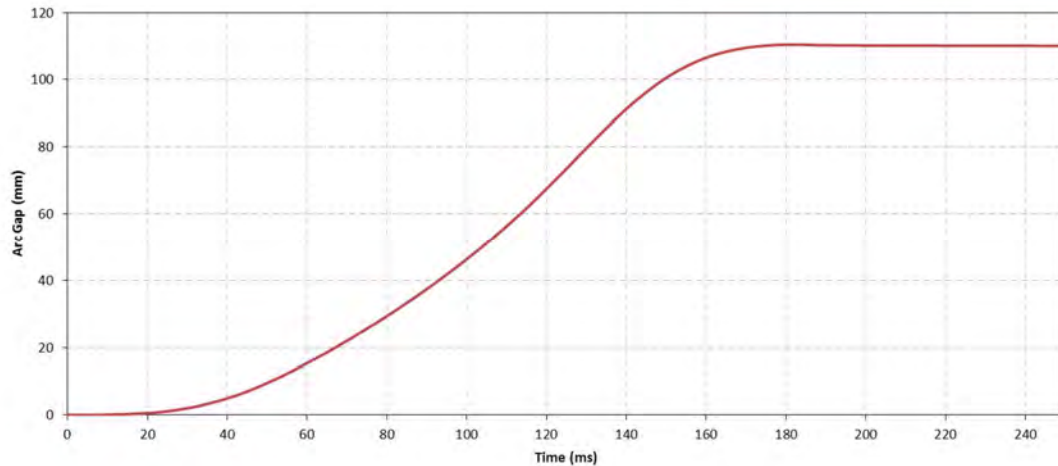


Figure 40. Electrode displacement (arc gap) for ignition tests

Video recording

High speed video recording was used to monitor the majority of ignition tests. It was not employed in the final set of tests (performed from the 15th to the 19th of August 2011) in order to maximise the number of tests carried out. Videos were typically recorded in high definition (1080 x 1920 pixels) at 1000 frames per second. At low fault current levels, the exposure settings of the camera were able to capture both good arc detail and the presence of any burning fuel. However, the intensity of the arc at fault currents above 50 A meant that the exposure had to be adjusted to view either arcing or ignition, but not both. A live action digital camcorder provided by TCA was also employed to record ignition for all tests.

Ignition Criterion

For the purposes of the test program, ignition was regarded as self-sustained flaming from the fuel, which continued after cessation of the arc. Other definitions have been used in other studies. For instance, smouldering of the fuel could be regarded as ignition, or the development of flames regardless of whether or not the flaming is sustained. Some of these alternatives might be more conservative than the sustained existence of flaming. In the test program, the behaviour of the fuel during the test was examined using both high speed and live action video and it was possible to definitively state whether flaming was sustained (denoted by an ignition result “1”), or if smouldering/temporary flaming occurred (ignition result “2”). These various conditions were noted in the test results, but only the sustained flaming condition was used in the ignition probability analysis. Non ignition events were allocated an ignition result of “0”.

Test Procedure

Ignition tests were typically conducted as follows. The exact sequence was not always identical, although consistency was exercised across tests wherever possible.

1. Prior to each test the electrode tips were examined for excessive melting/arc damage, and were re-dressed using a combination of hand file, angle grinder and emery paper if necessary.
2. The electrodes were brought into contact with one another and the appropriate displacement profile for the actuator was selected on the controller.
3. The temperature of the test cell was checked and adjusted if necessary by either changing the position of the electric heater or opening/closing the doors of the test cell.
4. A fuel basket was removed from the sealed plastic bag it was stored in after preparation at HRL Mulgrave. As fuel had typically settled and compacted during transportation, it was gently agitated to provide a reasonably uniform density/level of aeration. Velcro strips were stuck to the back of the basket and it was fixed to the fibre board mounting block attached to the PVC frame.

The time between opening of a sealed fuel bag and initiating the arc was of the order of five minutes. This interval could not be closely controlled due to the many variable factors involved in high voltage safety procedures prior to arc initiation.

5. The basket was positioned so that the electrodes were in contact with, and partially buried within, the fuel.
6. The test cell was cleared of personnel, barricading signage was erected and the location of all test personnel was confirmed through either visual or radio contact by the station controller.
7. Warning lights turned on and audible beeps sounded prior to energising the test cell.
8. Instantaneous power measurement recording, video recording and high speed video recording (if being used) commenced.
9. The test circuit was energised with current flow from one electrode to the other.
10. After a few cycles the electrodes were drawn apart while arc parameters were continuously recorded.
11. The circuit was de-energised when the arc extinguished or the arc duration reached the limit set for the test. Instantaneous power recording and high speed video recording stopped and the warning lights were turned off.
12. In the event of sustained ignition, fuel was extinguished using a portable carbon dioxide extinguisher and the test cell vented by leaving the door partially open or using the ceiling mounted fume extractor.
13. When deemed necessary wind speed measurements were taken at this point, typically following a non-ignition event.
14. The ignition result was determined by video and direct observation.

15. The CSV data file from TCA's data management system was transferred to Excel spread sheet.
16. Arc waveforms, duration, power and total energy and reviewed (see Section 8.3).
17. Data input to regression analysis at end of each test series (see Section 2.4).

Parameters for each test were determined by ignition results of previous tests. For each condition defined by arc current, air temperature, wind speed, fuel type and fuel moisture, arc duration was varied to obtain results spanning the full range of sustained ignition probability (i.e. 0% to 100%) on the basis of the procedure outlined in the most relevant industry standard³⁶. Details of all test conditions are included in Appendix 4.

³⁶ ASTM F1958/F1958M – 99 (Reapproved 2005) Standard test method for determining the ignitability of non-flame-resistant materials for clothing by electric arc exposure method using mannequins

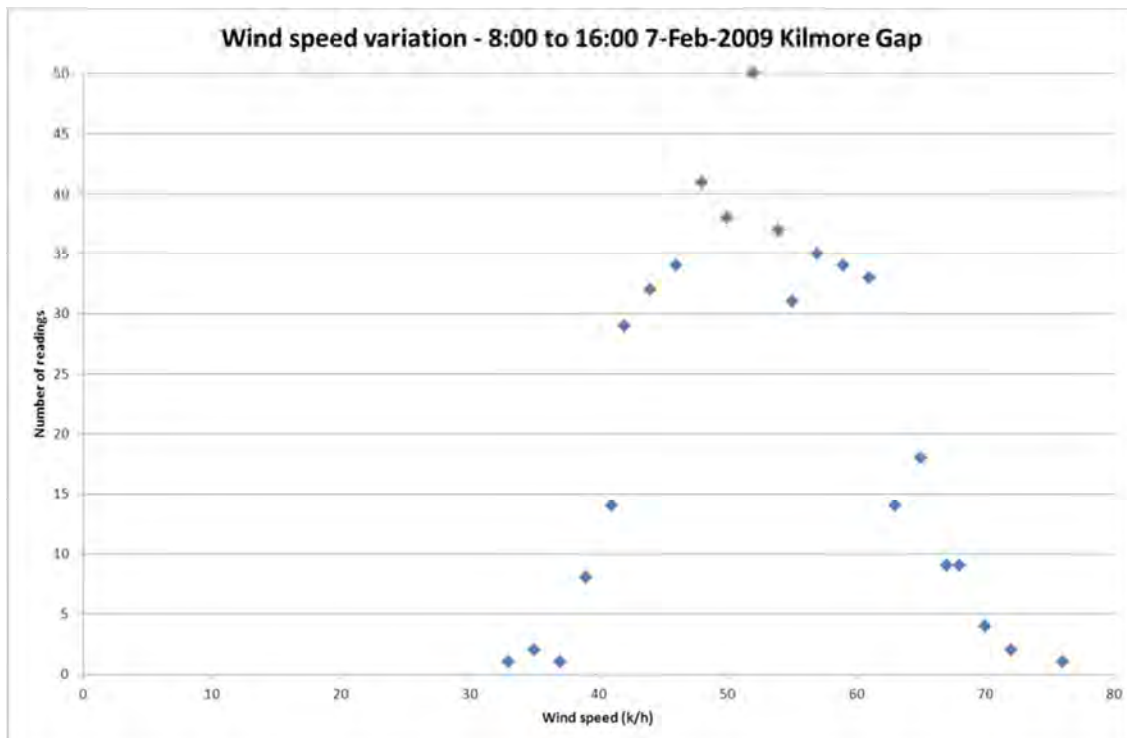
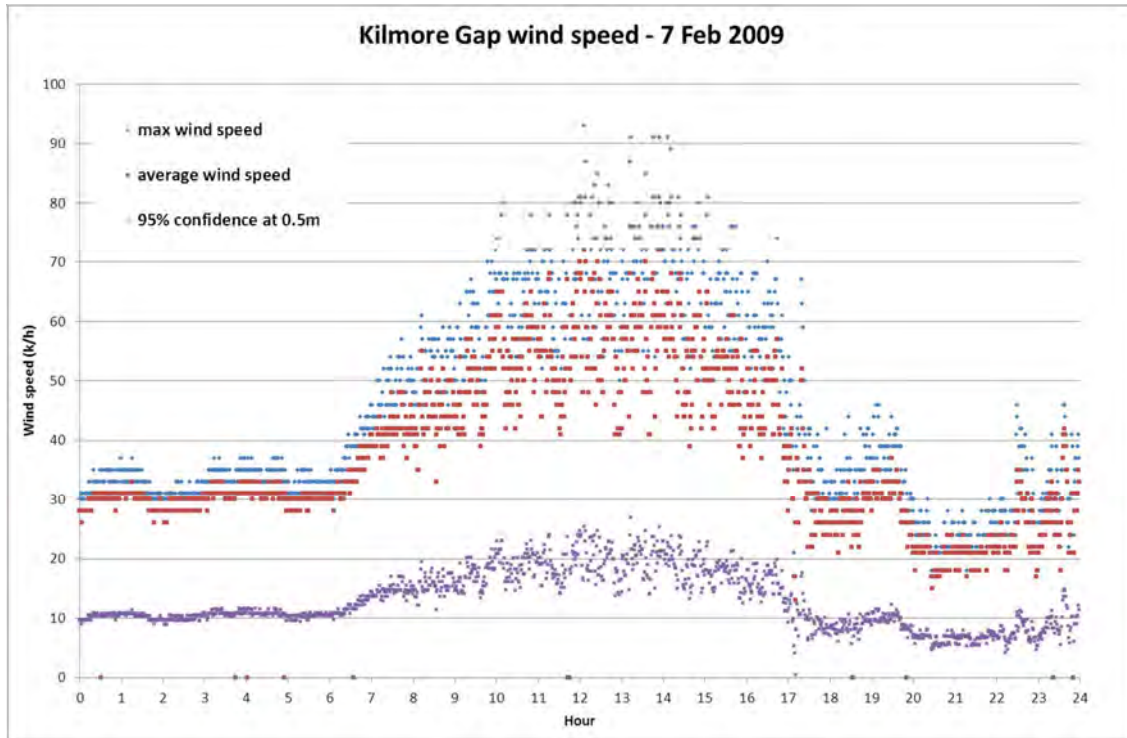
Appendix 2 – Wind speed data

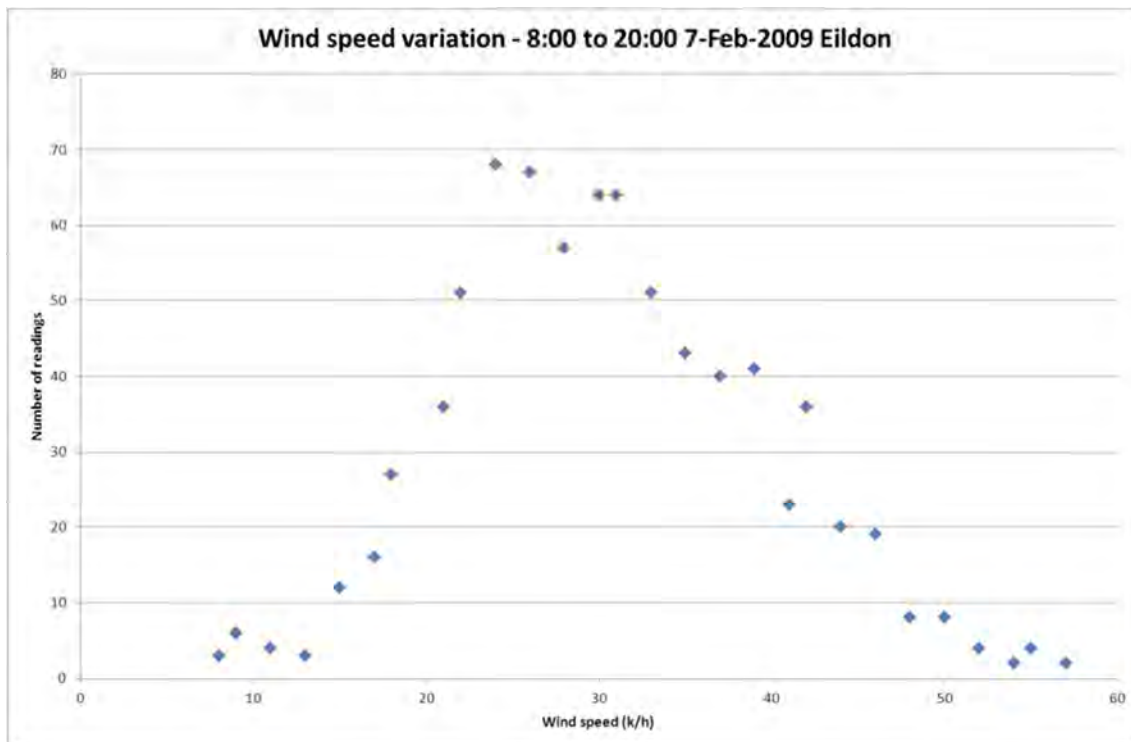
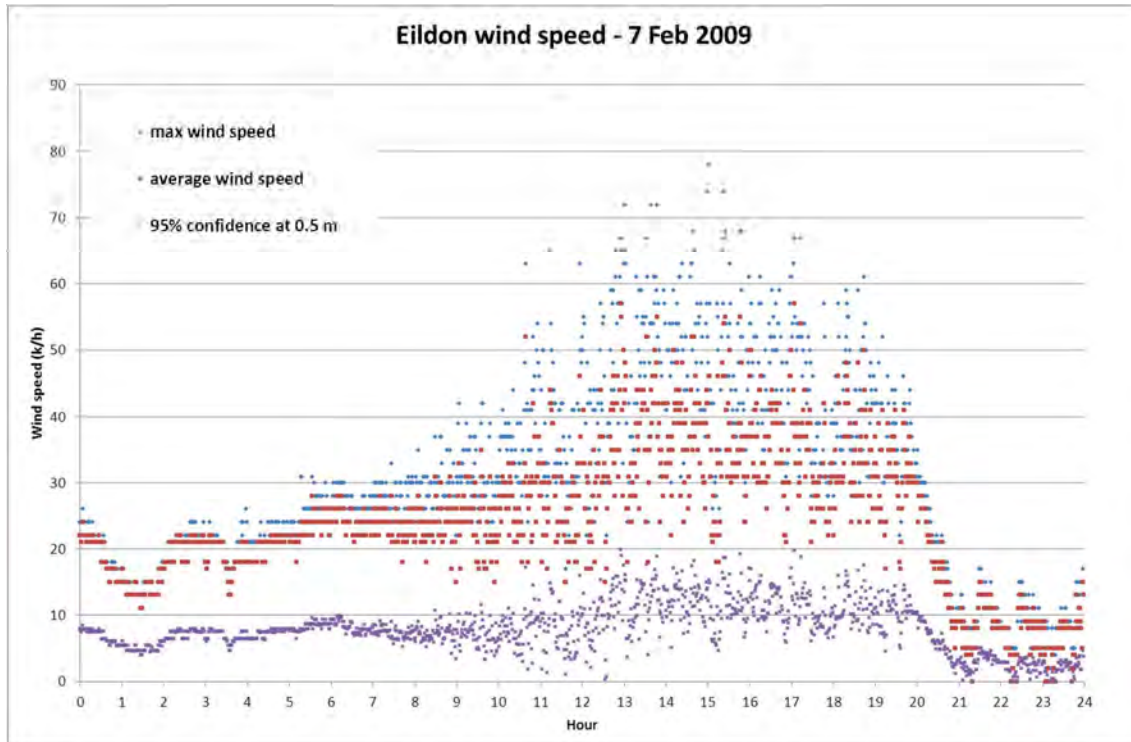
Data were obtained from the Bureau of Meteorology on the temperature and wind speed for the 24 hour period of Black Saturday. One-minute data were available for a number of monitoring stations, including Kilmore Gap, Eildon, Ballarat Airport and Melbourne Airport. The records provided the average and maximum wind speed as well as air temperature and wind direction.

