REPORT

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

Private and confidential

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Safer, Stronger, Smarter Networks

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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 weather conditions and co-incident temperatures of various conductors 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 CIGRE:** 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 and 4 degC higher than those calculated using the Cigre 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 to +9 degrees.

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 3.64 ± 1.34 °C for 2016 and 3.43 ± 1.75 °C for 2017.

C4. Two winter months in 2017 (November and December) and one in 2016 (January) gave significantly higher differences than the other months. A possible cause was that on the selected "hot days" for the months concerned, there were early morning periods when windspeed was low and temperatures were around freezing.

C5. Frequency distributions for measured and calculated conductor temperatures over a complete season (summer 2017, Ash 500) were quite similar, but there was a noticeable displacement between them, with the measured values shifted towards higher temperatures. An increase of just 1K in the calculated values caused the displacement between the two curves to more or less disappear. 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 approximately 1K lower than the measured values.

C6. A study of seasonal boundaries showed that for the initial 12-month period there was a clear summer period comprising June to September (cf May to August in P27) but a much less clear separation of the non-summer data into autumn/spring and winter. Overall, the best split was into just two seasons, namely a 4-month summer season and an 8-month winter season. i.e. summer period being June to September (4 months) and winter being October to May (8-month). A symmetrical four-season split was not really justified from the data.

C7. A radical seasonal split is proposed with four 3-month seasons, each with a different design ambient temperature Tamb (cf P27 which has the same Tamb for spring and autumn). Winter and summer would comprise the obvious three cold months (Dec–Jan–Feb) and the obvious three hot months (Jun–July–Aug) while spring and autumn would be replaced by more complex intermediate cool and intermediate warm seasons, respectively comprising the relatively cool spring and autumn months (Mar, Apr and Nov) and the relatively warm spring and autumn months (May, Sep and Oct). Provisionally, design ambient temperatures would be kept as close as possible to P27 values, with winter and summer values remaining at 2˚C and 20˚C, and the spring/autumn 9˚C split into 6˚C and 12˚C for the intermediate cool and intermediate warm values. This provisional scheme was subsequently ditched in favour of a more realistic set.

C8. Exceedence was found to depend upon the assumed design temperature, as expected from previous work. It was also found to be dependent, to a lesser extent, on ambient temperature.,

C9. CT curves for all the conductors, currents and seasons, based on the proposed seasonal split and provisional values of design ambient temperature, exhibited a significant amount of variation. This variation was mainly associated with different seasons rather than different currents. Replotting the CT curves using design Tamb values derived from our measured average Tamb values (14.3, 11.0, 6.6, 3.6°C) rather than the arbitrary provisional ones (20, 12, 6, 2°C) greatly reduced the seasonal variation.

C10. A plot of all 40 conductor-current-season combinations on the same plot using measured average Tamb values shows 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. Since our measured ambient temperatures were very similar to the Met Office 30-year UK averages, it was decided that the latter standard values should form the basis of our recommendations.

C11. A best fit to all the CT values for 2017, based on Met Office 30-year average temperatures, 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.

C12. 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. It is therefore recommended that a CT curve derived solely from the 2017 data be used.

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 Cigre 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 relating 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 CIGRE:** validated an updated CIGRÉ methodology [ref5: CIGRÉ Technical Brochure TB601 "Guide for thermal rating calculations of overhead lines" (2014]. 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 II:

- 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 **WPD Test Rig site**

The project 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[1], 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 a previous STP project[2] 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.

NB: Ratings can be much lower in sheltered areas. It must be noted that this project will not study this. As such, the resultant software tool to rate lines will not factor in shelter.

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, that enabled frequent consultation to assist with

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[1] The project recorded data collection for twenty four months. The project did not gather data from any other source, nor is it continuing to gather data beyond the planned twenty four months of data collection.

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 seen 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 LDC	Omitted from project scope
		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	Not Started
		Decommission Test-rig	Complete
7	Integrated Software Tool	Specification Developed	Complete
		"Beta"/Test version of software released	Complete
		Final Release of Software	In Progress
8	Project Conclusion	Final Project Report Complete	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;
- 150mm^2 "Ash" AAAC;
- 175mm^2 "Elm" AAAC.

The configuration of the overhead line test rig conductors is illustrated in the Outline Plan in Figure 2 and can visually be observed in Figure 3.

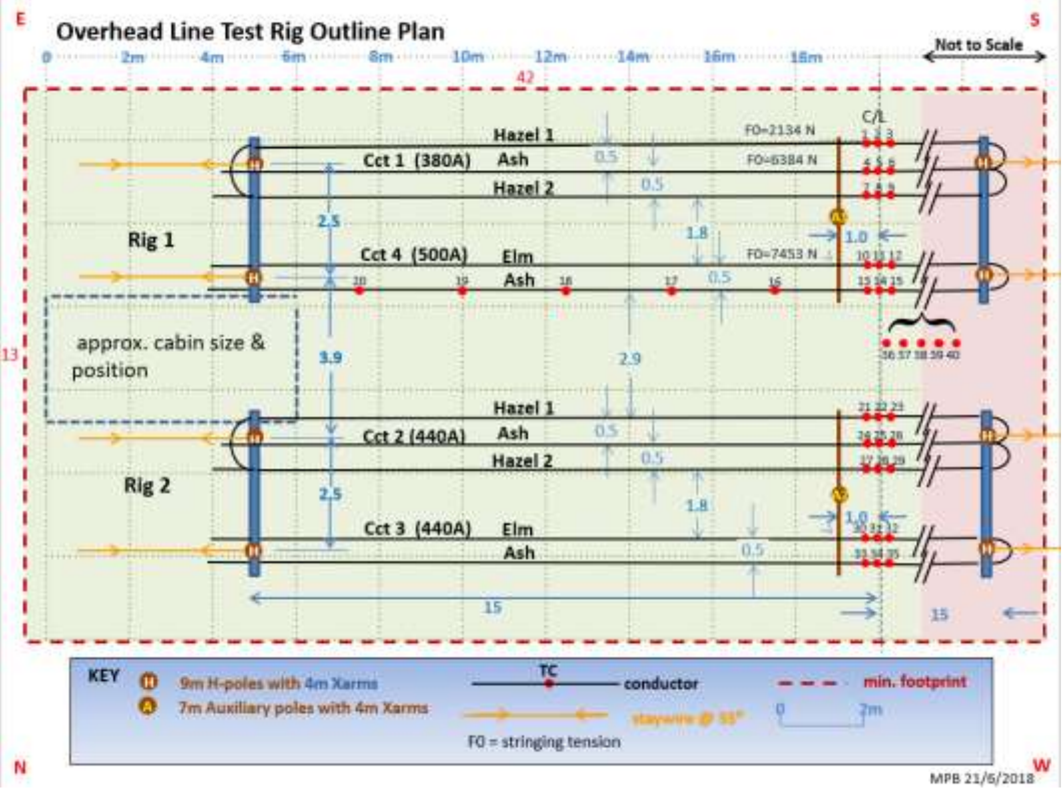


Figure 2 **Overhead line Rig construction diagram**

Figure 3 **OHL conductor configurations at Terminal H-poles**

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.

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

Figure 4 **Example of 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;
  - 0-510 A 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;
  - 0-400 A 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: 0-530 A AC input produces 0-10 V DC output;
  - ICC4: 0-660 A 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 (Hut);
  - Line approx. NE-SW (actually 40 degrees) so 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
- **Solar Radiation**
  - Two pyranometers (total radiation sensors), one at portacabin-end, one at mid-span;
  - Mounted horizontally 1 m 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 WPD, Stoke project site, are shown in Figure 5.

Figure 5 **Weather monitoring equipment installed on freestanding intermediate wood poles and conductor thermocouples**

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 6.

Figure 6 **Portacabin (Hut) 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) working 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 observed in Figure 7 and Figure 8.

Figure 7 **Post fire Portacabin Interior**

Figure 8 **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 (OHL) 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 21 months due to the fire in the instrumentation hut discussed above, which resulted in the rig's being out of action for the 3 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 9-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 are stored in the ***"condat"*** worksheet of the relevant CHECKDAT workbook for that day.

5.2 Data Acquisition Details

The data collection arrangements were as follows.

- The main parameters to be 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
  - Ambient temperatures (indoor and outdoor)
  - Power supply temperatures
  - Conductor currents
  - Power supply voltages
  - Wind speed and direction at line height
  - Solar radiation on a horizontal surface
  - Rainfall
- Measurements were made using 105 sensors of various types connected to an industrial data logger (DataTaker DT85).
- Sensors used include
  - thermocouples for temperature measurement,
  - current transformers and voltage transducers for current measurement,
  - 3D and 2D ultrasonic anemometers for wind magnitude and direction measurement,
  - solarimeters for sunshine measurement,
  - tipping bucket rain gauge for rainfall measurement.
- The data logger carried out a complex scanning and logging programme at 1-minute intervals.
  - “Driving” parameters, such as currents and voltages, wind and sunshine, were measured every 15 seconds from which 1-minute averages were calculated and logged.
  - “Dependent” parameters such as conductor temperatures and power supply temperatures, were both measured and logged just once a minute

  - Other temperatures were also only measured once a minute since they did not change rapidly enough to warrant 15-second scanning.
  - The number of tips of the rain gauge is also only measured once a minute but its readings are aggregated over an hour, with both minute and hourly readings logged.

- As well as calculating these 1-minute averages, the data logger, carried out further limited data processing of the various signals before logging them. It converted measured voltages into Engineering units, worked out wind directions from component wind speeds and vice versa, and calculated average “wind attack” angles on the conductor.

- The validated daily data was downloaded each day to a daily CHECKDAT file where they were checked and processed and then stored in the "condat" worksheet of the CHECKDAT file.

5.3 Data Acquisition Problems

- 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 Wind Master anemometer readings - did not generally result in any loss of data rows. Neither replacing the anemometer 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 23 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.

