Thermal Performance of Low Voltage Network Switchgear

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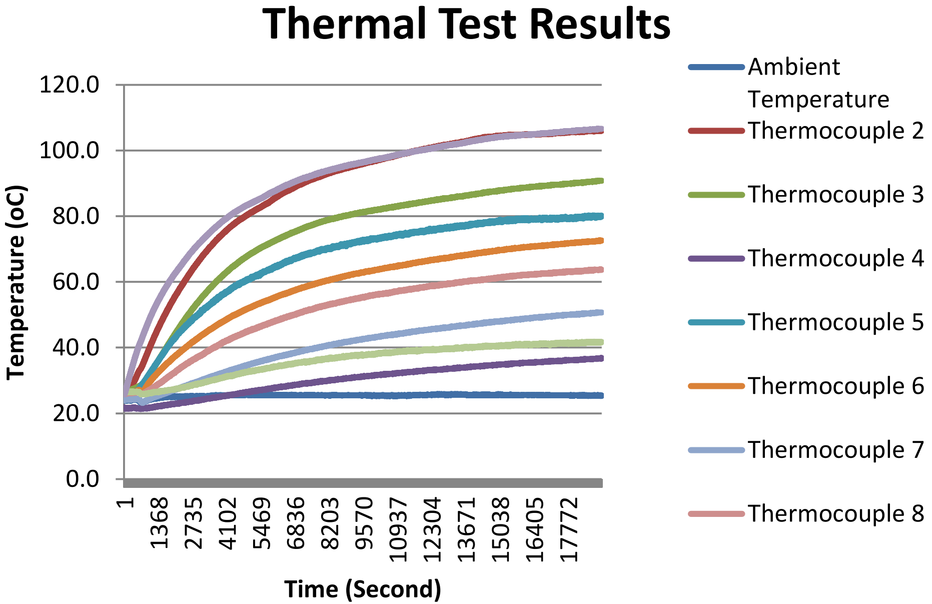

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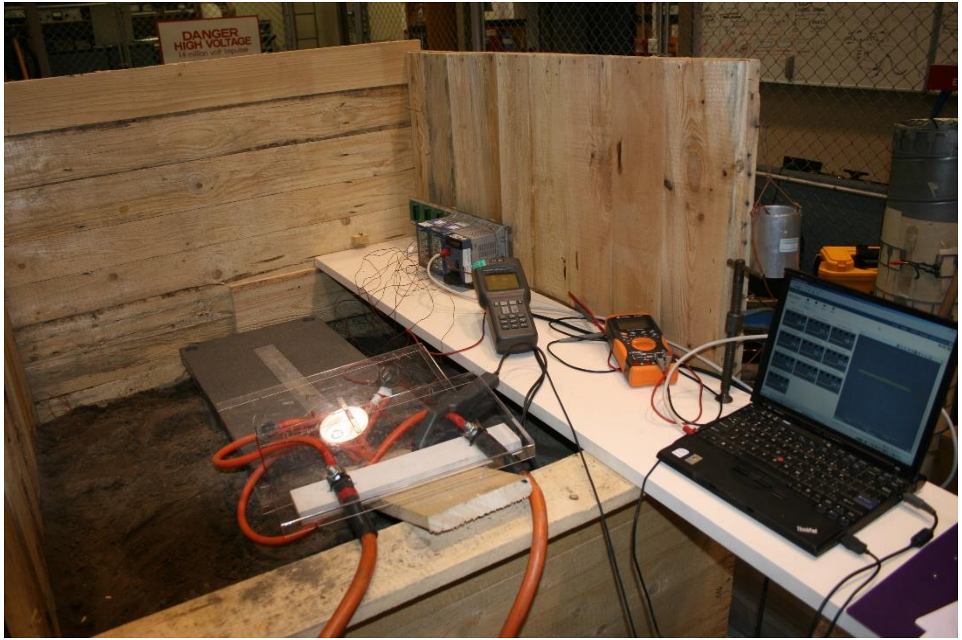
Overview

- Motivation
- U-Pillar Laboratory Testing
- Heat Transfer Modelling
- Equilibrium Temperature Estimation
- Conclusion
- Questions



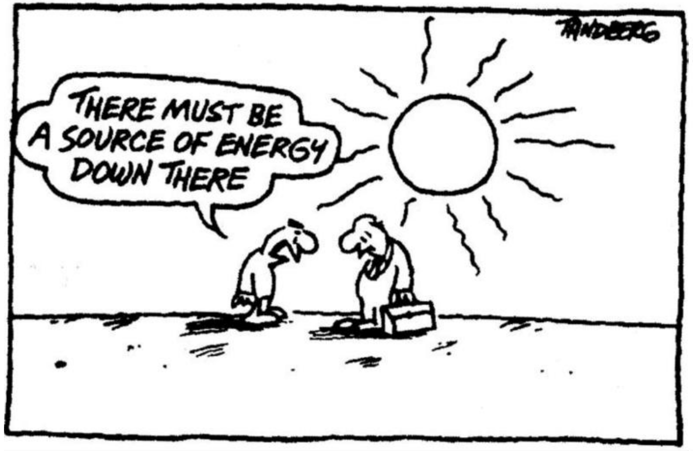
Motivation

- Underground network for reliability and public safety

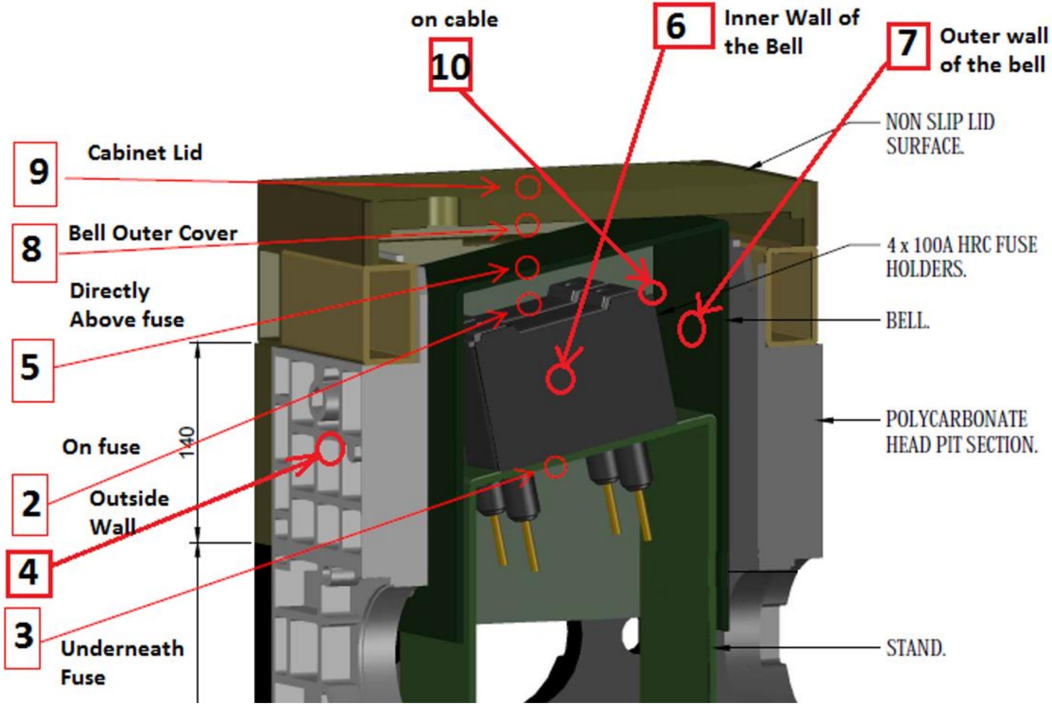
- Design challenges arise for thermal performance
  - Limited convection
  - Insulation material
  - Temperature limit
  - Standards