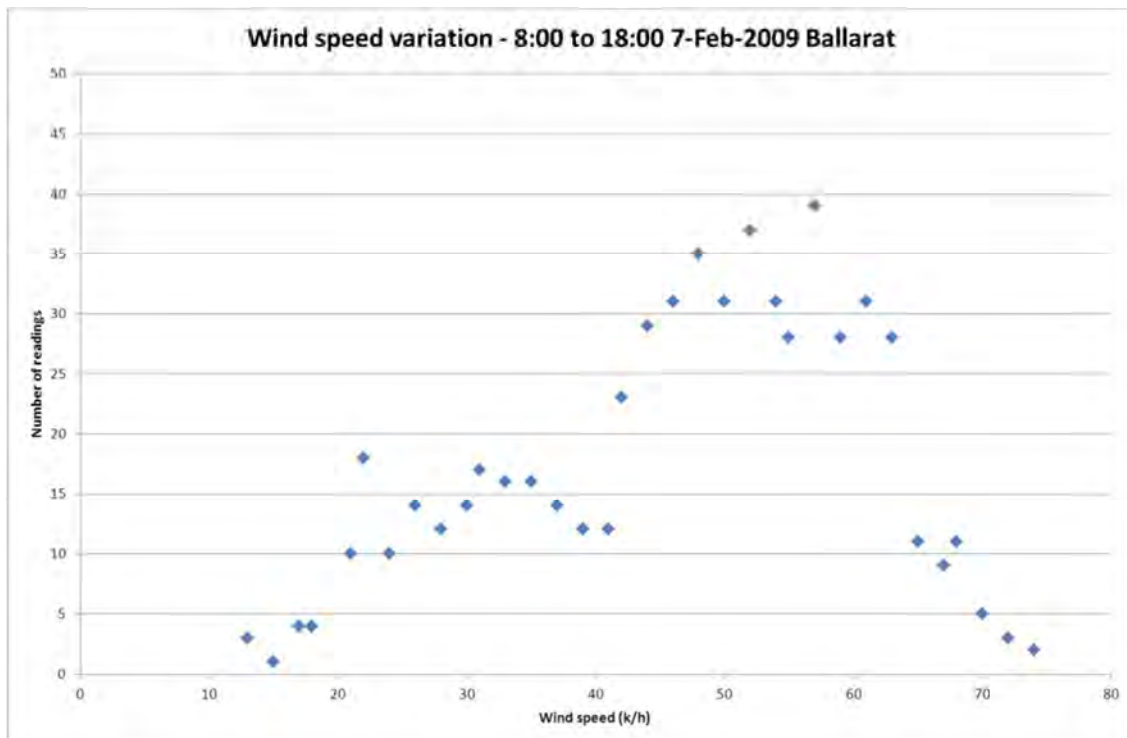
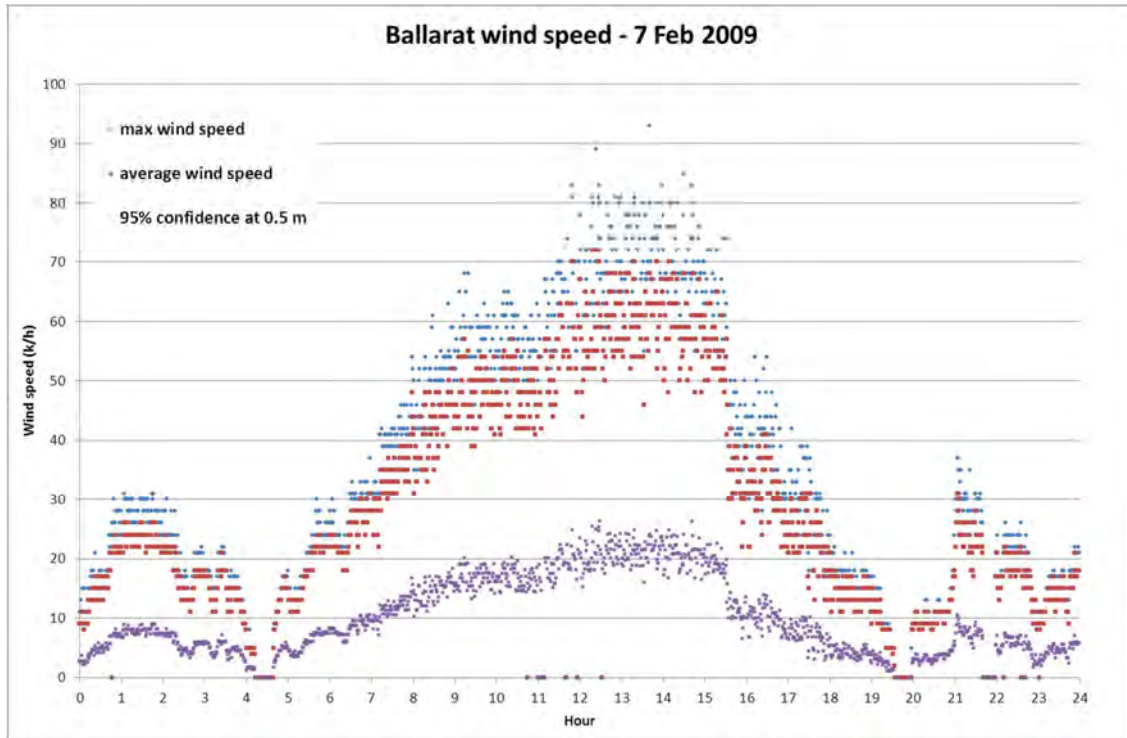
From the 1 minute data of wind speed the lower 95% confidence limit was determined – i.e. 95% of recorded wind speeds over the past minute are expected to be greater than this value.

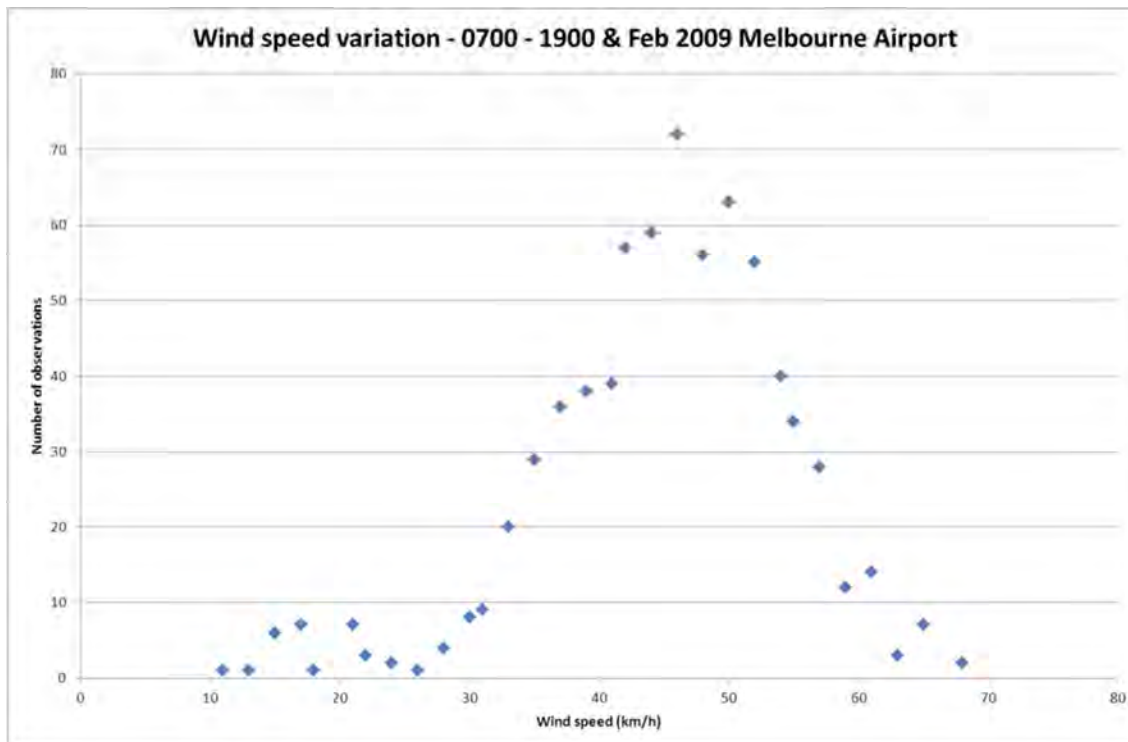
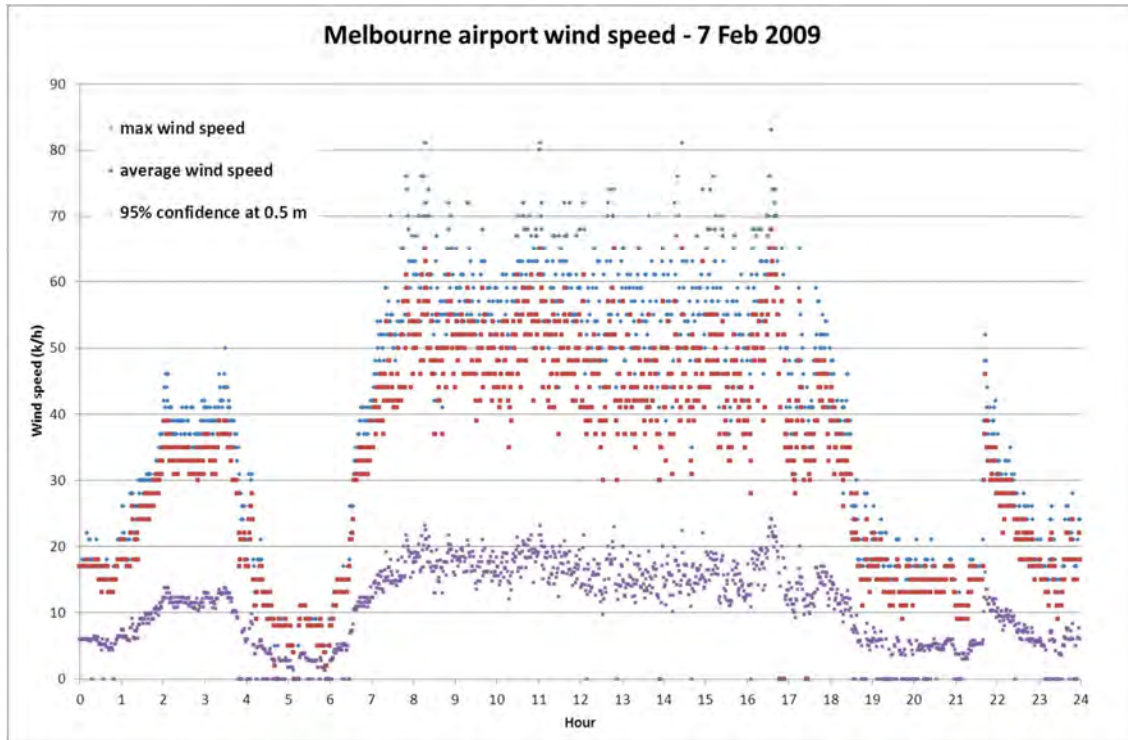
The wind speed is measured at a height of 10m and the wind speed decreases closer to the ground, depending on the terrain and air stability. The 95% confidence interval for wind speed at a height of 0.5m was estimated using a standard correlation.

Charts on the following pages show plots of the average, maximum and 95% confidence level of wind speeds for Black Saturday at each BOM measurement station. In addition the frequency distribution of wind speeds is plotted for each station.









Appendix 3 – Heat flux measurement

Heat flux probes

The design of the calorimeter and the procedure for determining heat flux is detailed in ASTM standards^{37,38}. In the current program of tests the 40 mm diameter copper disc heat flux probes specified in the standard were considered to be too large, particularly if measurements were to be taken relatively close to the arc. Probes using copper discs 14.9 mm diameter and 1.2 mm thick were used. Two holes were drilled into the back of each copper disc and fine (0.4 mm diameter) chromel-alumel thermocouple leads were peened into these to provide the thermocouple hot junction. Three to four discs were mounted into the one insulating block made from cement sheet (100 x 50 x 19) and the front face of the copper was blackened. During the arc event the thermocouple outputs were monitored through a low speed data logger – at approximately 1 Hz sampling rate. TCA³⁹ had reviewed the requirements of the standard and although this sampling rate did not comply they concluded that the output and results would be valid.

The incident energy from the arc heats the copper disc and from the temperature rise the heat input can be determined –there is no requirement to calibrate the calorimeter. The incident energy, Q (J/cm²), is determined from:

$$Q = \frac{c_p \times m \times \Delta T}{A}$$

where

C_p is the specific heat for copper, which can be determined at any temperature using a correlation in the standard, but as the temperature rise is typically less than 10°C a value of 0.385 J/g.°C has been used,

m is the mass (g) of the copper disc

A is the area of the disc exposed to the arc.

ΔT is the temperature rise from arc energy

ASTM methods and applicability

Various ASTM test methods use these slug calorimeters to measure the heat flux during arc testing. These tests have been developed to categorise the flammability and thermal performance of clothing that is to be used by personnel working where there is a danger of electric arcs. The tests are done at currents in the range 4,000 to 25,000 amps and the arc duration, which ranges from 0.05 to 1.5 seconds, is used to control the energy input. In the tests to assess the thermal performance of clothing fabric the acceptance criterion is that the heat flux transmitted through the material should be less than that identified in the Stoll curve. This is the limit below which second degree burns to human flesh should not occur.

³⁷ Test method for measuring heat transfer rate using a thermal capacitance (slug) calorimeter ASTM E-457

³⁸ Standard test method for determining the arc rating of materials and clothing ASTM F1959/F1959M – 06a

³⁹ Discussion of calorimeter temperature measurement frequency's influence on uncertainty of HAF and APTV determination according to IEC 61482-1:2002 M Mulcahy Lane Cove Testing Station – TCA 23 January 2008.

