REPORT

Improved Statistical Ratings For Distribution Overhead Lines (Phase 2) Final Report

Private and confidential

Prepared for: UK Electricity Distribution Network Operators

Project No: T7919
Document Version: Issue 2
Date: 5 September 2018

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Safer, Stronger, Smarter Networks

Version History

Date	Version	Author(s)	Notes
29th June 2018	Issue 1	Mark Bertinat Richard Wood Emily Marquand	
5th September 2018	Issue 2	Mark Bertinat Richard Wood Emily Marquand	Expanded version as requested by Project Champion

Final Approval

Approval Type	Date	Version	EA Technology Issue Authority
Final	29th June 2018	Issue 1	
Final	6th September 2018	Issue 2	

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Executive summary

Background to the Project

Demands on power distribution networks are increasing the pressure to maximise network asset capacity. Existing distribution overhead power line ratings are almost thirty years old and have not been formally reviewed regarding their accuracy and reliability and take no account of regional differences in climate.

The result being that for many years, Distribution Network Operators (DNOs) have made load-related decisions to replace or reinforce overhead powerlines, which have most likely been based on inaccurate ratings.

The aim of the project was to provide DNOs with a cost-effective, up-to-date and robust revised methodology, which included a new, bespoke software tool, that could be utilised for calculating overhead powerline line ratings at both a regional and circuit specific level.

A schedule of participating companies and their assigned representatives is shown in Appendix I.

Scope and Objectives

The scope of the project included:

- **Operate and Manage Test Rig:** EA Technology to operate overhead line test rig, perform maintenance and fault restoration over twenty-four months. Decommission Test Rig at the end of the twenty-four months of operation.

- **Data Collection and Validation:** including measurement of weather conditions and co-incident temperatures of various conductor types at various current levels at the Test Rig for twenty-four months in order to provide a new dataset for the assessment of the weather risk element of probabilistic ratings.

- **Data Analysis**: using the new dataset, quantify the weather risk, in combination with load risks, in order to calculate overhead line ratings.

- **New Dataset:** supply all collected raw, cleansed and averaged data collected over the twenty-four month test period.

- **Validate CIGRÉ:** validate an updated CIGRÉ methodology for calculating conductor temperature from load and weather data as laid out in CIGRÉ Technical Brochure TB601 "Guide for thermal rating calculations of overhead lines" (2014)

- **ENA ER P27 and ENA ACE 104**: provide an updated ENA ER P27 and ENA ACE 104.

- **Integrated Rating Software Tool**: provide a new Integrated Ratings Software Tool, incorporating the combined functionality of OHRAT and OHTEMP, the input of weather and load risk to enable static ratings and more comprehensive (regional or circuit specific) rating assessments to be made.

Conclusions

C1. The measured conductor temperatures averaged over a single "hot-conductor" day were generally between 2°C and 4°C higher than those calculated using the Cigré TB601 equations (OHTEMP2). Calculated values based on measured ambient conditions fluctuated wildly, necessitating the use of a 10-minute running mean for comparison.

C2. Minute-by-minute analysis for the hottest conductor (Ash 500), found the difference between measured conductor temperatures and calculated 10-minute running mean values ranged from -3°C to +9°C.

C3. Daily averages of the difference between measured and calculated temperatures for the hottest day in each month for each conductor produced an overall mean difference of 3.6°C for 2016 and 3.4°C for 2017.

C4. Frequency distributions for measured and calculated conductor temperatures over a complete season (summer 2017, Ash 500) indicated that there was generally good agreement between the calculated running means and the measured values, with the calculated values approximately 1K lower than the measured values.

C5. Possible reasons for these discrepancies are
- assumed emissivity and absorptivity too high (decreases Tcalc)
- response time of physical system
- measured wind speeds too high (decreases Tcalc)
- incorrectly measured solar gain

C6. Exceedance was found to depend upon the design temperature, as expected from previous work, with a 10°C increase in Tdes producing a factor of 3 decrease in the number of temperature excursions. A much weaker dependence on ambient temperature was also found, with a 10°C increase in Tamb producing a 1% - 2% decrease in the number of temperature excursions.

C7. A study of seasonal boundaries showed that whilst there was a clear summer period comprising June to August or September and a less clear winter season comprising December-to February, there was little evidence of a simple symmetrical split of the intermediate months into spring and autumn seasons with the same design ambient temperature Tamb,as assumed in P27.

C8. Consequently, a radical seasonal split is proposed with four 3-month seasons, each with a different design ambient temperature Tamb (unlike P27 which has the same Tamb for spring and autumn). Summer and Winter would comprise the obvious three hot months (Jun–July–Aug) and the obvious three cold months (Dec–Jan–Feb) but spring and autumn would be replaced by more complex "pseudo seasons" called intermediate cool and intermediate warm, comprising the relatively cool spring and autumn months (Mar, Apr and Nov) and the relatively warm spring and autumn months (May, Sep and Oct).

C9. CT curves (i.e. CT-vs-loge curves) enable one to calculate the probabilistic rating for an exceedance e from the deterministic rating. CT curves based on our measured data, and using the new proposed seasons, along with a provisional set of design ambient temperatures derived from P27 values, exhibited a significant amount of variation, but this variation was greatly reduced if design ambient temperatures were instead set equal to the average Tamb values obtained from our measured data. Significantly, these measured Tamb averages were very similar to the corresponding MetOffice 30-year average temperatures.

C10. A plot of all forty conductor-current-season combinations on the same graph using the measured average Tamb values showed a remarkable lack of scatter for such a wide variety of parameters, giving support to the claim made in the derivation of P27 that the CT curve is a universal constant, independent of conductor, current and season.

C11. The conductor temperatures measured in this project can therefore be used to derive a universal CT curve based on the proposed seasonal split and MetOffice 30-year average temperatures.

Season	Months	Tamb = MetO 30yr UK Avg (1981-2010)
Icool	Mar, Apr, Nov	6
Summer	Jun, Jul, Aug	14
Iwarm	May, Sep, Oct	11
Winter	Jan, Feb, Dec	4

C12. A best fit to all the CT(e) values for 2017 was determined and a lookup table produced. This can be used to find CT for any specific exceedance and hence to calculate the probabilistic rating for that exceedance.

C13. The CT curves are based on the full year's data obtained for 2017. The results from the nine months of data for 2016 are remarkably similar, but because the latter lacks any summer data, its use would introduce a bias into the results that would be hard to evaluate.

Recommendations

R1. The old P27 ratings should be revised in accordance with the findings of this work.

R2. The revised version of OHTEMP based on Cigré TB601 can be used to predict conductor temperatures.

R3. A revised seasonal structure should be used with simple winter and summer seasons, but non-contiguous intermediate cool and intermediate warm seasons.

R4. Design ambient temperatures based on the UK 30-year averages for these seasons should be used.

R5. The look-up table provided can be used to calculate the probabilistic rating for a specified exceedance.

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1. Background & Introduction

Overhead powerlines are designed and constructed to carry electrical loads whilst maintaining required electrical and safety clearances. The rating of an overhead line is a measure of the maximum current that can be passed through the powerline's conductors without these clearances being infringed. Current flowing through the conductor causes it to heat up, in turn causing the material to expand, and the conductor to sag closer to the ground. Too much current, may result in excessive conductor sag and a potential ground clearance infringement.

An overhead line conductor's temperature, however, is highly variable. The heat generated by the current is offset by the cooling effects of the weather, and while current levels may be fairly constant, the weather is not. Throughout most of the world, the requirement to maintain clearances is absolute – infringements are never permitted, and therefore an overhead power line's design maximum temperature may never be exceeded. Ratings are therefore calculated according to the most conservative assumptions about the cooling effects of the weather. In the UK, the Electricity Safety, Quality and Continuity Regulations (ESQCR), by contrast, require clearances to be maintained at a line's maximum likely temperature, allowing for the use of risk-based, or probabilistic, ratings.

UK probabilistic distribution overhead line ratings, as per Energy Networks Association (ENA) ER P27[1] which have been in place since 1986, were derived (as described in ENA ACE 104[2]) from research originally carried out at the Central Electricity Generating Board's (CEGB's) Leatherhead laboratories in the late 1970's/early 1980's. In applying the output of this research, which was focussed on transmission overhead line ratings, various assumptions were made as to the applicability of the results to distribution overhead line ratings.

The risk of an overhead line conductor exceeding its design temperature is a combination of two, separate risks:

- "Weather risk", which is the risk that the conductor will experience poor cooling, and
- "Load risk", which is the risk that a conductor will experience a high load. ENA ER P27 addresses only the "weather risk". The load risk element of line ratings, in ENA ER P27 and therefore for most distribution overhead power lines, is effectively 100%, i.e. it is assumed that the line will always be carrying 100% of its rated current.

A previous EA Technology Strategic Technology Programme (STP) project; S2126: *Monitoring of Conductor Temperatures at Fixed Current: Analysis of Collated Data*[3], sought to explore the validity of the assumptions relating to weather risk and found them not to be valid: the actual frequency of temperature excursions on monitored spans of conductor, was found to be much higher than expected according to ENA ER P27.

Further stages of the project sought to explore which specific assumptions were erroneous, with the results providing some clear evidence, primarily challenging the original assumption that an overhead line conductor's design temperature did not influence the probability that temperature would be exceeded (known as "exceedance") under fully loaded conditions.

It was also very noticeable that the seasonal boundaries currently in use were inconsistent with the results obtained by the EA Technology STP S2126 project. This inconsistency could be an indicator of the effects of climate change over the last 30 years, an issue that had not been investigated in detail in relation to overhead line ratings, and yet is predicted to have major cost implications for the distribution networks.

It is worth noting that although measured exceedances were much higher than expected, it does not necessarily follow that overhead lines in service are actually exceeding their design, profile temperatures (though the risks cannot currently be quantified). The exceedances measured, and the values indicated in ENA ER P27, are based on 100% rated load being applied continuously, effectively giving a maximum load risk. This is not representative of network conditions in reality. Another previous EA Technology STP project; S2148 *Re-appraisal of ACE 104*[4], explored load risk in more detail. It evaluated the effect on overhead line ratings of applying more realistic load risks, derived from actual load data and found that ratings could potentially be significantly enhanced.

However, with the increasing use of “smart” technologies and weather-dependent renewable generation (wind, solar), legacy assumptions related to network loading conditions (and their correlation with prevailing weather conditions) have become increasingly out of date and unrepresentative of today’s distribution networks.

Additionally, pressure to maximise the utilisation of existing assets continues to increase due, largely, to the continuing need to minimise the costs associated with reinforcing networks to accommodate load growth and/or new generation connections. As a result, it is becoming increasingly important that United Kingdom (UK) DNOs have an up-to-date and robust method of determining overhead line ratings for future use.

Finally, overhead power line conductor ratings are currently applied to all locations in the UK, despite regional differences in prevailing weather conditions. Thus, overhead lines in upland areas of the north of Scotland are given the same ratings as those in a sheltered low-lying area in the south of England. As such, overhead line ratings have to be planned on a worst-case scenario. It is therefore advantageous to be able to determine location-dependent ratings based on the relevant climate of a given location or type of location. Historically, the only way of doing this is to use Dynamic Line Rating (DLR) systems and these come at a significant cost and are often not wholly appropriate.

2. Scope and Objectives

2.1 Objective of project

The original Innovation Funding Initiative (IFI) FY15, funded Phase 1 project, completed the construction of a unique, purpose-built overhead power line test rig facility, to enable the Phase 2 Network Innovation Allowance (NIA) funded project to be delivered. Phase 2 of the project, utilising the overhead line Test Rig, was required to deliver the following objectives:

- **Manage Test Rig:** EA Technology effectively operated the test rig, performed maintenance and fault restoration where required throughout the twenty-four month period of operation. The Test Rig was decommissioned at the end of the twenty-four months of operation.
- **Data Collection and Validation:** which included weather conditions and co-incident temperatures of the various installed conductors at various current levels at the Test Rig for twenty-four months which has provided a new dataset for the assessment of the weather risk element of probabilistic ratings.
- **Data Analysis**: utilised the new dataset to quantify weather risk, in combination with load risks, to calculate overhead line ratings.
- **New Dataset:** supplied all collected raw, cleansed and averaged data collected over the twenty-four month test period.
- **Validate CIGRÉ:** validated an updated CIGRÉ methodology, CIGRÉ Technical Brochure TB601 "Guide for thermal rating calculations of overhead lines" (2014)[5], for calculating conductor temperature from load and weather data.
- **ENA ER P27 and ENA ACE 104**: provided an updated ENA ER P27 and ENA ACE 104.
- **Integrated Rating Software Tool**: provided a new Integrated Ratings Software Tool, incorporating the combined functionality of OHRAT and OHTEMP, the input of weather and load risk to enable static ratings and more comprehensive (regional/line specific) rating assessments to be made.

By successfully delivering the Phase 2 Network Innovation Allowance (NIA) funded project objectives, this project has the potential to have a direct impact on the network licensees' network and will meet the following Set 1 Specific Requirements of NIA:

- A novel operational practice directly related to the operation of UK Electricity Distribution Networks
  - The project will enable electricity distribution licensees to manage load on overhead lines to meet their statutory obligations, avoiding the need to invest in new assets (Dynamic Line Rating monitoring and control equipment, upgrading of lines and construction of new lines).

In addition, the project will meet all of the Set 2 Specific Requirements of NIA as outlined in Appendix III:

- Generates new knowledge that can be shared amongst all GB electricity distribution network licensees;
- Has the potential to deliver net financial benefits to existing and / or future electricity customers;
- Does not lead to unnecessary duplication.

2.2 Scope of Project

A test rig site was identified at the Western Power Distribution office/depot site at Victoria Road, Stoke-on-Trent. An aerial view of the constructed test rig site is illustrated in Figure 1.

Figure 1 Aerial view of WPD Test Rig site

The project's overhead line test rig site became operational on January 4th, 2016.

The overhead line Test Rig operated by the project utilised three sizes of conductor:

- 50mm^2 "Hazel" AAAC;
- 150mm^2 "Ash" AAAC;
- 175mm^2 "Elm" AAAC.

Three load currents, broadly representative of the three rating seasons currently employed, were chosen to give equivalent design temperatures typically in the range of 50ºC to 75ºC, encompassing the overwhelming majority of UK distribution overhead line designs. Multiple test spans allowed each test current to be applied for the full duration of the project, removing inconsistencies involved in choosing seasonal boundaries in advance.

The project utilised the Test Rig, to monitor, over a period of twenty-four months[*], the temperatures of a range of conductors subjected to a range of applied currents representative of a range of design temperatures in order to determine a robust, statistical relationship between conductor rating and the risk of a temperature excursion (exceedance), applicable to the UK distribution networks.

Additionally, the co-incident site weather parameters pertinent to conductor thermal rating calculations (ambient temperature, wind speed & direction, solar radiation) were monitored, in order to validate the updated CIGRÉ methodology for calculating conductor temperatures.

The fundamental approach originally adopted by Price and Gibbon for deriving probabilistic CEGB transmission line ratings (which is considered to be acceptable) was used in conjunction with the new temperature dataset (the original dataset now being considered inappropriate for distribution lines) in order to establish a reliable methodology for calculating distribution line ratings having known weather risks.

As noted above, the risk of a temperature exceedance is a combination of two separate risks: a weather risk and a load risk. The experimental results from this work effectively address the weather risk. This was used, together with a previous STP project[†] which addressed the load risk, in order to:

1. Develop an Integrated Ratings Software Tool with:
    a. combined functionality of OHTEMP & OHRAT
    b. batch weather data loading functionality
2. Production of a revised version of ENA ACE104 and ENA ER P27.

To fully realise the benefits of this project, the Integrated Ratings Software Tool allows for future, "desk-top" re-runs of this project to be conducted utilising weather datasets, removing the need for costly and time-consuming monitoring exercises. Achieving this functionality is in part dependent on a parallel contract between WPD and the Met Office intended to provide a Site-Specific Weather Data product appropriate to overhead line rating studies.

The size of the overhead line Test Rig was designed to allow modelling of conductor design temperatures and ratings by testing a range of conductors with differing design criterion. The duration of the project was essential to modelling the effects of the widest practically attainable range of weather conditions on different conductor sizes.

It should be noted that ratings can be much lower in sheltered areas. This project will not study this. As such, the resultant software tool to rate overhead lines will not factor in 'shelter'.

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[*] The project recorded data for twenty four months. The project did not gather data from any other source, nor has it gathered data beyond the twenty four months.

2.3 Project Progress Reporting Process

Throughout the two-year, Phase 2 NIA funded project, a quarterly reporting system (detailing general operation, project developments, concerns, risks, lessons learned, outstanding actions etc) was employed and communicated to appropriate project supporters throughout project execution. Regular teleconferences and/or face-to-face meetings were held with Sven Hoffmann (WPD) as the main Project Sponsor and Technical Advisor, which enabled frequent consultation to assist with governance of timely and cost-effective project delivery. Electronic copies of the project Quarterly Reports are available upon request.

As the quarterly reports are produced during the project, and therefore while the data analysis work was ongoing, some decisions and analysis have changed and been updated during the course of the project as would be expected with development work of this type. This final report has been produced following completion of the data analysis and therefore, for this reason, any inconsistencies with the previous reports should not be considered as a cause for concern.

3. Project Activity Schedule

Activity / Project Deliverable		Item Description	Status
1	Test-rig Running and Maintenance	Operation and Management Plan	Complete.
		Decommission Plan	Complete
2	Data Entry Checking and Validation	Data Collection and Validation Method Statement	Complete
3	Data Collection and Validation	Data Download Tool	Complete
4	Data Analysis	Data Analysis Method Statement	Complete
		Data Analysis Tool; OHRAT & OHTEMP Functionality	Complete
		Data Analysis Tool; C-T Curve Production Capability	Complete
		Data Analysis Tool; Ability to incorporate Load Duration Curve (LDC)	Removed from project scope. This was a project aim at the outset, but as the project went on it became apparent that DNOs were making increased use of Active Network Management systems, and that such systems are likely to see even greater use as DNOs transition to DSOs. As a result, any assumptions made about typical Load Duration Curves were likely to have a very short shelf life, limiting the value of incorporating them into the statistical rating calculation. It should be noted, though, that the software tool batch run feature will allow DNOs to explore the impact of different loading scenarios on line temperatures in conjunction with weather data sets.

		Validation of CIGRÉ Methodology	Complete
5	Year One	Year One Data Collection Completion	Complete
		Year One Interim Report	Complete as part of QR process
6	Year Two	Year Two Data Collection Completion	Complete
		Year Two Interim Report	Complete as part of QR process
		Update ACE104 and ENA ER P27	This report in conjunction with the project closedown report (due end September 2018) will essentially replace ACE 104. The conclusions and recommendations contained in these reports, in conjunction with the software tool (delivery imminent), will form the basis of a draft revision of P27.
		Decommission Test-rig	Complete
7	Integrated Software Tool	Specification Developed	Complete
		"Beta"/Test version of software released	Complete
		Final Release of Software	Delayed by personnel changes and unexpected operational snags, but now imminent
8	Project Conclusion	Final Project Report Complete	Issue 2 Complete

4. Overhead Line Test Rig Operation

The Overhead Line conductor test-rig was operational from January 4th, 2016 until its planned official "switch-off" date, which was 5th January 2018, but for logistical reasons, the rig was formally switched off on 15th January 2018.

During its two-year operation, the overhead line rig had been operating in a predominantly stable condition, with only a small number of issues arising. Where any operational issues had arisen, they were addressed swiftly by the EA Technology project team, with support and guidance from Project Sponsor, Sven Hoffmann, in order that any overhead line rig "downtime" would be kept to a minimum.

Remote monitoring systems, including web-cams, sensory threshold alarms and remote isolation apparatus, have been incorporated into the test-rig control system in order to attempt to prevent component failure and mitigate against unnecessary down-time.

It is also worth noting that there were no security issues with the test rig site throughout the two year operation.

The overhead line Test Rig operated by the project utilised the following three sizes of conductor and the rig construction is shown in Figure 2:

- 50mm^2 “Hazel” AAAC (alloy AL3);
- 150mm^2 “Ash” AAAC (alloy AL5);
- 175mm^2 “Elm” AAAC (alloy AL5).

The configuration of the overhead line test rig is shown in Figure 2 and an Outline Plan is given in Figure 3.

Figure 2 Conductor configurations

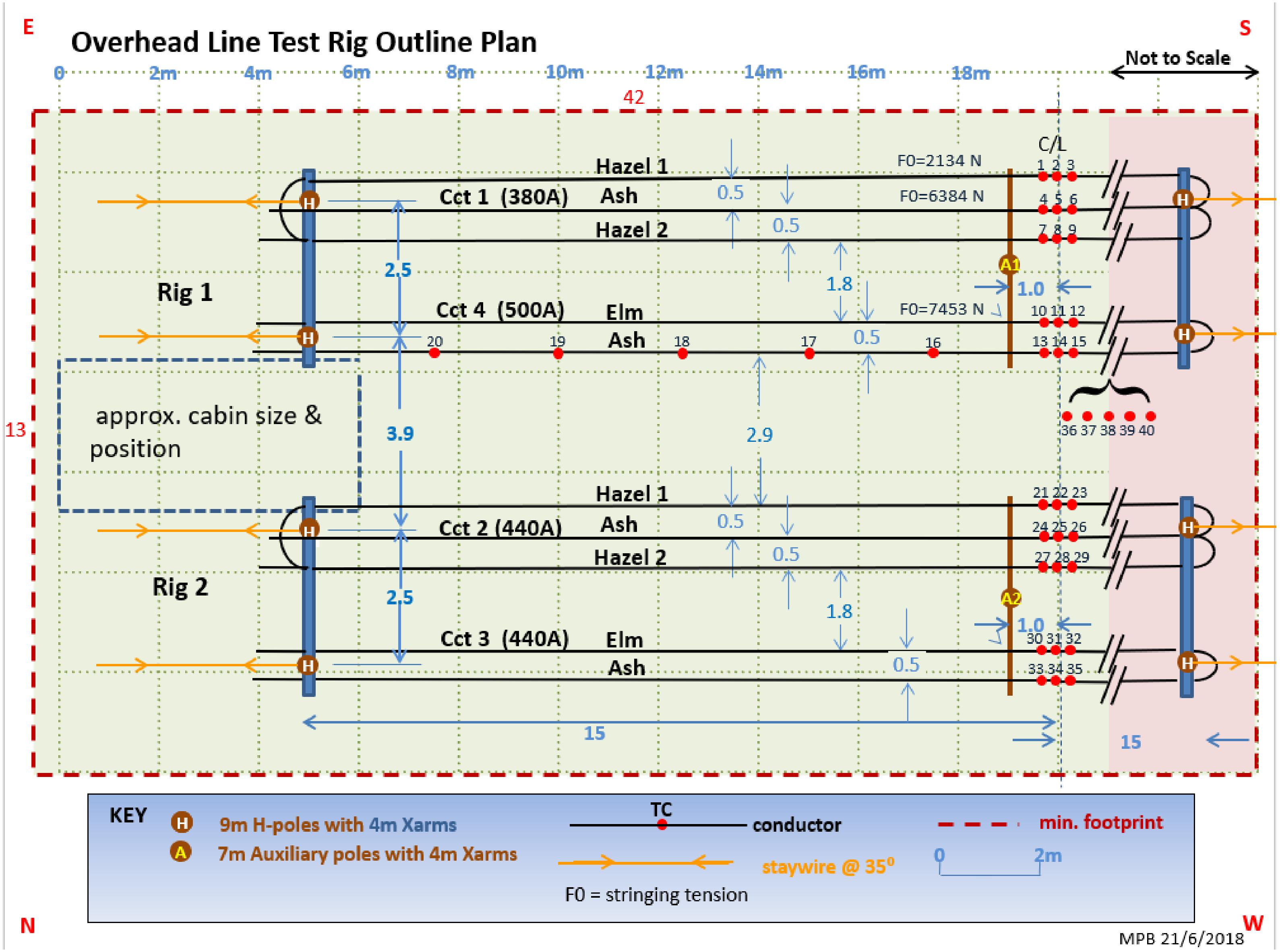


Figure 3 **Overhead line test rig plan**

4.1 Details of Overhead Line Rig Monitoring Equipment

4.1.1 Conductor Temperatures

- 30 mid-span thermocouples (plus 10 spares)
  - Three to be mounted mid-span on each of the ten conductor spans approximately 100mm apart. Three allows for detection of poor thermal connection (low reading) or failure due to electrical shorting etc. of any of the thermocouples. Fourth (unconnected) thermocouple installed alongside each trio as a spare.
  - 1mm diameter, type T (copper-constantan), stainless-steel-sheathed, insulated tip, PFA tails connected directly into logger pods mounted on mid-span auxiliary poles.
- 10 distributed thermocouples
  - Mounted along the length of Ash circuit 4 span (hottest span) at approximately 2.5 m intervals.
  - Same arrangement as above but with extended leads.

Conductor thermocouple arrangement and method of attachment is illustrated in Figure 4.

Figure 4 Conductor thermocouple installation

4.1.2 Conductor Currents

- **Primary measurement (IC1-IC4)**
  - Four AC-to-DC current transducers, one for each circuit;
  - Chenyang type CYCS11;
  - 0-510A AC input produces 0-20 mA DC output;
  - 100-ohm burden resistor on logger input converts to 0-2000mV.
- **Primary measurement (IH1-IH2)**
  - Two AC-to-DC current transducers for Hazel1 conductor in Circuits 1 & 2;
  - Smith- Hobson Minor CT 400A/5A plus LEM AP50-B420L;
  - 0-400A AC input produces 4-20 mA DC output;
  - 100-ohm burden resistor on logger input converts to 400-2000mV.
- **Secondary measurement (ICC1-ICC4)**
  - DC voltage primarily a control signal for current regulation but also monitored by logger;
  - Four AC-current to DC-voltage transducers, one for each circuit, Chenyang type CYCS11:

    ICC1-ICC3: 0-530A AC input produces 0-10 V DC output;

    ICC4: 0-660A AC input produces 0-10 V DC output.

