UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION
REGARDING AMPACITY DERATING ISSUES
DUQUESNE LIGHT COMPANY
OHIO EDISON COMPANY
THE CLEVELAND ELECTRIC ILLUMINATING COMPANY
THE TOLEDO EDISON COMPANY
BEAVER VALLEY POWER STATION, UNIT NO. 2
DOCKET NO. 50-412

BACKGROUND

By letter dated October 13, 1997, and supplemented by letter dated May 27, 1998, Duquesne Light Company (the licensee) submitted a response to the second NRC Request for Additional Information (RAI) related to Generic Letter (GL) 92-08, "Thermo-Lag 330-1 Fire Barriers," for Beaver Valley Power Station, Unit No. 2 (BVPS-2).

The thermal model described in the licensee's submittal dated October 13, 1997, is based on a methodology utilized by the industry to calculate heat losses from insulated pipes. The model is implemented in two steps. In the first step, the licensee model analyzes the heat transfer behavior from the outer surface of an individual cable out to the ambient environment. The second step involves the evaluation of the heat transfer behavior through the cable jacket and insulation for an individual conductor. The objective of the licensee's thermal model is to estimate the actual ampacity limits for the cables in Thermo-Lag enclosed conduits based on the actual installation characteristics.

The subject NRC staff's RAI had identified a number of open issues and concerns requiring clarification by the licensee. The subject licensee's submittal contained the response to the NRC staff's questions regarding its ampacity derating methodology. A follow-up conference call was held on March 26, 1998, between the NRC staff, its contractor Sandia National Laboratories (SNL), and the licensee to discuss the licensee's response regarding the disposition of the overloaded cables in conduits 2CL213ND and 2CL6070E. The NRC staff's evaluation of the ampacity derating methodology for BVPS-2 follows.

EVALUATION

After reviewing the licensee's submittals and SNL Technical Letter Report (see Attachment), the NRC staff agrees with the SNL analyses and conclusions. The ampacity derating analysis questions, the licensee's responses, and the NRC staff's evaluations of the responses follow.

Ampacity Derating Analysis Review

- Question 1

  SNL identified a number of potential concerns regarding the licensee's heat transfer analysis methodology and implementation. SNL recommended that the licensee pursue one of the following options to permit a more comprehensive review and assessment of the licensee's modeling approach:

ENCLOSURE

Option 1 - Continued Reliance on Wetted Perimeter Approach: If the licensee desires to continue its reliance on the partially filled pipe/wetted diameter approach, then additional documentation of the model development and implementation is needed, and the resolution of specific points of apparent error or inconsistency should be addressed as follows:

- Provide, for review, a copy of the Okonite Bulletin EHB-90 as referenced in the licensee's submittal dated March 25, 1997. This document is cited as the basis for the wetted diameter calculation approach.

- Correct or explicitly derive and justify the first term in the denominator of the expression for U_0 appearing near the center of Page 3 of the attachment to the licensee's submittal dated March 25, 1997. This term, associated with heat transfer to and through the conduit itself, appears to be in error, and does not appear to properly account for the reduction in heat transfer rates associated with the partial "wetted diameter" approach.

- Explicitly state the intent of the apparent air interface term appearing in the expression for cable conductor temperature calculation as it appears on Page 5 of the attachment to the licensee's submittal dated March 25, 1997. Explain the consistency of this expression with the stated intent to base the analysis on a "wetted diameter" approach to analysis. If it is the licensee's intent to include an air gap at this stage of analysis, then the selected value of the "film coefficient", 1.65 BTU/hr/ft^2/°F, should be explicitly justified as applicable to this analysis. Alternatively, the air gap should be treated as an annular ring similar to the treatment provided for the conduit-to-fire barrier air gap.

- Explicitly state how the effects of heat transfer within the cable bundle have been addressed in the licensee's model. In particular, discuss how the thermal model includes consideration of heat conduction through to the center of the cable bundle in addition to the thermal effects of the individual conductor insulation and jacket materials.

Option 2 - Implementation of the Buller/Neher Approach: As an alternative, the licensee should consider modification of the thermal model so as to comply with the accepted Buller/Neher (1950 AIEE) approach to analysis of cable bundle to conduit heat transfer behavior. This would require that the second step of the licensee's analysis model be replaced by an implementation of the Buller/Neher correlations for hot-spot to conduit thermal resistance factors. In particular, Buller/Neher's Equation 1 is recommended for use. This option would also require that the discrepancy regarding the equation for U_0 as it appears at the center of Page 3 of the attachment be addressed.