The flux depends on the arc duration, and for arc durations of the order of 1 second the allowable transmitted energy is approximately 50 kJ/m^2 and the heat flux limit is 50 kW/m^2 .

The clothing ignition tests are carried out with very high arc power, as a result of the high currents used and the arc gap, which is of the order of 300 mm. The heat flux from these arcs will range from 84 to over $25,000 \text{ kW/m}^2$ (ASTM F1959) and the energy for a 50% probability of ignition of clothing materials of various weights varies from 250 to 800 kJ/m^2 . If ignition occurred from an arc duration of 0.5 seconds the heat flux range would be 500 to 1500 kW/m^2 , i.e. considerably greater than the typical heat flux for ignition of solid fuels.

The range of conditions explored in the two ASTM test methods spans the range used in standard ignition tests for solid fuels, which supports the use of this heat flux measurement technique for the current program.

Appendix 4 – Details of test conditions

Tranche 1	19th to 21st April 2011	Test numbers 000 to 074
Tranche 2	12th to 13th May 2011	Test numbers 076 to 128
Tranche 3.1	31st May to 3rd June 2011	Test numbers 132 to 350
Tranche 3.2	8th to 10th June 2011	Test numbers 351 to 460
Tranche 4	15th to 19th August 2011	Test numbers 461 to 861

18 April to 20 April 2011 – Tests 006 to 074

Test ID		TCA Test ID	Date	Approx. Time	Voltage (kV)	Current (amps)	Initial Gap (mm)	Actuator Acceleration (m s ⁻²)	Max. velocity (m s ⁻¹)	Max. Gap (mm)	Electrode material	Notes
E (Current condition)	ET-1	6	18/04/2011	15:18	7.4	2.37	0.1	9.8	2	250	Tungsten	Initial trials
	ET-2	7	18/04/2011	15:35	7.4	2.37	0.9	9.8	0.25	260	Tungsten	Initial trials, velocity, initial gap
	EA-1	8	18/04/2011	15:45	7.4	2.37	0.9	9.8	0.25	260	Aluminium	Initial trials, electrode material
	EA-2	9	18/04/2011	16:09	7.4	2.37	-	1	0.01	260	Aluminium	Initial trials, velocity, material
	ET-3	12	18/04/2011	16:33	11.5	4.25	-	1	0.01	260	Tungsten	Initial trials, current correction
	ET-4	13	18/04/2011	16:43	11.5	4.25	-	1	0.25	260	Tungsten	Initial trials, velocity
	ET-5	14	18/04/2011	16:55	11.5	4.25	-	9.8	2	250	Tungsten	Initial trials, actuator velocity established
	ET-6	15	18/04/2011	17:05	11.5	4.25	-	9.8	2	425	Tungsten	Initial trials, max. gap established
	ES-1	16	19/04/2011	9:36	11.5	4.25	-	9.8	2	425	Steel	Initial trials, material
	ES-2	22	19/04/2011	11:16	12.7	4.25	-	9.8	2	425	Steel	Power conditions established and calibrated
	ES-3	23	19/04/2011	11:33	12.7	4.25	-	9.8	2	425	Steel	Electrode material test
	ET-7	24	19/04/2011	12:03	12.7	4.25	-	9.8	2	425	Tungsten	Control
	ET-8	25	19/04/2011	13:09	12.7	4.25	-	9.8	2	425	Tungsten	Reproducibility Trial
	ET-9	26	19/04/2011	13:24	12.7	4.25	-	9.8	2	425	Tungsten	Reproducibility Trial
	ET-10	27	19/04/2011	13:29	12.7	4.25	-	9.8	2	425	Tungsten	Reproducibility Trial
	ET-11	28	19/04/2011	13:03	12.7	4.25	-	9.8	2	425	Tungsten	Wind speed A
	ET-12	29	19/04/2011	13:56	12.7	4.25	-	9.8	2	425	Tungsten	Wind speed B
	ET-13	30	19/04/2011	14:04	12.7	4.25	-	9.8	2	425	Tungsten	Wind speed B repeat
	EA-1	31	19/04/2011	14:46	12.7	4.25	-	9.8	2	425	Aluminium	Electrode material test
	EA-2	32	19/04/2011	14:54	12.7	4.25	-	9.8	2	425	Aluminium	Electrode material test
	EG-1	33	19/04/2011	15:10	12.7	4.25	-	9.8	2	425	Galvanised	Electrode material test
	EG-2	34	19/04/2011	15:16	12.7	4.25	-	9.8	2	425	Galvanised	Electrode material test
Calibration												
D	DT-1	39	19/04/2011	17:10	12.7	10	-	9.8	2	425	Tungsten	Control
	DA-1	40	19/04/2011	17:24	12.7	10	-	9.8	2	425	Aluminium	Electrode material test
	DA-2	42	19/04/2011	17:43	12.7	10	-	9.8	0.25	425	Aluminium	Velocity of moving arc gap test
	DS-1	43	19/04/2011	17:55	12.7	10	-	9.8	2	425	Steel	Electrode material test
	DS-2	44	19/04/2011	18:04	12.7	10	-	9.8	2	425	Steel	Electrode material test
	DG-1	45	20/04/2011	8:32	12.7	10	-	9.8	2	425	Galvanised	Electrode material test
	DG-2	46	20/04/2011	8:45	12.7	10	-	9.8	0.25	425	Galvanised	Velocity of moving arc gap test
	DT-2	47	20/04/2011	9:00	12.7	10	425	-	-	425	Tungsten	Fixed gap 35 guage fuse
	DWD-1	48	20/04/2011	9:20	12.7	10	-	1	0.01	10	Dry wood	10mm thickness dry timber
	DWW-1	49	20/04/2011	9:35	12.7	10	-	1	0.01	10	Green wood	10mm thickness wet timber
	DWD-2	50	20/04/2011	9:50	12.7	10	-	1	0.01	10	Dry wood	60mm thickness dry timber
	DWW-2	51	20/04/2011	10:10	12.7	10	-	1	0.01	10	Green wood	60mm thickness dry timber
Calibration												
C	CS-1	54	20/04/2011	11:30	12.7	50	-	9.8	2	425	Steel	Electrode material test
	CT-1	55	20/04/2011	12:00	12.7	50	-	9.8	2	425	Tungsten	Wind speed
	CT-2	56	20/04/2011	12:11	12.7	50	-	9.8	2	425	Tungsten	Control
	CA-1	57	20/04/2011	12:25	12.7	50	-	9.8	2	425	Aluminium	Electrode material test
Calibration												
B	BT-1	59	20/04/2011	13:54	12.7	200	-	9.8	2	425	Tungsten	Control
	BT-2	60	20/04/2011	14:04	12.7	200	-	9.8	2	425	Tungsten	Control
	BT-3	61	20/04/2011	14:20	12.7	200	100	-	-	100	Tungsten	Fixed gap
	BT-4	62	20/04/2011	14:33	12.7	200	200	-	-	200	Tungsten	Heat flux measurements taken, fixed gap
	BT-5	63	20/04/2011	14:49	12.7	200	50	-	-	50	Tungsten	Heat flux measurements taken, fixed gap
	BT-6	64	20/04/2011	15:00	12.7	200	20	-	-	20	Tungsten	Heat flux measurements taken, fixed gap
	BT-7	65	20/04/2011	15:12	12.7	200	425	-	-	425	Tungsten	Heat flux measurements taken, fixed gap
	BS-1	66	20/04/2011	15:25	12.7	200	-	9.8	2	425	Steel	Electrode material test
	BG-1	67	20/04/2011	15:40	12.7	200	-	9.8	2	425	Galvanised	Electrode material test
	BT-8	68	20/04/2011	15:50	12.7	200	-	9.8	2	425	Tungsten	Heavy TRV
A	BT-9	69	20/04/2011	16:10	12.7	200	-	9.8	2	425	Tungsten	Pure Resistance ~9deg
	BT-10	70	20/04/2011	16:21	12.7	200	-	9.8	2	425	Tungsten	Pure Reactance ~88deg
Calibration												
A	AT-1	73	20/04/2011	16:47	12.7	1000	-	9.8	2	425	Tungsten	Control
	AS-1	74	20/04/2011	17:03	12.7	1000	-	9.8	2	425	Steel	Electrode material test

12 May to 13 May 2011 – Tests 076 to 128

Test ID	TCA Test ID	Date	Approx. Time	Voltage (kV)	Current (amps)	Actuator Acceleration ($m s^{-2}$)	Max. velocity ($m s^{-1}$)	Max. Gap (mm)	Approx Arc Duration (ms)	Electrode material	Calorimeter positioning	Fuel positioning	Fuel distance (mm)	Wind speed (km/h)	Notes	Comments
ET-14	076	12/05/2011	11:44	12.7	4.25	9.8	2	425	1300	Tungsten	1,2,3 - side 250mm 7,9,10,11 - end 95mm	-	-	~2-4	Reproducibility tests and experimenting with heat flux probes.	
ET-15	077	12/05/2011	13:14	12.7	4.25	9.8	2	425	1300	Tungsten	1,2,3 - side 250mm 7,12,13,11 - end 45mm	-	-	~2-4		Arc to TC13
ET-16	078	12/05/2011	13:46	12.7	4.25	9.8	2	425	1300	Tungsten	7 only - end 95mm	-	-	~2-4		
ET-17	079	12/05/2011	14:02	12.7	4.25	9.8	2	425	1300	Tungsten	7 only - end 95mm	-	-	~2-4		
ET-18	080	12/05/2011	14:09	12.7	4.25	9.8	2	425	1300	Tungsten	7 only - end 95mm	-	-	~2-4		
ET-19	081	12/05/2011	14:23	12.7	4.25	9.8	2	425	1300	Tungsten	7 only - end 95mm	-	-	~2-4		
ET-20	082	12/05/2011	14:30	12.7	4.25	9.8	2	425	1300	Tungsten	7 only - end 95mm	-	-	~2-4		
ET-21	083	12/05/2011	14:42	12.7	4.25	9.8	2	425	1300	Tungsten	-	side & top	200 / 500	~2-4	Effect of calorimeters/fuel baskets on arc dynamics and evaluating risk of placing heat flux probes above arc. Investigating likelihood of fuel ignition at different distances to arc.	Arc didn't reach fuel, no ignition
ET-22	084	12/05/2011	14:52	12.7	4.25	9.8	2	425	300	Tungsten	-	side & top	100 / 200	~2-4		Arc passed through dry grass fuel causing ignition.
ET-23	085	12/05/2011	15:26	12.7	4.25	9.8	2	425	270	Tungsten	-	side & top	100 / 200	~2-4		Arc missed basket due to air flow.
ET-24	086	12/05/2011	15:38	12.7	4.25	9.8	2	425	300	Tungsten	-	side & top	100/200	~2-4		Arc duration too short.
ET-25	087	12/05/2011	15:43	12.7	4.25	9.8	2	425	350	Tungsten	-	side & top	100/200	~2-4		Superheated air hit fuel. No ignition. Some evidence of smoking in TCA video.
ET-26	088	12/05/2011	15:51	12.7	4.25	9.8	2	425	400	Tungsten	-	side & top	100/200	~2-4		Ignition through arc and superheated air
ET-27	089	12/05/2011	16:06	12.7	4.25	9.8	2	425	400	Tungsten	1,2,3 - Top 220mm	side only	100	~2-4	Investigate heat flux above the arc with superheated air contacting calorimeters.	Superheated air passed near calorimeters - negligible flux
ET-28	090	12/05/2011	16:22	12.7	4.25	9.8	2	425	400	Tungsten	1,2,3 - Top 220mm	side only	100	~2-4		Superheated air passed across calorimeters - negligible flux
ET-29	91	13/05/2011	8:25	12.7	4.25	9.8	2	425	400	Tungsten	-	-	-	20	Test to see how wind speed affects the arc geometry, tendency to self extinguish and ignition of the fuel at various distances and arc durations.	Very short arc duration. 450mm diameter fan. 1650 from electrodes.
ET-30	92	13/05/2011	8:03	12.7	4.25	9.8	2	425	400	Tungsten	-	side only	50	20		Very short arc duration, no ignition
ET-31	93	13/05/2011	8:50	12.7	4.25	9.8	2	425	400	Tungsten	-	side only	20	20		Very short arc duration, no ignition
ET-32	94	13/05/2011	9:08	12.7	4.25	9.8	2	425	400	Tungsten	-	side only	0	20		Ignition, self extinguished
ET-33	95	13/05/2011	9:17	12.7	4.25	9.8	2	425	300	Tungsten	-	side only	0	~2-4		Ignition and burning
ET-34	96	13/05/2011	9:22	12.7	4.25	9.8	2	425	85	Tungsten	-	side only	0	~2-4		Ignition and burning, 50ms of low current TRV arcing at end
ET-35	97	13/05/2011	9:37	12.7	4.25	9.8	2	425	30	Tungsten	-	side only	0	~2-4		No ignition. 50ms of ~0.75 TRV arcing at end

