ENCLOSURE 4

CONSUMERS ENERGY COMPANY
PALISADES PLANT
DOCKET 50-255

Exerpt from:
EA-ELEC-AMP-041, “Ampacity Evaluation for Continuously Energized Power Cables Routed Through Fire Stops”

111 Pages

Consumers Power
POWERING MICHIGAN'S PROGRESS

PALISADES NUCLEAR PLANT
ENGINEERING ANALYSIS COVER SHEET

EA-ELEC-AMP-041

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itle Ampacity Evaluation For Continuously Energized Power Cables Routed Through Firestops

INITIATION AND REVIEW

Calculation Status	Preliminary ☐	Pending ☐	Final ☒	Superseded ☐

Rev #	Description	Initiated		Init Appd By	Review Method			Technically Reviewed		Revr Appd By	CPCo Appd
		By	Date		Alt Calc	Detail Review	Qual Test	By	Date		
0	Original Issue	R. Hernandez	3/24/97	JDR		X		J. Nehls	3/24/97	JDR	MTN
1	See Description Below	J. Nehls	7/9/97			X		R. Desai	7/9/97		

This analysis supersedes the portion of EA-ELEC-AMP-034 for cables in firestops.

Revision 1

Revised Sections:

pdated text to include additional measured load data, updated assuming the tray cover for XP600 has been raised, update cable tray analysis for XP121 to include measured room temperature and to document additional analysis to determine maximum expected conductor temperature in conduit.

Attachments 15 and 16 - updated for assumed raised tray cover and measured room temperature.

Attachments 19, 22 and 25 - incorporated measured load data into table.

Attachment 27 - incorporated measured load data for affected cables

Attachment 26 and 32 - updated to included documentation of measured loads

Attachment 30 - updated to include 75°C ampaciy tables.

Added Section:

Attachment 10 - Ltr between K. Toner (CECo) and D. Crutchfield (NRC), dated November 1, 1982

Attachment 34 - methodology for determining the conductor temperature in conduits

tachment 35 - supporting data for attachment 34

Attachment 36 - supporting data for analyzing cable trays above a temperature of 75°C

ATTACHMENT 37 - documentation for cable type code determination.

I. OBJECTIVE

Background

During an analysis being performed in response to Condition Report C-PAL-96-0756, it was discovered that analysis does not exist to confirm the adequacy of ampacity values for power cables routed through penetration containing firestop material. As required per the FSAR, the ampacity of power cables shall be adjusted due to the effects of firestop material. ①

Power cables are installed in penetrations in one of four different configurations; conduit, sleeves, free air and cable trays. This EA will establish the methodology for establishing the adjusted ampacity for continuously energized power cables routed through penetration containing firestop material at the Palisades Nuclear Plant.

Purpose

The purpose of this analysis is to evaluate the ampacity associated with the continuously energized power cables installed in penetrations. This analysis will consist of the following:

Cable Trays

1.) use of a computer model and program (Reference IX.11) which calculates the maximum cable mass temperature for a cable in a raceway and applies further derating for the firestop. ①

2.) compare the maximum calculated cable temperature with the expected cable insulation temperature rating.

Conduits, Sleeves and Openings

1.) determine a derating factor for the installed configuration and adjust the allowable ampacity using the derating factor.

2.) Compare the established full load current with the derated ampacity of a cable at a given raceway.

3.) For those cables with derated ampacity less than the full load current, compare the maximum calculated conductor temperature with the cable insulation temperature rating. ①

Scope

The scope of this analysis is limited to an ampacity evaluation of continuously energized power cables installed in penetrations documented in Manual M66F (Reference IX.5) and any additional penetrations discovered during the penetration walkdown and documented in Attachment 4 of this analysis.

II. INPUT DATA

1.) Appendix R, Manual M66F, "Penetration Seal Database Entries" (Reference IX.5)

2.) The Palisades Circuit and Raceway Schedule (CRS). This includes, but is not limited to, quantity of cables per conduit, type and size of cable. The existing CRS database required some minor enhancements to ensure accurate results. These enhancements include verifying data such as cable size, cable type, cable use and are documented in Attachment 9 .

3.) Attachment 27 contains a complete listing of the cables identified as power and the associated load current The load current was determined using Palisades plant documentation, as identified in Reference IX.9.

4.) Ampacity values for the various cable sizes were obtained from IPCEA Pub. No. P-46-426 and the National Electric Code. (Reference IX.13) The ampacity values are based on an ambient air temperature of 40°C (Reference IX.1). ①

5.) A walkdown was performed to determine the electrical components routed through each affected penetration. The results of this walkdown are documented in Attachment 3.

6.) Documentation required for the Heat Transfer Model for Cable Ampacity in cable tray is referenced in Attachment 28 and included in Attachment 29.

7.) S&L performed a calculation to determine the derating required for multiple cables in conduits. This includes both multiple power feeds in the same conduits and multiple cable types in the same conduit. This calculation is included as Attachment 31.

Reference/Comment

II. **INPUT DATA** (continued)

8.) The methodology for the heat transfer model used for cable tray analysis is included in Attachment 28 and is based on a horizontal section of cable tray. The justification for using this methodology in vertical sections of cable tray is provided in EA-ELEC-AMP-033, Rev. 0 (Reference IX.4).

9.) The ambient air temperature for general areas of the plant is 40°C per Reference IX.1. Area specific temperatures are available per Reference IX.17 and were utilized for cable tray routing point XP121, located in the Cable Spreading Room. ①

III. ASSUMPTIONS

Major Assumptions

None

Minor Assumptions

1.) The engineering judgements required for the development of the analytical ampacity and heat transfer model are included in Attachment 28.

2) The purpose of Attachment 31 is to determine the ampacity derating factors for multiple power and control cables in a single conduit. The ampacity values included in the IPCEA for cables installed in conduit is not a function of conduit size. Although by calculation, the ampacity may be slightly impacted by conduit size, the IPCEA considers them to be free of variations. The calculated derating factors assume that the cable is carrying its rated current and the selection of a 3" conduit is considered representative of the conduits at the Palisades Plant.

Based on the above approach, the selection of 3" as the basis for the conduit derating values will be conservative and can be used for all conduit sizes.

3.) In the determination of the full load current for each power cable, some conservative assumptions were used. These assumptions are identified and documented in Attachments 26 & 27.

Reference/Comment

III. ASSUMPTIONS (continued)

4.) Attachment 5 documents conduits installed in penetrations without conduit numbers. The cables associated with these conduits could not be determined and therefore these conduits were excluded from further analysis. However, it is not expected that the cables installed in these conduits will have a significant impact on the results of this analysis and therefore, verification is not required.

5.) A review of the CRS database indicates that the insulation temperature rating of power cables at Palisades can be 75°C, 85°C, 90°C and 125°C. The insulation rating used in this analysis are as follows:

Conduits, Sleeves and Openings

The insulation temperature rating from the CRS will be determined and the ampacity value from the appropriate tables included in Attachment 30 will be used. If the CRS database does not identify the insulation temperature rating, a rating of 75°C will be used. This is the lowest rated cable at Palisades and therefore is a conservative assumption. No verification is required.

Cable Trays

①

As previously stated, the conductor insulation rating of 75°C is the lowest rated cable installed at Palisades. Therefore, the cable trays will be evaluated using this assumed insulation rating of 75°C for all power cables.

However, if the calculated temperature of a cable tray is above the assumed 75°C value, the power cables installed in the tray will be reviewed to determine the actual insulation rating. The insulation rating for cable types not identified in CRS were conservatively determined and are documented in Attachment 37, and the analysis for cable trays above 75°C is included in Attachment 36. No further verification is required.

6.) Work Order 24712044 (included in Attachment 26) requires the cover on cable tray routing point XP600 be raised by 1-1/2". This analysis assumes the cable tray cover has been raised and is pending completion of the Work Order.

IV. ACCEPTANCE CRITERIA

For each cable within the scope of this analysis, a comparison will be made between either:

- the calculated derated ampacity for the cable and the calculated loading of the cables.
- the calculated expected maximum conductor temperature and the insulation temperature rating of the cable.

If the calculated ampacity of each cable exceeds the calculated loading, or the insulation temperature rating exceeds the maximum calculated cable temperature, no further disposition is required.

V. METHODOLOGY

General Overview

In order to perform an ampacity evaluation of power cables installed in firestops, a comprehensive list of electrical components installed in penetrations had to be developed. Once the electrical components were identified, which was done by data review and walkdown, it was necessary to determine the appropriate derating factors associated with penetrations containing firestop material.

In an attempt to reduce the current derating values in EGAD-ELEC-05 (Reference IX.2), temperatures of the cables inside and outside of various penetrations were measured. Using these measured values, temperature factors and ampacity multipliers were developed for penetrations containing firestop material (Attachment 8).

Using these calculated values, an evaluation of the temperature and ampacity for continuously energized power cables installed in the penetrations was performed.

Determination of Affected Raceways

In discussions with Palisades personnel in the Appendix R group, it was learned that a walkdown of penetrations had been previously completed and is documented in Manual M66F, "Penetration Seal Database Entries (Reference IX.5). This walkdown provides a unique "FZ" identification to each penetration.

Reference/Comment

One of the supporting documents for this database includes a walkdown checklist for each penetration. This checklist identifies the general location, size, material and, in part, the identification of the components installed in the penetration.

However, unique numbers for all the electrical raceways are not identified. Based on this, it was determined that a walkdown of each penetration containing electrical components would be performed. A list of penetrations containing electrical components was developed to determine those requiring field verification. This list is included in Attachment 1.

Using the data on the walkdown checklists, drawings were created to show the location of these firestops in the general plant areas . These drawings were created to act as a guide to ensure the affected penetrations were walked down in an efficient manner and to provide a tool for documentation of the electrical components found during the walkdown. These drawings are identified on Attachment 1 with an "RFZ" prefix and are included in Attachment 2.

The results of the walkdown are documented in Attachment 3. This attachment is sorted by electrical installation drawing and identifies each penetration by its corresponding "FZ" number and the associated electrical raceways installed in the penetration.

During the walkdown, penetrations were found in the plant that were not documented in Manual M66F and do not have a corresponding "FZ" number. The electrical components installed in these penetrations were identified, if possible, and are included in Attachment 3 by a penetration number of either "DET" or SECT." A separate listing of these penetrations are included in Attachment 4.

Another item discovered during the walkdown was that some conduits did not have unique identification labels. Therefore, the cables associated with these conduits, which are included in Attachment 5, could not be determined and these conduits were excluded from further analysis (See Minor Assumption 3).

A comprehensive list of raceways installed in the penetrations was generated from the data included in Attachment 3. It was noted during a review of this attachment that there are 4 types of electrical raceways installed in these penetrations. A cable is either in a conduit, a conduit sleeve (short piece of conduit embedded in the wall), a cable tray or in open air.

Therefore, the evaluation of the cables will be based on the above installation conditions. Attachment 6 is a comprehensive list, sorted by the 4 types of installed conditions, of the raceways installed in the various firestops.

Testing

In an attempt to reduce the existing derating values in EGAD-ELEC-05 (Reference IX.2), actual measurements of cable tray, conduit and conduit sleeve temperatures inside and outside of various penetrations was performed. A test procedure was generated providing the instructions for gathering the temperature data. The test procedure, supporting documentation and the test results are included in Attachment 7. Based on the measurements documented during the test, temperature factors and ampacity multipliers were developed for firestops. The methodology for these factors and the results of the calculations are included in Attachment 8.

Evaluation

Using the results of Attachment 8, which identified temperature factors and ampacity multipliers, an evaluation of the cables installed in the penetrations was performed. The evaluation depended on the type of raceway installed in the penetration. Below is a description of each evaluation.

1.) Cable Trays

An analytical model which calculates the maximum expected temperature is being used for cable trays installed in penetrations. This model uses the Mathcad Software to perform the labor intensive calculations associated with the analytical model. This model utilizes the cable loading diversity (i.e. the fact that cables at Palisades are not all carrying their rated current and that physical distribution of continuously energized power cables in trays exists).
A feature of this model predicts the maximum cable mass steady state temperature that exists in a single horizontal cable tray in open air. The temperature is then corrected for the firestop material using the temperature factors identified in Attachment 8. The methodology for the development of the heat transfer model is discussed in Attachment 28. This adapted model and approach are discussed in IEEE paper, 94WM100-8 PWRD (Reference IX.15)

The cable data for trays identified in Attachment 6 was reviewed to determine the population of cable trays requiring analysis. Cable trays with a segregation of "Instrumentation," as identified in EGAD-EP-06 (Reference IX.3), were removed from further analysis. Attachment 11 documents the remaining 34 cable trays which require further analysis using the methodology described in Attachment 28.

A report was generated for each of these 34 tray points. This report identifies the cable tray and the cables routed in each point along with cable characteristic data required to perform the temperature analysis. This report is included as Attachment 12.

The load current for each continuously energized power cable is required as an input into the ampacity analytical model. These values will be used to determine the "layer" arrangement adopted in the model discussed in Attachment 28. In order to determine the actual load current, a review of existing plant calculations, load center sheets, MCC setting sheets, plant drawings, outstanding change paper and vendor documents was performed. The documentation associated with this detailed review is included in Attachment 26. Each power cable for the 34 tray points was included in a unique file. These files include a reference to the source data for the respective current values, and are included in Attachment 13. In addition, a cumulative listing of the power cables that were researched for this analysis are included as Attachment 27.

Utilizing the Ampacity Program

The S&L Mathcad Ampacity Program is executed by linking two input files for a specific routing point to the executable version of the program. The input files are text files that consists of raceway and cable data that specify the composition and characteristics of the cables (size, diameter, amps, etc.) in the tray. The assembly of these input files consisted of reviewing the cable data included in Attachment 12 and 13 for each routing point and determining those cables that have similar cable characteristics. Cables that have the same characteristics are "bundled" together as one cable group. The result is an input file which lists unique cable groups that represent the total cables in each routing point. These input files, and an explanation of the data included in the files are included in Attachment 14.

Reference/Comment

The output of the Ampacity Program contains the input data used by the executable program and the resulting calculated cable tray temperatures. This output file for each cable tray routing point is included in Attachment 15. The output of this program is a set of approximately 34 pages for each routing point analyzed. The majority of these pages contain various equations and calculations that are repeated for each routing point. Therefore, one complete sample output report is included as an appendix to Attachment 28 and the data included in Attachment 15 will be the unique input and output data (usually two pages) for each of the 34 routing points.

Installation of 75°C Cables in Tray Located in Firestops

Per Minor Assumption 5, this analysis assumes that power cables at Palisades have an insulation rating of 75°C. A review of Attachment 16, which is a summary of the calculations for the 34 affected routing points, indicates that the calculated maximum conductor temperature for all but 6 of the cable trays is below 75°C. Therefore, using minor assumption 5, which assumes 75°C as the conductor insulation rating for all power cables, these 6 cable tray routing points require additional analysis. A listing of the 6 routing points and the data supporting the additional analysis is included in Attachment 36 and is described below.

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The Mathcad output files for the 6 routing points were reviewed and the power cables with the highest percent of the IPCEA ampacity were submitted to Palisades to obtain measured load data. The documentation for these cables is included in Attachment 36.

The 6 mathcad input files were then revised to reflect these measured load values and the 6 files were rerun using the S&L Ampacity Program. The documentation of these load changes, the revised input files and the Mathcad output files are included in Attachment 36, pages 3 through 26.

Page 2 of Attachment 36 summarizes the temperatures from Revision 0 and the revised temperatures. A review of this summary sheet shows that 4 cable tray routing points still have a calculated temperature above the 75°C maximum allowable.

Reference/Comment

value. These 4 cable tray points were reviewed to determine the actual insulation rating of the cables installed in each tray. The E39.db file in the CRS database identifies insulation ratings of most of the cable types at Palisades. However, 18 cable type codes were found that did not have a rating associated with them in the E39.db file. These 18 codes were assumed to be 75°C (See minor assumption 5) and the supporting data for this assumption is included in Attachment 37. ①

A query was then performed using the E39.db and the cablcode.db data files in the CRS to determine the insulation rating of the cables installed in these 4 routing points. The results of this query is included in Attachment 36, pages 27 through 32. A review of these results indicates that 2 cable trays contain cables with a potential insulation rating of 75°C and a temperature above the maximum of 75°C.

2.) Conduits

The cable data for conduits identified in Attachment 6 was reviewed to determine the population of conduits requiring analysis. A review of Attachment 6 indicated that there are 397 numbered conduits installed in penetrations. These 397 conduits are documented in Attachment 17. A review of CRS indicated that 126 of these conduits contain continuously energized power cables. These 126 conduits, which require additional analysis, are included in Attachment 18.

The approach for conduit analysis first looked at the conduit prior to the installation of the firestop material. In this environment, the ampacity for the installed cables in conduit is obtained from IPCEA or NEC, depending on the cable size and cable insulation rating. The rating of the cable was determined using the existing CRS database (E39.db) and the results of Attachment 37. These ampacity values are included in Attachment 30. ①

The ampacity values from the IPCEA/NEC require derating due to the installation of both multiple power and control cables in the same conduit. The appropriate derating factor from Attachment 31 was obtained based on the total number of power cables in the conduit. This derating value was then applied to the ampacity values listed in Attachment 30 for a given cable size.

Next, the derating for the firestop materials identified in Attachment 8, is required. A review of the location of the conduits indicated that they penetrate 12" or 24" walls, and 12" floors. The worst case ampacity multiplier for these installations, which is 0.87, was used.

Based on the above, a derating factor for each of the 126 conduits was calculated. This derating factor was multiplied by the ampacity value listed in IPCEA/NEC and a new derated ampacity was calculated. The full load current for each energized cable in the conduit was compared to the new derated ampacity and the percent loading was identified. This analysis is included in Attachment 19.

3.) Conduit Sleeves

The approach for conduit sleeves is similar to that of conduits except for the ampacity values from the IPCEA/NEC. Conduit sleeves installed without firestop material use the free air ampacity value from the tables in Attachment 30.

The cable data for conduit sleeves identified in Attachment 6 was again reviewed, but this time for conduit sleeves. This review determined that 63 conduit sleeves are impacted by firestop material, as documented in Attachment 20. However, a review of CRS indicated that only 32 of these sleeves contain power cables, as listed in Attachment 21, and require further analysis.

As with conduit, sleeves can contain both power and control cables. Therefore, the derating factors in Attachment 31 will be used for sleeves as well. This derating value was then applied to the open air ampacity values listed in Attachment 30 for a given cable size.

Next, the derating for the firestop materials identified in Attachment 8, is required. A review of the location of the sleeves indicated that they penetrate 12" or 24" walls. The worst case ampacity multiplier for these installations, which is 0.87, was used.

Again, a derating factor for each of the 32 sleeves was calculated. This derating factor was multiplied by the open air ampacity value listed in IPCEA/NEC and a new derated ampacity was calculated. The full load current for each energized cable in the sleeves was compared to the new derated ampacity and the percent loading was identified. This analysis is included in Attachment 22.

4.) **Openings**

The approach for openings is quite similar to sleeves in that the free air ampacity values from the IPCEA/NEC are used if no firestop material was installed. However, the derating factor for multiple cables was obtained from Table VIII, page V of the IPCEA (Attachment 30). This table provides a derating factor for multiple cables when spacing is not maintained.

The cable data for openings identified in Attachment 6 was once more reviewed and it was determined that there are 119 openings in walls or floors where open air cables are routed, as documented in Attachment 23. The CRS was again reviewed and only 74 of these openings required additional analysis due to containing power cables, as documented in Attachment 24.

Next, the derating for the firestop materials identified in Attachment 8, was required. A review for the location of the openings indicated that they penetrate 12" floors and 12" or 24" walls. The worst case ampacity multiplier for these installations, which is 0.87, was used.

Finally, a derating factor for each of the 74 openings was calculated. This derating factor was multiplied by the open air ampacity value listed in IPCEA/NEC and a new derated ampacity was calculated. The full load current for each energized cable in the openings was compared to the new derated ampacity and the percent loading was identified. This analysis is included in Attachment 25.

VI. CALCULATION AND RESULTS

Each continuously energized power cable installed in a penetration containing firestop material was derated based on the appropriate derating values (from IPCEA, Attachment 8 and Attachment 31) and applied to the appropriate ampacity/temperature values. The results of this analysis are as follows:

Reference/Comment

Cable Trays	Attachments 16 and 36 ①
Conduits	Attachment 19
Sleeves	Attachment 22
Openings	Attachment 25

A summary of the cable tray results is included in Attachment 16 and 36 and the remaining attachments are summarized in Attachment 32.

VII. CONCLUSIONS

A review of Attachment 16 and 36 indicates that continuously energized power cables installed in cable trays located in penetrations containing firestop material are within the allowable conductor insulation temperature rating, except for routing points XP020 and XP310. The calculated temperatures are as follows:

XP020	75°C	77.5°C
XP310	75°C	77.9°C

A review of Attachment 32 indicates that 2 conduits contain cables that exceed the derated ampacity values. These 2 conduits were further evaluated using the methodology in Attachment 34 and the resultant calculated conductor temperatures were below the insulation temperature ratings. Attachment 32 documents both derated ampacity and the maximum calculated conductor temperature for the 2 raceways. ①

VIII. RECOMMENDATION

A review of the summary data included in Attachments 16 and 36 indicate that there are 2 raceways containing cables whose calculated temperature is above the insulation rating of 75°C. Though the majority of the cables in these trays are rated at 90°C, the cables listed below have an expected insulation temperature rating of 75°C and should be analyzed to determine any loss of life.

XP020	B08/M57/1
	B08/Z211/1
	B12/M05/1
XP310	B08/M47/1
	B08/M57/1
	B08/Z211/1

Reference/Comment

IX. REFERENCES

1. Design Basis Document 1.07, "Auxiliary Building HVAC Systems"
2. EGAD-ELEC-05, Revision 1, "Cable Sizing Guidelines - Ampacity"
3. EGAD-EP-06, Revision 2, "Circuit And Raceway Schedule Number Designation"
4. EA-ELEC-AMP-033, Revision 0, "Allowable Heat Intensity for Power Cables in Vertical Versus Horizontal Cable Trays."
5. Manual M66F, "Penetration Seal Database Entries"
6. Penetration Walkdown Data. (Attachment 3)
7. Computer Output from 'S&L Mathcad Ampacity Program" for the 34 Cable Tray Routing Points (Attachment 15)
8. Miscellaneous Reports from the CRS Raceway Database, Attachments 9, 12, 17, 20 and 23.
9. Data required to support the load currents for continuously energized power cables was obtained from data included in Attachment 26 and the data listed below:
    - Calculation DRS-032591-1 "Determine capacity for all transformers, cables, circuit breakers, load centers, and MCC's".
    - Meeting Notes for a meeting between R. Hernandez (S&L) and B. Baker (CPCo)
    - Palisades Drawings and other Plant Data
    - Measured load data
10. Listing of Power Cables and their Associated Load Currents Used in the Ampacity Analysis. (Attachment 27)
11. Methodology for Development of the Heat Transfer Model for Cables in Tray (Attachment 28)

IX. REFERENCES (continued)

12. Supporting Data for the Development of the Heat Transfer Model (Attachment 29)
    - ICEA Standard P-54-440, Rev. # 2, August 1986, "Ampacities in Open-top Cable Tray".
    - IEEE Transactions on Power Apparatus and Systems, Paper 70 TP-557-PWR, entitled "Ampacities for Cables in Randomly Filled Trays", by Stolpe, PAS-90, 1971, pg. 962-974
13. Ampacity Values included in Attachment 30 were obtained from:
    - IPCEA Pub. No. P-46-426, "Power Cable Ampacities, Volume 1 - Copper Conductors"
    - NEC Handbook, Sixth edition, Based on the 1993 Edition
14. Ampacity derating values due to instrumentation/control cable mass occupying the conduit with the power cable and multiple power cables in the same conduit (Attachment 31).
15. IEEE Papers (Attachment 33)
    - 94 WM100-8 PWRD, entitled "Ampacity of Cables in Single Open-Top Cable Trays", by Harshe and Black, 1994.
    - 96 WM-209-7-PWRD, entitled "Ampacity of Cables in Single Covered Trays", by Harshe and Black, 1996.
16. Methodology for Determining the Conductor Temperature of Cables in Conduit Routing Points (Attachment 34)
17. Ltr between K. Toner (CECo) and D. Crutchfield (NRC), dated November 1, 1982 (Attachment 10)

①

Reference/Comment

X. ATTACHMENTS

1. Penetrations Containing Electrical Components.
2. Penetration Firestop Drawings
3. Walkdown Results by Electrical Drawing
4. Miscellaneous Penetrations
5. Unidentified Electrical Components Through Penetrations
6. Listing of Raceways Passing Through Firestops
7. Supporting Data for Temperature Measurements
8. Development of Temperature Factors and Ampacity Multipliers
9. Enhancements To The CRS Database
10. Ltr between K. Toner (CPCo) and D. Crutchfield (NRC) for the Reduction of Ambient Air Temperature ①
11. Cable Trays Through Firestops
12. Cables By Tray Routing Point Installed In Firestops
13. Power Cables Per Tray Routed Through Firestops
14. Mathcad Input Files
15. S&L Mathcad Ampacity Program, Output For Cables in Trays Located In penetrations With Firestop Material
16. Summary Of Mathcad Output For Cable Trays Through Firestops
17. Listing of 397 Conduits and Their Respective Quantities of Cables and Remarks
18. 126 Conduits Containing Power Cables for Analysis and Their Respective 'FZ' Number

Reference/Comment

X. <u>ATTACHMENTS</u> (continued)

19. Listing of Derated Ampacity Values and Percent of FLC for Cables in Conduits

20. Listing of 63 Conduit Sleeves and Their Respective Quantities of Cables and Remarks

21. 32 Conduit Sleeves Containing Power Cables for Analysis and Their Respective 'FZ' Number

22. Listing of Derated Ampacity Values and Percent of FLC for Cables in Conduit Sleeves

23. Listing of 119 Openings and Their Respective Quantities of Cables and Remarks

24. 74 Openings Containing Power Cables for Analysis and Their Respective 'FZ' Number

25. Listing of Derated Ampacity Values and Percent of FLC for Cables in Openings

26. Supporting Documentation Required for the Development of Load Currents for Power Cables in Firestops

27. Listing of Power Cables and their FLC

28. Methodology for the Development of Heat Transfer Model for Cables in Tray

29. Supporting Documentation Required for the Development of the Heat Transfer Model for Cables in Tray

30. Industry Documentation for Ampacity values

31. Methodology for Determining Ampacity Derating Factors

32. Summary of Conduits, Conduit Sleeves and Openings with Loading Greater Than the Derated Ampacity

33. IEEE Papers 94 WM100-8 PWRD and 96 WM-209-7-PWRD

Reference/Comment

X. ATTACHMENTS (continued)

34. Methodology for Determining the Conductor Temperature of Cables in Conduit Routing Points.

35. Supporting Documentation for Attachment 34

36. Analysis of Cable Trays With Temperature Above 75°C

37. Supporting Documentation For Insulation Rating of Power Cables

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Attachment 8

The purpose of this attachment is to develop temperature factors and ampacity multipliers for fire stops based on the tests that were conducted at Palisades during March 1997.