- Laboratory testing to gain understanding of thermal issues

- Thermal modelling



U-Pillar Laboratory Testing



Temperature measurements

- 10 J-type thermocouples
- Connected to MX100 unit

Includes all reference points specified in AS/NZS 3439.1

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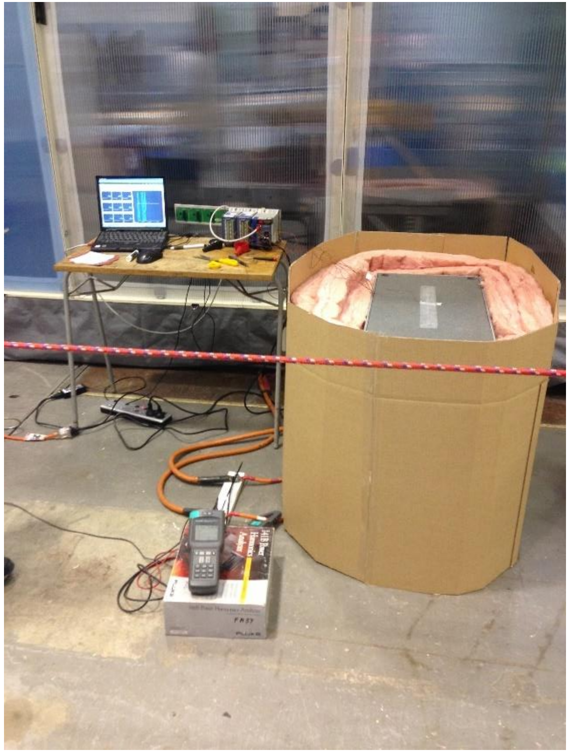
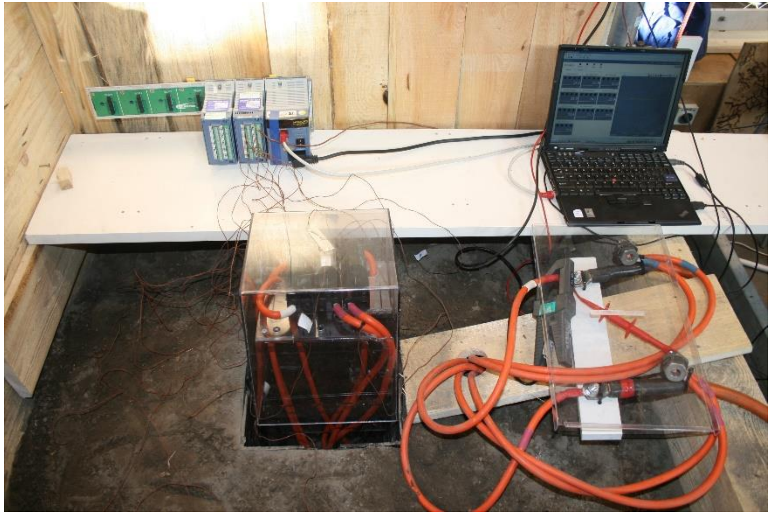
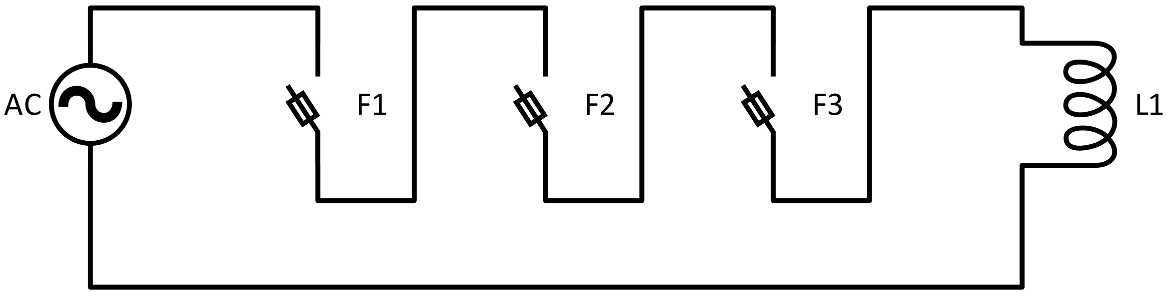




Test Settings:

- Insulation Jacket
- Above ground
- Underground

U-Pillar Laboratory Testing



- Series Connection
- Using transformer as an inductive load

U-Pillar Laboratory Testing

- Switchgear Standards:
  IEC 60439-1 AS/NZS 3439.1:2002
  Low-voltage switchgear and control gear assembly
  Part 1: Type-tested and partially type-tested assemblies

- Section 7.3 Temperature rise
- Table 2 - Temperature Rise Limit

- Test sample passes the test if it meets the criteria in Section 7.3 and Table 2

U-Pillar Laboratory Testing

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Test	Box size (mm)	Equipment type	Fuse rating, current (A)	Number of Fuses	Fuse connection	Short link	Above ground / in ground	External insulation medium	Approx cable length (m)	Incomer cable size (mm2)	Feeder cable size (mm2)
1	550 x 250	Fuse holders	100	6	Series	Y	Above	Insulation jacket	3	25	25
2	550 x 250	Fuse holders	100	6	Series	Y	Above	Air	3	25	25
3	550 x 250	Fuse holders	100	3	Series	Y	Above	Air	3	25	25
4	550 x 250	Disconnect in sealed box	160	3	Series	Y	Above	Air	3	35	35
5	550 x 250	Disconnect	160	3	Series	Y	Above	Air	3	35	35
6	550 x 250	Disconnect	160	3	Series	Y	Above	Air	3	35	35
7	550 x 250	Disconnect	160	3	Series	N	Above	Air	7	35	35
8	250 x 250	Fuse holders	100	3	Series	Y	Above	Air	3	35	35
9	250 x 250	Disconnect	160	3	Series	Y	Above	Air	7	35	35
10	250 x 250	Disconnect	250	3	Series	N	Above	Air	7	95	95
11	250 x 250	Disconnect	160	3	Series	N	In ground	Soil	7	35	35
12	250 x 250	Disconnect	160	3	Series	N	In ground	Soil	7	35	35

