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CALCULATION TITLE PAGE

Calculation No.: BYR 96-059 / G-70-96-092 Page No.: *1 of 40*

☒ Safety Related ☐ Regulatory Related ☐ Non-Safety Related

Calculation Title:
Verification of Models for Fire-Wrapped Conduits and Cable Trays against Test Data

Station/Unit: Byron / Braidwood, Units 1 & 2 System Abbreviation: AP

Equipment No. (If appl.): Project No. (If appl.) *09050-051 & 09135-200*

Rev.: 0 Status: QA Serial No. or Chron No. Date:

Prepared by: William G Bloetto Date: April 19, 1996

Revision Summary:

Initial issue for all pages.

Electronic Calculation Data Files Revised:
(Name ext/size/date/hour/: min/verification method/remarks)

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Do any assumptions in this calculation require later verification? ☐ Yes ☒ No

Reviewed by: Nedal Deeb Date: 4/19/1996

Review Method: Review of original calculation Comments (C or NC): NC

Approved by: S. Haddad Date: 4/19/96

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CALCULATION TABLE OF CONTENTS

	PROJECT NO. 09050-051 / 09135-200	
CALCULATION NO. BYR 96-059	REV. NO. 0	PAGE NO. 2 OF 40
DESCRIPTION	PAGE NO.	SUB-PAGE NO.

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PURPOSE/OBJECTIVE

The purpose of this calculation is to develop mathematical models for determining the conductor temperature for cables installed in a conduit or cable tray that is wrapped with a material such as TSI Thermolag®. The validity of the mathematical model is then verified by demonstrating that the conductor temperatures calculated by the model match the conductor temperatures found in industry testing conducted by the Tennessee Valley Authority (TVA) and by Texas Utilities (Comanche Peak).

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METHODOLOGY AND ACCEPTANCE CRITERIA

Methodology for Conduits

The model for conduits uses basic heat transfer relationships outside of the conduit and the Neher-McGrath equations inside the conduit (Ref. 1). The heat dissipated by the cables inside of the conduit is calculated first. Energy balance equations can then be written at each interface or discontinuity in the fire wrap system. The temperature at the interfaces can then be determined so that the amount of heat being transferred across the interface is equal to the amount of heat being generated by the cables.

The first interface is at the surface of the conduit. Heat will be dissipated from the surface of the conduit by radiation and convection. The radiation relationship assumes that the conduit is located in free space, and the area dissipating heat per unit length is equal to the circumference of the wrapped conduit (Equation 8-43a of Reference 2). Convection is calculated using the simplified relationship for a horizontal cylinder in air (Table 7-2 of Reference 2). The resulting non-linear equations are solved using the solve block feature of Mathcad (Reference 3).

The outer layer of fire wrap is treated as a cylindrical shell. The temperature drop can be calculated using Equation 2-8 of Reference 2.

Heat conduction across the air gap between the inner and outer layer of fire wrap is assumed to be by radiation, conduction, and in some cases convection. The heat transferred by radiation is taken into account by treating the two layers of fire wrap material as concentric cylinders (Equation 8-43 of Reference 2). The heat transferred by conduction is calculated by treating the gap as a cylindrical shell. Since the thermal conductivity of air is a function of temperature, a section of the calculation makes a linear interpolation of the conductivity based on data points taken from Reference 2. The conductivity is calculated for the average of the temperatures on either side of the gap. Depending on the size of the gap and the temperature difference, convection may or may not be significant in the air gap. Any convection is taken into account by an adjustment factor to the thermal conductivity of air. This adjustment multiplier is given in Section 7-2, Equations 7-49 and 7-60, and Table 7-3 of Reference 2. The Prandtl number and the kinematic viscosity of air are non-linear functions of the temperature. Cubic splines are used to perform interpolations of the values of these quantities taken from Table A-5 of Reference 2. The function for the adjustment of the conductivity of air is placed in an "if" statement so that its minimum value is 1 (no additional heat transfer due to convection). A Mathcad solve block is used to solve the heat transfer equations at the gap.

The temperature drop across the inner layer of fire wrap material is calculated in the same way that the temperature drop was calculated across the outer layer of fire wrap material. The temperature drop across the gap between the conduit and the inner layer of fire wrap material is calculated in the same manner as was used for the air gap between the inner and outer layers of fire wrap material. In cases where there is no gap between the conduit and the fire wrap or where there is only a single layer of fire wrap material, the gap between the conduit and the inner layer of fire wrap material or the gap between the inner and outer layers of fire wrap material can be made infinitesimally small.

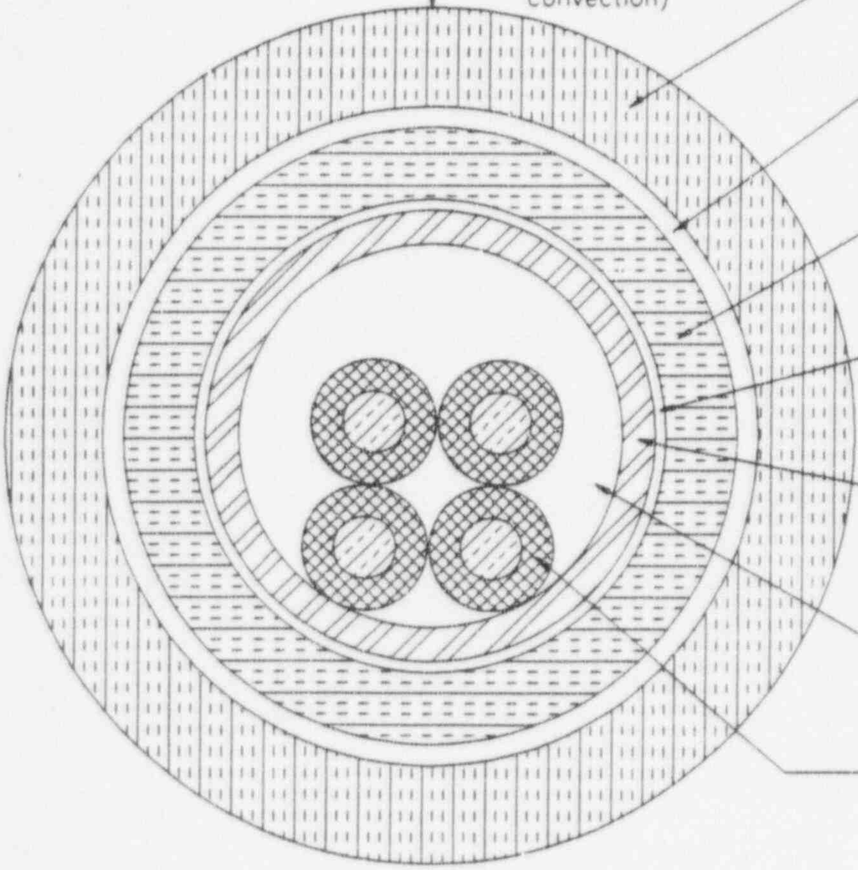
The temperature drop across the conduit is calculated by treating the conduit as a cylindrical shell.

The temperature drop in the gap between the outside of the cable and the inner wall of the conduit is calculated using Equation 41A of Reference 1. This equation is partly based on experimental data. Since the cable rests on the bottom of the conduit, an analysis of this temperature drop based on simple heat transfer theory is not possible. The circumscribed diameter of the conductors can be calculated by trigonometry, and the numeric value of the multiplier is tabulated in Table 1 on page 80 of Reference 4.

The temperature rise through the insulation is calculated using Equation 39 of Reference 1. The coefficient of 0.00522 used in this equation includes various unit conversion factors. Since the Mathcad calculation uses consistent units, the appropriate coefficient is $\frac{1}{2\pi}$. Because of the presence of the other three conductors of the

four conductor bundle, a geometric factor from Figure 2 of Reference 5 is used, as recommended in Reference 1.

The various temperature drops are summarized in the following figure:



Methodology for Cable Trays

The model for cable trays is similar to the model for conduits from the surface of the fire wrap to the surface of the cable mass. The cables in the tray are modeled as a cable mass using Stolpe's method (Reference 6). The heat generated by the cables in the tray is first calculated. Energy balance equations are then developed at each interface or discontinuity in the fire wrap system. The temperatures at the interfaces are calculated so that the amount of heat transmitted across the interface is equal to the heat generated by the cables.

Heat is dissipated at the interface between the outside of the fire wrap and the ambient by convection and radiation. The outer surface of the fire wrap is treated as an isothermal surface. The radiation relationship

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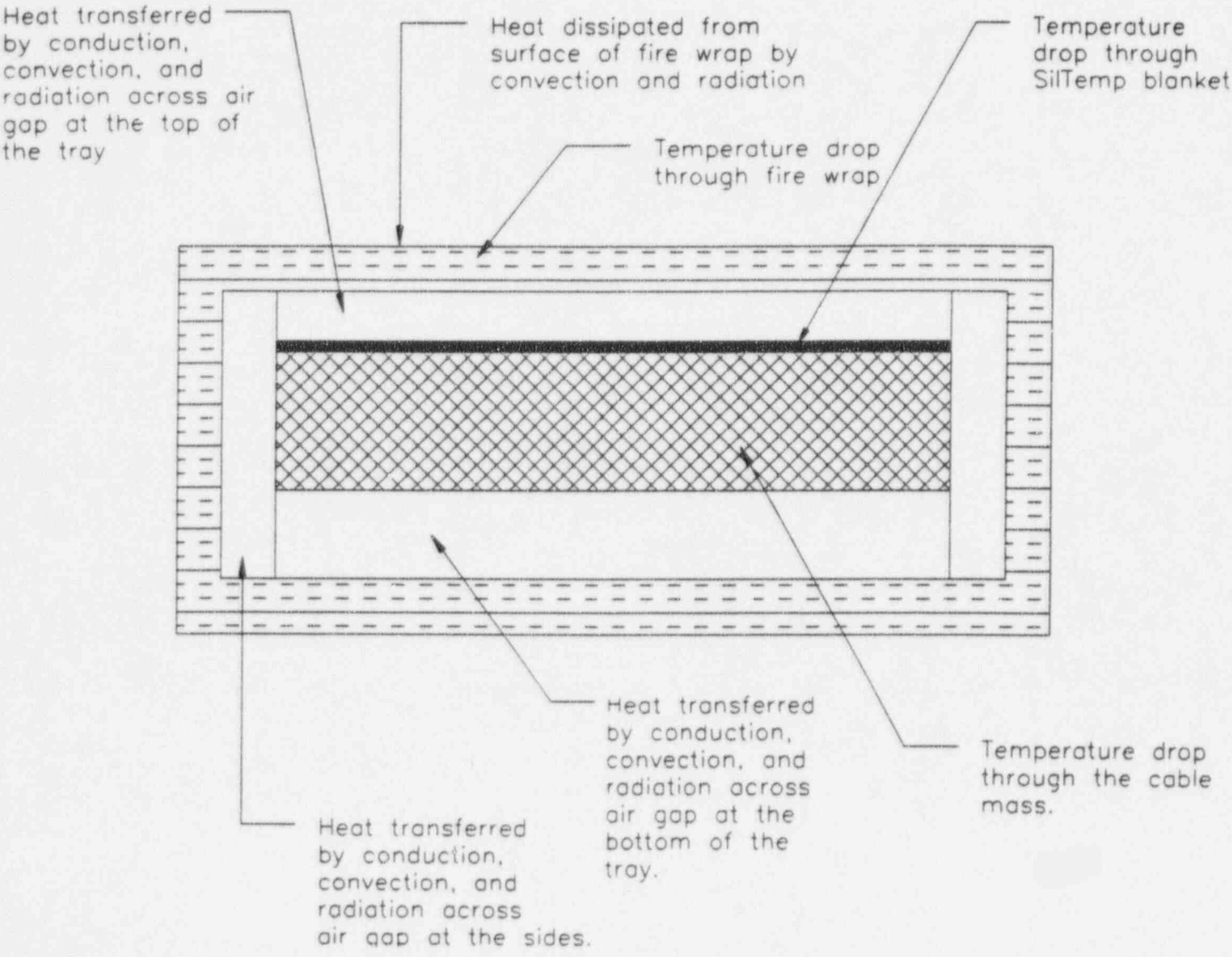
assumes that the cable tray is located in free space and the area dissipating heat is equal to the circumference of the fire wrap (Equation 8-43a of Reference 2). Convection is calculated for the top, bottom, and sides of the fire wrap using the simplified expressions for heated plates in air (Table 7-2 of Reference 2). The resulting non-linear equations are solved using the solve block feature of Mathcad (Reference 3).