	Test ID	TCA Test ID	Date	Approx. Time	Voltage (kV)	Current (amps)	Actuator Acceleration (m s ⁻²)	Max. velocity (m s ⁻¹)	Max. Gap (mm)	Approx Arc Duration (ms)	Electrode material	Calorimeter positioning	Fuel positioning	Fuel distance (mm)	Wind speed (km/h)	Notes	Comments
B	BT-11	101	13/05/2011	11:03	12.7	200	9.8	2	425	500	Tungsten	1,3 - side 250mm 7,12,11 - end 95mm	-	-	~2-4	Reproducibility tests and experimenting with heat flux probes.	
	BT-12	102	13/05/2011	11:13	12.7	200	9.8	2	425	500	Tungsten	1,3 - side 200mm 7,12,11 - end 95mm	-	-	~2-4		
	BT-13	103	13/05/2011	11:21	12.7	200	9.8	2	425	500	Tungsten	1,3 - side 200mm 7,12,11 - end 95mm	-	-	~2-4		
	BT-14	104	13/05/2011	11:33	12.7	200	9.8	2	425	500	Tungsten	1,3 - side 200mm 7,12,11 - end 95mm	-	-	~2-4		
	BT-15	105	13/05/2011	11:39	12.7	200	9.8	2	425	500	Tungsten	1,3 - side 200mm 7,12,11 - end 45mm	-	-	~2-4		
	BT-16	106	13/05/2011	11:55	12.7	200	9.8	2	425	500	Tungsten	1,3 - side 250mm 7,12,11 - end 95mm	side & top	200 / 400	~2-4	Effect of calorimeters/fuel baskets on arc dynamics and evaluating risk of placing heat flux probes above arc. Investigating likelihood of fuel ignition at different distances to arc.	Ignition of top basket
	BT-17	107	13/05/2011	12:41	12.7	200	9.8	2	425	300	Tungsten	7 only - end 95mm	side, top & bottom	200/300	~2-4		No ignition
	BT-18	109	13/05/2011	12:52	12.7	200	9.8	2	425	300	Tungsten	7 only - end 95mm	side & top	150/200	~2-4		Ignition of top baset
	BT-19	110	13/05/2011	13:05	12.7	200	9.8	2	425	300	Tungsten	1,2,3 - top 200mm	side only	100	~2-4		Ignition of side basket
	BT-20	113	13/05/2011	13:34	12.7	200	9.8	2	425	300	Aluminium	1,2,3 - top 200mm	side & bottom	100/150	~2-4	Evaluating the influence of electrode material on the heat flux/fuel ignition/ignition through molten particles.	No ignition
	BT-21	114	13/05/2011	13:49	12.7	200	9.8	2	425	300	Galvanised steel	1,2,3 - top 200mm	bottom only	150	~2-4		No ignition
	BT-22	115	13/05/2011	14:09	12.7	200	9.8	2	425	300	Tungsten	-	side & top	250/300	20	Test to see how wind speed effects the arc geometry, tendency to self extinguish and ignition of the fuel under various distances and orientations.	Singed side
	BT-23	116	13/05/2011	14:18	12.7	200	9.8	2	425	300	Tungsten	-	side & top	220/220	20		Singed side
	BT-24	117	13/05/2011	14:27	12.7	200	9.8	2	425	300	Tungsten	-	side & top	150/150	20		Ignition of side basket. Arc passed through fuel basket repeatedly. Wind extinguished fire.
	BT-25	118	13/05/2011	14:41	12.7	200	9.8	2	425	730	Tungsten	-	side & top	150/150	20		Arc did not self extinguish. Very long arc thread.
	BT-26	119	13/05/2011	14:58	12.7	200	9.8	2	425	300	Tungsten	-	side & top	150/150	10		450mm diameter fan. 2300 from electrodes. No ignition. Arc directed down.
	BT-27	120	13/05/2011	15:03	12.7	200	9.8	2	425	300	Tungsten	-	side & top	150/150	10		Ignition of top basket.
Calibration																	
C	CT-3	123	13/05/2011	15:35	12.7	200.0	9.8	2	425.0	300	Tungsten	-	side & top	150/150	16	Effect of calorimeters/fuel baskets on arc dynamics and consider risk of placing heat flux probes above arc. Investigate likelihood of ignition at different distances to arc. Determine max duration to only just cause ignition for a particular length.	Singed fuel only. Arc didn't extinguish. Arc passed through fuel
	CT-4	124	13/05/2011	15:40	12.7	200	9.8	2	425	300	Tungsten	-	side & top	150/125	10		Singed fuel only. Arc didn't extinguish. Arc passed through fuel
	CT-5	125	13/05/2011	16:04	12.7	200	9.8	2	425	300	Tungsten	-	side only	0	10		Smoking and smoldering but extinguished by wind.
	CT-6	126	13/05/2011	16:11	12.7	200	9.8	2	425	155	Tungsten	-	side only	0	~2-4		Virtually instantaneous ignition (test 155ms)
	CT-7	127	13/05/2011	16:17	12.7	200	9.8	2	425	25	Tungsten	-	side only	0	~2-4		No ignition (test 25ms)
	CT-8	128	13/05/2011	16:22	12.7	200	9.8	2	425	50	Tungsten	-	side only	0	~2-4		Virtually instantaneous ignition (test 50ms)

30 May to 10 June 2011 – Tests 132 to 460

Note: Highlighted tests not used in regression analysis. Ignition result key: 0 = no ignition, 1 = sustained ignition

TCA Test ID	Condition ID	Date	Approx. Time	Voltage (kV)	Actuator Acceleration (m/s ²)	Electrode material	Fuel type	Nominal Temperature (°C)	Fuel moisture (%)	Wind speed (km/h)	Current (amps)	Nominal Arc Duration (ms)	Sustained Ignition Result	Test Notes	Arc Energy (J)	Avg Arc Power (kW)	Temperature (°C)	Arc Duration (ms)
132	1L30	30/05/2011	14:56	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	30	0		7	0	20	39
133	1L30	30/05/2011	15:04	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	30	0		3	0	20	40
134	1L50	30/05/2011	15:19	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	50	0		10	0	20	48
135	1L50	30/05/2011	15:26	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	50	0		12	0	20	50
136	1L70	30/05/2011	15:31	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	70	1		21	0	20	70
137	1L70	30/05/2011	15:41	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	70	0		22	0	20	71
138	1L70	30/05/2011	15:47	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	70	0	Scorched	23	0	20	71
139	1L70	30/05/2011	15:49	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	70	0		21	0	20	71
140	1L70	31/05/2011	8:09	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	70	0		32	0	22	73
141	1L70	31/05/2011	8:23	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	70	0		26	0	22	71
142	1M70	31/05/2011	8:39	12.7	9.8	Mild Steel	Grass	20	10	5	4.25	70	0		24	0	22	71
143	1M70	31/05/2011	8:47	12.7	9.8	Mild Steel	Grass	20	10	5	4.25	70	0		22	0	23	72
144	1L100	31/05/2011	8:53	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	100	1		63	1	24	100
145	1L100	31/05/2011	9:03	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	100	0		117	1	24	100
146	1L100	31/05/2011	9:10	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	100	0		96	1	23	101
148	1L100	31/05/2011	9:15	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	100	0		46	0	23	100
149	1L150	31/05/2011	9:20	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	150	0	Smoldering	226	1	23	152
150	1L150	31/05/2011	9:24	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	150	1		234	2	22	152
151	1L150	31/05/2011	9:30	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	150	0		133	1	22	151
152	1L150	31/05/2011	9:34	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	150	0		226	2	21	150
153	1M150	31/05/2011	9:39	12.7	9.8	Mild Steel	Grass	20	10	5	4.25	150	0		142	1	20	150
154	1L200	31/05/2011	9:42	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	200	1		381	2	20	201
155	1M200	31/05/2011	10:16	12.7	9.8	Mild Steel	Grass	20	10	5	4.25	200	0	Ignition, self extinguished	557	3	20	197
156	1M200	31/05/2011	10:19	12.7	9.8	Mild Steel	Grass	20	10	5	4.25	200	0	Ignition, self extinguished	548	3	21	194

157	1L200	31/05/2011	10:27	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	200	0	Ignition, self extinguished	441	2	21	191
158	1L200	31/05/2011	10:37	12.7	9.8	Mild Steel	Grass	20	5	5	4.25	200	0	Ignition, self extinguished	585	3	20	198
159	2M70	31/05/2011	10:53	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	70	0		26	0	33	67
160	2M70	31/05/2011	11:15	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	70	0	Ignition, self extinguished	27	0	41	71
161	2L70	31/05/2011	11:20	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	70	0		31	0	42	70
162	2L70	31/05/2011	11:23	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	70	0		35	0	42	70
163	2L100	31/05/2011	11:29	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	100	1		55	1	42	100
164	2L100	31/05/2011	11:39	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	100	0		58	1	43	100
165	2L100	31/05/2011	11:42	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	100	1		80	1	42	100
166	2L100	31/05/2011	11:52	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	100	1		106	1	44	100
167	2M100	31/05/2011	11:56	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	100	0		77	1	44	100
168	2M100	31/05/2011	12:00	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	100	1		62	1	44	100
169	2M100	31/05/2011	12:05	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	100	1		74	1	44	100
170	2M100	31/05/2011	12:10	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	100	0		68	1	45	100
171	2M100	31/05/2011	12:13	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	100	0		61	1	45	100
172	2L70	31/05/2011	12:59	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	70	0		64	1	48	70
173	2L70	31/05/2011	13:02	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	70	0	Poor electrode contact-slight early arcing	33	0	47	70
174	2L150	31/05/2011	13:06	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	150	1		184	1	47	151
175	2M150	31/05/2011	13:14	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	150	0	Smouldering	137	1	45	150
176	2M150	31/05/2011	13:18	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	150	1		295	2	47	150
177	2M150	31/05/2011	13:23	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	150	1		139	1	45	150
178	2L150	31/05/2011	13:28	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	150	1		152	1	46	150
179	3L150	31/05/2011	13:41	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	150	1		478	3	50	150
180	Ignore	31/05/2011	13:46	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	150	1	Intended 150: Arc blew out after 110ms. Temp high, allowed to cool before 181	207	2	56	110
181	3M150	31/05/2011	14:13	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	150	0		258	2	44	150
182	3L150	31/05/2011	14:21	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	150	1		171	1	45	151
183	3L150	31/05/2011	14:26	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	150	0		211	1	46	150
184	3L150	31/05/2011	14:30	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	150	1		235	2	47	150
185	3L150	31/05/2011	14:37	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	150	0		314	2	45	150
186	3M150	31/05/2011	14:45	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	150	0	Ignition, self extinguished	267	2	46	150

187	3M150	31/05/2011	14:52	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	150	1	Smoking, not a ball of flames	194	1	46	150
188	3M150	31/05/2011	15:03	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	150	0		222	1	47	150
189	3M200	31/05/2011	15:07	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	200	1	Took a while to take off	527	3	46	200
190	3M200	31/05/2011	15:16	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	200	1	Intended 200: Arc blew out after 170ms	469	3	46	170
191	IgnoreL200	31/05/2011	15:22	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	200	0	Stroke too long	700	3	46	200
192	IgnoreL200	31/05/2011	15:28	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	200	0	Stroke too long. Ignition, self extinguished after long period of burning	565	3	45	200
193	IgnoreL200	31/05/2011	15:38	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	200	0	Stroke too long	356	2	46	190
194	3L200	31/05/2011	15:45	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	200	1	Stroke changed from 250 to 110mm.	401	2	45	200
196	3L200	31/05/2011	15:59	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	200	1		400	2	45	200
197	3L200	31/05/2011	16:03	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	200	0		623	3	45	200
198	3M200	1/06/2011	8:15	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	200	0		425	2	44	200
199	3L100	1/06/2011	8:23	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	100	0		58	1	44	101
200	3L100	1/06/2011	8:25	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	100	0		56	1	43	100
201	3M100	1/06/2011	8:29	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	100	0		183	2	43	100
202	3M100	1/06/2011	8:33	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	100	0		75	1	44	100
203	3L200	1/06/2011	8:36	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	200	1		598	3	44	200
204	3L150	1/06/2011	8:41	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	150	0	Intended 200: Arc blew out after 160ms	625	4	45	160
205	3L100	1/06/2011	8:48	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	100	0	Intended 200: Arc blew out after 90ms	98	1	43	90
206	3L200	1/06/2011	8:54	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	200	0	Full duration, no ignition	800	4	44	200
207	4L200	1/06/2011	9:14	12.7	9.8	Mild Steel	Grass	45	5	20	4.25	200	0	Intended 200: Arc blew out after 50ms	10	0	46	50
208	4L200	1/06/2011	9:18	12.7	9.8	Mild Steel	Grass	45	5	20	4.25	200	0	Intended 200: Arc blew out after 180ms	315	2	47	180
209	4L200	1/06/2011	9:23	12.7	9.8	Mild Steel	Grass	45	5	20	4.25	200	0	Intended 200: Ignition, self extinguished. Arc lasted ~150ms	328	2	47	150
210	4L200	1/06/2011	9:28	12.7	9.8	Mild Steel	Grass	45	5	20	4.25	200	0	Intended 200: Arc blew out after 160ms	60	1	47	90
211	4L200	1/06/2011	9:32	12.7	9.8	Mild Steel	Grass	45	5	20	4.25	200	0	Intended 200: Arc blew out after 50ms	11	0	48	50
212	5M150	1/06/2011	10:14	12.7	9.8	Mild Steel	Leaf	45	10	5	4.25	150	0		164	1	44	150
213	5M150	1/06/2011	10:20	12.7	9.8	Mild Steel	Leaf	45	10	5	4.25	150	0		166	1	44	150
214	5L150	1/06/2011	10:29	12.7	9.8	Mild Steel	Leaf	45	5	5	4.25	150	0		143	1	44	150
215	5L150	1/06/2011	10:32	12.7	9.8	Mild Steel	Leaf	45	5	5	4.25	150	0		134	1	45	150
216	5L200	1/06/2011	10:36	12.7	9.8	Mild Steel	Leaf	45	5	5	4.25	200	0	Intended 250: Arc blew out after 140ms	291	2	44	140
217	5L200	1/06/2011	10:42	12.7	9.8	Mild Steel	Leaf	45	5	5	4.25	200	0	Seld extinguished	338	2	44	200

218	5L200	1/06/2011	10:49	12.7	9.8	Mild Steel	Leaf	45	5	5	4.25	200	0	Intended 250: Arc blew out after 90ms	371	2	45	200
219	5L250	1/06/2011	10:55	12.7	9.8	Mild Steel	Leaf	45	5	5	4.25	250	0		122	1	45	90
220	5L250	1/06/2011	11:02	12.7	9.8	Mild Steel	Leaf	45	5	5	4.25	250	1		477	2	46	250
221	5L250	1/06/2011	11:09	12.7	9.8	Mild Steel	Leaf	45	5	5	4.25	250	1		649	3	45	250
222	5L250	1/06/2011	11:14	12.7	9.8	Mild Steel	Leaf	45	5	5	4.25	250	0		378	2	45	250
223	5L250	1/06/2011	11:18	12.7	9.8	Mild Steel	Leaf	45	5	5	4.25	250	1		911	4	46	250
224	5M250	1/06/2011	11:28	12.7	9.8	Mild Steel	Leaf	45	10	5	4.25	250	0		865	3	44	250
225	5M250	1/06/2011	11:34	12.7	9.8	Mild Steel	Leaf	45	10	5	4.25	250	0		508	2	44	250
226	5M250	1/06/2011	11:38	12.7	9.8	Mild Steel	Leaf	45	10	5	4.25	250	0		373	1	45	250
227	5M300	1/06/2011	11:42	12.7	9.8	Mild Steel	Leaf	45	10	5	4.25	300	0		1187	4	45	300
229	5M300	1/06/2011	11:47	12.7	9.8	Mild Steel	Leaf	45	10	5	4.25	300	1		698	2	45	300
231	6L50	1/06/2011	13:40	12.7	9.8	Mild Steel	Grass	20	5	5	200	50	0	Self extinguished	493	8	27	58
233	6M50	1/06/2011	14:10	12.7	9.8	Mild Steel	Grass	20	10	5	200	50	1		461	8	28	56
234	6M50	1/06/2011	14:18	12.7	9.8	Mild Steel	Grass	20	10	5	200	50	0		520	9	28	57
235	6M50	1/06/2011	14:22	12.7	9.8	Mild Steel	Grass	20	10	5	200	50	0		446	8	28	56
236	6M50	1/06/2011	14:26	12.7	9.8	Mild Steel	Grass	20	10	5	200	50	0		493	9	28	58
237	6L50	1/06/2011	14:33	12.7	9.8	Mild Steel	Grass	20	5	5	200	50	1		510	9	28	56
238	6L50	1/06/2011	14:40	12.7	9.8	Mild Steel	Grass	20	5	5	200	50	1		560	10	28	53
239	6L50	1/06/2011	14:46	12.7	9.8	Mild Steel	Grass	20	5	5	200	50	0		527	9	27	58
240	6L30	1/06/2011	15:01	12.7	9.8	Mild Steel	Grass	20	5	5	200	30	0		167	6	28	29
241	6L30	1/06/2011	15:09	12.7	9.8	Mild Steel	Grass	20	5	5	200	30	0		173	6	28	30
242	6L30	1/06/2011	15:14	12.7	9.8	Mild Steel	Grass	20	5	5	200	30	0	Self extinguished	172	5	28	37
243	6L70	1/06/2011	15:19	12.7	9.8	Mild Steel	Grass	20	5	5	200	70	1		751	11	28	68
244	6L70	1/06/2011	15:23	12.7	9.8	Mild Steel	Grass	20	5	5	200	70	1		766	11	28	67
245	6L70	1/06/2011	15:29	12.7	9.8	Mild Steel	Grass	20	5	5	200	70	0		696	10	27	70
246	6L70	1/06/2011	15:33	12.7	9.8	Mild Steel	Grass	20	5	5	200	70	1		690	9	27	73
247	6L70	1/06/2011	15:40	12.7	9.8	Mild Steel	Grass	20	5	5	200	70	1		721	11	26	65
248	6M70	1/06/2011	15:47	12.7	9.8	Mild Steel	Grass	20	10	5	200	70	0		737	11	26	65
249	6M70	1/06/2011	15:55	12.7	9.8	Mild Steel	Grass	20	10	5	200	70	1		757	10	27	73
250	6M70	2/06/2011	8:18	12.7	9.8	Mild Steel	Grass	20	10	5	200	70	0		749	11	20	66