Option 3 - Implementation of a Conservative Air Gap Approach: As an alternative the licensee might consider implementation of a conservative approach to conduit-to-cable heat transfer in which the cable bundle and conduit are separated by an annular air gap, and heat transfer within the bundle is treated based on simplified correlations for the temperature at the center of a cylinder with uniform heating. Holman's *Heat Transfer* (1976) provides such an expression as Equation 2-25, and Stolpe (1957 AIEE) provides an estimate of cable bundle conductivity appropriate for such an application. This option would also require that the discrepancy regarding the equation for U_0 as it appears at the center of Page 3 of the attachment be addressed.

The concerns addressed by the above comments and options are primarily associated with the heat transfer behavior internal to the conduit. In addition to these concerns, there is one additional point of concern that would be relevant to all three of these options:

- With regard to the treatment of external system heat transfer, SNL finds that the licensee has not established a basis for the cited "ambient air film coefficient" for exchange between the outer surface of the fire barrier and the ambient environment (a uniform value of 1.65 BTU/hr-sq.ft.-deg F has been cited in the example analyses). The licensee is requested to explain the intent of this factor, to explicitly state how it was derived, and to discuss its relevance to the conduits and fire barrier systems under consideration in this analysis specifically, the physical size of the system, the driving temperature difference, and the surface emissivity.

In conclusion, the licensee is requested to consider the adoption of one of the above options in order to achieve closure on the concerns identified or propose an alternate approach which addresses the thermal modeling issues. (See Sections 2.1 and 2.2 of the SNL Letter Report dated July 18, 1997, for further details).

Licensee's Response

In its submittal dated October 13, 1997, the licensee stated that the wetted perimeter approach has been abandoned in favor of an alternate approach based on analysis of the standard ampacity tables and included a detailed description of the revised method.

NRC Staff's Response

The information provided by the licensee fully resolves the NRC staff's concerns (see our conclusion below).

Question 2

SNL made the following comments regarding the licensee's validation case study:

- SNL finds that the licensee has incorrectly cited the test results (i.e., measured clad case ampacity) from the Texas Utilities Electric (TUE) test program, and has incorrectly set the fire barrier thickness to 1/4" as compared to the actual tested value of ½" nominal. The results of this case analysis appear conservative but are uncertain. The licensee is requested to correct its analysis to address the apparent errors.

SNL had the following comments regarding the two plant applicable example cases:

- Both case examples appear to have resulted in very conservative estimates of cable ampacity limits. However, given the apparent errors in approach and implementation, SNL views these results with some skepticism.

- In the case of conduit 2CL6070D the information provided in the calculation is not consistent with the information provided in the licensee's application summary table in regard to the conductor count for the three #4AWG cables. The calculation cites that these are 4-conductor cables whereas the table indicates that they are of a 3-conductor configuration (size and conductor count may have been confused in the calculation). This apparent error has compromised the calculation by artificially increasing the estimated heat load.

The licensee is requested to reconsider its validation and example case calculations in light of the specific SNL findings and the thermal modeling concerns identified in Question 1 above. (See Sections 2.3 and 2.4 of the SNL Letter Report dated July 18, 1997, for further details).

Licensee's Response

In its submittal dated October 13, 1997, the licensee stated that: (1) the revised model has been validated against the TUE and Tennessee Valley Authority (TVA) test results; and (2) a detailed description of the cable fill for the subject conduit was provided in the subject submittal for NRC staff review.

NRC Staff's Response

The information provided by the licensee fully resolves the NRC staff's concerns (see our conclusion below).

Question 3

After a review of the licensee's application summary table which was provided in the submittal of March 25, 1997, SNL finds that the ampacity concerns for 24 of the 26 conduits identified have been adequately resolved by the subject documentation. The licensee is requested to provide explicit justification for the ampacity loads for the cables in the remaining two conduits for which an adequate ampacity margin had not yet been demonstrated; namely, electrical raceways 2CL213ND and 2CL6070E which were cited in the subject summary table. (See Section 3.3 of the SNL Letter Report dated July 18, 1997, for further details).

Licensee's Response

In its submittal dated October 13, 1997, the licensee provided the following response:

- 2CL213ND: For this conduit there are five duplex cables present (10 conductors), of which two are nominally identified as severely overloaded (margins of -41% and

-63% respectively). The licensee assessment for this case is based on crediting diversity in the cable loads and on an assessment of the total heat load for the installed cables compared to that of the cables at their rated current. On this basis, the licensee concludes that the cable loads are acceptable because the raceway "has sufficient diversity so that overloading of the two cables...is compensated by the underloading of the remaining three cables." A "condition report" has been initiated "to evaluate the remaining life expectancy" for the overloaded cables.

- 2CL607OE: The licensee cites that there are three cables in this conduit of which two are heavily loaded and nominally identified as significantly overloaded (by 20%). The licensee stated that one of the two overloaded cables is actually not normally energized. A re-analysis assuming this cable remains non-energized demonstrated a 2% margin for the other overloaded cable under these conditions. The licensee goes on to cite a heat load comparison as an additional diversity acceptance basis. Finally, the licensee has provided an assessment of the amount of time during the life of the plant that the normally deenergized cable has been energized. This estimate compared favorably to the manufacturer overload conditions and limits. On this basis the licensee concludes that the loads are acceptable. A "condition report" has been initiated "to evaluate the cable life expectancy."