5.4 Compilation of the Cleansed Dataset

The Cleansed Dataset comprises a concatenation of the daily "condat" data into monthly blocks. Significant effort was expended to ensure the "cleanliness" of the daily files. The procedure is described in the December 2017 Quarterly Report QR8.

As noted in QR8, the cleansed data files needed 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 is usually the mean of the two or three readings.

Initially, it was thought that the conductor thermocouple trios might be an exception to this 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 was therefore deemed to be the most appropriate value to choose. However, in the present project, the trio means appear to give better agreement with the values calculated using the Cigré equations than do the trio maxima, so the means will be used for the conductor thermocouples too.

The parameters for which average values need to be determined are shown in Table 1.

Table 1 : 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 (single t/c TC41after 9th Nov)
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

The concatenated files are split into two versions: version 3a covers data obtained prior to the 11th May 2017 and version 3b covers data obtained after 11th May 2017. The two versions are necessary because of the relocation on 11th May of the hut-end solarimeter, solh2, to the outer H-pole to avoid shadows. Prior to this, version 3a sets sol equal to the **higher of two solarimeter readin**gs but after the move, version 3b sets sol equal to the **average of the two solarimeter readings**.

6. Data Analysis

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

6.1.1 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 degC. 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).

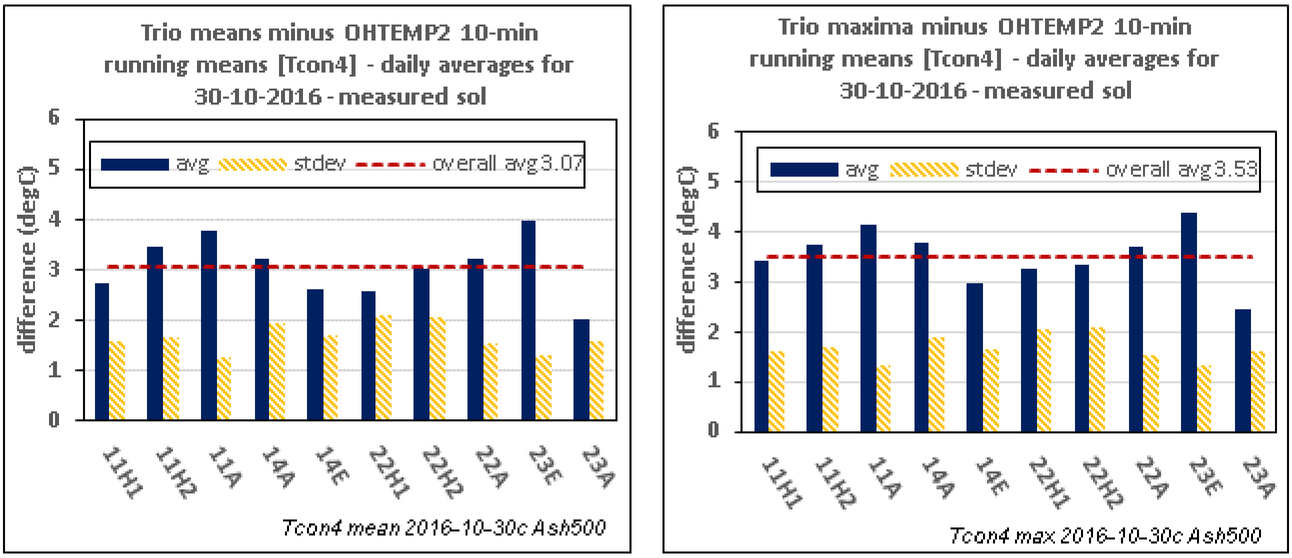
It was found that

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 9 shows the daily averages of the differences obtained for each conductor using 10-minute running means for the calculated values and either the trio means or the trio maxima for the measured values.



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

Figure 9 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 10 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.

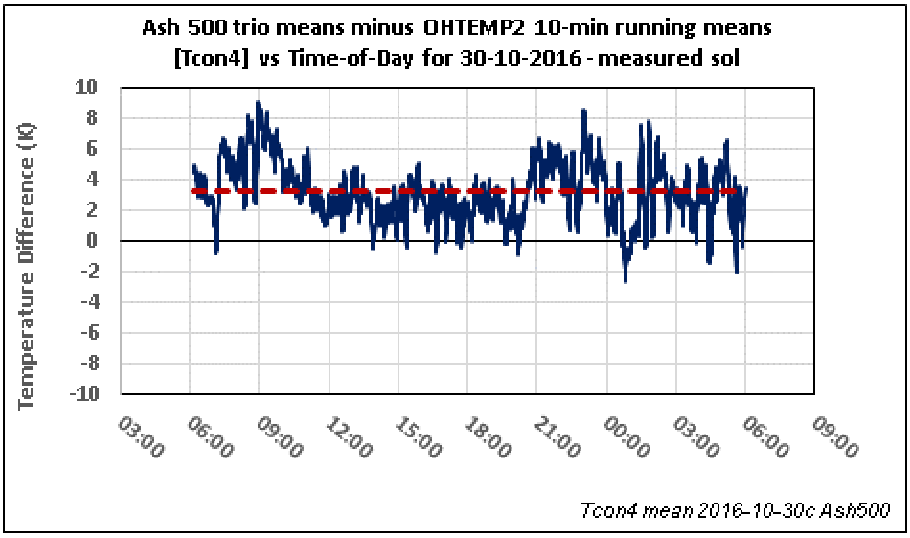


Figure 10 : 1-minute temperature difference (trio means minus calculated 10-minute running means) for the hottest conductor (Ash500) on a "high-temperature day" (29-30 October 2016)

6.1.2 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 0 for 2016 and Table 3 for 2017. The overall mean difference for 2016 was 3.64 ± 1.34 °C whilst for 2017, it was 3.43 ± 1.75 °C.

Table 2 **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 3 **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

It is worth noting that in Table 3, 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 0, in the January 2016 results.

A possible cause for these abnormally 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 11 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.

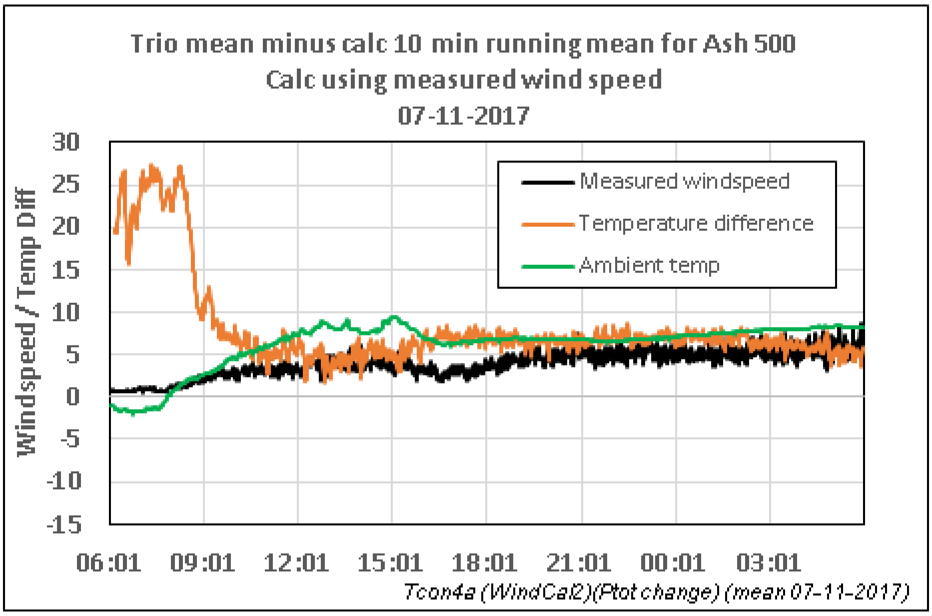


Figure 11 **Trio means minus calculated conductor temperatures (orange) for 7th Nov 2017 for Ash 500 along with measured windspeed (black) and measured ambient temperature at line height (green)**

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 0.5 m/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 Cigre TB601).

6.1.3 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 (3 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 12.

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

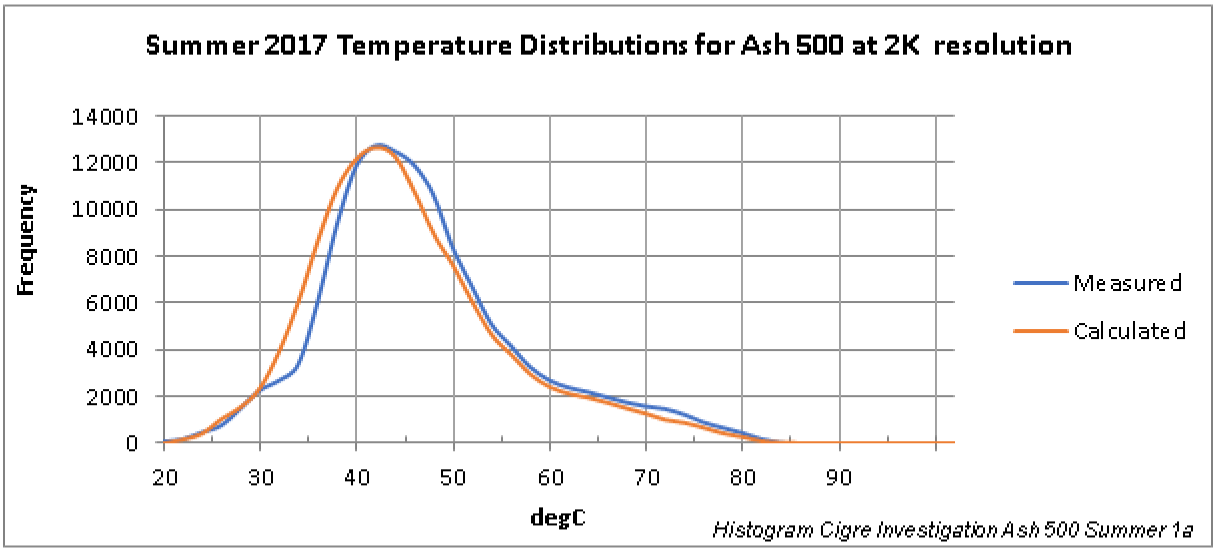


Figure 12 Frequency Distributions of Measured and Calculated Conductor Temperatures for the 2017 Summer (3 months) for Ash 500

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 13.