U-Pillar Laboratory Testing

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Test	Result	Duration	Final fuse temp (°C)	Final lid temp (°C)
1	Stopped	4 hours	92.3	34.1
2	Completed, passed	8 hours	99.8	40.3
3	Completed, passed	3 hours	73.1	40.1
4	Stopped	3 hours	133.6	39.6
5	Stopped	5 hours	160.0	35.5
6	Stopped	1.5 hours	89.4	17.8
7	Stopped	1.5 hours	119.4	16.4
8	Completed, passed	3 hours	97.0	31.7
9	Stopped	1.5 hours	109.5	27.7
10	Completed, passed	8 hours	41.8	33.7
11	Stopped	1.5 hours	120.2	17.0
12	Completed, failed	5.5 hours	160.1	41.7

- Test is stopped if the temperature is too high
- The equilibrium temperature is not reached for most of the test
- Equilibrium point can be extrapolated

U-Pillar Laboratory Testing

- Findings from the first test
  - Testing in series is unrealistic (too onerous), due to the heat generated in the extra short links
  - Testing in an insulation jacket or in air is also unrealistic, due to lack of conduction to the soil
  - The cable size is a major contributor to heat transfer
  - Competitor set up is not a good idea!

Heat Transfer Modelling

- Heat Production of the fuse:

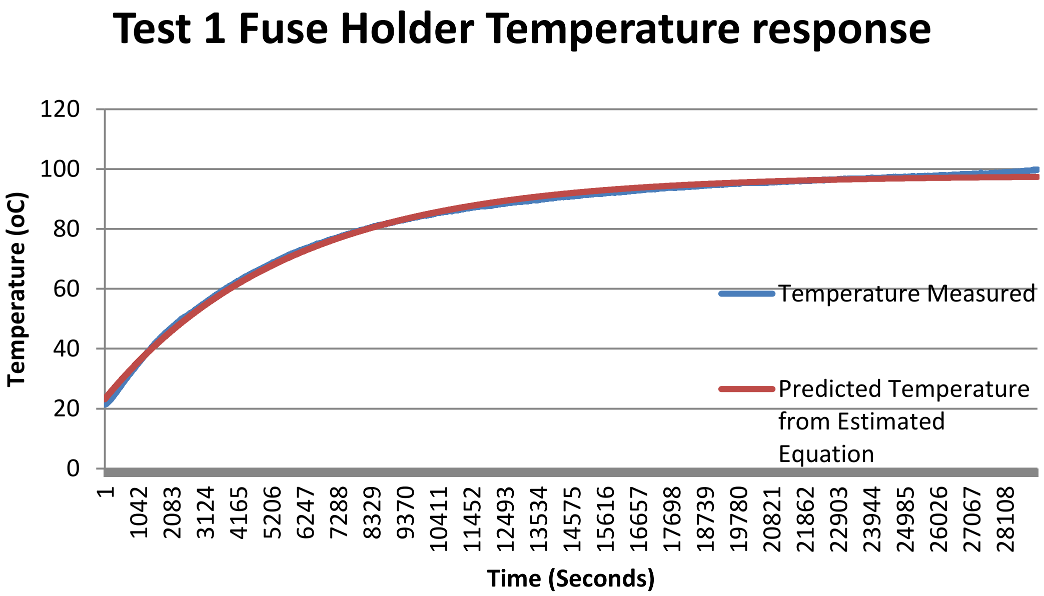
$$P_f = nV_f I_f$$

- Heat Production of the cable:

  The skin depth of the copper is 9.266mm, if the cable area is less than 270mm2, $R_{ac} \approx R_{dc}$

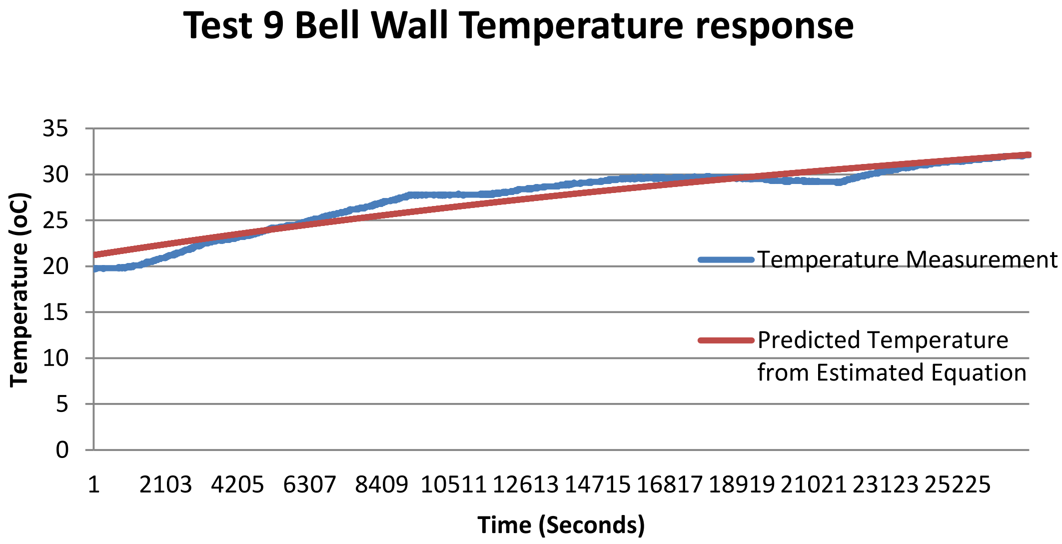
$$P_c = I_f R_{ac} L$$

Heat Transfer Modelling



- $T = T_{\infty}(1 - e^{-K(t-t_0)})$
- Parameter ID using Excel
- Estimation is reasonable
- Good enough extrapolation model
- Using estimated equation from solver to predict the equilibrium temperature