NRC Staff's Response

The information provided by the licensee did not resolve the NRC staff's concerns. The licensee stated that previous field measurements of the cable jacket resistance had not indicated the presence of service life degradation. However, megger test measurements are not sufficient to fully evaluate cable life degradation. During a follow-up conference call held on March 26, 1998, between the NRC staff, its contractor SNL, and licensee representatives to discuss the resolution of the disposition of the overloaded cables in conduits 2CL213ND and 2CL6070E, the licensee agreed to perform additional corrective actions. The licensee documented those future corrective actions in their submittal dated May 27, 1998. This commitment resolves the NRC staff's concerns on this matter.

Application of Ampacity Derating Methodology

The NRC staff finds that the licensee has provided sufficient information to conclude that the alternate approach based on an analysis of the standard ampacity tables as described in its submittal dated October 13, 1997, is fully consistent with good engineering practice. Therefore, the subject methodology is acceptable for the analysis of installed conduit ampacity limits.

In its submittal dated May 27, 1998, the licensee agreed to address the age-related cable degradation concerns for the cables in conduits 2CL213ND and 2CL6070E by taking the following actions:

(1) Take field current measurements of the subject cables and evaluate the impact of normal and transient cable temperature conditions using the methodology in SNL Report SAND96-0344, "Aging Management Guideline for Commercial Nuclear Power Plants - Electrical Cables and Terminations," to evaluate cable service life.

(2) Based upon preliminary results, the licensee will monitor the operating time of heater 2HVS*CH219A to be consistent with the applicable age-related evaluation in order to ensure that operation will not unacceptably degrade the life of the subject cables.

Given these observations and the licensee's commitment described above, the NRC staff finds that the licensee has provided adequate information to resolve the ampacity-related points of concern raised in GL 92-08.

CONCLUSIONS

From the above evaluation, the NRC staff concludes that although the original licensee thermal model was not acceptable for ampacity derating assessments, the revised model identified in its submittal dated October 13, 1997, was appropriate for the analysis of installed conduit ampacity limits. In its submittal dated May 27, 1998, the licensee stated that additional corrective actions will be taken to evaluate and monitor as necessary conditions for the cables in conduits 2CL213ND and 2CL6070E. Therefore, given the licensee commitment to address age-related cable degradation there are no outstanding safety concerns with respect to ampacity. Due to the nature of the issues raised during this review, it is recommended that the subject safety evaluation be used in any follow-up site inspection.

Date: October 1, 1998

A Technical Evaluation of the Beaver Valley Fire Barrier Clad Cable Ampacity Assessments

A Letter Report to the USNRC

Revision 0

January 23, 1998

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ATTACHMENT

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FORWARD

The United States Nuclear Regulatory Commission (USNRC) has solicited the support of Sandia National Laboratories (SNL) in the review of licensee submittals associated with fire protection and electrical engineering. This letter report represents the second report in a series of review reports associated with a set of submittals from the Beaver Valley Power Station Unit 2 (BVPS-2). The submittals under review deal with the assessment of ampacity loads for conduits protected by Thermo-Lag 330-1 fire barriers. This report documents the results of a SNL review of the licensee responses to a USNRC RAI of August 29, 1997. Documentation of these issues was originally submitted by the licensee in response to USNRC Generic Letter 92-08. This work was performed as Task Order 4, Sub-task 2 of USNRC JCN J-2503.

1.0 INTRODUCTION

1.1 Background

This report is the second in a series of technical review reports associated with licensee submittals from the Beaver Valley Power Station (BVPS). The submittals under review are related to the assessment of cable ampacity loads for fire barrier clad cables. For this particular plant all of the cables in question are housed in conduits rather than cable trays. The history of this review effort is summarized as follows:

- March 25, 1997: In response to Generic Letter 92-08 and a subsequent USNRC Request for Additional Information (RAI) of December 1, 1995, the licensee submits documentation of its methodology for the assessment of fire barrier clad cable ampacity limits including a summary of the assessment results.

- July 18, 1997: SNL completes a letter report documenting the results of a technical review of the licencee 3/97 submittal. The findings include significant concerns regarding the licensee thermal model, but also includes a finding that adequate margin was demonstrated for all but two of the cited conduits.

- August 29, 1997: A second RAI is forwarded to the licensee.

- October 13, 1997: The licensee responds to the USNRC RAI of 8/97.

The objective of this report is to document an SNL review and evaluation of this licensee's 10/97 RAI response submittal. The submittal reviewed by SNL is identified as follows:

- Letter, Sushil C. Jain, Duquesne Light Company BVPS, to the USNRC Document Control Desk, October 13, 1997 (with two attachments).