The layer of fire wrap is treated as flat plates on each side of the fire wrap enclosure, with the inner surface of the fire wrap also treated as an isothermal surface (Equation 2-1 of Reference 2). In calculating the size of the plates, the inside dimensions of the fire wrap are used for conservatism. (In effect, the material in the corners of the "box" of fire wrap material are ignored.) The temperature drop through the layer of fire wrap material is calculated so that the amount of heat transmitted through the fire wrap material is equal to the heat generated by the cables. The temperature of the inside surface of the fire wrap can then be calculated from the temperature of the outside surface of the fire wrap calculated in the previous step and the temperature drop through the fire wrap.

Heat transfer between the outer surface of the cable mass and the inside of the fire wrap material is primarily by radiation and conduction. Under some circumstances conduction may be augmented by convection. The exposed surface of the cable mass along with the sides and bottom of the cable tray are treated as another isothermal surface. Another assumption that is made in the calculation of heat transfer by radiation is that all heat radiated from the cable mass and associated surfaces reaches the inside of the cable wrap. Therefore, the view factors are only functions of the area of the surfaces and the emissivities, and are not sensitive to the details of the configuration. In the test configuration, a sheet of SilTemp glass fiber cloth was laid on top of the cable mass. The temperature drop through this blanket is taken into account in calculating the heat being dissipated from the top of the cable tray and calculating the temperature drop of the SilTemp blanket. The basic method used is to calculate cable mass temperature required to transfer an amount of heat to the inside of the fire wrap material by conduction and radiation. The linear and non-linear equations are solved using the solve block feature of Mathcad. The conductivity of air is determined by linear interpolation using the average of the temperatures of the cable mass and the inside of the fire wrap material. Convection (if any) is taken into account by adjusting the thermal conductivity of air, as was done for the conduit temperature calculation. The kinematic viscosity and the Prandtl number of air are determined by interpolating data using cubic splines. These quantities are evaluated at the average of the surface temperature and the temperature at the inside of the fire wrap. The expression for the conductivity adjustment checks to see if the product of the Grashof and Prandtl numbers is high enough for the expression to be valid. Also, the minimum value of the conductivity adjustment is forced to be 1. In order to solve the equations, the surface temperature of the cable mass is written as a function of the surface temperature of the SilTemp blanket. As a result, the solve block only needs to solve for one unknown. The surface temperature of the cable mass can then be solved by back substitution.

The temperature drop through the cable mass is calculated using Equation 5 of Reference 6, which is equivalent to Equation 2-23 of Reference 2. The conductor temperature is then calculated by adding the temperature rise in the cable mass to the surface temperature of the cable mass.

The various components of the model can be summarized as follows:



Acceptance Criterion

The calculated conductor temperature should agree to within 3 K (3 °C) of the conductor temperature obtained by test.

ASSUMPTIONS

None

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DESIGN INPUT

Conduit Test

1. The test was of 4-750 MCM cables in a 4 inch (trade size) conduit (Reference 7)

2. The cables used in the test were Rockbestos 1/C, 750 MCM, with XLPE insulation and CSPE jackets (Reference 7, page 4).

3. The thickness of the cable insulation is 80 mils and the thickness of the cable jacket is 65 mils (Reference 8, pages UP-7 and UP-8)

4. The thermal resistivity of "rubber-like" insulation is 500 °C·cm·W^{-1} (5 K·m·W^{-1}) (Reference 9, page III)

5. The inside diameter of a 4" conduit is 4.05 inches and its outside diameter is 4.5 inches. (Reference 10, Table 2, page 5)

6. The emissivity of a galvanized steel surface is 0.33 (Reference 11, Page 17)

7. The thermal conductivity of Thermolag is 0.1 BTU·hr^{-1}·ft^{-1}·R^{-1}. The emissivity of Thermolag is 0.3–0.45 (Reference 12)

8. The thermal conductivity of a steel conduit is 2.08 °C·cm·W^{-1} (Reference 13)

9. The conduit was wrapped with a 3/8" (nominal) and a 5/8" (nominal) layer of Thermolag. The overall circumference of the completed assembly was 22.51" (Reference 7, pages 1, 2, 3, C-1, D-11, and I-2)

10. The Thermolag sections are coated with trowel grade Thermolag to fill any gaps between the conduit and the inner layer of Thermolag and between the two Thermolag layers. (Reference 7, page 4)

11. The test current was 431.52 amperes (Reference 7, pages F-6 and I-2)

12. The ambient temperature was 40.3 °C (Reference 7, pages F-6 and I-2)

13. The conductor temperature is 91.4 °C (Reference 7, pages F-6 and I-2)

14. The surface temperature of the fire wrap was 47.95–48.75 °C (Reference 7, page I-4)

15. The value of the Stefan-Boltzmann constant is 5.6697 10^{-8} W·m^{3}·K^{-4} (Reference 14, page F-158)

16. The characteristics of Air are as follows (Reference 2, Table A-5):

Temperature (K)	Thermal Conductivity, k (W·m^{-1}·K^{-1})	Kinematic Viscosity, (m^{2}·s^{-1})	Prandtl Number, Pr
300	0.02624	16.84 10^{-6}	0.708
350	0.03003	20.76 10^{-6}	0.697
400	0.03365	25.90 10^{-6}	0.689

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Temperature (K)	Thermal Conductivity, k ($W \cdot m^{-1} \cdot K^{-1}$)	Kinematic Viscosity, ($m^2 \cdot s^{-1}$)	Prandtl Number, Pr
450	0.03707	$31.71\ 10^{-6}$	0.683

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17. The geometric factors for calculating the temperature drop through the cable insulation are as follows (Reference 5):

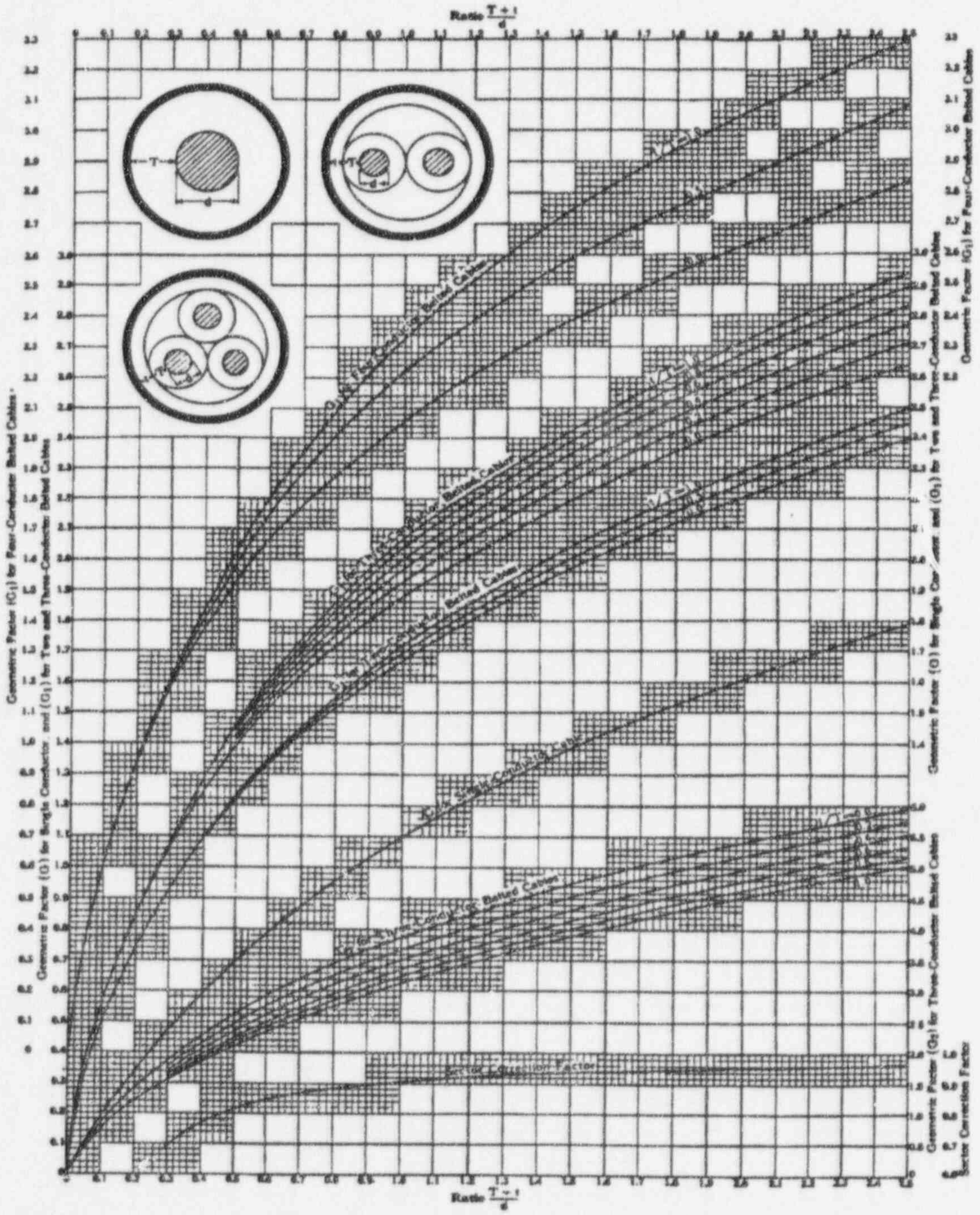


Fig. 2—Geometric factors for single-conductor cable and multi-conductor belted cable with round or sector conductors

Geometric factors can be obtained by calculating the ratios $(T + t)/d$ and t/T (d being defined for sector cables as the diameter of a round conductor of the same area as the sector), and then reading the required value of geometric factor from a curve above. The value thus obtained will be the correct geometric factor for a round-conductor cable. For sector conductors the values so obtained should be multiplied by the sector correction factor. In cables of the non-type H form without belts, such as multi-conductor rubber cables, the ratio becomes T/d, and $t/T = 0$.