4.1.3 Weather

- **Ambient Temperature**
  - Four sensors mounted on auxiliary poles at mid-span;
  - Two each side of rig, one at 1.25m (Met Office standard height), one at 6.0m (average height of conductors);
  - Type T thermocouples inside radiation shields.
- **Wind Speed and Direction**
  - Two ultrasonic anemometers mounted on auxiliary poles at mid-span;
  - One each side of rig at 6m (average height of conductors);
  - Aligned along conductors with “pseudo North” towards portacabin;
  - Line approx. NE-SW (actually 40 degrees) hence U = wind component towards NE, i.e. component from SW;

- Two types of anemometer, both analogue o/p:

  Rig 1 (LH looking along OHL rig from portacabin) - Gill WindMaster (3D), output = u, v & w

  Rig 2 (RH looking along OHL rig from portacabin) - Gill WindSonic (2D), output = speed and direction

Figure 5 shows the overhead line and anemometer alignments diagrammatically.

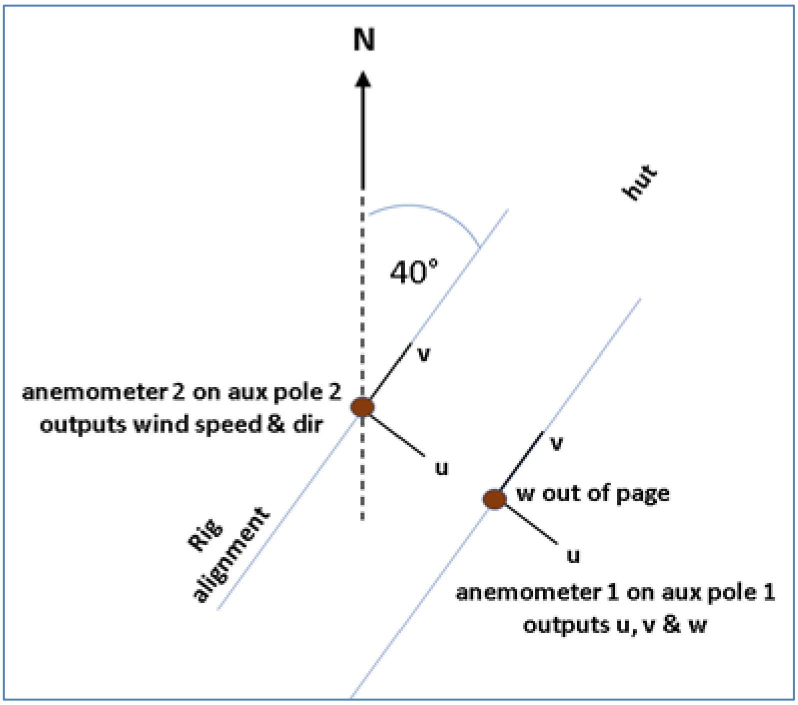


Figure 5 Diagram of overhead line & anemometer alignments

- **Solar Radiation**
  - Two pyranometers (total radiation sensors), one at portacabin-end, one at mid-span;
  - Mounted horizontally 1m above ground,
  - Kipp and Zonen CMP3
- **Rainfall**
  - Tipping-bucket rain gauge mounted about 50cm above ground at portacabin end.

An example of the weather monitoring equipment installed on freestanding, intermediate wood poles at the project site, are shown in Figure 6.

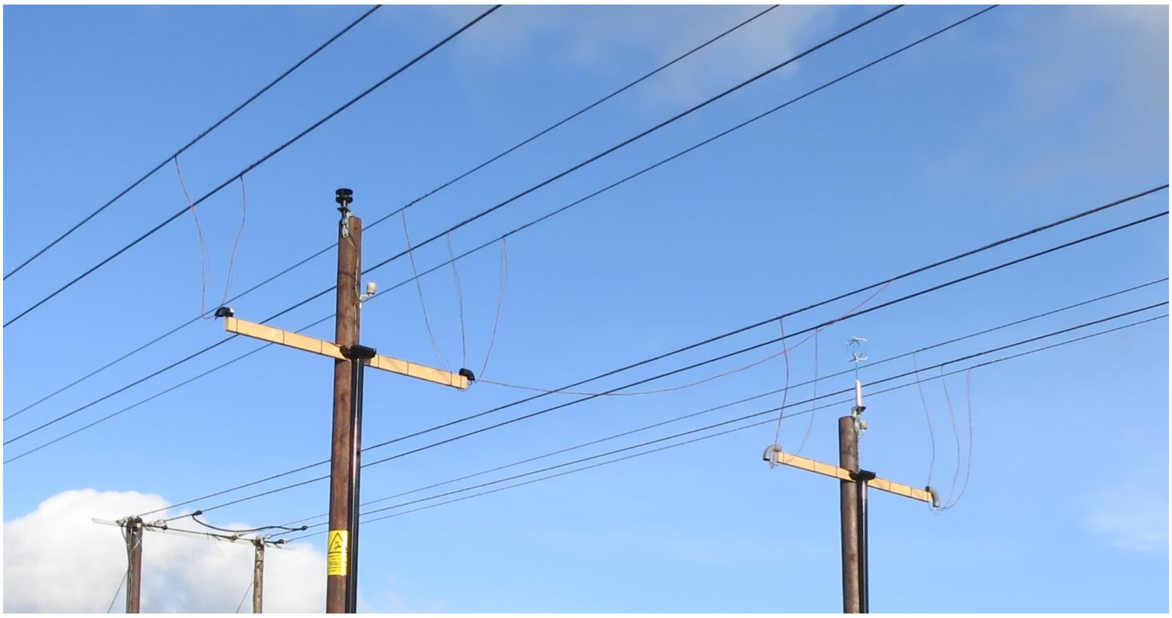


Figure 6 **Weather monitoring equipment installed on freestanding intermediate wood poles**

4.1.4 Auxiliary Temperatures

- **Monitoring to check on well-being of rig equipment**
  - Portacabin ambient air temperature at two locations – 2 off
  - PSU (power supply unit) representative surface temperature – 4 off
  - Inside air temperature of pole-mounted connection boxes – 2 off
  - Type T thermocouples

A general view of the overhead line rig operational equipment contained within the project site portacabin, is illustrated in Figure 7.

Figure 7 **Portacabin Interior – operational equipment**

Conductor thermocouples worked effectively from initial overhead line rig operation in January 2016, with only one thermocouple suspected of malfunction throughout the entire twenty-four month project, which was replaced as a precaution.

The data acquisition system worked effectively right up until the final overhead line rig switch-off in January 2018.

A back-up independent alarm and automatic trip system, incorporating an Eltek Squirrel data logger, had been installed in addition to the primary automated alarm function hard-wired into the DT-85 Datataker logging system.

All ambient sensors (i.e. temperature, wind, sunshine, rainfall) worked well throughout the entire twenty-four month project operation.

Note; a major operational incident occurred at the test rig site, WPD Stoke, at 19.14hrs on Friday 3rd June 2016. During this incident, a Power Factor Correction Unit suffered a catastrophic failure and a brief, localised, self-extinguishing fire developed within the test site porta-cabin. No personnel were on site at the time of the fire, hence there were no personal injuries and there was no operational or reputational impact to WPD from the resultant fire damage. The fire alarm panel and test-rig monitoring equipment inside the porta-cabin ensured that the automatic trip protection operated appropriately. This near catastrophic incident left a significant gap in the test rig data collection throughout the 2016 summer period.

Damage from the fire to the portacabin interior and more specifically, the Power Factor Correction Unit, can be seen in Figure 8 and Figure 9.

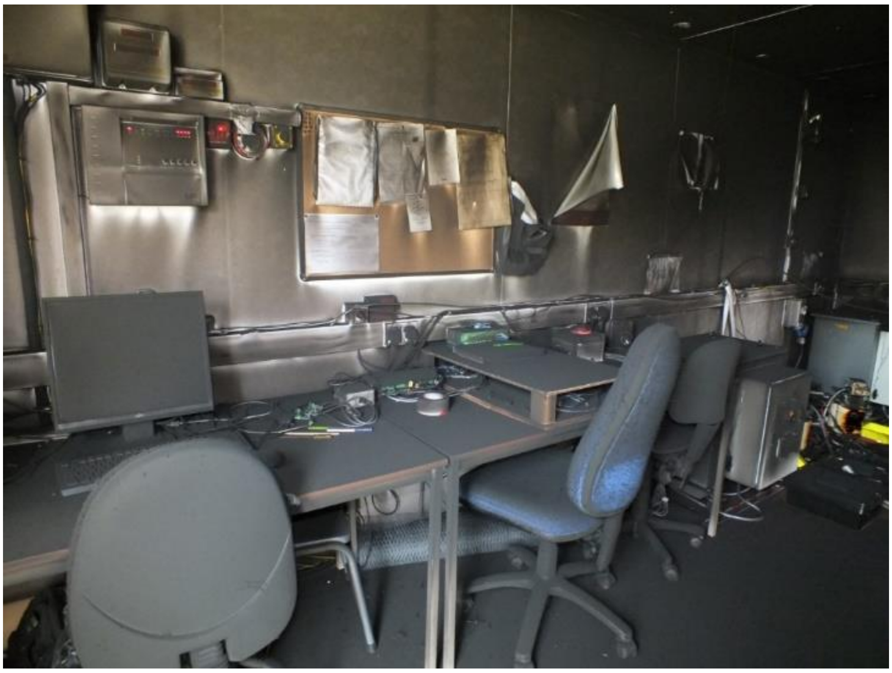


Figure 8 **Portacabin Interior post-fire**

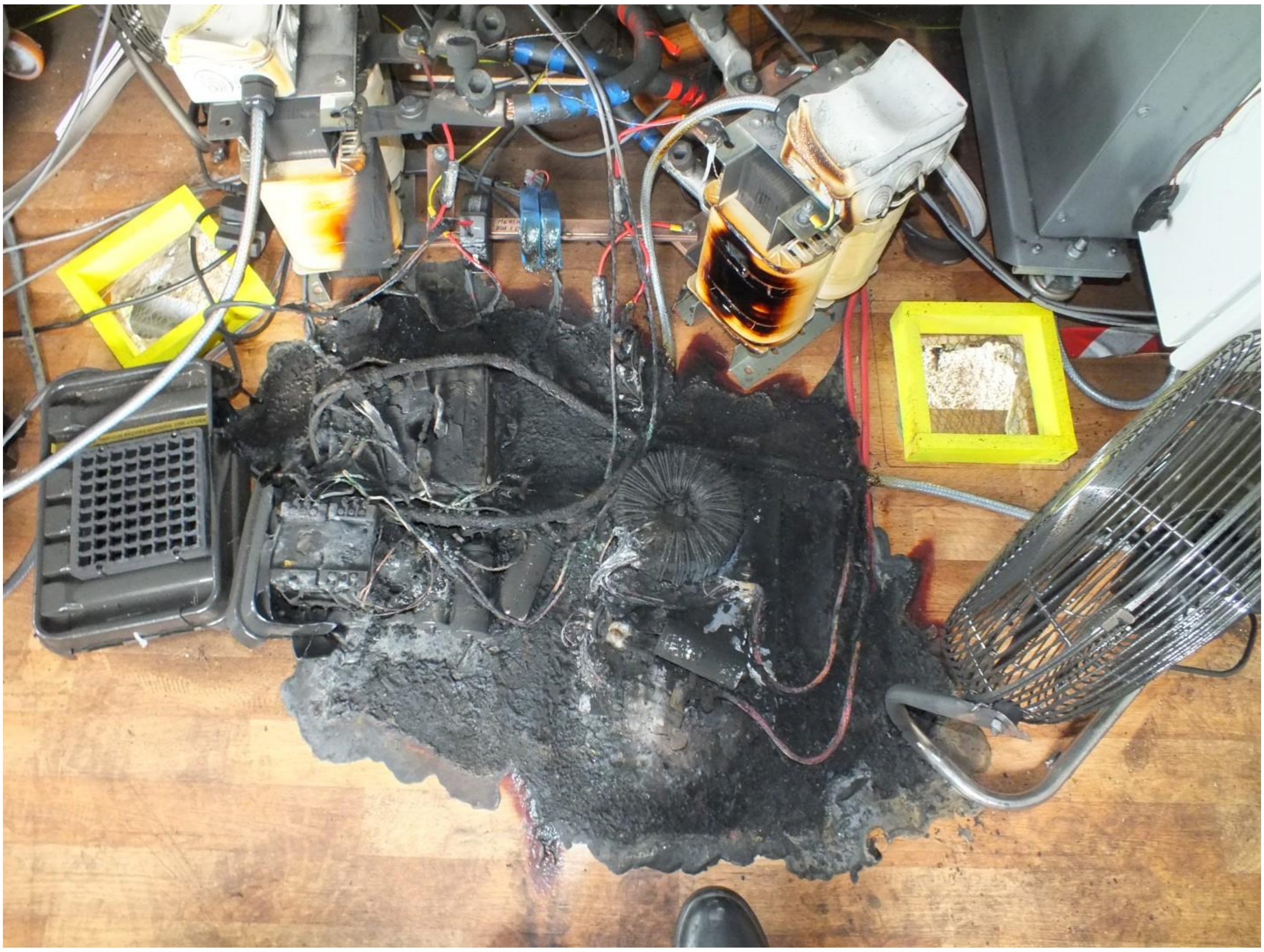


Figure 9 **Power Factor Correction Unit**

EA Technology project staff visited the test-rig site on numerous occasions during the fire reparation stage to perform clean-up operations and repairs to a variety of equipment within the porta-cabin. A number of components were removed and transported back to EA Technology's workshops at Capenhurst, for intensive cleaning and testing. The Power Factor Correction Unit enclosure was modified from the original specification and was subsequently contained within two bespoke ventilated metal enclosures, with higher rated components.

In order to prevent recurrence of a similar fire fault incident, the rig monitoring and control equipment was re-designed to reduce the likelihood of overheating:

- Two control transformers replaced the original single unit; each running well below their maximum rating.
- Plastic component enclosures were replaced with metallic alternatives.
- Air flow and powered ventilation was increased significantly, with steel flooring sections positioned beneath the majority of rig-control equipment.

The overhead line test rig was fully re-commissioned following the fire incident and logging data as of 4th August 2016.

5. Data Acquisition

5.1 Data Acquisition Summary

The Overhead Line conductor test rig was formally operational from January 4th 2016 until 5th January 2018, a period of just over two years. However, the actual running time was only about twenty-one months due to the fire in the instrumentation portacabin discussed above, which resulted in the rig's being out of action for the three months June-August 2016. EA Technology therefore obtained a complete year's dataset for 2017 (January to December) and a partial year's dataset for 2016 (January to May plus September to December, i.e. a nine-month dataset with the summer months missing.

The validated daily data comprise a minute-by-minute record of the readings of each measurement transducer (thermocouple, current transducer, anemometer etc) converted into engineering units. Each day's data were stored in the "***condat***" worksheet of the relevant CHECKDAT workbook for that day.

5.2 Parameter and Sensor Details

The data collection arrangements were as follows.

- The main parameters measured in this project were conductor temperature, conductor current, and ambient conditions. Other measurements enabled the running state of the rig to be monitored and any incipient faults to be detected and dealt with.
- The measured parameters fall into seven categories.
  - Conductor temperatures
  - Conductor currents
  - Ambient temperatures at line height and head height
  - Wind speed and direction at line height
  - Solar radiation on a horizontal surface
  - Rainfall
  - Power supply temperatures and voltages
- Measurements were made using 105 sensors of various types connected to an industrial data logger (DataTaker DT85).
- The main sensors used were:
  - Copper-constantan thermocouples (TC Ltd 1mm dia stainless steel sheath, insulated junction) for temperature measurement
    - conductor temperatures: 3 at centre of each conductor span in drilled holes (plus a 4th unconnected spare);
    - distributed conductor temperatures*: at 2.5m intervals along Ash 500 conductor
    - ambient temperatures: 2 at line height, 2 at head height;
  - Current transducers for conductor current measurement: Chenyang CYCS11;

* These distributed temperatures have not been analysed in this report.

- Ultrasonic anemometers for wind speed and direction measurement (line height 2 off):

  Gill WindMaster 3D: output = u, v and w components – speed and direction calculated by logger from u & v;

  Gill WindSonic 2D: output = speed and direction directly;
- Pyranometers for solar flux measurement: Kipp& Zonen CMP3 (2 off)
- tipping bucket rain gauge for rainfall measurement: Texas Electronics TR-525.

Table 1 summarises the above parameter and sensor details.

Table 1 Details of Parameters logged every minute

Parameter	Sensor	Model	Duplication	Units	Scan Frequency	Averaging Period
Conductor Temperature	Cu-Con T/C (St St sheath)	TC Ltd	3	degC	1 min	n/a
Conductor Current	Current Transducer	Chenyang CYCS11	2	Amps	15 sec	1 min
Ambient Temperature	Cu-Con T/C (St St sheath)	TC Ltd	2	degC	1 min	n/a
Wind Speed	Ultra Sonic Anemometer	Gill WindMaster Gill WindSonic	2	m/s	15 sec	1 min
Wind Direction*				deg	15 sec	n/a
Sunshine	Pyranometer	Kipp & Zonen CMP3	2	W/m^2 on horiz surface	15 sec	1 min
Rainfall	Tipping Bucket	Texas Electronics TR-525		mm/min	1 min	cumulative (reset hourly)

5.3 Logger Processes

The data logger carried out a complex scanning and logging programme at 15-second, 1-minute and 24-hour intervals:

1) Basic scanning, averaging and logging

   - "Driving" parameters (currents, voltages, wind speed and direction, and sunshine) were measured every 15 seconds from which 1-minute averages were calculated and logged.
   - "Dependent" parameters (conductor temperatures) and all other temperatures were measured and logged just once a minute since they did not change rapidly enough to warrant 15-second scanning.

* Cannot simply average wind direction because averaging North-plus-x (=x) and North-minus-x (=360-x) gives 180 i.e. South). But can average the "attack angle", the acute angle that the wind direction makes with the conductor (always between 0 and 90), and this is the important quantity.

- The number of tips of the rain gauge was measured once a minute but its readings were aggregated over an hour, with both minute and hourly readings logged. (Note that the rain data were not actually used in the analysis.)

2) Limited processing of various signals before logging them:
   - conversion of measured voltages into Engineering units
   - calculated wind speeds and directions from component wind speed data of 3D anemometer, and vice versa for 2D anemometer data
   - calculated "wind attack" angles on the conductor (see above).
3) Downloading its processed data each day (at 06:00) to a daily csv file. This was then copied into the "rawdat" sheet of a daily Excel file (CHECKDAT) where they were checked and processed and then stored in the "condat" worksheet of the CHECKDAT file.

Table 2 summarises the above logger details. An example of a daily CHECKDAT file (for 3rd March 2017) can be found in Appendix I.

Table 2 Details of Data Logger Processing

Function	Process	Parameters	Scan Frequency	Logging Frequency
Basic logging and averaging	"Driving" Parameters	Currents, voltages, wind speeds & directions, sunshine	15 sec	1 min
	"Dependent" Parameters	Temperatures	1 min	1 min
	Rain gauge	Rain in last/min	1 min	1 min
		Rain in last hour	1 min	1 min
Basic processing	Conversion to Engineering units		1 min	
	Calculation of wind speeds, directions and attack angles		15 sec	1 min
Daily download	Download to daily CHECKDAT file		1 min	daily (06:00)

5.4 Data Acquisition Problems

Various data acquisition problems arose during the two years the rig was running:

- Occasional unexplained logger glitches - dealt with by deleting the suspect row in *condat*, plus one row either side of it.
- Occasional unexplained glitches in the 3D anemometer (WindMaster) readings - did not generally result in any loss of data rows because we still had the 2D WindSonic readings. Neither replacing the WindMaster with a similar instrument, nor replacing the cable connection between anemometer and logger completely cured the problem.

- The 30 conductor temperature thermocouples, deployed in trios at the mid-point of each of the 10 conductor spans, worked effectively, with one exception, throughout. The one exception was TC21, on conductor 22H1 (rig 2 circuit 2 Hazel 1), which began behaving erratically on 23rd November 2017 during high-wind conditions. It was replaced on 5 December by the back-up spare thermocouple on that conductor, 22H1S.
- One of the four ambient temperature thermocouples, TC43, failed on 9th October 2017. Subsequently, ambient temperature at line height was taken to be simply the TC41 reading rather than average of TC41 & TC43.

5.5 Compilation of the Cleansed Dataset

The Cleansed Dataset comprises a concatenation of the daily data files, suitably cleansed and processed, into monthly blocks. Significant effort was expended to ensure the "cleanliness" of the concatenated data.

The daily csv files downloaded from the logger were each copied into the "rawdat" worksheet of a daily Excel spreadsheet workbook file (CHECKDAT), where they were checked and processed to produce the "condat" worksheet of the CHECKDAT file ("condat" = converted data). Minute-by-minute time plots of all the "condat" data were also produced in a series of worksheets within CHECKDAT, enabling a quick visual check to be made of each day's data.

An example of a daily CHECKDAT file (for 3rd March 2017) showing these worksheets can be found in Appendix I.

The daily CHECKDAT data files were automatically corrected for logger and anemometer glitches using an automated version AUTOCHECKDAT*. They were then manually inspected and further cleansed and corrected if necessary. Details of this process were recorded in each AUTOCHECKDAT file in a line or two of notes and comments for each day.

Table 3 shows the daily notes for November 2017 as an example.

Figure 10 summarises the processing and cleansing of the daily data.

* Automated data validation software based on a data-checking-and-visualisation Excel workbook (AUTOCHECKDAT) processed the automatic daily data downloads and validated the integrity of the data. Parameters that showed up any malfunctioning of either the datalogger or instrumentation were evaluated and any variation from set values was notified to relevant personnel via email. The daily values of these integrity parameters (which were a mixture of daily totals, daily averages and daily max or min values) were automatically recorded as a row in a monthly output table (one row per day), which featured conditional colouring based on how close a parameter was to its set value. This OUTPUT TABLE (another Excel spreadsheet) provided a visual monthly record of the data gathering process.

Table 3 Example notes on cleansing and correction of daily data for (November 2017)

Filename	Issue & Action Taken
November 2017	
26n_v38c 2017-11-01cn	OK
26n_v38c 2017-11-02cn	OK
26n_v38c 2017-11-03cn	OK
26n_v38c 2017-11-04cn	OK
26n_v38c 2017-11-05cn	OK
26n_v38c 2017-11-06cr	1 WMaster Glitch 1104. Deleted 11:03-05 data in condat.
26n_v38c 2017-11-07cn	OK
26n_v38c 2017-11-08cn	OK
26n_v38c 2017-11-09cn	OK
26n_v38c 2017-11-10cn	OK
26n_v38c 2017-11-11cn	OK
26n_v38c 2017-11-12cn	OK
26n_v38c 2017-11-13cn	OK
26n_v38c 2017-11-14cn	OK
26n_v38c 2017-11-15cn	OK
26n_v38c 2017-11-16cn	OK
26n_v38c 2017-11-17cn	OK. WMaster glitch at 1102 also on WSonic so likely a gust: reinstated auto-deleted data.
26n_v38c 2017-11-18cn	OK
26n_v38c 2017-11-19cn	OK
26n_v38c 2017-11-20cn	OK
26n_v38c 2017-11-21cr	1 WMaster glitch 0237-0241 (5 rows).
26n_v38c 2017-11-22cn	OK
26n_v38c 2017-11-23cr	TC21 started misreading in high wind. -0.1 at 1627. Deleted TC21 from 1539-2317 in condat.
	Logger & WMaster OK
26n_v38c 2017-11-24cn	OK
26n_v38c 2017-11-25cn	OK
26n_v38c 2017-11-26cn	OK
26n_v38c 2017-11-27cr	TC21 glitching high & low from 1909 to 0254. Deleted TC21 from 1909 to 0254 in condat.
26n_v38c 2017-11-27c	2 WMaster Glitches (6 rows).
26n_v38c 2017-11-28cr	TC21 glitching hgh & low during 0707 to 1419. Deleted TC21 from 0707 to 1419 in condat.
	Logger & WMaster OK
26n_v38c 2017-11-29cn	OK
26n_v38c 2017-11-30cn	OK

(Data Download\5. auto check data\Outputs\2017\2017-notes)

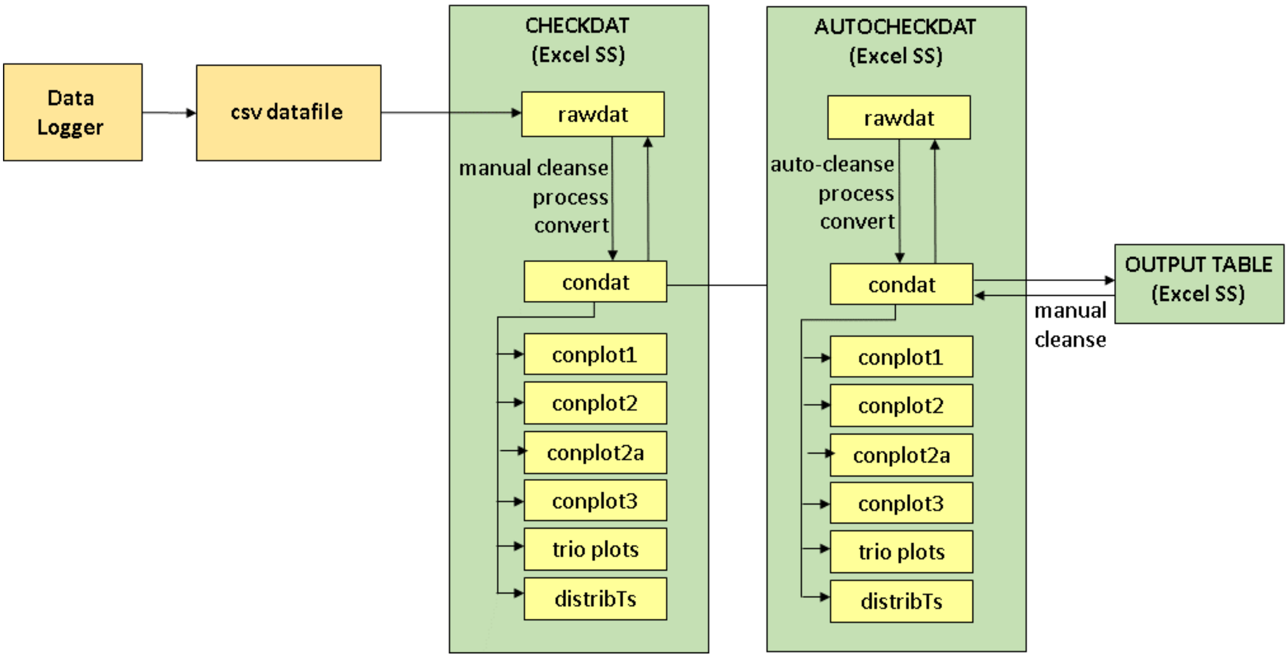


Figure 10 **Flowchart of data handling process to produce cleansed daily datafiles**

The cleansed daily data files required some additional data processing before concatenation since many of the measuring instruments were duplicated or triplicated in order to provide redundancy in the event of a malfunction. For these parameters, the obvious "best" value was usually the mean of the two or three readings.