Prepared by: William G Blatts March 21 1997

Reviewed by: Nedal Deeb 3/21/1997

Purpose

The purpose of this calculation section is to determine temperature factors and ampacity multipliers for the Kaowool fire stops at Palisades based on the tests that were carried out in March 1997. The measurements were made in accordance with the "Fire-Stop Derating Test Guideline", which is included in Attachment 9. The selection of the measurement locations was made to include the bounding cases in the test measurements.

Methodology

Temperature measurements were taken on the raceways passing through seven fire stops at Palisades during the normal full load operation of the plant. All of the fire stops were constructed of Kaowool ceramic fiber. The fire stops contained various combinations of cable trays, conduits, and sleeves. The fire stops were installed in both 12 inch and 24 inch thick walls. As a part of the tests, the Kaowool fire stops were opened and thermocouples were installed on the cables and tray of cable trays at intervals of approximately 2 inches and on the each quadrant of the outer surface of conduits in the center of the fire stops. A similar number of thermocouples were installed outside of the fire stop to measure the temperature of the race way in free air. Additional thermocouples were installed to measure the ambient temperature in the test area on the same side of the wall in which the temperature of the race way in free air was measured. In the cases of Fire Stops FZ0179 and FZ0553 additional thermocouples were installed to measure the ambient temperature on the opposite side of the wall. After the installation of the thermocouples, the fire stops were restored to their condition before the test. Temperature measurements were taken at intervals of 10–15 minutes over a period of at least two hours when the unit was operating at normal full load output. The details of the test procedure are described in Attachment 7. The data that were collected during the tests is shown in Tables 1–8. Information on the wall construction is given in Table 9.

The collected data were examined, and a suitable measurement time period was selected for each race way. The rule for selecting the measurement to be used for calculating the temperature factor was to select the measurement that had the largest difference between the temperature measured in the middle of the wall and the temperature measured outside of the wall. Since the ambient temperatures remain relatively constant during the test period, this measurement will result in the largest temperature factor out of the measurements in a given test.

The temperature rise of the surface of the raceway outside the fire stop is calculated directly from the measured values as the temperature difference between the raceway temperature outside of the wall and the ambient temperature. In several cases, the ambient temperatures on the opposite sides of a fire stop was significantly different. Therefore, the reference temperature for calculating the temperature rise inside the fire stop was taken to be the average of the ambient temperatures on both sides of the wall. This average ambient temperature was calculated in one of four ways:

1. Ambient temperature measurements were made on both sides of the wall for Fire Stop FZ0179 and these measurements were used directly to calculate the average ambient temperature.
2. The measured temperature for Case FZ0132 of Conduit X1568 inside the wall represents the average ambient temperature on both sides of the wall.
3. The average ambient temperature was calculated by using data collected in more than one test for Fire Stops FZ0134 and the conduits in FZ0138. The temperature on one side of the wall was measured in one test, and the other test provided data for the other side of the wall.
4. The average ambient temperature for the cable trays in FZ0138 was calculated by assuming that the ratios of the thermal resistances between each of two cable trays and ambient inside and outside of the fire stop was the same and then solving simultaneous equations to determine the ambient temperature to be used in the wall.

The temperature factor that is desired is the ratio of the temperature rises of the cable *conductor* outside and inside the fire stop. However, the cable conductors are not accessible for measurement in an operating power plant. Therefore, the temperature rise of an accessible surface of each raceway was measured. The temperature rise of the parts of the thermal circuit between the point where the measurements took place and the conductor must be added to the measured temperature rises inside and outside of the cable tray to calculate the desired temperature factor.

Detailed heat transfer calculations have been made in calculations EA-ELEC-AMP-034 and EA-ELEC-AMP-032. These calculations determine the temperature of the conductor (hot layer temperature) and the cable mass surface temperature (where the temperature measurements were made) for a given ambient and loading condition. Assuming that the thermal resistances between the surface of the cable mass in open air and ambient and between the cable conductors and the surface of the cable mass are constant, the temperature drop between the cable mass surface and the cable conductors can be estimated as follows:

$$T_{\text{test conductor}} - T_{\text{test cable surface}} = \left(T_{\text{test cable surface}} - T_{\text{test ambient}}\right) \times \frac{\left(T_{\text{calc conductor}} - T_{\text{calc surface}}\right)}{\left(T_{\text{calc surface}} - T_{\text{calc ambient}}\right)}$$

$$= \left(T_{\text{test cable surface}} - T_{\text{test ambient}}\right) \times \left(\frac{\left(T_{\text{calc conductor}} - T_{\text{calc ambient}}\right)}{\left(T_{\text{calc surface}} - T_{\text{calc ambient}}\right)} - 1\right)$$

where: $T_{\text{test conductor}}$ is the estimated cable conductor temperature

$T_{\text{test cable surface}}$ is the measured cable surface temperature

$T_{\text{calc conductor}}$ is the cable conductor temperature taken from the calculation

$T_{\text{calc surface}}$ is the cable mass surface temperature taken from the calculation

$T_{\text{calc ambient}}$ is the ambient temperature used in the calculation

This method of calculating the temperature drop through the conductor mass is used for both cable trays and sleeves.

A similar approach is used for conduits where the temperatures are measured on the outer surface of the conduit. The condition where a single power cable is installed in a 3" trade size conduit with sufficient unloaded or control and instrumentation cables to achieve 40% fill is considered as being representative of all conduits. The detailed calculation for this condition is taken from pages 5–13 of Attachment H of Calculation EA-ELEC-AMP-039.

Since the temperature range of the measurements is quite small, errors due to the deviation of the thermocouple characteristics from the ideal thermocouple characteristic are expected to be quite uniform. Since the differences in two sets of thermocouple measurements are being taken, much of this error will cancel out. Also, the absolute temperatures are low, suggesting that there is significantly more margin in the actual design than has been indicated by previous calculations. Therefore, no special allowance was made for the measurement tolerance of the thermocouples.

Ampacity multipliers for the fire stops are derived from the temperature factors. The ampacity multiplier for a fire stop is defined as:

$$Mult_{amp} = \sqrt{\frac{T_{open} - T_{ambient}}{T_{rated} - T_{ambient}}}$$

where: $Mult_{amp}$ is the ampacity multiplier

T_{rated} is the rated conductor temperature

T_{open} is the conductor temperature outside of the fire stop when the conductor inside the fire stop is at rated temperature

$T_{ambient}$ is the ambient temperature

Since the concept of an ampacity multiplier implies the assumption of a constant thermal resistance between the cable conductors and ambient inside and outside of the fire stop, the definition of the ampacity multiplier can be restated:

$$k = \frac{T_{test\ wall} - T_{ambient}}{T_{rated} - T_{ambient}}$$

$$Mult_{amp} = \sqrt{\frac{k \cdot \left(T_{open} - T_{ambient}\right)}{k \cdot \left(T_{rated} - T_{ambient}\right)}}$$

$$= \sqrt{\frac{T_{test\ open} - T_{ambient}}{T_{test\ wall} - T_{ambient}}}$$

$$= \sqrt{\frac{1}{\dfrac{T_{test\ wall} - T_{ambient}}{T_{test\ open} - T_{ambient}}}}$$

$$= \sqrt{\frac{1}{TF}}$$

where: $T_{test\ open}$ is the conductor temperature under test conditions with the raceway in open air

$T_{test\ wall}$ is the conductor temperature inside the wall under test conditions

Input Data

The following calculated cable tray temperatures were used:

Cable Tray	Ambient Temperature used in Calculation (°C)	Calculated Cable Mass Surface Temperature (°C)	Calculated Cable Conductor Temperature (°C)	Source Reference (data included in Attachment 7 of this EA)
XP010	40.	60.697	77.97	EA-ELEC-AMP-034, pp 1536-1557
XK016	40.	53.474	62.238	EA-ELEC-AMP-034, pp 683-704
XH021	40.	50.023	59.336	EA-ELEC-AMP-032, pp 490-491
TK600	40.	62.983	76.936	EA-ELEC-AMP-032, pp 350-351

The data from the test measurements are the following. The measurements that are to be used in the calculations are shown with an asterisk.

$$^{\circ}C := 1 \cdot K$$

FZ0134, Cable Tray XP010

The test data for FZ0134 includes ambient temperature data for Room 106. Ambient temperature data for the room on the opposite side of the fire stop (Room 116A) is available from the test of Fire Stop FZ0138a. Therefore, the ambient temperature in the wall will be taken as the average of the ambient temperatures at FZ0134 and FZ0138a.

First, the temperature drop through the cable mass must be calculated. From Reference 1:

$\mathrm{calcAmbTemp} := 40 \cdot {}^{\circ}C$	Ambient temperature used in calculation
$\mathrm{calcSurfaceTemp} := 60.697 \cdot {}^{\circ}C$	Calculated surface temperature of the cable mass
$\mathrm{calcCondTemp} := 77.97 \cdot {}^{\circ}C$	Calculated conductor temperature

The test data are as follows:

$\mathrm{testInsideTemp} := 30.28 \cdot {}^{\circ}C$	Measured temperature inside wall
$\mathrm{testAmbientTemp} := 27.90 \cdot {}^{\circ}C$	Measured ambient temperature
$\mathrm{testOutsideTemp} := 28.71 \cdot {}^{\circ}C$	Measured temperature outside of wall
$\mathrm{oppositeAmbientTemp} := 30.35 \cdot {}^{\circ}C$	Ambient temperature on the opposite side of the wall

$$\mathrm{wallAmbientTemp} := \frac{\mathrm{testAmbientTemp} + \mathrm{oppositeAmbientTemp}}{2} \qquad \mathrm{wallAmbientTemp} = 29.125 \cdot {}^{\circ}C$$

$$\Delta T_{\mathrm{mass}} := \left(\frac{\mathrm{calcCondTemp} - \mathrm{calcAmbTemp}}{\mathrm{calcSurfaceTemp} - \mathrm{calcAmbTemp}} - 1 \right) \cdot (\mathrm{testOutsideTemp} - \mathrm{testAmbientTemp})$$

$$\Delta T_{\mathrm{mass}} = 0.676 \cdot {}^{\circ}C$$

$$\Delta T_{\mathrm{outside}} := \Delta T_{\mathrm{mass}} + (\mathrm{testOutsideTemp} - \mathrm{testAmbientTemp}) \qquad \Delta T_{\mathrm{outside}} = 1.486 \cdot {}^{\circ}C$$

$$\Delta T_{\mathrm{inside}} := \Delta T_{\mathrm{mass}} + (\mathrm{testInsideTemp} - \mathrm{wallAmbientTemp}) \qquad \Delta T_{\mathrm{inside}} = 1.831 \cdot {}^{\circ}C$$

$$\mathrm{temperatureFactor} := \frac{\Delta T_{\mathrm{inside}}}{\Delta T_{\mathrm{outside}}} \qquad \mathrm{temperatureFactor} = 1.232$$

FZ0138 and FZ-0138A

These data consist of two separate measurements, one for conduits and another for cable trays. The ambient temperatures were measured on opposite sides of the wall for each test. Therefore, the average ambient temperature, used to calculate the temperature rise in the wall will be determined by averaging the ambient temperatures from the two tests. The test data for Room 125 was taken on March 11 and that for Room 116a was taken on March 10. However, additional data taken on March 8 in Room 116a for FZ0003 and FZ0132 indicates that the ambient temperature in Room 116a is quite stable.

The estimate of the temperature drop between the surface of the conduit and the conductors will be based on the case for one power cable in a 3 inch trade size conduit given in Attachment 31 of this EA. The following values are taken from the calculation:

$\text{calcAmbientTemp} := 40 \cdot °\text{C}$ Ambient temperature used in the calculation

$\text{calcSurfaceTemp} := 54.161 \cdot °\text{C}$ Calculated conduit surface temperature

$\text{calcConductorTemp} := 90.043 \cdot °\text{C}$ Calculated conductor temperature

$$\text{conduitRatio} := \frac{\text{calcConductorTemp} - \text{calcAmbientTemp}}{\text{calcSurfaceTemp} - \text{calcAmbientTemp}} \qquad \text{conduitRatio} = 3.534$$

Average ambient temperature used for wall calculations

$\text{FZ0138AmbientTemp} := 24.50 \cdot °\text{C}$ Ambient temperature from conduit tests

$\text{FZ0138aAmbientTemp} := 30.5 \cdot °\text{C}$ Ambient temperature from cable tray tests

$$\text{wallAmbientTemp} := \frac{\text{FZ0138AmbientTemp} + \text{FZ0138aAmbientTemp}}{2} \qquad \text{wallAmbientTemp} = 27.5 \cdot °\text{C}$$

FZ0138, Conduit X1706

The test data are as follows:

$\text{testInsideTemp} := 27.18 \cdot °\text{C}$

$\text{testOusideAmbient} := 24.55 \cdot °\text{C}$

$\text{testOutsideTemp} := 24.18 \cdot °\text{C}$

In this case there is no temperature rise inside or outside of the wall from the respective ambients. This indicates that the loading of the cables in the conduit is negligible. Therefore, it is not possible to calculate a temperature factor for this conduit.

FZ0138, Conduit X1709

The test data are as follows:

$\text{testInsideTemp} := 28.75 \cdot °\text{C}$

$\text{testOutsideAmbient} := 24.45 \cdot °\text{C}$

$\text{testOutsideTemp} := 25.25 \cdot °\text{C}$

Then the temperature drop between the conduit surface and the conductors is:

$$\Delta T_{\text{inCond}} := (\text{conduitRatio} - 1) \cdot (\text{testOutsideTemp} - \text{testOutsideAmbient}) \qquad \Delta T_{\text{inCond}} = 2.027 \cdot °\text{C}$$

$$\Delta T_{\text{outside}} := \Delta T_{\text{inCond}} + (\text{testOutsideTemp} - \text{testOutsideAmbient}) \qquad \Delta T_{\text{outside}} = 2.827 \cdot °\text{C}$$

$$\Delta T_{\text{inside}} := \left(\Delta T_{\text{inCond}} + \text{testInsideTemp}\right) - \text{wallAmbientTemp} \qquad \Delta T_{\text{inside}} = 3.277 \cdot °\text{C}$$

$$\text{temperatureFactor} := \frac{\Delta T_{\text{inside}}}{\Delta T_{\text{outside}}} \qquad \text{temperatureFactor} = 1.159$$

FZ0138a, Cable Trays XK016 and XH021

First, estimate the temperature drop in the cable mass of XK016

$calcAmbTemp := 40 \cdot °C$ Ambient temperature used in calculation

$calcSurfaceTemp := 53.474 \cdot °C$ Calculated surface temperature of the cable mass

$calcCondTemp := 62.238 \cdot °C$ Calculated conductor temperature

The test data for XK016 are as follows:

$testInsideXK016 := 31.05 \cdot °C$ Measured temperature inside wall

$testOutsideAmbient := 30.50 \cdot °C$ Measured ambient temperature

$testOutsideXK016 := 31.21 \cdot °C$ Measured temperature outside of wall

$$\Delta T_{massXK016} := \left(\frac{calcCondTemp - calcAmbTemp}{calcSurfaceTemp - calcAmbTemp} - 1 \right) \cdot (testOutsideXK016 - testOutsideAmbient)$$

$$\Delta T_{massXK016} = 0.462 \cdot °C$$

First, estimate the temperature drop in the cable mass of XH021

$calcAmbTemp := 40 \cdot °C$ Ambient temperature used in calculation

$calcSurfaceTemp := 50.023 \cdot °C$ Calculated surface temperature of the cable mass

$calcCondTemp := 59.336 \cdot °C$ Calculated conductor temperature

The test data are as follows:

$testInsideXH021 := 34.48 \cdot °C$ Measured temperature inside wall

$testOutsideXH021 := 34.00 \cdot °C$ Measured temperature outside of wall

$$\Delta T_{massXH021} := \left(\frac{calcCondTemp - calcAmbTemp}{calcSurfaceTemp - calcAmbTemp} - 1 \right) \cdot (testOutsideXH021 - testOutsideAmbient)$$

$$\Delta T_{massXH021} = 3.252 \cdot °C$$

The concept of derating and temperature factors imply that the ratio of the temperature rise inside the fire stop to the temperature rise in open air should be constant for cable trays installed in the same fire stop. Therefore, the equations describing this proportionality can be solved simultaneously to obtain the ambient temperature inside the fire stop and the temperature factor for the surface temperatures. Therefore:

$\Delta T_{outsideXK016} := testOutsideXK016 - testOutsideAmbient \quad \Delta T_{outsideXK016} = 0.71 \cdot {}^\circ C$

$\Delta T_{outsideXH021} := testOutsideXH021 - testOutsideAmbient \quad \Delta T_{outsideXH021} = 3.5 \cdot {}^\circ C$

$T_{guess} := 27 \cdot {}^\circ C$ **Intial guess for ambient temperature inside wall**

$SF := 2$ **Initial guess of temperature factor for surface temperatures**

given

$testInsideXK016 - T_{guess} = SF \cdot \Delta T_{outsideXK016}$

$testInsideXH021 - T_{guess} = SF \cdot \Delta T_{outsideXH021}$

$\begin{pmatrix} wallAmbient \\ surfaceTempFact \end{pmatrix} := find(T_{guess}, SF)$

$wallAmbient = 30.177 \cdot {}^\circ C$

$surfaceTempFact = 1.229$

$\Delta T_{massXK016} = 0.462 \cdot {}^\circ C$

$\Delta T_{massXH021} = 3.252 \cdot {}^\circ C$

$$temperatureFactorXK016 := \frac{\Delta T_{massXK016} + testInsideXK016 - wallAmbient}{\Delta T_{massXK016} + \Delta T_{outsideXK016}}$$

$temperatureFactorXK016 = 1.139$

$$temperatureFactorXH021 := \frac{\Delta T_{massXH021} + testInsideXH021 - wallAmbient}{\Delta T_{massXH021} + \Delta T_{outsideXH021}}$$

$temperatureFactorXH021 = 1.119$

FZ0184

The test data for Conduit T2069 are:

testInsideTemp := 40.58·°C

testOutsideTemp := 44.13·°C

testAmbientTemp := 43.70·°C

FZ0184, Conduit T2063

The test data are as follows:

testInsideTemp := 44.25·°C

testOutsideAmbient := 43.70·°C

testOutsideTemp := 44.58·°C

The data for the two raceways (T2069 and T2063) are inconsistent. Also, nearby hot pipes may have affected the measurements. Therefore, the test results for this fire stop will not be used to calculate temperature factors.

FZ0003

The following data were obtained for Conduit X1614

testInsideTemp := 31.43·°C

testOutsideTemp := 30.23·°C

testAmbientTemp := 30.35·°C

The following data were obtained for Conduit X1615:

testInsideTemp := 30.43·°C
testOutsideTemp := 30.75·°C
testAmbientTemp := 30.35·°C

Fire Stop FZ0003, Conduit X1590
The following test data were obtained:
testInsideTemp := 31.28·°C

testOutsideAmbient := 30.35·°C

testOutsideTemp := 31.83·°C

Fire Stop FZ0003, Conduit X1613

The following test data were obtained:

testInsideTemp := 30.15·°C

testOutsideAmbient := 30.35·°C

testOutsideTemp := 31.38·°C

The temperature rises outside of the wall are low in all cases. Two conduits show a temperature rise outside of the wall, one conduit has a surface temperature less than the ambient temperature outside of the wall, and one conduit outside of the wall is at ambient temperature. Two conduits have temperatures inside the wall that are higher than the temperatures outside the wall; the opposite is true for the other two conduits. The data for this fire stop is too inconsistent to allow the evaluation of the temperature factors.

FZ0132

The wall ambient temperature is based on the data for Conduit X1568. The measured temperature outside of the fire stop is slightly less than the ambient temperature measured nearby. The cable inside this conduit was off during the test. The measured temperature of Conduit X1568 inside the wall is, therefore, representative of the average ambient temperature on both sides of the wall.

$\text{wallAmbientTemp} := 28.40 \cdot {}^\circ\text{C}$

Fire Stop FZ0132, Conduit X1567

The following test data were obtained:

$\text{testInsideTemp} := 36.63 \cdot {}^\circ\text{C}$

$\text{testOutsideAmbient} := 30.35 \cdot {}^\circ\text{C}$

$\text{testOutsideTemp} := 34.23 \cdot {}^\circ\text{C}$

Then the temperature drop between the conduit surface and the conductors is:

$\Delta T_{\text{inCond}} := (\text{conduitRatio} - 1) \cdot (\text{testOutsideTemp} - \text{testOutsideAmbient})$ $\Delta T_{\text{inCond}} = 9.831 \cdot {}^\circ\text{C}$

$\Delta T_{\text{outside}} := \Delta T_{\text{inCond}} + (\text{testOutsideTemp} - \text{testOutsideAmbient})$ $\Delta T_{\text{outside}} = 13.711 \cdot {}^\circ\text{C}$

$\Delta T_{\text{inside}} := \left(\Delta T_{\text{inCond}} + \text{testInsideTemp}\right) - \text{wallAmbientTemp}$ $\Delta T_{\text{inside}} = 18.061 \cdot {}^\circ\text{C}$

$\text{temperatureFactor} := \dfrac{\Delta T_{\text{inside}}}{\Delta T_{\text{outside}}}$ $\text{temperatureFactor} = 1.317$

FZ0179, Cable Tray TK600

Temperature measurements were taken on both sides of the wall. The average temperature (used as the ambient temperature in the wall) is taken directly from the spread sheet. The following data were obtained:

$\text{testInsideTemp} := 27.82 \cdot {}^\circ\text{C}$

$\text{testOutsideTemp} := 26.92 \cdot {}^\circ\text{C}$

$\text{testAmbientTemp} := 24.70 \cdot {}^\circ\text{C}$

$\text{wallAmbientTemp} := 25.45 \cdot {}^\circ\text{C}$

First, estimate the temperature drop in the cable mass

$\text{calcAmbTemp} := 40 \cdot {}^\circ\text{C}$ Ambient temperature used in calculation

$\text{calcSurfaceTemp} := 62.983 \cdot {}^\circ\text{C}$ Calculated surface temperature of the cable mass

$\text{calcCondTemp} := 76.936 \cdot {}^\circ\text{C}$ Calculated conductor temperature

$$\Delta T_{\text{mass}} := \left(\frac{\text{calcCondTemp} - \text{calcAmbTemp}}{\text{calcSurfaceTemp} - \text{calcAmbTemp}} - 1\right) \cdot (\text{testOutsideTemp} - \text{testAmbientTemp})$$

$\Delta T_{\text{mass}} = 1.348 \cdot {}^\circ\text{C}$

$\Delta T_{\text{outside}} := \Delta T_{\text{mass}} + (\text{testOutsideTemp} - \text{testAmbientTemp})$ $\Delta T_{\text{outside}} = 3.568 \cdot {}^\circ\text{C}$

$\Delta T_{\text{inside}} := \Delta T_{\text{mass}} + (\text{testInsideTemp} - \text{wallAmbientTemp})$ $\Delta T_{\text{inside}} = 3.718 \cdot {}^\circ\text{C}$

$\text{temperatureFactor} := \dfrac{\Delta T_{\text{inside}}}{\Delta T_{\text{outside}}}$ $\text{temperatureFactor} = 1.042$

Fire Stop F0553, Cable Tray XP600

The test data are as follows:

coverTemp := 27.43·°C Surface temperature in covered tray section

coverAmbient := 25.90·°C Ambient temperature corresponding to surface temperature in covered tray section

openCoverAmbient := 26.10·°C Ambient temperature for open tray in tray cover test

openCoverTemp := 27.90·°C Surface temperature in open tray for tray cover test

wallSurfaceTemp := 27.33·°C Cable surface temperature inside the fire stop

wallRoomAmbient := 25.95·°C Ambient temperature in the stairwell area for the fire stop test

wallOpenAmbient := 26.10·°C Ambient temperature opposite the stairwell for the fire stop test

openWallTemp := 27.87·°C Surface temperature in the open tray for the fire stop test

The temperature rises are very small. The results of this test are inconclusive and are inconsistent with the thermal behavior of cable trays with tightly fitting covers and fire stops.