18. The resistance of a 750 MCM copper conductor at 90°C is 0.00187 $10^{-2}\ \Omega \cdot ft^{-1}$. The conductor diameter is 0.998". (Reference 15)

Cable Tray Test

19. The cable tray was covered with ½" minimum (" ± ") Thermolag panels (Reference 16, pages 9–10). Also, see Reference 7 , page 1 for an explanation of the dimension tolerances on Thermolag material.

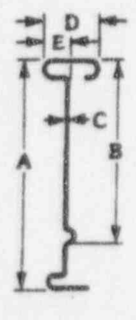
20. A skim coat, approximately 1/16" thick, of trowel grade Thermolag was applied where the corners of the Thermolag enclosure was reinforced. Additional material was also applied where sections of the Thermolag panels were spliced together (Reference 16. Page 10).

21. The cable tray is filled with 126 lengths of 3/C, #6 AWG, 600 V cable to a depth of fill of 2.95". The cable had cross-linked polyethylene insulation and a polyvinyl chloride jacket. (Reference 16, pages 8, 20, and 22)

22. The cable tray is a B-Line Model 248P0924144. This is a 24" wide ladder-type cable tray with rungs spaced 9" apart. (Reference 16, Page 4).

23. The configuration of the tray rail is as follows (Reference 17):

Steel



A—Overall Depth
B—Loading Depth
C—Web Thickness
D—Flange Width

B-Line Series	Nominal Depth	A (in.)	B (in.)	C (in.)	D (in.)	E (in.)	Sx (in.³)	Ix (in.⁴)	D.S. (psi) S.F. 2	Area (in.²)	Weight (lbs./ft.)	Page No.
248	4	4.188	3.14	048	1.00	392	36	67	25.000	313	1.17	38
346	4	4.188	3.13	.060	1.50	655	58	1.02	22.400	449	1.64	38
444	4	4.188	3.11	075	1.50	67	73	1.28	30.000	561	2.02	38
258	5	5.188	4.14	.048	1.00	392	49	[illegible]	18.500	.361	1.34	40
356	5	5.188	4.13	.060	1.50	6.	[illegible]	1.76	20.500	509	1.86	40
454	5	5.188	4.11	.075	1.50	67	[illegible]	2.19	27.500	636	2.29	40
268	6	6.188	5.14	.048	1.00	392	57	1.70	16.000	409	1.52	42
368	6	6.188	5.13	048	1.50	643	82	2.19	17.000	457	1.70	42
366	6	6.188	5.16	.060	1.50	655	[illegible]	2.74	17.000	569	2.08	44
464	6	6.188	5.11	075	1.50	67	1.27	3.42	25.000	711	2.56	44
378	7	7.188	6.14	.048	1.50	643	94	2.98	15.500	505	1.88	46
476	7	7.188	6.13	.060	1.50	655	1.18	3.74	18.800	629	2.30	46
574	7	7.188	6.11	.075	1.50	67	1.47	4.67	22.500	792	[illegible]	46

Design Factors: Ix = Moment of Inertia, Sx = Section Modulus, DS = Design Stress

2

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Total height of tray rails, including rungs: 4.188"
Height of tray available for cables: 3.14"
Gap as side of tray formed by the tray rails: 0.344"

24. The tray rungs are 1.5 inches wide. (Reference 17):

Ladder Type Rungs

RUNG TYPE	DESIGN FACTORS	SAFETY FACTOR	SINGLE RUNG LOAD CAPACITY (IN LBS.) TRAY WIDTH 6	9	12	18	24	30	36
A (1.50", 1.00", 1.50") Aluminum	Ix = .0361 in^4 Sx = .0707 in^3 DS = 15.000 psi. (for S.F. 2.0)	1.5	2856	1845	1356	882	660		
	DS = 20.000 psi. (for S.F. 1.5)	2.0	2146	1383	1017	661	495		
B (1.50", 1.00", 1.50") Aluminum	Ix = .0432 in^4 Sx = .0877 in^3 DS = 15.000 psi. (for S.F. 2.0)	1.5						661	540
	DS = 20.000 psi. (for S.F. 1.5)	2.0						488	406
A (1.00", 1.00", 1.50") Steel	Ix = .0249 in^4 Sx = .0628 in^3 DS = 20.000 psi. (for S.F. 2.0)	1	2703	1769	1314	868	647		
	DS = 26.700 psi. (for S.F. 1.5)	2.0	2027	1327	985	651	485		
B (1.00", 1.00", 1.50") Steel	Ix = .0312 in^4 Sx = .0661 in^3 DS = 20.000 psi. (for S.F. 2.0)	1.5						646	537
	DS = 26.700 psi. (for S.F. 1.5)	2.0						484	403
B44AL (1") Aluminum	Ix = .044 in^4 Sx = .077 in^3 DS = 10.000 psi. (for S.F. 2.0)	1.5	2100	1355	998	653	485	386	320
	DS = 13.333 psi. (for S.F. 1.5)	2.0	1575	1016	743	490	364	290	240
B44 (1") Steel	Ix = .044 in^4 Sx = .077 in^3 DS = 25.000 psi. (for S.F. 2.0)	1.5	4992	3267	2427	1602	1196	954	793
	DS = 33.333 psi. (for S.F. 1.5)	2.0	3744	2450	1820	1201	897	715	595

"A" rungs used for trays 6" through 24" wide. "B" rungs used for trays 30" and 36" wide.

25. The emissivity of cable jackets is 0.95. (Reference 11, page 17)

26. The thermal resistivity of the cable mass in a cable tray is 400 °C·cm·W^{-1}. (Reference 6, page 964)

27. The cable mass is covered with a sheet of SilTemp® glass fiber cloth (Reference 16, page 682)

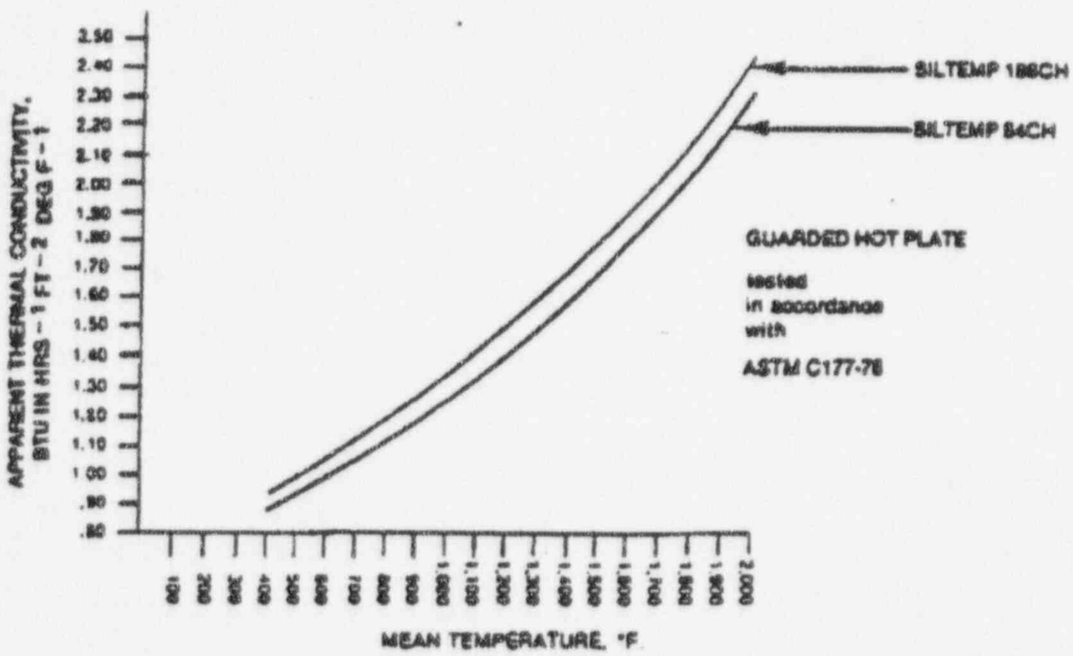
28. SilTemp® is essentially silicon dioxide (quartz or glass). (Reference 18)

29. SilTemp® 188CH cloth is 0.054" thick (Reference 18)

30. The emissivity of glass (silicon dioxide) is 0.94. (Reference 2, Table A-10)

31. The thermal conductivity of SilTemp® is as follows (Reference 19):

TYPICAL APPARENT THERMAL CONDUCTIVITY



Based on the above, use a value of thermal conductivity of 0.8 BTU·in·hr^{-1}·ft^{-2}·°F^{-1}.

32. The resistance of a #6 AWG conductor is 0.0513 10^{-2} Ω·ft^{-1} at 90 °C. The conductor diameter is 0.184". (Reference 15).

33. The ambient temperature is 39.9 °C (Reference 16, page 11).

34. The test current is 15.9 amperes (Reference 16, page 11).

35. The measured conductor temperature is 90.3 °C (Reference 16, page 11).

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REFERENCES

1. Neher, J. H. and Mc Grath, M. H. 1957. The Calculation of the Temperature Rise and Load Capability of Cable Systems. *AIEE Transactions*, Part III Power Apparatus and Systems 76 (October):752-772.

2. Holman, J. P. 1981. *Heat Transfer*. (5th Edition, 4th printing, 1983) New York and Tokyo: McGraw-Hill Kogakusha, Ltd.

3. Mathsoft, Inc. 1993. *Mathcad 4.0 User's Guide*. Cambridge, Massachusetts: Mathsoft, Inc.

4. Horton, H. L.; Schubert, P. B.; and Garratt, G. (ed.) 1973 *Machinery's Handbook* (19th Edition). New York: Industrial Press, Inc.