251	6M70	2/06/2011	8:39	12.7	9.8	Mild Steel	Grass	20	10	5	200	70	0		724	10	21	70
252	6M70	2/06/2011	8:44	12.7	9.8	Mild Steel	Grass	20	10	5	200	70	0		790	11	22	70
253	6M100	2/06/2011	8:49	12.7	9.8	Mild Steel	Grass	20	10	5	200	100	0		1445	14	22	102
254	6L100	2/06/2011	8:55	12.7	9.8	Mild Steel	Grass	20	5	5	200	100	1		1444	15	22	95
255	6L100	2/06/2011	9:05	12.7	9.8	Mild Steel	Grass	20	5	5	200	100	1		1468	14	22	102
256	6M100	2/06/2011	9:23	12.7	9.8	Mild Steel	Grass	20	10	5	200	100	0		1393	14	22	99
257	6M100	2/06/2011	9:29	12.7	9.8	Mild Steel	Grass	20	10	5	200	100	0		1425	15	23	95
258	6M100	2/06/2011	9:35	12.7	9.8	Mild Steel	Grass	20	10	5	200	100	1		1609	17	23	97
259	6M100	2/06/2011	9:59	12.7	9.8	Mild Steel	Grass	20	10	5	200	100	0		1485	14	23	107
260	6M150	2/06/2011	10:04	12.7	9.8	Mild Steel	Grass	20	10	5	200	150	1		3505	23	23	150
261	6M150	2/06/2011	10:21	12.7	9.8	Mild Steel	Grass	20	10	5	200	150	1		3357	23	23	145
262	6M150	2/06/2011	10:29	12.7	9.8	Mild Steel	Grass	20	10	5	200	150	1		3494	23	23	152
263	7M50	2/06/2011	11:07	12.7	9.8	Mild Steel	Grass	45	10	5	200	50	1	Intended as 70 ms test, arcing only lasted 46ms	463	11	37	44
264	7M70	2/06/2011	11:17	12.7	9.8	Mild Steel	Grass	45	10	5	200	70	1	Smouldered and smoked for long duration. Eventually extinguished.	732	11	37	68
265	7M70	2/06/2011	11:26	12.7	9.8	Mild Steel	Grass	45	10	5	200	70	0	Smouldered and smoked for long duration. Eventually extinguished. Called a "0"	776	11	37	70
266	7M70	2/06/2011	11:33	12.7	9.8	Mild Steel	Grass	45	10	5	200	70	0	Smouldered and smoked for long duration. Eventually extinguished. Called a "0"	758	11	37	67
267	7M70	2/06/2011	11:40	12.7	9.8	Mild Steel	Grass	45	10	5	200	70	1		753	11	40	69
268	7M70	2/06/2011	11:50	12.7	9.8	Mild Steel	Grass	45	10	5	200	70	1		699	10	43	70
269	7L70	2/06/2011	11:57	12.7	9.8	Mild Steel	Grass	45	5	5	200	70	1	Slow burn	728	10	44	70
270	7L70	2/06/2011	12:06	12.7	9.8	Mild Steel	Grass	45	5	5	200	70	1		798	11	46	70
271	7L50	2/06/2011	12:12	12.7	9.8	Mild Steel	Grass	45	5	5	200	50	1		400	8	46	47
272	7M50	2/06/2011	12:59	12.7	9.8	Mild Steel	Grass	45	10	5	200	50	1		440	9	45	52
273	7M50	2/06/2011	13:09	12.7	9.8	Mild Steel	Grass	45	10	5	200	50	1		386	8	45	49
274	7M50	2/06/2011	13:18	12.7	9.8	Mild Steel	Grass	45	10	5	200	50	0		409	8	45	49
275	7M30	2/06/2011	13:27	12.7	9.8	Mild Steel	Grass	45	10	5	200	30	0		161	6	44	28
276	7M30	2/06/2011	13:35	12.7	9.8	Mild Steel	Grass	45	10	5	200	30	0		166	6	44	30
277	7L30	2/06/2011	13:40	12.7	9.8	Mild Steel	Grass	45	5	5	200	30	0		162	6	43	28
278	7L30	2/06/2011	13:46	12.7	9.8	Mild Steel	Grass	45	5	5	200	30	0		187	6	43	29
279	7M50	2/06/2011	13:52	12.7	9.8	Mild Steel	Grass	45	10	5	200	50	1		388	9	43	45
280	7M100	2/06/2011	14:00	12.7	9.8	Mild Steel	Grass	45	10	5	200	100	1		1391	15	44	95

281	7M100	2/06/2011	14:06	12.7	9.8	Mild Steel	Grass	45	10	5	200	100	1		1540	15	44	104
282	8M100	2/06/2011	14:15	12.7	9.8	Mild Steel	Grass	45	10	10	200	100	1	Ignition escalated after ~7 sec of smouldering without evidence of fire	1383	15	48	95
283	8M100	2/06/2011	14:23	12.7	9.8	Mild Steel	Grass	45	10	10	200	100	1		1445	15	49	100
284	8M100	2/06/2011	14:28	12.7	9.8	Mild Steel	Grass	45	10	10	200	100	1		1403	15	49	95
285	8M70	2/06/2011	14:36	12.7	9.8	Mild Steel	Grass	45	10	10	200	70	0		759	11	49	69
286	8M70	2/06/2011	14:41	12.7	9.8	Mild Steel	Grass	45	10	10	200	70	0		756	11	49	67
287	8M70	2/06/2011	14:45	12.7	9.8	Mild Steel	Grass	45	10	10	200	70	1	Smoked for ~40sec before escalating into flames	676	10	49	65
288	8M50	2/06/2011	14:54	12.7	9.8	Mild Steel	Grass	45	10	10	200	50	0		393	8	48	50
289	8L50	2/06/2011	15:00	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	1		394	8	48	49
290	Lag Angle	2/06/2011		12.7	9.8	Tungsten	V recording saturated				200			Power factor test, 435 stroke, 1.5s duration				
291	Lag Angle	2/06/2011		12.7	9.8	Tungsten	55deg run 1				200			Power factor test, 435 stroke, 1.5s duration				
293	Lag Angle	2/06/2011		12.7	9.8	Tungsten	55deg run 2				200			Power factor test, 435 stroke, 1.5s duration				
294	Lag Angle	2/06/2011		12.7	9.8	Tungsten	88deg run 1				200			Power factor test, 435 stroke, 1.5s duration				
295	Lag Angle	2/06/2011		12.7	9.8	Tungsten	88deg run 2				200			Power factor test, 435 stroke, 1.5s duration				
296	Lag Angle	2/06/2011		12.7	9.8	Tungsten	8deg run 1				200			Power factor test, 435 stroke, 1.5s duration				
297	Lag Angle	2/06/2011		12.7	9.8	Tungsten	8deg run 2				200			Power factor test, 435 stroke, 1.5s duration				
298	8M50	3/06/2011	8:41	12.7	9.8	Mild Steel	Grass	45	10	10	200	50	0		390	8	52	50
299	8M50	3/06/2011	8:49	12.7	9.8	Mild Steel	Grass	45	10	10	200	50	1	Smoked for prolonged period escalating into flames	380	8	56	50
300	8L50	3/06/2011	8:54	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	0		377	8	54	47
301	8L50	3/06/2011	8:59	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	0		393	9	51	46
302	8L50	3/06/2011	9:06	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	0		402	9	49	46
303	8L70	3/06/2011	9:11	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	1		777	11	48	72
304	8L70	3/06/2011	9:16	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	1	Slow to take off	804	11	48	74
305	8L70	3/06/2011	9:23	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	1		776	11	47	69
306	8L70	3/06/2011	9:29	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	1	Slow to take off and burn	810	11	46	74
307	8M70	3/06/2011	9:34	12.7	9.8	Mild Steel	Grass	45	10	10	200	70	0		742	11	44	65
308	8M50	3/06/2011	10:04	12.7	9.8	Mild Steel	Grass	45	10	10	200	50	0		403	8	49	50
309	8M50	3/06/2011	10:10	12.7	9.8	Mild Steel	Grass	45	10	10	200	50	0		403	9	49	46
310	8M30	3/06/2011	10:14	12.7	9.8	Mild Steel	Grass	45	10	10	200	30	0		171	6	45	30
311	8L30	3/06/2011	10:20	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0		150	6	48	25

312	8L30	3/06/2011	10:25	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0		168	6	49	30
313	8L30	3/06/2011	10:28	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0		118	5	49	22
314	9M100	3/06/2011	10:46	12.7	9.8	Mild Steel	Grass	45	10	20	200	100	0		1256	13	42	100
315	9M100	3/06/2011	10:53	12.7	9.8	Mild Steel	Grass	45	10	20	200	100	0		1409	14	43	98
316	9L100	3/06/2011	10:58	12.7	9.8	Mild Steel	Grass	45	5	20	200	100	0		1361	14	42	100
317	9L100	3/06/2011	11:05	12.7	9.8	Mild Steel	Grass	45	5	20	200	100	1		1334	14	44	93
318	9L100	3/06/2011	11:11	12.7	9.8	Mild Steel	Grass	45	5	20	200	100	0	Possible slight ignition	1429	15	42	97
319	9L100	3/06/2011	11:16	12.7	9.8	Mild Steel	Grass	45	5	20	200	100	0		1461	14	43	102
320	9L100	3/06/2011	11:27	12.7	9.8	Mild Steel	Grass	45	5	20	200	100	0		1488	15	42	100
321	9L100	3/06/2011	11:31	12.7	9.8	Mild Steel	Grass	45	5	20	200	100	0		1533	15	41	104
322	9L150	3/06/2011	11:38	12.7	9.8	Mild Steel	Grass	45	5	20	200	150	1	Slow burn. Ignition escalated after several seconds	4200	28	44	152
323	9L150	3/06/2011	11:45	12.7	9.8	Mild Steel	Grass	45	5	20	200	150	1	Slow burn. Ignition escalated after several seconds	3454	23	46	150
324	9M150	3/06/2011	11:57	12.7	9.8	Mild Steel	Grass	45	10	20	200	150	0		3530	24	48	150
326	9M150	3/06/2011	12:08	12.7	9.8	Mild Steel	Grass	45	10	20	200	150	0		6389	43	48	149
327	9L150	3/06/2011	13:03	12.7	9.8	Mild Steel	Grass	45	5	20	200	150	1	Slow burn. Ignition escalated after several seconds	5418	37	46	146
328	9M150	3/06/2011	13:10	12.7	9.8	Mild Steel	Grass	45	10	20	200	150	1		3336	23	47	145
329	9M200	3/06/2011	13:16	12.7	9.8	Mild Steel	Grass	45	10	20	200	200	1	Fast burn	7655	39	49	198
330	9M200	3/06/2011	13:21	12.7	9.8	Mild Steel	Grass	45	10	20	200	200	1	Ignition escalated after several seconds	5277	27	49	195
331	9L150	3/06/2011	13:26	12.7	9.8	Mild Steel	Grass	45	5	20	200	150	1		3419	23	49	147
332	9L70	3/06/2011	13:31	12.7	9.8	Mild Steel	Grass	45	5	20	200	70	0		721	11	48	68
333	9L70	3/06/2011	13:36	12.7	9.8	Mild Steel	Grass	45	5	20	200	70	0		656	10	49	64
334	9L70	3/06/2011	13:39	12.7	9.8	Mild Steel	Grass	45	5	20	200	70	0		706	11	49	67
335	9L70	3/06/2011	13:42	12.7	9.8	Mild Steel	Grass	45	5	20	200	70	0		749	12	49	64
336	10L100	3/06/2011	13:51	12.7	9.8	Mild Steel	Leaf	45	5	5	200	100	0	Very minor ignition, self extinguished	1452	15	46	100
337	10L150	3/06/2011	13:57	12.7	9.8	Mild Steel	Leaf	45	5	5	200	150	1		4013	27	45	150
338	10M150	3/06/2011	14:04	12.7	9.8	Mild Steel	Leaf	45	10	5	200	150	0		3705	24	44	152
339	10M200	3/06/2011	14:09	12.7	9.8	Mild Steel	Leaf	45	10	5	200	200	1		6388	33	45	196
340	10H200	3/06/2011	14:15	12.7	9.8	Mild Steel	Leaf	45	20	5	200	200	0		7302	37	45	195
341	10H500	3/06/2011	14:24	12.7	9.8	Mild Steel	Leaf	45	20	5	200	500	1		27087	54	47	501
342	10H250	3/06/2011	14:35	12.7	9.8	Mild Steel	Leaf	45	20	5	200	250	1		11073	43	45	255

343	Fuse wire	3/06/2011	14:45	12.7	9.8	Mild Steel		45		5	200			Fuse Wire				
344	10M150	3/06/2011	15:11	12.7	9.8	Mild Steel	Leaf	45	10	5	200	150	0	Ignition, self extinguished.	3318	23	41	146
345	10M150	3/06/2011	15:19	12.7	9.8	Mild Steel	Leaf	45	10	5	200	150	0		3736	25	43	147
346	10M200	3/06/2011	15:23	12.7	9.8	Mild Steel	Leaf	45	10	5	200	200	1		6849	34	43	200
347	10L100	3/06/2011	15:37	12.7	9.8	Mild Steel	Leaf	45	5	5	200	100	1		1786	18	45	100
348	10L100	3/06/2011	15:42	12.7	9.8	Mild Steel	Leaf	45	5	5	200	100	0		1647	17	45	95
349	10L100	3/06/2011	15:46	12.7	9.8	Mild Steel	Leaf	45	5	5	200	100	1		1838	19	45	94
350	10L70	3/06/2011	15:53	12.7	9.8	Mild Steel	Leaf	45	5	5	200	70	0		890	13	45	67
351	2L100	8/06/2011	9:22	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	100	1		69	1	45	100
352	2L100	8/06/2011	9:29	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	100	1		94	1	45	99
353	2L100	8/06/2011	9:33	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	100	1		69	1	45	100
354	2L100	8/06/2011	9:38	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	100	0		65	1	45	100
355	2L100	8/06/2011	9:45	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	100	1		59	1	45	100
356	2L70	8/06/2011	10:16	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	70	0		30	0	45	69
357	2L70	8/06/2011	10:19	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	70	0		35	1	45	69
358	2L70	8/06/2011	10:23	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	70	0		36	1	45	69
359	2L70	8/06/2011	10:25	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	70	0		47	1	45	69
360	2L150	8/06/2011	10:29	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	150	1		206	1	45	149
361	2L150	8/06/2011	10:33	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	150	1		351	2	45	149
362	2L150	8/06/2011	10:37	12.7	9.8	Mild Steel	Grass	45	5	5	4.25	150	1		148	1	45	149
363	2M150	8/06/2011	10:41	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	150	0	Sif extinguished	242	2	45	149
364	2M150	8/06/2011	10:45	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	150	1		159	1	45	149
365	2M150	8/06/2011	10:50	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	150	1		225	2	45	149
366	2M200	8/06/2011	10:55	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	200	1		480	2	45	199
367	2M200	8/06/2011	10:59	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	200	1		343	2	45	200
368	2M200	8/06/2011	11:05	12.7	9.8	Mild Steel	Grass	45	10	5	4.25	200	1		299	1	45	200
369	3M100	8/06/2011	11:13	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	100	0	Intended 200: Arc Duration too short	294	3	45	110
370	3M200	8/06/2011	11:20	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	200	0		918	5	45	199
371	3M150	8/06/2011	11:25	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	150	0	Intended 200: Arc Duration too short	217	2	45	130
372	3GAPM200	8/06/2011	11:30	12.7	9.8	Mild Steel	Grass	45	10	10	4.25	200	0	Shorter gaps to investigate longer low current arcs	212	1	45	199