Table 9— Summary of Calculation Results

Fire Stop	Raceway	Raceway Type	Wall Thick-ness	Opening Size	Temp-erature Factor	Ambient Temp-erature	Temp-erature Outside Wall	Temp-erature Inside Wall	Effective Wall Ambient	Remarks
FZ0134	XP010	Tray	2'	3'-9"×3'-9"	1.23	27.90°C	28.71°C	30.28°C	29.12°C	Test for FZ0138a used to estimate appropriate ambient temperature for wall. The results from FZ0003 and FZ0132 suggest that the temperature on the opposite side of the wall is relatively stable.
FZ0138	X1706	Conduit	1'	6'-6"×8'-9"	—	24.55°C	24.18°C	27.18°C	27.50°C	Since the conduit surface temperature is less than the ambient temperature, it is assumed that the heat generation inside the conduit is negligible. Therefore, no meaningful calculation of the temperature factor is possible. There is a steam line in the upper part of the opening.

Fire Stop	Raceway	Raceway Type	Wall Thickness	Opening Size	Temperature Factor	Ambient Temperature	Temperature Outside Wall	Temperature Inside Wall	Effective Wall Ambient	Remarks
	X1709	Conduit			1.16	24.45°C	25.25°C	28.75°C		Ambient temperature calculating temperature rise in wall developed using cable tray test (FZ0138a). The resulting ambient temperature (27.5°C) gives reasonable agreement with the temperature measured inside the wall for X1706 (27.18°C).
	XK016	Tray			1.14	30.50°C	31.21°C	31.05°C	30.18°C	Ambient temperature for wall temperature rise determined solving relationships for XK016 and XH021 simultaneously.
	XH021	Tray			1.12	30.50°C	34.00°C	34.48°C		
FZ0184	T2069	Sleeve	2'	Sleeves	—	43.70°C	44.13°C	40.58°C		Data for the two raceways (T2069 and T2063) are inconsistent. Also, nearby hot pipes may have affected the measurements. Therefore, the results from this test are rejected.
	T2063	Sleeve			—	43.70°C	44.58°C	44.25°C		

Fire Stop	Raceway	Raceway Type	Wall Thickness	Opening Size	Temperature Factor	Ambient Temperature	Temperature Outside Wall	Temperature Inside Wall	Effective Wall Ambient	Remarks
FZ0003	X1614	Sleeve	1'	Sleeves	—	30.35°C	30.23°C	31.43°C	—	The temperature rise outside of the wall are low in all cases. Two conduits show a temperature rise outside of the wall, one conduit shows a temperature fall outside of the wall, and one conduit outside of the wall is at ambient temperature. Two conduits have temperatures inside the wall that are higher than outside the wall; two conduits have temperatures inside the wall that are lower than outside of the wall. The data for this fire stop is too inconsistent to allow evaluation of temperature factors.
	X1615	Sleeve			—		30.75°C	30.43°C		
	X1590	Sleeve			—		31.83°C	31.28°C		
	X1613	Sleeve			—		31.38°C	30.15°C		

Fire Stop	Raceway	Raceway Type	Wall Thickness	Opening Size	Temperature Factor	Ambient Temperature	Temperature Outside Wall	Temperature Inside Wall	Effective Wall Ambient	Remarks
FZ0132	X1568	Conduit	2'	8'-6"×3'-3"	—	30.40°C	30.13°C	28.4°C	28.40°C	The test data for Conduit X1568 was used to determine the appropriate ambient temperature to be used to calculate the temperature rise inside the wall, since the cable in this conduit was not energized at the time of the test.
	X1567	Conduit			1.32	30.35°C	34.23°C	36.63°C		
FZ0179	TK600	Tray			1.04	24.70°C	26.92°C	27.82°C	25.45°C	The temperature rises for this test are quite small. Therefore, the temperature factor calculated from this test has a high tolerance.
FZ0553	XP600	Tray	2'	5'-0"×2'-8"	—	25.95°C	27.87°C	27.33°C	26.10°C	Temperature rises were very small. The results are inconclusive and are inconsistent with the anticipated thermal behavior of cable trays with tightly fitting covers and fire stops.

Summary and Conclusions

Information on the temperature factors for cable trays can be obtained from the tests on Fire Stops FZ0134, FZ0138a, and FZ0179. The temperature rise for the cable tray associated with Fire Stop FZ0553 (XP600) was small and the test results are inconclusive. Therefore, it is not possible to obtain reliable information for calculating temperature factors from the data for Fire Stop FZ0553.

Information on the temperature factor for conduits can be obtained from the tests on Fire Stops FZ0138 and FZ0132. The tests on conduit sleeves did not yield reliable data which could be used to calculate the temperature factor for a fire stop. The temperature factor for conduit sleeves can be considered equal to that of cable trays.

The test data was obtained through fire stops in walls. Reference 3 determined that the temperature rise of a fire stop in a wall was 61°C, while the temperature rise in a similar penetration mounted in a floor was 70°C. Therefore, the temperature factor for a floor fire stop is $\frac{70}{61}$ times that of the corresponding wall fire stop. The highest calculated temperature factor for each type of raceway and wall factor will be used. Therefore, the temperature factors that will be used elsewhere in the calculation are:

	Wall		Floor	
	1' Thick	2' Thick	1' Thick	2' Thick
Cable Trays & Sleeves	1.14	1.23	1.31	1.41
Conduit	1.16	1.32	1.33	1.52

The corresponding ampacity multipliers are:

	Wall		Floor	
	1' Thick	2' Thick	1' Thick	2' Thick
Cable Trays & Sleeves	0.94	0.90	0.87	0.84
Conduit	0.93	0.87	0.87	0.81

References

1. Attachment 5 of Palisades Calculation EA-ELEC-AMP-034, Revision 0, "Ampacity Evaluation for Cable Trays Containing the Power Cables Identified in EA-ELEC-AMP-028, initiated by R. Hernandez and technically reviewed by J. Nehls, and dated January 21, 1997.

2. Appendix A of Attachment 8 of Palisades Calculation EA-ELEC-AMP-032, Revision 0, "Ampacity Evaluation for Open Air Cable Trays with a Percent Fill Greater than 30% of the Useable Cross Sectional Area", initiated by R. Hernandez and technically reviewed by J. Nehls, and dated March 18, 1997.

3. Brand Industrial Services, Inc. (BISCO) 1976. "BISCO Ampacity Test Performed at Portland Cement Association, Test No. 9027-10". Elk Grove Village, Illinois: Brand Industrial Services, Inc.

METHODOLOGY FOR DEVELOPMENT OF HEAT TRANSFER MODEL FOR CABLES IN TRAY

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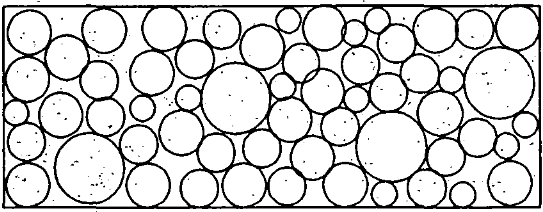
Calculation Methodology

The accepted method for evaluating the ampacity of cables in tray has been the Stolpe method(1). This method assumes that all cables in the tray have equal loading. In actual power plant cable trays, the currents of the various cables vary significantly. Therefore, an evaluation of the ampacity based on the Stolpe method for the most heavily loaded cable is overly conservative, given the presence of a significant number of lightly loaded cables.

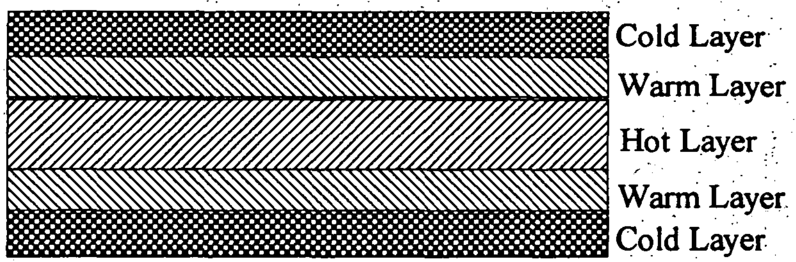
Cables are installed in the cable tray in a more or less random fashion. While a group of heavily loaded cables may run together in one part of the tray, they will be redistributed in the tray in other locations. Therefore, it is overly conservative to place all heavily loaded cables together in a compact mass. Reference 2 suggests a model arrangement that is less conservative than placing all heavily loaded cables together in a compact mass, while providing a reasonable degree of conservatism.

The maximum temperature of the cables in a cable tray is calculated by first grouping the cables in three layers, namely, "Hot", "Warm" and "Cold" layers. The resulting grouped cable arrangement along with their respective actual load currents is used to calculate the maximum temperature of the cable mass for the above mentioned three layers. After obtaining the maximum cable mass temperature using the layered model, the diversity of the cable loading is taken into account and the temperature for the most heavily loaded cable in the "Hot" layer is estimated based on its loading.

The depth of fill for any tray is determined based on the width of the tray and the total cross sectional area of the cable mass. The available cable mass is divided into three different categories, namely, "Hot", "Warm", and "Cold".



The "hot" cables are put in the center of the cable tray, and will be called the "hot layer". The "hot layer" is sandwiched between the "warm" cables. These layers are called "warm layers". The "hot layer" and "warm layers" are sandwiched between the "cold" cables. These layers are called "cold layers". This layer arrangement is shown in the figure below.



The above cable arrangement is acceptable when there are large number of "hot" cables, such that the sum of the diameters of the "hot" cables exceed the physical width of the tray. When there are a small number of "hot" cables, spreading the "hot layer" across the entire physical width of the cable tray results in the area used for heat dissipation being larger than the actual area producing non conservative results. Therefore, when there are smaller number of "hot" cables only the hot spot part of the cable tray is modeled. The model tray width is calculated as:

$$W_{model} = \sum D_{hot\ cables} + \tfrac{1}{2}\ \text{Depth of Fill}$$

where,

$D_{hot\ cables}$ - Diameter of hot cables

The ½ Depth of fill term accounts for fringing effects of the heat transfer path from the hot cables to the surface of the cable mass.

In the model tray all the "hot" cables are included. In addition, one "warm" and one "cold" cable, etc. is included until the depth of fill of the model cable try is equal to the depth of fill of the physical tray. The selection of the "warm" and "cold" cables is performed using the following rules:

- Warmest large cables are selected first
- Coldest small cables are selected first

After including the "hot", "warm", and "cold" cables if the depth of fill is greater than the depth of fill for the physical tray, the model tray width is adjusted to achieve the same depth of fill.

Introduction to the Mathcad Calculations

The Mathcad calculation scratch sheet contains sections to perform four tasks:

- Gather parameters, such as ambient temperature and thermal emissivities, that are entered manually and read the cable tray width and the data on the cable groups from files that have been prepared externally.
- Calculate key parameters that will be used in the remainder of the calculation including the depth of fill, the ampacities of the cables calculated according to ICEA P-54-440 / NEMA WC 51-1986, and the loading of each cable in per unit of its ICEA ampacity.
- Separate the cables in the tray into "hot", "medium", and "cold" cables. Then determine the model width of the cable tray required to contain the "hot" cables. Finally, add a sufficient number of "warm" and "cold" cables so that the depth of fill in the model tray is the same as in the actual cable tray. If necessary, the width of the model cable tray is adjusted to ensure this.
- Calculate the conductor temperature using the Harshe - Black model for the cable mass.

Gather Input Data

Most of the input data is manually entered into the scratch sheet by simple equations. However, because of the large number of cable groups (a set of identical cables carrying the same load current) and the amount of data associated with each cable group, the cable group data is read from a text file. The cable tray width is read from a separate text file due to the limitations of Mathcad 4.0's data file functions. The following information is entered manually:

- The ambient temperature
- The emissivity of the top of the cable tray
- The emissivity of the bottom of the cable tray
- Three possible break points for separating "hot" cables from "warm" cables. The appropriate break point is selected based on the loading of the most heavily loaded cable in the cable tray.
- The break point used to separate "cold" cables from "warm" cables
- A code indicating the type of fire stop (or no fire stop) installed in the cable tray

- The thermal resistivity of the cable mass
- The maximum allowable conductor temperature

The cable tray width is read from a data file that contains this value and is associated with the file variable hdr_name. The following cable group information is read from a second data file associated with the variable input_file:

- The cable sizes in the 0th column. (Mathcad numbers arrays beginning with 0 in the manner of the C language.) In order for Mathcad to read the cable size, a "1" must be substituted for all "/" and a "0" or space must be substituted for "#". Therefore, "410" is interpreted as #4/0 AWG and 010 or 10 is interpreted as #10 AWG.
- The number of cables in each group in the 1st column.
- The number of conductors in each cable in the 2nd column.
- The cable diameter in inches in the 3rd column.
- The copper area in the 4th column. In the Black program this is used to calculate the cable resistance. Since this does not account for skin effect, etc., the Mathcad scratch sheet determines the cable resistance by looking up the resistance in a table based on the conductor trade size. Therefore, the scratch sheet ignores this field.
- The conductor load current in amperes in the 5th column.

Note: *The displayed array includes the index number of the rows of the array which is not part of the input data. The zeroth column is obtained by augmenting the input array with the row indices. This is done to make examining the data contained in the array easier for the reader.*

The next subsection of the scratch sheet contains a series of look up tables for pre-defined values, such as conductor resistance versus size; air characteristics such as the thermal conductivity, kinematic viscosity, and Prandtl number; the effect on the temperature rise due to fire stops; and some miscellaneous constants, such as the Stefan-Boltzmann constant.

First the cable resistances are defined. This is done by a look up table consisting of the vector Table_size containing the conductor size code and the vector Table_resist containing the conductor resistance in ohms per foot at 90°C. The Mathcad linear interpolation function "linterp" is used to look up resistances from the cable size codes.

Next temperature rise factors for various fire stop configurations are defined. The source of these factors is Attachment 8 of this EA. These factors are applied to the conductor temperature rise at the end of the calculation. The temperature factors for fire stops in vertical risers are calculated from those for horizontal cable trays using the information contained in Reference 6.

The values of the thermal conductivity, kinematic viscosity, and Prandtl number of air are based on the data given in Holman. As a simplification, a single value for these items and for the coefficient of expansion of air is given for an assumed film temperature of 60°C.

Next the offset between degrees Celsius and Kelvin and the Stefan-Boltzmann constant are defined. The acceleration due to gravity is already defined by Mathcad.

Calculate Key Parameters

The next section breaks down the data for use to the calculation. The ambient and maximum conductor temperatures are converted to Kelvin. The cable size (Cable_size), number of cables (n_cables), number of conductors per cable (n_conductors), cable diameter (Cable_dia), and load current (I_{load}) are unloaded from the data read from the cable group data file (Cable_data). Next a vector with the conductor resistance of the cables (R_{cable}) is created by looking up the conductor resistance of each cable group based on the cable size code.

The depth of fill of the actual configuration of the cable tray is then calculated. This will be used later in the scratch sheet to calculate the ampacity as defined in ICEA P-54-440 and to develop an equivalent cable tray to analyze the "hot" cables. The depth of fill is defined simply as the sum of the squares of the diameters of all the cables in the tray divided by the width of the tray.

The next section of the calculation calculates the ampacity of each cable as defined by ICEA P-54-440. This is a "stand alone" section which is designed to reproduce the results shown in the standard as closely as possible. The heat transfer function and constants are defined independently from the rest of the calculation and are defined and used *exactly* as in the standard. First the heat intensity, that is the amount of heat that can be produced per unit volume of cable mass, is calculated. The Stolpe method used in the standard treats the cables as a uniform mass that generates a constant amount of heat per unit volume. The heat dissipated by the slab of cables is removed by convection and radiation using the constants and formulae given on page 17 of the standard. The temperature drop through the cable mass itself is calculated using Equation 5 of the Stolpe paper (equivalent to

Holman's Equation 2-23). The equations are solved to find the amount of heat generation that results in a conductor temperature of T_{cond} in the center of the cable mass. A Mathcad solve block[1] is used to find the allowable heat generation per unit length of the tray. The heat intensity is this value divided by the cross sectional area of the cable mass. The ICEA ampacity is the current which will produce the amount of heat allowed by the heat intensity within the square area occupied by each cable. The ICEA ampacities are stored in the vector I_{ICEA}. The load current in each cable is then expressed in per unit of the ICEA ampacity in the vector I_{ICEAu}.

Classification of the Cables as "Hot", "Warm", and "Cold"

The definition of a "hot" cable is based on the ICEA ampacity of the cables and depends on the loading of the cables in the tray. If at least one cable is loaded to more than 1.00 per unit of the ICEA rating or more, a "hot" cable is defined as a cable loaded above 1.00 per unit of its ICEA ampacity. If the most heavily loaded cable is loaded to greater than 0.80 per unit of the ICEA ampacity but less than 1.00 per unit of the ICEA ampacity, a "hot" cable is defined as a cable loaded to greater than 0.8 per unit of the ICEA ampacity. If no cable is loaded to more than 0.80 per unit of the ICEA ampacity, "hot" cables are defined as those loaded to more than 0.60 per unit of their ICEA ampacity. In a few cases none of the cable groups meets the definition of a "hot" cable. In this case, the hottest cable group in the tray is selected as the "hot" cables. The Mathcad max function is applied to I_{ICEAu} to find the loading of the most heavily loaded cable (Hottest). The value of Hottest determines the applicable definition of a "hot" cable. The scratch sheet then compares the loading of each cable (I_{ICEAu}) with the criteria and marks the "hot" cables in the vector Hot_set. The members of Hot_set with indices that correspond to hot cables are set to 1 with the remaining members set to 0. Therefore, once the index of a given cable is known, Hot_set can be used to determine if it is a "hot" cable or not. A summation is used to count the hot cables marked in Hot_set. The number of hot cables is stored in the scalar variable NumHot. The number of "warm" and "cold" cables is then calculated from the total number of cables

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[1] The Mathcad solve block automatically performs a numerical solutions using the Levenberg-Marquardt method of a set of non-linear equations. The scratch sheet uses the Mathcad default tolerance of 10^{-3}. The solve block consists of three parts. The initial value of the variables to be solved for are defined immediately before the key word "Given". The equations to be solved are defined between the key words "Given" and "Find". The variables that contain the final solution and the variables in the equation definitions are defined by the "Find" function.

(Data_size) and NumHot. This value is stored in the scalar NumNotHot. "Cold" cables are defined as those cables loaded to 10% of their ICEA ampacity or less. Cables that are neither "hot" nor "cold" are "warm".

The next step is to calculate an interim value for the width of the model cable tray. As described elsewhere in this calculation, the width of the model cable tray is set to the sum of the diameters of the "hot" cables plus half of the physical depth of fill, so long as the calculated width of the model cable tray is less than the physical width of the actual cable tray. The maximum width of the model cable tray is the actual width of the cable tray.

Next a matrix (WarmArray) is created to determine the order that cable groups should be added to the tray in order to bring the depth of fill in the model cable tray to the physical depth of fill. The 0th column of WarmArray contains the indices of the cable groups, the 1st column contains the cable loading in per unit of the ICEA ampacity, the second column contains the number of cables in the group, and the 3rd column contains the area occupied by the cable group in the tray (equal to the number of cables times the square of the diameter). It is intended that the rows of the matrix be sorted using the cable loading as the primary key and the cable area as the secondary key. However, the Mathcad sort functions do not provide for such multiple sorts. Therefore, a 4th column is added to use as a sort key. This is set to 10000 times the cable loading plus the area occupied by the cable group in per unit of the cable group occupying the most area. The sort index of the "hot" cables is set to -∞. This forces the hot cables to one end of the matrix. WarmArray is then sorted in descending order by row. The sorted matrix has the "warm" cables at the top, the "cold" cables below the warm cables, and the "hot" cables at the bottom.

Next, a summation is used to count the "warm" cables (Num_Warm). The number of cold cables (Num_Cold) is also calculated. In the sorted WarmArray, the "warm" cables lie from 0 to (Num_Warm-1), the "cold" cables from Num_Warm to (NumNotHot-1), and the "hot" cables from NumNotHot to (Data_size-1).

Next, a matrix of cables to be considered for addition to the model tray will be created. While there are unused "warm" and "cold" cables, the cables will be added in the order of warmest, largest; coldest, smallest; next warmest, largest; next coldest, smallest; etc. If all of the "cold" cables are exhausted first, the remaining "warm" cables are added in order of descending loading and descending area occupied by the group. If all the "warm" cables are exhausted first, the remaining cold cables are added in order of ascending heat generation and area occupied by the cable groups.

This process is controlled by the flag Most_of. This has a value of 1 if there are more "warm" cables than "cold" cables, 0 if there are equal numbers of "warm" and "cold" cables, and -1 if there are more "cold" cables than "warm" cables. The variable Max_Alternate gives the number of cables that can be added in an alternating fashion (the lesser of twice the number of "warm" or "cold" cables). The information about the cable groups is now inserted into the matrix Add_Pointer in the order in which the cables will be added to the model tray. The 0th column of Add_Pointer contains the index of the cable group and the 1st column contains the number of cables in the group. Because of the way WarmArray has been sorted, "warm" cables are taken from the top of WarmArray working downward. "Cold" cables are taken from the bottom of WarmArray working towards the top. The range variable "I" controls the addition of alternating "warm" and "cold" cables.

The remaining "warm" or "cold" cables are then added. This is controlled by the vector "iik". A vector is used here rather than a range variable as it allows defeating this section of code if all of Add_Pointer has been filled with alternating "warm" and "cold" cables. In this case, all members of "iik" are set to 0 and the 0th row of Add_Pointer is copied back to itself. Otherwise, "iik" is used to fill Add_Pointer with "warm" or "cold" cables as required.

In the next section the vector Hot_Pointer is created. It is filled with the indices of the "hot" cables. It is used to access them quickly during later computations.

The next task is to determine how many cables are to be added. In order to do this, a vector of depths of fill, DOF_{trial} is created. The 0th member contains the depth of fill in the model tray with just the "hot" cables. The 1st member contains the depth of fill with the "hot" cables and the first additional cable to be added, the 2nd member contains the depth of fill with the "hot" cables plus the first two additional cables to be added, etc.

DOF_{trial} is then searched from the bottom up to find the number of cable groups to be added so that the depth of fill in the model cable tray is the closest to the depth of fill in the physical cable tray while being greater than or equal to that in the physical cable tray. This is done by a summation that decrements the number of cables in the group for each member of DOF_{trial} for which the depth of fill equals or exceeds the physical depth of fill. The result is stored into NumCables_in_Set. This is set to 1 for "hot" cables only, 2 for "hot" cables plus one additional group, etc. A check is made on the result. If alternating "warm" and "cold" cables are being added to the tray, the number of cables to be added is adjusted so that equal numbers of "warm" and "cold" cable groups are added to the tray. In those cases where all cables in the physical tray are included in the model tray, it is possible for the value

| of NumCables_in_Set to exceed the maximum value due to the round off error of calculating the depth of fill. The check ensures that the value of NumCables_in_Set does not exceed the maximum possible value of NumNotHot+1. Finally, the width of the model cable tray is adjusted so that the depth of fill of the model cable tray is the same as that of the physical cable tray.

Next, the number of "warm" cables in the set to be added is determined and placed in the variable Num_Warm. This is done by searching the Add_Pointer matrix and comparing the cable loading in per unit of the ICEA ampacity against the definition of a warm cable. The number of "cold" cables in the cables is then calculated and placed in the variable NumCold.