5. Simmons, D. M. 1932. Calculation of the Electrical Problems of Underground Cables. *The Electric Journal*. (May-November).

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

7. Rutledge, C. L. and Deviney, F. A. 1993. *Final Report – Testing to Determine Ampacity Derating Factors for Fire Protected Cables for Watts Bar Nuclear Plant*. Chattanooga, Tennessee: Tennessee Valley Authority Central Laboratory Service (TVA-CLS).

8. The Rockbestos Co. 1989. Catalogue for Firewall III-J Cable, Specification RSS-3-021.

9. Insulated Power Cable Engineers Association (IPCEA) 1962. *Power Cable Ampacities, Volume I – Copper Conductors* (AIEE Publication S-135-1 / IPCEA Publication P-46-426). New York: American Institute of Electrical Engineers (AIEE).

10. National Electrical Manufacturers Association (NEMA) 1990. *American National Standard for Rigid Steel Conduit – Zinc Coated* (ANSI Standard C80.1). New York: American National Standards Institute, Inc.

11. Insulated Cable Engineers Association (ICEA) 1986. *Ampacities of Cables in Open-Top Cable Trays*. (ICEA Publication P-54-440 / NEMA Publication WC-51). Washington, D. C.: National Electrical Manufacturers Association.

12. Q/A Calculation 0020-EAD-1, "Check for Ampacity Derating for TSI's 3-Hour Fire Barrier Used on Trays", Revision 0, and prepared on May 8, 1984 by G. A. Poletto.

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

14. Weast, R. C. (Ed.) 1967. *Handbook of Chemistry and Physics*. Cleveland, Ohio: The Chemical Rubber Co.

15. Sargent & Lundy Standard ESA-102, dated April 14, 1993.

16. Stansbury, H. W. II; Humphrey, C. A.; and Priest, D. N. 1993. *Ampacity Derating of Fire Protected Cables – Electrical Test to Determine the Ampacity Derating of a Protective Envelope for Class 1E Electrical Cables*. San Antonio, Texas: Omega Point Laboratories.

17. B-Line Systems, Inc. 1984. *Cable Tray Systems.* (Catalogue CT2) Highland, Illinois: B-Line Systems, Inc.

18. Industrial Energy Products, Inc. 1984. Product Bulletin HS-108, "SilTemp Fabric-CH Thermal Barrier". Little Ferry, N. J. : Industrial Energy Products, Inc.

19. Industrial Energy Products, Inc. 1982. Product Bulletin HS-117, "SilTemp Fabric-CH-SR Thermal Barrier". Little Ferry, N. J. : Industrial Energy Products, Inc.

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CALCULATIONS

Model for a Themolag Wrapped Conduit

Cable Data

Cable is 4- 1/C, 750 MCM Rockbestos XLPE-CSPE cable

Conductor Resistance and Diameter

$r_{cab} = 0.00187 \cdot 10^{-2} \cdot ohm \cdot ft^{-1}$ Conductor resistance at 90 °C

$d_{cab} = 0.998 \cdot in$ Conductor diameter

$t_{insul} = 0.08 \cdot in$ Insulation thickness

$t_{jacket} = 0.065 \cdot in$ Jacket thickness

Thermal Resistivities

$\rho_{insul} = 5 \cdot K \cdot m \cdot watt^{-1}$ Insulation

$\rho_{jacket} = 5 \cdot K \cdot m \cdot watt^{-1}$ Jacket

Conduit Data

Inner and Outer Diameters, Thermal Conductivity, and Emissivity

$d_{condi} = 4.05 \cdot in$ Inside diameter of a 4" trade size conduit

$d_{condo} = 4.5 \cdot in$ Outside diameter of a 4" trade size conduit

$\rho_{cond} = 2.08 \cdot K \cdot cm \cdot watt^{-1}$ Conduit thermal conducrivity

$\varepsilon_{cond} = 0.33$ Conduit emissivity

Thermolag Data

Thermal Conductivity

$k_{Thermolag} = 0.1 \cdot BTU \cdot hr^{-1} \cdot ft^{-1} \cdot R^{-1}$

Emissivity is in the range 0.3 to 0.45; use 0.4 based on the range and the relatively low measured surface temperature

$\varepsilon_{Thermolag} = 0.4$

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Thicknesses of Thermolag

Outer Layer

$t_{Tho} = 0.375 \cdot in$ Use nominal thickness for calculation

Inner Layer (calculate from circumference of wrapped conduit of 22.51")

$$t_{Thi} = \frac{22.51 \cdot in}{2 \cdot \pi} - t_{Tho} - \frac{d_{condo}}{2} \qquad t_{Thi} = 0.958 \cdot in$$

Gap Thicknesses

Gap between Conduit and Inner Thermolag Layer

$g_{inner} = 0.000001 \cdot in$

Gap between the Two Thermolag Layers

$g_{outer} = 0.000001 \cdot in$

Since the gaps between the layers of Thermolag were eliminated in the TVA installation, the gap size will be set to an infinitessimal value so that the temperature drop across the "air gap" will be neglegible.

Test Parameters

Test Current

$I = 431.52 \cdot amp$

Ambient Temperature

$T_{amb} = 40.3 \cdot K + 273.16 \cdot K \qquad T_{amb} = 313.46 \cdot K$

Conductor Temperature Determined by Test

$T_{test} = 91.4 \cdot K + 273.16 \cdot K \qquad T_{test} = 364.56 \cdot K$

Miscellaneous Constants

Stefan-Boltzmann Constant

$\sigma = 5.6697 \cdot 10^{-8} \cdot watt \cdot m^{-2} \cdot K^{-4}$

Acceleration due to gravity

$g = 9.8 \cdot m \cdot sec^{-2}$

Conversion factor between degrees Celsius and Kelvin

$CtoK = 273.16 \cdot K$

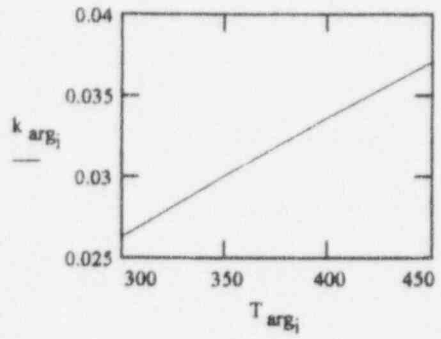
Develop Interpolation Functions for the Characteristics of Air which are Functions of Temperature. These parameters are required for the calculation of heat transfer by conduction and convection in air gaps.

Thermal conductivity of air

$$T_{arg} = \begin{bmatrix} 300 \\ 350 \\ 400 \\ 450 \end{bmatrix} \cdot K \qquad k_{arg} = \begin{bmatrix} 0.02624 \\ 0.03003 \\ 0.03365 \\ 0.03707 \end{bmatrix} \cdot watt \cdot m^{-1} \cdot K^{-1}$$

Lookup tables of temperature and thermal conductivity (Table A-5 of Ref. 2)

$i = 0..3$



Since the variation of the conductivity with temperature is nearly linear, the use of linear interpolation is appropriate.

$$k_{air}(T_a, T_b) = \text{linterp}\left(T_{arg}, k_{arg}, \frac{T_a + T_b}{2}\right)$$

Function to find the thermal conductivity of air by linear interpolation of the average of two temperatures

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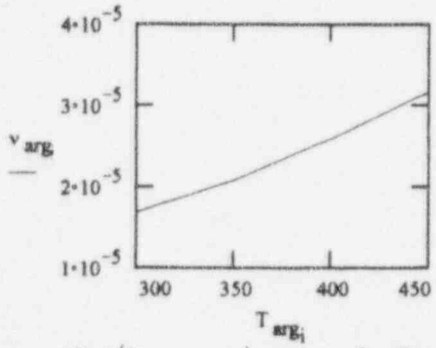
Interpolate to calculate the kinematic viscosity of air

$$\nu_{arg} := \begin{bmatrix} 16.84 \cdot 10^{-6} \\ 20.76 \cdot 10^{-6} \\ 25.9 \cdot 10^{-6} \\ 31.71 \cdot 10^{-6} \end{bmatrix} \cdot m^2 \cdot sec^{-1}$$

Lookup table for kinematic viscosity. The temperatures for these points were defined with the thermal conductivity of air (Table A-5 of Reference 2)



Plot shows that the kinematic viscosity is not a linear function of temperature. Therefore, the use of cubic spline interpolation is appropriate.

$\nu_{aux} := \mathrm{cspline}(T_{arg}, \nu_{arg})$ Auxiliary vector for cubic spline interpolation

$\nu_{air}(T_a, T_b) := \mathrm{interp}\left(\nu_{aux}, T_{arg}, \nu_{arg}, \frac{T_a + T_b}{2}\right)$ Perform cubic spline interpolation for kinematic viscosity

$\beta(T_a, T_b) := \frac{2}{T_a + T_b}$ Volume coefficient of expansion (assuming air behaves as an ideal gas)

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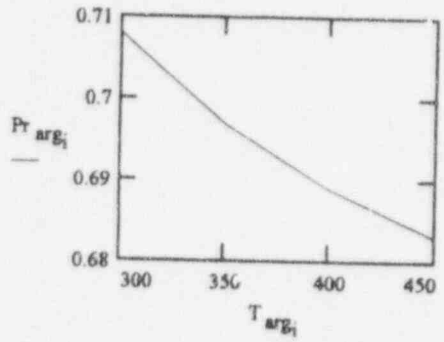
Prandtl Number

$$Pr_{arg} = \begin{bmatrix} 0.708 \\ 0.697 \\ 0.689 \\ 0.683 \end{bmatrix}$$

Data points for lookup table. The corresponding temperature values are shown in the section on the thermal conductivity of air. (Table A-5 of Reference 2)



Since the Prandtl number is a non-linear function of temperature, cubic spline interpolation will be used.