Initially, it was thought that the conductor thermocouple trios might be an exception to this "best" value is the mean, since in previous work it had been found that if one of the trio read particularly low, it was often an indication of poor thermal contact between that thermocouple and the conductor. The maximum of the trio had therefore been deemed to be the most appropriate value to choose. However, in the present project, the trio means appeared to give better agreement with the values calculated using the Cigré equations than do the trio maxima, so with the present data, the trio means will be used for the conductor thermocouples too.

The parameters for which average values needed to be determined are shown in Table 4 .

Table 4 **Parameters for which an average value needs to be determined during concatenation**

	Parameter	Sensors
Tcon	conductor temperatures	trios of thermocouples
Tamb	ambient temperature (at line height)	pair of thermocouples (only 1 from 9-11-2017)
Wspd	wind speed (at line height)	WindMaster & WindSonic ultrasonic anemometers (only WindSonic during WindMaster glitches)
Waa	wind attack angle	*same as for Wspd*
Sol	solar insolation	pair of solarimeters

Finally, the averaged cleansed daily data files were concatenated into monthly cleansed data files to produce the **final cleansed dataset.** Details of the concatenation process are summarised below and have also been supplied to the Project Sponsor as an adjunct to the cleansed data set.

Four Python programs (P1-P4) were used to carry out the concatenation process:

P1. Excel to CSV

Concatenation of the daily data into monthly Excel spreadsheets would have produced files that were too large to work with (43200 rows of 50 columns of data), so the daily ***condat*** sheets were first converted to smaller and easier-to-work-with CSV files.

P2. Monthly Concatenation

All the daily CSV files for a particular month were concatenated and their multiple readings processed to give average or maximum values as follows:

- mid-span conductor temperatures (TC1-TC15, TC21-TC35) ➔ average and maximum value of thermocouple trios;
- distributed conductor temperatures (TC16-TC20 and TC36-TC40) ➔ individual measured values;
- conductor currents
  - Ash & Elm currents (IC1-IC4) ➔ measured values,
  - Hazel currents (I11H1, I11H2, I22H1 and I22H2) ➔ calculated from IC1 and IC2;
- ambient temperatures at line-height & head height (Tamb) ➔ each an average of two measured values;
- wind parameters
  - horizontal wind speed, direction and attack angle (WS, WD & WAA) ➔ average of two anemometers,
  - vertical wind speed (WS1W) ➔ single anemometer value;
- solar radiation ➔ greater of two horizontal pyranometer readings;
- hourly aggregate rainfall ➔ single value. (incremental readings in version concat2a)

P3. Graphs

An overview of each month's data is provided by three sets of graphs produced from the monthly CSV files. These can be found in the ***Tplots, Iplots*** and ***Ambplots*** sheets of the ***concat4*** workbook (not to be confused with the ***condat*** sheet in the CHECKDAT workbook) and provided a quick means of checking the data during the cleansing process.

- ***Tplots*** contains two sets of four graphs (one for each circuit) of mid-span conductor temperatures and a fifth graph showing the distributed thermocouple temperatures. One of the sets of four shows trio averages, the other shows trio maxima. Each graph contains 2 or 3 plots, one for each of the conductors in the relevant circuit.
- ***Iplots*** shows the eight different conductor currents.
- ***Ambplots*** contains four sets of graphs
  - one for horizontal and vertical wind speeds
  - one for wind direction and attack angle
  - one for the two ambient temperatures (line-height and head-height),
  - one for the solar radiation and rainfall

P4. Final Spreadsheet

This program produces the final Excel spreadsheet for each month. The spreadsheet includes the data from the monthly csv files, all the graphs produced in step P3, and a notes page.

The concatenated files are split into two versions – see Table 5. Version 4a covers data obtained prior to the 11th May 2017 and version 4b covers data obtained after 11th May 2017. The two versions are necessary because of the relocation on 11th May of the portacabin-end solarimeter, solh2, to the outer H-pole to avoid shadows. Prior to this, version 4a sets sol equal to the **higher of two solarimeter readin**gs but after the move, version 4b sets sol equal to the **average of the two solarimeter readings**.

Table 5 List of files making up the Final Cleansed Dataset

concat4a 2016-01	concat4a 2017-01
concat4a 2016-02	concat4a 2017-02
concat4a 2016-03	concat4a 2017-03
concat4a 2016-04	concat4a 2017-04
concat4a 2016-05	concat4a (until 10th) 2017-05
concat4a 2016-06 (until 4th)	concat4b (from 11th) 2017-05
	concat4b 2017-06
	concat4b 2017-07
	concat4b 2017-08
concat4a 2016-09	concat4b 2017-09
concat4a 2016-10	concat4b 2017-10
concat4a 2016-11	concat4b 2017-11
concat4a 2016-12	concat4b 2017-12

Dataset\concatenated data (months)

6. Calculated Conductor Temperatures

6.1 Steady state heat balance

The thermal state of an overhead conductor depends on prevailing ambient weather parameters such as wind speed and direction, ambient temperature and solar flux, and on the electrical current flowing through it. Assuming that all these parameters remain fairly constant over time, the conductor can be considered in a “steady state” with both the current and temperature constant. In this situation, the heat supplied primarily by resistive heating (often referred to as Joule heating) and solar gain is equal to the heat dissipated primarily by convection and radiation to the surrounding atmosphere. With steel core conductors, magnetic heating of the core may also be significant.

The basic heat balance equation is:

$$Pj + Ps + Pm = Pc + Pr$$

where the three terms on the left are heat inputs (Joule, solar and magnetic), and the two on the right are heat losses (convective cooling and radiative cooling).

Cigré TB601 aims to provides all the equations necessary to calculate the core temperature of an overhead line carrying a specified current under specified ambient conditions. It also provides equations for calculating design values to use for determining the corresponding deterministic ratings. These equations have been used to produce revised versions of the OHTEMP and OHRAT spreadsheets (OHTEMP2 and OHRAT5) which in turn form the basis of the software package delivered by this project. (The original OHTEMP and OHRAT spreadsheets were based on earlier Cigré publications.)

Hereafter in this Section, the name OHTEMP2 will be used as the generic name for the new algorithms in OHTEMP2, OHRAT5 and the software package.

Not all the algorithms given in TB601 have been used in OHTEMP2. Some contain serious errors (solar heating) and are inappropriate anyway (minute-by-minute estimates of solar heating), and some contain suspected errors and are too complicated to easily correct (magnetic heating). The basis of the actual calculations used for each parameter are given below:

6.1.1 Joule heating including skin-effect (Pj)

The Joule heating calculation in OHTEMP2 is the same as in Section 3.1 of TB601. It is basically the I^2R heating due to the current but takes into account the AC "skin effect". The latter is the tendency of AC current to preferentially flow along the surface of a conductor: this causes the current density to fall off with depth (distance from the conductor surface), which effectively increases the resistance of the conductor.

The conductor's DC resistance at temperature T is calculated from the 20°C value using linear and quadratic temperature coefficients (the quadratic correction is very small for temperatures below 130°C).

The skin-effect factor is calculated using the simplified Bessel-function method described in Annex A Section A.2 of TB601 for all except ACSR conductors. For ACSR, Price's AC1 is used instead (see Magnetic Heating below).

6.1.2 Magnetic heating (Pm)

For steel-cored conductors such as ACSR, the alternating magnetic flux causes heating in the steel core and a redistribution of current between the conductor layers leading to further heating. This magnetic heating may be significant at high current densities in certain ACSR conductors.

The calculation of Pm in TB601 Section 3.2 and Annex B is quite complicated and confusing. This, coupled with the fact that TB601 states that Pm is generally negligible, led to a joint decision with the project champion that OHTEMP2 would retain the empirical approach to magnetic heating in ACSR conductors devised by Price and Gibbon[6],[7] that was used in earlier versions of OHTEMP & OHRAT. This derives two factors, AC1 (the skin depth – see above) and AC2 (a function of Pm) and these are used as multipliers to produce an effective AC resistance.

Note: some conductor manufacturers include these magnetic effects in an effective AC resistance, in which case, magnetic heating calculations will not be required. Input values for conductor resistance in OHTEMP should therefore always be the DC values.

6.1.3 Solar heating (Ps)

For one-off calculations with OHTEMP2, incident solar flux is an input variable specified by the user. This can be a measured value or a single reference value such as zero (as in the original OHRAT which was designed to reproduce the original probabilistic P27 ratings), or 980 W/m2 (as in Cigré Technical Brochure 207[6] which used the maximum likely solar flux for estimating the worst-case).

For batch calculations, measured (or simulated measured) values for each row of input data are required.

In principle, the solar heating algorithm in Section 3.3 of TB601 allows one to estimate the maximum solar flux (clear sky) that is incident on a conductor at any time of day for any date at any location. Unfortunately, the algorithm contains several significant errors, making it unusable. Together with the chairman of the TB601 Working Group, one of us (MPB) has spent a lot of time trying to produce a corrected version but there still seems to be a magnitude problem and there is no funding to look into it further.

6.1.4 Conductor temperature distribution

The heat generated in the internal layers of the conductor is transported to the outermost layer by means of conduction, convection and radiation. This heat transfer depends on a number of variables which are very difficult to assess: strand contact area, contact pressure between layers, degree of corrosion of the strands, air voids (interstices), air gaps between strands.

OHTEMP2 uses the simplified equations for radial temperature variation given in TB601 Section 3.4.

TB601 notes that for these simplified equations, the effective radial thermal conductivity is the key factor. It suggests that this can lie in the range from 0.5 W/m·K to 7 W/m·K but does not recommend any particular value. OHTEMP2 therefore follows the recommendation of the earlier Cigré Technical Brochure TB207, and uses a mean value of 2 W/m·K.

6.1.5 Convective cooling (Pc)

Convection is almost always the most important factor for cooling overhead conductors, even for still air conditions (zero wind speed). Conductor temperatures can only be high when convective cooling is low. Hence, for thermal rating purposes, the focus is on situations where wind speed is low or zero. Two types of convection need to be considered: natural convection, which occurs when wind speed is zero; and forced convection, which depends on wind speed and direction relative to the line. At moderate-to-high wind speeds, forced convection dominates and natural convection can be ignored. At low wind speeds, natural convection may have a significant effect, becoming the dominant convection mechanism at very low wind speeds.

The convection calculations are complicated and are covered in great detail in TB601 Section 3.5 and Appendix C.

The convective cooling algorithm in OHTEMP2 is the same as that given in Section 3.5 of TB601.

6.1.6 Radiative cooling (Pr)

The radiative cooling calculation in OHTEMP2 is straightforward and is the same as that given in Section 3.6 of TB601.

6.2 Validation of CIGRÉ Equations - Comparison of Measured and Calculated Conductor Temperatures

6.2.1 Initial Single-Day Comparison

A comparison of the measured conductor temperatures with the values calculated from the measured weather data using OHTEMP2 was carried out on a limited scale for all the conductors and the initial results were promising. A relatively "high-temperature day" was selected, namely 29-30 Oct 2016, when the hottest conductor, Ash 500 (14A), reached 78°C. The measured and calculated values for each conductor were compared every minute of the day and the average difference determined.

Comparisons were carried out using both the trio means (the mean of the readings of the three thermocouples mounted on each conductor) and the trio maxima (the maximum of the three readings).

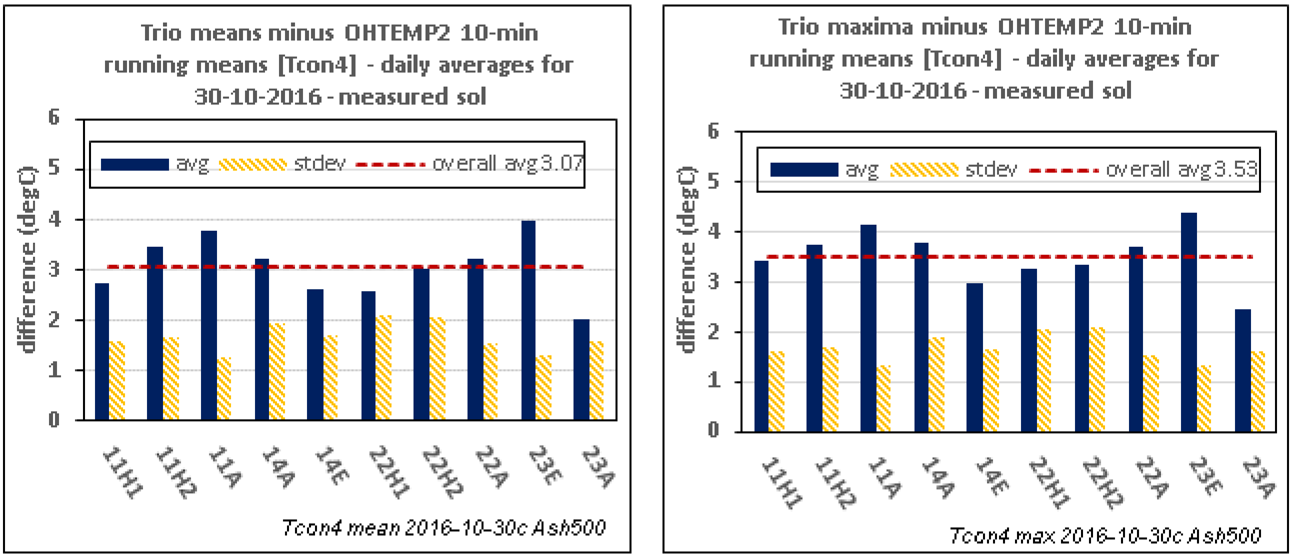
It was found that

a) The calculated temperatures fluctuated much faster than the measured ones, presumably because a conductor's response to fluctuations in wind speed and direction is constrained by its thermal time constant which is of the order of 10 minutes.

b) Hence, better overall agreement was obtained if a 10-minute running mean was used for the calculated values.

c) Using delayed measured values rather than instantaneous ones had little effect.

Figure 11 shows the daily averages of the differences obtained for each conductor using 10-minute running means for the calculated values and either (a) the trio means or (b) the trio maxima for the measured values.



(a) trio means *(b) trio maxima*

Figure 11 **Difference between measured conductor temperatures and values calculated using OHTEMP2 (CIGRÉ 2014 equations) for a "high-temperature day" (29-30 October 2016)**

From the graphs we can see that

a) Measured values are generally between 2 and 4 degC higher than the calculated values.
b) Trio means give rather better agreement than trio maxima (overall averages 3.07 and 3.53 degC respectively).
c) For the hottest conductor, 14A (i.e. Ash 500), the average differences are
   - trio means 3.2 ± 2.0
   - trio maxima 3.8 ± 1.9

where the ± figure is the standard deviation.

Figure 12 shows the raw (1-minute) difference data behind these average values. It indicates that for a particular conductor (Ash 500) on a particular day, the difference between measured conductor temperatures and 10-minute mean values calculated using OHTEMP2 ranged from -3 to +9 degrees.

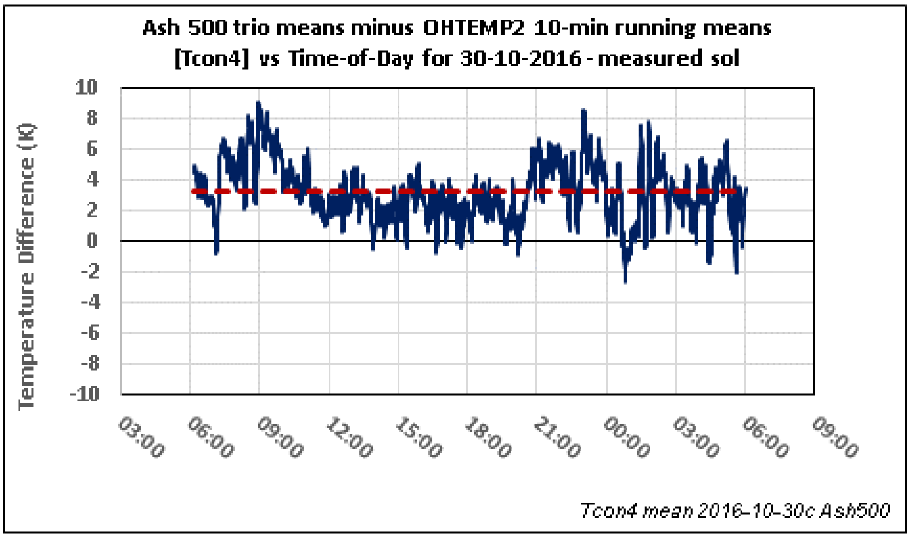


Figure 12 **: 1-minute temperature difference (trio means minus calculated 10-minute running means) for the hottest conductor (Ash500) on a "high-temperature day" (29-30 October 2016)**

6.2.2 Month-by-Month Hot-Day Comparison (21 months)

The above analysis was repeated for a selected day in each month. The selected day was the one when conductor temperatures were highest for that month. The measured and calculated temperatures for each of the 10 conductor-current combinations conductor were compared every minute of the day and the average difference determined.

Comparisons were carried out using both the trio means (the mean of the readings of the three thermocouples mounted on each conductor) and the trio maxima (the maximum of the three readings) as the measured values. Trio means were consistently found to give better agreement than trio maxima.

Calculated temperatures were obtained using three different values of solar flux:

a) TB601 solar equations for solar flux
b) measured solar flux on a horizontal surface
c) zero solar flux (as in P27 and OHRAT1).

The "best" results, i.e. those for trio means, 10-minute running means and measured solar flux are given below in Table 6 for 2016 and Table 7 for 2017. The overall mean difference for 2016 was 3.64 ± 1.34°C whilst for 2017, it was 3.43 ± 1.75°C.

It is worth noting that in Table 7, the last two months, November and December 2017, give significantly higher differences than any other months in that year, i.e. average differences of 6.37˚C and 7.39˚C compared with a maximum value for January to October of 4.33˚C. A similar anomaly can be seen in Table 6, in the January 2016 results.

A possible cause for these anomalously large differences was that on the selected "hot day" for the months concerned, there were early morning periods when windspeed was low and temperatures were around freezing. Figure 13 shows the difference between trio means and conductor temperature 10-minute running means for Ash 500 calculated using 1-minute measured windspeeds for the chosen hot November day, 7th Nov 2017. Also shown are measured windspeeds and measured ambient temperatures at line height.

Table 6 Measured trio means vs calculated conductor temperatures (using measured solar flux) – 2016 hot days

2016 Trio means minus calculated values with 10-min running mean (calculated values use measured solar flux on a horizontal plane) Average differences over hottest day of each month											
2016	**20-Jan**	**27-Feb**	**13-Mar**	**14-Apr**	**27-May**	**03-Jun**	**21-Sep**	**30-Oct**	**16-Nov**	**19-Dec**	**mean**	**st dev**
11H1	5.37	3.16	3.67	2.98	4.17	2.01	3.74	2.76	1.87	4.12	**3.39**	**1.06**
11A	6.82	3.79	5.05	3.82	5.08	3.34	4.47	3.80	2.36	4.90	**4.34**	**1.22**
11H2	6.16	3.61	4.15	3.32	4.24	2.60	3.98	3.47	2.44	4.68	**3.86**	**1.07**
14E	6.27	3.76	3.61	2.80	4.10	2.01	4.39	2.62	1.63	4.43	**3.56**	**1.36**
14A	7.56	3.00	4.11	2.27	3.97	1.30	4.26	3.22	1.73	5.29	**3.67**	**1.84**
22H1	4.72	2.75	2.14	1.54	2.72	0.43	3.58	2.60	1.40	3.45	**2.53**	**1.23**
22A	6.95	3.42	4.43	3.02	4.66	2.60	4.36	3.21	2.07	4.64	**3.93**	**1.39**
22H2	6.08	3.32	3.21	2.42	4.08	1.60	3.82	3.03	1.78	4.04	**3.34**	**1.30**
23E	6.91	3.92	5.03	3.96	5.49	3.91	5.31	3.97	2.99	5.97	**4.75**	**1.19**
23A	5.83	2.63	3.43	2.09	3.74	1.72	3.55	2.02	1.14	4.05	**3.02**	**1.38**
mean	**6.27**	**3.34**	**3.88**	**2.82**	**4.22**	**2.15**	**4.15**	**3.07**	**1.94**	**4.56**	**3.64**	**1.27**
st dev	**0.84**	**0.45**	**0.88**	**0.76**	**0.75**	**1.01**	**0.53**	**0.59**	**0.54**	**0.72**	**0.64**	**1.34**

2016 Tcon4 Solar Comparison Summary

Table 7 Measured trio means vs calculated conductor temperatures (using measured solar flux) – 2017 hot days

2017 Trio means minus calculated values with 10-min running mean (calculated values use measured solar flux on a horizontal plane) Average differences over hottest day of each month													
2017	**08-Jan**	**06-Feb**	**25-Mar**	**20-Apr**	**24-May**	**20-Jun**	**09-Jul**	**28-Aug**	**26-Sep**	**09-Oct**	**07-Nov**	**21-Dec**	**mean**	**st dev**
11H1	2.58	2.95	1.66	2.24	2.37	1.85	2.27	2.34	3.35	4.17	5.38	6.61	**3.15**	**1.51**
11A	3.21	4.13	2.58	3.22	2.95	2.45	2.82	3.01	3.63	4.39	6.33	6.54	**3.77**	**1.37**
11H2	2.92	3.50	2.29	2.24	2.61	2.06	2.50	2.56	3.60	4.47	6.06	7.18	**3.50**	**1.63**
14E	2.84	3.38	2.00	2.33	2.23	2.15	2.27	2.05	3.27	4.06	7.03	7.14	**3.40**	**1.84**
14A	2.67	3.67	1.81	2.62	2.22	1.69	2.23	2.97	4.17	5.16	8.04	9.22	**3.87**	**2.45**
22H1	2.18	2.06	1.12	2.43	1.75	1.08	1.64	1.36	3.15	4.03	5.70	7.79	**2.86**	**2.05**
22A	2.94	3.73	2.25	2.70	2.36	1.86	2.22	2.51	3.65	4.30	6.68	7.38	**3.55**	**1.78**
22H2	2.33	2.49	1.46	2.17	2.14	1.34	1.94	1.74	3.53	4.28	5.97	7.87	**3.10**	**2.01**
23E	3.87	5.15	3.30	3.71	3.54	2.96	3.52	3.79	4.75	5.16	6.79	7.80	**4.53**	**1.48**
23A	2.24	2.84	1.37	1.73	1.72	1.14	1.49	1.00	2.53	3.29	5.72	6.32	**2.62**	**1.74**
mean	**2.78**	**3.39**	**1.98**	**2.54**	**2.39**	**1.86**	**2.29**	**2.33**	**3.56**	**4.33**	**6.37**	**7.39**	**3.43**	**1.77**
st dev	**0.51**	**0.88**	**0.65**	**0.57**	**0.54**	**0.59**	**0.58**	**0.83**	**0.59**	**0.54**	**0.79**	**0.85**	**0.55**	**1.75**

Tcon4 2017 Solar Comparison Summary

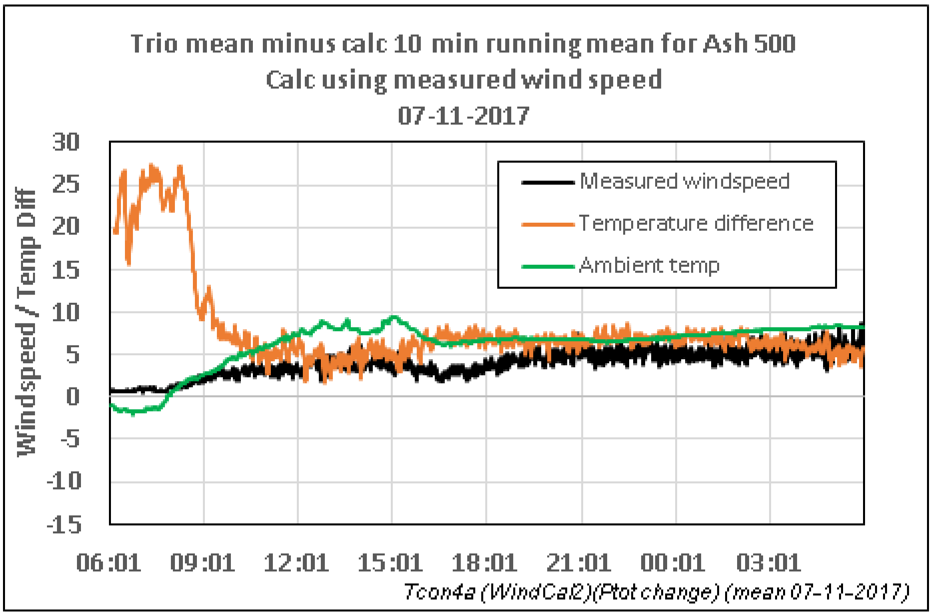


Figure 13 Trio means minus calculated conductor temperatures (orange) for Ash 500, measured windspeeds (black) and ambient temperatures at line height (green) 7th Nov 2017

It is apparent that for the first 2½ hours of the day, the difference between measured and calculated conductor temperature is an enormous 20-25 degrees and this coincides with a steady windspeed of about 0.5m/s and an ambient temperature of about minus 2°C. It is notoriously difficult to determine conductor heat loss under such conditions and it is a topic of much debate (it is much discussed in Cigré TB601).