The last step before performing the actual heat transfer calculations is to calculate the amount of heat generated and the depth of fill of the "hot", "warm", and "cold" cables. The vector Hot_Pointer is used to select the cables to be included in the summations for the hot cables. Similar calculations are performed for the "warm" and the "cold" cables. The data for the "warm" cables is located using the pointers at the top of WarmArray and that for the "cold" cables using the bottom of WarmArray.

The amount of heat generated in the cable trays is calculated for a temperature of 90°C. A function is then created that can determine the heat generated at any layer temperature. This function will be used during the solution of the heat transfer equations where the heat generated by the cables is calculated using the conductor electrical resistance corresponding to the actual layer temperature for each of the three layers.

Solution of the Heat Transfer Problem

The various heat transfer equations are first stated as a series of functions. These equations are then solved to give the conductor temperature. First the heat dissipated by radiation from the cable mass is given as a function of the surface temperature of the cable mass.

The functions for convection are more complicated. First, a function for the Grashof number is written using the functions for the characteristics of air described earlier and the definition of the Grashof function. Next, the function for the Rayleigh number (product of the Grashof and Prandtl numbers) is written. The function for the Nusselt number for the top of the cable mass can then be written. This function has two definitions, one for laminar flow (Rayleigh number less than 8×10^6) and another for turbulent flow (Rayleigh number greater than 8×10^6). The overall heat transfer function for convection from the top of the cable mass can then be written based on the definition of the Nusselt number.

Holman recommends that the characteristic length of an irregular object be taken as the ratio of the area to the perimeter of the object. The characteristic length, l_{char} of a cable tray of width w and length l is:

$$l_{char} = \frac{l \cdot w}{2(l+w)}$$

In the case of the cable tray, $l \gg w$, so:

$$l_{char} \approx \frac{l \cdot w}{2 \cdot l} = \frac{w}{2}$$

Note that the two terms for the width (the characteristic length and the area of the cable tray per unit length) cancel each other out.

The function for the overall heat transfer from the bottom of the cable tray can be written in a similar manner, except that only one flow regime needs to be considered. Two alternate forms of the heat transfer function are written, but only Q_{bot_conv} is actually used. Q_{bot_conv1} is an alternate function that is only used for comparison with an alternate solution method.

A solve block is now used to solve the heat transfer equations. The equations for the temperature rise through the cable mass are written based on Harshe and Black's Equation 6. This equation can be derived as the superposition of the temperature rise through a mass with uniform heat generation per unit volume (as was done in the original Stolpe method) and the temperature drop from conducting the heat generated by the layers inside the layer under consideration. The solve block calculates the surface temperature of the cable mass and the temperature inside the "cold", "warm", and "hot" layers.

The last step is to incorporate the effect of the fire stop and/or tray cover (if present). The conductor temperature rise, which is the temperature difference between the hot layer and the ambient temperature is multiplied by the temperature factor that corresponds to the fire stop or tray cover type in question.

This modified temperature rise is then used to calculate the conductor temperature at the routing point. The factors for fire stops are based on the calculations in Atachment 8 of this EA. When fire stops and tray covers are both present, the temperature rise will be higher than if only the fire stop was present. However, some of the heat whose dissipation would be restricted by the tray covers can escape through the opposite side of the fire stop, provided there are no tray covers on the opposite side. Intuitively, the additional temperature rise due to tray covers on one side of the fire stop is about half of that caused by tray covers on both sides of the fire stop (i.e. half the 15% derating attributed to covered trays).

The layered model used in calculating the maximum cable temperature in a cable tray is an interim step in estimating the maximum temperature of the cable in a cable tray with random cable arrangement. The final step focuses on the real cable tray - not the layered model - considering the random layout and loading distributions of the cables in the tray.

The temperature of the "hot" cable layer that has been calculated above represents the maximum cable temperature in the tray provided that the cable loadings as a percent of the ICEA ampacity ratios of the hot cables are within a reasonable threshold of the average loading of these cables based on the field testing as reported in the Reference 2. Cables with higher loading ratios than this threshold will have a higher temperature than that calculated for the hot layer and cables with loading ratios below this threshold will have temperatures below that calculated for the hot layer. The temperature of the most heavily loaed cable is calculated by adjusting the temperature rise calculated for the hot layer with the ratio of the cables heat intensity to the heat intensity corresponding to the threshold current. This is equivalent to multiplying the temperature rise of the hot layer by the square of the per unit ICEA current of the cable to the threshold per unit ICEA current of the hot layer.

The threshold current was selected to be 20% higher than the average hot layer per unit ICEA current. The use of this threshold value is conservative since it limits the credit taken for the temperature averaging that takes place in the actual tray installation as a result of random cable layout. If the loading of the most heavily loaded cable does not exceed the threshold current, the cable temperature is taken to be the temperature of the "hot" layer.

References

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4. Haddad, S. Z.; Bloethe, W. G.; Lamken, D. C.; Stolt, H. K.; and Sykora, G. 1982. Tests at Braidwood Station on the Effects of Fire Stops on the Ampacity Rating of Power Cables. Chicago: *Proceedings of the American Power Conference.*
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Case XP600

Cable Tray Emissivities

$\varepsilon_{top} := 0.95$ Top surface of cable tray

$\varepsilon_{bottom} := 0.65$ Bottom surface of cable tray

$\varepsilon_{mean} := \dfrac{\varepsilon_{top} + \varepsilon_{bottom}}{2}$ $\varepsilon_{mean} = 0.8$ Emissivity used for calculations

Break Points Considered for Selecting Hot Cables

$BreakPoint_1 := 1.0$

$BreakPoint_2 := 0.8$

$BreakPoint_3 := 0.6$

Maximum Loading for "Cold" Cables

$Max\_Cold := 0.10$

Physical Width of the Tray

$w_{physical} := READ(hdr\_name) \cdot 1 \cdot in$ $w_{physical} = 24 \cdot in$

Fire Stop Code

$Fire\_Stop\_Code := 2$

Tray Cover Code

$Tray\_Cover\_Code := 2$

Cable Mass Resistivity

$\rho_{mass} := 400 \cdot K \cdot cm \cdot watt^{-1}$

Ambient Temperature

$T_{ambC} := 40.0 \cdot K$ °C

Get the cable data from an external file

$Cable\_data := READPRN(input\_file)$

$Data\_size := rows(Cable\_data)$ $Data\_size = 31$

$Data\_index := 0, 1 .. (Data\_size - 1)$

$Index\_array_{Data\_index} := Data\_index$

Threshold Factor for Temperature of "Hot" Cables

$F_{Threshold} := 1.2$

Fire Stop Codes:

0— NO fire stop
1— 24" horizontal concrete
2— 24" horizontal Kaowool
3— 24" horizontal silicone foam
4— 24" horizontal double sided 3M caulk
5— 24" horizontal single sided 3M caulk
6— 24" vertical concrete
7— 24" vertical Kaowool
8— 24" vertical silicone foam
9— 24" vertical double sided 3M caulk
10— 24" vertical double sided 3M caulk
11— 12" horizontal concrete
12— 12" horizontal Kaowool
13— 12" horizontal silicone foam
14— 12" vertical concrete
15— 12" vertical Kaowool
16— 12" vertical silicone foam

Allowable Conductor Temperature

$T_{condC} := 90 \cdot K$ °C

Tray Cover Codes

0— NO Cover
1— Raised Covers
2— Closed Covers

Lookup Table for Conductor Resistances at 90°C (See Sargent & Lundy Standard ESA-102)

$$\text{Table\_size} = \begin{bmatrix} 1 \\ 2 \\ 4 \\ 6 \\ 8 \\ 9 \\ 10 \\ 12 \\ 14 \\ 16 \\ 110 \\ 210 \\ 250 \\ 300 \\ 310 \\ 350 \\ 400 \\ 410 \\ 500 \\ 600 \\ 750 \\ 1000 \\ 1250 \\ 1500 \\ 1750 \\ 1922 \\ 1925 \\ 2000 \\ 2500 \end{bmatrix} \qquad \text{Table\_resist} = \begin{bmatrix} 0.0161 \\ 0.0203 \\ 0.0324 \\ 0.0513 \\ 0.0818 \\ 0.103 \\ 0.130 \\ 0.206 \\ 0.328 \\ 0.523 \\ 0.0128 \\ 0.0101 \\ 0.00542 \\ 0.00453 \\ 0.00804 \\ 0.00389 \\ 0.00341 \\ 0.00639 \\ 0.00275 \\ 0.00231 \\ 0.00187 \\ 0.00144 \\ 0.00119 \\ 0.00103 \\ 0.000913 \\ 0.108 \\ 0.217 \\ 0.000831 \\ 0.000723 \end{bmatrix} 10^{-2}\,\Omega\cdot\text{ft}^{-1}$$

Temperature Factors for Fire Stops

$$FS\_Temp\_Factor = \begin{vmatrix} 1.000 \\ 1.06399 \\ 1.23 \\ 1.23 \\ 1.23 \\ 1.23 \\ 1.22098 \\ 1.41 \\ 1.41 \\ 1.41 \\ 1.41 \\ 1.00000 \\ 1.14 \\ 1.14 \\ 1.00000 \\ 1.31 \\ 1.31 \end{vmatrix}$$

$$Cover\_Temp\_Factor = \begin{pmatrix} 1.00000 \\ 1.10803 \\ 1.38408 \end{pmatrix}$$

Miscellaneous Constants

$g := 9.807 \cdot m \cdot sec^{-2}$ Acceleration due to gravity

Stefan-Boltzmann Constant

$\sigma := 5.669 \cdot 10^{-8} \cdot watt \cdot m^{-2} \cdot K^{-4}$ Holman, page 307

Conversion between °C and K

$CtoK := 273.15 \cdot K$

Physical Characteristics of Air

The characteristics of air are given for an assumed film temperature of 60°C (333K)

Thermal conductivity

$k_{air}(T1, T2) := 0.029 \cdot watt \cdot m^{-1} \cdot K^{-1}$

Kinnematic Viscosity

$\nu_{air}(T1, T2) := 1.928 \cdot 10^{-5} \cdot m^2 \cdot sec^{-1}$

Volume coefficient of expansion

$$\beta(T_a, T_b) := \frac{1}{60 \cdot K + CtoK}$$

Prandtl Number

$Pr_{air}(T1, T2) := 0.700$

Get Basic Data about Cables in Tray

$Cable\_size := Cable\_data^{<0>}$

$n\_cables := Cable\_data^{<1>}$

$n\_conductors := Cable\_data^{<2>}$

$Cable\_dia := Cable\_data^{<3>} \cdot 1 \cdot in$

$I_{load} := Cable\_data^{<5>} \cdot 1 \cdot amp$

$R_{cable_{Data\_index}} := linterp\left(Table\_size, Table\_resist, Cable\_size_{Data\_index}\right)$

$T_{amb} := T_{ambC} + CtoK$ Ambient temperature in Kelvin

$T_{cond} := T_{condC} + CtoK$ Conductor temperature in Kelvin

Physical Depth of Fill

$$DOF_{physical} := \frac{\displaystyle\sum_{i=0}^{(Data\_size-1)} n\_cables_i \cdot \left(Cable\_dia_i\right)^2}{w_{physical}} \qquad DOF_{physical} = 1.573 \cdot in$$

Calculate the Heat Intensity according to NEMA WC51-9986 / ICEA P-54-440 (1986)

Note: The formulae used in this section are taken directly from NEMA WC51 to ensure that the results match those in the standard.

$DOF_{ICEA} := DOF_{physical}$ $\quad T_{ambICEA} := T_{amb}$

Calculate the surface temperature of the cable mass as a function of heat generation

$$Ts(Q) := T_{cond} - \frac{Q \cdot \rho_{mass} \cdot DOF_{ICEA}}{8 \cdot w_{physical}}$$ Stolpe, Equation 5

Heat dissipated by convection

$$Q_{cICEA}(T) := 0.223 \cdot watt \cdot ft^{-2} \cdot in^{\frac{1}{4}} \cdot K^{-\frac{5}{4}} \cdot \frac{\left(T - T_{ambICEA}\right)^{\frac{5}{4}}}{w_{physical}^{\frac{1}{4}}} \cdot 2 \cdot w_{physical}$$

NEMA WC 51-1986 /
ICEA P-54-440,
Appendix B

Heat dissipated by radiation

$$\sigma_{ICEA} := 0.530 \cdot 10^{-8} \cdot watt \cdot ft^{-2} \cdot K^{-4}$$

NEMA WC 51-1986 /
ICEA P-54-440,
Appendix B

$$Q_{rICEA}(T) := \sigma_{ICEA} \cdot \varepsilon_{mean} \cdot \left(T^4 - T_{ambICEA}{}^4\right) \cdot 2 \cdot w_{physical}$$

Holman, Equation 8-43a for tray completely enclosed in a large area

Find the heat dissipated by the tray to give rated conductor temperature

$Q_{test} := 5 \cdot watt \cdot ft^{-1}$

Given

$Q_{test} = Q_{cICEA}\left(Ts\left(Q_{test}\right)\right) + Q_{rICEA}\left(Ts\left(Q_{test}\right)\right)$

$Q_{totICEA} := Find\left(Q_{test}\right)$

$Q_{totICEA} = 126.243 \cdot watt \cdot ft^{-1}$

$Ts\left(Q_{totICEA}\right) = 349.575 \cdot K$

$Q_{cICEA}\left(Ts\left(Q_{totICEA}\right)\right) = 36.063 \cdot watt \cdot ft^{-1}$

$Q_{rICEA}\left(Ts\left(Q_{totICEA}\right)\right) = 90.18 \cdot watt \cdot ft^{-1}$

$HI_{ICEA} := \dfrac{Q_{totICEA}}{DOF_{ICEA} \cdot w_{physical}}$ $HI_{ICEA} = 3.344 \cdot watt \cdot in^{-2} \cdot ft^{-1}$ Stolpe's Equation 7

Calculate the ICEA Ampacitities of the Cables

$ICEA\_ampacity(d, n, R) := d \cdot \sqrt{\dfrac{HI_{ICEA}}{n \cdot R}}$ The NEMA standard treats cables as squares occupying an area of d^2

$I_{ICEA_{Data\_index}} := ICEA\_ampacity\left(Cable\_dia_{Data\_index}, n\_conductors_{Data\_index}, R_{cable_{Data\_index}}\right)$

$I_{ICEAu_{Data\_index}} := \dfrac{I_{load_{Data\_index}}}{I_{ICEA_{Data\_index}}}$

Find the Loading on the Hottest Cable and Select the Appropriate Definition for a "Hot" Cable

$Hottest := max\left(I_{ICEAu}\right)$ $Hottest = 1.195$

$CutPoint := if\left(Hottest \le BreakPoint_1, BreakPoint_1, BreakPoint_2\right)$

$CutPoint := if\left(Hottest \le BreakPoint_2, CutPoint, BreakPoint_3\right)$

$CutPoint := if\left(Hottest < BreakPoint_3, Hottest, CutPoint\right)$

$CutPoint = 1$

$Hot\_set_{Data\_index} := \mathrm{if}\left(I_{ICEAu_{Data\_index}} \geq CutPoint, 1.0, 0.0\right)$

$NumHot := \sum Hot\_set$

$NumHot = 3$ Number of cable groups in hot layer

$NumNotHot := Data\_size - NumHot$ Number of cable groups not in hot layer

$NumNotHot = 28$ $MultiGroup := NumNotHot > 0$ Flag indicating some cold/warm cables

The effective tray width to be used in the model is equal to the sum of the diameters of the hot cables plus half of the actual depth of fill. The upper bound on the modeled tray width is the physical tray width plus half of the depth of fill in the physical cable tray

$j2 := Data\_size - 1$

$$w_{model} := \sum_{j=0}^{j2} Hot\_set_j \cdot n\_cables_j \cdot Cable\_dia_j + \frac{DOF_{physical}}{2}$$

$w_{model} = 3.727 \cdot in$ $w_{model} - \frac{DOF_{physical}}{2} = 2.94 \cdot in$

$w_{model} := \mathrm{if}\left(w_{model} > w_{physical}, w_{physical}, w_{model}\right)$

$w_{model} = 3.727 \cdot in$

In order to add cables to the cable mass pointers will be developed so that the hottest and coldest cables can be added in order to the cable mass. The pointer matrix will consist of the element number in the original cable vectors (the pointers) in the 0th column, the load current in per unit of the ICEA ampacity in the 1st column, the number of cables in the group in the 2nd column, the area occupied by the cables in the cable group in the 3rd column, and an artificial index used for sorting in the 4th column. The column of ICEA ampacities will be modified as to force the hot cables to the bottom of the matrx after it is sorted. The cables that are not "hot" will be at the top of the column in order of descending loading in per unit of the ICEA and descending area occupied.

Pointers for warm cables

$WarmArray_{Data\_index,0} := Data\_index$

$WarmArray_{Data\_index,1} := I_{ICEAu_{Data\_index}}$

$$WarmArray_{Data\_index,3} := \frac{n\_cables_{Data\_index}\left(Cable\_dia_{Data\_index}\right)^2}{1 \cdot in^2}$$

$Max\_Area := \max\left(WarmArray^{\langle 3 \rangle}\right)$ $Max\_Area = 9.011$

$$\mathrm{WarmArray}_{\mathrm{Data\_index},4} = \mathrm{if}\left(\mathrm{Hot\_set}_{\mathrm{Data\_index}}>0, -\infty, \mathrm{floor}\left(10000\cdot I_{\mathrm{ICEAu}_{\mathrm{Data\_index}}}\right) + \frac{\mathrm{WarmArray}_{\mathrm{Data\_index},3}}{\mathrm{Max\_Area}}\right)$$

$$\mathrm{WarmArray}_{\mathrm{Data\_index},2} = \mathrm{n\_cables}_{\mathrm{Data\_index}}$$

$$\mathrm{WarmArray} = \mathrm{reverse}(\mathrm{csort}(\mathrm{WarmArray},4))$$

$$\mathrm{Num\_Warm} = \mathrm{if}\left[\mathrm{MultiGroup}, \sum_{i=0}^{(\mathrm{NumNotHot}-1)} \mathrm{if}\left(\mathrm{WarmArray}_{i,1}>\mathrm{Max\_Cold},1,0\right), 0\right]$$

$\mathrm{Num\_Warm} = 12$

$\mathrm{Num\_Cold} = \mathrm{NumNotHot} - \mathrm{Num\_Warm}$ $\quad$ $\mathrm{Num\_Cold} = 16$

$\mathrm{Most\_of} = \mathrm{if}(\mathrm{Num\_Warm}>\mathrm{Num\_Cold}, 1, -1)$ 1 if more warm cables; -1 if more cold cables

$\mathrm{Most\_of} = \mathrm{if}(\mathrm{Num\_Warm}=\mathrm{Num\_Cold}, 0, \mathrm{Most\_of})$ 0 if the same number of warm and cold cables

$\mathrm{Most\_of} = -1$

$\mathrm{Max\_Alternate} = \mathrm{if}(\mathrm{Most\_of}>0, 2\cdot\mathrm{Num\_Cold}, 2\cdot\mathrm{Num\_Warm})$

$\mathrm{Max\_Alternate} = 24$

Select the number of alternating warm and cold cables to add depending on whether the warm or cold cables run out first

Start out selecting cables to add alternating warm and cold cables until the supply of one or the other runs out.

$i = 0, 2 .. \mathrm{if}(\mathrm{Max\_Alternate}>0, (\mathrm{Max\_Alternate}-1), 0)$

$\mathrm{Add\_Pointer}_{i,0} = \mathrm{WarmArray}_{\left(\frac{i}{2}\right),0}$ Warm Pointer

$\mathrm{NumNotHot} = 28$

$\mathrm{NumNotHot} - 1 - \mathrm{Max\_Alternate} = 3$

$\mathrm{Add\_Pointer}_{i,1} = \mathrm{WarmArray}_{\left(\frac{i}{2}\right),2}$ Number of Cables in Group

$\mathrm{Add\_Pointer}_{(i+1),0} = \mathrm{if}\left[\mathrm{MultiGroup}, \mathrm{WarmArray}_{\left(\mathrm{NumNotHot}-1-\frac{i}{2}\right),0}, 0\right]$ Cold Cable Pointer

$\mathrm{Add\_Pointer}_{(i+1),1} = \mathrm{if}\left[\mathrm{MultiGroup}, \mathrm{WarmArray}_{\left(\mathrm{NumNotHot}-1-\frac{i}{2}\right),2}, 0\right]$ Number of Cables in Group

Fill up the remainder of the array with warm or cold cables depending on what is left.

$\mathrm{iii} = 0, 1 .. \mathrm{if}(\mathrm{Num\_Cold}=\mathrm{Num\_Warm}, 0, (\mathrm{NumNotHot}-1-\mathrm{Max\_Alternate}))$

$\mathrm{iik}_{\mathrm{iii}} = \mathrm{if}(\mathrm{Most\_of}=0, 0, \mathrm{iii}+\mathrm{Max\_Alternate})$

Since Mathcad 4 does not allow placing an if condition around a block of code, we will use an index here. If there are the same number of warm and cold cables, we filled the pointer array already, so this if will cripple the following statements in that case by only repacing the 0th element with itself.

$$\text{Add\_Pointer}_{\text{iik}_{\text{iii}},0} = \text{if}\left[\text{Most\_of}>0, \text{WarmArray}_{\left(\text{iii}+\frac{\text{Max\_Alternate}}{2}\right),0}, \text{Add\_Pointer}_{\left(\text{iik}_{\text{iii}}\right),0}\right]$$

$$\text{Add\_Pointer}_{\text{iik}_{\text{iii}},1} = \text{if}\left[\text{Most\_of}>0, \text{WarmArray}_{\left(\text{iii}+\frac{\text{Max\_Alternate}}{2}\right),2}, \text{Add\_Pointer}_{\text{iik}_{\text{iii}},1}\right]$$

$$\text{Add\_Pointer}_{\text{iik}_{\text{iii}},0} = \text{if}\left[\text{Most\_of}<0, \text{WarmArray}_{\left(\text{NumNotHot}-1-\frac{\text{Max\_Alternate}}{2}-\text{iii}\right),0}, \text{Add\_Pointer}_{\left(\text{iik}_{\text{iii}}\right),0}\right]$$

$$\text{Add\_Pointer}_{\text{iik}_{\text{iii}},1} = \text{if}\left[\text{Most\_of}<0, \text{WarmArray}_{\left(\text{NumNotHot}-1-\frac{\text{Max\_Alternate}}{2}-\text{iii}\right),2}, \text{Add\_Pointer}_{\text{iik}_{\text{iii}},1}\right]$$

Set up pointer for hot cables

$k := 0, 1 .. (\text{Data\_size} - \text{NumNotHot} - 1)$

$\text{khot}_k := k + \text{NumNotHot}$

$\text{Hot\_Pointer}_k := \text{WarmArray}_{\left(\text{khot}_k\right),0}$

Calculate a vector of depths of fill for various numbers of cables added in the order specified by Add_Pointer.