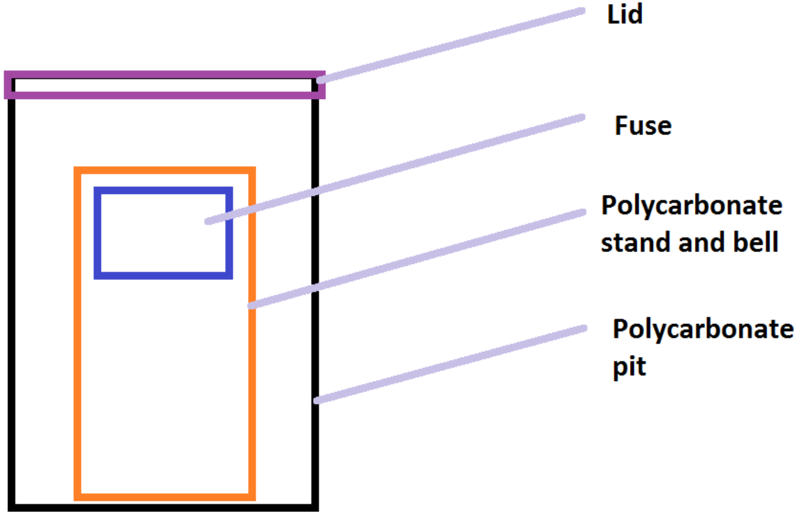
Heat Transfer Modelling

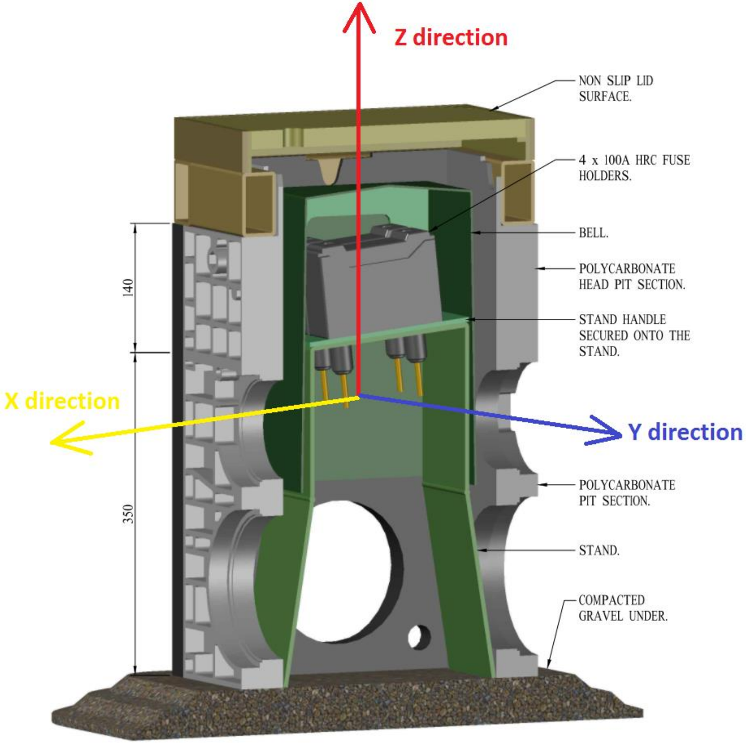


- Estimation does not fit so well at some locations
- Estimated Equilibrium temperature is then used in thermal modelling

Heat Transfer Modelling

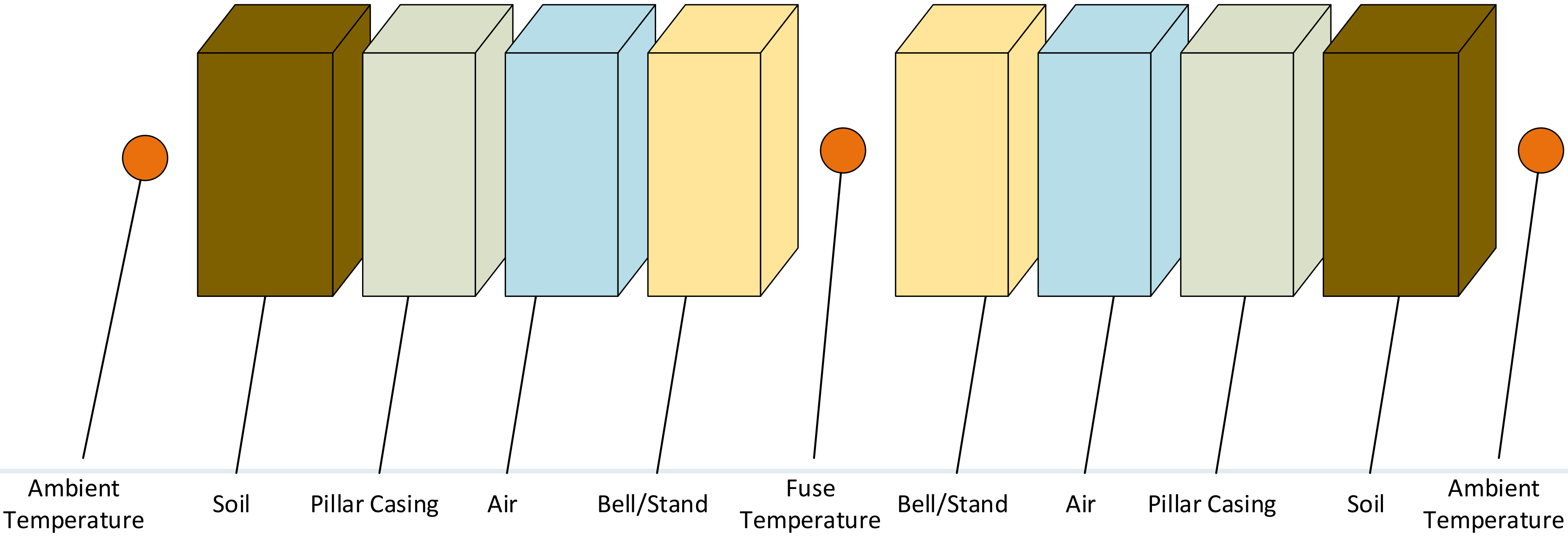
- Composed Wall Analysis





Heat Transfer Modelling

- x-direction thermal equivalent circuit



Heat Transfer Modelling

- Conduction Thermal Resistance:

$$R_{t,cond} = \frac{T_{s,2} - T_{s,1}}{\mathrm{q}} = \frac{L}{kA}$$

- Convection Thermal Resistance:

$$R_{t,conv} = \frac{T_s - T_\infty}{q} = \frac{1}{\mathrm{h}A}$$

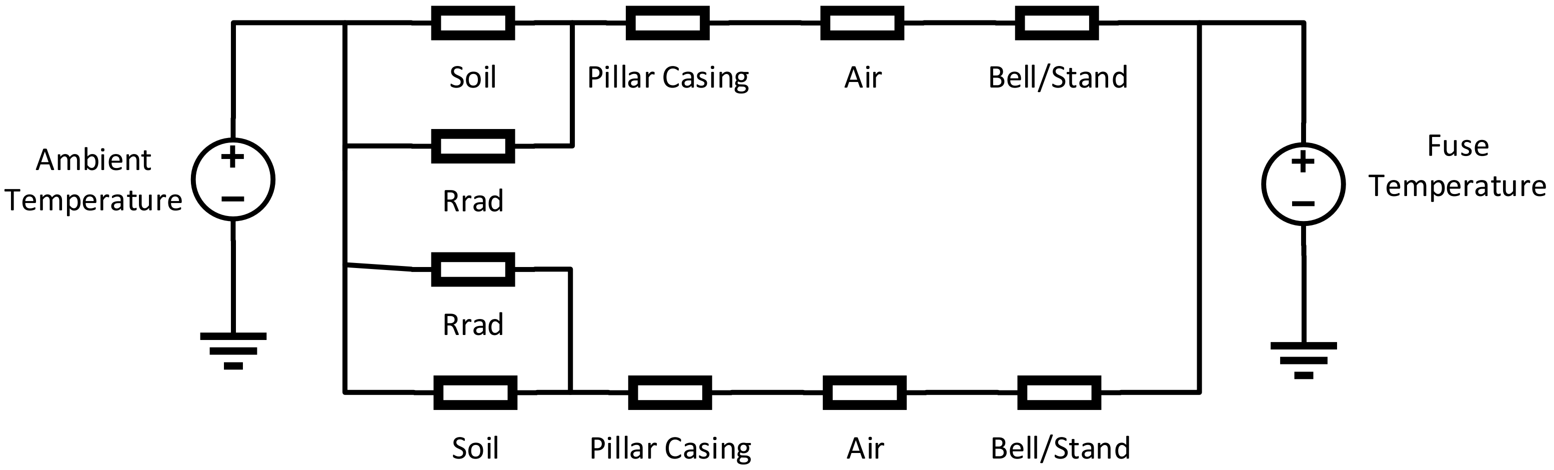
- Radiation Thermal Resistance:

$$R_{t,rad} = \frac{T_s - T_\infty}{q} = \frac{1}{\mathrm{h}_r A}$$

- L = thickness of the wall
- A = Area
- k = thermal conductivity of the material
- h = convection constant
- h_r = Radiation Constant:

$$\mathrm{h}_r = \varepsilon\sigma(T_s - T_\infty)(T_s^2 - T_\infty^2)$$

Heat Transfer Modelling

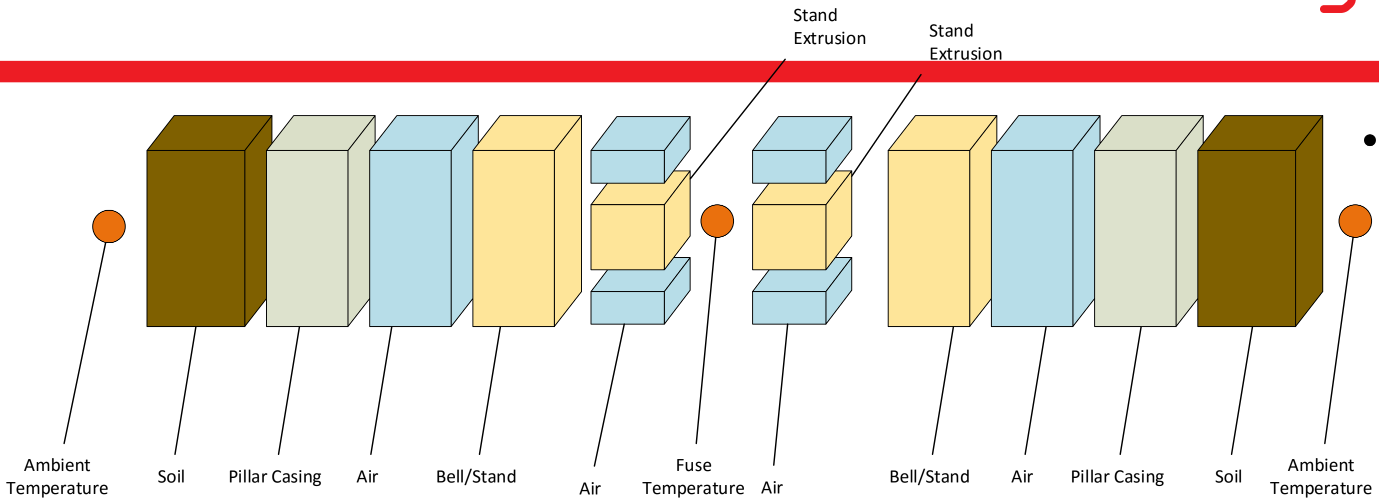


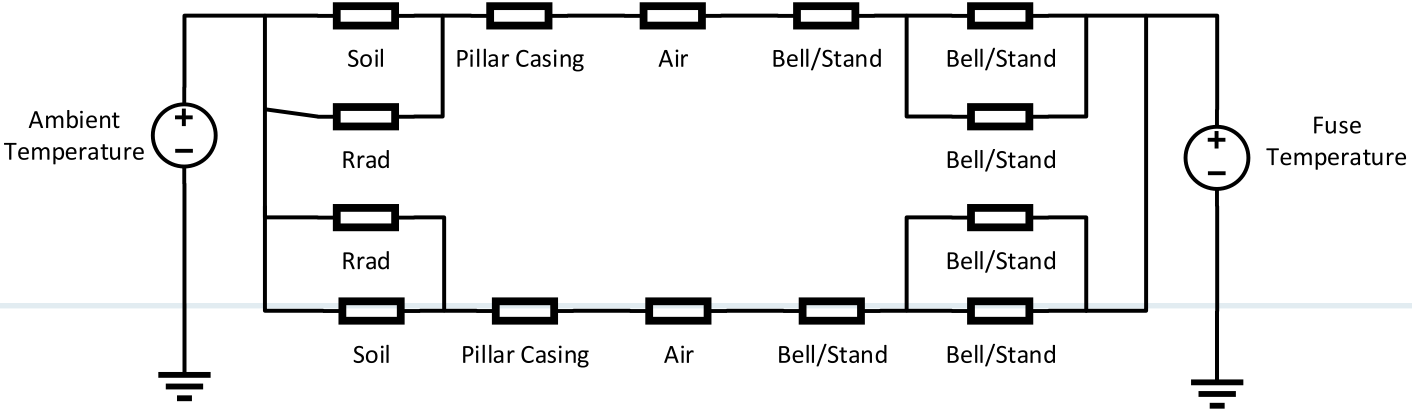
$$R_{x-total} = (R_{\mathrm{soil}}//R_{rad} + R_{\mathrm{pillar}} + R_{\mathrm{air}} + R_{\mathrm{bell}})//(R_{\mathrm{soil}} + R_{\mathrm{pillar}} + R_{\mathrm{air}} + R_{\mathrm{bell}})$$

$$= \frac{R_{\mathrm{soil}}//R_{rad} + R_{\mathrm{pillar}} + R_{\mathrm{air}} + R_{\mathrm{bell}}}{2}$$