6.2.3 Frequency Distribution of Conductor Temperatures (Ash 500)

To get the full picture of how the calculated temperatures compare with the measured ones, we should consider not only the average differences (as above) but also the frequency distributions of the two sets of data (measured and calculated).

Frequency distributions were obtained for a complete season, summer 2017 (three months, June-August) again for the hottest conductor Ash 500, and again the calculated values were 10-minute running means. Various bin sizes were tried, ranging from 1K to 10K, and a bin size of 2K was found to be the optimum; the results are shown in Figure 14.

The two curves are quite similar, but there is a noticeable displacement between them, with the measured values shifted towards higher temperatures.

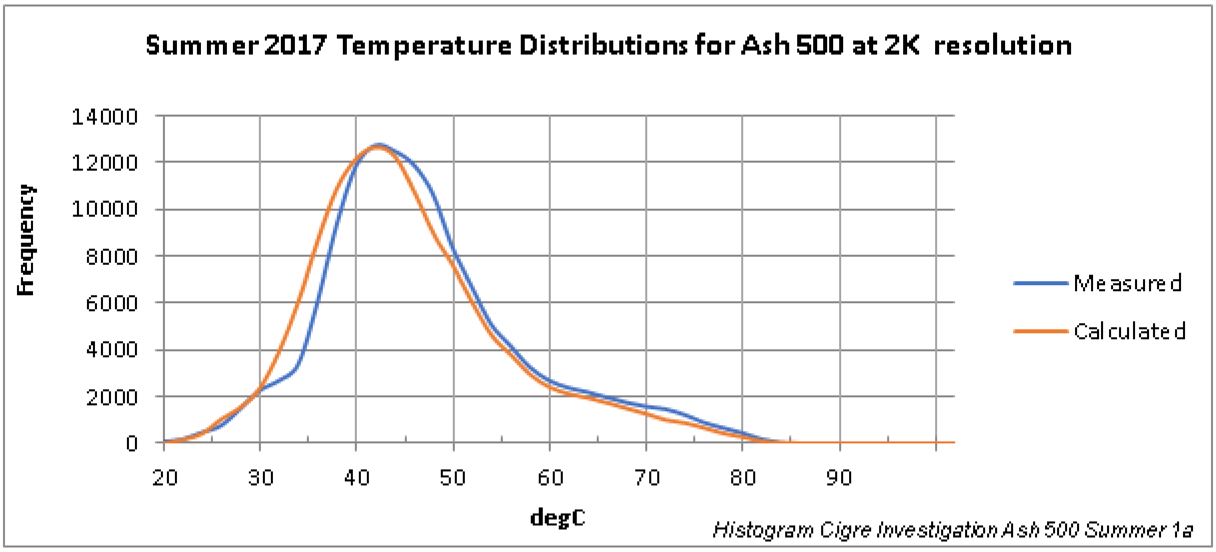


Figure 14 Frequency Distributions of Measured and Calculated Conductor Temperatures for the 2017 Summer (3 months) for Ash 500

The relative position of the two curves can be altered without changing their shapes by simply increasing or decreasing all the calculated values by a fixed amount. An increase of just 1K in the calculated values (equivalent to a shift of half a bin) results in the displacement between the two curves largely disappearing, as can be seen in Figure 15.

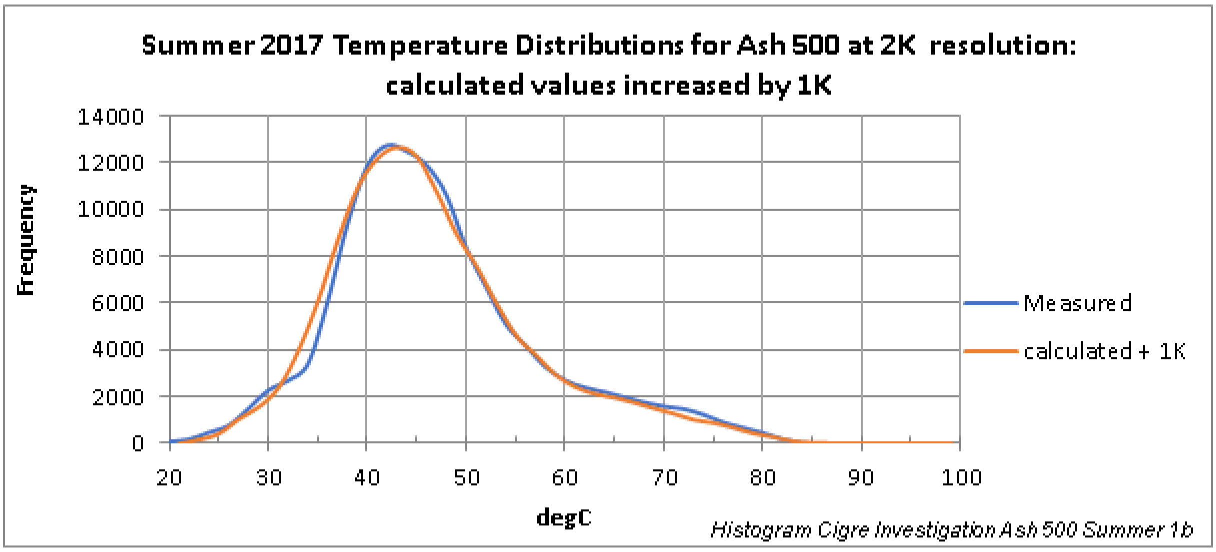


Figure 15 Same data as Figure 14 but with calculated values increased by 1K

It can be concluded that, for summer 2017 and Ash 500 data at least, there is generally good agreement between the calculated running means and the measured values, with the calculated values typically about 1K lower than the measured values.

6.2.4 Possible Reasons for Discrepancy Between Measured and Calculated Temperatures

It is difficult to get a direct comparison between measured and calculated temperatures because of the different time frames involved. Calculated values are effectively instantaneous 1-minute steady state values, suitably averaged, whereas measured values are the end result of integration over some unspecified time-scale. Although 1-minute instantaneous values of measured trio means and minute-by-minute values of 10-minute running means of calculated values seemed to be the optimum comparison, agreement was far from perfect, with measured values typically 3-4˚C higher than calculated values for a selection of "hot days", one for each month of the year.

Note that this figure is a multiply averaged quantity. The minute-by-minute differences between measured and calculated values for a randomly chosen day (30 Oct 2017) range from -3 to +9 degrees. Note also that 7 November and 21 December 2017, give significantly higher average differences, 6.4˚C and 7.4˚C than any other months in that year.

Frequency distributions (for Ash 500A) of measured and calculated conductor temperatures over a whole season (Summer 2017) showed a displacement between the two curves of about 1˚C (Tmeas greater than Tcalc).

Possible reasons for these discrepancies

1. Emissivity and absorptivity assumed too high (0.8).

   New conductors are shiny and therefore have low emissivity and absorptivity (approx. 0.2). They oxidise and get dirty with age, increasing their emissivity and absorptivity to about 0.8 after about a year or two.

   The effect of **too-high an emissivity** is to increase radiative cooling and hence to reduce the calculated conductor temperature, Tcalc. Conversely, the effect of **too-high an absorptivity** is to increase solar gain and hence to increase Tcalc. The magnitude of the effect on Tcalc of a change in emissivity is greater than that due to the same change in absorptivity, so the net effect of reducing them both by the same amount (they tend to be roughly equal) would be to increase the calculated conductor temperature.

   Reducing emissivity and absorptivity from 0.8 to 0.7 in OHTEMP increases Tcalc for Ash 500A under summer conditions by 2-3˚C depending on the value of solar flux. So most, if not all, of the discrepancy could be due to the relatively low emissivity and absorptivity of our relatively new conductors compared with the Cigré recommended values.

2. Different Time Constants

   The wide range of minute-by-minute differences (from -3 to +9˚C for the selected day) is probably due to the large variation in the time constants of the various elements of the system.

3. Incorrect wind speeds

   A possible cause of the anomalously high average differences of 7 November and 21 December 2017, was that on those days, there were early morning periods when wind speed was low and temperatures were around freezing. For the first 2½ hours of the November day, the difference between measured and calculated conductor temperature is an enormous 20-25˚C, and this coincides with a steady wind speed of about 0.5 m/s (average of the two anemometers) and an ambient temperature of about minus 2˚C.

   These large early morning temperature differences seem to be caused by a problem with the calculated values (≈ 36˚C) rather than the measured values (≈ 63˚C). A possible explanation is that the wind speed readings are too high. If the wind speed had actually been nearer 0 m/s rather than 0.5 m/s, the calculated temperatures would have been much higher and the measured-vs-calculated temperature differences correspondingly lower. Further investigation has found that the 3D anemometer reading was often about 1m/s higher than the 2D reading (see Figure 16), which would be a significant difference at very low windspeeds. If a 2D-anemometer reading was correct at 0.5m/s, taking the average of this and a 3D-anemometer reading of 1.5m/s would have resulted in a significant over-estimate of wind speed (1m/s) and hence a significant underestimate of conductor temperature.

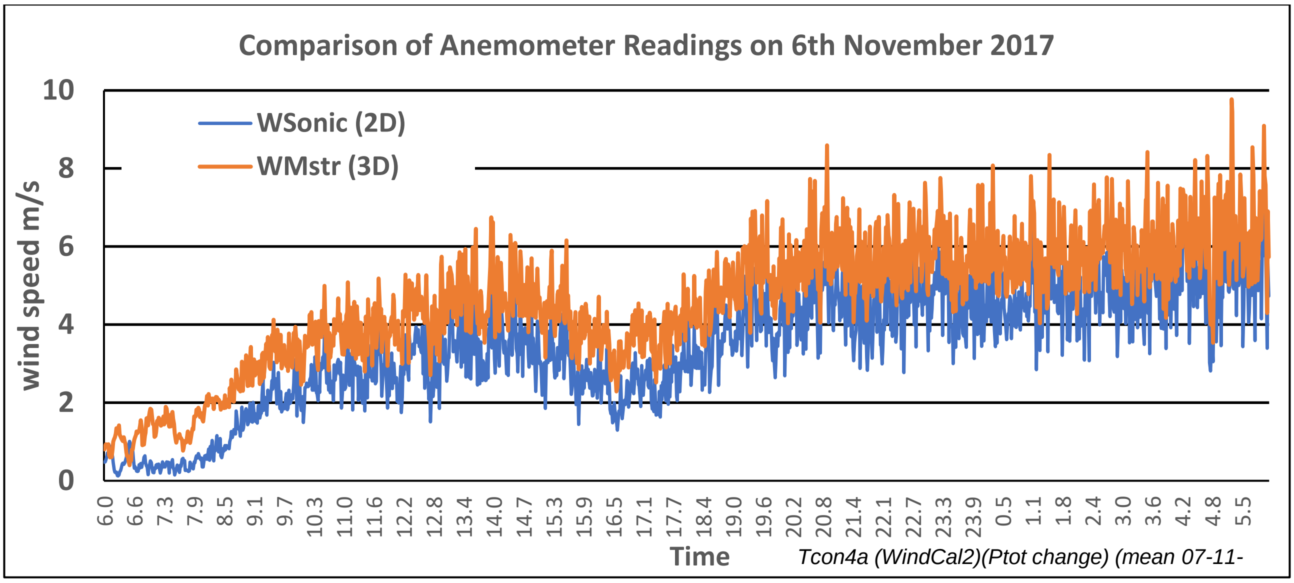


Figure 16 Discrepancy between the two anemometer readings

4. Incorrect solar gain

   Another possible source of error in the calculated conductor temperatures is that the solar gain was assumed to be equal to the measured solar flux on a horizontal surface. The solar elevation will tend to make this an underestimate of the solar flux incident on the conductor, especially at low sun angles, whilst the relative solar azimuth (the angle between the sun's direction and the line of the conductor) will tend to make it an overestimate. Moreover, simply correcting for low sun angles is problematic because much of the measured "solar flux" at low angles is indirect radiation from the sky and this does not need to be corrected. To avoid these complications, it was agreed with the Project Champion that using the measured values of solar flux on a horizontal surface for solar gain was the best compromise.

6.3 Seasonal Boundaries

6.3.1 The P27 Seasonal Split (3-2-4-3)

The original P27 ratings assume that the year can be split into four seasons along the lines of the standard meteorological 3-month seasons of winter (Dec-Feb), spring (Mar-May), summer (May-Aug) and autumn (Sep-Nov), with separate ratings for winter and summer and a single rating for spring and autumn. However, to accommodate the fact that May can be a lot warmer than March and April, May is included in summer rather than spring giving a 3-2-4-3 split rather than a 3-3-3-3 split.

P27 then assumes that the appropriate design ambient temperatures for these seasons are 20 °C and 2 °C for summer and winter respectively and 9 °C for spring and autumn:

P27 3-2-4-3 seasonal split

–	winter:	December, January and February	2 °C
–	spring/normal:	March, April	9 °C
–	summer:	May, June, July August	20 °C
–	autumn/normal:	September, October, November	9 °C

STP project S2126 (Phase 2 2007/8 and Phase 3, 2009/10) had indicated that these seasons may not be optimum, and in particular, that September should maybe be moved into Summer, like May. It found that the P27 seasonal split resulted in a disproportionately high number of temperature excursions in September, probably because, like May, September has a lot of days where the ambient temperature is a lot higher than the assumed value of 9°C.

A preliminary analysis of 12 months of data from the Ash 500A conductor (see QR8 December 2017), confirmed this "September problem" and it was suggested that tinkering about with the season boundaries was never going to produce an entirely satisfactory four-season split based on 3-month seasons and three values of Tamb0. The safest option would be to have just two seasons, winter and summer, but this would mean unduly pessimistic ratings for most of the winter season and also for May and September.

The S2126 "September problem" is illustrated in 0, which shows the monthly mean ambient temperatures recorded during the current project. The colours indicate the P27 seasonal groupings. (Note lack of summer 2016 data due to fire in instrumentation portacabin.)

It can be seen that, for both 2016 and 2017:

- the average temperature for September is similar to, and higher than, that of May, implying that if May is included in summer (as in P27) then September should be too.
- the spreads of monthly average temperatures in spring and autumn (as defined in P27) are significantly greater than the spreads in winter and summer.

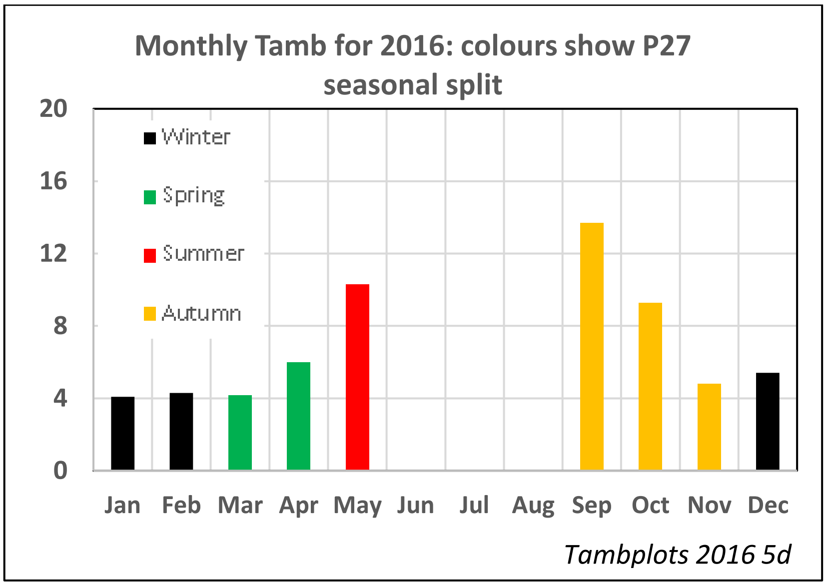


Figure 17 (a) Measured monthly mean ambient temperatures for 2016
Colours denote P27 seasons.

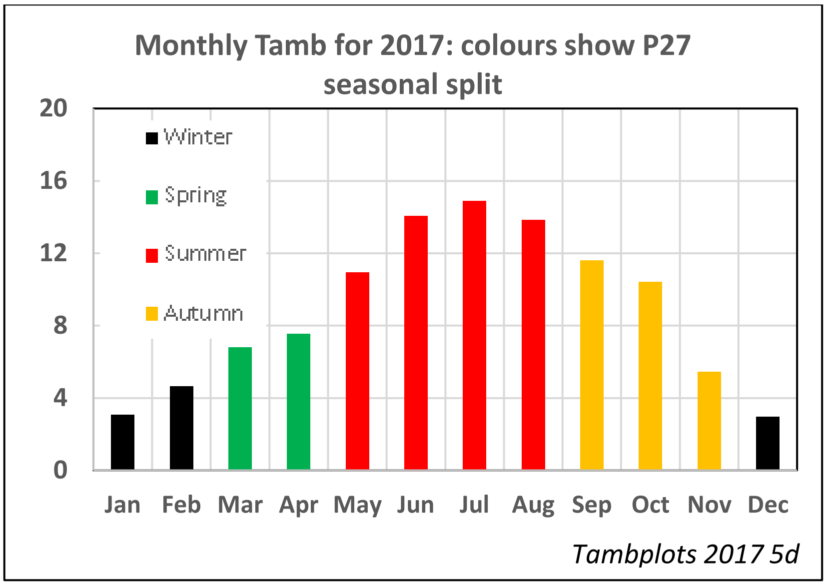


Figure 17 (b) **Measured monthly mean ambient temperatures for 2017**
Colours denote P27 seasons

6.3.2 Monthly Excursions and Seasonal Boundaries

A preliminary analysis of conductor temperatures was undertaken to further investigate the seasonal boundary problem. The first complete twelve months of continuous data, October 2016 to September 2017, was used to calculate four important excursion parameters for the Ash 500A conductor (conductor 14A), the hottest of the 10 conductors. The four parameters were:

- Count = Number of distinct occasions that conductor temperature Tcon exceeded a reference temperature Tref.
- Total Minutes = Aggregate time Tcon was higher than Tref.
- Maximum (excursion) = Highest excursion i.e. largest value of Tcon minus Tref.
- Total Degree-Minutes = Aggregate value of size of an excursion times its duration.

Tref values were chosen in accordance with the range of rig design values originally calculated from OHTEMP1.10g using the P27 parameters when designing the rig. These are shown in Figure 18, from which we can see that the appropriate range of Tref for Ash 500 is 65°C to 85°C.

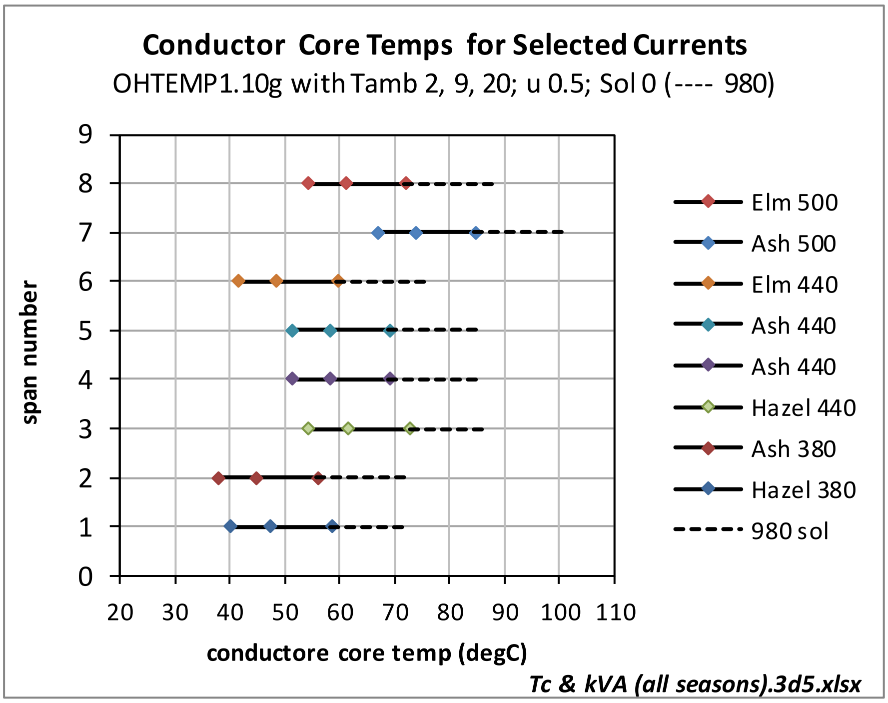


Figure 18 Rig design values of Tcon from OHRAT

Figure 19 shows the values of the four excursion parameters obtained for Ash 500 for reference temperatures of 65, 70, 75, 80 and 85°C. Each row shows the four excursion parameters for a particular temperature and the five rows correspond to the five reference temperatures.

For example, the bottom row shows that:

- there were 3 excursion events over 85;
- Tcon exceeded 85°C for 6 minutes in all;
- the maximum excursion was 0.5°C, i.e. the maximum temperature was 85.5°C;
- the integral excursion time was 1.6 degree-minutes.

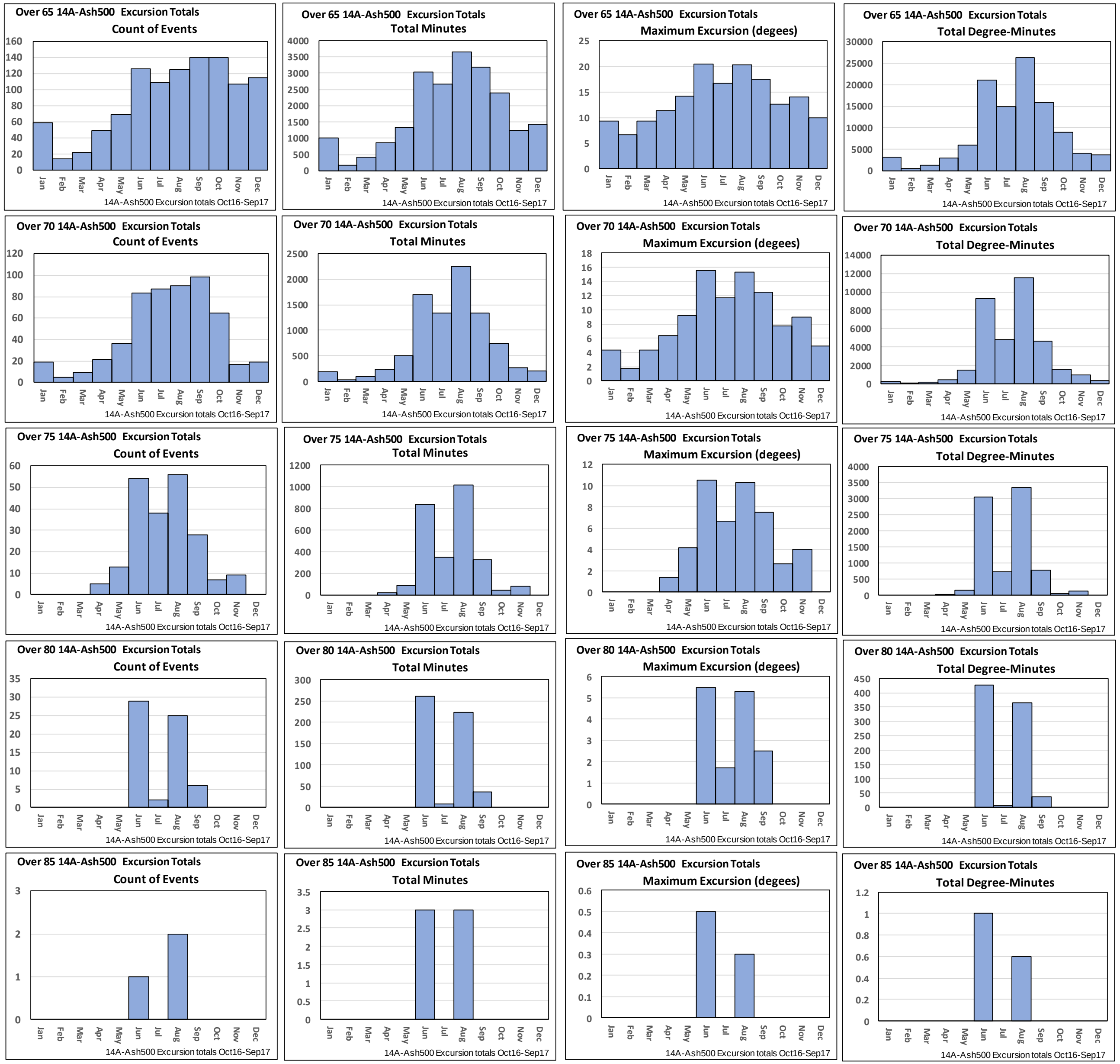


Figure 19 Excursion data for Ash 500 Oct 2016 to Sep 2017

It is apparent from these graphs that for this particular 12-month period

- there is a clear summer period comprising June to September (cf May to August in P27);
- there is a much less clear separation of the non-summer data into autumn/spring and winter;
- overall, the best split is probably into just two seasons, namely a 4-month summer season and an 8-month winter season:
  - summer: June to September (4 months)
  - winter: October to May (8-month).
- if more symmetry is preferred, May and October should be shifted into summer, giving two 6-month seasons;
- a four-season split is not really justified from the data;
- if a four-season split is required, we need to find autumn and spring seasons that give similar results to each other;
- the best choice would appear to be two 2-month seasons: October-November for autumn, April-May for spring;
- this would give a 4-2-4-2 split, i.e.
  - winter: December to March
  - spring: April to May
  - summer: June to September
  - autumn: October to November

6.3.3 Proposed Four-Way Seasonal Split (3-3-3-3)

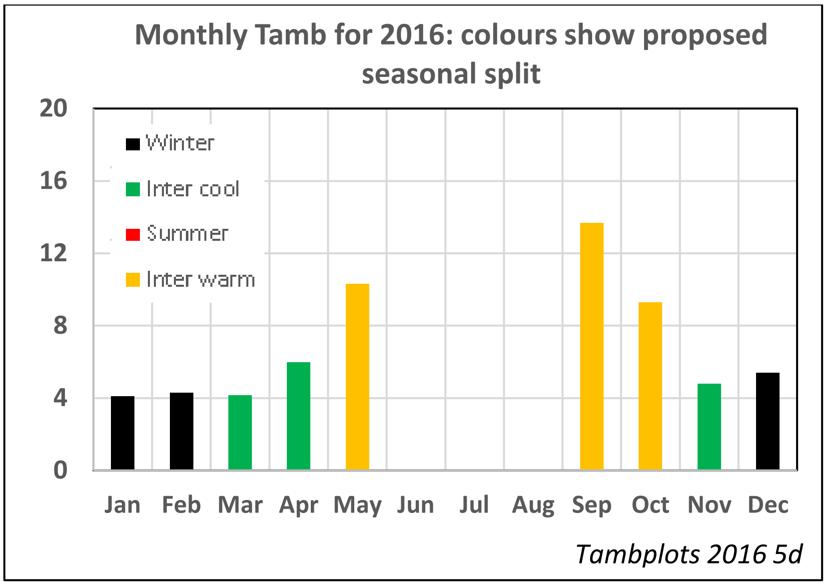
In view of the above, the following alternative and somewhat radical solution to these problems is proposed:

- revert to the basic idea of four 3-month seasons
- revert to the simple winter and summer seasons, comprising the obvious three cold months (Dec–Jan–Feb) and the obvious three hot months (Jun–July–Aug)
- dispense with the requirement that the six intermediate (normal) months need to be "shoe-horned" into a single rating
- dispense with the requirement that the three months in each "intermediate season" must be contiguous
- define "intermediate cool" (Mar, Apr and Nov) and "intermediate warm" (May, Sep and Oct) seasons, reflecting the fact that March, April and November are generally significantly cooler than May, September and October.