$Pr_{aux} = \mathrm{cspline}(T_{arg}, Pr_{arg})$ Auxiliary vector for cubic spline interpolation

$Pr_{air}(T_a, T_b) = \mathrm{interp}\left(Pr_{aux}, T_{arg}, Pr_{arg}, \frac{T_a + T_b}{2}\right)$ Interpolation function using cubic splines for the Prandtl number

Outer Diameter of Wrapped Conduit

$$d_{assem} = d_{condo} + 2\cdot\left(t_{fno} + g_{outer} + t_{Thi} + g_{inner}\right)$$

$$d_{assem} = 7.165\cdot in$$

Heat Generated by Cables

$$Q_{cab} = 4\cdot I^2\cdot r_{cab} \qquad Q_{cab} = 13.928\cdot watt\cdot ft^{-1}$$

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

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

Heat Dissipated by Convection

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

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

$T_{guess} \coloneqq 330 \cdot K$

Given

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

$T_{outer} \coloneqq \mathrm{Find}(T_{guess})$

$T_{outer} = 325.368 \cdot K$ $T_{outer} - CtoK = 52.208 \cdot K$ °C Surface temperature of the wrapped conduit

Temperature Drop Across the Outer Thermolag Layer

$d_{ITho} \coloneqq d_{condo} + 2 \cdot (t_{Thi} + g_{inner} + g_{outer})$ Inside diameter of layer

$d_{ITho} = 6.415 \cdot in$

$$\Delta T_{Tho} \coloneqq \frac{1}{2 \cdot \pi} \cdot \frac{1}{k_{Thermolag}} \cdot \ln\left(\frac{d_{assem}}{d_{ITho}}\right) \cdot Q_{cab}$$ Where Q_{cab} is in watts per foot

$\Delta T_{Tho} = 4.646 \cdot K$ Temperature drop through the outer Thermolag Layer

Temperature on the Inside of the Outer Thermolag Layer

$T_{ITho} \coloneqq T_{ou[illegible]} + \Delta T_{Tho}$

$T_{ITho} = 33[illegible]015 \cdot K$ $T_{ITho} - 273.16 \cdot K = 56.855 \cdot K$ °C

Grashof Number

$$Gr(T_a, T_b, d_1, d_2) \coloneqq \frac{g \cdot \beta(T_a, T_b) \cdot (T_a - T_b) \cdot (d_2 - d_1)^3}{\nu_{air}(T_a, T_b)^2}$$ Grashof number for a cylindrical space (Equation 7-21 of Reference 2) The Grashof number is a major parameter in determining convection.

Heat Transferred across an Air Gap

Heat Transfer by Conduction

$$Q_{gcond}(T_a, T_b, d_1, d_2) := \frac{2 \cdot \pi \cdot k_{air}(T_a, T_b)}{\ln\left(\frac{d_2}{d_1}\right)} \cdot (T_a - T_b)$$

Function for heat transferred by conduction across a cylindrical shell (Equation 2-8 of Reference 2)

Adjustment of the Heat Transferred by Conduction to Account for Any Convection
The IF function is used to force the minimum value of the adjustment to be 1. (Conduction and convection can't be worse than conduction alone.) The convection correlation is given in Equation 7-60 and Table 7-3 of Reference 2.

$$k_{ratio}(T_a, T_b, d_1, d_2) := 0.11 \cdot \left(Gr(T_a, T_b, d_1, d_2) \cdot Pr_{air}(T_a, T_b)\right)^{0.29}$$

$$kfunc(T_a, T_b, d_1, d_2) := if\left(k_{ratio}(T_a, T_b, d_1, d_2) > 1, k_{ratio}(T_a, T_b, d_1, d_2), 1\right)$$

$$Q_{gconv}(T_a, T_b, d_1, d_2) := Q_{gcond}(T_a, T_b, d_1, d_2) \cdot kfunc(T_a, T_b, d_1, d_2)$$

Heat Transferred by Radiation

$$Q_{grad}(T_a, T_b, d_1, d_2, \varepsilon_1, \varepsilon_2) := \frac{\sigma \cdot \pi \cdot d_1 \left(T_a^4 - T_b^4\right)}{\left[\frac{1}{\varepsilon_1} + \frac{d_1}{d_2} \cdot \left(\frac{1}{\varepsilon_2} - 1\right)\right]}$$

Heat transfer by radiation between concentric cylinders. Since the heat transferred per unit length is desired, circumference is area per unit length. See Equation 8-43 of Reference 2.

Heat Transferred across the Air Gap between the Thermolag Layers

$d_{OThi} := d_{condo} + 2 \cdot (t_{Thi} + g_{inner})$ Outside diameter of the inner layer of Thermolag

$d_{OThi} = 6.415 \cdot in$

Find the temperature of the outside of the inner Thermolag layer

$T_{guess1} := 335 \cdot K$ Initial value for iterative solution.

Given

Heat transferred across the gap equals heat generated by cables.

$Q_{cab} = Q_{gconv}(T_{guess1}, T_{ITho}, d_{OThi}, d_{ITho}) \cdots$ Conduction/convection

$+ Q_{grad}(T_{guess1}, T_{ITho}, d_{OThi}, d_{ITho}, \varepsilon_{Thermolag}, \varepsilon_{Thermolag})$ Radiation

$T_{OThi} := Find(T_{guess1})$

$T_{OThi} = 330.015 \cdot K$ $T_{OThi} - T_{ITho} = 7.952 \cdot 10^{-5} \cdot K$ Temperature drop across gap (neglegible since there is no gap)

Review the relative contribution of the various mechanisms to heat transfer

$Q_{gcond}(T_{OThi}, T_{ITho}, d_{OThi}, d_{ITho}) = 13.928 \cdot watt \cdot ft^{-1}$ Heat transferred by conduction

$Gr(T_{OThi}, T_{ITho}, d_{OThi}, d_{ITho}) \cdot Pr_{air}(T_{OThi}, T_{ITho}) = 0$ Grashof number

$k_{ratio}(T_{OThi}, T_{ITho}, d_{OThi}, d_{ITho}) = 5.716 \cdot 10^{-7}$ Raw multiplier for convection value indicates no convectio

$Q_{gconv}(T_{OThi}, T_{ITho}, d_{OThi}, d_{ITho}) = 13.928 \cdot watt \cdot ft^{-1}$ Conduction / Convection

$Q_{grad}(T_{OThi}, T_{ITho}, d_{OThi}, d_{ITho}, \varepsilon_{Thermolag}, \varepsilon_{Thermolag}) = 2.528 \cdot 10^{-5} \cdot watt \cdot ft^{-1}$ Radiation

Temperature Drop through the Inner Thermolag Layer

$d_{IThi} := d_{condo} + 2 \cdot g_{inner}$ Inside diameter of the inner Thermolag layer

$d_{IThi} = 4.5 \cdot in$

$\Delta T_{Thi} := \frac{1}{2 \cdot \pi} \cdot \frac{1}{k_{Thermolag}} \cdot \ln\left(\frac{d_{OThi}}{d_{IThi}}\right) \cdot Q_{cab}$ Temperature drop (Equation 2-8 of Reference 2)

$\Delta T_{Thi} = 14.9 \cdot K$

$T_{IThi} := T_{OThi} + \Delta T_{Thi}$ Temperature of the inner surface of the inner fire wrap layer

$T_{IThi} = 344.915 \cdot K$

Temperature at the Outer Surface of the Conduit

$T_{guess} := 375 \cdot K$ Initial value for iterative solution

Given

$Q_{cab} = Q_{gconv}(T_{guess}, T_{IThi}, d_{condo}, d_{IThi}) \ldots + Q_{grad}(T_{guess}, T_{IThi}, d_{condo}, d_{IThi}, \varepsilon_{cond}, \varepsilon_{Thermolag})$

The amount of heat transferred across the air gap between the conduit and the inner layer of Thermolag must equal the amount of heat generated by the cables.

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

$T_{condo} = 344.915 \cdot K$ Temperature of the outer surface of the conduit

$T_{condo} - T_{IThi} = 1.09 \cdot 10^{-4} \cdot K$ Since there is no gap in this case, the temperature drop is negligible.

Review the breakdown of how the heat was transferred

$Q_{gcond}(T_{condo}, T_{ITThi}, d_{condo}, d_{ITThi}) = 13.928 \cdot watt \cdot ft^{-1}$ Conduction

$Gr(T_{condo}, T_{ITThi}, d_{condo}, d_{ITThi}) \cdot Pr_{air}(T_{condo}, T_{ITThi}) = 0$ Grashof number

$k_{ratio}(T_{condo}, T_{ITThi}, d_{condo}, d_{ITThi}) = 5.947 \cdot 10^{-7}$ Raw multiplier for convection- value indicates no convection

$Q_{gconv}(T_{condo}, T_{ITThi}, d_{condo}, d_{ITThi}) = 13.928 \cdot watt \cdot ft^{-1}$ Heat transferred by convection

$Q_{grad}(T_{condo}, T_{ITThi}, d_{condo}, d_{ITThi}, \varepsilon_{cond}, \varepsilon_{Thermolag}) = 2.451 \cdot 10^{-5} \cdot watt \cdot ft^{-1}$ Heat transferred by radiation

Temperature Drop through the Conduit

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

$\Delta T_{cond} = 0.016 \cdot K$

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

$T_{condi} = 344.931 \cdot K$ Temperature of the inside wall of the conduit

Temperature Drop through the Air Gap Inside the Conduit

Diameter of a Single Cable

$d_{1cab} = d_{cab} + 2 \cdot (t_{insul} + t_{jacket})$

$d_{1cab} = 1.288 \cdot in$

Circumscribed Diameter of Four Cables

$d_{4cab} = (1 + \sqrt{2}) \cdot d_{1cab}$

$d_{4cab} = 3.11 \cdot in$

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

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

$B' := 0.19 \cdot in$

$\Delta T_{condgap} := \frac{A'}{B' + d_{4cab}} \cdot Q_{cab}$ See Equation 41A of Reference 1

$\Delta T_{condgap} = 13.508 \cdot K$

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

$T_{jacket} = 358.44 \cdot K$

$T_{jacket} - 273.16 \cdot K = 85.28 \cdot K$ (°C)

Geometric Factor for Four Cables

Ratio (t+T)/d

$Ratio_{insul} := \frac{t_{insul} + t_{jacket}}{d_{cab}}$

$Ratio_{insul} = 0.145$

$G_1 := 0.79$ This value is obtained by looking it up on the curve in Reference 5

Temperature Rise through the Cable Insulation and Jacket

$\Delta T_{insul} := \frac{1}{2 \cdot \pi} \cdot \rho_{insul} \cdot G_1 \cdot \frac{Q_{cab}}{4}$ $\frac{Q_{cab}}{4} = 3.482 \cdot watt \cdot ft^{-1}$

$\Delta T_{insul} = 7.182 \cdot K$ Temperature drop through the cable insulation. See Equation 39 of Reference 1

$T_{conductor} := T_{jacket} + \Delta T_{insul}$ Conductor temperature

$T_{conductor} = 365.622 \cdot K$

$T_{conductor} - 273.16 \cdot K = 92.462 \cdot K$ °C

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Model for a Wrapped Cable Tray

Cable Tray Dimensions

$w_{tray} = 24 \cdot in$ Inside width of tray

$h_{tray\_rail} = 4.188 \cdot in$ Total height of tray rails (including rungs)