373	3GAPL200	8/06/2011	11:36	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	200	0		134	1	45	200
374	3GAPL400	8/06/2011	11:42	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	400	1		591	1	45	400
375	3GAPL300	8/06/2011	11:47	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	300	1		212	1	45	300
376	3GAPL2000	8/06/2011	11:53	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	2000	1	20mm - Arc didn't extinguish	364	0	45	2001
377	3GAPL2000	8/06/2011	12:04	12.7	9.8	Mild Steel	Grass	45	5	10	4.25	2000	1	50mm - arc didn't extinguish	404	0	45	2001
378	4GAPL2000	8/06/2011	13:28	12.7	9.8	Mild Steel	Grass	45	5	20	4.25	2000	0	50mm - Arc extinguished after ~40ms	15	0	45	40
379	4GAPL2000	8/06/2011	13:29	12.7	9.8	Mild Steel	Grass	45	5	20	4.25	2000	0	20mm - Arc didn't extinguish	10	0	45	30
380	9L150	8/06/2011	13:56	12.7	9.8	Mild Steel	Grass	45	5	20	200	150	0		3437	23	43	150
381	9L150	8/06/2011	14:02	12.7	9.8	Mild Steel	Grass	45	5	20	200	150	1	fireslow to take off	3994	27	44	150
382	9L150	8/06/2011	14:09	12.7	9.8	Mild Steel	Grass	45	5	20	200	150	1	fireslow to take off	4036	26	44	154
383	9M150	8/06/2011	14:19	12.7	9.8	Mild Steel	Grass	45	10	20	200	150	1		3307	23	45	145
384	9M150	8/06/2011	14:28	12.7	9.8	Mild Steel	Grass	45	10	20	200	150	0		2967	20	45	148
385	9M150	8/06/2011	14:33	12.7	9.8	Mild Steel	Grass	45	10	20	200	150	0		3108	21	46	146
386	9M200	8/06/2011	14:38	12.7	9.8	Mild Steel	Grass	45	10	20	200	200	0		13089	67	45	195
387	9M200	8/06/2011	14:47	12.7	9.8	Mild Steel	Grass	45	10	20	200	200	1		5240	25	45	207
388	9M250	8/06/2011	14:54	12.7	9.8	Mild Steel	Grass	45	10	20	200	250	1	Good example of delayed ignition	8351	33	46	250
389	9M250	8/06/2011	15:03	12.7	9.8	Mild Steel	Grass	45	10	20	200	250	1	Good example of delayed ignition	7700	31	46	246
390	9L200	8/06/2011	15:10	12.7	9.8	Mild Steel	Grass	45	5	20	200	200	1		5859	30	48	198
391	9L200	8/06/2011	15:15	12.7	9.8	Mild Steel	Grass	45	5	20	200	200	1		5981	31	46	195
392	Other	8/06/2011	15:25	12.7	9.8	Mild Steel	Grass	45		20	200		0	Single straw test for arcing. Excellent video	11387	59	46	194
393	9L120	9/06/2011	8:46	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	0		2177	19	47	114
394	9L120	9/06/2011	8:52	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	1		2291	19	48	120
395	9L120	9/06/2011	8:57	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	1	Photo taken of basket	2108	18	45	120
396	9L120	9/06/2011	9:05	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	0		2001	17	45	120
397	9L120	9/06/2011	9:08	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	0	Photo taken of basket	1910	17	44	114
398	9L120	9/06/2011	9:13	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	0	Photo taken of basket	2255	19	44	120
399	9L120	9/06/2011	9:18	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	0		1972	17	45	115
400	9L120	9/06/2011	9:22	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	0		2188	18	44	120
401	9L120	9/06/2011	9:28	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	0		2009	17	44	120
402	9L120	9/06/2011	10:03	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	1		2099	18	46	117

403	9L120	9/06/2011	10:11	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	1	Fast burning	2194	19	47	115
404	9L120	9/06/2011	10:19	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	0		1984	17	49	120
405	9L120	9/06/2011	10:27	12.7	9.8	Mild Steel	Grass	45	5	20	200	120	1		2001	17	46	120
406	Other	9/06/2011	10:55	12.7	9.8	Mild Steel	Grass	45		20	200			Redclose Trial			50	
407	9L120R5	9/06/2011	11:10	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	1	First of tests	1972	17	49	114
408	9L120R5	9/06/2011	11:20	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	1	Fire after first strike. No second strike required	2115	18	49	118
409	9L120R5	9/06/2011	11:28	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	0		1926	16	50	119
410	9L120R5	9/06/2011	11:33	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	0	Extinguished after first strike. Violent flames after second strike. Self extinguished in the end.	2067	17	49	119
411	9L120R5	9/06/2011	11:41	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	1	Extinguished after first strike. Ignition after second strike.	2026	17	48	118
412	9L120R5	9/06/2011	11:53	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	0		1826	16	49	116
413	9L120R5	9/06/2011	11:59	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	0	Extinguished after first strike. Flames after second strike. Self extinguished in the end.	1854	16	50	114
414	9L120R5	9/06/2011	12:06	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	1		2117	18	49	117
415	9L120R5	9/06/2011	12:51	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	1	Fire after first strike. No second strike required	2132	18	48	115
416	9L120R5	9/06/2011	12:57	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	1		2020	18	49	115
417	9L120R5	9/06/2011	13:03	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	1		1916	16	45	117
418	9L120R5	9/06/2011	13:09	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	1		2074	18	43	115
419	9L120R5	9/06/2011	13:14	12.7	9.8	Mild Steel	Grass	45	5	20	200	120R5	1		1957	17	44	113
420	90150R10	9/06/2011	13:32	12.7	9.8	Mild Steel	Grass	45		20	200	150R10	1	One strike only needed			49	
421	90120R10	9/06/2011	13:41	12.7	9.8	Mild Steel	Grass	45		20	200	120R10	1	Ignition after second strike	2023	17	43	120
422	90120R10	9/06/2011	13:53	12.7	9.8	Mild Steel	Grass	45		20	200	120R10	1	Ignition after second strike. Second strike ~10ms longer than intended	2004	17	45	116
423	90120R10	9/06/2011	14:04	12.7	9.8	Mild Steel	Grass	45		20	200	120R10	0	Ignition after second strike. Second strike ~10ms shorter than intended	2240	19	45	117
424	90120R10	9/06/2011	14:17	12.7	9.8	Mild Steel	Grass	45		20	200	120R10	1	One strike only needed	2063	18	49	115
425	90120R10	9/06/2011	14:27	12.7	9.8	Mild Steel	Grass	45		20	200	120R10	1	Ignition after 1st strike would probably have continued	1829	19	48	96
426	90120R10	9/06/2011	14:36	12.7	9.8	Mild Steel	Grass	45		20	200	120R10	1		2031	17	46	120
427	90120R10	9/06/2011	14:43	12.7	9.8	Mild Steel	Grass	45		20	200	120R10	1	One strike only needed	2111	19	47	114
428	90120R10	9/06/2011	14:54	12.7	9.8	Mild Steel	Grass	45		20	200	120R10	1	Second strike caused v. slow burn after many seconds	2053	17	43	118
429	90120R10	9/06/2011	15:06	12.7	9.8	Mild Steel	Grass	45		20	200	120R10	1		1948	17	45	114
430	90120R10	9/06/2011	15:12	12.7	9.8	Mild Steel	Grass	45		20	200	120R10	1		2067	17	43	120
431	90120R60	9/06/2011	15:25	12.7	9.8	Mild Steel	Grass	45		20	200	120R60	1	One strike only needed	2039	17	45	120
432	90120R60	9/06/2011	15:33	12.7	9.8	Mild Steel	Grass	45		20	200	120R60	1		2238	19	46	118

433	GFN-L10	9/06/2011	15:54	12.7	9.8	Mild Steel	Grass	45	5	20	200 peak	10		50mm fuse wire	224	4	38	53
434	GFN-L10	9/06/2011	16:18	12.7	9.8	Mild Steel	Grass	45	5	20	200 peak	10		20mm fuse wire	216	4	25	53
435	GFN-L10	10/06/2011	8:46	12.7	9.8	Mild Steel	Grass	45	5	20	200 peak	10		25mm fuse wire	91	2	48	53
436	GFN-L10	10/06/2011	8:57	12.7	9.8	Mild Steel	Grass	45	5	20	200 peak	10		30mm fuse wire	121	2	48	53
437	GFN-L10	10/06/2011	0.390277778	12.7	9.8	Mild Steel	Grass	45	5	5	200 peak	10	1	30mm fuse wire - with fuel - heavy angle	119	13	42	9
438	GFN-L10	10/06/2011	0.408333333	12.7	9.8	Mild Steel	Grass	45	5	5	200 peak	10	1	30mm fuse wire - with fuel	94	10	41	9
439	GFN-L10	10/06/2011	0.420833333	12.7	9.8	Mild Steel	Grass	45	5	5	200 peak	10	1	30mm fuse wire - with fuel	135	14	41	10
440	GFN-L10	10/06/2011	0.428472222	12.7	9.8	Mild Steel	Grass	45	5	5	200 peak	10	1	15mm fuse wire - with fuel	83	9	42	9
441	GFN-L10	10/06/2011	0.436805556	12.7	9.8	Mild Steel	Grass	45	5	5	200 peak	10	0	10mm fuse wire - with fuel	58	7	42	9
442	GFN-L10	10/06/2011	0.445138889	12.7	9.8	Mild Steel	Grass	45	5	5	200 peak	10	0	10mm fuse wire - with fuel	61	7	41	9
443	GFN-L10	10/06/2011	0.452083333	12.7	9.8	Mild Steel	Grass	45	5	5	200 peak	10	0	10mm fuse wire - with fuel	63	7	42	9
444	GFN-L10	10/06/2011	0.461805556	12.7	9.8	Mild Steel	Grass	45	5	10	200 peak	10	0	30mm fuse wire - with fuel	110	11	47	10
445	GFN-L10	10/06/2011	0.471527778	12.7	9.8	Mild Steel	Grass	45	5	10	200 peak	10	0	30mm fuse wire - with fuel	96	10	48	10
446	GFN-L10	10/06/2011	0.476388889	12.7	9.8	Mild Steel	Grass	45	5	10	200 peak	10	0	30mm fuse wire - with fuel	112	12	50	10
447	GFN-L10	10/06/2011	0.490277778	12.7	9.8	Mild Steel	Grass	45	5	10	320peak	10	0	5mm fuse wire - with fuel	82	7	49	11
448	GFN-L10	10/06/2011	0.503472222	12.7	9.8	Mild Steel	Grass	45	5	10	440peak	10	0	5mm fuse wire - with fuel	131	13	50	10
449	GFN-L10	10/06/2011	0.511805556	12.7	9.8	Mild Steel	Grass	45	5	5	440peak	10	0	5mm fuse wire - with fuel	135	14	51	10
453	GFN-L2	10/06/2011	0.642361111	12.7	9.8	Mild Steel	Grass	45	5	5	230peak	2	0	5mm fuse wire - with fuel. Wrong range on CSV Voltage			47	
454	GFN-L2	10/06/2011	0.648611111	12.7	9.8	Mild Steel	Grass	45	5	5	230peak	2	0	5mm fuse wire - with fuel	11	6	47	2
455	GFN-L2	10/06/2011	0.654861111	12.7	9.8	Mild Steel	Grass	45	5	5	230peak	2	0	5mm fuse wire - with fuel	12	6	44	2
456	GFN-L2	10/06/2011	0.659722222	12.7	9.8	Mild Steel	Grass	45	5	5	230peak	2	0	5mm fuse wire - with fuel	10	5	45	2
457	GFN-L2	10/06/2011	0.664583333	12.7	9.8	Mild Steel	Grass	45	5	5	230peak	2	0	5mm fuse wire - with fuel	12	6	45	2
458	GFN-L2	10/06/2011	0.672222222	12.7	9.8	Mild Steel	Grass	45	5	5	230peak	2	0	5mm fuse wire - with fuel	11	6	46	2
459	GFN-L2	10/06/2011	0.677083333	12.7	9.8	Mild Steel	Grass	45	5	5	230peak	2	0	30mm fuse wire - with fuel	30	15	46	2
460	GFN-L2	10/06/2011	0.68125	12.7	9.8	Mild Steel	Grass	45	5	5	230peak	2	0	30mm fuse wire - with fuel	36	18	46	2

15 August to 19 August 2011 – Tests 461 to 868

Note: Highlighted tests not used in regression analysis. Ignition result key: 0 = no ignition, 1 = sustained ignition

TCA Test ID	Condition ID	Date	Approx. Time	Voltage (kV)	Actuator Acceleration (m s ⁻²)	Electrode material	Fuel type	Nominal Temperature (°C)	Fuel moisture (%)	Wind speed (km/h)	Current (amps)	Nominal Arc Duration (ms)	Sustained Ignition Result	Test Notes	Arc Energy (J)	Avg Arc Power (kW)	Temperature (°C)	Arc Duration (ms)
461	Trial	15/08/2011		12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0	Trial and Calibration, no basket				
462	Trial	15/08/2011		12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0	Trial and Calibration, no basket				
463	Trial	15/08/2011		12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0	Test started from 11:10am, noise in Current due to breaker issue				
464	Trial	15/08/2011		12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0	VCB in circuit				
465	Trial	15/08/2011		12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0	Trial Test restarted at 1:50pm and duration needs to be modified and T is too high				
466	Trial	15/08/2011		12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0	Self extinguished. Also duration is 60ms.				
467	11L40	15/08/2011	02:30 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0		77	2	49	40
468	11L40	15/08/2011	02:35 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0		60	2	48	39
469	11L40	15/08/2011	02:40 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0		61	2	48	40
470	11L40	15/08/2011	02:53 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0		60	2	47	39
471	11L40	15/08/2011	03:01 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0	Self extinguished	68	2	46	39
472	11L40	15/08/2011	03:06 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0		60	2	46	39
473	11L40	15/08/2011	03:15 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0		60	1	45	44
474	11L40	15/08/2011	03:21 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0		56	1	46	42
475	11L40	15/08/2011	03:25 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	40	0		59	1	46	41
476	11L60	15/08/2011	03:33 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	1	Invalid - retested	134	2	47	62
477	11L60	15/08/2011	03:38 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	1	Invalid - retested	162	3	48	60
478	11L60	15/08/2011	03:46 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	0	Invalid - retested	125	2	46	61
479	11L60	15/08/2011	03:50 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	1	Invalid - retested	116	2	45	60
480	11L60	15/08/2011	03:55 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	1	Invalid - retested	132	2	46	63
481	11L60	15/08/2011	04:00 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	1	Invalid - retested	138	2	46	63
482	11L60	15/08/2011	04:05 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	0	Invalid - retested	166	3	45	59
483	11L60	15/08/2011	04:08 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	1	Invalid - retested	160	3	45	60
484	11L60	15/08/2011	04:13 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	1	Invalid - retested	140	2	44	60
485	11L60	15/08/2011	04:18 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	0	Invalid - retested	137	2	45	59