Just the hot cables

$$\text{DOF}_{\text{hot}} := \frac{\displaystyle\sum_{j=0}^{(\text{Data\_size}-\text{NumNotHot}-1)} \left[\text{Cable\_dia}_{\left(\text{Hot\_Pointer}_j\right)}\right]^2 \cdot \text{n\_cables}_{\left(\text{Hot\_Pointer}_j\right)}}{w_{\text{model}}}$$

$\text{DOF}_{\text{hot}} = 0.395 \cdot \text{in}$ Hot cables alone

$\text{DOF}_{\text{trial}_0} := \text{DOF}_{\text{hot}}$ The 0th element of the vector represents just the hot cables

$\text{lMax} := \text{if}(\text{MultiGroup}, \text{NumNotHot}, 3)$ $\quad l := 1, 2 .. \text{lMax}$

Calculate the depth of fill for the combined group adding one cable group at a time.

$$\text{DOF}_{\text{trial}_l} := \text{DOF}_{\text{hot}} + \text{if}\left[\text{MultiGroup}, \frac{\displaystyle\sum_{j=1}^{l} \left[\text{Cable\_dia}_{\left[\text{Add\_Pointer}_{(j-1),0}\right]}\right]^2 \cdot \text{n\_cables}_{\left[\text{Add\_Pointer}_{(j-1),0}\right]}}{w_{\text{model}}}, \infty \cdot \text{in}\right]$$

Look at the list to find the index of $\mathrm{DOF}_{\mathrm{trial}}$ that is the smallest that is greater than or equal to the physical depth of fill. This indicates which cables ought to be added to the hot cables

$$\mathrm{NumCables\_in\_Set} := \mathrm{NumNotHot} + 2 + \sum_{j=\mathrm{NumNotHot}}^{0} \mathrm{if}\left(\mathrm{DOF}_{\mathrm{trial}_j} - \mathrm{DOF}_{\mathrm{physical}}, -1, 0\right)$$

$$\mathrm{is\_even} := \mathrm{NumCables\_in\_Set} - 2\cdot\mathrm{floor}\left(\frac{\mathrm{NumCables\_in\_Set}}{2}\right) \qquad \mathrm{is\_even} = 1$$

0 if value is even

$$\mathrm{no\_more} := (\mathrm{NumCables\_in\_Set} - 1) - \mathrm{Max\_Alternate} \qquad \mathrm{no\_more} = 0$$

0 if alternating cables left

$$\mathrm{bump} := \mathrm{is\_even} + \mathrm{no\_more}$$

$$\mathrm{NumCables\_in\_Set} := \mathrm{if}(\mathrm{bump}=0, \mathrm{NumCables\_in\_Set} + 1, \mathrm{NumCables\_in\_Set})$$

Put an upper limit on the number of cables in the set in case the counter goes out of range due to round off errors.

$$\mathrm{NumCables\_in\_Set} := \mathrm{if}(\mathrm{NumCables\_in\_Set} > (\mathrm{NumNotHot} + 1), (\mathrm{NumNotHot} - 1), \mathrm{NumCables\_in\_Set})$$

$$\mathrm{NumCables\_in\_Set} = 11$$

Hot cables + number of warm and cold groups to be added; 1 means hot cables only, 2 means hot cables + 1 warm or cold group, etc.

$$w_{\mathrm{model}} := \frac{\mathrm{DOF}_{\mathrm{trial}_{(\mathrm{NumCables\_in\_Set}-1)}}}{\mathrm{DOF}_{\mathrm{physical}}}\cdot w_{\mathrm{model}}$$

$$w_{\mathrm{model}} = 3.787\cdot\mathrm{in}$$

Calculate the depth of fill of the whole set as a check on the logic

$$\mathrm{DOF}_{\mathrm{model}} := \frac{\mathrm{if}\left[\mathrm{MultiGroup}, \sum_{j=0}^{(\mathrm{NumCables\_in\_Set}-2)} \left[\mathrm{Cable\_dia}_{\left[\left(\mathrm{Add\_Pointer}^{\langle 0\rangle}\right)_j\right]}\right]^2\cdot\mathrm{n\_cables}_{\left[\left(\mathrm{Add\_Pointer}^{\langle 0\rangle}\right)_j\right]}, 0\cdot\mathrm{in}^2\right] \ldots + \sum_{j=0}^{(\mathrm{NumHot}-1)} \left[\mathrm{Cable\_dia}_{\left(\mathrm{Hot\_Pointer}_j\right)}\right]^2\cdot\mathrm{n\_cables}_{\left(\mathrm{Hot\_Pointer}_j\right)}}{w_{\mathrm{model}}}$$

$$\mathrm{DOF}_{\mathrm{model}} = 1.573\cdot\mathrm{in}$$

$$\mathrm{DOF}_{\mathrm{model}} - \mathrm{DOF}_{\mathrm{physical}} = 0\cdot\mathrm{in}$$

Establish Separate Lists of Pointers for the Various Categories of Cables

Warm Cables

Go through the list of cables to be added and count the number of warm ones by brute force. (Not elegant, put probably the most reliable way.)

$$\text{NumWarm} := \text{if}\left[\text{NumCables\_in\_Set}\_1, 0, \sum_{j=0}^{(\text{NumCables\_in\_Set}-2)} \text{if}\left[I_{\text{ICEAu}\left[\left(\text{Add\_Pointer}^{\langle 0\rangle}\right)_j\right]} > \text{Max\_Cold}, 1, 0\right]\right]$$

$$\text{NumWarm} = 5$$

Cold Cables

$$\text{NumCold} := \text{NumCables\_in\_Set} - 1 - \text{NumWarm}$$ Allow 1 for hot cables, then if it is not warm it has to be cold

$$\text{NumCold} = 5$$

Calculate the Depth of Fill and Heat Generation at 90°C for Each Layer of the Black Model

Hot Cables

Calculate the Heat Generation

$$j2 := \text{NumHot} - 1$$

$$Q_{\text{hot90C}} := \sum_{j=0}^{j2} \text{n\_cables}_{\left(\text{Hot\_Pointer}_j\right)} \cdot \text{n\_conductors}_{\left(\text{Hot\_Pointer}_j\right)} \cdot \left[I_{\text{load}\left(\text{Hot\_Pointer}_j\right)}\right]^2 \cdot R_{\text{cable}\left(\text{Hot\_Pointer}_j\right)}$$

$$Q_{\text{hot90C}} = 6.388 \cdot \text{watt} \cdot \text{ft}^{-1}$$

$$Q_{\text{hot}}(T) := Q_{\text{hot90C}} \cdot \left(\frac{234.5 \cdot K - \text{CtoK} + T}{234.5 \cdot K + 90 \cdot K}\right)$$

Depth of fill

$$\text{DOF}_{\text{hot}} := \frac{\displaystyle\sum_{j=0}^{j2} \text{n\_cables}_{\left(\text{Hot\_Pointer}_j\right)} \cdot \left[\text{Cable\_dia}_{\left(\text{Hot\_Pointer}_j\right)}\right]^2}{w_{\text{model}}}$$

$$\text{DOF}_{\text{hot}} = 0.389 \cdot \text{in}$$

Warm Cables

Calculate theHeat Generation

$$j2 := \text{it}(\text{NumWarm}\_1, \text{NumWarm} - 1, 0)$$

$$Q_{\text{warm90C}} := \sum_{j=0}^{j2} \text{n\_cables}_{\left[\left(\text{WarmArray}^{\langle 0\rangle}\right)_j\right]} \cdot \text{n\_conductors}_{\left[\left(\text{WarmArray}^{\langle 0\rangle}\right)_j\right]} \cdot \left[I_{\text{load}\left[\left(\text{WarmArray}^{\langle 0\rangle}\right)_j\right]}\right]^2 \cdot R_{\text{cable}\left[\left(\text{WarmArray}^{\langle 0\rangle}\right)_j\right]}$$

$$Q_{\text{warm90C}} := \text{if}\left(\text{NumWarm} > 0, Q_{\text{warm90C}}, 0 \cdot \text{watt} \cdot \text{ft}^{-1}\right)$$

$$Q_{\text{warm}}(T) := Q_{\text{warm90C}} \cdot \left(\frac{234.5 \cdot K - \text{CtoK} + T}{234.5 \cdot K + 90 \cdot K}\right)$$

$$Q_{\text{warm90C}} = 7.725 \cdot \text{watt} \cdot \text{ft}^{-1}$$

Depth of Fill

$$DOF_{warm} := \frac{\sum_{j=0}^{j2} n\_cables_{\left[\left(WarmArray^{\langle 0\rangle}\right)_j\right]} \cdot \left[Cable\_dia_{\left[\left(WarmArray^{\langle 0\rangle}\right)_j\right]}\right]^2}{w_{model}}$$

$$DOF_{warm} := if\left(NumWarm>0, DOF_{warm}, 0\cdot in\right) \qquad DOF_{warm} = 0.857 \cdot in$$

Cold Cables

Calculate the Heat Generation

$$j1 := NumNotHot - 1$$

$$j2 := if(NumCold \geq 1, NumNotHot - NumCold, 0) \qquad Z := 0\cdot watt\cdot ft^{-1}$$

$$Q := if\left[MultiGroup, \sum_{j=j1}^{j2} n\_cables_{\left[\left(WarmArray^{\langle 0\rangle}\right)_j\right]} \cdot n\_conductors_{\left[\left(WarmArray^{\langle 0\rangle}\right)_j\right]} \cdot \left[I_{load\left[\left(WarmArray^{\langle 0\rangle}\right)_j\right]}\right]^2 \cdot R_{cable\left[\left(WarmArray^{\langle 0\rangle}\right)_j\right]}, Z\right]$$

$$Q_{cold90C} := if\left(NumCold>0, Q, 0\cdot watt\cdot ft^{-1}\right)$$

$$Q_{cold90C} = 0 \cdot watt\cdot ft^{-1}$$

$$Q_{cold}(T) := Q_{cold90C} \cdot \left(\frac{234.5\cdot K - CtoK + T}{234.5\cdot K + 90\cdot K}\right)$$

Depth of Fill

$$DOF_{cold} := \frac{if\left[MultiGroup, \sum_{j=j1}^{j2} n\_cables_{\left[\left(WarmArray^{\langle 0\rangle}\right)_j\right]} \cdot \left[Cable\_dia_{\left[\left(WarmArray\right)^{\langle 0\rangle}\right]_j}\right]^2, 0\cdot in^2\right]}{w_{model}}$$

$$DOF_{cold} := if\left(NumCold>0, DOF_{cold}, 0\cdot in\right)$$

$$DOF_{cold} = 0.328 \cdot in$$

Function for Radiation from the Tray Assembly as a Function of Cable Mass Surface Temperature

$$Q_{rad}(T) := \sigma \cdot \varepsilon_{mean} \cdot \left(T^4 - T_{amb}^{\ 4}\right) \cdot 2 \cdot w_{model}$$ Holman, Equation 8-43a

Convection Functions

Function to Give the Grashof and Rayleigh Numbers

$$Gr(T1, T2, w) := \frac{g \cdot \beta(T1, T2) \cdot (T1 - T2) \cdot \left(\frac{w}{2}\right)^3}{\nu_{air}(T1, T2)^2}$$ Holman, Equation 7-21 Since the length of the tray is much larger than the width, take the characteristic length as ½w

$$Ra(T1, T2, w) := Gr(T1, T2, w) \cdot Pr_{air}(T1, T2)$$ Holman, Equation 7-26

Convection from the Top Surface

Nusselt Number

$$Nu_{top}(T1,T2,w) := if\left(Ra(T1,T2,w)<8\cdot 10^{6}, 0.54\cdot Ra(T1,T2,w)^{\frac{1}{4}}, 0.15\cdot Ra(T1,T2,w)^{\frac{1}{3}}\right)$$

Holman, Table 7-1, Equation 7-25

Overall Convection

$$Q_{top\_conv}(T1,T2,w) := \frac{Nu_{top}(T1,T2,w)}{\left(\frac{1}{2}\right)}\cdot k_{air}(T1,T2)\cdot(T1-T2)$$

Holman, Equation 5-42 (Since the tray area per unit length is w, the w in the denominator for the expression for h is canceled out.

Convection from the Bottom Surface

$$Nu_{bottom}(T1,T2,w) := 0.58\cdot Ra(T1,T2,w)^{\frac{1}{5}}$$

Holman, Table 7-1

$$Q_{bot\_conv}(T1,T2,w) := \frac{Nu_{bottom}(T1,T2,w)}{\left(\frac{1}{2}\right)}\cdot k_{air}(T1,T2)\cdot(T1-T2)$$

$$Q_{bot\_conv1}(T1,T2,w) := 0.27\cdot\frac{Ra(T1,T2,w)^{\frac{1}{4}}}{\left(\frac{1}{2}\right)}\cdot k_{air}(T1,T2)\cdot(T1-T2)$$

Holman, Equation 5-42 (Since the tray area per unit length is w, the w in the denominator for the expression for h is canceled out.

Intitial Values for the Surface, Cold Layer, Warm Layer, and Hot Layer

$$Tgs := T_{amb} + 1\cdot K$$

$$Tgc := Tgs + 0.1\cdot K$$

$$Tgw := Tgc + 0.1\cdot K$$

$$Tgh := Tgw + 0.1\cdot K$$

Given

$$Q_{hot}(Tgh) + Q_{warm}(Tgw) + Q_{cold}(Tgc) = Q_{rad}(Tgs) + Q_{top\_conv}(Tgs, T_{amb}, w_{model}) + Q_{bot\_conv}(Tgs, T_{amb}, w_{model})$$

$$Tgc = Tgs + \frac{\rho_{mass}}{4\cdot w_{model}}\cdot\left[\left(Q_{hot}(Tgh) + Q_{warm}(Tgw)\right)\cdot DOF_{cold} + Q_{cold}(Tgc)\cdot\frac{DOF_{cold}}{2}\right]$$

Harshe and Black, Equation 6

$$Tgw = Tgc + \frac{\rho_{mass}}{4\cdot w_{model}}\cdot\left(Q_{hot}(Tgh)\cdot DOF_{warm} + Q_{warm}(Tgw)\cdot\frac{DOF_{warm}}{2}\right)$$

$$Tgh = Tgw + \frac{\rho_{mass}}{4 \cdot w_{model}} \cdot Q_{hot}(Tgh) \cdot \frac{DOF_{hot}}{2}$$

$$\begin{bmatrix} T_{surface} \\ T_{cold} \\ T_{warm} \\ T_{hot} \end{bmatrix} := Find(Tgs, Tgc, Tgw, Tgh)$$

$T_{surface} = 333.722 \cdot K$ $\quad T_{surface} - CtoK = 60.572 \cdot K$ °C Cable Surface

$T_{cold} = 337.508 \cdot K$ $\quad T_{cold} - CtoK = 64.358 \cdot K$ °C Cold Layer

$T_{warm} = 344.697 \cdot K$ $\quad T_{warm} - CtoK = 71.547 \cdot K$ °C Warm Layer

$T_{hot} = 345.716 \cdot K$ $\quad T_{hot} - CtoK = 72.566 \cdot K$ °C Hot Layer

$$T_{hot\_layer} := T_{amb} + FS\_Temp\_Factor_{Fire\_Stop\_Code} \cdot Cover\_Temp\_Factor_{Tray\_Cover\_Code} \cdot \left(T_{hot} - T_{amb}\right)$$

$T_{hot\_layer} = 368.59 \cdot K$ $\quad \Delta T_{FS} := T_{hot\_layer} - T_{hot}$ $\quad \Delta T_{FS} = 22.875 \cdot K$

$\Delta T_{hw} := T_{hot} - T_{warm}$

$T_{hot\_layer} - CtoK = 95.44 \cdot K$ °C, adjusted for fire stop

$Q_{rad}\left(T_{surface}\right) = 7.412 \cdot watt \cdot ft^{-1}$

$Q_{top\_conv}\left(T_{surface}, T_{amb}, w_{model}\right) = 3.707 \cdot watt \cdot ft^{-1}$ $\quad k_{air}\left(T_{surface}, T_{amb}\right) = 0.029 \cdot watt \cdot m^{-1} \cdot K^{-1}$

$Q_{bot\_conv}\left(T_{surface}, T_{amb}, w_{model}\right) = 2.212 \cdot watt \cdot ft^{-1}$ $\quad Pr_{air}\left(T_{surface}, T_{amb}\right) = 0.7$

$Q_{cold}\left(T_{cold}\right) = 0 \cdot watt \cdot ft^{-1}$

$Q_{warm}\left(T_{warm}\right) = 7.286 \cdot watt \cdot ft^{-1}$

$Q_{hot}\left(T_{hot}\right) = 6.045 \cdot watt \cdot ft^{-1}$ $\quad \Delta T_{hot} := T_{hot\_layer} - T_{amb}$ $\quad \Delta T_{hot} = 55.44 \cdot K$

$$HI_{hot} := \frac{Q_{hot}\left(T_{hot}\right)}{w_{model} \cdot DOF_{hot}} \qquad HI_{hot} = 4.106 \cdot watt \cdot ft^{-1} \cdot in^{-2} \qquad HI_{ICEA} = 3.344 \cdot watt \cdot ft^{-1} \cdot in^{-2}$$

$$I_{av\_hot} := \sqrt{\frac{HI_{hot} \cdot \dfrac{234.5 \cdot K - CtoK + T_{cond}}{234.5 \cdot K - CtoK + T_{hot}}}{HI_{ICEA}}} \qquad I_{av\_hot} = 1.139$$

$I_{Threshold} := I_{av\_hot} \cdot F_{Threshold}$

$I_{worst} := \max\left(I_{ICEAu}\right)$ $\quad I_{worst} = 1.195$ Loading of the most heavily loaded cable in per unit of the ICEA ampacity

Get the index of the most heavily loaded cable

$TMax\_Index := reverse\left(csort\left(augment\left(Index\_array, I_{ICEAu}\right), 1\right)\right)_{0,0}$ $\quad TMax\_Index = 26$

Estimated temperature of the most heavily loaded cable

$$T_{expMax} := \mathrm{if}\left[I_{worst} > I_{Threshold}, \left[\Delta T_{hot} \cdot \left(\frac{I_{worst}}{I_{Threshold}}\right)^2 + T_{amb}\right], T_{hot\_layer}\right] - CtoK$$

$T_{expMax} = 95.44 \cdot K$ (°C)

$Display := augment(Index\_array, Cable\_data)$

$Display_{Data\_index, 7} := I_{ICEAu_{Data\_index}}$

Routing Point Data:

$$\text{Display} = \begin{bmatrix} 0 & 10 & 1 & 3 & 0.58 & 0.008 & 0 & 0 \\ 1 & 10 & 1 & 3 & 0.58 & 0.008 & 12 & 0.707 \\ 2 & 10 & 1 & 3 & 0.58 & 0.008 & 13 & 0.765 \\ 3 & 10 & 2 & 3 & 0.58 & 0.008 & 19 & 1.119 \\ 4 & 12 & 1 & 2 & 0.49 & 0.005 & 0 & 0 \\ 5 & 12 & 1 & 3 & 0.52 & 0.005 & 0 & 0 \\ 6 & 12 & 2 & 3 & 0.52 & 0.005 & 3 & 0.248 \\ 7 & 12 & 1 & 3 & 0.52 & 0.005 & 7 & 0.579 \\ 8 & 12 & 3 & 3 & 0.52 & 0.005 & 10 & 0.827 \\ 9 & 12 & 1 & 3 & 0.52 & 0.005 & 13 & 1.075 \\ 10 & 14 & 1 & 2 & 0.37 & 0.003 & 0 & 0 \\ 11 & 14 & 36 & 2 & 0.42 & 0.003 & 0 & 0 \\ 12 & 14 & 1 & 2 & 0.42 & 0.003 & 5 & 0.527 \\ 13 & 14 & 6 & 3 & 0.48 & 0.003 & 0 & 0 \\ 14 & 14 & 1 & 5 & 0.59 & 0.003 & 5 & 0.594 \\ 15 & 14 & 3 & 5 & 0.6 & 0.003 & 0 & 0 \\ 16 & 14 & 3 & 5 & 0.62 & 0.003 & 0 & 0 \\ 17 & 14 & 1 & 7 & 0.54 & 0.003 & 0 & 0 \\ 18 & 14 & 22 & 7 & 0.64 & 0.003 & 0 & 0 \\ 19 & 14 & 1 & 7 & 0.65 & 0.003 & 0 & 0 \\ 20 & 14 & 2 & 9 & 0.66 & 0.003 & 0 & 0 \\ 21 & 14 & 7 & 9 & 0.71 & 0.003 & 0 & 0 \\ 22 & 14 & 4 & 12 & 1.03 & 0.003 & 0 & 0 \\ 23 & 2 & 4 & 1 & 0.5 & 0.052 & 41 & 0.639 \\ 24 & 4 & 3 & 1 & 0.37 & 0.033 & 37 & 0.984 \\ 25 & 4 & 3 & 1 & 0.42 & 0.033 & 0 & 0 \\ 26 & 4 & 3 & 1 & 0.42 & 0.033 & 51 & 1.195 \\ 27 & 6 & 1 & 3 & 0.99 & 0.021 & 38 & 0.823 \\ 28 & 8 & 2 & 1 & 0.33 & 0.013 & 13 & 0.616 \\ 29 & 8 & 1 & 1 & 0.55 & 0.013 & 0 & 0 \\ 30 & 8 & 1 & 3 & 0.84 & 0.013 & 26 & 0.839 \end{bmatrix}$$

Col. 0: Index for identification
Col. 1: Cable Size
Col. 2: Number of Cables
Col. 3: Number of Conductors per cable
Col. 4: Cable Diameter (in.)
Col. 5: Copper Area
Col. 6: Load Current
Col. 7: Load Current in Per Unit of the Cable ICEA Ampacity

Index of the Cable with the Highest Loading:

$\text{TMax\_Index} = 26$

Maximum Expected (°C) Temperature in the CableTray:

$T_{\text{expMax}} = 95.4 \cdot K$

Threshold Current

$I_{\text{Threshold}} = 1.367$

$$\text{Cable\_size} = \begin{bmatrix} 10 \\ 10 \\ 10 \\ 10 \\ 12 \\ 12 \\ 12 \\ 12 \\ 12 \\ 12 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 2 \\ 4 \\ 4 \\ 4 \\ 6 \\ 8 \\ 8 \\ 8 \end{bmatrix} \qquad R_{cable} = \begin{bmatrix} 0.0013 \\ 0.0013 \\ 0.0013 \\ 0.0013 \\ 0.00206 \\ 0.00206 \\ 0.00206 \\ 0.00206 \\ 0.00206 \\ 0.00206 \\ 0.00328 \\ 0.00328 \\ 0.00328 \\ 0.00328 \\ 0.00328 \\ 0.00328 \\ 0.00328 \\ 0.00328 \\ 0.00328 \\ 0.00328 \\ 0.00328 \\ 0.00328 \\ 0.00328 \\ 0.000203 \\ 0.000324 \\ 0.000324 \\ 0.000324 \\ 0.000513 \\ 0.000818 \\ 0.000818 \\ 0.000818 \end{bmatrix} \cdot \Omega \cdot ft^{-1} \qquad \text{n\_cables} = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 2 \\ 1 \\ 1 \\ 2 \\ 1 \\ 3 \\ 1 \\ 1 \\ 36 \\ 1 \\ 6 \\ 1 \\ 3 \\ 3 \\ 1 \\ 22 \\ 1 \\ 2 \\ 7 \\ 4 \\ 4 \\ 3 \\ 3 \\ 3 \\ 1 \\ 2 \\ 1 \\ 1 \end{bmatrix} \qquad \text{n\_conductors} = \begin{bmatrix} 3 \\ 3 \\ 3 \\ 3 \\ 2 \\ 3 \\ 3 \\ 3 \\ 3 \\ 3 \\ 2 \\ 2 \\ 2 \\ 3 \\ 5 \\ 5 \\ 5 \\ 7 \\ 7 \\ 7 \\ 9 \\ 9 \\ 12 \\ 1 \\ 1 \\ 1 \\ 1 \\ 3 \\ 1 \\ 1 \\ 3 \end{bmatrix}$$

$$\text{Cable\_size} = \begin{bmatrix} 10 \\ 10 \\ 10 \\ 10 \\ 12 \\ 12 \\ 12 \\ 12 \\ 12 \\ 12 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 2 \\ 4 \\ 4 \\ 4 \\ 6 \\ 8 \\ 8 \\ 8 \end{bmatrix} \qquad \text{Cable\_dia} = \begin{bmatrix} 0.58 \\ 0.58 \\ 0.58 \\ 0.58 \\ 0.49 \\ 0.52 \\ 0.52 \\ 0.52 \\ 0.52 \\ 0.52 \\ 0.37 \\ 0.42 \\ 0.42 \\ 0.48 \\ 0.59 \\ 0.6 \\ 0.62 \\ 0.54 \\ 0.64 \\ 0.65 \\ 0.66 \\ 0.71 \\ 1.03 \\ 0.5 \\ 0.37 \\ 0.42 \\ 0.42 \\ 0.99 \\ 0.33 \\ 0.55 \\ 0.84 \end{bmatrix} \cdot \text{in} \qquad I_{\text{load}} = \begin{bmatrix} 0 \\ 12 \\ 13 \\ 19 \\ 0 \\ 0 \\ 3 \\ 7 \\ 10 \\ 13 \\ 0 \\ 0 \\ 5 \\ 0 \\ 5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 41 \\ 37 \\ 0 \\ 51 \\ 38 \\ 13 \\ 0 \\ 26 \end{bmatrix} \cdot \text{amp}$$

$$\mathrm{Cable\_size} = \begin{bmatrix} 10 \\ 10 \\ 10 \\ 10 \\ 12 \\ 12 \\ 12 \\ 12 \\ 12 \\ 12 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 14 \\ 2 \\ 4 \\ 4 \\ 4 \\ 6 \\ 8 \\ 8 \\ 8 \end{bmatrix} \quad I_{ICEA} = \begin{bmatrix} 16.983 \\ 16.983 \\ 16.983 \\ 16.983 \\ 13.959 \\ 12.095 \\ 12.095 \\ 12.095 \\ 12.095 \\ 12.095 \\ 8.353 \\ 9.482 \\ 9.482 \\ 8.848 \\ 8.424 \\ 8.567 \\ 8.853 \\ 6.517 \\ 7.723 \\ 7.844 \\ 7.024 \\ 7.556 \\ 9.493 \\ 64.17 \\ 37.587 \\ 42.666 \\ 42.666 \\ 46.145 \\ 21.098 \\ 35.164 \\ 31.006 \end{bmatrix} \cdot \mathrm{amp} \quad I_{ICEAu} = \begin{bmatrix} 0 \\ 0.707 \\ 0.765 \\ 1.119 \\ 0 \\ 0 \\ 0.248 \\ 0.579 \\ 0.827 \\ 1.075 \\ 0 \\ 0 \\ 0.527 \\ 0 \\ 0.594 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0.639 \\ 0.984 \\ 0 \\ 1.195 \\ 0.823 \\ 0.616 \\ 0 \\ 0.839 \end{bmatrix}$$

$$\mathrm{WarmArray} = \begin{bmatrix} 24 & 0.984 & 3 & 0.411 & 9.843\cdot10^{3} \\ 30 & 0.839 & 1 & 0.706 & 8.385\cdot10^{3} \\ 8 & 0.827 & 3 & 0.811 & 8.267\cdot10^{3} \\ 27 & 0.823 & 1 & 0.98 & 8.234\cdot10^{3} \\ 2 & 0.765 & 1 & 0.336 & 7.654\cdot10^{3} \\ 1 & 0.707 & 1 & 0.336 & 7.066\cdot10^{3} \\ 23 & 0.639 & 4 & 1 & 6.389\cdot10^{3} \\ 28 & 0.616 & 2 & 0.218 & 6.161\cdot10^{3} \\ 14 & 0.594 & 1 & 0.348 & 5.935\cdot10^{3} \\ 7 & 0.579 & 1 & 0.27 & 5.787\cdot10^{3} \\ 12 & 0.527 & 1 & 0.176 & 5.273\cdot10^{3} \\ 6 & 0.248 & 2 & 0.541 & 2.48\cdot10^{3} \\ 18 & 0 & 22 & 9.011 & 1 \\ 11 & 0 & 36 & 6.35 & 0.705 \\ 22 & 0 & 4 & 4.244 & 0.471 \\ 21 & 0 & 7 & 3.529 & 0.392 \\ 13 & 0 & 6 & 1.382 & 0.153 \\ 16 & 0 & 3 & 1.153 & 0.128 \\ 15 & 0 & 3 & 1.08 & 0.12 \\ 20 & 0 & 2 & 0.871 & 0.097 \\ 25 & 0 & 3 & 0.529 & 0.059 \\ 19 & 0 & 1 & 0.423 & 0.047 \\ 0 & 0 & 1 & 0.336 & 0.037 \\ 29 & 0 & 1 & 0.302 & 0.034 \\ 17 & 0 & 1 & 0.292 & 0.032 \\ 5 & 0 & 1 & 0.27 & 0.03 \\ 4 & 0 & 1 & 0.24 & 0.027 \\ 10 & 0 & 1 & 0.137 & 0.015 \\ 9 & 1.075 & 1 & 0.27 & -1\cdot10^{307} \\ 3 & 1.119 & 2 & 0.673 & -1\cdot10^{307} \\ 26 & 1.195 & 3 & 0.529 & -1\cdot10^{307} \end{bmatrix}$$

The warmest cables are at the top of the list and the coldest cables are near the bottom running to (NumNotHot-1). The hot cables are at NumNotHot through (Data_size-1). (Mathcad numbers arrays beginning with 0 in C style.)