This effort was performed under general technical support contract JCN J-2503, Task Order 4, Sub-task 2.

1.3 Organization of Report

This review has focused primarily on two areas: Section 2 provide an assessment of the licensee's direct RAI responses; Section 3 documents a technical review of the licensee's modified thermal model and analyses. Section 4 summarizes the SNL findings and recommendations. Section 5 identifies referenced documents.

2.0 THE LICENSEE DIRECT RAI RESPONSES

2.1 RAI item 1: Cable-to-Conduit Heat Transfer

Synopsis of the Question: The licensee was asked to justify its application of the "wetted perimeter" approach normally applied to fluid filled pipes to the analysis of a cable filled conduit.

Synopsis of the Licensee Response: The licensee response cites that the wetted perimeter approach has been abandoned in favor of an alternate approach based on analysis of the standard ampacity tables. A detailed description of the revised method is attached to the submittal.

Assessment of the Licensee Response: The licensee implementation of an alternate assessment method effectively renders this RAI item moot. The new method has no direct similarities to the old method. The new method is reviewed in detail in Section 3 below.

Findings and Recommendations: The licensee response has rendered this RAI item moot. No further interactions on this RAI item are recommended.

2.2 RAI Item 2

2.2.1 Item 2a: Validation

Synopsis of the Question: The licensee was requested to provide additional validation of the analysis method using the available industry test data.

Synopsis of the Licensee Response: The licensee response cites that the revised model has been validated against the TUE and TVA test results. Documentation is provided.

Assessment of the Licensee Response: The licensee implementation of a new thermal model has rendered the validation of the original thermal model moot. The new model has been reviewed in detail by SNL as discussed in Section 3 below.

Findings and Recommendations: The validation of the original model is rendered moot by implementation of the new model. No further interactions on this RAI item are recommended.

2.2.2 Item 2b: Cable Fills for Conduit 2CL607OD

Synopsis of the Question: The licensee was asked to clarify the nature of the cable fill for the subject conduit.

Synopsis of the Licensee Response: The licensee has provided a detailed description of the cable fill for the cited conduit.

Assessment of the Licensee Response: The licensee has provided the requested information.

Findings and Recommendations: The licensee response is fully adequate to resolve the identified concerns. No further interactions on this RAI item are recommended.

2.3 RAI Item 3: Ampacity Loads for Conduits 2CL213ND and 2CL607OE

Synopsis of the Question: The licensee was asked to further justify the ampacity loads for cables in the two subject conduits.

Synopsis of the Licensee Response: The licensee has responded as follows for each of the two conduits:

> 2CL213ND: For this conduit there are five duplex cables present (10 conductors), of which two are nominally identified as severely overloaded (margins of -41% and -63% respectively). The licensee assessment for this case is based on crediting diversity in the cable loads and on an assessment of the total heat load for the as-installed cables compared to that of the cables at their rated current. On this basis, the licensee concludes that the cable loads are acceptable because the raceway "has sufficient diversity so that overloading of the two cables .... is compensated by the underloading of the remaining three cables." A "condition report" has been initiated "to evaluate the remaining life expectancy" for the overloaded cables.
>
> 2CL607OE: The licensee cites that there are three cables in this conduit of which two are heavily loaded and nominally identified as significantly overloaded (by 20%). The licensee cites that one of the two overloaded cables is actually not normally energized. A re-analysis assuming this cable remains non-energized demonstrated a 2% margin for the other overloaded cable under these conditions. The licensee goes on to cite a heat load comparison as an additional diversity acceptance basis. Finally, the licensee has provided an assessment of the amount of time during the life of the plant that the normally de-energized cable has been energized. This is compared favorably to the manufacturer overload conditions and limits. On this basis the licensee concludes that the loads are acceptable. A "condition report" has been initiated "to evaluate the cable life expectancy."

Assessment of the Licensee Response

> 2CL213ND: SNL finds the licensee response for this conduit to be inappropriate and unacceptable. The licensee is attempting to credit diversity. While in general this may be appropriate, the manner in which credit is given is not. The licensee assumption that the total heat load is the dominant concern is not correct. This fails to consider the localized effects of ampacity load on a single cable and is not consistent with accepted practice.
>
> SNL submits the following alternate exploration of a diversity credit: First, it should be noted that this conduit is nominally not eligible for a diversity credit as defined by the NEC. This is because NEC requires that any conductor with a

current load of more than 1 ampere be included in the conductor count. Nonetheless, diversity does exist. Four of the conductors do indeed carry very small power loads, less than 20% of the derated ampacity limit. Two additional conductors carry modest loads, about 54% of the derated limit. Indeed, these six conductors represent the larger conductors in the conduit. If we argue that this is equivalent to a 50% diversity in cable loading, then we would be justified in applying the alternate NEC diversity based conductor count correction factors in lieu of the non-diversity based values used by the licensee (even at this point we are on somewhat "shaky ground"). In this case, a correction factor of 0.7 would apply to the baseline ampacities instead of the 0.5 value assumed by the licensee. Given this, the derated ampacity limit, including the 15.7% fire barrier ADF, for the two #6 AWG cables would be 44.3 A (I(clad) = 75 A * 0.7 * 0.843 = 44.3 A). Even given this more generous interpretation, the actual loads exceed this modified limit; for one cable only very slightly (cable 2SCANNL025 at 44.6 A) and for the second cable by a significant margin (cable 2SCANNL026 at 51.5 A).