Proposed 3-3-3-3 split:

- winter (cold): December to February (3 months)
- intermediate cool: March, April and November (3 months)
- summer (hot): June to August (3 months)
- intermediate warm: May, September and October (3 months)

Figure 20 again shows the monthly mean ambient temperatures recorded during the current project, with colours this time denoting the new proposed four-way "seasonal" split. The difference between the two intermediate seasons, Inter cool & Inter warm is now quite obvious.



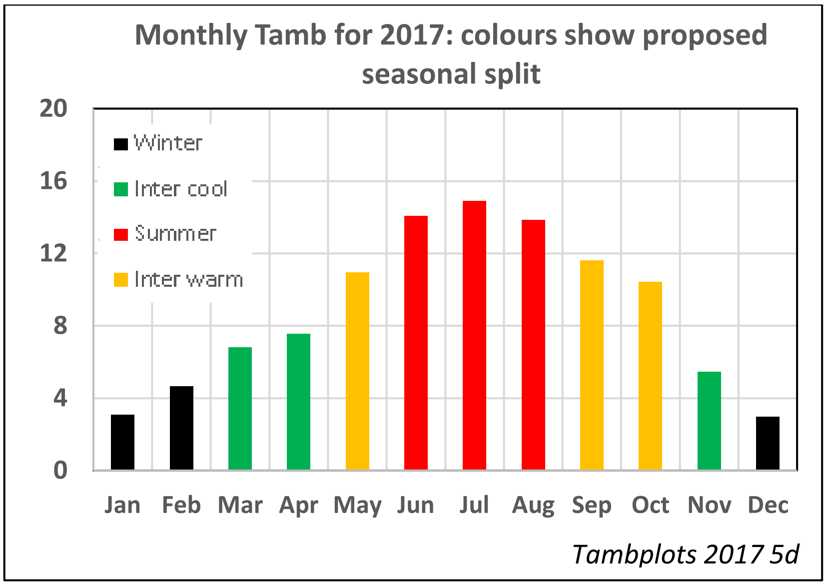


Figure 20 **Measured monthly mean ambient temperatures for 2016 & 2017. Colours denote Proposed Seasonal Split**

Consideration was given to keeping design ambient temperatures as close as possible to P27 values. A provisional scheme was drawn up: winter and summer values could remain at P27 values (2°C and 20°C), whilst the P27 spring/autumn 9°C could be simply split into 6°C and 12°C for the intermediate cool and intermediate warm values. However, comparison with the actual ambient temperature ranges (Table 8) suggests that this provisional scheme is not optimum, and this was confirmed by analysis of the resulting CT curves (see next Section).

Table 8 Ranges of monthly mean ambient temperatures for the proposed seasonal split and provisional design Tamb values

	winter	intermediate cool	intermediate warm	summer
Provisional Design Tamb	2°C	6°C	12°C	20°C
Actual monthly mean Tamb				
2016	4-5°C	4-6°C	7-14°C	
2017	3-5°C	5-7°C	10-11°C	14-15°C

6.4 Dependence of Exceedance on Design Temperature

In previous work (STP project S2126 - Phase 2 2007/8 and Phase 3 2009/10), there was evidence of a strong dependence of exceedance on conductor design temperature Tdes with little or no evidence of an independent dependence of exceedance on size of conductor or conductor current.

The data obtained in the present project enables us to investigate these dependencies in more detail.

Figure 21 shows the variation of NNe, the Normalised Number of Excursions/year (effectively the exceedance), with Tdes for 2017. Each line corresponds to a particular conductor-current combination and is the best-fit to the four points on each line corresponding to the four seasons. Note that to obtain the Tdes values for this NNe–vs-Tdes analysis, EA Technology has assumed the provisional design Tamb values given in Table 8 namely 2°C, 6°C, 12°C, and 20°C.

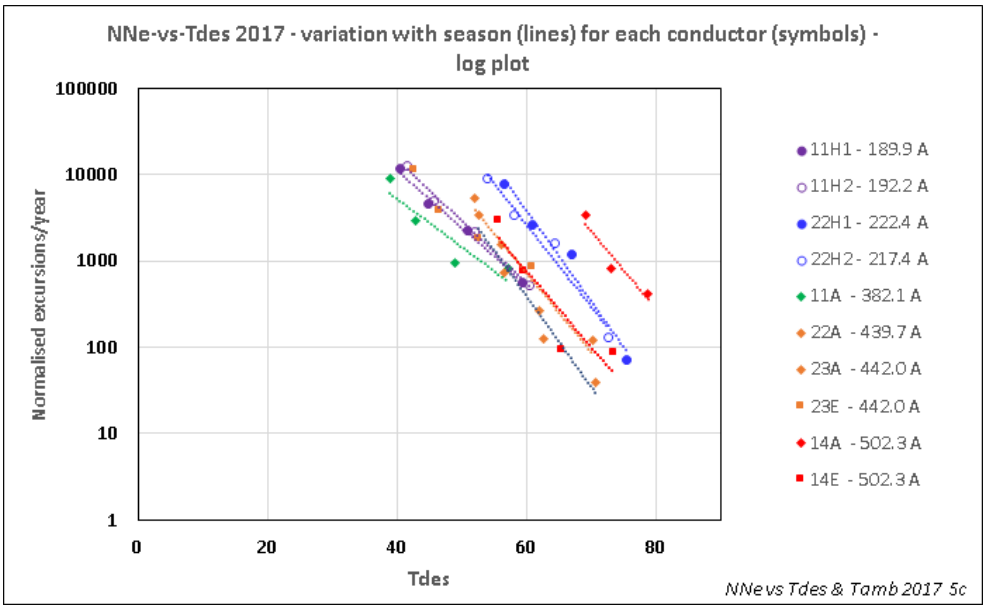


Figure 21 NNe vs Tdes - Variation with season for each conductor 2017

It is obvious from Figure 21 that the slope of the lines is approximately the same for all our conductor-current combinations, with NNe decreasing by a factor of between 10 and 100 for each 20°C increase in Tdes. However, the displacement of the lines implies that exceedance also varies with some other parameter. Analysis shows that the most important second parameter is ambient temperature rather than any of the three conductor-current variables, current, conductor size, or current density.

6.4.1 Dependence of Exceedance on Ambient Temperature

A plot like Figure 21 is useful for seeing how NNe varies with the main variable Tdes but is less useful for comparing NNe with two or more variables. For this we need to do a multiple least-squares fit (i.e. a multiple regression) and then plot the values of NNe calculated using the regression coefficients against the actual values of NNe. To see how much effect the second variable (Tamb) has we can compare the plot obtained with a single-variable fit (Tdes only) with the plot obtained with a two-variable fit (Tdes and Tamb).

A single variable (Tdes) fit of all the data in Figure 21 to the equation logNNe = A + B x Tdes gives coefficient values A = 6.027, B = -0.051.

A 2-variable (Tdes and Tamb) fit of the same data to the equation logNNe = A + B x Tdes + C x Tamb gives A = 6.125, B = -0.0489, C = -0.00058.

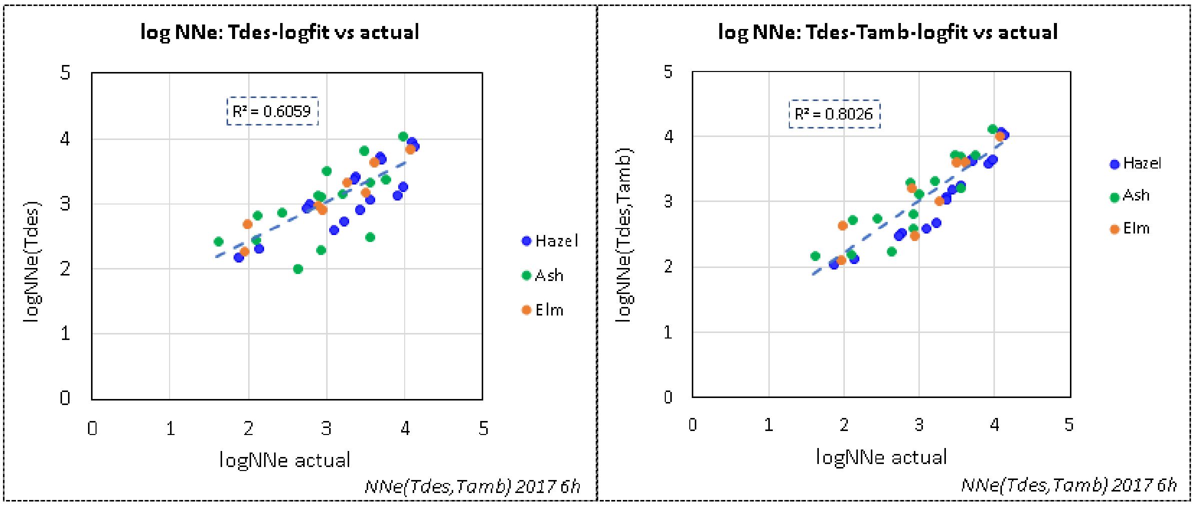


Figure 22 logNNe calculated values (using linear fit of logNNe) vs actual values (2017 data)
(a) single regression - Tdes only (b) double regression - Tdes and Tamb

Figure 22 shows plots of calculated logNNe values versus actual logNNe values. In Figure 22a, the calculated values are based on the single-variable coefficients from Figure 21 (A & B above). In Figure 22b the calculated values are based on the 2-variable coefficients from Figure 21 (A B & C above). The improvement in the fit due to the 2nd variable is apparent.

(The regression coefficient R-squared shown on the plots indicates the percentage of the variability in the data that is explained by the fit. The increase from 0.6059 to 0.8026 confirms that the two-variable fit gives a significant improvement.)

6.5 CT Curves (1) – Variation with Current and Season

The CT curve is a tool for obtaining the probabilistic rating Irat for a specified exceedance from the calculated deterministic rating. In P27, CT is effectively defined as the square of the ratio of the probabilistic rating Iprob to the deterministic rating Idet:

i.e. $CT = (Iprob/Idet)^2$.

The deterministic rating Idet is the current that gives the specified design temperature under design conditions in conductor temperature algorithms such as OHTEMP: it is sometimes referred to as the design current, Ides. The probabilistic rating for a given exceedance Iprob(e) is determined experimentally by counting the number of excursions occuring when the applied current Iapp is equal to Iprob.

CT is a function of exceedance, which is the probability that a conductor will exceed its design temperature, averaged over a year. A knowledge of the relationship CT(e) therefore enables one to deduce a probabilistic rating for the required exceedance:

$Iprob(e) = Idet \sqrt{CT(e)}$

A CT curve is a plot of exceedance (on a log scale) against CT. In P27, it is asserted that given the right design conditions, the CT curve is the same for all conductor-current combinations, i.e. it is a universal constant, and hence the probabilistic rating for any conductor can be determined for any given exceedance. We shall see that our data corroborates this assertion.

An analysis tool has been developed to produce CT curves from the concatenated monthly data files obtained in this project. This tool counts the numbers of excursions above each of a set of reference temperatures set at 5°C intervals between 40°C and 95°C values. (Note that here an excursion is defined as being any one-minute reading when the measured conductor temperature was above the design temperature.)

Figure 23 shows the set of CT curves obtained from the 2017 data for the Ash conductors using the proposed seasonal split discussed above and the provisional design Tamb values given in Table 8 (i.e. Summer 20°C, Inter warm 12°C, Inter cool 6°C, Winter 2°C). It is quite obvious that the curves are far from coincident.

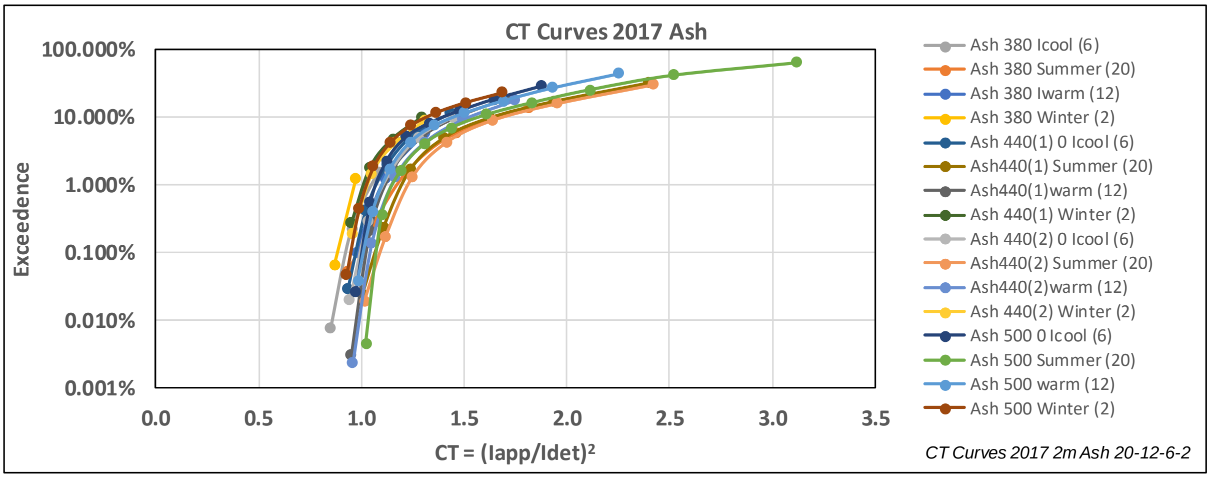


Figure 23 CT curves for the four Ash conductors based on the provisional design Tamb values given in Table 8 (i.e. Summer 20, Inter warm 12, Inter cool 6, Winter 2)

Splitting the data into four plots, one for each season, as in Figure 24 with the four curves in each plot corresponding to the four applied currents, gives plots with far less variation from curve to curve.

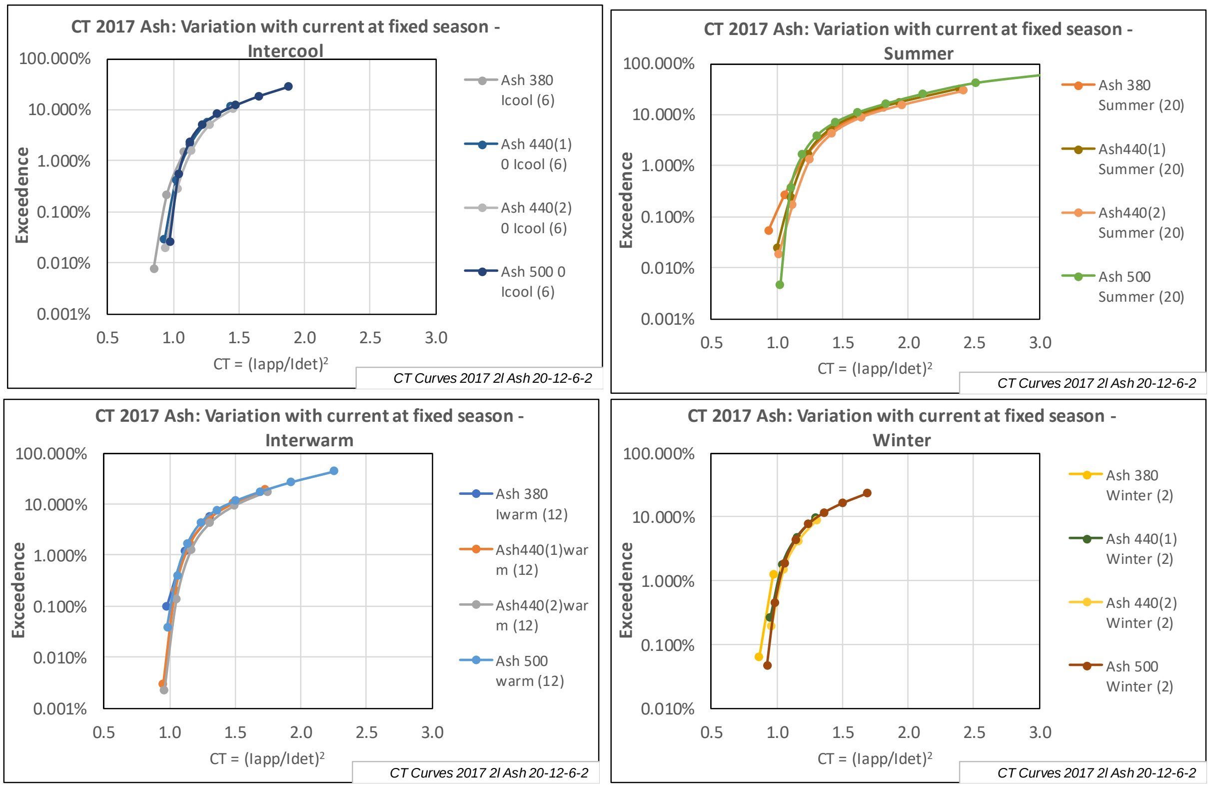


Figure 24 Same data as Figure 23 but with separate plot for each season. The four curves in each plot correspond to the four currents. (Based on provisional design Tamb: 20-12-6-2)

If instead, the data are split into separate plots for each current so that each comprises four curves, one for each season, as in Figure 25, much of the variation returns. This implies that the variation seen in Figure 24 is mainly associated with different seasons rather than different currents.

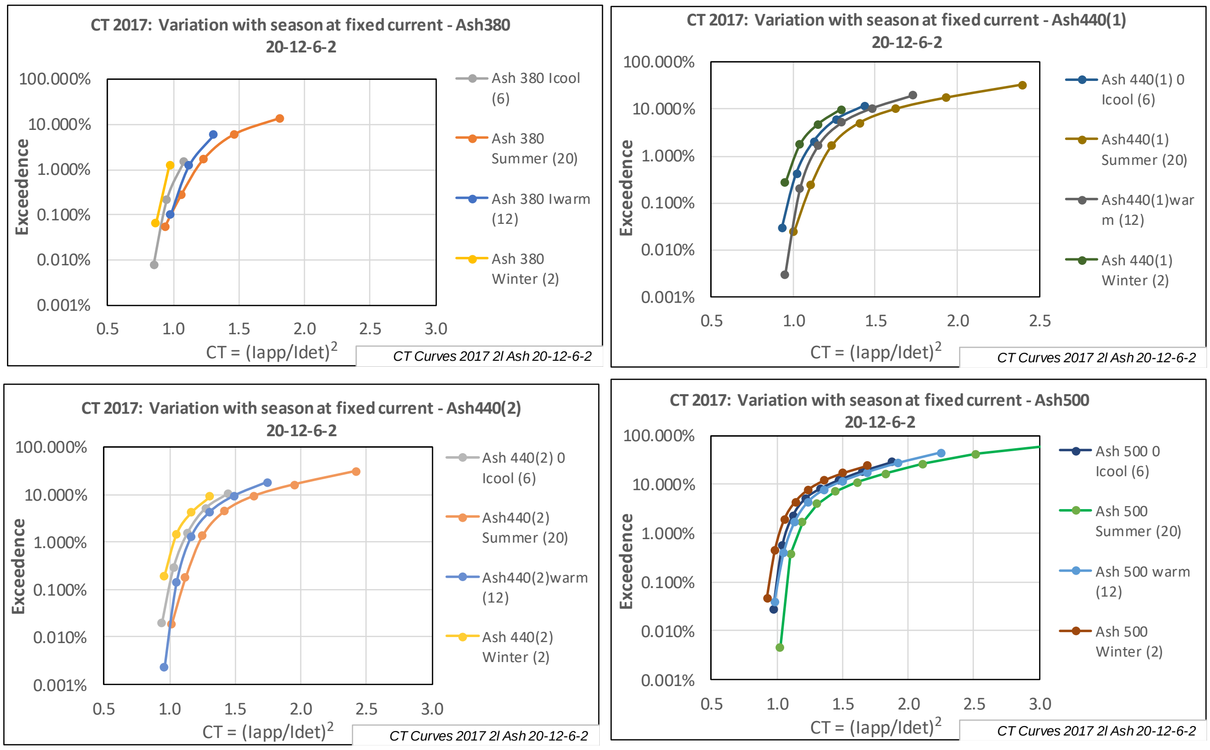


Figure 25 Same data as Figure 23 but with separate plot for each current. The four curves in each plot correspond to the four seasons. (Based on provisional design Tamb: 20-12-6-2)

6.6 CT Curves (2) – Importance of Design Tamb Values

The above CT curves were calculated using the somewhat arbitrary set of provisional design Tamb values: 20°C, 12°C, 6°C, and 2°C. The actual measured average Tamb values differed significantly from these provisional values, particularly the summer and winter values, as can be seen from Table 9. The table also shows the corresponding Met Office average values of Tamb for Stoke in 2017, and the Met Office 30-year averages for the whole of the UK. These are much closer to the projects' measured values than the provisional values, especially for summer.

Table 9 Alternative design values of Tamb

Season	Months	P27	Provisional	Measured (Stoke)	MetO 2017 Stoke	MetO 30yr Avg UK (1981-2010)
				Avg of 1-min values	Avg of daily max and min	
Icool	Mar, Apr, Nov	9	6	6.6	6	6.4
Summer	Jun, Jul, Aug	20	20	14.3	16.0	14.4
Iwarm	May, Sep, Oct	20/9	12	11.0	12.8	10.8
Winter	Jan, Feb, Dec	2	6	3.6	4.6	3.7

Figure 26 shows the same plots as Figure 20 but this time using design Tamb values derived from the measured Tamb values (14.3, 11.0, 6.6, 3.6) rather than the arbitrary provisional ones (20, 12, 6, 2). The reduction in the variation with season is striking, indicating the importance of using appropriate design Tamb values.

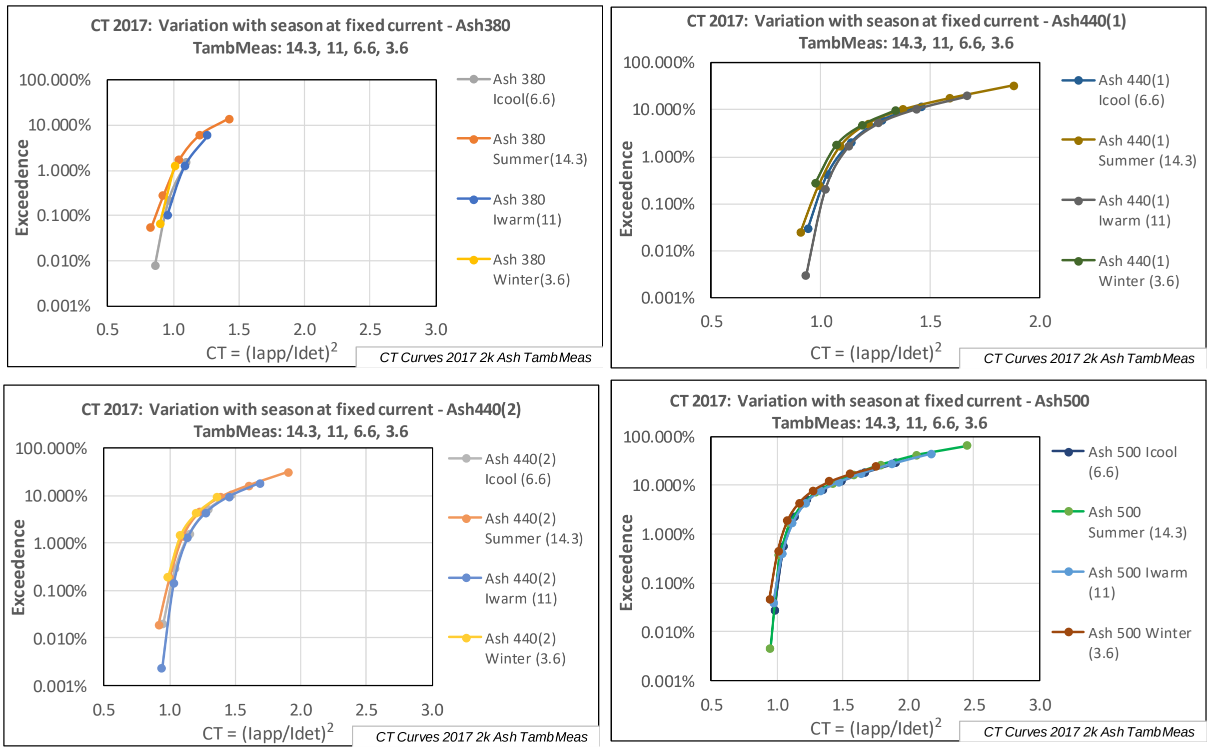


Figure 26 Same plots as Figure 20 but using design Tamb derived from measured Tamb

A useful measure of the reduction in the variation with season due to changing the design Tamb values can be obtained by comparing exceedances at CT = 1.2. This lies in the important region around the knee of the curve where exceedances are in the 1% to 10% range. Figure 27 shows the situation when the provisional design Tamb values (20-12-6-2) are used: the difference between summer and winter values is very obvious.