Warm cables will always be taken out of WarmArray from the top down. Cold cables will always be taken out of WarmArray from the bottom up.

$$\mathrm{Add\_Pointer} = \begin{bmatrix} 24 & 3 \\ 10 & 1 \\ 30 & 1 \\ 4 & 1 \\ 8 & 3 \\ 5 & 1 \\ 27 & 1 \\ 17 & 1 \\ 2 & 1 \\ 29 & 1 \\ 1 & 1 \\ 0 & 1 \\ 23 & 4 \\ 19 & 1 \\ 28 & 2 \\ 25 & 3 \\ 14 & 1 \\ 20 & 2 \\ 7 & 1 \\ 15 & 3 \\ 12 & 1 \\ 16 & 3 \\ 6 & 2 \\ 13 & 6 \\ 21 & 7 \\ 22 & 4 \\ 11 & 36 \\ 18 & 22 \end{bmatrix}$$

0th column is pointer to cable data. 1st column is the number of cables in the group.

$$\mathrm{Hot\_Pointer} = \begin{pmatrix} 9 \\ 3 \\ 26 \end{pmatrix}$$

$$\mathrm{DOF}_{\mathrm{trial}} = \begin{bmatrix} 0.395 \\ 0.505 \\ 0.542 \\ 0.731 \\ 0.796 \\ 1.013 \\ 1.086 \\ 1.349 \\ 1.427 \\ 1.518 \\ 1.599 \\ 1.689 \\ 1.779 \\ 2.048 \\ 2.161 \\ 2.219 \\ 2.361 \\ 2.455 \\ 2.689 \\ 2.761 \\ 3.051 \\ 3.098 \\ 3.408 \\ 3.553 \\ 3.924 \\ 4.871 \\ 6.01 \\ 7.714 \\ 10.132 \end{bmatrix} \cdot \mathrm{in}$$

ATTACHMENT 31

The purpose of this attachment is to provide the methodology for determining the ampacity derating factor for conduits carrying both power and control cables in a single conduit.

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Reviewed by: Ismail Manasra

Purpose

The purpose of this section is to determine derating factors for conduits with multiple power and control cables in a single conduit. The conduit is assumed to have 1, 2, 3, or 4 power cables. In addition, the conduit is assumed to contain control cables that generate negligible heat, but which act as a "blanket" around the power cables.

Methodology

The derating calculation considers both 3" and 5" trade size conduits containing three phase circuits of single conductor, #2 AWG, 600 volt cables. The ampacity for a single circuit with no other cables in the conduit is 130 amperes according to AIEE S-135-1 / IPCEA P-46-426. The conductor temperature of conduits containing 1, 2, 3, and 4 circuits in a 3" conduit and 1, 2, and 3 circuits in a 5" conduit plus sufficient 2 conductor #14 AWG control cables to fill 40% of the conduit cross sectional area of a 3" conduit are calculated using a Mathcad sheet. The load current in the power cables is then adjusted by hand to achieve the rated conductor temperature of 90°C. The ampacity multiplier is then the ampacity of the cables in the test conduit divided by the nominal ampacity of 130 amperes.

The Mathcad sheet used for the calculations is a modification of the Mathcad sheet used for the calculation of the conductor temperature of cables in a conduit in free air. The principle modifications is that the load currents of the power cables are multiplied by a factor $F_{current}$. A Mathcad global define statement is used so that $F_{current}$ can be set near where the conductor temperature is displayed for convenience.

Within the Mathcad sheet, the cables in the conduit are divided into three groups. The cables that are unloaded are considered "cold", and are assumed to surround the other cables. The group of cables that generates the maximum amount of heat per unit volume are the "hot" cables and are located in the center of all of the cables. Cables that are neither "hot" or "cold" are considered "warm" cables. The "warm" cables are located between the "cold" and "hot" cables. (Because of the nature of the test cases used in this calculation the data only contains "hot" and "cold" cables.)

The conduit trade size is entered into the Mathcad sheet. The inside and outside diameters of the conduit can then be determined by a lookup table in the sheet. The conductor size, number of cables in the group, number of conductors in each cable, cable diameter, cable area, and load current for the cable is read from a data file. The conductor resistance of the various conductors are determined from the conductor size using another look-up table. The sheet then calculates the heat generated by each cable group. Next, the sheet divides the heat generated by each cable group by the area occupied by each cable group to give the heat intensity for the cable group. In order to facilitate later calculations, an array, Hot_Flag is set up. Each member of Hot_Flag is set to 0 if the cable group generates no heat ("cold"), 1 if the cable generates heat but does not have the greatest heat intensity of all the groups in the conduit ("warm"), and 2 if the cable group has the highest heat intensity in the conduit ("hot").

Using Hot_Flag to classify the cable groups, the sheet calculates the area occupied the "cold", "warm", and "hot" cables. Since circular cables will have spaces between them when they are bundled together, the area calculations assume that the cables are square to allow for this additional area when there is more than one cable in the group. Based on the area occupied by each layer, the diameter of the layer can then be calculated.

The heat generated by the "warm" and "hot" layers is then calculated. The heat intensity of the two layers is then calculated using the areas of the layers. Also, the total heat generated in the conduit is determined. All of the heat calculations are based on cable conductor temperatures of 90°C, the rated operating temperature of the cable conductors.

The surface temperature of the conduit can then be calculated. The heat dissipated from the outer surface by convection and radiation is first written as a function of the surface temperature. These equations can be solved iteratively to find the surface temperature at which the total heat dissipated in the conduit equals the heat generated inside. The temperature drop through the conduit itself can be calculated based on the conduit being a hollow cylinder.

The temperature drop through the air gap between the inside surface of the conduit and the outer surface of the cable mass is then calculated using the semi-empirical formula given by Neher and McGrath. The temperature drop through the "cold" cables is calculated by treating the "cold" layer as a hollow cylinder.

The temperature drop through the "warm" cable layer has two components. The temperature drop caused by the flow of heat from the "hot" cables inside is calculated by treating the "warm" cables as a hollow cylinder. An additional temperature drop is caused by the heat generated within the "warm" layer. This temperature drop is calculated by a formula similar to that given in Section 2-8 of Holman, except the equation is fitted to a different initial condition to account for the hollow core of this layer.

The temperature drop through the "hot" layer is calculated using Holman's Equation 2-26. The conductor temperature is then the surface temperature of the conduit plus the sum of the temperature drops described above.

Results and Conclusions

The results of the cases examined are as follows:

Number of Power Circuits	Conduit Nominal Size	Mathcad File Name	Ampacity Multiplier
1	3"	p1c40s.mcd	0.915
1	5"	p1c40l.mcd	0.955
2	3"	p2c40s.mcd	0.688
2	5"	p2c40l.mcd	0.722
3	3"	p3c40s.mcd	0.584
3	5"	p3c40l.mcd	0.615
4	3"	p4c40s.mcd	0.519

Based on these results, the ampacity multipliers to be used in conduit ampacity calculations are the following. The ampacity multiplier for 4 power cables will be applied to conduits with more than 4 power cables because:

1. It is unlikely that all of the power cables in the conduit would be loaded to the limit of their ampacity due to load diversity and the selection of cables with ampacity higher than the rated load current based on available cable sizes (granularity).
2. The results of the fire stop tests carried out in March 1997 indicated that race ways were relatively cool, indicating that the operating conditions encountered in normal station operation are less severe than indicated by the calculations
3. The increased area occupied by power cables will reduce the area available for the blanket of control cables:

Number of Power Circuits	Ampacity Multiplier
1	91%
2	69%
3	58%
≥4	52%

References

1. Holman, J. P. 1981. *Heat Transfer.* Tokyo: McGraw-Hill Kogakusha, Ltd.

2. Neher, J. H. and McGrath, M. H. 1957. The Calculation of the Temperature Rise and Load Capability of Cable Systems. *AIEE Transactions on Power Apparatus and Systems.* 76 (October): 752–772.

3. Insulated Power Cable Engineers Association and Insulated Conductors Committee of the Power Division, AIEE 1962. AIEE Publication S-135-1 / IPCEA Publication P-46-426, *Power Cable Ampacities, Volume 1—Copper Conductors.* New York: American Institute of Electrical Engineers.

Test Case: Three Power Feeders in Conduit; 40% Cold Fill— ρ3c40s.mcd

Conduit Data

$\text{Conduit\_Trade\_Size} := 3\cdot\text{in}$

Enter Cable Data

$$\text{Cable\_data} := \begin{pmatrix} 2 & 9 & 1 & 0.5 & 0.0 & 130 & 1 \\ 14 & 28 & 2 & 0.37 & 0.0 & 0 & 0 \end{pmatrix}$$

$\text{Data\_size} := \text{rows}(\text{Cable\_data})$ $\quad\text{Data\_size} = 2$ $\quad$ Number of cable groups in the data

$\text{Data\_index} := 0, 1 .. (\text{Data\_size} - 1)$

$\text{Index\_array}_{\text{Data\_index}} := \text{Data\_index}$

Thermal Resistivities

$\rho_{\text{insul}} := 500\cdot K\cdot cm\cdot watt^{-1}$ Insulation $\quad \rho_{\text{mass}} := 400\cdot K\cdot cm\cdot watt^{-1}$ Cable Mass (Stolpe)

$\rho_{\text{jacket}} := 500\cdot K\cdot cm\cdot watt^{-1}$ Jacket $\quad \rho_{\text{cond}} := 2.08\cdot K\cdot cm\cdot watt^{-1}$ Conduit thermal conducrivity (S&L Standard ESA-105)

Ambient Temperature

$T_{\text{ambC}} := 40\cdot K$ °C

Miscellaneous Constants

Stefan-Boltzmann Constant

$\sigma := 5.669\cdot 10^{-8}\cdot watt\cdot m^{-2}\cdot K^{-4}$ $\quad$ Holman, page 307

$\varepsilon_{\text{cond}} := 0.33$ $\quad$ Conduit emissivity

Conversion factor between degrees Celsius and Kelvin

$\text{CtoK} := 273.15\cdot K$

$T_{\text{amb}} := T_{\text{ambC}} + \text{CtoK}$ $\quad T_{\text{amb}} = 313.15\cdot K$

Conduit Data

Inner and Outer Diameters, Thermal Conductivity, and Emissivity

$$\mathrm{Conduit\_Sizes} := \begin{bmatrix} 0.375 & 0.493 & 0.675 \\ 0.5 & 0.622 & 0.840 \\ 0.75 & 0.824 & 1.050 \\ 1.00 & 1.049 & 1.315 \\ 1.25 & 1.380 & 1.660 \\ 1.50 & 1.610 & 1.900 \\ 2.00 & 2.067 & 2.375 \\ 2.50 & 2.469 & 2.875 \\ 3.00 & 3.068 & 3.500 \\ 3.50 & 3.548 & 4.000 \\ 4.00 & 4.026 & 4.500 \\ 5.00 & 5.047 & 5.563 \\ 6.00 & 6.065 & 6.625 \end{bmatrix} \cdot \mathrm{in}$$

Reference: ANSI C80.1-1966

Note: The inside diameters for conduits built to ANSI C80.1-1983 and later are somewhat different. The 1966 version of the standard was selected based on the commerical operating date of Palisades Station

$$d_{condi} := \mathrm{linterp}\left(\mathrm{Conduit\_Sizes}^{<0>}, \mathrm{Conduit\_Sizes}^{<1>}, \mathrm{Conduit\_Trade\_Size}\right) \quad d_{condi} = 3.068 \cdot \mathrm{in}$$

$$d_{condo} := \mathrm{linterp}\left(\mathrm{Conduit\_Sizes}^{<0>}, \mathrm{Conduit\_Sizes}^{<2>}, \mathrm{Conduit\_Trade\_Size}\right) \quad d_{condo} = 3.5 \cdot \mathrm{in}$$

Lookup Table for Conductor Resistances at 90°C (See Sargent & Lundy Standard ESA-102)

$$\mathrm{Table\_size} := \begin{bmatrix} 1 \\ 2 \\ 4 \\ 6 \\ 8 \\ 9 \\ 10 \\ 12 \\ 14 \\ 16 \\ 110 \\ 210 \\ 250 \\ 300 \\ 310 \\ 350 \\ 400 \\ 410 \\ 500 \\ 600 \\ 750 \\ 1922 \\ 1925 \end{bmatrix} \qquad \mathrm{Table\_resist} := \begin{bmatrix} 0.0161 \\ 0.0203 \\ 0.0324 \\ 0.0513 \\ 0.0818 \\ 0.103 \\ 0.130 \\ 0.206 \\ 0.328 \\ 0.523 \\ 0.0128 \\ 0.0101 \\ 0.00542 \\ 0.00453 \\ 0.00804 \\ 0.00389 \\ 0.00341 \\ 0.00639 \\ 0.00275 \\ 0.00231 \\ 0.00187 \\ 0.108 \\ 0.217 \end{bmatrix} \cdot 10^{-2} \cdot \Omega \cdot \mathrm{ft}^{-1}$$

$$\mathrm{Cable\_size} := \mathrm{Cable\_data}^{<0>} \quad \mathrm{Number\_cables} := \mathrm{Cable\_data}^{<1>} \quad \mathrm{Number\_conductors} := \mathrm{Cable\_data}^{<2>}$$

$$\mathrm{Cable\_dia} := \mathrm{Cable\_data}^{<3>} \cdot \mathrm{in} \quad I_{\mathrm{load}} := \mathrm{Cable\_data}^{<5>} \cdot F_{\mathrm{current}} \cdot \mathrm{amp}$$

$$Q_{\mathrm{cable}_{\mathrm{Data\_index}}} := \mathrm{Number\_cables}_{\mathrm{Data\_index}} \cdot \mathrm{Number\_conductors}_{\mathrm{Data\_index}} \cdot \left(I_{\mathrm{load}_{\mathrm{Data\_index}}}\right)^2 \cdot \Omega \cdot \mathrm{ft}^{-1}$$

$$Q_{\mathrm{cable}_{\mathrm{Data\_index}}} := \frac{Q_{\mathrm{cable}_{\mathrm{Data\_index}}}}{\Omega \cdot \mathrm{ft}^{-1}} \cdot \mathrm{linterp}\left(\mathrm{Table\_size}, \mathrm{Table\_resist}, \mathrm{Cable\_size}_{\mathrm{Data\_index}}\right)$$

$$Q_{\mathrm{density}_{\mathrm{Data\_index}}} := \frac{Q_{\mathrm{cable}_{\mathrm{Data\_index}}}}{\left(\mathrm{Cable\_dia}_{\mathrm{Data\_index}}\right)^2 \cdot \mathrm{Number\_cables}_{\mathrm{Data\_index}}} \qquad \mathrm{Hottest} := \max\left(Q_{\mathrm{density}}\right)$$

$$\mathrm{Hot\_Flag}_{\mathrm{Data\_index}} := \mathrm{if}\left(Q_{\mathrm{density}_{\mathrm{Data\_index}}} > 0 \cdot \mathrm{watt} \cdot \mathrm{ft}^{-1} \cdot \mathrm{in}^{-2}, 1, 0\right)$$

$$\text{Temp} := \text{reverse}\left(\text{csort}\left(\text{augment}\left(\text{Index\_array}, \frac{Q_{\text{density}}}{\text{watt}\cdot\text{ft}^{-1}\cdot\text{in}^{-2}}\right), 1\right)\right)$$

$\text{Hot\_index} := \text{Temp}_{0,0}$ $\qquad$ $\text{Hot\_index} = 0$

$Q_{\text{density}_{\text{Hot\_index}}} - \text{Hottest} = 0 \cdot \text{watt}\cdot\text{ft}^{-1}\cdot\text{in}^{-2}$

$\text{Hot\_Flag}_{\text{Hot\_index}} := 2$ $\qquad$ Hot Flag now has values of:

0 for unloaded cables
1 for "warm" cables
2 for the hottest cable in the conduit

Diameters of Layers

Diameter of Hottest Cable

$\text{Number\_cables}_{\text{Hot\_index}} = 9$

$A_{\text{hot}} := \text{Number\_cables}_{\text{Hot\_index}} \cdot \left(\text{Cable\_dia}_{\text{Hot\_index}}\right)^2$ $\qquad$ $A_{\text{hot}} = 2.25 \cdot \text{in}^2$

$$A_{\text{hotf}} := \pi \cdot \text{Number\_cables}_{\text{Hot\_index}} \cdot \left(\frac{\text{Cable\_dia}_{\text{Hot\_index}}}{2}\right)^2$$

$d_{\text{hottest}} := \text{Cable\_dia}_{\text{Hot\_index}}$ $\qquad$ $d_{\text{hottest}} = 0.5 \cdot \text{in}$

$d_{\text{hot}} := \text{if}\left(\text{Number\_cables}_{\text{Hot\_index}} > 1, 2 \cdot \sqrt{\frac{A_{\text{hot}}}{\pi}}, d_{\text{hottest}}\right)$ $\qquad$ $d_{\text{hot}} = 1.693 \cdot \text{in}$

Area and diameter of "warm" cable layer

$A_{\text{warm}} := \sum_{j=0}^{(\text{Data\_size}-1)} \text{if}\left[\text{Hot\_Flag}_j = 1, \left(\text{Cable\_dia}_j\right)^2 \cdot \text{Number\_cables}_j, 0 \cdot \text{in}^2\right]$ $\qquad$ $A_{\text{warm}} = 0 \cdot \text{in}^2$

$$A_{\text{warmf}} := \sum_{j=0}^{(\text{Data\_size}-1)} \text{if}\left[\text{Hot\_Flag}_j = 1, \left(\frac{\text{Cable\_dia}_j}{2}\right)^2 \cdot \pi \cdot \text{Number\_cables}_j, 0 \cdot \text{in}^2\right]$$

$d_{\text{warm}} := 2 \cdot \sqrt{\frac{A_{\text{warm}}}{\pi} + \left(\frac{d_{\text{hot}}}{2}\right)^2}$ $\qquad$ $d_{\text{warm}} = 1.693 \cdot \text{in}$

Area and diameter of "cold" cable layer

$A_{\text{cold}} := \sum_{j=0}^{(\text{Data\_size}-1)} \text{if}\left[\text{Hot\_Flag}_j = 0, \left(\text{Cable\_dia}_j\right)^2 \cdot \text{Number\_cables}_j, 0 \cdot \text{in}^2\right]$ $\qquad$ $A_{\text{cold}} = 3.833 \cdot \text{in}^2$

$$A_{\text{coldf}} := \sum_{j=0}^{(\text{Data\_size}-1)} \text{if}\left[\text{Hot\_Flag}_j = 0, \left(\frac{\text{Cable\_dia}_j}{2}\right)^2 \cdot \pi \cdot \text{Number\_cables}_j, 0 \cdot \text{in}^2\right]$$

$d_{\text{cold}} := 2 \cdot \sqrt{\frac{A_{\text{cold}}}{\pi} + \left(\frac{d_{\text{warm}}}{2}\right)^2}$ $\qquad$ $d_{\text{cold}} = 2.783 \cdot \text{in}$

$A_{cond} := \pi \cdot \left(\frac{d_{condi}}{2} \right)^2 \qquad A_{cond} = 7.393 \cdot in^2$

$A_{cable} := \sum_{j=0}^{(Data\_size - 1)} Number\_cables_j \cdot \pi \cdot \left(\frac{Cable\_dia_j}{2} \right)^2 \qquad A_{cable} = 4.778 \cdot in^2$

$A_{power} := \sum_{j=0}^{(Data\_size - 1)} if\left[I_{load_j} > 0 \cdot amp, Number\_cables_j \cdot \pi \cdot \left(\frac{Cable\_dia_j}{2} \right)^2, 0 \cdot in^2 \right] \qquad A_{power} = 1.767 \cdot in^2$

$Fill\_u := \frac{A_{hotf} + A_{coldf} + A_{warmf}}{A_{cond}} \quad Fill\_power\_u := \frac{A_{hotf}}{A_{cond}} \quad Fill\_cold\_u := \frac{A_{coldf}}{A_{cond}} \quad Fill\_warm\_u := \frac{A_{warmf}}{A_{cond}}$

Heat generated by hot cables

$Q_{hot} := Q_{cable_{Hot\_index}} \qquad Q_{hot} = 10.531 \cdot watt \cdot ft^{-1}$

Heat generated by "warm" cables

$Q_{warm} := \sum_{j=0}^{(Data\_size - 1)} if\left(Hot\_Flag_j = 1, Q_{cable_j}, 0 \cdot watt \cdot ft^{-1} \right) \qquad Q_{warm} = 0 \cdot watt \cdot ft^{-1}$

$qdot_{warm} := \frac{Q_{warm}}{A_{warm}} \qquad qdot_{warm} = 0 \cdot watt \cdot ft^{-1} \cdot in^{-2}$

$Q_{total} := Q_{warm} + Q_{hot} \qquad Q_{total} = 10.531 \cdot watt \cdot ft^{-1}$

Calculate the Surface Temperature of the Wrapped Assembly

Note: In order to solve the energy balance equations, the equations for the heat dissipated by the wrapped assembly will be written as functions of the surface temperature. The area of the wrapped conduit per unit length is equal to π times the diameter of the wrapped assembly.

Heat Dissipated by Radiation

$$Q_r(T) := \pi \cdot d_{condo} \cdot \varepsilon_{cond} \cdot \sigma \cdot \left(T^4 - T_{amb}{}^4\right)$$

Heat Dissipated by Convection

$$Q_c(T) := 1.32 \cdot \mathrm{watt} \cdot K^{-\frac{5}{4}} \cdot m^{-2} \cdot m^{\frac{1}{4}} \cdot \left(\frac{T - T_{amb}}{d_{condo}}\right)^{\frac{1}{4}} \cdot \pi \cdot d_{condo} \cdot \left(T - T_{amb}\right)$$

Initial guess for iterative solution of the surface temperature of the wrapped conduit

$T_{guess} := 330 \cdot K$

Given

$Q_{total} = Q_r\left(T_{guess}\right) + Q_c\left(T_{guess}\right)$ Heat dissipated by radiation and convection must equal heat generated by cables.