On this basis SNL finds that the diversity arguments for this conduit are not sufficient to justify the overloaded condition of the cables. It would appear that the two cables cited immediately above are, in fact, loaded beyond their ampacity limits. It is recommended that the USNRC request the licensee to provide some additional remedial actions to resolve these overloads.

2CL607OE: The licensee re-assessment of the conduit assuming the one cable is not energized is an appropriate basis for the re-analysis of this conduit under normal operating conditions. However, the arguments regarding the total heat load under diversity are found by SNL to be inappropriate and SNL recommends that this aspect of the response not be credited by the USNRC. The licensee discussion of the overload operation limits is, in this case, an appropriate consideration. That is, it would appear that the licensee has a firm understanding of both the concerns and the actual operating conditions of the cable. Hence, the extent of the overload conditions can be accurately assessed. Given this, SNL recommends that the reliance on the overload condition is appropriate. SNL recommends that the USNRC follow-up with the licensee to ensure that once the overload limits have been reached, some remedial actions to replace the subject cables is taken. Note that the overload operation will, at the least, apply to both of the nominally overloaded cables as both will be subject to overheating during operation of the normally de-energized cable. Hence, SNL recommends that remedial action for both cables, and a life assessment for the third cable, be requested.

Findings and Recommendations:

SNL finds the licensee resolution for Raceway 2CL213ND is inappropriate and unacceptable. SNL finds that two of the cables in this raceway are, in fact, overloaded. It is recommended that the USNRC ask the licensee for additional remedial actions to resolve these cable overloads.

SNL finds that the interim licensee resolution for the overloaded cables in Raceway 2CL607OE based on the overload conditions of operation has been adequately justified and is acceptable. However, it is also recommended that the USNRC follow-up with the licensee to ensure that remedial actions are taken for all three cables in the conduit once these overload limitations have been reached.

3.0 THE LICENSEE THERMAL MODEL

3.1 Background

The ultimate objective of the licensee thermal model is to estimate the actual ampacity limits for cables in clad conduits based on the actual installation characteristics of the individual conduits and cables. This objective has not changed in the most recent submittal. However, the licensee thermal model used to obtain this objective has been substantially changed in the current submittal as compared to the model originally reviewed by SNL in July of 1997.

The original thermal model documented in the licensee's 3/97 submittal used a rather unique approach based on methods for calculating heat losses from insulated pipes partially filled with liquids; the "wetted perimeter" or "wetted diameter" approach. SNL raised a number of potential concerns regarding the appropriateness and specific implementation of this method in our review of 7/97. The USNRC RAI of 8/97 requested that the licensee address these concerns.

Rather than attempting to correct or further justify the original thermal model, the licensee has chosen to instead implement an entirely different thermal model in its RAI response. The new thermal model is based on a far more conventional approach to thermal modeling. Given the application of an entirely new thermal model, and the abandonment of the original model, all of SNL's previous findings regarding the development, application, and validation of the original licensee model are effectively rendered moot. The modified model has no direct relationship to the previously documented thermal model; hence, SNL has performed a review of the revised model equivalent to the original review performed in July 1997.

3.2 The Modified Thermal Model

The new thermal model documented in the licensee submittal is substantially different from that documented in the original submittal. Indeed, the model was apparently implemented under contract by Duke Engineering and Services (DE&S) and appears virtually identical to the thermal model used by PECO in the analysis of conduit ampacity loads for the Peach Bottom and Limerick plants. The PECO implementation was reviewed in detail by SNL in September 1997.[1]

Based on a review of the thermal model SNL has made the following positive findings:

- The model is based on the application of well documented and widely accepted heat transfer correlations. All of the critical elements of an appropriate conduit analysis have been incorporated including heat transfer within the cable bundle and between the cable bundle and the conduit, heat transfer through the fire

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[1]See SNL letter report of September 23, 1997 entitled "An Initial Review of the Proposed PECO Ampacity Assessment Methodology for Limerick and Peach Bottom"; work performed under Task Order 4 of USNRC JCN J-2503.

barrier system, and heat exchange with the ambient through both convection and radiation. This treatment includes the consideration of an air gap between the conduit and the fire barrier system, the most conservative configuration.