$h_{tray\_active} = 3.14 \cdot in$ Height of area in tray available for cables

$g_{tray\_side} = 0.344 \cdot in$ Width of gap formed by lip at side of tray

Depth of Fill

$DOF = 2.95 \cdot in$

Dimensions of Thermolag

$t_{wrap} = 0.63 \cdot in$ Thickness of Thermolag; The value of 5/8" nominal (1/2" minimum) is increased slightly due to the buildup of Thermolag at the edges and joints

Emissivity of cable mass

$\varepsilon_{cable\_top} = 0.95$ Cable jackets

$\varepsilon_{steel} = 0.33$ Galvanized steel

$\varepsilon_{cable\_side} = \varepsilon_{steel}$ Emissivity of cable tray rail

$s_{rung} = 9 \cdot in$ Spacing between cable tray rungs

$w_{rung} = 1.5 \cdot in$ Width of rungs

Emissivity of Thermolag Wrap

$\varepsilon_{Thermolag} = 0.4$

$\varepsilon_{wrap\_top} = \varepsilon_{Thermolag}$

$\varepsilon_{wrap\_side} = \varepsilon_{Thermolag}$

$\varepsilon_{wrap\_bottom} = \varepsilon_{Thermolag}$

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Emissivity of the Outside of the Fire Wrap:

$\varepsilon_{out\_wrap} = \varepsilon_{Thermolag}$

Themal Conductivity of Thermolag Wrap

$k_{wrap} = 0.1 \cdot BTU \cdot hr^{-1} \cdot ft^{-1} \cdot R^{-1}$

Chara..eristics of SilTemp

$t_{SilTemp} = 0.054 \cdot in$ Thickness of SilTemp 188CH

$k_{SilTemp} = 0.8 \cdot BTU \cdot hr^{-1} \cdot in \cdot ft^{-2} \cdot R^{-1}$ Thermal conductivity of SilTemp

$\varepsilon_{SilTemp} = 0.94$ Emissivity of glass (chemically almost identical to SilTemp)

Cable Mass Thermal Resistivity

$\rho_{mass} = 400 \cdot K \cdot cm \cdot watt^{-1}$ This is the standard value from the Stolpe paper

$CtoK = 273.16 \cdot K$ Conversion factor between °C and K

Test Conditions

Ambient Temperature

$T_{ambient} = 39.9 \cdot K + CtoK$

$T_{ambient} = 313.06 \cdot K$

Test Current

$I = 15.9 \cdot amp$

Cable Data

$r_{cab} = 0.0513 \cdot 10^{-2} \cdot ohm \cdot ft^{-1}$ Cable is 3/C, #6 AWG, 600V

$n_{cab} = 3$ Three conductor cable

$n_{tray} = 126$ Number of cables in tray

Physical Constants

Stefan-Boltzman Constant

$\sigma = 5.6697 \cdot 10^{-8} \cdot watt \cdot m^{-2} \cdot K^{-4}$

Acceleration due to Gravity

$g = 9.8 \cdot m \cdot sec^{-2}$

Physical Characteristics of Air

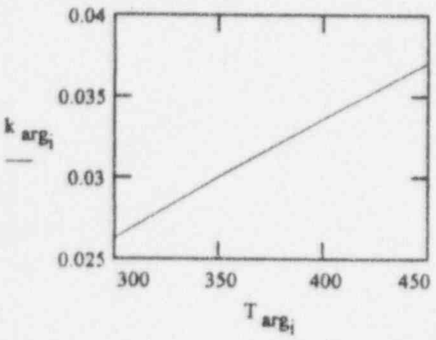
Since the characteristics of air are functions of temperature, and since the temperature is unknown until the calculation is complete, develop interpolation functions that will make the critical characteristics for convection functions ot temperature that can be incorporated into the heat transfer equations and evaluated during the solution.

Thermal conductivity

$$T_{arg} = \begin{bmatrix} 300 \\ 350 \\ 400 \\ 450 \end{bmatrix} \cdot K \qquad k_{arg} = \begin{bmatrix} 0.02624 \\ 0.03003 \\ 0.03365 \\ 0.03707 \end{bmatrix} \cdot watt \cdot m^{-1} \cdot K^{-1}$$

Lookup table of temperature and thermal conductivity (Table A-5 of Reference 2)

$i = 0..3$



Variation of conductivity is nearly linear with temperature

$$k_{air}(T_a, T_b) = \text{linterp}\left(T_{arg}, k_{arg}, \frac{T_a + T_b}{2}\right)$$

Function to find the thermal conductivity of air by linear interpolation of the average of the two temperatures.

Kinematic Viscosity of Air

$$\nu_{arg} = \begin{bmatrix} 16.84 \cdot 10^{-6} \\ 20.76 \cdot 10^{-6} \\ 25.9 \cdot 10^{-6} \\ 31.71 \cdot 10^{-6} \end{bmatrix} \cdot m^2 \cdot sec^{-1}$$

Lookup table for kinematic viscosity. The corresponding temperatures were defined in the section on the thermal conductivity of air. (See Table A-5 of Reference 2)

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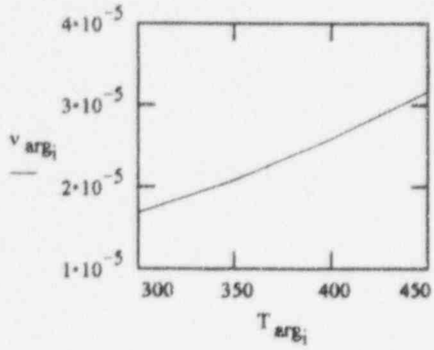


The plot shows that the kinematic viscosity is not a linear function of temperature. Therefore, cubic spline interpolation will be used.

$\nu_{aux} := \mathrm{cspline}(T_{arg}, \nu_{arg})$ Auxiliary vector for cubic spline interpolation

$\nu_{air}(T_a, T_b) := \mathrm{interp}\left(\nu_{aux}, T_{arg}, \nu_{arg}, \frac{T_a + T_b}{2}\right)$ Function to perform cubic spline interpolation to determine the kinematic viscosity of air at the average of two temperatures.

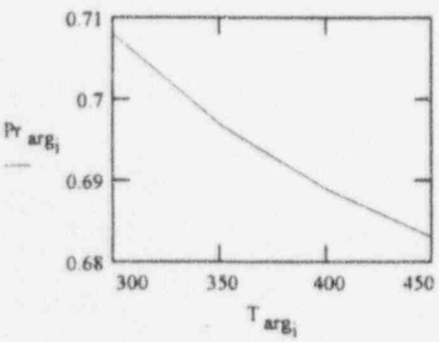
Volume coefficient of expansion

$$\beta(T_a, T_b) := \frac{2}{T_a + T_b}$$

Prandtl Number

$$Pr_{arg} := \begin{bmatrix} 0.708 \\ 0.697 \\ 0.689 \\ 0.683 \end{bmatrix}$$

Data points for the lookup table for the Prandtl number of air. The corresponding temperature values are shown in the section on the thermal conductivity of air. See Table A-5 of Reference 2.



The plot shows that the Prandtl number is not a linear function of temperature, so cubic spline interpolation will be used.

$Pr_{aux} := \mathrm{cspline}(T_{arg}, Pr_{arg})$ Auxiliary vector for cubic spline interpolation

$Pr_{air}(T_a, T_b) := \mathrm{interp}\left(Pr_{aux}, T_{arg}, Pr_{arg}, \frac{T_a + T_b}{2}\right)$ Interpolation for cubic spline interpolati for the Prandtl number

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Gap at bottom of cable tray for rungs

$g_{tray\_bottom} = h_{tray\_rail} - h_{tray\_active}$

$g_{tray\_bottom} = 1.048 \cdot in$

Gap at top of tray between cable mass and Thermolag

$g_{top} = h_{tray\_active} - DOF$

$g_{top} = 0.19 \cdot in$ Part of this gap is taken up by the SilTemp blanket

Miscellaneous Dimensions of the Cable Wrap "Box"

$w_{in\_wrap} = w_{tray} + 2 \cdot g_{tray\_side}$ inside width of Thermolag box

$w_{in\_wrap} = 24.688 \cdot in$

$w_{out\_wrap} = w_{in\_wrap} + 2 \cdot t_{wrap}$ Outside width of Thermolag box

$w_{out\_wrap} = 25.948 \cdot in$

$h_{in\_wrap} = h_{tray\_rail}$ Inside height of Thermolag box

$h_{out\_wrap} = h_{in\_wrap} + 2 \cdot t_{wrap}$ Outside height of Thermolag box

$h_{out\_wrap} = 5.448 \cdot in$

Take a weigted average of the emissivities at the bottom of the tray to account for the cable tray rungs

$$\varepsilon_{cable\_bottom} = \frac{w_{rung} \cdot \varepsilon_{steel} + (s_{rung} - w_{rung}) \cdot \varepsilon_{cable\_top}}{s_{rung}}$$

$\varepsilon_{cable\_bottom} = 0.847$

Heat Generated in Tray

$$Q_{tray} = n_{tray} \cdot n_{cab} \cdot I^2 \cdot r_{cab}$$

$Q_{tray} = 49.023 \cdot watt \cdot ft^{-1}$

Grashof Number

$$Gr(T_a, T_b, gap) = \frac{g \cdot \beta(T_a, T_b) \cdot (T_a - T_b) \cdot (gap)^3}{\nu_{air}(T_a, T_b)^2}$$

Function to calculate the Grashof number for an air gap. The product of the Grashof and Prandtl numbers is a major parameter for convection calculations. See Equation 7-21 of Reference 2.