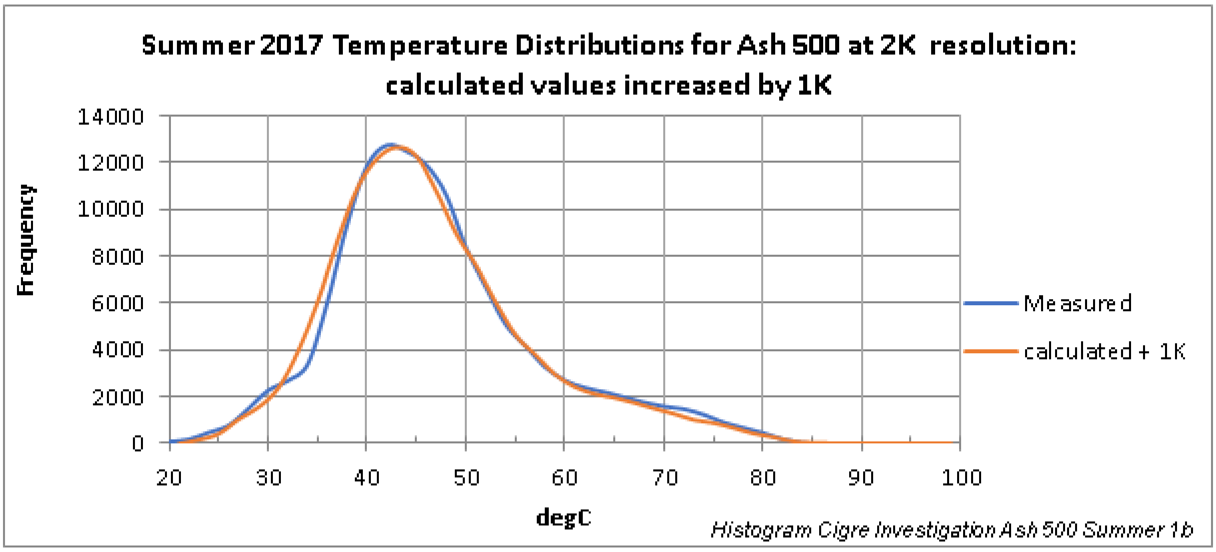


Figure 13 Same data as Figure 12 but with calculated values increased by 1K

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 Seasonal Boundaries

6.2.1 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 one.

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 Figure 14, 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 hut.)

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.

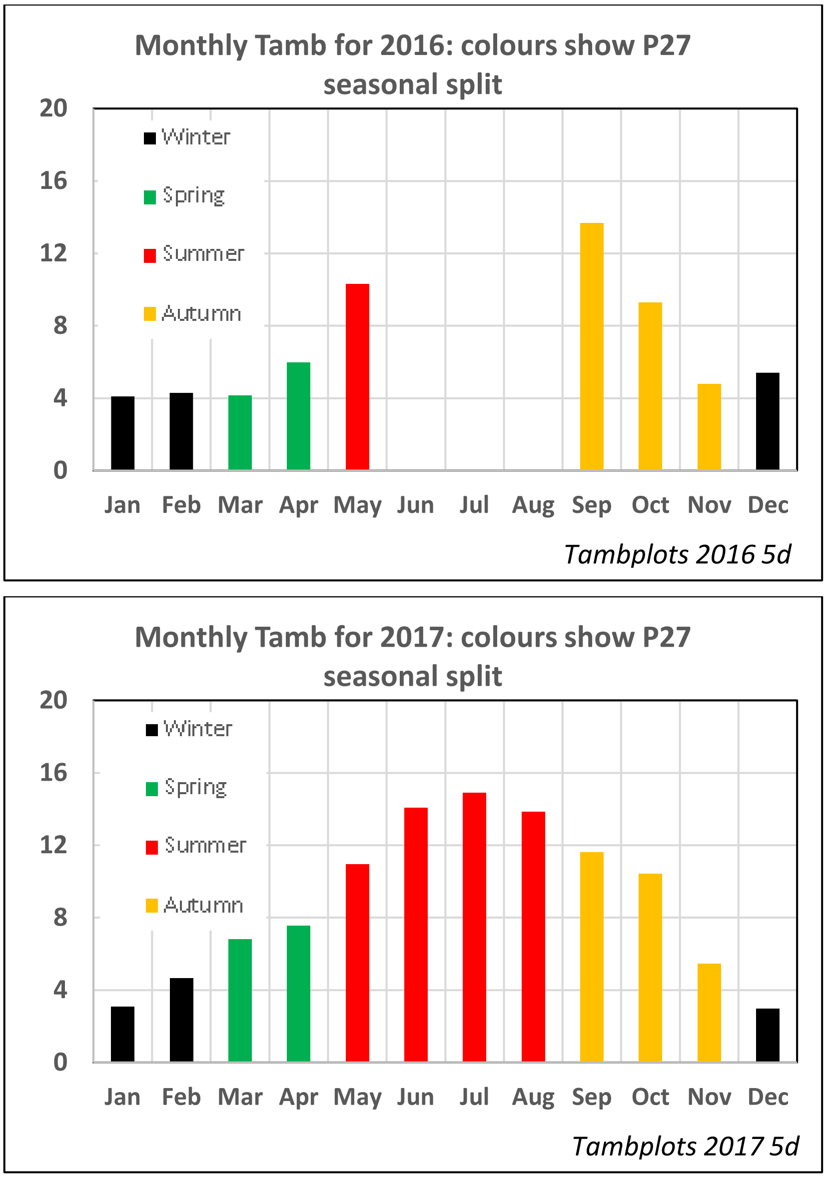


Figure 14 **Measured monthly mean ambient temperatures for 2016 & 2017 Colours denote <u>P27 seasons</u>**

6.2.2 Monthly Excursions and Seasonal Boundaries

A preliminary analysis of conductor temperatures was undertaken to further investigate the seasonal boundary problem. The first complete 12 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 15, from which we can see that the appropriate range of Tref for Ash 500 is 65°C to 85°C.

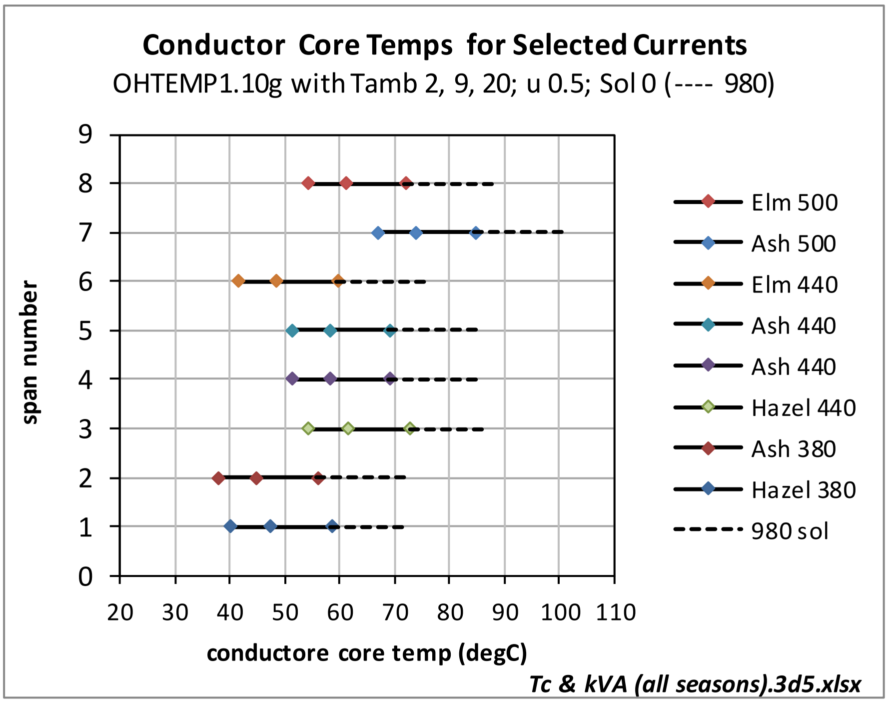
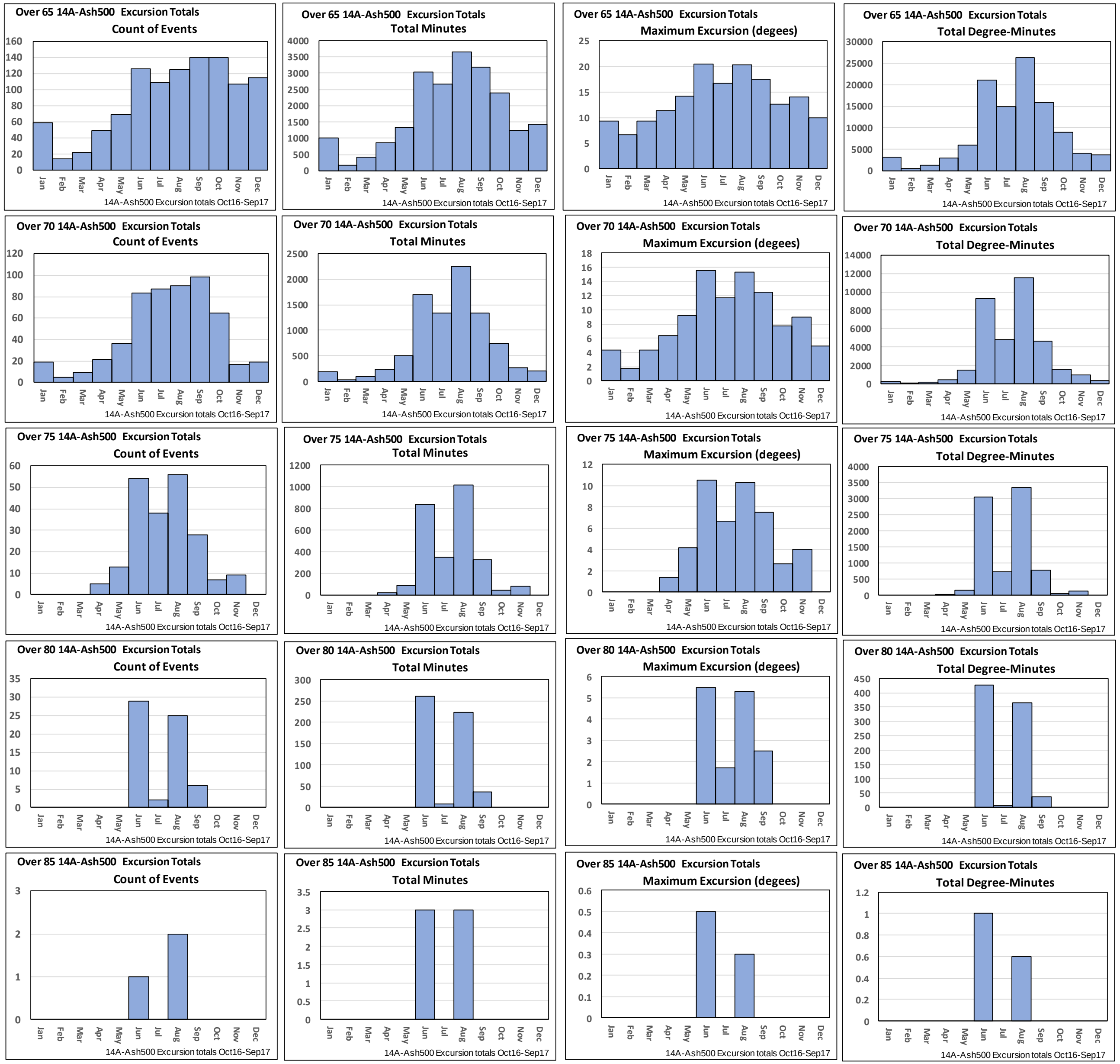