- The thermal model is internally self-consistent in that both the baseline and clad cases are considered using consistent heat transfer treatments.

- The licensee thermal model neglects the temperature drop through the conduit itself. SNL finds this practice to be acceptable because while there will be some temperature drop through the conduit, the actual values will be trivial in comparison to other temperature drops in the system.

- The approach to analysis provides a nominal inherent consistency with accepted practice in the analysis of ampacity limits for the conduits. In particular, the current accepted practice for the analysis of conduits derives from the work of Buller/Neher and Neher/McGrath [1,2] as documented in IPCEA P-46-426 [3]. Of most significance is the treatment of heat transfer internal to the conduit (within the cable bundle and between the cables and the conduit). Under the licensee approach, the standard IPCEA tables of ampacity are analyzed directly to determine the value of this internal thermal resistance in the baseline case analysis. The same value is then applied in the analysis of the clad case as well. This nominally ensures both internal self consistency (as noted directly above) and consistency of the baseline case with the standard ampacity tables.

3.3 Clarification of Case Analysis Approach

SNL did note two specific factors in the treatment of the baseline versus clad case analyses that are important to recognize if one is attempting to reproduce the licensee calculation. The first is quite minor and is related to the treatment of convection. The second is quite important and is related to the assumed conduit emissivity. Both items are identified in the side notes provided in the calculations themselves.

3.3.1 Convection Coefficients

The first point is related to the treatment of convection. The licensee discussion presented in Section A.3.6 of the supporting calculations regarding convection from a conduit (equations A.25 through A.28) implies the equation A.28 will ultimately be used as a conservative bounding correlation for both horizontal and vertical conduits. This equation derives from Equation A.27 with the coefficients 'a' and 'n' set to 0.2 and 1/4 respectively. Indeed, this does prove true for the treatment of the clad case. However, in the treatment of the baseline case, Equation A.27 with the coefficient 'a' set to 0.27 is used. Ultimately, as shown by the sensitivity studies, this has a modest impact on the final results. The baseline treatment corresponds to the recommended correlation for a horizontal conduit, and is perfectly acceptable for this case where reproduction of the standard tables is the objective. In addition, the licensee has applied a more conservative correlation to the clad case, and hence, any impact will be conservative. Hence, SNL finds the licensee practice in this regard to be acceptable. Further discussion of consistency questions for this particular approach are provided in 3.3.3 below.

3.3.2 Conduit Emissivity

The second point worthy of clarification is far more important and relates to the assumed value of the conduit surface emissivity. In the calculations, two different values of the conduit emissivity will be used, one in the baseline analysis and one in the clad analysis. On the surface this may appear to be poor practice as consistency in the calculations is desired. However, in this specific approach, this practice is actually quite appropriate and quite important.

To summarize and clarify the approach, the clad case analyses are uniformly performed using a conduit emissivity of 0.8 for all cases. The clad case analyses are then performed using the actual (or assumed) emissivity of the as-installed in-plant or tested conduit. In the validation cases this value ranged from 0.4 to 0.69 depending on the specific case. For the actual licensee in-plant applications, a value of either 0.2 or 0.23 has been used depending on the conduit material. Ultimately, SNL finds this to be a fully appropriate basis for analysis. This may appear to be a counterintuitive finding; hence, a further explanation will be provided.

First, it is important to note how the assumed value of 0.8 for emissivity was derived. The DE&S attachment includes a discussion of the emissivity used in formulating the IPCEA P-46-426 tables. Indeed the report makes and inaccurate statement in this regard. The report states that "the source document [P-46-426], where the baseline ampacity is obtained, does not specify what emissivity value was used to determine the baseline ampacity." It goes on to state that it is assumed that an upper bound value was used, and that 0.8 represents a reasonable upper bound limit. In fact, the IPCEA assumed value is specified in the standard. The ampacity tables are based on an assumed conduit emissivity of 0.82 as documented in Table IV of the standard. Ultimately the assumed value of 0.8 is very close to the actual value used in the tables, and the differences will not be significant.

Second, it should be recognized that the chosen value of the emissivity used in assessing the internal cable-to-conduit thermal resistance may be quite important to the analysis. The actual importance will vary from case to case depending on a number of factors. However, thermal radiation in the baseline case will always be a critical factor in any conduit analysis. For the clad case, radiation is also important if an air gap between the conduit and barrier is assumed to exist as is the case in the licensee assessments. If no air gap is present, then conduit emissivity has no role whatsoever in the clad case analysis.

Third, and most importantly, recall that the licensee's entire objective in the baseline case analysis is to "back out" the internal thermal resistance value used in formulating the standard ampacity tables. In order to perform this calculation accurately, it is critical that the analysis of the baseline case be at least nominally consistent with the standard tables. There will inevitably be some difference because the licensee is not using the exact same external heat transfer formulations. This difference should, however, be quite modest. Of far more importance is using a value of emissivity that is consistent with that used in formulating the tables. This conclusion is based on the following observations:

- Under the licensee approach, the overall heating rate of the cables is determined using the tabulated cable ampacity limits.