$T_{condo} := \mathrm{Find}\left(T_{guess}\right)$

$T_{condo} = 329.911 \cdot K$ $T_{condo} - \mathrm{CtoK} = 56.761 \cdot K$ °C Surface temperature of the conduit

Temperature Drop through the Conduit

$$\Delta T_{cond} = \frac{1}{2\cdot\pi}\cdot\rho_{cond}\cdot\ln\left(\frac{d_{condo}}{d_{condi}}\right)\cdot Q_{total}$$ See Equation 2-8 of Holman

$\Delta T_{cond} = 0.015\cdot K$

$T_{condi} = T_{condo} + \Delta T_{cond}$

$T_{condi} = 329.926\cdot K$ Temperature of the inside wall of the conduit

$T_{condi} - CtoK = 56.776\cdot K$ °C

Temperature Drop through the Air Gap Inside the Conduit

Constants for Neher-McGrath Formula for Temperature Drop in the Conduit Air Gap

$A' := 3.2\cdot K\cdot ft\cdot watt^{-1}\cdot in$

$B' := 0.19\cdot in$

$$\Delta T_{condgap} = \frac{A'}{B' + d_{cold}}\cdot Q_{total}$$ See Equation 41A of Neher-McGrath

$\Delta T_{condgap} = 11.334\cdot K$

$T_{mass} = T_{condi} + \Delta T_{condgap}$ Temperature at the outside surface of the cable mass

$T_{mass} = 341.261\cdot K$

$T_{mass} - CtoK = 68.111\cdot K$ (°C)

Temperature drop through the "cold" cables

$$\Delta T_{cold} = Q_{total}\cdot\frac{\rho_{mass}}{2\cdot\pi}\cdot\ln\left(\frac{d_{cold}}{d_{warm}}\right)$$ $\Delta T_{cold} = 10.938\cdot K$

$T_{cold} = T_{mass} + \Delta T_{cold}$ $T_{cold} = 352.199\cdot K$ $T_{cold} - CtoK = 79.049\cdot K$°C

Temperature drop through the "warm" cables

$$k_{mass} = \frac{1}{\rho_{mass}}$$

$$\Delta T_{warm} = Q_{hot} \cdot \frac{\rho_{mass}}{2 \cdot \pi} \cdot \ln\left(\frac{d_{warm}}{d_{hot}}\right) + \frac{qdot_{warm} \cdot \left[\left(\frac{d_{warm}}{2}\right)^2 - \left(\frac{d_{hot}}{2}\right)^2\right]}{4 \cdot k_{mass}} - \frac{qdot_{warm}}{2 \cdot k_{mass}} \cdot \left(\frac{d_{hot}}{2}\right)^2 \cdot \ln\left(\frac{d_{warm}}{d_{hot}}\right)$$

$$\Delta T_{warm} = 0 \cdot K$$

$T_{warm} = T_{cold} + \Delta T_{warm}$ $\quad$ $T_{warm} - CtoK = 79.049 \cdot K$ °C

Temperature Rise through the hot cables

$$\Delta T_{hot} = \frac{Q_{density_{Hot\_index}} \cdot \left(\frac{d_{hot}}{2}\right)^2}{4 \cdot k_{mass}}$$ Holman, Equation 2-26

$$\Delta T_{hot} = 10.997 \cdot K$$

$T_{cable} = T_{warm} + \Delta T_{hot}$ $\quad$ $T_{cable} - CtoK = 90.046 \cdot K$ °C

$F_{current} = 0.584$

$$\mathrm{augment(Index\_array, Cable\_data)} = \begin{pmatrix} 0 & 2 & 9 & 1 & 0.5 & 0 & 130 & 1 \\ 1 & 14 & 28 & 2 & 0.37 & 0 & 0 & 0 \end{pmatrix}$$

$Q_{total} = 10.531 \cdot watt \cdot ft^{-1}$

$Q_{cable_{Hot\_index}} = 10.531 \cdot watt \cdot ft^{-1}$

Fill_u = 0.646

Fill_power_u = 0.239

Fill_warm_u = 0

Fill_cold_u = 0.407

ATTACHMENT 34

Methodology for Determining the Conductor Temperature of Cables in Conduit Routing Points

Prepared By : William [illegible] May 30, 1997

Reviewed By: Ismail Manassa 5/30/97

Purpose

The purpose of this section is to determine the conductor temperatures of cables in selected conduit routing points. The additional temperature rise due to installation in fire stops is included for those conduits that are installed in fire stops.

Methodology

The temperature of the conductors in the conduit are calculated by a Mathcad scratch sheet. Information on the conduit size and the type of fire stop is entered manually. The required information is then obtained from look-up tables within the sheet (References 4–6). Information on the cables inside the conduit, such as the conductor size, number of conductors in the cable, number of cables in the group, cable diameter, and load current, is read from an external data file. The contents of these data files are shown in Attachment 34 of this calculation. The conductor resistance per unit length is obtained from a look-up table based on the conductor size.

Within the Mathcad sheet, the cables in the conduit are divided into three groups. The cables that are unloaded are considered "cold", and are assumed to surround the other cables. The group of cables that generates the maximum amount of heat per unit volume are the "hot" cables and are located in the center of all of the cables. Cables that are neither "hot" or "cold" are considered "warm" cables. The "warm" cables are located between the "cold" and "hot" cables.

The conduit trade size is entered into the Mathcad sheet. The inside and outside diameters of the conduit can then be determined by a lookup table in the sheet. The conductor size, number of cables in the group, number of conductors in each cable, cable diameter, cable area, and load current for the cable is read from a data file. The conductor resistance of the various conductors are determined from the conductor size using another look-up table. The sheet then calculates the heat generated by each cable group. Next, the sheet divides the heat generated by each cable group by the area occupied by each cable group to give the heat intensity for the cable group. In order to facilitate later calculations, an array, Hot_Flag is set up. Each member of Hot_Flag is set to 0 if the cable group generates no heat ("cold"), 1 if the cable generates heat but does not have the greatest heat intensity of all the groups in the conduit ("warm"), and 2 if the cable group has the highest heat intensity in the conduit ("hot").

Using Hot_Flag to classify the cable groups, the sheet calculates the area occupied the "cold", "warm", and "hot" cables. Since circular cables will have spaces between them when they are bundled together, the area calculations assume that the cables are square to allow for this additional area when there is more than one cable in the group. Based on the area occupied by each layer, the diameter of the layer can then be calculated.

The heat generated by the "warm" and "hot" layers is then calculated. The heat intensity of the two layers is then calculated using the areas of the layers. Also, the total heat generated in the conduit is determined. All of the heat calculations are based on cable conductor temperatures of 90°C, the rated operating temperature of the cable conductors.

The surface temperature of the conduit can then be calculated. The heat dissipated from the outer surface by convection and radiation is first written as a function of the surface temperature. These equations can be solved iteratively to find the surface temperature at which the total heat dissipated in the conduit equals the heat generated inside. The temperature drop through the conduit itself can be calculated based on the conduit being a hollow cylinder.

The temperature drop through the air gap between the inside surface of the conduit and the outer surface of the cable mass is then calculated using the semi-empirical formula given by Neher and McGrath. The temperature drop through the "cold" cables is calculated by treating the "cold" layer as a hollow cylinder.

The temperature drop through the "warm" cable layer has two components. The temperature drop caused by the flow of heat from the "hot" cables inside is calculated by treating the "warm" cables as a hollow cylinder. An additional temperature drop is caused by the heat generated within the "warm" layer. This temperature drop is calculated by a formula similar to that given in Section 2-8 of Holman, except the equation is fitted to a different initial condition to account for the hollow core of this layer.

The temperature drop through the "hot" layer is calculated using Holman's Equation 2-26. The conductor temperature exclusive of the additional heating associated with fire stops is then the surface temperature of the conduit plus the sum of the temperature drops described above. From this the temperature rise of the conductor above the ambient temperature is calculated. The additional temperature rise due to fire stops is included by the use temperature multipliers that were obtained by testing in Reference 4 for those conduits that pass through Kaowool fire stops. The corresponding factors for concrete grout fire stops, which are made from materials with higher thermal conductivity and produce less temperature rise are taken form Reference 12.

Results and Conclusions

The results of the cases examined are as follows:

Routing Point	Conduit Nominal Size	Fire Stop Type	Conductor Temperature (°C)
X1514	3" Rigid Steel	24" wall	84.13
X1516	3" Rigid Steel	24" wall	73.0

Based on the results shown above, the conductor temperatures are below the conductor rated temperature of 90°C. Therefore, the performance of the cables at these routing points is satisfactory.

References

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4. Attachment 8 of Palisades Engineering Analysis (EA) EA-ELEC-AMP-041, "Ampacity Evaluation for Continuously Energixed Power Cables Routed through Fire Stops", Rev. 0 by R. Hernandez, dated March 24, 1997.

5. U. S. A. National Standards Institute. 1966. Standard C80.1 "USA Standard Specification for Rigid Steel Conduit, Zinc Coated". New York: U. S. A. National Standards Institute.

6. National Electrical Manufacturers Association (NEMA). 1983. "American National Standard for Electrical Metallic Tubing— Zinc Coated". New York:

American National Standards Institute (ANSI).

7. Stolpe, J. "Ampacities for Cables in Randomly Filled Trays". *IEEE Transactions on Power Apparatus and Systems.* PAS-90 (May / June 1971); 962–974.

8. Hudson, R. G. 1961. *The Engineer's Manual.* New York: John Wiley & Sons, page 317

9. Sargent & Lundy Standard ESA-102, "Electrical Engineering Standard for Electrical and Physical Characteristics of Class B Electrical Cables.", Revised April 14, 1993.

10. Insulated Conductor Engineers Association (ICEA) 1986. NEMA WC51 / ICEA P54-440, "Ampacities of Cables in Open Top Cable Trays." Washington, D. C.: National Electrical Manufacturers Association.

11. Attachment 34 of this calculation (Cable data)

12. Attachment 28, Appendix A of Palisades Engineering Analysis (EA) EA-ELEC-AMP-041, "Cable Ampacity Evaluation for Firestop Penetrations", Rev. 0 by R. Hernandez, dated March 24, 1997.

Conduit at Routing Point X1514 Passing through a 24" Wall Fire Stop FZ-0588

Conduit Data
Nominal size— Rigid steel
Nominal size + 0.0002"— EMT

Conduit_Trade_Size := 3.0·in

Enter Cable Data

Fire Stop Code

Fire_Stop_Code := 2

Fire Stop Codes
0— Free air
1— 12" wall
2— 24" wall
3— 12" floor
4— 24" floor

Cable_data := READPRN(data_file)

Data_size := rows(Cable_data)   Data_size = 7   Number of cable groups in the data

Data_index := 0, 1 .. (Data_size − 1)

$\text{Index\_array}_{\text{Data\_index}}$:= Data_index

Thermal Resistivities

$\rho_{insul} := 500 \cdot K \cdot cm \cdot watt^{-1}$ Insulation $\rho_{mass} := 400 \cdot K \cdot cm \cdot watt^{-1}$ Cable Mass (Stolpe)

$\rho_{jacket} := 500 \cdot K \cdot cm \cdot watt^{-1}$ Jacket $\rho_{cond} := 2.08 \cdot K \cdot cm \cdot watt^{-1}$ Conduit thermal conducrivity (Hudson, page 317)

Ambient Temperature

$T_{ambC} := 40 \cdot K$ °C

Miscellaneous Constants

Stefan-Boltzmann Constant

$\sigma := 5.669 \cdot 10^{-8} \cdot watt \cdot m^{-2} \cdot K^{-4}$ Holman, page 307

$\varepsilon_{cond} := 0.33$ Conduit emissivity (NEMA WC51, page 17)

Conversion factor between degrees Celsius and Kelvin

CtoK := 273.15·K

$T_{amb} := T_{ambC} + CtoK$ $T_{amb} = 313.15 \cdot K$

Conduit Data
Inner and Outer Diameters

$$\mathrm{Conduit\_Sizes} := \begin{bmatrix} 0.375 & 0.493 & 0.675 \\ 0.3752 & 0.493 & 0.577 \\ 0.5 & 0.622 & 0.840 \\ 0.5002 & 0.622 & 0.706 \\ 0.75 & 0.824 & 1.050 \\ 0.7502 & 0.824 & 0.922 \\ 1.00 & 1.049 & 1.315 \\ 1.0002 & 1.049 & 1.163 \\ 1.25 & 1.380 & 1.660 \\ 1.2502 & 1.380 & 1.510 \\ 1.50 & 1.610 & 1.900 \\ 1.5002 & 1.610 & 1.740 \\ 2.00 & 2.067 & 2.375 \\ 2.0002 & 2.067 & 2.197 \\ 2.50 & 2.469 & 2.875 \\ 2.5002 & 2.731 & 2.875 \\ 3.00 & 3.068 & 3.500 \\ 3.0002 & 3.356 & 3.500 \\ 3.50 & 3.548 & 4.000 \\ 3.5002 & 3.834 & 4.000 \\ 4.00 & 4.026 & 4.500 \\ 4.0002 & 4.334 & 4.500 \\ 5.00 & 5.047 & 5.563 \\ 6.00 & 6.065 & 6.625 \end{bmatrix} \cdot \mathrm{in}$$

References: ANSI C80.1-1966 & C80.3-1983

Note: The inside diameters for rigid steel conduits built to ANSI C80.1-1983 and later are somewhat different. The 1966 version of the standard was selected based on the commerical operating date of Palisades Station

$$d_{condi} := \mathrm{linterp}\left(\mathrm{Conduit\_Sizes}^{\langle 0\rangle}, \mathrm{Conduit\_Sizes}^{\langle 1\rangle}, \mathrm{Conduit\_Trade\_Size}\right) \qquad d_{condi} = 3.068 \cdot \mathrm{in}$$

$$d_{condo} := \mathrm{linterp}\left(\mathrm{Conduit\_Sizes}^{\langle 0\rangle}, \mathrm{Conduit\_Sizes}^{\langle 2\rangle}, \mathrm{Conduit\_Trade\_Size}\right) \qquad d_{condo} = 3.5 \cdot \mathrm{in}$$

$$\mathrm{FS\_Temp\_Factor} := \begin{array}{cl} \left[\begin{matrix} 1.00 \\ 1.00 \\ 1.064 \\ 1.00 \\ 1.22 \end{matrix}\right] & \begin{matrix} \text{Free air} \\ \text{12" wall} \\ \text{24" wall} \\ \text{12" floor} \\ \text{24" floor} \end{matrix} \end{array}$$

(Calculation EA-ELEC-AMP-041, Attachment 28, Appendix A for concrete grout fire stops)

Lookup Table for Conductor Resistances at 90°C (See Sargent & Lundy Standard ESA-102)

$$\text{Table\_size} := \begin{bmatrix} 1 \\ 2 \\ 4 \\ 6 \\ 8 \\ 9 \\ 10 \\ 12 \\ 14 \\ 16 \\ 110 \\ 210 \\ 250 \\ 300 \\ 310 \\ 350 \\ 400 \\ 410 \\ 500 \\ 600 \\ 750 \\ 1922 \\ 1925 \end{bmatrix} \qquad \text{Table\_resist} := \begin{bmatrix} 0.0161 \\ 0.0203 \\ 0.0324 \\ 0.0513 \\ 0.0818 \\ 0.103 \\ 0.130 \\ 0.206 \\ 0.328 \\ 0.523 \\ 0.0128 \\ 0.0101 \\ 0.00542 \\ 0.00453 \\ 0.00804 \\ 0.00389 \\ 0.00341 \\ 0.00639 \\ 0.00275 \\ 0.00231 \\ 0.00187 \\ 0.108 \\ 0.217 \end{bmatrix} \cdot 10^{-2} \cdot \Omega \cdot \text{ft}^{-1}$$

$$\text{Cable\_size} := \text{Cable\_data}^{\langle 0 \rangle} \quad \text{Number\_cables} := \text{Cable\_data}^{\langle 1 \rangle} \quad \text{Number\_conductors} := \text{Cable\_data}^{\langle 2 \rangle}$$

$$\text{Cable\_dia} := \text{Cable\_data}^{\langle 3 \rangle} \cdot \text{in} \quad \text{I}_{\text{load}} := \text{Cable\_data}^{\langle 5 \rangle} \cdot \text{amp}$$

$$\text{Q cable}_{\text{Data\_index}} := \text{Number\_cables}_{\text{Data\_index}} \cdot \text{Number\_conductors}_{\text{Data\_index}} \cdot \left(\text{I load}_{\text{Data\_index}}\right)^{2} \cdot \Omega \cdot \text{ft}^{-1}$$

$$\text{Q cable}_{\text{Data\_index}} := \frac{\text{Q cable}_{\text{Data\_index}}}{\Omega \cdot \text{ft}^{-1}} \cdot \text{linterp}\left(\text{Table\_size}, \text{Table\_resist}, \text{Cable\_size}_{\text{Data\_index}}\right)$$

$$\text{Q density}_{\text{Data\_index}} := \frac{\text{Q cable}_{\text{Data\_index}}}{\left(\text{Cable\_dia}_{\text{Data\_index}}\right)^{2} \cdot \text{Number\_cables}_{\text{Data\_index}}} \qquad \text{Hottest} := \max\left(\text{Q density}\right)$$

$$\text{Hot\_Flag}_{\text{Data\_index}} := \text{if}\left(\text{Q density}_{\text{Data\_index}} > 0 \cdot \text{watt} \cdot \text{ft}^{-1} \cdot \text{in}^{-2}, 1, 0\right)$$

$$\text{Temp} := \text{reverse}\left(\text{csort}\left(\text{augment}\left(\text{Index\_array}, \frac{Q_{\text{density}}}{\text{watt}\cdot\text{ft}^{-1}\cdot\text{in}^{-2}}\right), 1\right)\right)$$

$\text{Hot\_index} := \text{Temp}_{0,0}$ $\quad$ $\text{Hot\_index} = 4$

$Q_{\text{density}_{\text{Hot\_index}}} - \text{Hottest} = 0 \cdot \text{watt}\cdot\text{ft}^{-1}\cdot\text{in}^{-2}$

$\text{Hot\_Flag}_{\text{Hot\_index}} := 2$ $\quad$ Hot Flag now has values of:

0 for unloaded cables
1 for "warm" cables
2 for the hottest cable in the conduit

Diameters of Layers

Diameter of Hottest Cable

$\text{Number\_cables}_{\text{Hot\_index}} = 3$

$A_{\text{hot}} := \text{Number\_cables}_{\text{Hot\_index}} \cdot \left(\text{Cable\_dia}_{\text{Hot\_index}}\right)^2$ $\quad$ $A_{\text{hot}} = 0.529 \cdot \text{in}^2$

$$A_{\text{hotf}} := \pi \cdot \text{Number\_cables}_{\text{Hot\_index}} \cdot \left(\frac{\text{Cable\_dia}_{\text{Hot\_index}}}{2}\right)^2$$

$d_{\text{hottest}} := \text{Cable\_dia}_{\text{Hot\_index}}$ $\quad$ $d_{\text{hottest}} = 0.42 \cdot \text{in}$

$$d_{\text{hot}} := \text{if}\left(\text{Number\_cables}_{\text{Hot\_index}} > 1, 2 \cdot \sqrt{\frac{A_{\text{hot}}}{\pi}}, d_{\text{hottest}}\right) \qquad d_{\text{hot}} = 0.821 \cdot \text{in}$$

Area and diameter of "warm" cable layer

$$A_{\text{warm}} := \sum_{j=0}^{(\text{Data\_size}-1)} \text{if}\left[\text{Hot\_Flag}_j = 1, \left(\text{Cable\_dia}_j\right)^2 \cdot \text{Number\_cables}_j, 0 \cdot \text{in}^2\right] \qquad A_{\text{warm}} = 1.682 \cdot \text{in}^2$$

$$A_{\text{warmf}} := \sum_{j=0}^{(\text{Data\_size}-1)} \text{if}\left[\text{Hot\_Flag}_j = 1, \left(\frac{\text{Cable\_dia}_j}{2}\right)^2 \cdot \pi \cdot \text{Number\_cables}_j, 0 \cdot \text{in}^2\right]$$

$$d_{\text{warm}} := 2 \cdot \sqrt{\frac{A_{\text{warm}}}{\pi} + \left(\frac{d_{\text{hot}}}{2}\right)^2} \qquad d_{\text{warm}} = 1.678 \cdot \text{in}$$

Area and diameter of "cold" cable layer

$$A_{\text{cold}} := \sum_{j=0}^{(\text{Data\_size}-1)} \text{if}\left[\text{Hot\_Flag}_j = 0, \left(\text{Cable\_dia}_j\right)^2 \cdot \text{Number\_cables}_j, 0 \cdot \text{in}^2\right] \qquad A_{\text{cold}} = 1.181 \cdot \text{in}^2$$

$$A_{\text{coldf}} := \sum_{j=0}^{(\text{Data\_size}-1)} \text{if}\left[\text{Hot\_Flag}_j = 0, \left(\frac{\text{Cable\_dia}_j}{2}\right)^2 \cdot \pi \cdot \text{Number\_cables}_j, 0 \cdot \text{in}^2\right]$$

$$d_{\text{cold}} := 2 \cdot \sqrt{\frac{A_{\text{cold}}}{\pi} + \left(\frac{d_{\text{warm}}}{2}\right)^2} \qquad d_{\text{cold}} = 2.078 \cdot \text{in}$$

$A_{cond} := \pi \cdot \left(\frac{d_{condi}}{2}\right)^2 \qquad A_{cond} = 7.393 \cdot in^2$

$A_{cable} := \sum_{j=0}^{(Data\_size-1)} Number\_cables_j \cdot \pi \cdot \left(\frac{Cable\_dia_j}{2}\right)^2 \qquad A_{cable} = 2.664 \cdot in^2$

$A_{power} := \sum_{j=0}^{(Data\_size-1)} if\left[I_{load_j} > 0 \cdot amp, Number\_cables_j \cdot \pi \cdot \left(\frac{Cable\_dia_j}{2}\right)^2, 0 \cdot in^2\right] \qquad A_{power} = 1.736 \cdot in^2$

$Fill\_u := \frac{A_{hotf} + A_{coldf} + A_{warmf}}{A_{cond}} \quad Fill\_power\_u := \frac{A_{hotf}}{A_{cond}} \quad Fill\_cold\_u := \frac{A_{coldf}}{A_{cond}} \quad Fill\_warm\_u := \frac{A_{warmf}}{A_{cond}}$

Heat generated by hot cables

$Q_{hot} := Q_{cable_{Hot\_index}} \qquad Q_{hot} = 3.27 \cdot watt \cdot ft^{-1}$

Heat generated by "warm" cables

$Q_{warm} := \sum_{j=0}^{(Data\_size-1)} if\left(Hot\_Flag_j = 1, Q_{cable_j}, 0 \cdot watt \cdot ft^{-1}\right) \qquad Q_{warm} = 5.327 \cdot watt \cdot ft^{-1}$

$qdot_{warm} := \frac{Q_{warm}}{A_{warm}} \qquad qdot_{warm} = 3.168 \cdot watt \cdot ft^{-1} \cdot in^{-2}$

$Q_{total} := Q_{warm} + Q_{hot} \qquad Q_{total} = 8.596 \cdot watt \cdot ft^{-1}$

Calculate the Surface Temperature of the Wrapped Assembly

Note: In order to solve the energy balance equations, the equations for the heat dissipated by the wrapped assembly will be written as functions of the surface temperature. The area of the wrapped conduit per unit length is equal to π times the diameter of the wrapped assembly.

Heat Dissipated by Radiation

$$Q_r(T) := \pi \cdot d_{condo} \cdot \varepsilon_{cond} \cdot \sigma \cdot \left(T^4 - T_{amb}^{\;4}\right)$$ (Holman, Equation 8-43a)

Heat Dissipated by Convection

$$Q_c(T) := 1.32 \cdot watt \cdot K^{-\frac{5}{4}} \cdot m^{-2} \cdot m^{\frac{1}{4}} \cdot \left(\frac{T - T_{amb}}{d_{condo}}\right)^{\frac{1}{4}} \cdot \pi \cdot d_{condo} \cdot \left(T - T_{amb}\right)$$

(Holman, Table 7-2 and Equation 1-8)

Initial guess for iterative solution of the surface temperature of the wrapped conduit

$T_{guess} := 330 \cdot K$

Given

$Q_{total} = Q_r\left(T_{guess}\right) + Q_c\left(T_{guess}\right)$ Heat dissipated by radiation and convection must equal heat generated by cables.