Figure 15 **Rig design values of Tcon from OHRAT**

Figure 16 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.



Over 65 14A-Ash500 Excursion Totals Count of Events

Over 65 14A-Ash500 Excursion Totals Total Minutes

Over 65 14A-Ash500 Excursion Totals Maximum Excursion (degees)

Over 65 14A-Ash500 Excursion Totals Total Degree-Minutes

Over 70 14A-Ash500 Excursion Totals Count of Events

Over 70 14A-Ash500 Excursion Totals Total Minutes

Over 70 14A-Ash500 Excursion Totals Maximum Excursion (degees)

Over 70 14A-Ash500 Excursion Totals Total Degree-Minutes

Over 75 14A-Ash500 Excursion Totals Count of Events

Over 75 14A-Ash500 Excursion Totals Total Minutes

Over 75 14A-Ash500 Excursion Totals Maximum Excursion (degees)

Over 75 14A-Ash500 Excursion Totals Total Degree-Minutes

Over 80 14A-Ash500 Excursion Totals Count of Events

Over 80 14A-Ash500 Excursion Totals Total Minutes

Over 80 14A-Ash500 Excursion Totals Maximum Excursion (degees)

Over 80 14A-Ash500 Excursion Totals Total Degree-Minutes

Over 85 14A-Ash500 Excursion Totals Count of Events

Over 85 14A-Ash500 Excursion Totals Total Minutes

Over 85 14A-Ash500 Excursion Totals Maximum Excursion (degees)

Over 85 14A-Ash500 Excursion Totals Total Degree-Minutes

Figure 16 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

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

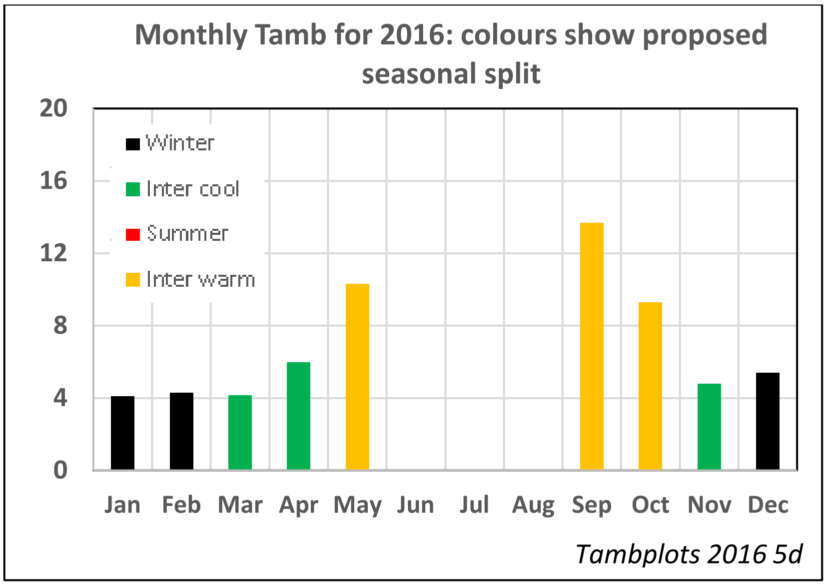
In view of the above, the following alternative and somewhat radical solution to these problems is proposed:

- 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 17 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.



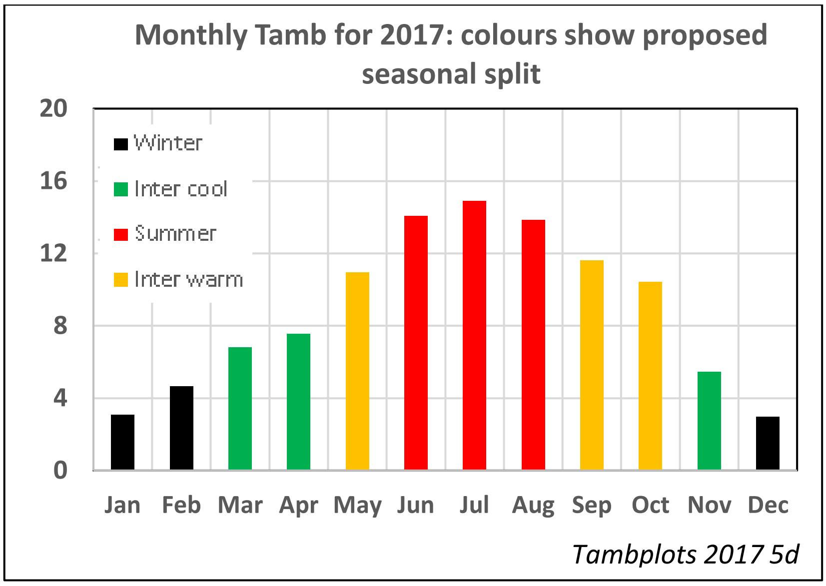


Figure 17 **Measured monthly mean ambient temperatures for 2016 & 2017. Colours denote Proposed Seasonal Split**

Consideration was given to keep design ambient temperatures as close as possible to P27 values. Winter and summer values could remain at 2°C and 20°C, whilst the 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 4) suggests that this scheme is not optimum, and this was confirmed by analysis of the resulting CT curves (see next Section).

Table 4 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

6.3 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 18 shows the variation of NNe, the normalised no. 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 4 namely 2°C, 6°C, 12°C, and 20°C.

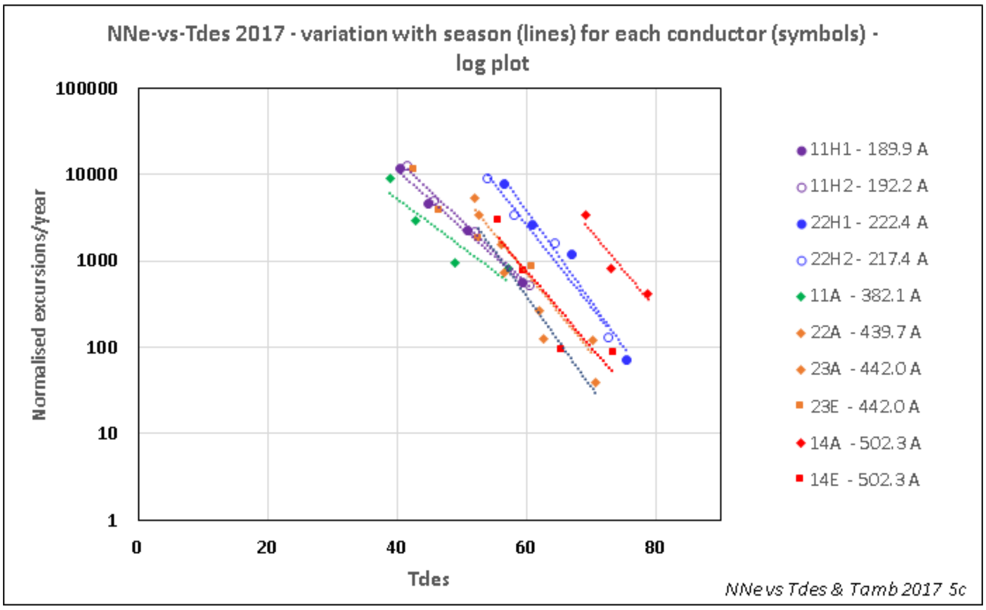


Figure 18 NNe vs Tdes - Variation with season for each conductor 2017

It is obvious from Figure 18 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.

6.3.1 Dependence of Exceedance on Ambient Temperature

A plot like Figure 18 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 18 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.