- This value, coupled with the overall cable-to-ambient temperature difference predetermines the total thermal resistance for the baseline system (cable-to-ambient). Because the same temperature and heat load assumptions are made, the value should ideally match the value assumed in the tables exactly.

- The total thermal resistance (cable-to-ambient) is in turn assumed to be the simple sum of the internal (cable-to-conduit) and external (conduit-to-ambient) resistance values because these two elements act in series.

- The external resistance (conduit-to-ambient) is independently estimated using standard correlations for convection and radiation. Thermal radiation is very important to the external heat transfer. The standard tables assume an emissivity of 0.82. Hence, to reproduce the external resistance values, the same emissivity should be used. In practice BVPS has used 0.8 in this calculation.

- The internal resistance (cable-to-conduit) is then calculated as the simple difference between the total thermal resistance (cable-to-ambient) and the external thermal resistance (conduit-to-ambient). Provided that the external resistance has been appropriately estimated, the internal resistance will also be appropriately calculated. From this point the internal resistance estimate is carried forward into the clad case analysis.

Based on these observations SNL finds that the licensee use of 0.8 for the conduit emissivity in the analysis of the baseline cases dependent on ampacity limits from the IPCEA tables is acceptable given that only very minor errors in comparison to the IPCEA values of 0.82 for emissivity will result. Further, SNL finds that this practice is critical to our overall assessment of the acceptability of the method and analyses. That is, any other practice in this regard would have been deemed unacceptable by SNL. In "backing out" the internal resistance values it is critical to maintain consistency with the standard ampacity tables.

3.3.3 Modeling Consistency

Finally, some discussion of the need for consistency between the clad and baseline case analyses is appropriate. Clad and baseline case analysis consistency is an overriding concern in the assessment of any ampacity model. Under this approach, the baseline/clad case consistency is maintained simply by using the same internal resistance value (appropriately calculated) and the same basic external heat transfer correlations. The licensee implementations have, indeed, achieved this with some inherent conservatism derived from the more conservative convection correlation used in the clad analysis. Customizing the conduit or barrier parameters for the clad case analysis to reflect the actual conditions of the as-installed clad conduit is entirely appropriate. In the estimation of the underlying parameters based on the ampacity tables, in this case the internal resistance, it is consistency between the actual ampacity tables that is of primary concern.

To explain further, as noted above, the only real purpose of the baseline case analysis is to determine the internal resistance. Hence, this part of the analysis should be performed fully consistent with assumptions underlying the standard ampacity tables. In contrast, the objective of the clad case analysis is to directly estimate the clad case ampacity limit assuming the same internal thermal resistance. Hence, the clad case analysis can proceed on the basis of the actual as-installed conditions, including factors such as grouping of conduits and surface emissivity that deviates from that assumed by the standard tables. For example, if the licensee concludes that 0.2 or 0.23 is indeed the emissivity of the installed conduits, then by all means this value should be used in the as-installed clad case analysis. Conduit emissivity is a legitimate parameter to consider in the assessment of case specific ampacity limits. The case specific ADF would simply reflect this additional factor which deviates from the values assumed in the tables, and this is appropriate.

3.4 Treatment of Interfering Walls

Some of the analyzed fire barriers involve conduits that are so close to an adjacent wall that the fire barrier system actually merges with the wall. For these cases, the licensee has assumed that the derating impact of a barrier in open air will bound that of a barrier with some interference from such walls. In general, SNL would agree with this assessment, but we must point out that the licensee's supporting basis for this assumption is somewhat questionable.

In particular, to support this conclusion the licensee presents a case analysis in which a conduit is assumed to be surrounded by a fire barrier which is in turn surrounded by a 2-foot thick concrete barrier as well. The licensee analyzes this case in comparison to the case with only the fire barrier and concludes that the increase in surface area more than compensates for the insulating effects of the concrete.

There is at least one flaw in this calculation; namely, the assumed thermal conductivity of the concrete. Holman [4], for example, lists a range of concrete thermal conductivity values ranging from 0.44 to 0.79 BTU/hr*ft*°F. In contrast the licensee has assumed a value of 0.9 BTU/hr*ft*°F. Hence, the licensee treatment appears to be a somewhat optimistic. For example, if the conductivity is reduced by half (to the lower bound value) then the estimated temperature rise through the concrete would be doubled for a given heating rate, and this would certainly reverse the results (the concrete would be found to be a more severe thermal barrier).