486	11L80	15/08/2011	04:23 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	0	Self extinguished	207	3	45	79
487	11L80	15/08/2011	04:27 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	1		237	3	44	80
488	11L80	15/08/2011	04:31 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	1		253	3	44	80
489	11L80	15/08/2011	04:36 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	1		275	3	45	80
490	11L80	15/08/2011	16:40	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	1		228	3	44	82
491	11L80	15/08/2011	04:44 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	1		251	3	47	80
492	11L80	15/08/2011	04:51 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	1		234	3	42	81
493	11L80	15/08/2011	04:56 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	0	Self extinguished	234	3	43	80
494	11L80	15/08/2011	05:00 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	1		208	3	43	80
495	11L80	15/08/2011	05:05 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	0	Self extinguished	245	3	44	79
496	11L100	15/08/2011	05:11 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1		338	3	43	100
497	11L100	15/08/2011	05:16 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1		328	3	44	100
498	11L100	15/08/2011	05:20 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1		439	4	43	100
499	11L100	15/08/2011	05:23 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1		354	4	48	100
500	11L100	15/08/2011	05:27 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1		326	3	46	100
501	11L100	15/08/2011	05:30 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1		329	3	46	101
502	11L100	15/08/2011	05:34 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1		348	3	45	100
503		16/08/2011	08:29 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	120	0	16/08/2011, trial test no current	46			
504	11L120	16/08/2011	08:34 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	120	1	started at 8:30	571	5	47	120
505	11L120	16/08/2011	08:39 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	120	1		608	5	46	120
506	11L120	16/08/2011	08:43 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	120	1		640	5	45	125
507	11L120	16/08/2011	08:48 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	120	1		454	4	45	120
508	11L120	16/08/2011	08:52 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	120	1		575	5	45	125
509	11L50	16/08/2011	09:01 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0		90	2	44	50
510	11L50	16/08/2011	09:05 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0		87	2	45	50
511	11L50	16/08/2011	09:08 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0		92	2	45	50
512	11L50	16/08/2011	09:14 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	1		84	2	45	50
513	11L50	16/08/2011	09:18 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	Self extinguished	97	2	44	50
514	11L50	16/08/2011	09:22 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	Self extinguished	86	2	45	50
515	11L50	16/08/2011	09:27 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0		86	2	45	50

516	11L50	16/08/2011	09:31 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0		94	2	45	50
517	11L50	16/08/2011	09:35 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	Self extinguished	91	2	44	50
518	11L50	16/08/2011	09:43 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0		90	2	46	55
519	11L50	16/08/2011	09:46 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0		89	2	46	50
520	11L50	16/08/2011	09:51 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	1		92	2	47	50
521	11L50	16/08/2011	09:56 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	Self extinguished	92	2	50	50
522	11L50	16/08/2011	10:32 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0		80	2	47	50
523	11L50	16/08/2011	10:34 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	Proposed tests finished at 10:40am	87	2	47	50
524	Test	16/08/2011	11:21 AM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	220	0	Trial test , no sample	51			
525	error	16/08/2011	11:27 AM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	220	1	Test started from 11:26am, duration needs to be corrected	49			
526	error	16/08/2011	11:35 AM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	220	1	Duration needs to be corrected	916	4	48	230
527	3L220	16/08/2011	11:44 AM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	220	1		996	4	48	225
528	3L220	16/08/2011	11:52 AM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	220	1		830	4	49	220
529	3L220	16/08/2011	11:56 AM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	220	1		577	3	47	220
530	3L220	16/08/2011	12:00 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	220	1		598	3	46	220
531	3L220	16/08/2011	12:03 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	220	1		530	2	46	220
532	3L150	16/08/2011	01:01 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	150	1	Unverified test conditions	320	2	46	150
533	3L150	16/08/2011	01:04 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	150	1	Unverified test conditions	351	2	46	150
534	3L150	16/08/2011	01:07 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	150	1	Unverified test conditions	240	2	47	150
535	3L150	16/08/2011	01:10 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	150	1	Unverified test conditions	212	1	47	150
536	3L120	16/08/2011	01:13 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	1	Unverified test conditions	120	1	47	120
537	3L120	16/08/2011	01:17 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	0	Unverified test conditions	154	1	46	120
538	3L120	16/08/2011	01:21 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	1	Unverified test conditions	273	2	46	120
539	3L120	16/08/2011	01:31 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	1	Unverified test conditions	149	1	47	120
540	3L120	16/08/2011	01:34 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	1	Unverified test conditions	130	1	47	120
541	3L120	16/08/2011	01:38 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	1	Unverified test conditions	125	1	50	120
542	3L120	16/08/2011	01:41 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	1	Unverified test conditions	118	1	47	120
543	3L120	16/08/2011	01:46 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	1	Unverified test conditions	230	2	46	125
544	3L120	16/08/2011	01:52 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	1	Unverified test conditions	124	1	46	120
545	3L120	16/08/2011	01:56 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	1	Unverified test conditions	130	1	45	120

546	error	16/08/2011 02:07 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	80		Unverified test conditions		47		
547	3L80	16/08/2011 02:08 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	80	0	Unverified test conditions	78	1	47	80
548	3L80	16/08/2011 02:15 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	80	1	Unverified test conditions	66	1	45	80
549	3L80	16/08/2011 02:21 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	80	1	Unverified test conditions	60	1	45	80
550	3L90	16/08/2011 02:26 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	90	1	Unverified test conditions	56	1	45	90
551	3L80	16/08/2011 02:33 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	80	1	Unverified test conditions	60	1	45	80
552	3L80	16/08/2011 02:42 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	80	1	Unverified test conditions	69	1	45	80
553	3L80	16/08/2011 02:47 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	80	1	Unverified test conditions	57	1	45	80
554	3L80	16/08/2011 02:54 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	80	0	Unverified test conditions	67	1	44	80
555	3L80	16/08/2011 02:57 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	80	1	Unverified test conditions	52	1	45	80
556	3L80	16/08/2011 03:02 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	80	0	Unverified test conditions	74	1	45	80
557	3L80	16/08/2011 03:07 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	80	0	Unverified test conditions	76	1	44	80
558	3L120	16/08/2011 03:12 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	1	More compact sample trialled	228	2	44	120
559	3L120	16/08/2011 03:17 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	1	More compact sample trialled	239	2	44	120
560	3L120	16/08/2011 03:30 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	0	More compact sample trialled	212	2	42	120
561	3L120	16/08/2011 03:35 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	0	More compact sample trialled	273	2	42	120
562	3L120	16/08/2011 03:40 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	120	1	More compact sample trialled	276	2	43	115
563	3L50	16/08/2011 03:44 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	50	0	Intended as 60	15	0	43	55
564	3L50	16/08/2011 03:48 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	50	0	Intended as 60	27	1	43	50
565	3L50	16/08/2011 03:52 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	50	0	Intended as 60	23	0	45	50
566	3L50	16/08/2011 03:55 PM	12.7	9.8	Mild Steel	Grass	45	5	10	4.2	50	0	Intended as 60	31	1	45	50
567		17/08/2011 08:38 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	50 A Current check NFR (link issue)		47		
568		17/08/2011 08:48 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	50 A Current check - OK		47		
569	11L50	17/08/2011 08:56 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	1st test - series of 50 - 50 A, 50 ms (start time - 8:53 am)	95	2	48	50
570	11L50	17/08/2011 09:00 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	2	85	2	47	51
571	11L50	17/08/2011 09:05 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	3	90	2	46	53
572	11L50	17/08/2011 09:07 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	4	87	2	46	53
573	11L50	17/08/2011 09:10 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	5	87	2	46	53
574	11L50	17/08/2011 09:14 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	6	84	2	46	52
575	11L50	17/08/2011 09:17 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	7	85	2	47	51

576	11L50	17/08/2011	09:20 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	8	82	2	47	50
577	11L50	17/08/2011	09:23 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	9	75	2	47	48
578	11L50	17/08/2011	09:27 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	10	81	2	48	46
579	11L50	17/08/2011	09:56 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	11	80	2	47	51
580	11L50	17/08/2011	09:58 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	12	82	2	47	49
581	11L50	17/08/2011	10:01 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	13	89	2	47	50
582	11L50	17/08/2011	10:03 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	14	85	2	47	50
583	11L50	17/08/2011	10:05 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	15	84	2	47	50
584	11L50	17/08/2011	10:08 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	16	84	2	47	51
585	11L50	17/08/2011	10:13 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	17	89	2	47	51
586	11L50	17/08/2011	10:15 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	1	18	90	2	47	52
587	11L50	17/08/2011	10:18 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	1	19	90	2	47	50
588	11L50	17/08/2011	10:22 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	20	110	2	46	50
589	11L50	17/08/2011	10:25 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	21	92	2	47	51
590	11L50	17/08/2011	10:27 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	1	22	97	2	47	50
591	11L50	17/08/2011	10:30 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	23	91	2	45	51
592	11L50	17/08/2011	10:32 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	24	82	2	45	52
593	11L50	17/08/2011	10:35 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	25	84	2	44	50
594	11L50	17/08/2011	10:37 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	26	89	2	44	50
595	11L50	17/08/2011	10:40 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	27	78	2	45	50
596	11L50	17/08/2011	10:43 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	28	86	2	45	50
597	11L50	17/08/2011	10:47 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	29	85	2	47	50
598	11L50	17/08/2011	10:50 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	30	87	2	46	50
599	11L50	17/08/2011	10:54 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	31	80	2	46	50
600	11L50	17/08/2011	10:56 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	32	92	2	48	50
601	11L50	17/08/2011	10:58 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	33	84	2	48	48
602	11L50	17/08/2011	11:00 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	34	79	2	47	50
603	11L50	17/08/2011	11:02 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	35	84	2	47	49
604	11L50	17/08/2011	11:05 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	36	81	2	47	50
605	11L50	17/08/2011	11:07 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	37	84	2	47	50

606	11L50	17/08/2011	11:09 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	38	80	2	47	50
607	11L50	17/08/2011	11:12 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	39	76	2	48	49
608	11L50	17/08/2011	11:14 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	40	82	2	48	48
609	11L50	17/08/2011	11:17 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	41	80	2	49	50
610	11L50	17/08/2011	11:20 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	42	79	2	48	50
611	11L50	17/08/2011	11:22 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	43	83	2	48	48
612	11L50	17/08/2011	11:26 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	44	81	2	49	50
613	11L50	17/08/2011	11:28 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	45	80	2	49	50
614	11L50	17/08/2011	11:31 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	46	88	2	48	50
615	11L50	17/08/2011	11:33 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	47	88	2	48	50
616	11L50	17/08/2011	11:35 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	48	88	2	48	50
617	11L50	17/08/2011	11:37 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	49	83	2	48	50
618	11L50	17/08/2011	11:39 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	50	93	2	48	50
619	11L50	17/08/2011	11:46 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	51	80	2	46	50
620	11L50	17/08/2011	11:50 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	52	79	2	45	51
621	11L50	17/08/2011	11:55 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	53	86	2	47	49
622	11L50	17/08/2011	12:01 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	54	75	2	47	47
623	11L50	17/08/2011	12:07 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	55	75	2	48	44
624	11L50	17/08/2011	12:09 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	56	74	2	48	44
625	11L50	17/08/2011	12:12 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	57	80	2	48	45
626	11L50	17/08/2011	12:14 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	58	77	2	48	46
627	11L50	17/08/2011	12:17 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	59	73	2	48	46
628	11L50	17/08/2011	12:22 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50	0	60	72	2	48	46
629	Reclose-50A	17/08/2011	02:10 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1st shot - Test #1	90	2	48	50
630	Reclose-50A	17/08/2011	02:10 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2nd shot - Test #1	98	2	48	47
631	Reclose-50A	17/08/2011	02:14 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - Only 20s interval, not 30s	76	2	48	46
632	Reclose-50A	17/08/2011	02:15 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	1	Reclose 2 - Only 20s interval, not 30s	135	2	50	70
633	Reclose-50A	17/08/2011	02:22 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 2	85	2	45	50
634	Reclose-50A	17/08/2011	02:23 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 2	157	2	45	70
635	Reclose-50A	17/08/2011	02:28 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 3	80	2	47	47

636	Reclose-50A	17/08/2011	02:28 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 3	195	3	47	70
637	Reclose-50A	17/08/2011	02:32 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 4	91	2	47	50
638	Reclose-50A	17/08/2011	02:33 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	1	Reclose 2 - 4	89	2	47	50
639	Reclose-50A	17/08/2011	02:37 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 5	91	2	47	51
640	Reclose-50A	17/08/2011	02:37 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 5	139	2	47	70
641	Reclose-50A	17/08/2011	02:59 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	1	Reclose 1 - no reclose required for ignition	86	2	46	50
643	Reclose-50A	17/08/2011	03:08 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 7	81	2	45	50
644	Reclose-50A	17/08/2011	03:09 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 7	81	2	45	50
645	Reclose-50A	17/08/2011	03:16 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 8	75	2	46	42
646	Reclose-50A	17/08/2011	03:16 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 8	103	2	46	45
647	Reclose-50A	17/08/2011	03:20 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 9	73	2	47	43
648	Reclose-50A	17/08/2011	03:21 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 9	160	2	47	70
649	Reclose-50A	17/08/2011	03:24 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 10	84	2	47	50
650	Reclose-50A	17/08/2011	03:25 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	1	Reclose 2 - 10	163	2	50	70
651	Reclose-50A	17/08/2011	03:28 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 11	78	2	50	50
652	Reclose-50A	17/08/2011	03:28 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 11	81	2	50	50
653	Reclose-50A	17/08/2011	03:34 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 12	81	2	49	52
654	Reclose-50A	17/08/2011	03:35 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 12	152	2	50	70
655	Reclose-50A	17/08/2011	03:39 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 13	78	2	50	50
656	Reclose-50A	17/08/2011	03:40 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 13	91	2	50	56
657	Reclose-50A	17/08/2011	03:44 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 14	86	2	50	52
658	Reclose-50A	17/08/2011	03:44 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 14	109	2	50	60
659	Reclose-50A	17/08/2011	03:50 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 15	90	2	48	50
660	Reclose-50A	17/08/2011	03:50 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 15	140	2	48	60
661	Reclose-50A	17/08/2011	03:56 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 16	86	2	49	50
662	Reclose-50A	17/08/2011	03:56 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	1	Reclose 2 - 16	157	3	49	60
663	Reclose-50A	17/08/2011	04:01 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 17	89	2	47	50
664	Reclose-50A	17/08/2011	04:01 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 17	111	2	47	60
667	Reclose-50A	18/08/2011	08:46 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	1	Reclose 1 - no reclose required for ignition	140	3	48	53
671	Reclose-50A	18/08/2011	09:04 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 1 - 0	122	2	48	51