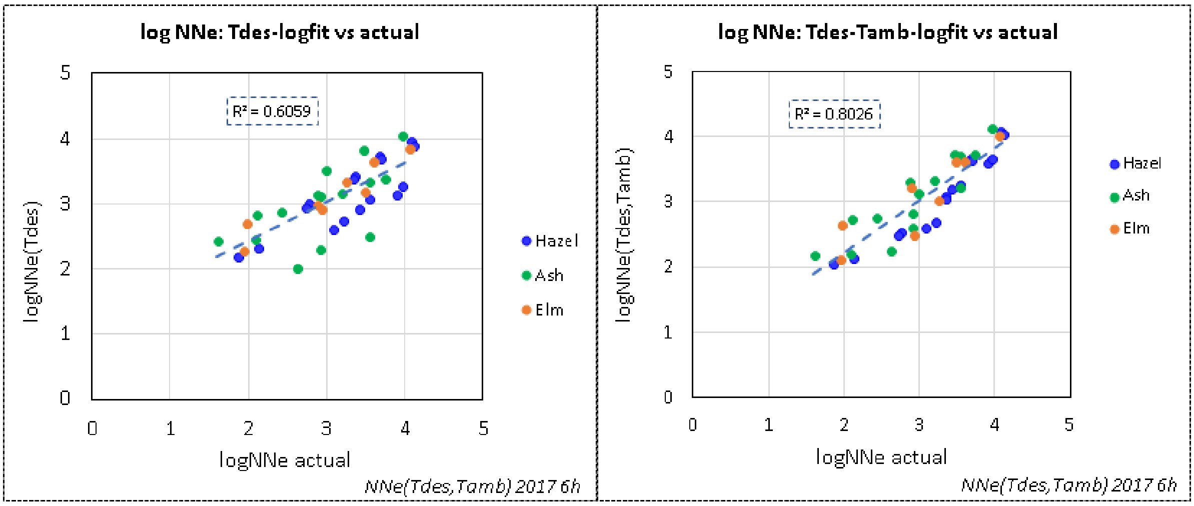


Figure 19 **logNNe calculated values (using linear fit of logNNe) vs actual values (2017 data)**
(a) single regression - Tdes only **(b) double regression - Tdes and Tamb**

Figure 19 shows plots of calculated logNNe values versus actual logNNe values. In Figure 19a, the calculated values are based on the single-variable coefficients from Figure 18 (A & B above). In Figure 19b the calculated values are based on the 2-variable coefficients from Figure 18 (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.)

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

In P27, CT is effectively defined as the square of the ratio of the applied or actual current Iapp to the deterministic rating Idet:

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

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 therefore referred to as the design current, Ides.

CT is a function of exceedance. A knowledge of the relationship CT(e) therefore enables one to deduce a rating for the required exceedance.

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.

An analysis tool has been developed to produce CT curves from the concatenated monthly data files. The 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 20 shows the set of CT curves obtained from the 2017 data for the Ash conductors using the suggested 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.

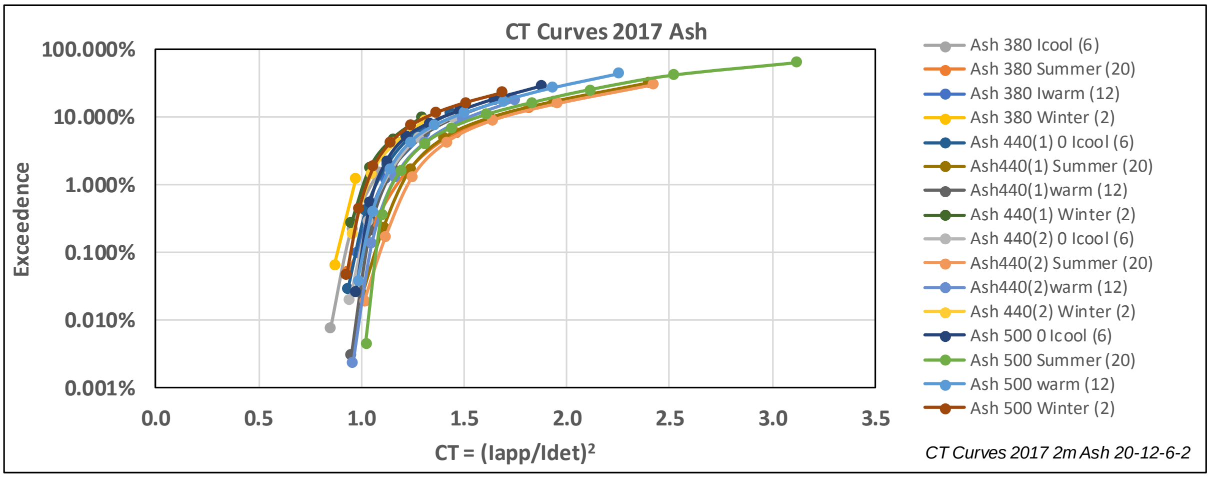


Figure 20 CT curves for the four Ash conductors based on the provisional design Tamb values given in Table 8 (i.e. Summer 20, Inter warm 12, Inter cool 6, Winter 2)

Splitting the data into four plots, one for each season, as in Figure 21 with the four curves in each plot corresponding to the four applied currents, gives plots with far less variation from curve to curve.

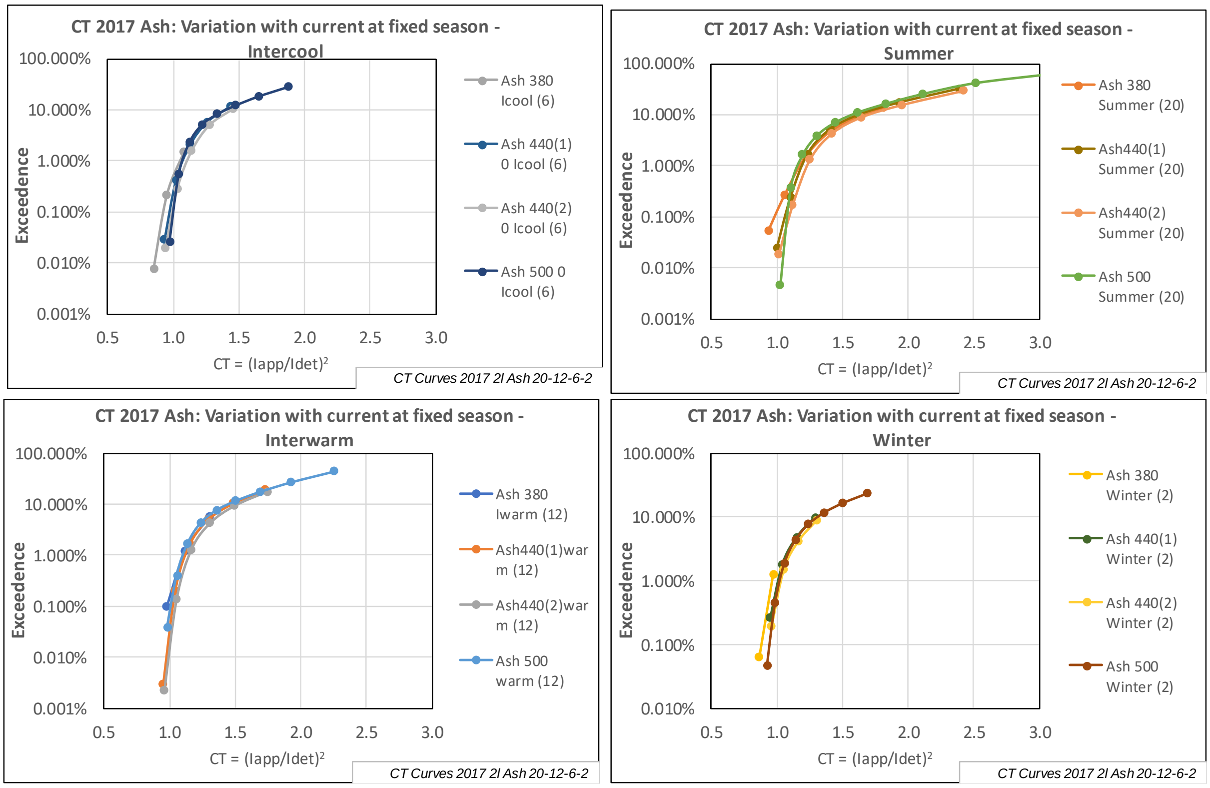


Figure 21 **Same data as Figure 20 but with separate plot for each season. The four curves in each plot correspond to the four currents. (Based on provisional design Tamb: 20-12-6-2)**

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 22, much of the variation remains. This implies that the variation seen in Figure 21 is mainly associated with different seasons rather than different currents.

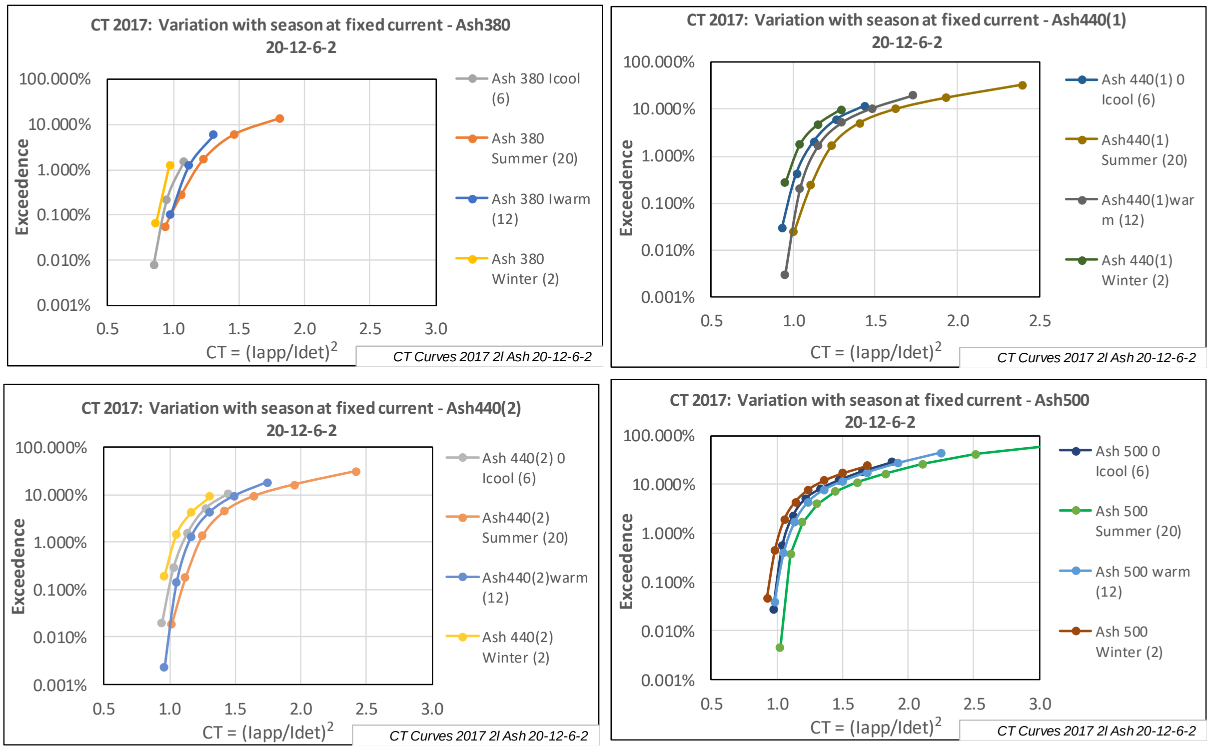


Figure 22 **Same data as Figure 20 but with separate plot for each current. The four curves in each plot correspond to the four seasons. (Based on provisional design Tamb: 20-12-6-2)**