Function for the product of the Grashof and Prandtl numbers

$$GrPr(T_a, T_b, gap) = Gr(T_a, T_b, gap) \cdot Pr_{air}(T_a, T_b)$$

Calculate an adjustment to the conductivity of air to take convection in the top air gap into account. Since the correlation is only valid for GrPr>1700, check if valid first. See Table 7-2 and Equation 7-60 of Reference 2.

$$k_{ratio\_top}(T_a, T_b, gap) = if\left[GrPr(T_a, T_b, gap) > 1700, 0.059 \cdot (GrPr(T_a, T_b, gap))^{0.4}, 1\right]$$

Conduction plus convection can never be less than conduction alone, so force the adjustment multiplier to be at least 1, representing conduction with no convection.

$$kfunc\_top(T_a, T_b, gap) = if(k_{ratio\_top}(T_a, T_b, gap) > 1, k_{ratio\_top}(T_a, T_b, gap), 1)$$

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Adjustment to the the thermal conductivity of air for the side air gaps to account for convection. Since the correlation is only valid for GrPr > 2000, check first. The development is similar to that for the air gap at the top.

$$k_{ratio\_side}(T_a, T_b, gap) := \text{if}\left[GrPr(T_a, T_b, gap) > 2000, 0.197 \cdot (GrPr(T_a, T_b, gap))^{\frac{1}{4}} \cdot \left(\frac{h_{in\_wrap}}{gap}\right)^{-\frac{1}{9}}, 1\right]$$

Convection plus conduction must transfer at least as much heat as conduction alone, so the minimum value of the adjustment is 1.

$$kfunc\_side(T_a, T_b, gap) := \text{if}(k_{ratio\_side}(T_a, T_b, gap) > 1, k_{ratio\_side}(T_a, T_b, gap), 1)$$

Temperature at the Outside of the Tray Wrap

Heat transferred by radiation as a function of the wrap and ambient temperatures

$$Q_{rad\_wrap}(T_1, T_2) := (2 \cdot h_{out\_wrap} + 2 \cdot w_{out\_wrap}) \cdot \varepsilon_{out\_wrap} \cdot \sigma \cdot (T_1^{\,4} - T_2^{\,4})$$

(Equation 8-43a of Reference 2)

Heat transferred by convection from the outside of the fire wrap as a function of the wrap and ambient temperatures and the dimensions of the surfaces (See Table 7-2 of Reference 2)

$$Q_{conv\_wrap}(T_1, T_2, h, w) := 1.42 \cdot watt \cdot K^{-\frac{5}{4}} \cdot m^{-\frac{7}{4}} \cdot h^{\frac{3}{4}} \cdot (T_1 - T_2)^{\frac{5}{4}} \cdot 2 \ldots \quad \text{Sides}$$

$$+ 1.32 \cdot watt \cdot K^{-\frac{5}{4}} \cdot m^{-\frac{7}{4}} \cdot w^{\frac{3}{4}} \cdot (T_1 - T_2)^{\frac{5}{4}} \ldots \quad \text{Top}$$

$$+ 0.61 \cdot watt \cdot K^{-\frac{6}{5}} \cdot m^{-\frac{8}{5}} \cdot w^{\frac{3}{5}} \cdot (T_1 - T_2)^{\frac{6}{5}} \quad \text{Bottom}$$

Perform iterative solution

$T_{guess} := 325 \cdot K$ Intitial guess of the temperature at the outside of the fire wrap

Given

The heat dissipated by radiation and convection must equal the heat generated by the cables

$$Q_{tray} = Q_{rad\_wrap}(T_{guess}, T_{ambient}) + Q_{conv\_wrap}(T_{guess}, T_{ambient}, h_{out\_wrap}, w_{out\_wrap})$$

$$T_{out\_wrap} := \text{find}(T_{guess})$$

$T_{out\_wrap} = 330.949 \cdot K$ $T_{out\_wrap} - CtoK = 57.789 \cdot K$ °C

Show the breakdown of the amount of heat dissipated by radiation and the amount of heat dissipated by convection

$Q_{rad\_wrap}(T_{out\_wrap}, T_{ambient}) = 26.359 \cdot watt \cdot ft^{-1}$ Radiation

$Q_{conv\_wrap}(T_{out\_wrap}, T_{ambient}, h_{out\_wrap}, w_{out\_wrap}) = 22.664 \cdot watt \cdot ft^{-1}$ Convection

Temperature Drop through the Thermolag Wrap

$$\Delta T_{wrap} := \frac{Q_{tray} \cdot t_{wrap}}{k_{wrap} \cdot 2 \cdot (w_{in\_wrap} + h_{in\_wrap})}$$

The formula is for conduction through a flat plate with dimensions equal to the inside of the box. For conservatism, the corners of the box are neglected.

$\Delta T_{wrap} = 10.138 \cdot K$

$$T_{in\_wrap} := T_{out\_wrap} + \Delta T_{wrap}$$

$T_{in\_wrap} = 341.086 \cdot K$ $T_{in\_wrap} - CtoK = 67.926 \cdot K$ °C

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Heat Transfer across the Air Gap

Heat Transfer by Radiation

The heat dissipated by radiation will be calculated considering each surface separately. Because the air gap is small compared to the linear dimensions of the tray, the view factor between the surfaces of the tray and the inside of the fire wrap will approach unity. Therefore, the view factors are neglected. Because heat is transferred from the SilTemp sheet rather than the cable mass at the top, the top surface must be treated separately.

$$Q_{rad\_gapb}(T_1,T_2) = \frac{\sigma \cdot w_{tray} \cdot \left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_{cable\_bottom}} + \left(\frac{w_{tray}}{w_{in\_wrap}}\right)\cdot\left(\frac{1}{\varepsilon_{wrap\_bottom}} - 1\right)}$$ Bottom

$$Q_{rad\_gaps}(T_1,T_2) = \frac{\sigma \cdot \left(2 \cdot h_{tray\_rail}\right) \cdot \left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_{cable\_side}} + \left(\frac{h_{tray\_rail}}{h_{in\_wrap}}\right)\cdot\left(\frac{1}{\varepsilon_{wrap\_side}} - 1\right)}$$ Sides

Bottom and sides T_1 is the surface temperature of the cable mass and cable tray (Equation 8-43 of Reference 2)

$$Q_{rad\_gapt}(T_3,T_2) = \frac{\sigma \cdot \left(w_{tray}\right) \cdot \left(T_3^4 - T_2^4\right)}{\frac{1}{\varepsilon_{SilTemp}} + \left(\frac{w_{tray}}{w_{tray}}\right)\cdot\left(\frac{1}{\varepsilon_{wrap\_top}} - 1\right)}$$

Top T_3 is the temperature of the top of the SilTemp sheet

Heat transferred by conduction and convection in the gap

Heat transferred by conduction and convection in the gap at the top of the tray. The gap at the top is reduced by the thickness of the SilTemp sheet.

$$Q_{top}\left(T_3,T_2,g_t,t_S\right) = \frac{w_{tray} \cdot k_{air}\left(T_3,T_2\right)}{g_t - t_S} \cdot kfunc\_top\left[T_3,T_2,\left(g_t - t_S\right)\right] \cdot \left(T_3 - T_2\right)$$

Heat dissipated by conduction and convection in the gaps at the sides of the tray

$$Q_{side}\left(T_1,T_2,g_s\right) = \frac{2 \cdot h_{tray\_rail} \cdot k_{air}\left(T_1,T_2\right)}{g_s} \cdot \left(T_1 - T_2\right) \cdot kfunc\_side\left(T_1,T_2,g_s\right)$$

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Total heat transferred by conduction and convection across the air gap

$$Q_{conv\_gap}(T_1, T_2, T_3, g_t, g_s, g_b, t_S) = Q_{top}(T_3, T_2, g_t, t_S) \cdots$$ Top
$$+Q_{side}(T_1, T_2, g_s) \cdots$$ Sides
$$+\frac{w_{tray} \cdot k_{air}(T_1, T_2)}{g_b} \cdot (T_1 - T_2)$$ Bottom (conduction only)

Thermal resistance of SilTemp Sheet

$$r_S = \frac{t_{SilTemp}}{w_{tray} \cdot k_{SilTemp}}$$

Express the temperature of the cable mass and cable tray in terms of the temperature of the SilTemp sheet. T_g was identified as T_1 in developing the heat transfer functions.

$$T_g(T_{g3}) = T_{g3} + (Q_{rad\_gapt}(T_{g3}, T_{in\_wrap}) + Q_{top}(T_{g3}, T_{in\_wrap}, g_{top}, t_{SilTemp})) \cdot r_S$$

Perform an iterative solution to find the temperature of the cable mass. Initially, the temperature of the top of the SilTemp sheet will be found.

$T_{guess3} = 355 \cdot K$ Initial guess for solution

Given

The amount of heat transferred across the air gap must equal the amount of heat generated by the cable mass

$$Q_{tray} = Q_{rad\_gapb}(T_g(T_{guess3}), T_{in\_wrap}) \cdots$$
$$+Q_{conv\_gap}(T_g(T_{guess3}), T_{in\_wrap}, T_{guess3}, g_{top}, g_{tray\_side}, g_{tray\_bottom}, t_{SilTemp}) \cdots$$
$$+Q_{rad\_gapt}(T_{guess3}, T_{in\_wrap}) + Q_{rad\_gaps}(T_g(T_{guess3}), T_{in\_wrap})$$

$T_{SilTemp} = Find(T_{guess3})$ Temperature of the top surface of the SilTemp sheet

$T_{out\_cab} = T_g(T_{SilTemp})$ Temperature

$T_{SilTemp} = 354.246 \cdot K$ $T_{SilTemp} - CtoK = 81.086 \cdot K$ °C SilTemp surface

$T_{out\_cab} = 356.18 \cdot K$ $T_{out\_cab} - CtoK = 83.02 \cdot K$ °C Cable mass surface

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Show the breakdown of the amount of heat dissipated by radiation and conduction / convection

$Q_{rad\_gapb}(T_{out\_cab}, T_{in\_wrap}) = 10.216 \cdot watt \cdot ft^{-1}$ Radiation from the bottom

$Q_{rad\_gaps}(T_{out\_cab}, T_{in\_wrap}) = 2.077 \cdot watt \cdot ft^{-1}$ Radiation from the sides

$Q_{rad\_gapt}(T_{SilTemp}, T_{in\_wrap}) = 9.093 \cdot watt \cdot ft^{-1}$ Radiation from the top

Conduction and convection

$Q_{conv\_gap}(T_{out\_cab}, T_{in\_wrap}, T_{SilTemp}, g_{top}, g_{tray\_side}, g_{tray\_bottom}, t_{SilTemp}) = 27.637 \cdot watt \cdot ft^{-1}$

$kfunc\_top(T_{out\_cab}, T_{in\_wrap}, g_{top}) = 1$ Value of 1 indicates no convection at top

$kfunc\_side(T_{out\_cab}, T_{in\_wrap}, g_{tray\_side}) = 1$ No convection at the sides, either

Temperature Rise through the Cable Mass

$$\Delta T_{mass} = \frac{Q_{tray}}{w_{tray} \cdot DOF} \cdot DOF^2 \cdot \frac{\rho_{mass}}{8}$$

Equation 5 of Reference 6 (See also Equation 2-23 of Reference 2)

$\Delta T_{mass} = 9.885 \cdot K$

Conductor Temperature

$T_{conductor} = T_{out\_cab} + \Delta T_{mass}$

$T_{conductor} = 366.065 \cdot K$ $T_{conductor} - CtoK = 92.905 \cdot K$ °C

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SUMMARY AND CONCLUSIONS

The models predicted the conductor temperature for the conduit and cable tray test with an accuracy that is within the acceptance criterion:

Installation	Conductor Temperature from Model (°C)	Conductor Temperature by Test (°C)	Difference (°C)
Conduit (TVA)	92.46	91.4	1.06
Cable Tray (TU)	92.90	90.3	2.60

The temperature differences between the models and the test values are within the acceptance criterion.