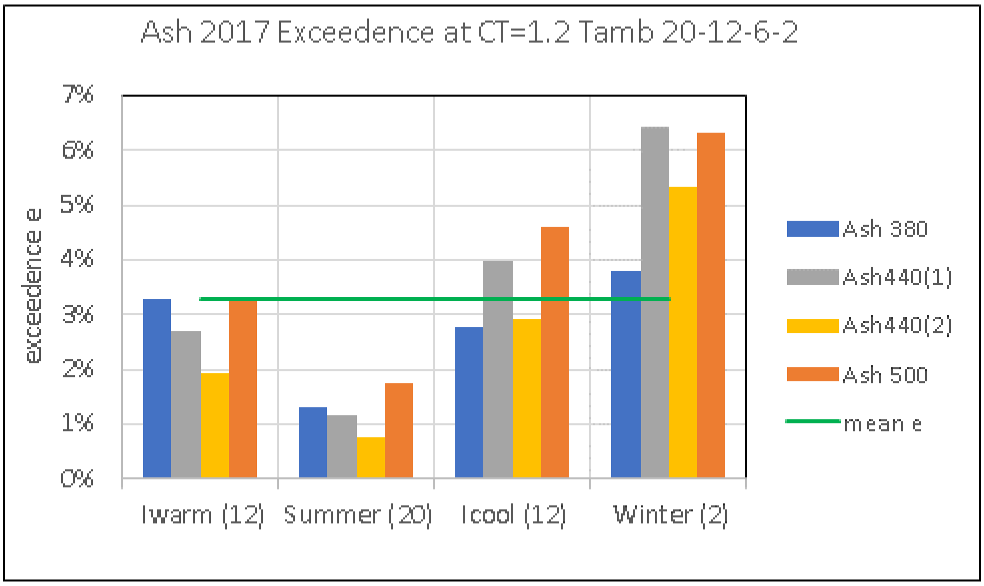


Figure 27 Exceedances at CT=1.2 for provisional design Tamb values (20-12-6-2).

Figure 28 is the corresponding plot for measured design Tamb values (14.3-11-6.6-3.6). It shows a much more consistent picture with far less seasonal variation.

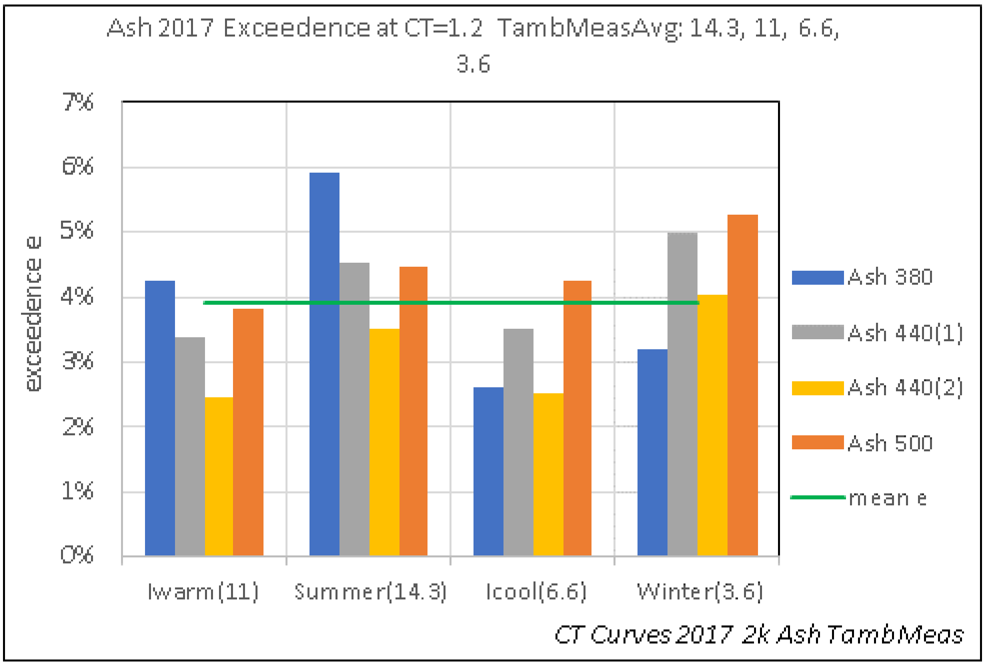


Figure 28 Exceedances at CT=1.2 for measured design Tamb values (14.3-11-6.6-3.6)

Table 10 shows the average seasonal values for both cases. Particularly noticeable is the reduction in the range of the seasonal averages, from 4.2% to 1.4%.

Table 10 Exceedances at CT = 1.2 for provisional and measured design Tamb values

	Iwarm	Summer	Icool	Winter	Range	Mean
Provisional Tamb	12	20	6	2	-	-
e (CT = 1.2)	2.8%	1.2%	3.6%	5.5%	**4.2%**	3.3%
Measured Tamb	11	14.3	6.6	3.6	-	-
e (CT = 1.2)	3.5%	4.6%	3.2%	4.4%	**1.4%**	3.92%

Figure 29 shows all the Ash CT curves on a single plot, based on Design Tamb values derived from the measured Tamb values.

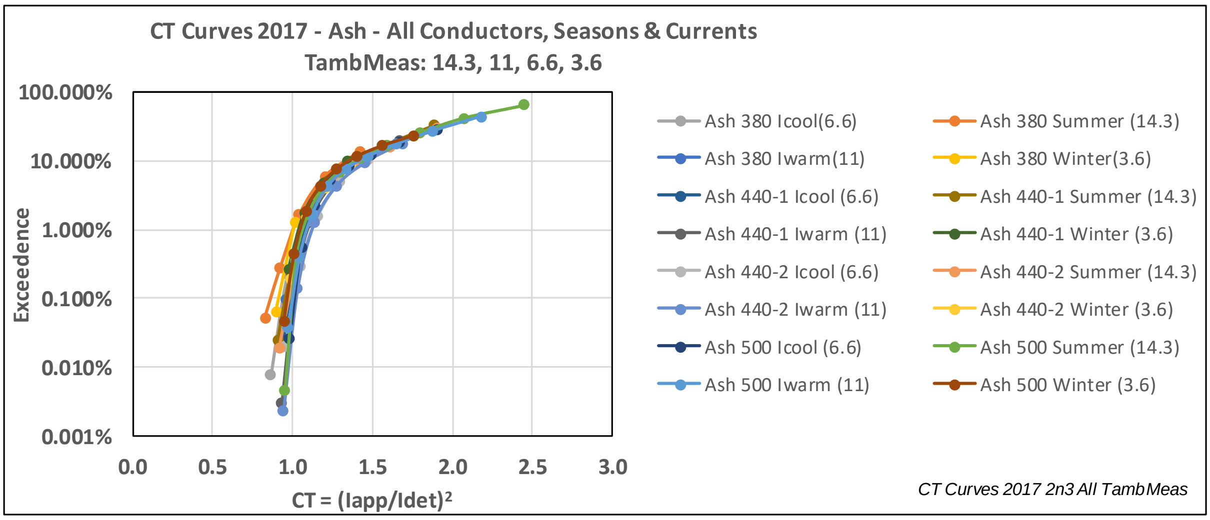


Figure 29 All the Ash data on single CT plot using measured Tamb as design values

Similar plots can be produced for the Hazel and Elm conductors. Figure 30 is a grand plot of these and the above Ash data, with all 40 conductor-current-season combinations on the same plot. The actual curves have been omitted for clarity, leaving just the points. The lack of scatter is remarkable for such a wide variety of parameters, giving support to the claim made in the derivation of P27 that the CTcurve is a universal constant, independent of conductor, current and season.

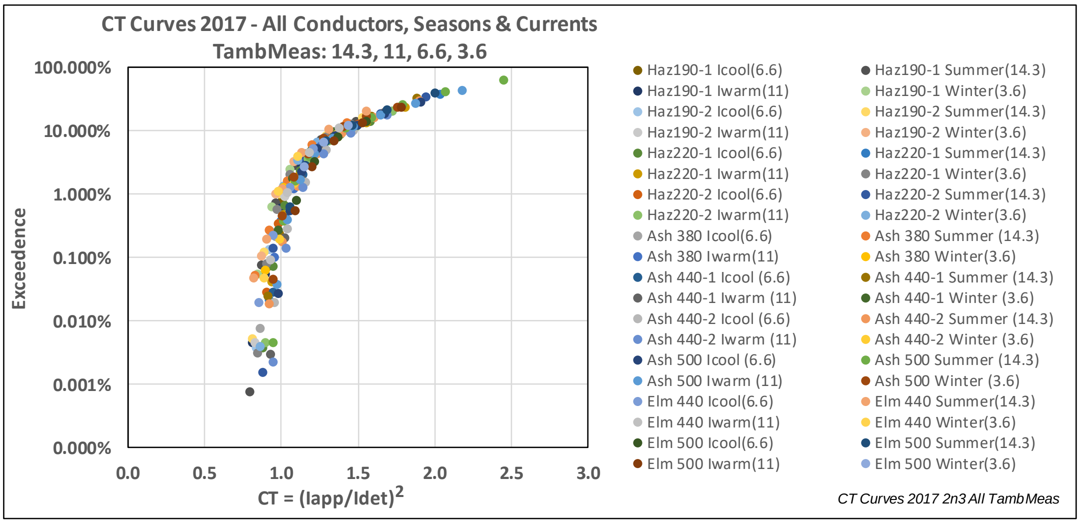


Figure 30 CT data for all 10 conductor-current combinations. Curves omitted for clarity

6.7 CT Curves (3) – Universal Fit using 30-year UK Average Temperatures as Design Tamb Values

For general use, EA Technology needed to produce a universal CT curve for use anywhere in the UK. It was therefore decided to use the Met Office 30-year UK Average Temperatures as the design Tamb values. From Table 9, we see that these 30-year UK averages are very similar to our measured values so changing from one to the other will make little difference qualitatively to the above findings. Table 11 summarises the chosen design parameters for our CT curve, with Tamb rounded to the nearest whole degree.

Table 11 Chosen design parameters for determining universal CT curve

Season	Months	Tamb = MetO 30yr UK Avg (1981-2010)
Icool	Mar, Apr, Nov	6
Summer	Jun, Jul, Aug	14
Iwarm	May, Sep, Oct	11
Winter	Jan, Feb, Dec	4

Figure 31 is similar to Figure 30 but with seasonal Tamb values set equal to the 30y UK averages for the relevant months. It is plotted as one single curve to enable curve fitting*.

Note that there have been some minor corrections to the raw data since the previous CT curves (Figure 23 to Figure 30) were drawn, causing additional slight discrepancies between the earlier curves and Figure 31.

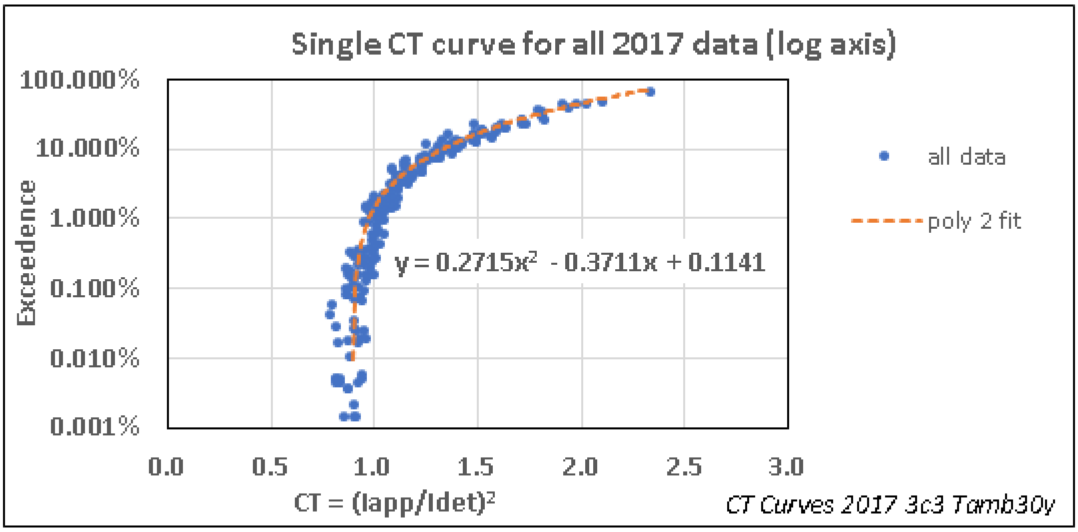


Figure 31 Similar curve to Figure 27 but with Tamb based on 30y UK averages and plotted as one single curve to enable curve fitting

* Note that there have been some minor corrections to the raw data since the previous CT curves (Figure 23 to Figure 30) were drawn, causing slight discrepancies between the earlier curves and Figure 31.

The best fit was obtained using a 2nd order polynomial. Note that the fitted curve stops short of the lowest points presumably because these have no effect on the fit. (The fit is actually a fit to the data plotted on a linear y-axis, as in Figure 32, which emphasises the irrelevance to the fit of e values below 0.01%.).

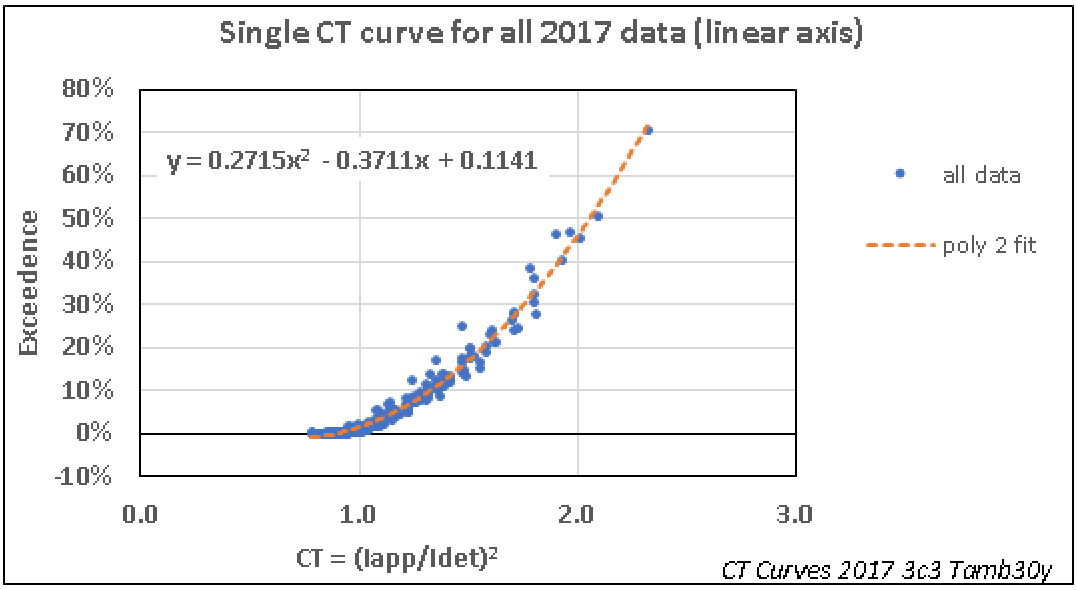


Figure 32 Same data as Figure 31 but plotted with a linear y axis (rather than log)

To get a fit that is valid at all e values, we can split the data into e two regions, one for "high" e (e > 0.05%) and one for "low" e (e< 0.05%), and obtain separate fits for each region:

- a second order polynomial Excel fit for e > 0.05%
- a "by-eye" fit for e < 0.05%.

This is illustrated in Figure 33 whilst Figure 34 shows the same fits but with the underlying data removed for clarity.

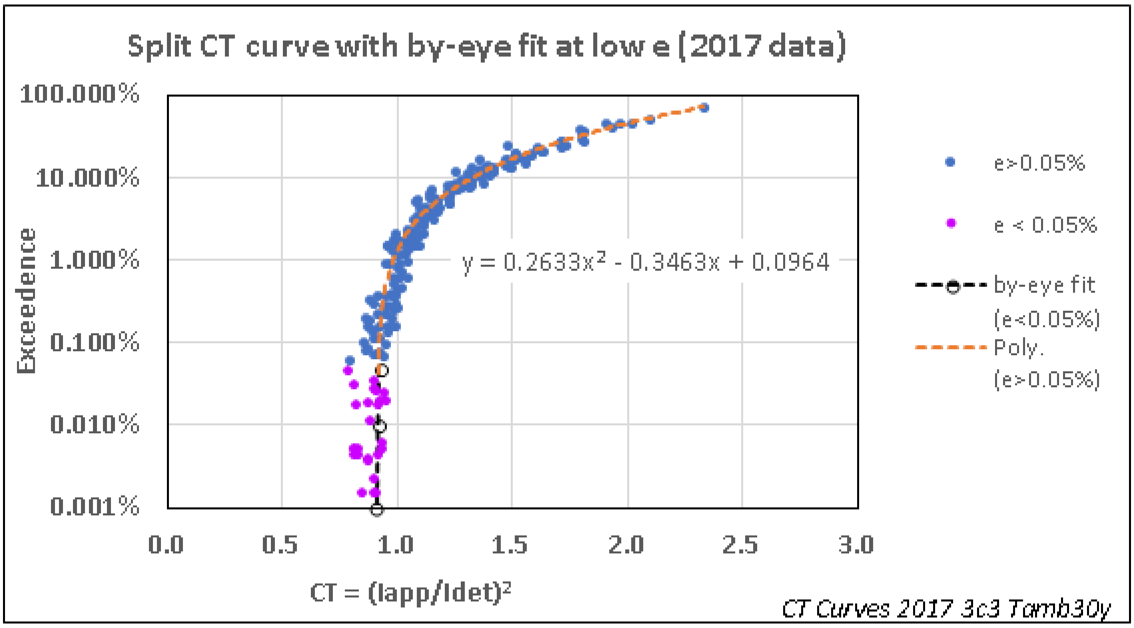


Figure 33 Split CT curve - same as Figure 31 but separate fits above and below e = 0.05%)

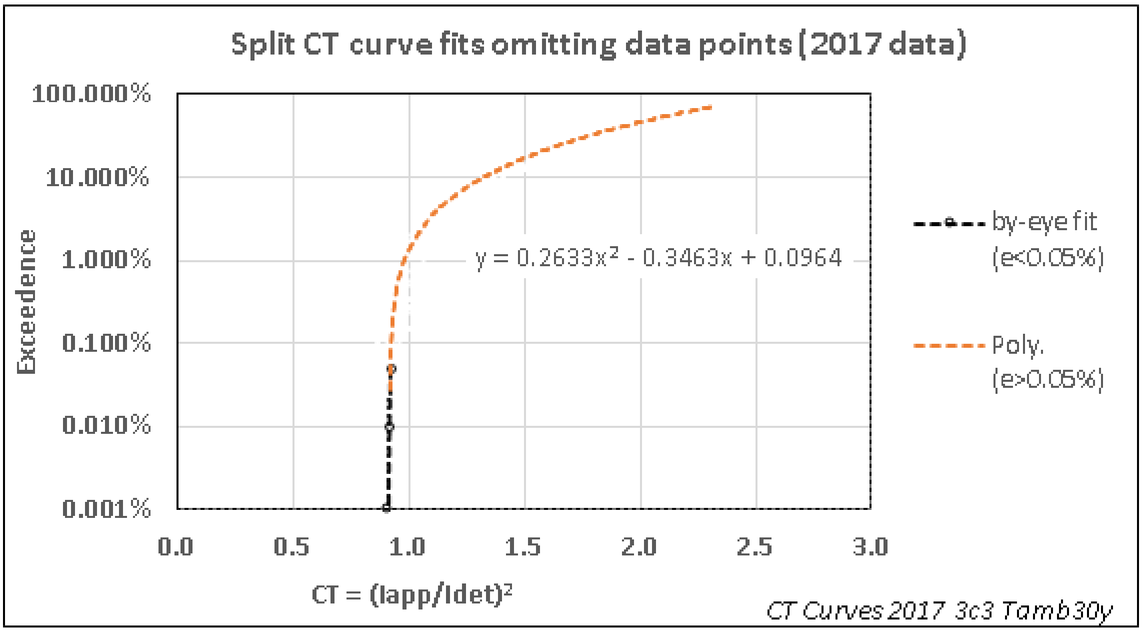


Figure 34 Split CT curve fits omitting underlying data for clarity

Table 12 is a lookup table for CT(e) compiled from the above fits. Figure 35 is a plot of this lookup table.

Table 12 Lookup Table for CT(e) based on 2017 data

e(=y)	CT(=x)
0.001%	0.90970
0.002%	0.91148
0.005%	0.91382
0.010%	0.91559
0.020%	0.91736
0.050%	0.91971
0.100%	0.92271
0.200%	0.92980
0.500%	0.95000
1.0%	0.98085
2.0%	1.03505
3.0%	1.08240
5.0%	1.16400
7.0%	1.23415
10.0%	1.32570
20.0%	1.56650
30.0%	1.75580
50.0%	2.05960
70.0%	2.30840

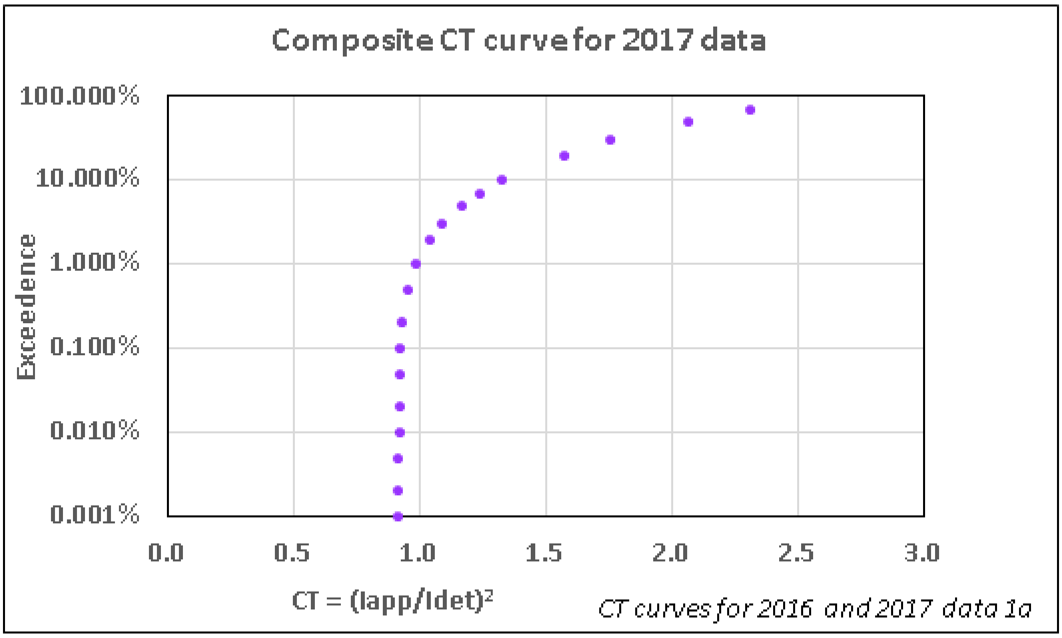


Figure 35 **Composite CT curve for 2017 data (graphical version of lookup table)**

Either the table or the graph can be used to find CT for a specific exceedance and hence to calculate the probabilistic rating Iapp for that exceedance using CT = $[Irat/Idet]^2$.

The above CT curves have all been based on the full year's data obtained for 2017. The results from the 9 months of data obtained for 2016 are remarkably similar, as can be seen from Figure 36 where the data for 2016 have been plotted alongside those for 2017.

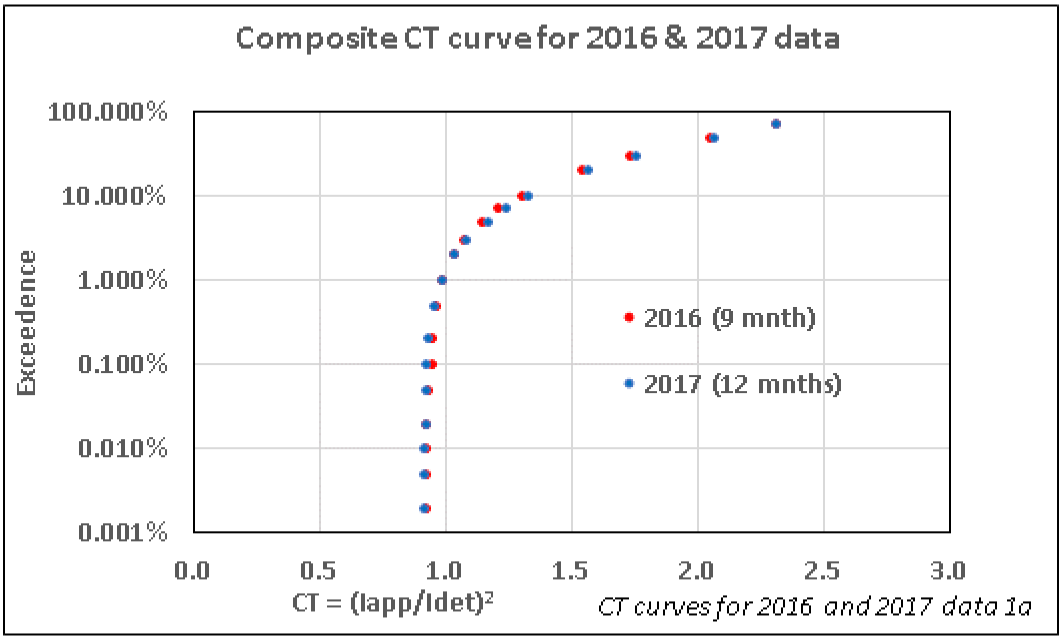


Figure 36 **Composite CT curve for 2016 and 2017 data**

There is an argument for aggregating the 2016 and 2017 data to produce a combined curve and thus make use of 75% more data. However, more is not necessarily better because the 2016 data lacks any summer data and its use would therefore introduce a bias into the CT plot that would be hard to evaluate. It is therefore recommended that a CT curve derived solely from the 2017 data be used, i.e. Table 12 and Figure 36.