6.5 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 5. 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 5 **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 23 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.

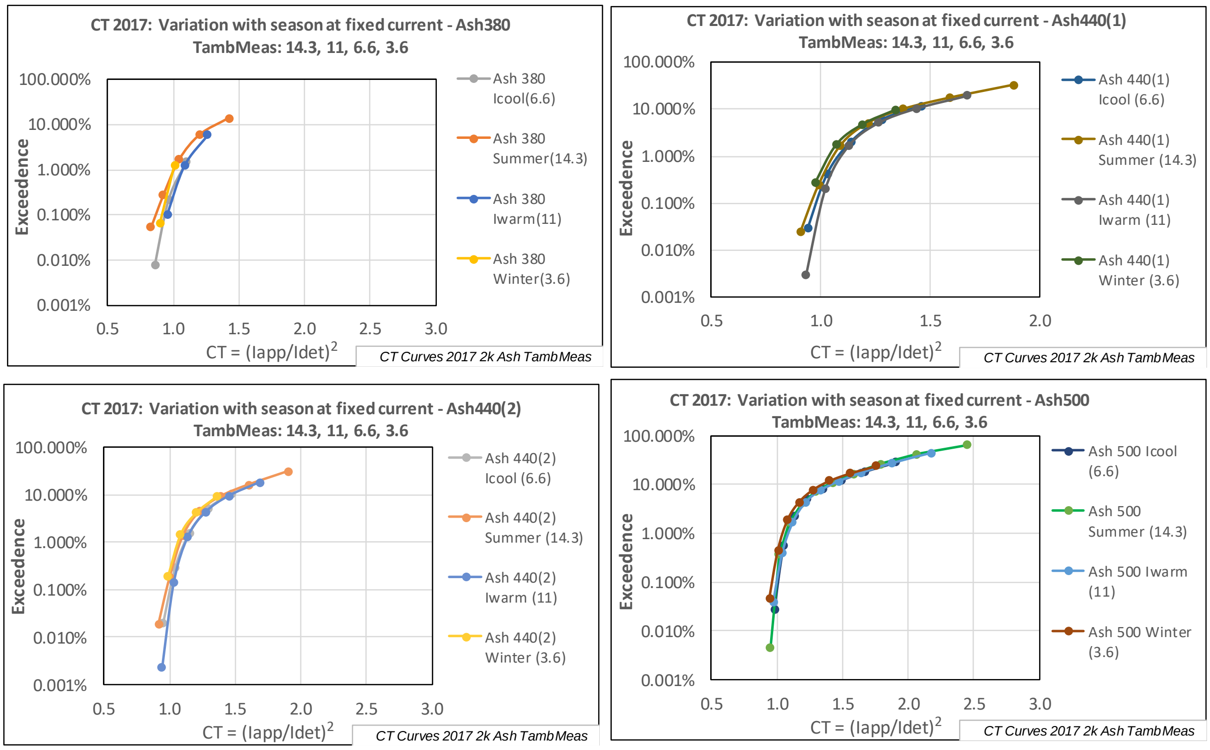


Figure 23 **Same plots as Figure 20 but using design Tamb derived from measured Tamb values**

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 24 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.

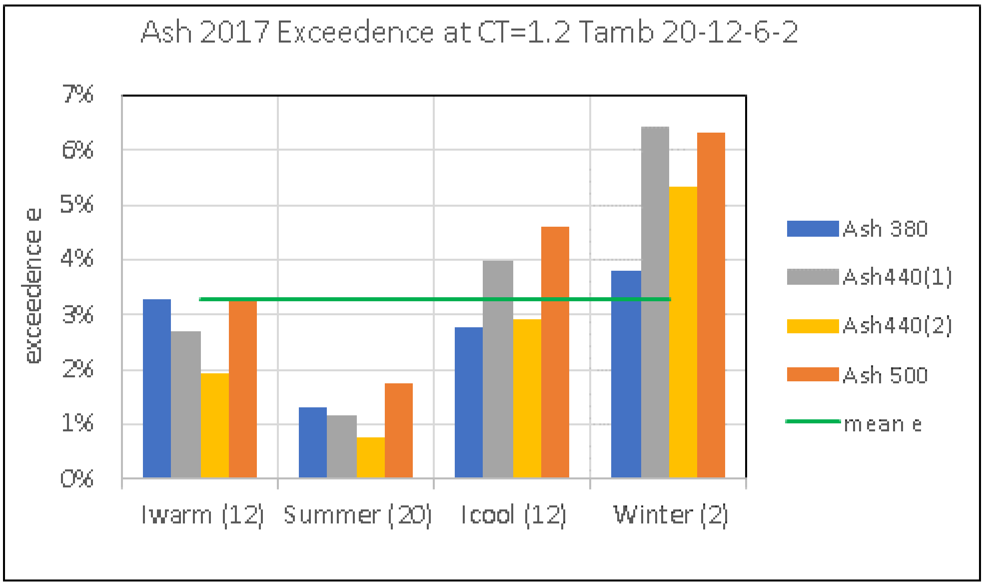


Figure 24 **Exceedances at CT=1.2 for provisional design Tamb values (20-12-6-2).**

Figure 25 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.

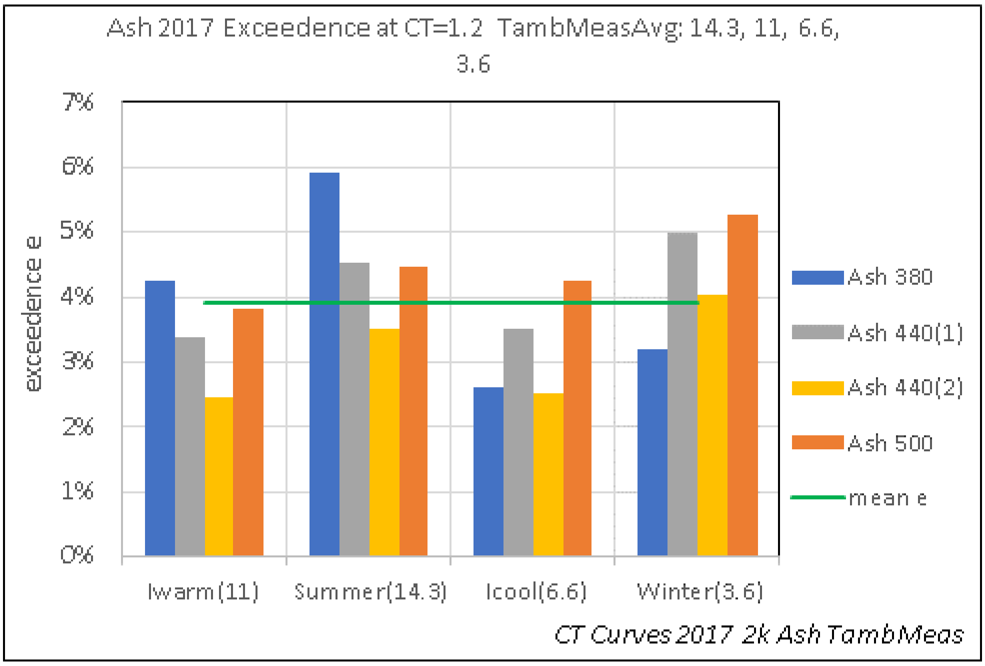


Figure 25 **Exceedances at CT=1.2 for measured design Tamb values (14.3-11-6.6-3.6)**

Table 6 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 6 **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 26 shows all the Ash CT curves on a single plot, based on Design Tamb values derived from the measured Tamb values.