Heat Transfer Modelling

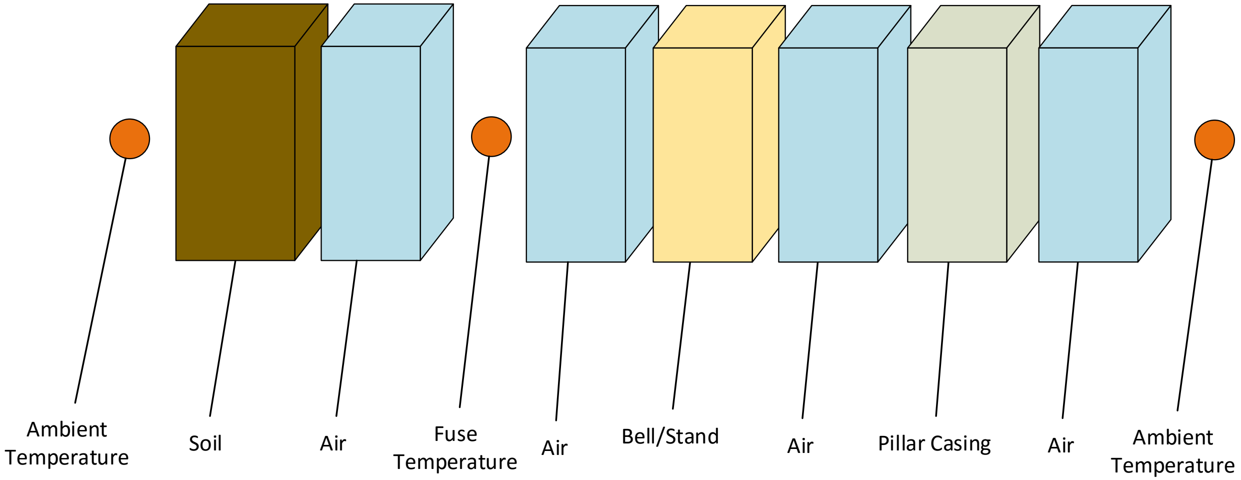
- y-direction thermal equivalent circuit

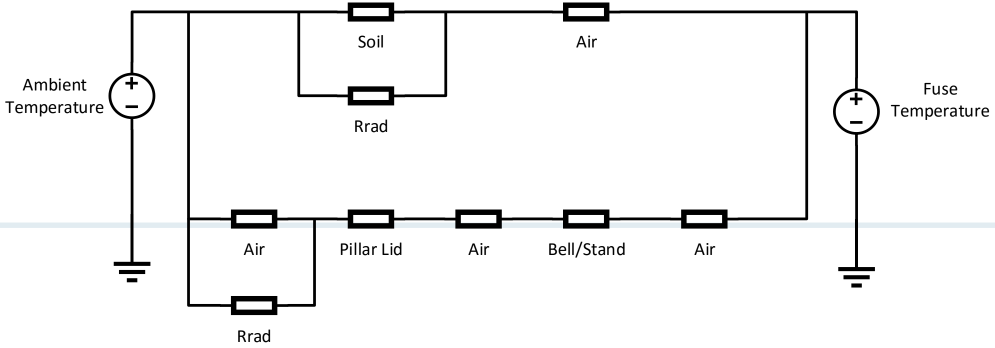




Heat Transfer Modelling

- z-direction thermal equivalent circuit





Heat Transfer Modelling

- Overall thermal resistivity

$$R_{sum} = \frac{1}{\frac{1}{Rx} + \frac{1}{Ry} + \frac{1}{Rz}}$$

- Heat transfer through convection on the cable surface (worst case scenario)

$$q''_{cable} = \frac{1}{2} h\pi rL$$

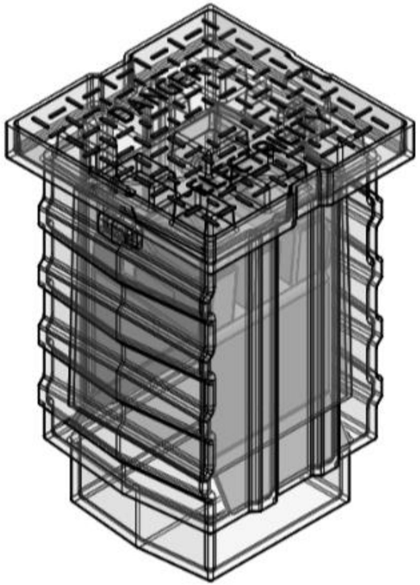
- Total Rate of heat transfer

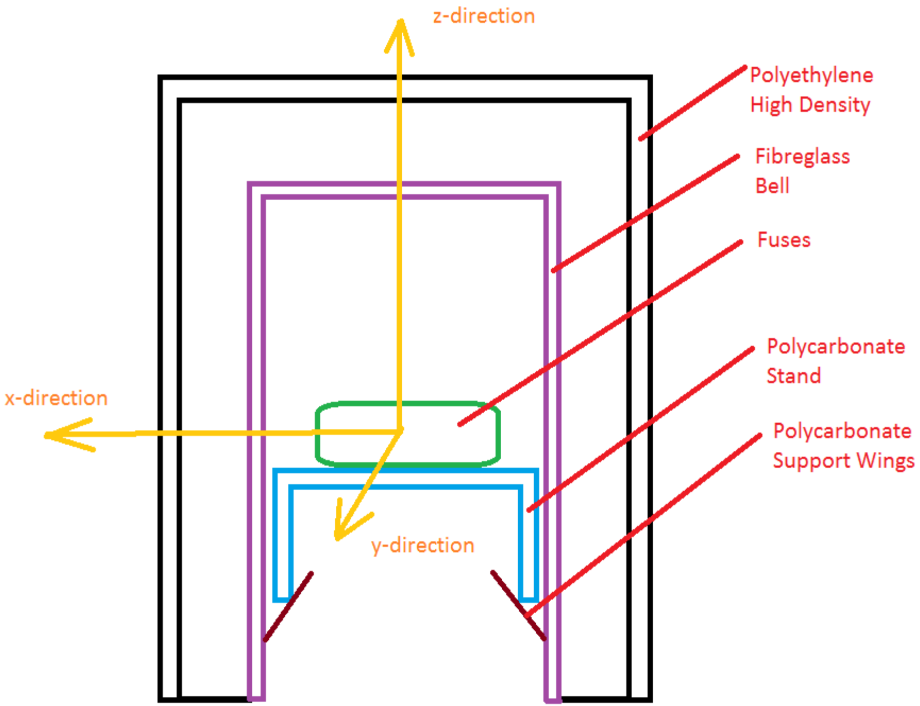
$$q''_{total} = \frac{T_{fuse} - T_{ambient}}{R_{sum}} + q''_{cable}$$

Heat Transfer Modelling

- The heat transfer rate is approximately equal to heat production rate
- The test results indicated that excessive temperatures could occur in some configurations, especially after three hours with full load
- This information was used to determine changes to the materials, dimensions and cable sizes for the new U-Pillar product