7. Software Development

A significant output of the project was to produce an Integrated Software Tool that incorporates the functionality of the OHRAT and OHTEMP Excel workbooks currently in use, incorporating the findings from this project's data analysis.

The resultant software tool will be provided alongside the P27 Issue 2 documentation, with an accompanying User Guide, which is currently being developed.

The Software Tool is a stand-alone Windows™ based program that will provide a variety of user-friendly functions. The calculations within the software are taken from OHTEMP and OHRAT and include the seasonal boundaries and ambient temperatures as defined in this report. A database sits behind the software that includes the definition of the seasons and a large number of overhead line conductors and their properties. These conductors were extracted from the OHTEMP workbook and include Aluminium Alloy, Aluminium, Copper, Cadmium Copper and Aluminium Conductor Steel Reinforced (ACSR) conductors. The software will include the ability to add new conductors into the system's database and store them for future calculations and analysis.

The input screen for single calculations includes a radio button to toggle between the two types of calculations – Rating or Temperature. The input screen also allows for two sets of calculations to be carried out and displayed alongside each other, meaning results for two conductors can be simultaneously compared.

Single calculations of either a Rating or a Temperature will be calculated, once all user input and selection requirements have been fulfilled. The basic requirements are a conductor, weather conditions and either a Rated Temperature or a Current depending on the calculation. Further information regarding the inputs and calculations will be provided in the User Guide that will accompany the software. It should be noted that when Ratings are being determined, deterministic Ratings are calculated unless a percentage exceedance has been entered.

The probabilistic Ratings are calculated using the CT curve data presented in this report. This is the default CT curve built into the software. However, there is an ability within the software to include and use a user-defined CT curve. This will be defined using a look-up table with pre-set percentage values.

The Integrated Software Tool can also be used to carry out batch runs of calculations of both Rating and Temperature from imported data files; for example, historical weather data set. The format of these datafiles is described in the User Guide but will be in the form of a .csv file and include weather conditions and, where desired, a current. Conductors will need to be selected and a Current or Rated Temperature can be entered.

The software will carry out the calculation for each row of data and export a new .csv file, with the calculation results appended to the import data in a new column. It should be noted that the batch run calculations of Ratings are deterministic Ratings only (the CT curve is only applicable to the predefined Seasons).

9. Conclusions

C1. The measured conductor temperatures averaged over a single "hot-conductor" day were generally between 2°C and 4 °C higher than those calculated using the Cigré TB601 equations (OHTEMP2). Calculated values based on measured ambient conditions fluctuated wildly, necessitating the use of a 10-minute running mean for comparison.

C2. Minute-by-minute analysis for the hottest conductor (Ash 500), found the difference between measured conductor temperatures and calculated 10-minute running mean values ranged from -3°C to +9 °C.

C3. Daily averages of the difference between measured and calculated temperatures for the hottest day in each month for each conductor produced an overall mean difference of 3.6 °C for 2016 and 3.4 °C for 2017.

C4. Frequency distributions for measured and calculated conductor temperatures over a complete season (summer 2017, Ash 500) indicated that there was generally good agreement between the calculated running means and the measured values, with the calculated values approximately 1K lower than the measured values.

C5. Possible reasons for these discrepancies are
- assumed emissivity and absorptivity too high (decreases Tcalc)
- response time of physical system
- measured wind speeds too high (decreases Tcalc)
- incorrectly measured solar gain

C6. Exceedence was found to depend upon the design temperature, as expected from previous work, with a 10°C increase in Tdes producing a factor of 3 decrease in the number of temperature excursions. A much weaker dependence on ambient temperature was also found, with a 10°C increase in Tamb producing a 1%-2% decrease in the number of temperature excursions.

C7. A study of seasonal boundaries showed that whilst there was a clear summer period comprising June to August or September and a less clear winter season comprising December-to February, there was little evidence of a simple symmetrical split of the intermediate months into spring and autumn seasons with the same design ambient temperature Tamb, as assumed in P27.

C8. Consequently, a radical seasonal split is proposed with four 3-month seasons, each with a different design ambient temperature Tamb (unlike P27 which has the same Tamb for spring and autumn). Summer and Winter would comprise the obvious three hot months (Jun–July–Aug) and the obvious three cold months (Dec–Jan–Feb) but spring and autumn would be replaced by more complex "pseudo seasons" called intermediate cool and intermediate warm, comprising the relatively cool spring and autumn months (Mar, Apr and Nov) and the relatively warm spring and autumn months (May, Sep and Oct).

C9. CT curves (i.e. CT-vs-loge curves) enable one to calculate the probabilistic rating for an exceedance e from the deterministic rating. CT curves based on our measured data, and using the new proposed seasons, along with a provisional set of design ambient temperatures derived from P27 values, exhibited a significant amount of variation but the variation was greatly reduced if design ambient temperatures were instead set equal to the average Tamb values obtained from our measured data. Significantly, these measured Tamb averages were very similar to the corresponding MetOffice 30-year average temperatures.

C10. A plot of all forty conductor-current-season combinations on the same graph using the measured average Tamb values showed a remarkable lack of scatter for such a wide variety of parameters, giving support to the claim made in the derivation of P27 that the CT curve is a universal constant, independent of conductor, current and season.

C11. The conductor temperatures measured in this project can therefore be used to derive a universal CT curve based on the proposed seasonal split and MetOffice 30-year average temperatures.

Season	Months	Tamb = MetO 30yr UK Avg (1981-2010)
Icool	Mar, Apr, Nov	6
Summer	Jun, Jul, Aug	14
Iwarm	May, Sep, Oct	11
Winter	Jan, Feb, Dec	4

C12. A best fit to all the CT(e) values for 2017 was determined and a lookup table produced. This can be used to find CT for any specific exceedance and hence to calculate the probabilistic rating for that exceedance.

C13. The CT curves are based on the full year's data obtained for 2017. The results from the nine months of data for 2016 are remarkably similar, but because the latter lacks any summer data, its use would introduce a bias into the results that would be hard to evaluate.

10. Recommendations

R1. The old P27 ratings should be revised in accordance with the findings of this work.

R2. The revised version of OHTEMP based on Cigré TB601 can be used to predict conductor temperatures.

R3. A revised seasonal structure should be used with simple winter and summer seasons, but non-contiguous intermediate cool and intermediate warm seasons.

R4. Design ambient temperatures based on the UK 30-year averages for these seasons should be used.

R5. The look-up table provided can be used to calculate the probabilistic rating for a specified exceedance.

11. References

[1] Engineering Recommendation P27, Current Rating Guide for High Voltage Overhead Lines Operating in the UK Distribution System, Energy Networks Association, 1986;

[2] ACE 104, Report on the Derivation of Overhead Line Ratings Applicable to High Voltage Distribution Systems, Energy Networks Association,1986

[3] S2126: *Monitoring of Conductor Temperatures at Fixed Current: Analysis of Collated Data,* (STP) project, EA Technology Ltd, Mark Bertinat, 2013;

[4] S2148 *Re-appraisal of ACE 104,* STP project, EA Technology Ltd, Mark Bertinat, 2014;

[5] CIGRÉ Technical Brochure TB601 "Guide for thermal rating calculations of overhead lines" (2014)

[6] "Statistical approach to thermal rating of overhead lines for power transmission and distribution." Price, C.F. and Gibbon, R.R., IEE Proceedings C (Generation, Transmission and Distribution) 130, no.5, p.245-56, Sept 1983.

[7] "The thermal behaviour of overhead conductors. Sections1 and 2: Mathematical model for evaluation of conductor temperature in the steady state and the application thereof." WG12, Electra 144, p 107-125, Cigré 1992.

[8] CIGRÉ, Technical Brochure 207, “Thermal behaviour of overhead conductors”, August 2002.

12. Acknowledgements

Special note of thanks to the following:

Western Power Distribution, for providing the site necessary to construct the overhead line test rig at their Victoria Road, Stoke Delivery Centre. WPD Stoke for also providing the necessary personnel for erection of the wood poles, conductors and other OHL hardware. A special mention for Shane Degg (WPD OHL Project Engineer), who provided essential assistance throughout the project duration and was exemplary in his support and professionalism.

The following suppliers and manufacturers deserve a special mention:

- Ellis Patents - www.ellispatents.co.uk
- B B Price Ltd - www.bbprice.co.uk
- Pfisterer Insulators - www.pfisterer.com
- Mosdorfer CCL - www.mosdorferccl.com
- PLP - http://www.preformed-gb.com
- PI Macdonald Civil Contractors - www.pimacdonald.co.uk

Appendix I Example CHECKDAT file (3rd Mar 2017)

Figure AI.1 "rawdat" sheet (1st 20 cols, 1st 30 minutes)

SN0004 Stoke Victoria Data ***06:01 02/03/17 to 06:00 03/03/17*** T:\NIA Folders\NIA Projects\Projects\SN0004\SN0004 - Data Download\5. auto check data\Outputs\2017\2017-03\2017-03 cleansed revised\[autocheckdatop26m
autocheckdatop26m_v38cEM 2017-03-03cr.xls For printout
Raw 1-min data 1st data row 18 | 1st data row 18 manual
15-sec data averaged over 1 min for imposed vars, inst 1-min values for Ts. Last data row 1457 | Last data row 1457 auto
15-sec data averaged over 1 min for Wind data No.of data rows 1440 | No.of data rows 1440
Wind directions are relative to line N not true N | 06:01 02/03/17 to 06:00 03/03/17

Extend condat and range(3s) Sheets

Rail1 Channels

Logger outputs	op1	op2	op3	op4	op5	op6	op7	op8	op9	op10	op11	op12	op13	op14	op15	op16	op17	op18	op19	op20
Name	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	TC15	TC16	TC17	TC18	TC19	TC20
Units	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC
Sensor	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	TC15	TC16	TC17	TC18	TC19	TC20
logger input address	R1S1Ch1	R1S3Ch2	R1S6Ch1	R1S1Ch2	R1S4Ch1	R1S6Ch2	R1S2Ch1	R1S4Ch2	R1S7Ch1	R1S2Ch2	R1S5Ch1	R1S7Ch2	R1S3Ch1	R1S5Ch2	R1S8Ch1	R1S8Ch2	R1S9Ch1	R1S9Ch2	R1S10Ch1	R1S10Ch2
sensor location	11H1L	11H1M	11H1R	11AL	11AM	11AR	11H2L	11H2M	11H2R	14EL	14EM	14ER	14AL	14AM	14AR	14ALa	14ALb	14ALc	14ALd	14ALe
logger span/conv	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T
	19.3	17.9	19.1	18.9	18.3	18.6	20.2	19.8	19.6	23.7	23.4	23.9	28.1	27.5	28.3	28.7	28.2	27.7	27.7	27.8
Timestamp	TC1 (degC)	TC2 (degC)	TC3 (degC)	TC4 (degC)	TC5 (degC)	TC6 (degC)	TC7 (degC)	TC8 (degC)	TC9 (degC)	TC10 (degC)	TC11 (degC)	TC12 (degC)	TC13 (degC)	TC14 (degC)	TC15 (degC)	TC16 (degC)	TC17 (degC)	TC18 (degC)	TC19 (degC)	TC20 (degC)
02/03/2017 06:01	14	12.3	13.5	13.6	13.1	13.3	14.900002	14.5	14.2	17.6	17.300002	18	21.5	20.9	21.800002	22.2	22.1	22.1	22.2	22
02/03/2017 06:02	13.900002	12.2	13.400002	13.5	13	13.3	14.8	14.4	14.1	17.300002	17	17.7	20.9	20.5	21.300002	21.7	21.4	21.2	21.300002	21.1
02/03/2017 06:03	14.1	12.3	13.5	13.6	13.1	13.400002	15.1	14.6	14.2	17.6	17.300002	18	21.300002	20.800002	21.7	22	22.1	22	21.6	21.2
02/03/2017 06:04	15.2	13.5	14.8	14.2	13.6	14	16.1	15.8	15.6	18.2	18	18.7	22.2	21.7	22.6	23	22.800002	22.6	22.300002	22
02/03/2017 06:05	14.8	12.900002	14.3	14.1	13.6	13.8	15.7	15.1	14.900002	18.2	17.9	18.5	22	21.5	22.300002	22.6	22.800002	22.6	22.1	21.7
02/03/2017 06:06	15	13.3	14.5	14.2	13.6	13.900002	15.7	15.3	15	18	17.7	18.4	21.800002	21.300002	22.2	22.5	22.5	22.300002	22	21.5
02/03/2017 06:07	14.900002	13.1	14.3	14.2	13.6	14	15.6	15.2	15	18.300002	18	18.7	22.1	21.6	22.5	23.1	23.2	23	22.800002	22.1
02/03/2017 06:08	13.5	11.8	12.900002	13.5	12.900002	13.2	14.3	13.8	13.5	17.300002	16.9	17.6	20.7	20.2	21.1	21.7	21.7	21.6	21.300002	20.7
02/03/2017 06:09	13.2	11.5	12.6	13	12.5	12.8	13.900002	13.4	13.2	16.6	16.200002	16.9	20	19.5	20.300002	20.9	21	20.800002	20.5	20
02/03/2017 06:10	12.900002	11.2	12.400002	12.8	12.2	12.5	13.6	12.9	12.8	16.5	16.1	16.800002	19.6	19.2	20	20.6	20.7	20.5	20.2	19.7
02/03/2017 06:11	12.1	10.5	11.6	12.1	11.5	11.8	12.6	12.1	12	15.3	14.900002	15.5	18.2	17.7	18.6	19	19.300002	19.1	18.9	18.7
02/03/2017 06:12	12.6	11	12.1	12.2	11.7	11.900002	13.1	12.6	12.400002	15.5	15.2	15.8	18.9	18.2	19.1	19.4	19.4	19.5	19.1	18.9
02/03/2017 06:13	13.5	11.8	13	12.6	12	12.400002	13.900002	13.4	13.400002	16	15.7	16.300002	19.5	18.9	19.800002	20	19.7	19.4	19.300002	19.1
02/03/2017 06:14	13.5	11.900002	13.1	12.7	12.1	12.400002	13.900002	13.4	13.3	16.200002	15.7	16.4	19.4	18.9	19.800002	20	19.7	19.6	19.300002	19.1
02/03/2017 06:15	13.5	12	13.2	12.8	12.3	12.5	14.1	13.6	13.5	16.5	16	16.6	19.7	19.2	20.1	20.300002	20.2	20	19.6	19.6
02/03/2017 06:16	12.1	10.5	11.6	12.1	11.400002	11.7	12.6	12	11.8	15.3	14.8	15.3	17.9	17.5	18.300002	18.5	18.4	18.2	18	17.9
02/03/2017 06:17	13.3	11.7	12.900002	12.5	11.900002	12.2	13.8	13.5	13.3	15.7	15.3	15.8	18.800002	18.300002	19.2	19.300002	19.2	18.9	18.7	18.5
02/03/2017 06:18	13.3	11.5	12.8	12.6	12	12.2	13.8	13.4	13.3	16	15.6	16.200002	19	18.7	19.5	19.6	19.300002	19.2	18.800002	18.7
02/03/2017 06:19	12.7	11	12.1	12.400002	11.8	12	13.3	12.8	12.7	15.7	15.400002	15.900002	18.300002	18.1	18.9	18.800002	18.4	18.1	17.800002	17.7
02/03/2017 06:20	11.400002	9.7	10.8	11.6	11	11.2	11.900002	11.5	11.2	14.7	14.3	14.7	16.6	16.6	17.300002	17.5	17.4	17.2	16.800002	16.800002
02/03/2017 06:21	11.1	9.5	10.7	11.3	10.7	10.8	11.6	11.2	11	14	13.6	14	15.8	15.7	16.4	16.700002	16.4	16.6	16.1	16.200002
02/03/2017 06:22	12.1	10.6	11.7	11.7	11.2	11.3	12.7	12.5	12.2	14.7	14.2	14.7	17	16.800002	17.6	17.9	17.6	17.5	17	17
02/03/2017 06:23	12.2	10.6	11.7	11.900002	11.3	11.400002	12.8	12.4	12.2	15	14.5	14.900002	17.2	17.1	17.9	18.2	18	17.800002	17.6	17.6
02/03/2017 06:24	12.6	11	12.2	12.1	11.5	11.7	13.1	12.8	12.6	15.2	14.7	15.2	17.6	17.4	18.2	18.4	18.2	17.800002	17.800002	17.800002
02/03/2017 06:25	13	11.400002	12.7	12.3	11.8	11.900002	13.5	13.2	13	15.5	15.1	15.5	18.2	17.800002	18.7	18.9	18.7	18.300002	17.9	18
02/03/2017 06:26	12.8	11.1	12.400002	12.3	11.7	11.900002	13.1	12.7	12.6	15.400002	14.900002	15.400002	17.9	17.6	18.5	18.6	18.4	18.300002	17.7	17.800002
02/03/2017 06:27	12.900002	11.3	12.5	12.3	11.8	12	13.3	12.9	12.8	15.400002	15	15.5	18	17.800002	18.6	18.800002	18.300002	17.9	17.300002	17.300002
02/03/2017 06:28	12.400002	10.7	11.8	12.2	11.6	11.7	12.8	12.3	12.1	15.3	14.8	15.2	17.6	17.4	18.2	18.2	17.9	17.7	17.1	17.1
02/03/2017 06:29	12.400002	10.8	12.1	12.1	11.400002	11.7	12.900002	12.5	12.3	15	14.5	14.900002	17.4	17.2	18	18	17.6	17.4	17.1	17.2
02/03/2017 06:30	12.900002	11.400002	12.6	12.3	11.8	11.900002	13.3	13	12.900002	15.5	15.1	15.400002	18.2	17.9	18.7	18.7	18.6	18.2	18.1	18.1

Figure AI.2 "condat" sheet (1st 25 cols, 1st 22 minutes)

SN0004 **Stoke Victoria Data** **06:01 02/03/17 to 06:00 03/03/17** 1st data row 25 manual
autocheckdatop26m_v38cEM 2017-03-03cr.xls Last data row 1464 auto

Printall Printsome

Conditioned 1-min data No.of data rows 1440
15-sec data averaged over 1 min for imposed vars, inst 1-min values for Ts. Wind directions are relative to line N not true N 06:01 02/03/17 to 06:00 03/03/17

		Rail1 Channels																				**Rail2 Channels**				
	Logger outputs	op1	op2	op3	op4	op5	op6	op7	op8	op9	op10	op11	op12	op13	op14	op15	op16	op17	op18	op19	op20	op21	op22	op23	op24	op25
	Name	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	TC15	TC16	TC17	TC18	TC19	TC20	TC21	TC22	TC23	TC24	TC25
	Units	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC	degC
	Sensor	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	TC15	TC16	TC17	TC18	TC19	TC20	TC21	TC22	TC23	TC24	TC25
	logger input address	R1S1Ch1	R1S3Ch2	R1S6Ch1	R1S1Ch2	R1S4Ch1	R1S6Ch2	R1S2Ch1	R1S4Ch2	R1S7Ch1	R1S2Ch2	R1S5Ch1	R1S7Ch2	R1S3Ch1	R1S5Ch2	R1S8Ch1	R1S8Ch2	R1S9Ch1	R1S9Ch2	R1S10Ch1	R1S10Ch2	R2S1Ch1	R2S3Ch2	R2S6Ch1	R2S1Ch2	R2S4Ch1
	sensor location	11H1L	11H1M	11H1R	11AL	11AM	11AR	11H2L	11H2M	11H2R	14EL	14EM	14ER	14AL	14AM	14AR	14ALa	14ALb	14ALc	14ALd	14ALe	22H1L	22H1M	22H1R	22AL	22AM
	logger span/conv	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T	type T
	bound1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	bound2		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	no. of valid TC readings		1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440
	Count	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440
	average	19.3	17.9	19.1	18.9	18.3	18.6	20.2	19.8	19.6	23.7	23.4	23.9	28.1	27.5	28.3	28.7	28.2	27.7	27.7	27.8	24.2	22.6	24.4	22.5	22.2
	stdev*	4.0	3.9	4.0	3.9	3.9	4.0	4.1	4.1	4.1	4.9	5.0	5.1	6.4	6.1	6.2	6.6	6.4	6.2	6.3	6.2	5.1	5.1	5.1	4.8	4.8
	max*	35.6	34.1	35.8	32.5	32.0	32.3	36.8	36.4	36.5	42.5	42.4	43.2	53.9	52.4	53.5	55.4	54.5	53.7	54.0	53.2	45.5	43.9	45.8	40.7	40.6
	min*	9.2	7.7	8.6	9.6	9.1	9.2	9.5	9.3	9.2	12.1	11.5	11.6	12.5	13.1	13.6	13.0	13.0	13.0	12.3	12.5	10.9	9.4	11.1	10.9	10.6
	range*	26.4	26.4	27.2	22.9	22.9	23.1	27.3	27.1	27.3	30.4	30.9	31.6	41.4	39.3	39.9	42.4	41.5	40.7	41.7	40.7	34.6	34.5	34.7	29.8	30.0
	open count (TCs)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	rawdat first row	14.0	12.3	13.5	13.6	13.1	13.3	14.9	14.5	14.2	17.6	17.3	18.0	21.5	20.9	21.8	22.2	22.1	22.1	22.2	22.0	18.9	16.7	18.4	17.0	16.7
6.02	02/03/2017 06:01	14.0	12.3	13.5	13.6	13.1	13.3	14.9	14.5	14.2	17.6	17.3	18.0	21.5	20.9	21.8	22.2	22.1	22.1	22.2	22.0	18.9	16.7	18.4	17.0	16.7
6.03	02/03/2017 06:02	13.9	12.2	13.4	13.5	13.0	13.3	14.8	14.4	14.1	17.3	17.0	17.7	20.9	20.5	21.3	21.7	21.4	21.2	21.3	21.1	18.0	15.9	17.5	16.3	16.1
6.05	02/03/2017 06:03	14.1	12.3	13.5	13.6	13.1	13.4	15.1	14.6	14.2	17.6	17.3	18.0	21.3	20.8	21.7	22.0	22.1	22.0	21.6	21.2	18.6	16.6	18.3	16.7	16.4
6.07	02/03/2017 06:04	15.2	13.5	14.8	14.2	13.6	14.0	16.1	15.8	15.6	18.2	18.0	18.7	22.2	21.7	22.6	23.0	22.8	22.6	22.3	22.0	19.9	17.9	19.6	17.2	16.9
6.08	02/03/2017 06:05	14.8	12.9	14.3	14.1	13.6	13.8	15.7	15.1	14.9	18.2	17.9	18.5	22.0	21.5	22.3	22.6	22.8	22.6	22.1	21.7	19.2	17.0	18.9	17.1	16.8
6.10	02/03/2017 06:06	15.0	13.3	14.5	14.2	13.6	13.9	15.7	15.3	15.0	18.0	17.7	18.4	21.8	21.3	22.2	22.5	22.5	22.3	22.0	21.5	18.6	16.5	18.2	16.7	16.4
6.12	02/03/2017 06:07	14.9	13.1	14.3	14.2	13.6	14.0	15.6	15.2	15.0	18.3	18.0	18.7	22.1	21.6	22.5	23.1	23.2	23.0	22.8	22.1	19.6	17.5	19.1	17.2	17.0
6.13	02/03/2017 06:08	13.5	11.8	12.9	13.5	12.9	13.2	14.3	13.8	13.5	17.3	16.9	17.6	20.7	20.2	21.1	21.7	21.7	21.6	21.3	20.7	17.4	15.3	17.0	16.1	15.8
6.15	02/03/2017 06:09	13.2	11.5	12.6	13.0	12.5	12.8	13.9	13.4	13.2	16.6	16.2	16.9	20.0	19.5	20.3	20.9	21.0	20.8	20.5	20.0	17.1	15.1	16.8	15.7	15.3
6.17	02/03/2017 06:10	12.9	11.2	12.4	12.8	12.2	12.5	13.6	12.9	12.8	16.5	16.1	16.8	19.6	19.2	20.0	20.6	20.7	20.5	20.2	19.7	16.9	15.0	16.8	15.5	15.2
6.18	02/03/2017 06:11	12.1	10.5	11.6	12.1	11.5	11.8	12.6	12.1	12.0	15.3	14.9	15.5	18.2	17.7	18.6	19.0	19.3	19.1	18.9	18.7	15.5	13.7	15.5	14.6	14.3
6.20	02/03/2017 06:12	12.6	11.0	12.1	12.2	11.7	11.9	13.1	12.6	12.4	15.5	15.2	15.8	18.9	18.2	19.1	19.4	19.4	19.5	19.1	18.9	16.5	14.7	16.4	14.9	14.6
6.22	02/03/2017 06:13	13.5	11.8	13.0	12.6	12.0	12.4	13.9	13.4	13.4	16.0	15.7	16.3	19.5	18.9	19.8	20.0	19.7	19.4	19.3	19.1	17.0	15.2	16.9	15.2	14.8
6.23	02/03/2017 06:14	13.5	11.9	13.1	12.7	12.1	12.4	13.9	13.4	13.3	16.2	15.7	16.4	19.4	18.9	19.8	20.0	19.7	19.6	19.3	19.1	17.1	15.2	16.9	15.2	14.8
6.25	02/03/2017 06:15	13.5	12.0	13.2	12.8	12.3	12.5	14.1	13.6	13.5	16.5	16.0	16.6	19.7	19.2	20.1	20.3	20.2	20.0	19.6	19.6	17.3	15.3	17.1	15.5	15.0
6.27	02/03/2017 06:16	12.1	10.5	11.6	12.1	11.4	11.7	12.6	12.0	11.8	15.3	14.8	15.3	17.9	17.5	18.3	18.5	18.4	18.2	18.0	17.9	14.9	13.0	14.7	14.2	13.8
6.28	02/03/2017 06:17	13.3	11.7	12.9	12.5	11.9	12.2	13.8	13.5	13.3	15.7	15.3	15.8	18.8	18.3	19.2	19.3	19.2	18.9	18.7	18.5	16.9	14.9	16.6	14.9	14.7
6.30	02/03/2017 06:18	13.3	11.5	12.8	12.6	12.0	12.2	13.8	13.4	13.3	16.0	15.6	16.2	19.0	18.7	19.5	19.6	19.3	19.2	18.8	18.7	16.8	14.9	16.3	14.9	14.7
6.32	02/03/2017 06:19	12.7	11.0	12.1	12.4	11.8	12.0	13.3	12.8	12.7	15.7	15.4	15.9	18.3	18.1	18.9	18.8	18.4	18.1	17.8	17.7	15.4	13.6	15.1	14.4	14.1
6.33	02/03/2017 06:20	11.4	9.7	10.8	11.6	11.0	11.2	11.9	11.5	11.2	14.7	14.3	14.7	16.6	16.6	17.3	17.5	17.4	17.2	16.8	16.8	13.9	12.3	13.7	13.6	13.3
6.35	02/03/2017 06:21	11.1	9.5	10.7	11.3	10.7	10.8	11.6	11.2	11.0	14.0	13.6	14.0	15.8	15.7	16.4	16.7	16.4	16.6	16.1	16.2	13.5	11.9	13.4	13.0	12.8
6.37	02/03/2017 06:22	12.1	10.6	11.7	11.7	11.2	11.3	12.7	12.5	12.2	14.7	14.2	14.7	17.0	16.8	17.6	17.9	17.6	17.5	17.0	17.0	15.6	14.0	15.5	14.0	13.7