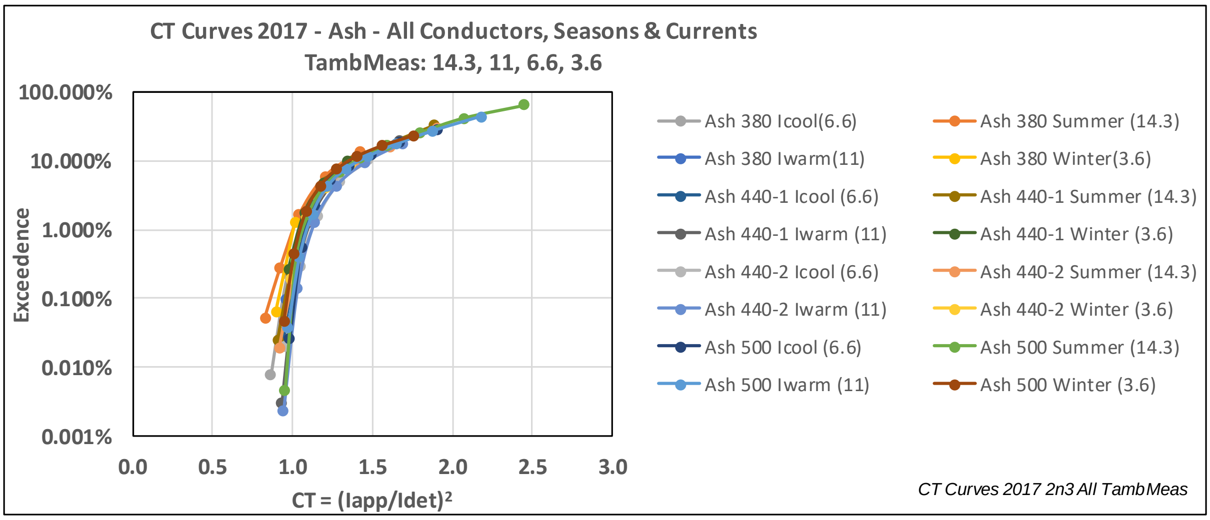


Figure 26 **All the Ash data combined on a single plot with measured Tamb values (14.3-11.0-6.6-3.6) as design values**

Similar plots can be produced for the Hazel and Elm conductors. Figure 27 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.

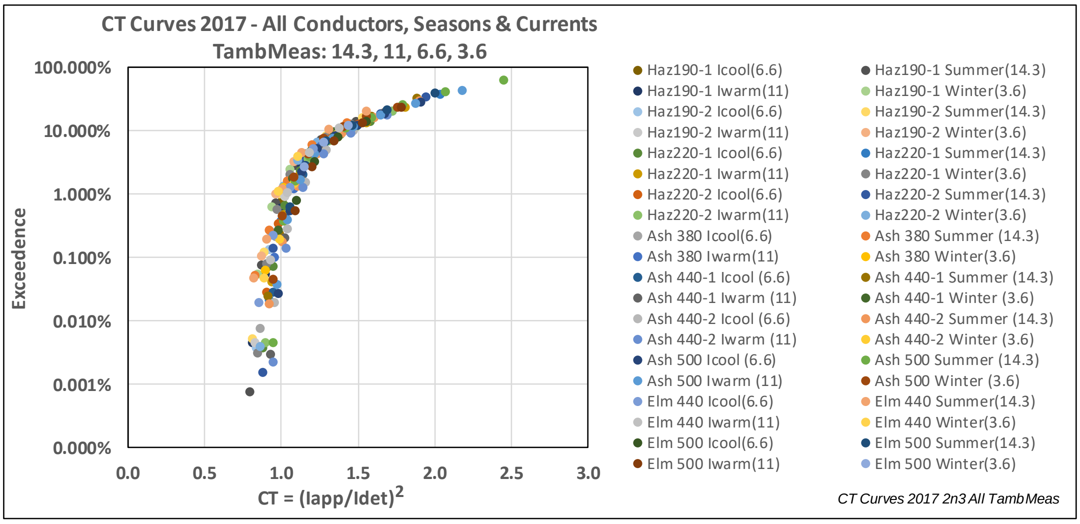


Figure 27 **CT data for all 10 conductor-current combinations. Curves omitted for clarity**

6.6 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 5, 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 7 summarises the chosen design parameters for our CT curve. Note that the Tamb values have been rounded to the nearest whole degree.

Table 7 **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 28 is similar to Figure 27 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 20 to Figure 27) were drawn, causing additional slight discrepancies between the earlier curves and Figure 28.

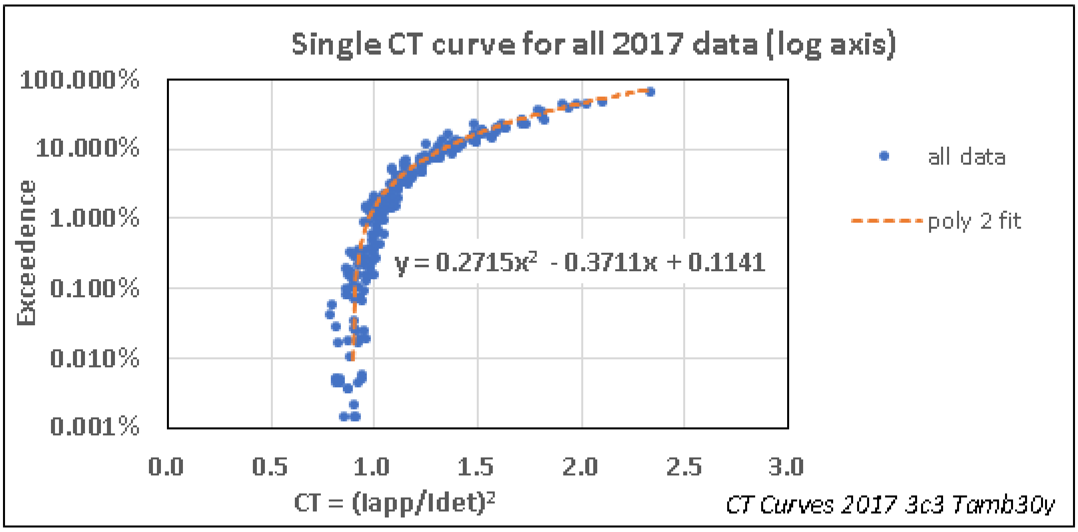


Figure 28 **Similar curve to Figure 27 but with Tamb based on 30y UK averages and plotted as one single curve to enable curve fitting**

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 29, which emphasises the irrelevance to the fit of e values below 0.01%.).

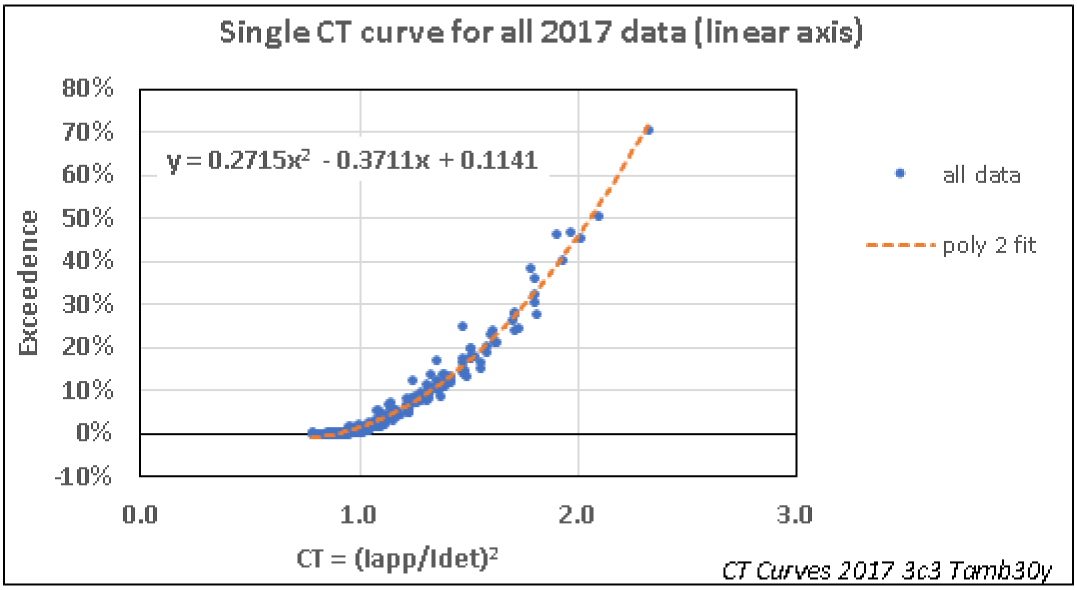


Figure 29 **Same data as Figure 28 but plotted with a linear y axis (rather than log)**

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 30 whilst Figure 31 shows the same fits but with the underlying data removed for clarity.

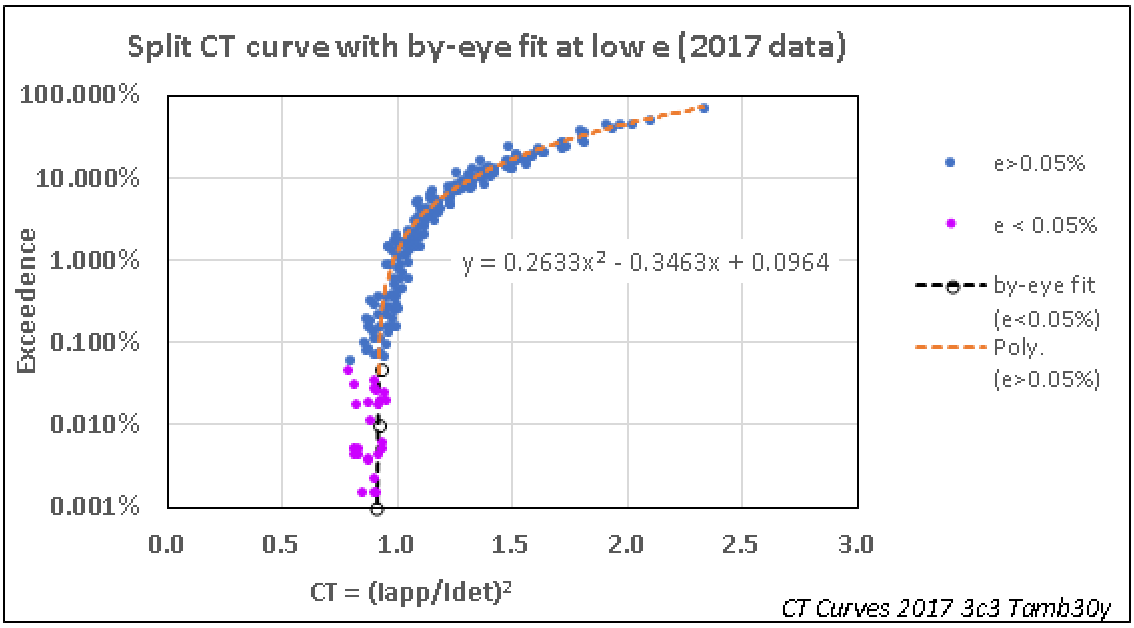


Figure 30 **Split CT curve (same data as Figure 28 but with separate fits above and below e = 0.05%)**