672	Reclose-50A	18/08/2011 09:04 AM	12.7	9.8	Mild Steel	Grass	45	5	10	50	50.0	0	Reclose 2 - 0	135	3	48	50
673	Trial	18/08/2011 09:34 AM	12.7	9.8	Mild Steel	Grass	45	5	10	40	50.0	0	Reclose 1 - Energy check, reclose shot failed	125	2	48	51
675	Trial	18/08/2011 10:08 AM	12.7	9.8	Mild Steel	Grass	45	5	10	30	50.0	0	Reclose 1 - Energy check	77	2	49	51
676	Trial	18/08/2011 10:09 AM	12.7	9.8	Mild Steel	Grass	45	5	10	30	50.0	0	Reclose 2 - Energy check	85	2	49	51
677	Trial	18/08/2011 10:16 AM	12.7	9.8	Mild Steel	Grass	45	5	10	30	50.0	0	Reclose 1 - Slight increase in V	70	1	48	50
678	Trial	18/08/2011 10:17 AM	12.7	9.8	Mild Steel	Grass	45	5	10	30	50.0	0	Reclose 2 - Slight increase in V	77	2	48	51
679	Reclose-35A	18/08/2011 10:33 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 1. no reclose required for ignition. Long basket exposure	118	2	48	51
680	Reclose-35A	18/08/2011 10:38 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 2	99	2	48	50
681	Reclose-35A	18/08/2011 10:39 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 2	70	1	48	51
682	Reclose-35A	18/08/2011 10:46 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 3.no reclose required for ignition	104	2	46	51
684	Reclose-35A	18/08/2011 10:50 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 4.no reclose required for ignition	117	2	44	51
690	Reclose-35A	18/08/2011 11:37 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 5	77	2	48	50
691	Reclose-35A	18/08/2011 11:38 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 5	90	2	48	50
692	Reclose-35A	18/08/2011 11:42 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 6. no reclose required for ignition	118	2	48	50
694	Reclose-35A	18/08/2011 11:47 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 7	93	2	49	50
695	Reclose-35A	18/08/2011 11:47 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 7	108	2	49	50
696	Reclose-35A	18/08/2011 11:51 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 8	109	2	47	50
697	Reclose-35A	18/08/2011 11:51 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 8	84	2	47	50
698	Reclose-35A	18/08/2011 11:55 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 9	88	2	47	50
699	Reclose-35A	18/08/2011 11:55 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 9	79	2	47	50
700	Reclose-35A	18/08/2011 11:59 AM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 10	104	2	48	50
701	Reclose-35A	18/08/2011 12:03 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - Single test no ignition. 51	98	2	48	50
702	Reclose-35A	18/08/2011 12:10 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 11	91	2	46	50
704	Reclose-35A	18/08/2011 01:07 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 12	109	2	47	50
706	Reclose-35A	18/08/2011 01:14 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 13	74	1	48	50
707	Reclose-35A	18/08/2011 01:15 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 13	61	1	48	50
708	Reclose-35A	18/08/2011 01:22 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 14	93	2	47	50
710	Reclose-35A	18/08/2011 01:26 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 15	92	2	50	50
711	Reclose-35A	18/08/2011 01:27 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 15	83	2	50	50
712	Reclose-35A	18/08/2011 01:31 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 16	102	2	48	50

713	Reclose-35A	18/08/2011	01:31 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 16	88	2	48	50
714	Reclose-35A	18/08/2011	01:40 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 17	87	2	46	50
716	Reclose-35A	18/08/2011	01:44 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 18	96	2	48	50
718	Reclose-35A	18/08/2011	01:48 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 19	76	2	48	50
719	Reclose-35A	18/08/2011	01:49 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 19	63	1	48	50
720	Reclose-35A	18/08/2011	01:52 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 20	87	2	48	50
721	Reclose-35A	18/08/2011	01:52 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 2 - 20	69	1	48	50
722	Reclose-35A	18/08/2011	01:58 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 21	72	1	48	51
723	Reclose-35A	18/08/2011	01:58 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 21	72	1	48	51
724	Reclose-35A	18/08/2011	02:03 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 22	75	2	48	50
725	Reclose-35A	18/08/2011	02:03 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 22	86	2	48	50
726	Reclose-35A	18/08/2011	02:07 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 23	67	1	48	50
727	Reclose-35A	18/08/2011	02:08 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 23	67	1	49	50
728	Reclose-35A	18/08/2011	02:12 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 24	114	2	49	51
729	Reclose-35A	18/08/2011	02:12 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 2 - 24	126	3	49	50
730	Reclose-35A	18/08/2011	02:15 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 25	126	3	49	50
731	Reclose-35A	18/08/2011	02:16 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 25	92	2	49	50
732	Reclose-35A	18/08/2011	02:20 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 26	85	2	47	50
733	Reclose-35A	18/08/2011	02:20 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 26	85	2	47	50
734	Reclose-35A	18/08/2011	02:26 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 27	74	1	47	50
735	Reclose-35A	18/08/2011	02:27 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 2 - 27	78	2	47	50
736	Reclose-35A	18/08/2011	02:30 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 28	96	2	48	50
738	Reclose-35A	18/08/2011	02:33 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 29	124	2	50	50
740	Reclose-35A	18/08/2011	02:37 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 30	128	3	50	50
742	Reclose-35A	18/08/2011	02:42 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 31	75	1	48	50
743	Reclose-35A	18/08/2011	02:42 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 2 - 31	115	2	48	50
744	Reclose-35A	18/08/2011	02:46 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 32	112	2	48	50
746	Reclose-35A	18/08/2011	02:50 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 33	102	2	47	50
747	Reclose-35A	18/08/2011	02:50 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 2 - 33	111	2	47	50
748	Reclose-35A	18/08/2011	02:54 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 34	113	2	48	50

750	Reclose-35A	18/08/2011	02:59 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 35	93	2	48	50
752	Reclose-35A	18/08/2011	03:03 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 36	115	2	50	52
754	Reclose-35A	18/08/2011	03:06 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 37	94	2	50	50
756	Reclose-35A	18/08/2011	03:10 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 38	105	2	45	52
757	Reclose-35A	18/08/2011	03:11 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 2 - 38	115	2	45	51
758	Reclose-35A	18/08/2011	03:23 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 39	63	1	50	51
760	Reclose-35A	18/08/2011	03:27 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 40	82	2	50	52
761	Reclose-35A	18/08/2011	03:27 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 40	95	2	50	50
762	Reclose-35A	18/08/2011	03:31 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 41	63	1	50	52
763	Reclose-35A	18/08/2011	03:32 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 41	66	1	50	52
764	Reclose-35A	18/08/2011	03:37 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 42	82	2	47	52
765	Reclose-35A	18/08/2011	03:38 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 42	86	2	48	52
766	Reclose-35A	18/08/2011	03:40 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 43	83	2	48	50
767	Reclose-35A	18/08/2011	03:41 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 2 - 43	93	2	48	50
768	Reclose-35A	18/08/2011	03:44 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 44	117	2	47	52
769	Reclose-35A	18/08/2011	03:44 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 2 - 44	95	2	47	51
770	Reclose-35A	18/08/2011	03:47 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 45	135	3	47	51
771	Reclose-35A	18/08/2011	03:48 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 2 - 45	118	2	48	52
772	Reclose-35A	18/08/2011	03:51 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 46	109	2	48	52
773	Reclose-35A	18/08/2011	03:51 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 46	93	2	48	52
774	Reclose-35A	18/08/2011	03:57 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 47	109	2	48	52
775	Reclose-35A	18/08/2011	03:57 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 47	97	2	48	52
776	Reclose-35A	18/08/2011	04:01 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 48	81	2	48	51
777	Reclose-35A	18/08/2011	04:01 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 48	71	1	48	51
778	Reclose-35A	18/08/2011	04:04 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	1	Reclose 1 - 49	98	2	47	52
780	Reclose-35A	18/08/2011	04:08 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 1 - 50	85	2	48	52
781	Reclose-35A	18/08/2011	04:08 PM	12.7	9.8	Mild Steel	Grass	45	5	10	35	50.0	0	Reclose 2 - 50	61	1	48	50
783	8L30	19/08/2011	09:22 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0	1	190	7	47	27
784	8L30	19/08/2011	09:28 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0	2	180	6	47	30
785	8L30	19/08/2011	09:34 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0	3	226	6	47	35

	Error	19/08/2011 09:40 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0	CSV Corrupted		48	32	
787	8L30	19/08/2011 10:11 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0	5	180	6	51	30
788	8L30	19/08/2011 10:13 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0	6	198	7	48	30
789	8L30	19/08/2011 10:16 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0	7	190	6	48	30
790	8L30	19/08/2011 10:18 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0	8	190	6	47	33
792	8L30	19/08/2011 10:24 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0	9	174	6	46	29
793	8L30	19/08/2011 10:26 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	30	0	10	173	6	46	30
794	8L50	19/08/2011 10:31 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	0	1	425	9	46	50
795	8L50	19/08/2011 10:34 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	0	2	409	8	47	50
796	8L50	19/08/2011 10:38 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	1	3	406	8	48	50
797	8L50	19/08/2011 10:41 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	0	4	378	8	48	50
798	8L50	19/08/2011 10:44 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	0	5	422	8	47	50
799	8L50	19/08/2011 10:48 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	0	6	411	8	49	50
800	8L50	19/08/2011 10:50 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	0	7	354	8	49	45
801	8L50	19/08/2011 10:53 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	0	8	411	8	49	50
802	8L50	19/08/2011 10:56 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	1	9	409	8	49	49
803	8L50	19/08/2011 11:00 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	50	1	10	421	8	49	53
804	8L40	19/08/2011 11:03 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	1	252	7	46	38
805	8L40	19/08/2011 11:05 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	2	256	7	46	38
806	8L40	19/08/2011 11:07 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	3	258	7	47	38
807	8L40	19/08/2011 11:10 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	4	284	8	47	37
808	8L40	19/08/2011 11:12 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	Actually 50	345	7	47	50
809	8L40	19/08/2011 11:15 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	5	297	8	47	39
810	8L40	19/08/2011 11:18 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	6	296	7	48	40
811	8L40	19/08/2011 11:21 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	7	300	7	48	42
812	8L40	19/08/2011 11:23 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	8	297	8	48	39
813	8L40	19/08/2011 11:25 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	9	301	8	48	39
814	8L40	19/08/2011 11:28 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	10	290	7	49	40
815	8L40	19/08/2011 11:31 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	11	294	7	49	39
816	8L40	19/08/2011 11:36 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	12	279	7	49	40

817	8L40	19/08/2011	11:39 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	13	283	7	49	40
818	8L40	19/08/2011	11:42 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	14	263	7	49	38
819	8L40	19/08/2011	11:45 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	40	0	15	283	7	49	38
820	8L70	19/08/2011	11:48 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	1	1	730	11	49	68
821	8L70	19/08/2011	11:51 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	0	2	763	11	49	70
822	8L70	19/08/2011	11:54 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	1	3	739	11	47	69
823	8L70	19/08/2011	11:58 AM	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	1	4	768	11	47	70
824	8L70	19/08/2011	12:51 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	1	5	778	11	47	69
825	8L70	19/08/2011	12:55 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	0	6 - Lots of flames. Almost kept going.	699	11	48	65
826	8L70	19/08/2011	12:59 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	1	7	690	10	47	67
827	8L70	19/08/2011	01:02 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	1	8	730	11	46	67
828	8L70	19/08/2011	01:07 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	0	9	871	12	45	75
829	8L70	19/08/2011	01:13 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	70	1	10	807	12	44	70
830	8L90	19/08/2011	01:16 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	90	1	1	1198	14	44	88
831	8L90	19/08/2011	01:22 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	90	1	2	1316	14	43	92
832	8L90	19/08/2011	01:26 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	90	1	3	1347	15	43	90
833	8L90	19/08/2011	01:29 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	90	1	4	1324	14	48	93
834	8L90	19/08/2011	01:34 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	90	1	5	1075	12	45	90
835	8L60	19/08/2011	01:40 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	60	0	1	610	10	44	63
836	8L60	19/08/2011	01:44 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	60	0	2	604	10	45	63
837	8L60	19/08/2011	01:47 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	60	1	3	594	10	44	60
838	8L60	19/08/2011	01:50 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	60	1	4	625	10	44	62
839	8L60	19/08/2011	01:54 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	60	0	5	613	10	44	60
840	8L60	19/08/2011	01:57 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	60	0	6	588	10	46	59
841	8L60	19/08/2011	02:05 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	60	1	7	649	10	49	63
842	8L60	19/08/2011	02:08 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	60	0	8	594	9	49	63
843	8L60	19/08/2011	02:14 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	60	1	9	632	10	47	63
844	8L60	19/08/2011	02:17 PM	12.7	9.8	Mild Steel	Grass	45	5	10	200	60	0	10	580	10	47	60
845	11L60	19/08/2011	02:52 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	0	1	128	2	49	60
846	11L60	19/08/2011	02:55 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	0	2	127	2	49	60

847	11L60	19/08/2011	02:57 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	0	3	130	2	48	64
848	11L60	19/08/2011	03:00 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	0	4	131	2	48	62
849	11L60	19/08/2011	03:03 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	1	5	128	2	47	63
850	11L60	19/08/2011	03:07 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	0	6	136	2	46	64
851	11L60	19/08/2011	03:12 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	0	7	131	2	47	62
852	11L60	19/08/2011	03:14 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	0	8	126	2	47	63
853	11L60	19/08/2011	03:18 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	0	9	134	2	48	64
854	11L60	19/08/2011	03:20 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	60	1	10	129	2	48	63
855	11L80	19/08/2011	03:24 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	0	1	255	3	48	83
856	11L80	19/08/2011	03:40 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	1	2	227	3	51	82
857	11L80	19/08/2011	03:46 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	0	3	206	3	49	80
858	11L80	19/08/2011	03:48 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	1	4	226	3	49	82
859	11L80	19/08/2011	03:51 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	0	5	279	3	49	82
860	11L80	19/08/2011	03:54 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	1	6	215	3	50	80
861	11L100	19/08/2011	03:57 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1	1	330	3	49	101
862	11L100	19/08/2011	03:59 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1	2	384	4	49	104
863	11L100	19/08/2011	04:02 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	0	3	351	3	47	103
864	11L100	19/08/2011	04:04 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1	4	360	4	47	102
865	11L100	19/08/2011	04:06 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1	5	392	4	47	103
866	11L100	19/08/2011	04:10 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1	6	350	3	48	101
867	11L100	19/08/2011	04:13 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	100	1	7	338	3	49	102
868	11L80	19/08/2011	04:17 PM	12.7	9.8	Mild Steel	Grass	45	5	10	50	80	1	7	228	3	47	80