Equilibrium Temperature Estimation





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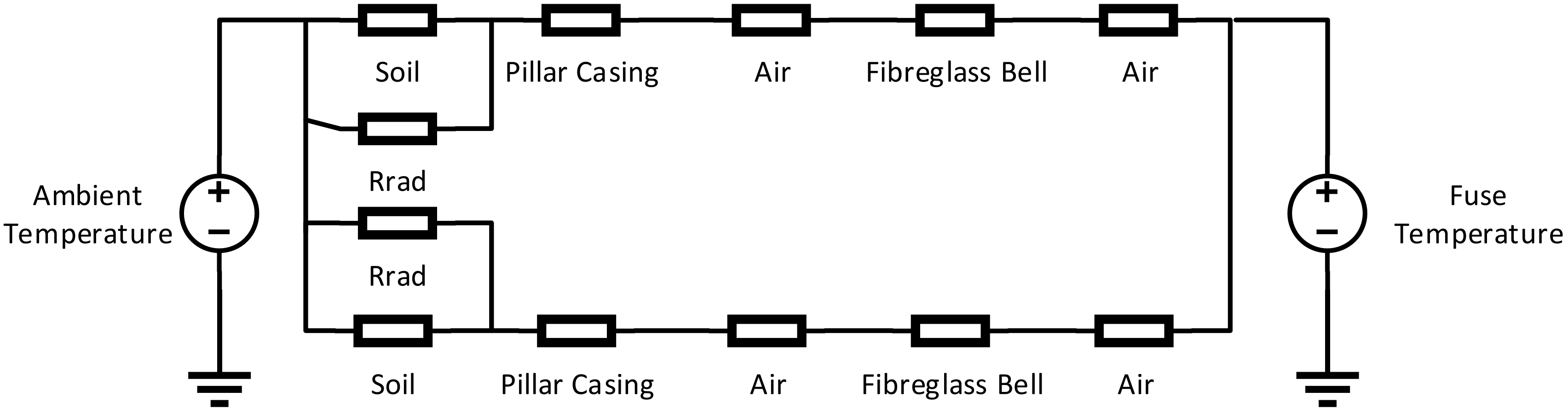
Equilibrium Temperature Estimation

- Similar composed wall analysis
- Symmetrical design, same equivalent circuit for x and y direction



Equilibrium Temperature Estimation

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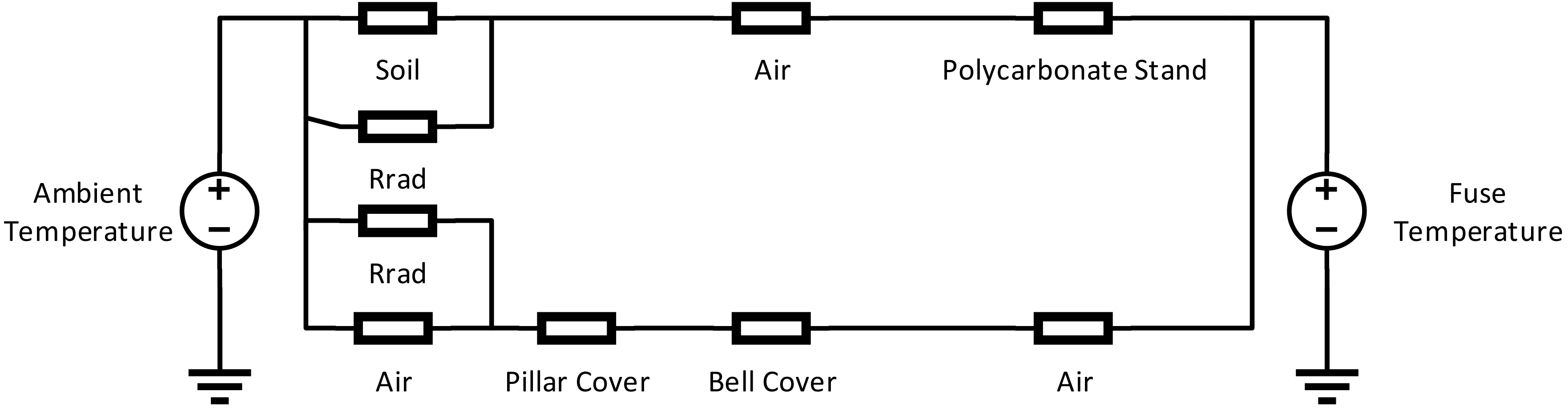
- z direction equivalent circuit



Equilibrium Temperature Estimation

- Total heat production:

$$P_t = P_{cable} + P_{fuse}$$

- The temperature difference between ambient to fuse:

$$\Delta T = \frac{P_t}{R_t}$$

- The fuse temperature can then be calculated as:

$$T_{fuse} = T_{ambient} + \Delta T$$

U-Pillar Laboratory Testing

Test	Box size (mm) (depth 600)	Equipment type	Fuse rating, current (A)	Number of Fuses	Fuse connection	Short link	Above ground / in ground	External thermal insulation medium	Approx cable length (m)
13	300 x 300	Fuse holders	100	3	Parallel	N	Underground	Soil	9
14	300 x 300	Fuse holders	63	6	Parallel	Y	Underground	Soil	9
15	300 x 300	Fuse holders	100	4	Parallel	Y	Underground	Soil	9
16	300 x 300	Fuse holders	160	3	Parallel	N	Underground	Soil	10.5
17	300 x 300	Fuse holders	160	3	Parallel	N	Underground	Soil	10.5
13	300 x 300	Fuse holders	100	3	Parallel	N	Underground	Soil	9
14	300 x 300	Fuse holders	63	6	Parallel	Y	Underground	Soil	9

U-Pillar Laboratory Testing

- Second thermal test to check the estimation

Test	Result	Duration	Final fuse temp (°C)	Final lid temp (°C)	Predict fuse temp (°C)	Error of prediction(°C)
13	Completed, passed	8 hours	91.8	44.8	105.8	14.0
14	Completed, passed	8 hours	88.8	47.8	91.5	2.7
15	Completed, passed	8 hours	107.3	53.9	96.0	-11.3
16	Operation error	8 hours	128.1	42.2	-	-
17	Completed, passed	8 hours	87.3	47.6	89.9	-2.6

Equilibrium Temperature Estimation

- The fuses are arranged in parallel for the second test
- There are several main circuits in the switchgear assembly, so Diversity Factor (in Section 4.7 AS/NZS3439.1