$T_{condo} := Find\left(T_{guess}\right)$

$T_{condo} = 327.283 \cdot K$ $T_{condo} - CtoK = 54.133 \cdot K \cdot °C$ Surface temperature of the conduit

$Q_{total} = 8.596 \cdot watt \cdot ft^{-1}$

$Q_r\left(T_{condo}\right) + Q_c\left(T_{condo}\right) = 8.596 \cdot watt \cdot ft^{-1}$

Temperature Drop through the Conduit

$\Delta T_{cond} := \frac{1}{2 \cdot \pi} \cdot \rho_{cond} \cdot \ln\left(\frac{d_{condo}}{d_{condi}}\right) \cdot Q_{total}$ See Equation 2-8 of Holman

$\Delta T_{cond} = 0.012 \cdot K$

$T_{condi} := T_{condo} + \Delta T_{cond}$

$T_{condi} = 327.295 \cdot K$ Temperature of the inside wall of the conduit

$T_{condi} - CtoK = 54.145 \cdot K$ °C

Temperature Drop through the Air Gap Inside the Conduit

Constants for Neher-McGrath Formula for Temperature Drop in the Conduit Air Gap

$A' := 3.2 \cdot K \cdot ft \cdot watt^{-1} \cdot in$ (Neher-McGrath, Table VII)

$B' := 0.19 \cdot in$

$\Delta T_{condgap} := \frac{A'}{B' + d_{cold}} \cdot Q_{total}$ See Equation 41A of Neher-McGrath

$\Delta T_{condgap} = 12.129 \cdot K$

$T_{mass} := T_{condi} + \Delta T_{condgap}$ Temperature at the outside surface of the cable mass

$T_{mass} = 339.424 \cdot K$

$T_{mass} - CtoK = 66.274 \cdot K$ (°C)

Temperature drop through the "cold" cables

$\Delta T_{cold} := Q_{total} \cdot \frac{\rho_{mass}}{2 \cdot \pi} \cdot \ln\left(\frac{d_{cold}}{d_{warm}}\right)$ $\Delta T_{cold} = 3.842 \cdot K$

$T_{cold} := T_{mass} + \Delta T_{cold}$ $T_{cold} = 343.266 \cdot K$ $T_{cold} - CtoK = 70.116 \cdot KC$

Temperature drop through the "warm" cables

$$k_{mass} := \frac{1}{\rho_{mass}}$$

$$\Delta T_{warm} := Q_{hot} \cdot \frac{\rho_{mass}}{2 \cdot \pi} \cdot \ln\left(\frac{d_{warm}}{d_{hot}}\right) + \frac{qdot_{warm} \cdot \left[\left(\frac{d_{warm}}{2}\right)^2 - \left(\frac{d_{hot}}{2}\right)^2\right]}{4 \cdot k_{mass}} - \frac{qdot_{warm}}{2 \cdot k_{mass}} \cdot \left(\frac{d_{hot}}{2}\right)^2 \cdot \ln\left(\frac{d_{warm}}{d_{hot}}\right)$$

$\Delta T_{warm} = 7.942 \cdot K$

(Based on Holman, section 2-8 solved for a different set of initial conditions)

$T_{warm} := T_{cold} + \Delta T_{warm}$ $\quad T_{warm} - CtoK = 78.058 \cdot K \ ^\circ C$

Temperature Rise through the hot cables

$$\Delta T_{hot} := \frac{Q\ density_{Hot\_index} \cdot \left(\frac{d_{hot}}{2}\right)^2}{4 \cdot k_{mass}}$$

Holman, Equation 2-26

$\Delta T_{hot} = 3.415 \cdot K$

$T_{cable} := T_{warm} + \Delta T_{hot}$ $\quad T_{cable} - CtoK = 81.473 \cdot K \ ^\circ C$

$$T_{conductor} := T_{amb} + FS\_Temp\_Factor_{Fire\_Stop\_Code} \cdot \left(T_{cable} - T_{amb}\right)$$

$T_{conductor} = 357.277 \cdot K$ $\quad T_{conductor} - CtoK = 84.127 \cdot temperature \quad ^\circ C$

$\text{Conduit\_Trade\_Size} = 3 \cdot \text{in}$

$T_{\text{conductor}} - \text{CtoK} = 84.127 \cdot \text{temperature} \quad {}^{\circ}\text{C}$

$$\text{augment}(\text{Index\_array}, \text{Cable\_data}) = \begin{bmatrix} 0 & 12 & 1 & 3 & 0.52 & 0.005 & 13 \\ 1 & 14 & 1 & 2 & 0.37 & 0.003 & 0 \\ 2 & 14 & 2 & 2 & 0.42 & 0.003 & 0 \\ 3 & 14 & 3 & 3 & 0.48 & 0.003 & 0 \\ 4 & 4 & 3 & 1 & 0.42 & 0.033 & 58 \\ 5 & 8 & 1 & 3 & 0.84 & 0.013 & 28 \\ 6 & 8 & 1 & 3 & 0.84 & 0.013 & 31 \end{bmatrix}$$

Column 0— Row number
Column 1— Cable size
Column 2— Number of cables
Column 3— Number of conductors
Column 4— Cable diameter
Column 5— Not used
Column 6— Load current

$Q_{\text{total}} = 8.596 \cdot \text{watt} \cdot \text{ft}^{-1}$

$Q_{\text{cable}_{\text{Hot\_index}}} = 3.27 \cdot \text{watt} \cdot \text{ft}^{-1}$

$\text{Fill\_u} = 0.36$

$\text{Fill\_power\_u} = 0.056$

$\text{Fill\_warm\_u} = 0.179$

$\text{Fill\_cold\_u} = 0.125$

Conduit at Routing Point X1516 Passing through Fire Stop FZ-0588

Conduit Data
Nominal size— Rigid steel
Nominal size + 0.0002"— EMT

Conduit_Trade_Size := 3.0·in

Fire Stop Code

Fire_Stop_Code := 2

Fire Stop Codes
0— Free air
1— 12" wall
2— 24" wall
3— 12" floor
4— 24" floor

Enter Cable Data

Cable_data := READPRN(data_file)

Data_size := rows(Cable_data) Data_size = 6 Number of cable groups in the data

Data_index := 0, 1 .. (Data_size − 1)

$\text{Index\_array}_{\text{Data\_index}}$:= Data_index

Thermal Resistivities

$\rho_{insul} := 500\cdot K\cdot cm\cdot watt^{-1}$ Insulation

$\rho_{mass} := 400\cdot K\cdot cm\cdot watt^{-1}$ Cable Mass (Stolpe)

$\rho_{jacket} := 500\cdot K\cdot cm\cdot watt^{-1}$ Jacket

$\rho_{cond} := 2.08\cdot K\cdot cm\cdot watt^{-1}$ Conduit thermal conducrivity (Hudson, page 317)

Ambient Temperature

$T_{ambC} := 40\cdot K$ °C

Miscellaneous Constants

Stefan-Boltzmann Constant

$\sigma := 5.669\cdot 10^{-8}\cdot watt\cdot m^{-2}\cdot K^{-4}$ Holman, page 307

$\varepsilon_{cond} := 0.33$ Conduit emissivity (NEMA WC51, page 17)

Conversion factor between degrees Celsius and Kelvin

$CtoK := 273.15\cdot K$

$T_{amb} := T_{ambC} + CtoK$ $T_{amb} = 313.15\cdot K$

Conduit Data

Inner and Outer Diameters

$$\mathrm{Conduit\_Sizes} := \begin{bmatrix} 0.375 & 0.493 & 0.675 \\ 0.3752 & 0.493 & 0.577 \\ 0.5 & 0.622 & 0.840 \\ 0.5002 & 0.622 & 0.706 \\ 0.75 & 0.824 & 1.050 \\ 0.7502 & 0.824 & 0.922 \\ 1.00 & 1.049 & 1.315 \\ 1.0002 & 1.049 & 1.163 \\ 1.25 & 1.380 & 1.660 \\ 1.2502 & 1.380 & 1.510 \\ 1.50 & 1.610 & 1.900 \\ 1.5002 & 1.610 & 1.740 \\ 2.00 & 2.067 & 2.375 \\ 2.0002 & 2.067 & 2.197 \\ 2.50 & 2.469 & 2.875 \\ 2.5002 & 2.731 & 2.875 \\ 3.00 & 3.068 & 3.500 \\ 3.0002 & 3.356 & 3.500 \\ 3.50 & 3.548 & 4.000 \\ 3.5002 & 3.834 & 4.000 \\ 4.00 & 4.026 & 4.500 \\ 4.0002 & 4.334 & 4.500 \\ 5.00 & 5.047 & 5.563 \\ 6.00 & 6.065 & 6.625 \end{bmatrix} \cdot \mathrm{in}$$

References: ANSI C80.1-1966 & C80.3-1983

Note: The inside diameters for rigid steel conduits built to ANSI C80.1-1983 and later are somewhat different. The 1966 version of the standard was selected based on the commerical operating date of Palisades Station

$$d_{\mathrm{condi}} := \mathrm{linterp}\left(\mathrm{Conduit\_Sizes}^{\langle 0\rangle}, \mathrm{Conduit\_Sizes}^{\langle 1\rangle}, \mathrm{Conduit\_Trade\_Size}\right) \qquad d_{\mathrm{condi}} = 3.068 \cdot \mathrm{in}$$

$$d_{\mathrm{condo}} := \mathrm{linterp}\left(\mathrm{Conduit\_Sizes}^{\langle 0\rangle}, \mathrm{Conduit\_Sizes}^{\langle 2\rangle}, \mathrm{Conduit\_Trade\_Size}\right) \qquad d_{\mathrm{condo}} = 3.5 \cdot \mathrm{in}$$

$$\mathrm{FS\_Temp\_Factor} := \begin{array}{l} \begin{bmatrix} 1.00 \\ 1.16 \\ 1.32 \\ 1.33 \\ 1.52 \end{bmatrix} \end{array} \begin{array}{l} \text{Free air} \\ \text{12" wall} \\ \text{24" wall} \\ \text{12" floor} \\ \text{24" floor} \end{array}$$

(Calculation EA-ELEC-AMP-041, Attachment 8)

Lookup Table for Conductor Resistances at 90°C (See Sargent & Lundy Standard ESA-102)

$$\mathrm{Table\_size} := \begin{bmatrix} 1 \\ 2 \\ 4 \\ 6 \\ 8 \\ 9 \\ 10 \\ 12 \\ 14 \\ 16 \\ 110 \\ 210 \\ 250 \\ 300 \\ 310 \\ 350 \\ 400 \\ 410 \\ 500 \\ 600 \\ 750 \\ 1922 \\ 1925 \end{bmatrix} \qquad \mathrm{Table\_resist} := \begin{bmatrix} 0.0161 \\ 0.0203 \\ 0.0324 \\ 0.0513 \\ 0.0818 \\ 0.103 \\ 0.130 \\ 0.206 \\ 0.328 \\ 0.523 \\ 0.0128 \\ 0.0101 \\ 0.00542 \\ 0.00453 \\ 0.00804 \\ 0.00389 \\ 0.00341 \\ 0.00639 \\ 0.00275 \\ 0.00231 \\ 0.00187 \\ 0.108 \\ 0.217 \end{bmatrix} \cdot 10^{-2} \cdot \Omega \cdot \mathrm{ft}^{-1}$$

$$\mathrm{Cable\_size} := \mathrm{Cable\_data}^{\langle 0 \rangle} \quad \mathrm{Number\_cables} := \mathrm{Cable\_data}^{\langle 1 \rangle} \quad \mathrm{Number\_conductors} := \mathrm{Cable\_data}^{\langle 2 \rangle}$$

$$\mathrm{Cable\_dia} := \mathrm{Cable\_data}^{\langle 3 \rangle} \cdot \mathrm{in} \quad I_{\mathrm{load}} := \mathrm{Cable\_data}^{\langle 5 \rangle} \cdot \mathrm{amp}$$

$$Q_{\mathrm{cable}_{\mathrm{Data\_index}}} := \mathrm{Number\_cables}_{\mathrm{Data\_index}} \cdot \mathrm{Number\_conductors}_{\mathrm{Data\_index}} \cdot \left(I_{\mathrm{load}_{\mathrm{Data\_index}}}\right)^{2} \cdot \Omega \cdot \mathrm{ft}^{-1}$$

$$Q_{\mathrm{cable}_{\mathrm{Data\_index}}} := \frac{Q_{\mathrm{cable}_{\mathrm{Data\_index}}}}{\Omega \cdot \mathrm{ft}^{-1}} \cdot \mathrm{linterp}\left(\mathrm{Table\_size}, \mathrm{Table\_resist}, \mathrm{Cable\_size}_{\mathrm{Data\_index}}\right)$$

$$Q_{\mathrm{density}_{\mathrm{Data\_index}}} := \frac{Q_{\mathrm{cable}_{\mathrm{Data\_index}}}}{\left(\mathrm{Cable\_dia}_{\mathrm{Data\_index}}\right)^{2} \cdot \mathrm{Number\_cables}_{\mathrm{Data\_index}}} \qquad \mathrm{Hottest} := \max\left(Q_{\mathrm{density}}\right)$$

$$\mathrm{Hot\_Flag}_{\mathrm{Data\_index}} := \mathrm{if}\left(Q_{\mathrm{density}_{\mathrm{Data\_index}}} > 0 \cdot \mathrm{watt} \cdot \mathrm{ft}^{-1} \cdot \mathrm{in}^{-2}, 1, 0\right)$$

$$\text{Temp} := \text{reverse}\left(\text{csort}\left(\text{augment}\left(\text{Index\_array}, \frac{Q_{\text{density}}}{\text{watt}\cdot\text{ft}^{-1}\cdot\text{in}^{-2}}\right), 1\right)\right)$$

$\text{Hot\_index} := \text{Temp}_{0,0}$ $\text{Hot\_index} = 4$

$Q_{\text{density}_{\text{Hot\_index}}} - \text{Hottest} = 0\cdot\text{watt}\cdot\text{ft}^{-1}\cdot\text{in}^{-2}$

$\text{Hot\_Flag}_{\text{Hot\_index}} := 2$

Hot Flag now has values of:

- **0 for unloaded cables**
- **1 for "warm" cables**
- **2 for the hottest cable in the conduit**

Diameters of Layers

Diameter of Hottest Cable

$\text{Number\_cables}_{\text{Hot\_index}} = 3$

$A_{\text{hot}} := \text{Number\_cables}_{\text{Hot\_index}}\cdot\left(\text{Cable\_dia}_{\text{Hot\_index}}\right)^2$ $A_{\text{hot}} = 0.529\cdot\text{in}^2$

$$A_{\text{hotf}} := \pi\cdot\text{Number\_cables}_{\text{Hot\_index}}\cdot\left(\frac{\text{Cable\_dia}_{\text{Hot\_index}}}{2}\right)^2$$

$d_{\text{hottest}} := \text{Cable\_dia}_{\text{Hot\_index}}$ $d_{\text{hottest}} = 0.42\cdot\text{in}$

$$d_{\text{hot}} := \text{if}\left(\text{Number\_cables}_{\text{Hot\_index}} > 1, 2\cdot\sqrt{\frac{A_{\text{hot}}}{\pi}}, d_{\text{hottest}}\right) \qquad d_{\text{hot}} = 0.821\cdot\text{in}$$

Area and diameter of "warm" cable layer

$$A_{\text{warm}} := \sum_{j=0}^{(\text{Data\_size}-1)} \text{if}\left[\text{Hot\_Flag}_j = 1, \left(\text{Cable\_dia}_j\right)^2\cdot\text{Number\_cables}_j, 0\cdot\text{in}^2\right] \qquad A_{\text{warm}} = 0.503\cdot\text{in}^2$$

$$A_{\text{warmf}} := \sum_{j=0}^{(\text{Data\_size}-1)} \text{if}\left[\text{Hot\_Flag}_j = 1, \left(\frac{\text{Cable\_dia}_j}{2}\right)^2\cdot\pi\cdot\text{Number\_cables}_j, 0\cdot\text{in}^2\right]$$

$$d_{\text{warm}} := 2\cdot\sqrt{\frac{A_{\text{warm}}}{\pi} + \left(\frac{d_{\text{hot}}}{2}\right)^2} \qquad d_{\text{warm}} = 1.146\cdot\text{in}$$

Area and diameter of "cold" cable layer

$$A_{\text{cold}} := \sum_{j=0}^{(\text{Data\_size}-1)} \text{if}\left[\text{Hot\_Flag}_j = 0, \left(\text{Cable\_dia}_j\right)^2\cdot\text{Number\_cables}_j, 0\cdot\text{in}^2\right] \qquad A_{\text{cold}} = 1.124\cdot\text{in}^2$$

$$A_{\text{coldf}} := \sum_{j=0}^{(\text{Data\_size}-1)} \text{if}\left[\text{Hot\_Flag}_j = 0, \left(\frac{\text{Cable\_dia}_j}{2}\right)^2\cdot\pi\cdot\text{Number\_cables}_j, 0\cdot\text{in}^2\right]$$

$$d_{\text{cold}} := 2\cdot\sqrt{\frac{A_{\text{cold}}}{\pi} + \left(\frac{d_{\text{warm}}}{2}\right)^2} \qquad d_{\text{cold}} = 1.657\cdot\text{in}$$

$A_{cond} := \pi \cdot \left(\frac{d_{condi}}{2}\right)^2$ $\quad A_{cond} = 7.393 \cdot in^2$

$A_{cable} := \sum_{j=0}^{(Data\_size-1)} Number\_cables_j \cdot \pi \cdot \left(\frac{Cable\_dia_j}{2}\right)^2$ $\quad A_{cable} = 1.694 \cdot in^2$

$A_{power} := \sum_{j=0}^{(Data\_size-1)} if\left[I_{load_j} > 0 \cdot amp, Number\_cables_j \cdot \pi \cdot \left(\frac{Cable\_dia_j}{2}\right)^2, 0 \cdot in^2\right]$ $\quad A_{power} = 0.811 \cdot in^2$

$Fill\_u := \frac{A_{hotf} + A_{coldf} + A_{warmf}}{A_{cond}}$ $\quad Fill\_power\_u := \frac{A_{hotf}}{A_{cond}}$ $\quad Fill\_cold\_u := \frac{A_{coldf}}{A_{cond}}$ $\quad Fill\_warm\_u := \frac{A_{warmf}}{A_{cond}}$

Heat generated by hot cables

$Q_{hot} := Q_{cable_{Hot\_index}}$ $\quad Q_{hot} = 2.73 \cdot watt \cdot ft^{-1}$

Heat generated by "warm" cables

$Q_{warm} := \sum_{j=0}^{(Data\_size-1)} if\left(Hot\_Flag_j = 1, Q_{cable_j}, 0 \cdot watt \cdot ft^{-1}\right)$ $\quad Q_{warm} = 1.823 \cdot watt \cdot ft^{-1}$

$qdot_{warm} := \frac{Q_{warm}}{A_{warm}}$ $\quad qdot_{warm} = 3.623 \cdot watt \cdot ft^{-1} \cdot in^{-2}$

$Q_{total} := Q_{warm} + Q_{hot}$ $\quad Q_{total} = 4.553 \cdot watt \cdot ft^{-1}$

Calculate the Surface Temperature of the Wrapped Assembly

Note: In order to solve the energy balance equations, the equations for the heat dissipated by the wrapped assembly will be written as functions of the surface temperature. The area of the wrapped conduit per unit length is equal to π times the diameter of the wrapped assembly.

Heat Dissipated by Radiation

$$Q_r(T) := \pi \cdot d_{condo} \cdot \varepsilon_{cond} \cdot \sigma \cdot \left(T^4 - T_{amb}^{\;4}\right)$$ (Holman, Equation 8-43a)

Heat Dissipated by Convection

$$Q_c(T) := 1.32 \cdot watt \cdot K^{-\frac{5}{4}} \cdot m^{-2} \cdot m^{\frac{1}{4}} \cdot \left(\frac{T - T_{amb}}{d_{condo}}\right)^{\frac{1}{4}} \cdot \pi \cdot d_{condo} \cdot \left(T - T_{amb}\right)$$

(Holman, Table 7-2 and Equation 1-8)

Initial guess for iterative solution of the surface temperature of the wrapped conduit

$T_{guess} := 330 \cdot K$

Given

$Q_{total} = Q_r(T_{guess}) + Q_c(T_{guess})$ Heat dissipated by radiation and convection must equal heat generated by cables.

$T_{condo} := Find(T_{guess})$

$T_{condo} = 321.396 \cdot K$ $T_{condo} - CtoK = 48.246 \cdot K°C$ Surface temperature of the conduit

$Q_{total} = 4.553 \cdot watt \cdot ft^{-1}$

$Q_c(T_{condo}) + Q_r(T_{condo}) = 4.553 \cdot watt \cdot ft^{-1}$

Temperature Drop through the Conduit

$\Delta T_{cond} := \frac{1}{2\cdot\pi}\cdot\rho_{cond}\cdot\ln\left(\frac{d_{condo}}{d_{condi}}\right)\cdot Q_{total}$ See Equation 2-8 of Holman

$\Delta T_{cond} = 0.007\cdot K$

$T_{condi} := T_{condo} + \Delta T_{cond}$

$T_{condi} = 321.402\cdot K$ Temperature of the inside wall of the conduit

$T_{condi} - CtoK = 48.252\cdot K$ °C

Temperature Drop through the Air Gap Inside the Conduit

Constants for Neher-McGrath Formula for Temperature Drop in the Conduit Air Gap

$A' := 3.2\cdot K\cdot ft\cdot watt^{-1}\cdot in$ (Neher-McGrath, Table VII)

$B' := 0.19\cdot in$

$\Delta T_{condgap} := \frac{A'}{B' + d_{cold}}\cdot Q_{total}$ See Equation 41A of Neher-McGrath

$\Delta T_{condgap} = 7.889\cdot K$

$T_{mass} := T_{condi} + \Delta T_{condgap}$ Temperature at the outside surface of the cable mass

$T_{mass} = 329.291\cdot K$

$T_{mass} - CtoK = 56.141\cdot K$ (°C)

Temperature drop through the "cold" cables

$\Delta T_{cold} := Q_{total}\cdot\frac{\rho_{mass}}{2\cdot\pi}\cdot\ln\left(\frac{d_{cold}}{d_{warm}}\right)$ $\Delta T_{cold} = 3.503\cdot K$

$T_{cold} := T_{mass} + \Delta T_{cold}$ $T_{cold} = 332.794\cdot K$ $T_{cold} - CtoK = 59.644\cdot KC$

Temperature drop through the "warm" cables

$$k_{mass} := \frac{1}{\rho_{mass}}$$

$$\Delta T_{warm} := Q_{hot} \cdot \frac{\rho_{mass}}{2 \cdot \pi} \cdot \ln\left(\frac{d_{warm}}{d_{hot}}\right) + \frac{qdot_{warm} \cdot \left[\left(\frac{d_{warm}}{2}\right)^2 - \left(\frac{d_{hot}}{2}\right)^2\right]}{4 \cdot k_{mass}} - \frac{qdot_{warm}}{2 \cdot k_{mass}} \cdot \left(\frac{d_{hot}}{2}\right)^2 \cdot \ln\left(\frac{d_{warm}}{d_{hot}}\right)$$

(Based on Holman, section 2-8 solved for a different set of initial conditions)

$\Delta T_{warm} = 2.471 \cdot K$

$T_{warm} := T_{cold} + \Delta T_{warm}$ $\quad T_{warm} - CtoK = 62.115 \cdot K$ °C

Temperature Rise through the hot cables

$$\Delta T_{hot} := \frac{Q_{density_{Hot\_index}} \cdot \left(\frac{d_{hot}}{2}\right)^2}{4 \cdot k_{mass}}$$

Holman, Equation 2-26

$\Delta T_{hot} = 2.851 \cdot K$

$T_{cable} := T_{warm} + \Delta T_{hot}$ $\quad T_{cable} - CtoK = 64.966 \cdot K$ °C

$$T_{conductor} := T_{amb} + FS\_Temp\_Factor_{Fire\_Stop\_Code} \cdot \left(T_{cable} - T_{amb}\right)$$

$T_{conductor} = 346.105 \cdot K$ $\quad T_{conductor} - CtoK = 72.955 \cdot temperature$ °C

$\text{Conduit\_Trade\_Size} = 3 \cdot \text{in}$

$T_{\text{conductor}} - \text{CtoK} = 72.955 \cdot \text{temperature}$ °C

$$\text{augment}(\text{Index\_array}, \text{Cable\_data}) = \begin{bmatrix} 0 & 12 & 2 & 3 & 0.52 & 0.005 & 0 \\ 1 & 14 & 2 & 2 & 0.42 & 0.003 & 0 \\ 2 & 14 & 1 & 2 & 0.42 & 0.003 & 5 \\ 3 & 14 & 1 & 3 & 0.48 & 0.003 & 0 \\ 4 & 4 & 3 & 1 & 0.42 & 0.033 & 53 \\ 5 & 8 & 3 & 1 & 0.33 & 0.013 & 26 \end{bmatrix}$$

Column 0— Row number
Column 1— Cable size
Column 2— Number of cables
Column 3— Number of conductors
Column 4— Cable diameter
Column 5— Not used
Column 6— Load current

$Q_{\text{total}} = 4.553 \cdot \text{watt} \cdot \text{ft}^{-1}$

$Q_{\text{cable}_{\text{Hot\_index}}} = 2.73 \cdot \text{watt} \cdot \text{ft}^{-1}$

$\text{Fill\_u} = 0.229$

$\text{Fill\_power\_u} = 0.056$

$\text{Fill\_warm\_u} = 0.053$

$\text{Fill\_cold\_u} = 0.119$