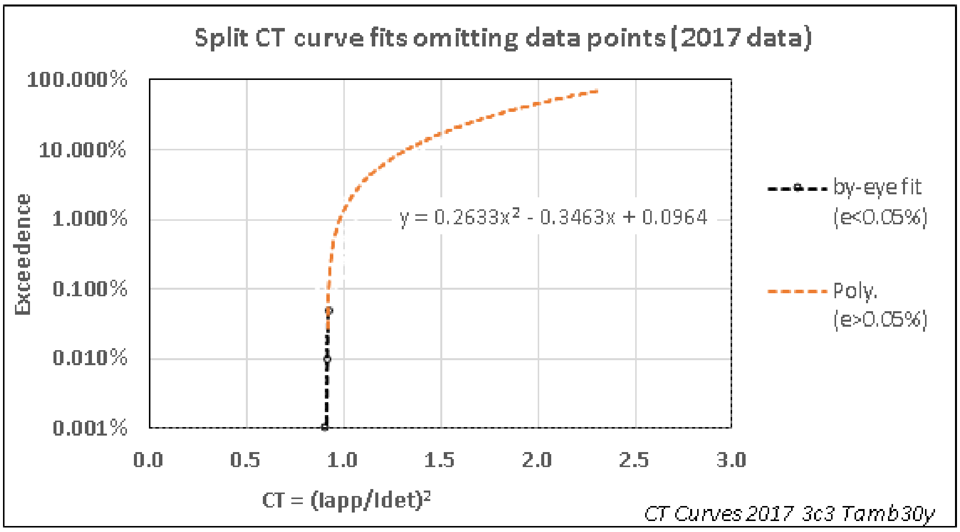


Figure 31 **Split CT curve fits omitting underlying data for clarity**

Table 8 is a lookup table for CT(e) compiled from the above fits. Figure 32 is a plot of this lookup table.

Table 8 **Lookup Table for CT(e) based on 2007 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

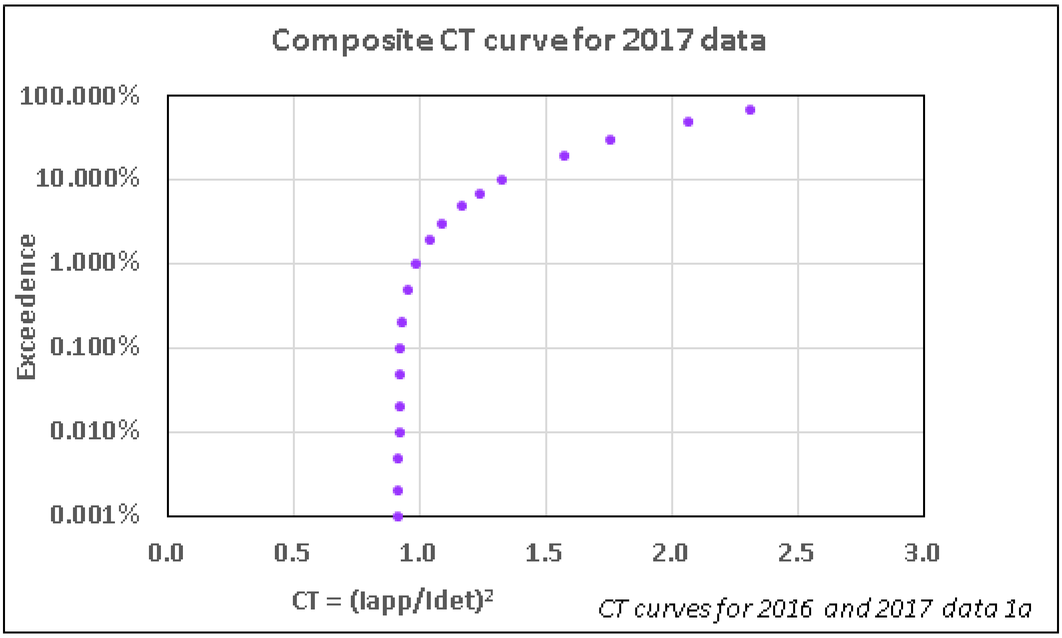


Figure 32 **Composite CT curve for 2017 data (graphical version of lookup table)**

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 33 where the data for 2016 have been plotted alongside those for 2017.

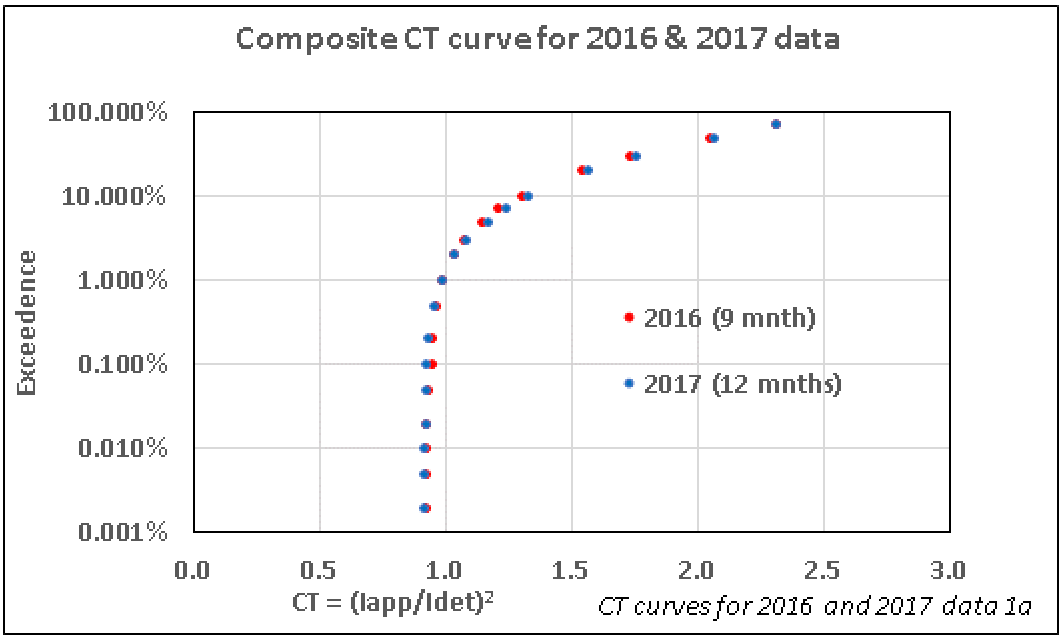


Figure 33 **Composite CT curve for 2016 and 2017 data**

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 8 and Figure 33.

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 and 4 degC higher than those calculated using the Cigre 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 to +9 degrees.

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 3.64 ± 1.34 °C for 2016 and 3.43 ± 1.75 °C for 2017.

C4. Two winter months in 2017 (November and December) and one in 2016 (January) gave significantly higher differences than the other months. A possible cause was that on the selected "hot days" for the months concerned, there were early morning periods when windspeed was low and temperatures were around freezing.

C5. Frequency distributions for measured and calculated conductor temperatures over a complete season (summer 2017, Ash 500) were quite similar, but there was a noticeable displacement between them, with the measured values shifted towards higher temperatures. An increase of just 1K in the calculated values caused the displacement between the two curves to more or less disappear. 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 approximately 1K lower than the measured values.

C6. A study of seasonal boundaries showed that for the initial 12-month period there was a clear summer period comprising June to September (cf May to August in P27) but a much less clear separation of the non-summer data into autumn/spring and winter. Overall, the best split was into just two seasons, namely a 4-month summer season and an 8-month winter season. i.e. summer period being June to September (4 months) and winter being October to May (8-month). A symmetrical four-season split was not really justified from the data.

C7. A radical seasonal split is proposed with four 3-month seasons, each with a different design ambient temperature Tamb (cf P27 which has the same Tamb for spring and autumn). Winter and summer would comprise the obvious three cold months (Dec–Jan–Feb) and the obvious three hot months (Jun–July–Aug) while spring and autumn would be replaced by more complex intermediate cool and intermediate warm seasons, respectively comprising the relatively cool spring and autumn months (Mar, Apr and Nov) and the relatively warm spring and autumn months (May, Sep and Oct). Provisionally, design ambient temperatures would be kept as close as possible to P27 values, with winter and summer values remaining at 2˚C and 20˚C, and the spring/autumn 9˚C split into 6˚C and 12˚C for the intermediate cool and intermediate warm values. This provisional scheme was subsequently ditched in favour of a more realistic set.

C8. Exceedence was found to depend upon the assumed design temperature, as expected from previous work. It was also found to be dependent, to a lesser extent, on ambient temperature.,

C9. CT curves for all the conductors, currents and seasons, based on the proposed seasonal split and provisional values of design ambient temperature, exhibited a significant amount of variation. This variation was mainly associated with different seasons rather than different currents. Replotting the CT curves using design Tamb values derived from our measured average Tamb values (14.3, 11.0, 6.6, 3.6°C) rather than the arbitrary provisional ones (20, 12, 6, 2°C) greatly reduced the seasonal variation.

C10. A plot of all 40 conductor-current-season combinations on the same plot using measured average Tamb values shows 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. Since our measured ambient temperatures were very similar to the Met Office 30-year UK averages, it was decided that the latter standard values should form the basis of our recommendations.

C11. A best fit to all the CT values for 2017, based on Met Office 30-year average temperatures, 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.

C12. 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. It is therefore recommended that a CT curve derived solely from the 2017 data be used.

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 Cigre 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)

12. Acknowledgements

Special note of thanks to the following:

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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 Schedule of Participants

Project Champion & Lead Company

Company	Project Champion
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Appendix II 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**[3]	
	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.	

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[3] 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.

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- 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