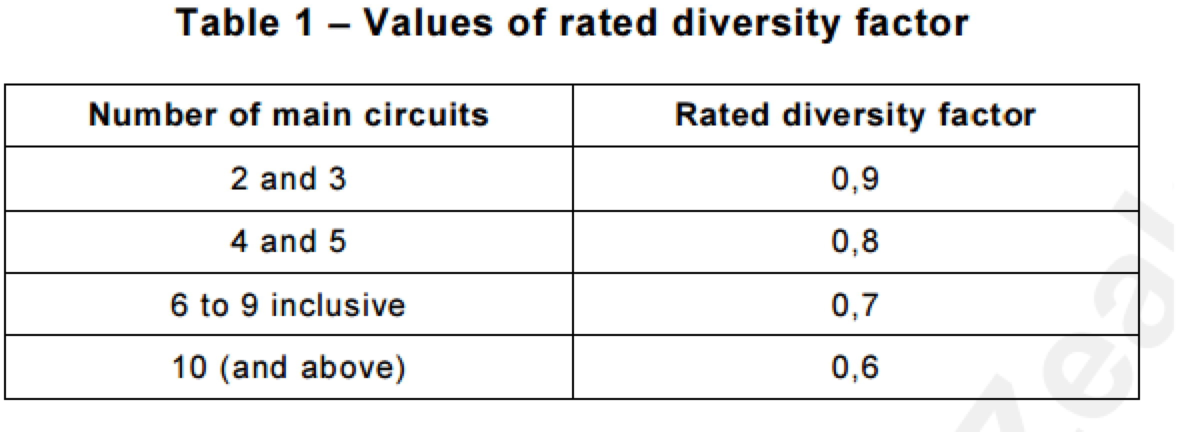


Table 1 – Values of rated diversity factor

Number of main circuits	Rated diversity factor
2 and 3	0,9
4 and 5	0,8
6 to 9 inclusive	0,7
10 (and above)	0,6

Equilibrium Temperature Estimation

- The new U-Pillar is likely to pass the test when Diversity Factor is applied

			Incomer Cable		Feeder Cable		Predicted Fuse Temp	
Test Current	Current with Diversity Factor	Number of Fuses	Cross Section (mm2)	Length (m)	Cross Section (mm2)	Length (m)	At Test Current	Diversity Factor Temp rise
160	144	3	50	11	50	11	100.2	69.6
100	90	3	25	9	16	19	95.2	63.9
100	80	4	25	12	16	25	96.0	54.0
60	44	6	25	9	16	9	91.5	49.9

Equilibrium Temperature Estimation

- ±15 degrees accuracy for fuse temperature

- Error can come from:
  - Resistance of the fuse increases over time (as its temperature increases)
  - Cable length and U-Pillar dimensions are approximate
  - The cable provides a parallel means of heat transfer by conduction, which was not accounted for in the model
  - Test data never reached true equilibrium, extrapolated temperature is used
  - Assume 20 degrees ambient temperature
  - Other factors contribute to heat transfer

- This is accurate enough for application

Conclusion

- Testing in the laboratory is critical to understanding the thermal performance of underground LV switchgear
- Cable sizing is an important determinant of the thermal performance of underground LV switchgear
- A heat transfer model was developed that allows the temperature rises in LV switchgear to be estimated reasonably accurately
- The model enables designers to make informed choices about switchgear configuration and design parameters

Questions

- Thank you for your attention!

Table 2 – Temperature-rise limits

Parts of ASSEMBLIES	Temperature rise K
Built-in components [1][6]	In accordance with the relevant requirements for the individual components, if any, or, in accordance with the manufacturer's instructions, taking into consideration the temperature in the ASSEMBLY
Terminals for external insulated conductors	70 [2]
Busbars and conductors, plug-in contacts of removable or withdrawable parts which connect to busbars [6]	Limited by: – mechanical strength of conducting material; – possible effect on adjacent equipment; – permissible temperature limit of the insulating materials in contact with the conductor; – effect of the temperature of the conductor on the apparatus connected to it; – for plug-in contacts, nature and surface treatment of the contact material.
Manual operating means:	
– of metal	15 [3]
– of insulating material	25 [3]
Accessible external enclosures and covers:	
– metal surfaces	30 [4]
– insulating surfaces	40 [4]
Discrete arrangements of plug and socket-type connections	Determined by the limit for those components of the related equipment of which they form part [5]

[1] The term 'built-in components' means:

- conventional switchgear and controlgear;
- electronic sub-ASSEMBLIES (e.g. rectifier bridge, printed circuit);
- parts of the equipment (e.g. regulator, stabilized power supply unit, operational amplifier).

[2] The temperature-rise limit of 70 K is a value based on the conventional test of 8.2.1. An ASSEMBLY used or tested under installation conditions may have connections, the type, nature and disposition of which will not be the same as those adopted for the test, and a different temperature rise of terminals may result and may be required or accepted. Where the terminals of the built-in component are also the terminals for external insulated conductors, the lower of the corresponding temperature-rise limits shall be applied.

[3] Manual operating means within ASSEMBLIES which are only accessible after the ASSEMBLY has been opened, for example emergency handles, draw-out handles which are operated infrequently, are allowed to assume higher temperature rises.

[4] Unless otherwise specified, in the case of covers and enclosures which are accessible but need not be touched during normal operation, an increase in the temperature-rise limits by 10 K is permissible.

[5] This allows a degree of flexibility in respect of equipment (e.g. electronic devices) which is subject to temperature-rise limits different from those normally associated with switchgear and controlgear.

[6] The requirements for built-in components, busbars and conductors, plug-in contacts of removable or withdrawable parts which connect to busbars, limited by:

- mechanical strength of conducting material;
- possible effect on adjacent equipment;
- permissible temperature limit of the insulating materials in contact with the conductors;
- the effect of the temperature of the conductor on the apparatus connected to it; and
- for plug-in contacts, the nature and surface treatment of the contact material

would generally be considered to be complied with if temperature rises do not exceed 70 K for H.C. copper busbars and 55 K for H.C. aluminium busbars. The temperature rise limits of 70 K and 55 K are based on maximum temperatures of 105°C and 90°C, respectively, under the normal service conditions according to Clause 6.1.

Table 8 – Test copper conductors for test currents up to 400 A inclusive

Range of test current 1)		Conductor size 2), 3)	
A		mm^2	AWG/MCM
0	8	1,0	18
8	12	1,5	16
12	15	2,5	14
15	20	2,5	12
20	25	4,0	10
25	32	6,0	10
32	50	10	8
50	65	16	6
65	85	25	4
85	100	35	3
100	115	35	2
115	130	50	1
130	150	50	0
150	175	70	00
175	200	95	000
200	225	95	0000
225	250	120	250
250	275	150	300
275	300	185	350
300	350	185	400
350	400	240	500

1) The value of the test current shall be greater than the first value in the first column and less than or equal to the second value in that column.

2) For convenience of testing and with the manufacturer's consent, smaller conductors than those given for a stated test current may be used.

3) Either of the two conductors specified for a given test current range may be used.