Figure AI.3 "conplot1" sheet (raw conductor temperatures)

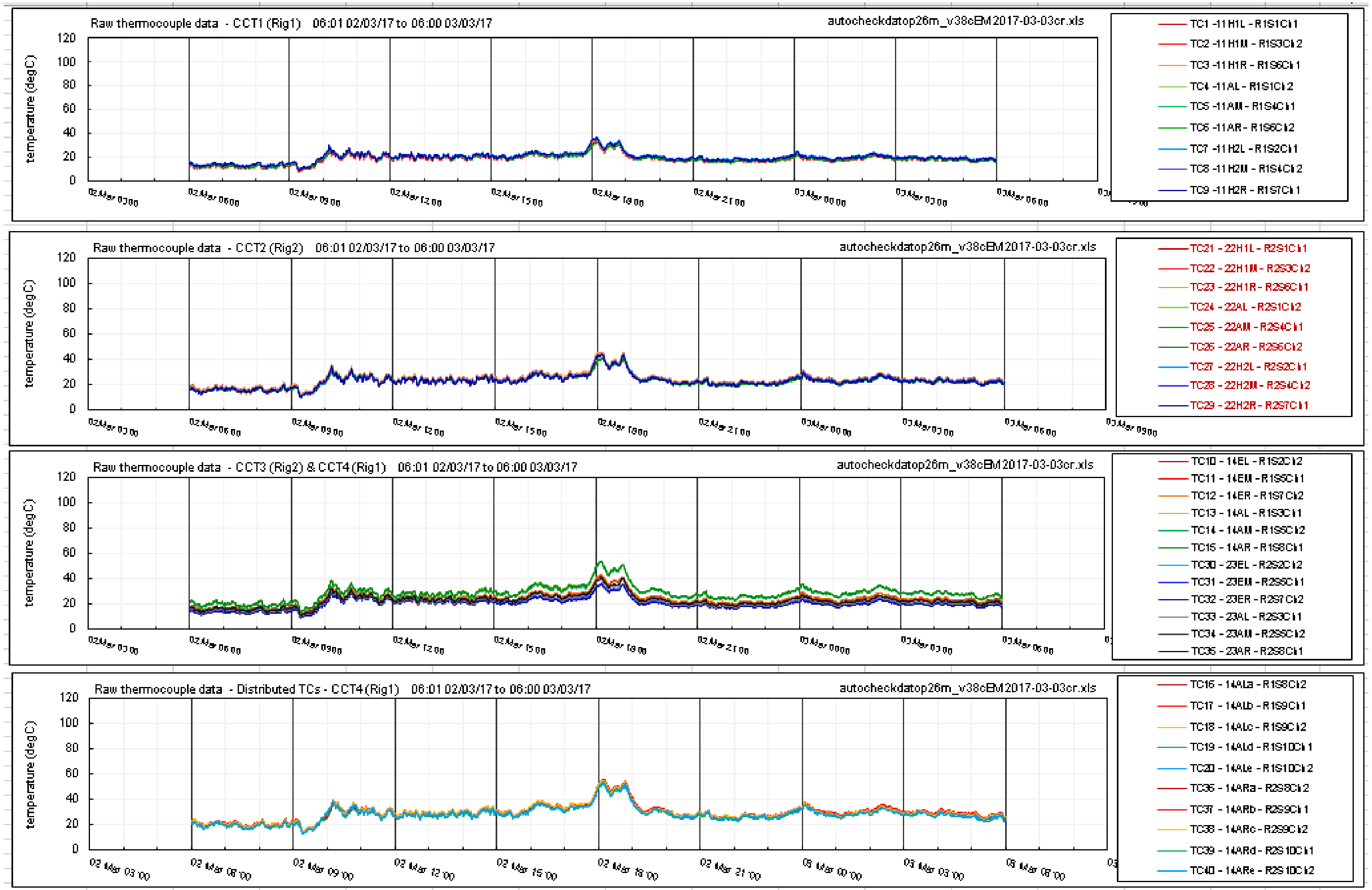


Figure AI.4 "conplot2" sheet (ambient temperatures + power supply volts and amps)

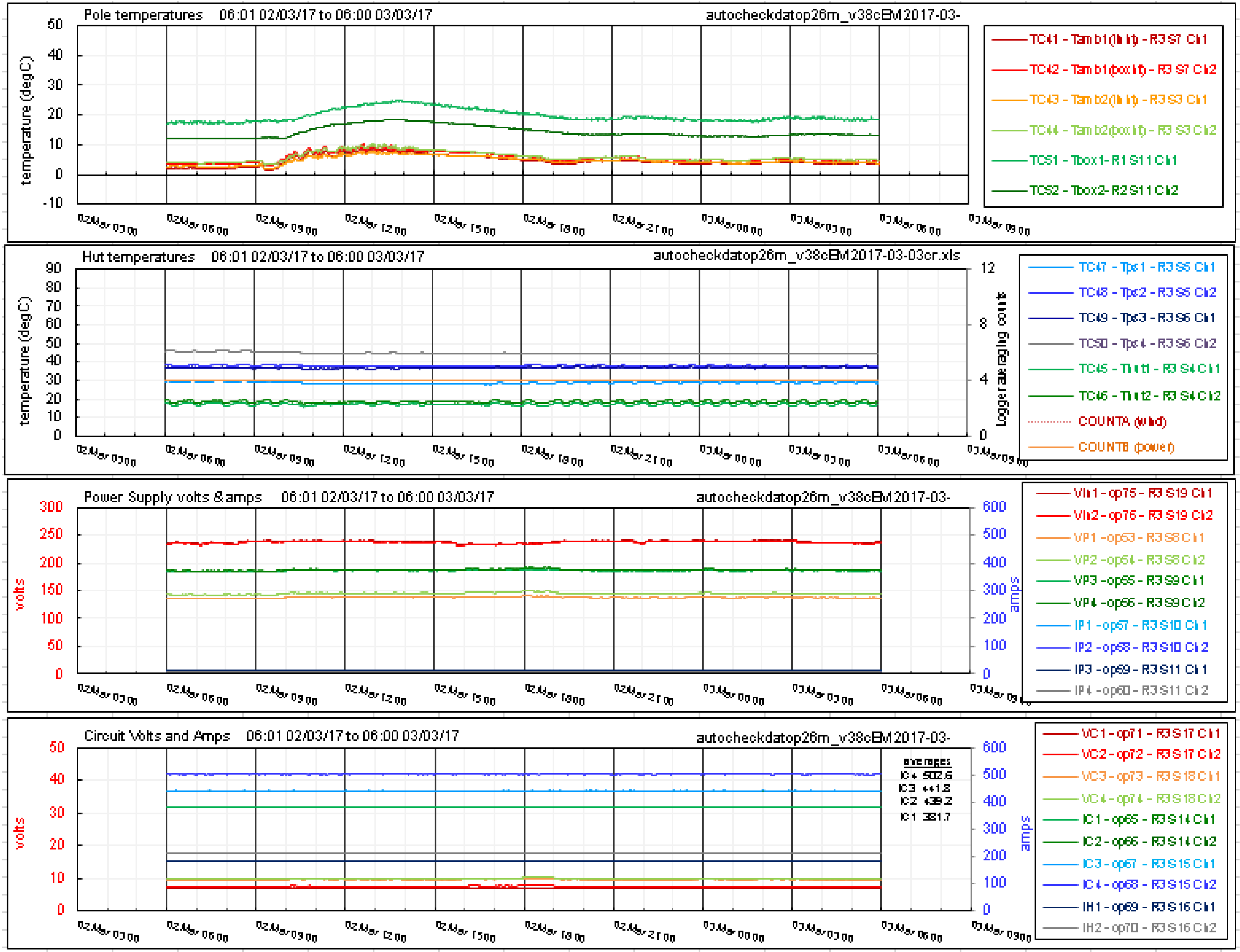


Figure AI.5 "conplot2a" sheet (conductor amps + portacabin temperatures)

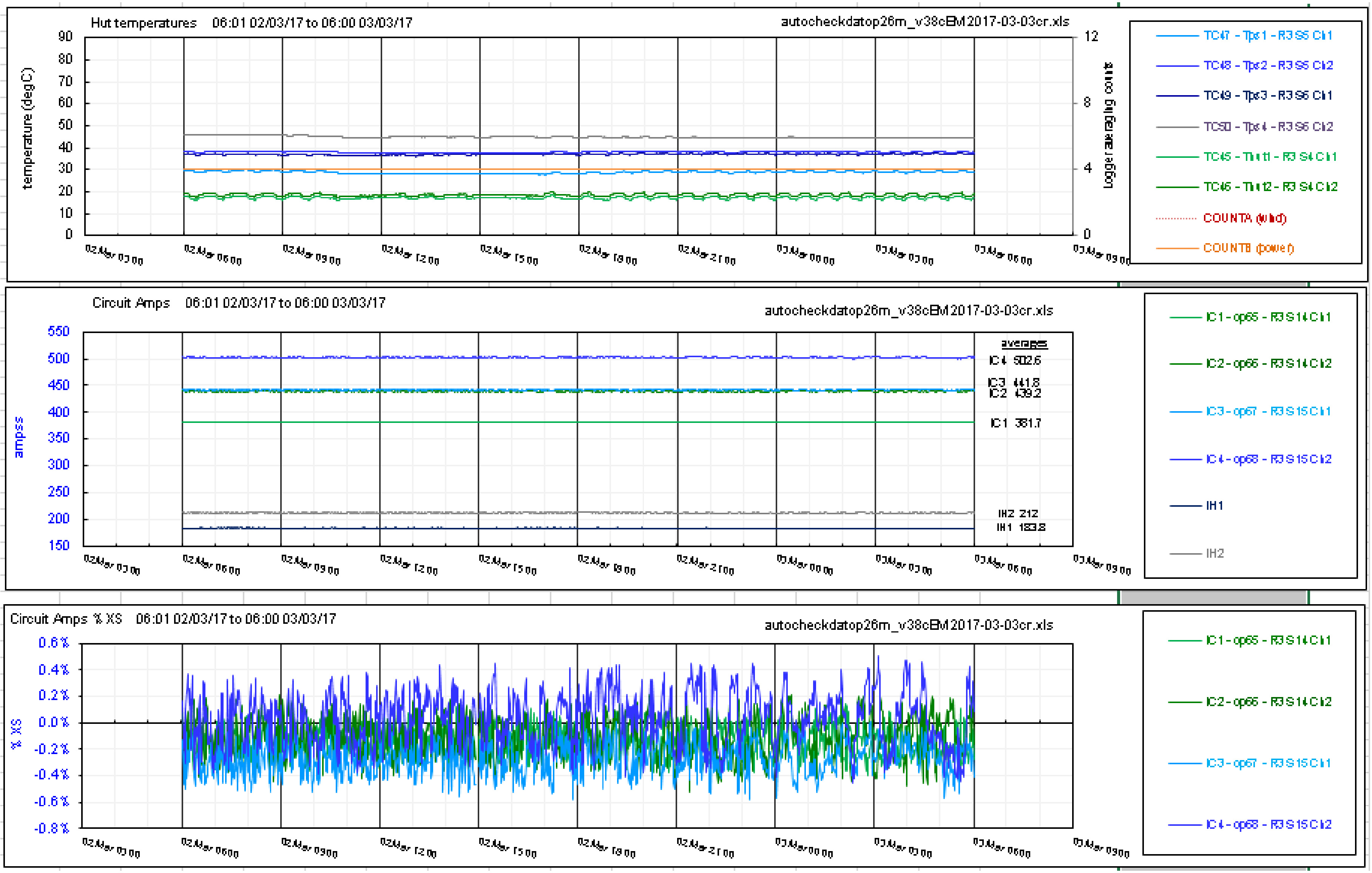


Figure AI.6 "conplot3" sheet (wind speed & direction + solar flux and rainfall)

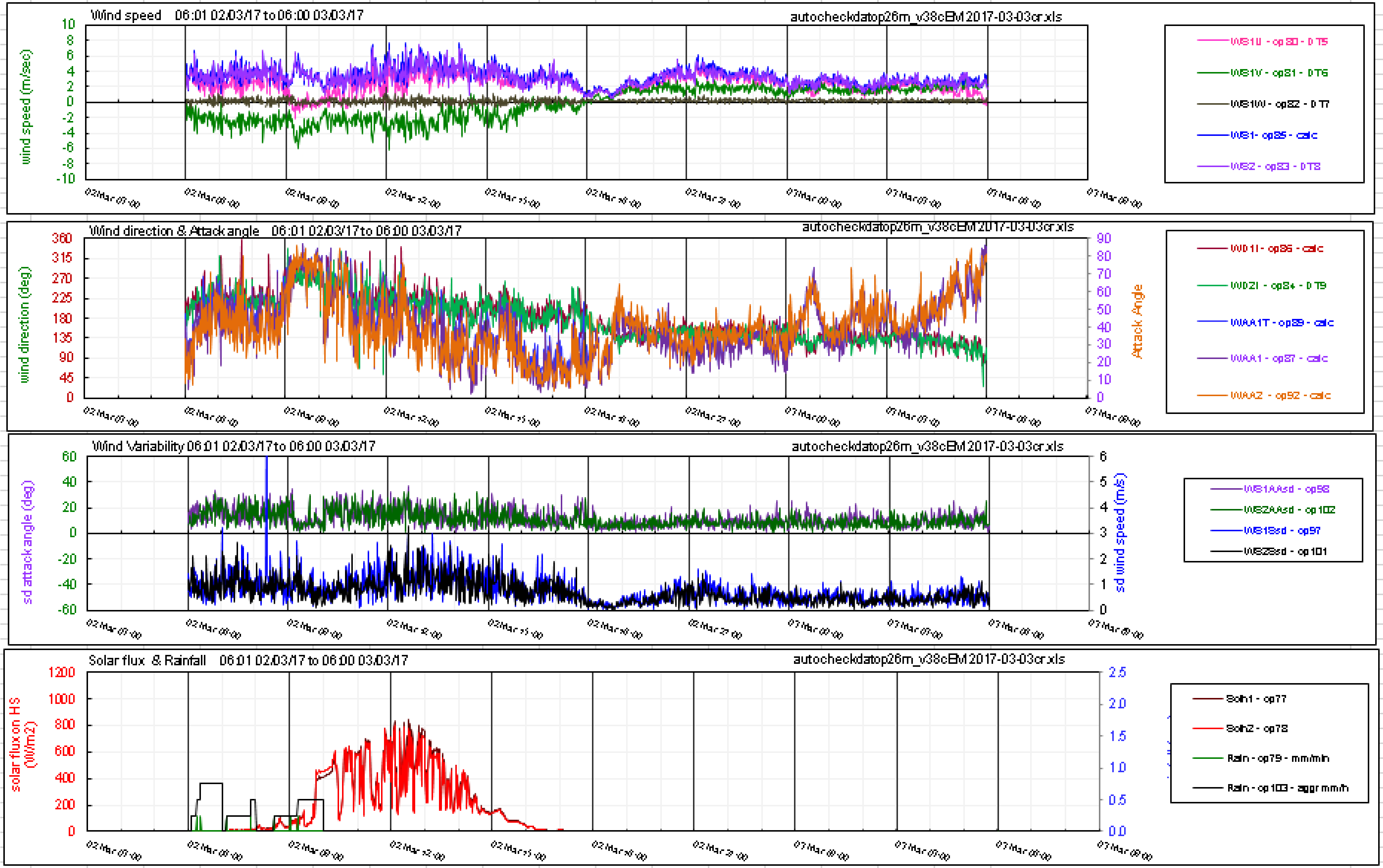


Figure AI.7 "trio plots" sheet (conductor thermocouple within-trios variation)

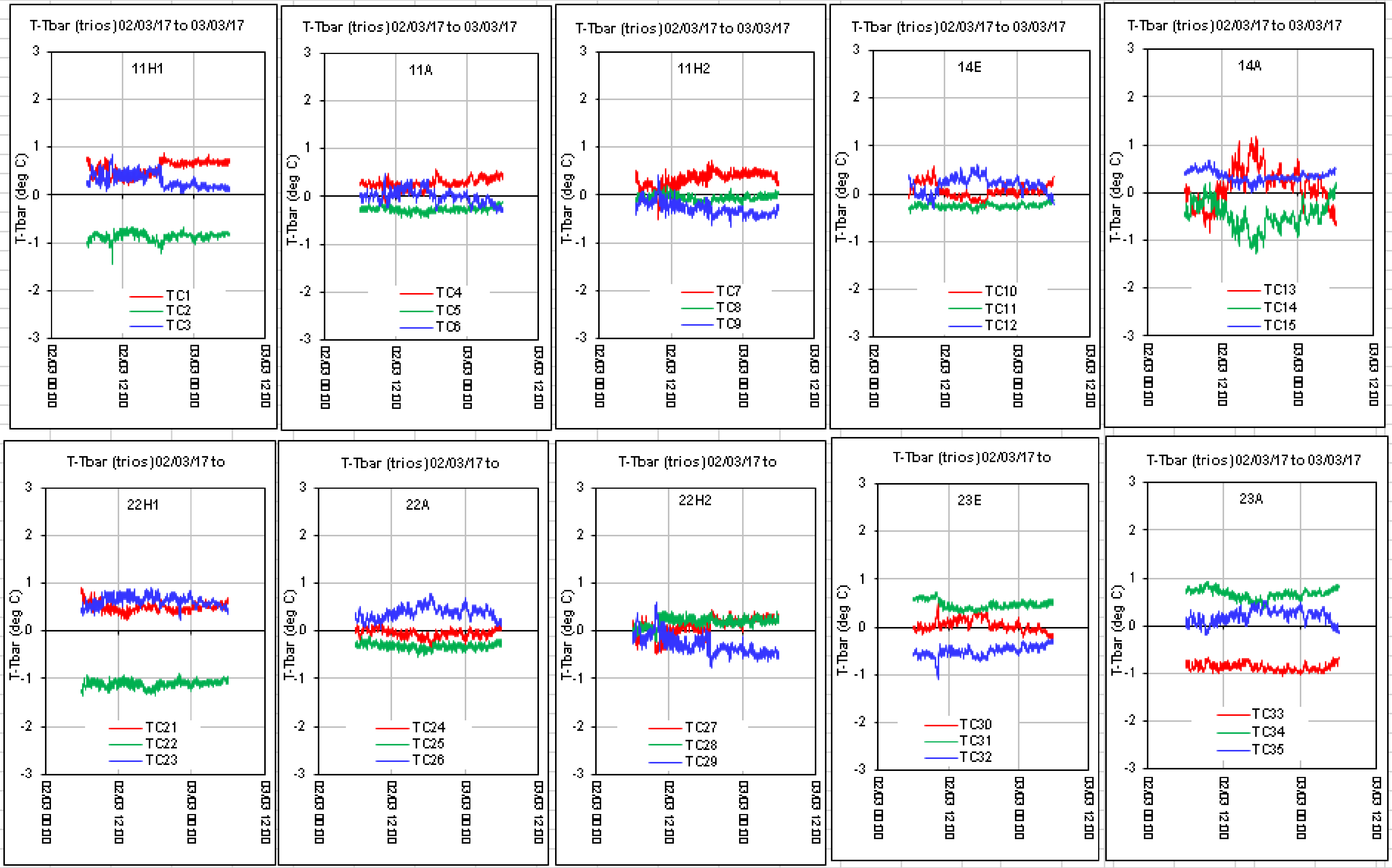
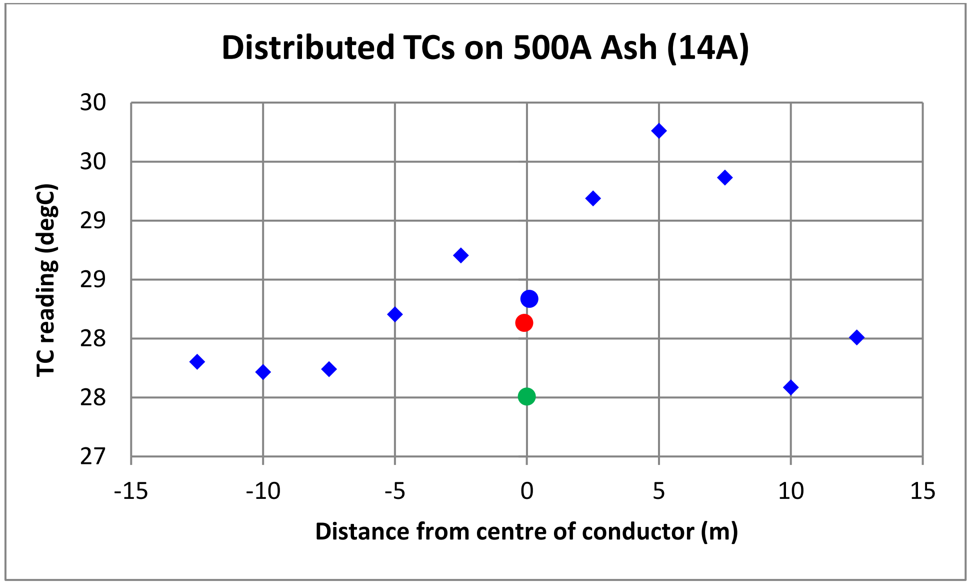


Figure AI.8 "distribTs" sheet (Ash 500 distributed conductor thermocouples + central trio)



Appendix II Schedule of Participants

Project Champion & Lead Company

Company	Project Champion
Western Power Distribution (South West) Plc Avonbank Feeder Road Bristol BS2 0TB	Sven Hoffmann shoffmann@westernpower.co.uk

Participants & Co-funders:

Company	Contact
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Western Power Distribution Avonbank Feeder Road Bristol BS2 0TB	Sven Hoffmann shoffmann@westernpower.co.uk

Appendix III NIA Project Eligibility Requirements

	Specific Requirements	Compliant (✓)
	Specific Requirements Set 1	
	A NIA Project must have the potential to have a Direct Impact on a Network Licensee's network or the operations of the System Operator and involve the Research, Development, or Demonstration of at least one of the following:	
	A specific piece of new (i.e. unproven in GB, or where a Method has been trialled outside GB the Network Licensee must justify repeating it as part of a Project) equipment (including control and communications systems and software);	
	A specific novel arrangement or application of existing electricity network equipment (including control and/or communications systems and/or software);	
	A specific novel operational practice directly related to the operation of the GB Electricity System; or	✓
	A specific novel commercial arrangement.	
	Specific Requirements Set 2	
	A NIA Project must, in addition, meet all 3 requirements described below. These should be clearly demonstrated in the PEA.	
(1)	Has the potential to develop learning that can be applied by all Relevant Network Licensees	
	The learning that will be generated could be applied by Relevant Network Licensees; and / or	✓
	The Project addresses a challenge(s) specific to the Network Licensee's own network (as addressed in its Innovation Strategy).	
	Where a Network Licensee wishes to deviate from the default requirement for Intellectual Property Rights set out in chapter 7 of the Governance Document, the PEA must:	
	Demonstrate how the learning from the Project can be successfully disseminated to network operators and other interested parties;	
	Consider any potential constraints or costs caused, or resulting from, the imposed IPR arrangements; and	
	Justify why the proposed IPR arrangements provide value for money for Customers.	
(2)	**Has the potential to deliver net financial benefits to existing and / or future Customers**	
	An estimate of the saving if the Problem is solved is provided.	✓
	A calculation of the expected financial benefits of a Development or Demonstration Project (not required for Research Projects) is included	
	An estimate of how replicable the Method is across GB in terms of the number of sites, the sort of site the Method could be applied to, or the percentage of the GB electricity network, where it could be rolled-out is provided.	

Specific Requirements		Compliant (✓)
	An outline of the costs of rolling out the Method across GB is included.	

(3)	Does not lead to unnecessary duplication*	
	This NIA Project does not unnecessarily duplicate other projects previously registered and funded under IFI, LCN Fund, NIA and NIC; or	✓
	Justification is provided in the PEA as to why the Network Licensee is undertaking a Project similar to one that has already been funded; and	
	The PEA demonstrates that no unnecessary duplication will occur as a result of the Project.	

* Unnecessary duplication is likely to occur if the new NIA Project is not expected to lead to new learning. Projects that address the same Problem, but use a different Method, will not be considered as unnecessarily duplicating other Projects. For the avoidance of doubt, Projects that are at different TRLs will not be considered as unnecessarily duplicating other Projects.

Global Footprint

We provide products, services and support for customers in 90 countries, through our offices in Australia, China, Europe, Singapore, UAE and USA, together with more than 40 distribution partners.

Our Expertise

We provide world-leading asset management solutions for power plant and networks.

Our customers include electricity generation, transmission and distribution companies, together with major power plant operators in the private and public sectors.

- Our products, services, management systems and knowledge enable customers to:
- Prevent outages
- Assess the condition of assets
- Understand why assets fail
- Optimise network operations
- Make smarter investment decisions
- Build smarter grids
- Achieve the latest standards
- Develop their power skills