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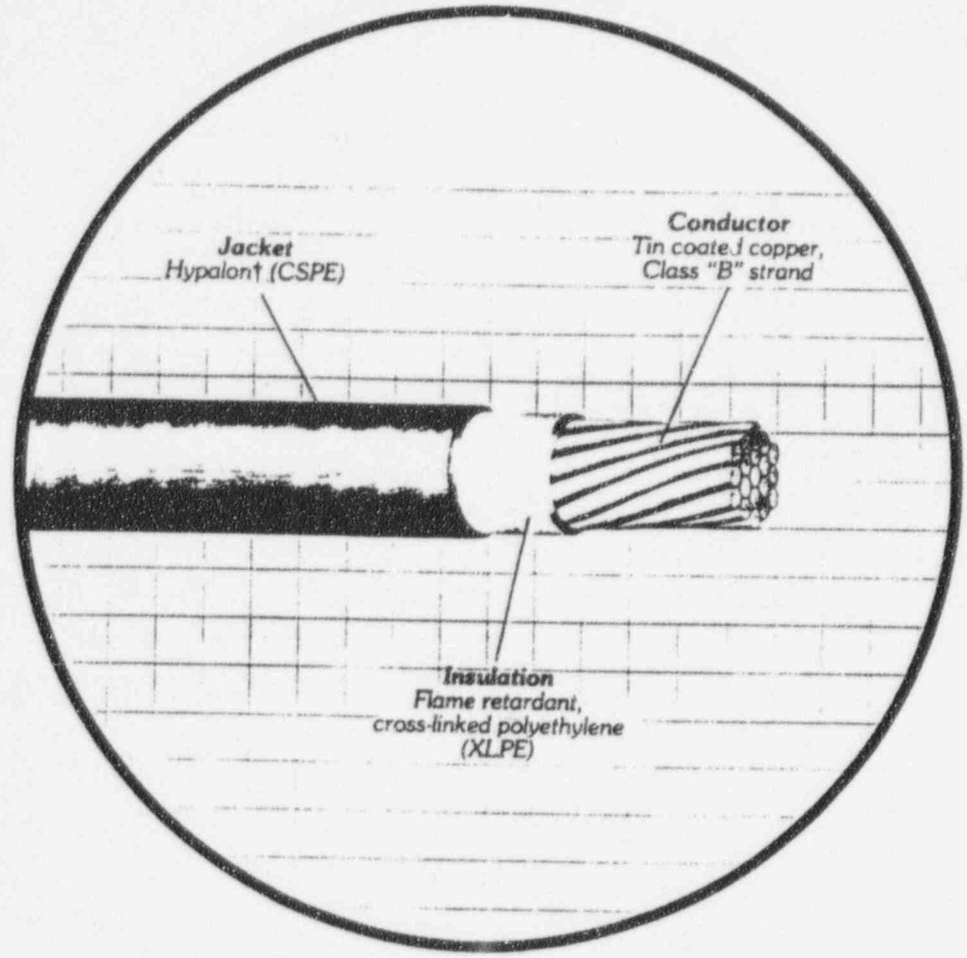
Appendix A— Data on Cable for Conduit Test

Firewall®III-J
Power Cable

(XLPE/CSPE)



90°C, 600 Volt
Class 1E Nuclear

Spec. RSS-3-021

Scope

Firewall®III-J is a jacketed one conductor power cable designed for applications in Utility generating plants and substations. It is intended for use in harsh and demanding environments including Class 1E nuclear applications. It may be installed in trays, ducts, conduits or in direct burial* applications to perform a variety of low voltage power or lighting functions.

Features

- Thermoset insulation and jacket for enhanced thermal stability
- Specially formulated insulation for superior long term water resistance
- Extremely flame retardant
- Nuclear qualified with a minimum 40 year thermal life expectancy at 90°C
- Radiation resistant (up to 200 megarads)
- Full traceability
- Excellent mechanical properties
- Tin coated copper conductors for improved terminations and corrosion resistance
- All singles pass a wet dielectric (tank) test prior to jacket application to verify insulation integrity
- Easy strippability for installation ease

Performance Standards

- Insulation in accordance with ICEA standard S-66-524
- Jackets in accordance with ICEA standard S-19-81 for heavy-duty chlorosulfonated polyethylene (CSPE)
- Class 1E qualified in accordance with IEEE-383 and IEEE-323 (Rockbestos Reports QR-5804 and QR-5805)
- Cable passes IEEE-383 70,000 BTU vertical tray flame test
- Cable passes ICEA 210,000 BTU vertical tray flame test (Standard T-29-520)
- Cable passes the vertical flame tests specified in IEEE-383 Para. 2.5.6 (ICEA S-19-81 Section 6.19.6), ICEA S-66-524 Para. 6.12.5 and UL VW-1
- Quality Assurance program in accordance with 10 CFR 50 Appendix B

Construction

Conductor:

Annealed tin coated copper, Class "B" strand (ASTM B-8 & B-33)

Insulation:

Proprietary heat, moisture and radiation resistant, flame retardant cross-linked polyethylene

Jacket:

Black heavy-duty Hypalon†

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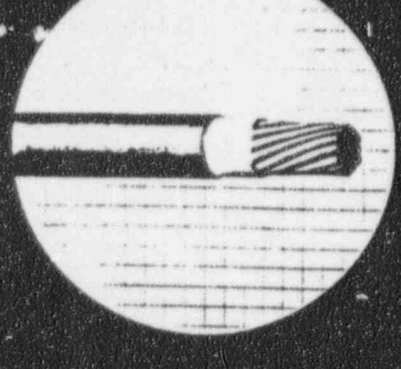
Page A2 of A3



Firewall®III-J
Power Cable
(XLPE/CSPE)

90°C, 600 Volt
Class 1E Nuclear

Spec. RSS-3-021

Product Code	Conductor Size	Number of Strands	Insulation Thickness (Mils)	Jacket Thickness (Mils)	Nominal Overall Diameter (In)	Approximate Net Weight (Lbs/M')
P62-3834	14 AWG	7	30	15	.18	25
P62-3835	12 AWG	7	30	15	.20	35
P62-3922	10 AWG	7	30	15	.22	50
P62-3848	8 AWG	7	45	15	.29	80
P62-3847	6 AWG	7	45	30	.35	125
P62-5090	4 AWG	7	45	30	.40	180
P62-3973	2 AWG	7	45	30	.46	270
P62-5091	1 AWG	19	55	45	.55	360
P62-3902	1/0 AWG	19	55	45	.59	430
P62-3901	2/0 AWG	19	55	45	.63	530
P62-5092	3/0 AWG	19	55	45	.68	650
P62-5093	4/0 AWG	19	55	45	.74	790
P62-3954	250 kcmil	37	65	65	.85	970
P62-3846	350 kcmil	37	65	65	.95	1310
P62-3806	500 kcmil	37	65	65	1.08	1810
P62-5094	750 kcmil	61	80	65	1.31	2690

*Sizes 9 AWG and smaller are not recommended for direct burial in earth.

†Hypalon is a registered trademark for DuPont's chlorosulfonated polyethylene (CSPE).

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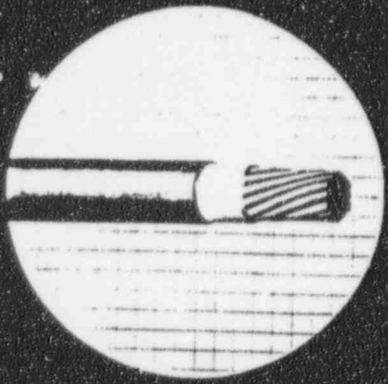
Calc. No. 96-059 / G-70-96-092
Page A3 of A3



Firewall®III-J
Power Cable
(XLPE/CSPE)

90°C, 600 Volt
Class 1E Nuclear

Spec. RSS-3-021

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P62-3848	8 AWG	7	45	15	.29	80
P62-3847	6 AWG	7	45	30	.35	125
P62-5090	4 AWG	7	45	30	.40	180
P62-3973	2 AWG	7	45	30	.46	270
P62-5091	1 AWG	19	55	45	.55	360
P62-3902	1/0 AWG	19	55	45	.59	430
P62-3901	2/0 AWG	19	55	45	.63	530
P62-5092	3/0 AWG	19	55	45	.68	650
P62-5093	4/0 AWG	19	55	45	.74	790
P62-3954	250 kcmil	37	65	65	.85	970
P62-3846	350 kcmil	37	65	65	.95	1310
P62-3806	500 kcmil	37	65	65	1.08	1810
P62-5094	750 kcmil	61	80	65	1.31	2690

*Sizes 9 AWG and smaller are not recommended for direct burial in earth.

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Page A3 of A3

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Appendix B— Data Sheet for SilTemp®

INDUSTRIAL ENERGY PRODUCTS INC.

INDUSTRIAL ENERGY PRODUCTS, INC.
203 Gales Road, Little Ferry, NJ 07643
PHONE: 201-939-6647 FAX: 201-933-1305
201-229-0444 201-229-0404

SILTEMP

FABRIC-CH
THERMAL BARRIER

PRODUCT
BULLETIN HS-108
JANUARY, 1984

CONTAINS NO ASBESTOS

THE ALTERNATIVE TO ASBESTOS CLOTH FOR HIGH-TEMPERATURE INSULATION

DESCRIPTION

SILTEMP™ is a family of flexible silica textiles with excellent break strength and improved abrasion resistance. SILTEMP has been especially developed to replace asbestos cloth in applications where protection against extreme heat is required.

SILTEMP has excellent thermal insulation characteristics over a very wide temperature range and does not melt until temperature exceeds 3,000°F. SILTEMP also offers excellent chemical resistance and electrical insulation properties. Both SILTEMP 84CH and 188CH can be certified to meet military specification MIL-I-24244B on request.

APPLICATIONS

SILTEMP is used primarily in hot work such as welding and burning operations, particularly for replacement of asbestos cloth. It is also useful for thermal and electrical insulation in stress-relieving. SILTEMP can also help conserve energy by reducing heat loss at openings in oven and furnace operations.

AVAILABILITY

SILTEMP is also available as sleeving, mat, tape, and cord.

not often used ↓   current production ↓

TYPICAL PROPERTIES OF SILTEMP 84CH AND 188CH

	SILTEMP 84CH	SILTEMP 188CH
Color	Tan	Tan
Weight, oz./yd.²	18	36
Thickness, in.	.030	.054
Break strength, lbs./in.		
Warp	90	220
Fill	70	170
Silica content, %	>96	>96
Melting temperature, °F	>3,000	>3,000
Roll width, in.	38	38
Roll length, yds.	50	50

Natural glass fiber (amorphous silica finish).

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