As noted, SNL would, in general agree with the assessment that for single conduit cases an open configuration will bound a configuration with an intervening wall. However, our assessment is based on the tremendous heat sink that a concrete wall would represent. That is, the contact of the fire barrier with the concrete would be an intimate contact with highly efficient heat transfer. The heat load from a single conduit would be trivial in comparison to the thermal mass of the wall. Hence, it is safe to assume that the concrete wall would easily absorb the heat normally lost to convection and radiation of that portion of the barrier which has been disrupted from direct air contact. Natural convection and radiation are simply not as efficient as would be direct contact with a massive heat sink at ambient temperatures. Hence, the ampacity limit for this situation would be at least equal to that of a conduit in a more open situation fully surrounded by a fire barrier system. Hence, SNL recommends that this assumption be accepted for the single conduit configurations at Beaver Valley.

3.5 Summary of Findings

SNL has identified no technical concerns related to the licensee thermal modeling approach, nor the specific case analyses. SNL has been able to fully reproduce the licensee results for a number of selected cases and has also performed some supplemental validation calculations (see Appendix A to this report). No significant numerical discrepancies nor errors in implementation were noted. SNL finds the licensee approach to analysis and the implementation of the approach to be fully consistent with accepted practice; hence, fully appropriate to the analysis of in-plant conduit ampacity limits.

4.0 SUMMARY OF FINDINGS AND RECOMMENDATIONS

4.1 The Licensee RAI Responses

The USNRC RAI included four questions identified as items 1, 2a, 2b, and 3. Two of these RAI items were rendered moot because the licensee has fully abandoned the previously reviewed analysis methodology in favor of an entirely new methodology; namely, RAI items 1 and 2a. For RAI item 2b SNL found that the licensee response was fully adequate to resolve the identified concerns. For these three RAI items no additional licensee interactions are recommended.

RAI item 3, identified two specific conduits that appeared to contain cables loaded in excess of their ampacity limits. The licensee was specifically requested to address these two conduits. SNL made the following findings and recommendations related to this RAI item:

> SNL finds the licensee resolution for Raceway 2CL213ND based on diversity arguments is inappropriate and unacceptable. SNL finds that two of the five cables in this raceway are, in fact, overloaded. It is recommended that the USNRC ask the licensee for additional remedial actions to resolve these cable overloads.
>
> SNL finds that the interim licensee resolution for the overloaded cables in Raceway 2CL607OE based on the overload conditions of operation has been adequately justified and is acceptable. However, it is also recommended that the USNRC follow-up with the licensee to ensure that remedial actions are taken for all three cables in the conduit once these overload limitations have been reached.

4.2 The Licensee Thermal Model

SNL has identified no technical concerns related to the licensee thermal modeling approach, nor the specific case analyses. SNL has been able to fully reproduce the licensee results for a number of selected cases, performed some supplemental validation case analyses, and identified no significant numerical or implementation errors. SNL finds the licensee approach to analysis and the implementation of the approach to be fully consistent with accepted practice; hence, fully appropriate to the analysis of in-plant conduit ampacity limits. It is recommended that the DE&S method and the BVPS implementation of that method be accepted by the USNRC.

4.3 BVPS Installation Findings and Recommendations

SNL finds that the licensee has adequately responded to the concerns raised in Generic Letter 92-08 for all but two of its fire barrier clad conduit installations. Both exceptions are related to RAI item 3 as discussed in Section 4.1 above. The first is related to an inadequate resolution provided for just one conduit (2CL213ND), and the second involves a recommendation for the USNRC to follow-up with the licensee to ensure appropriate tracking and ultimate resolution of a second conduit (Raceway 2CL607OE).

5.0 REFERENCES

1. F. H. Buller and J. H. Neher, "The Thermal Resistance Between Cables and a Surrounding Pipe or Duct Wall," *AIEE Transactions*, Volume 69, pgs 342-349, 1950.

2. J. H. Neher and M. H. McGrath, "The Calculation of the Temperature rise and Load Capability of Cable Systems," *AIEE Transactions*, pgs 752-772, Oct. 1957.

3. *Power Cable Ampacities*, IPCEA P-46-426, AIEE S-135-1, a joint publication of the Insulated Power Cables Engineers Association (now ICEA) and the Insulated Conductors Committee Power Division of AIEE (now IEEE), 1962.

Appendix A: Exercising the Licensee Model

A.1 Overview

SNL has implemented and exercised a version of the licensee thermal model. A printout of the actual program is provided as the end of this appendix. The program has been implemented using the commercial software package MATHCAD Version 4.0. It utilizes all of the exact same correlations and analysis assumptions as the original licensee thermal model as documented in the supporting Duke Engineering and Services (DE&S) report attached to the licensee submittal.

The reader will note that SNL's implementation is somewhat more direct in certain respects. In particular, SNL has taken advantage of the capabilities of MATHCAD in that all of the heat transfer correlations are written as callable functions, and then, a simultaneous equation set solve block (a MATHCAD Given/Find block) is used to obtain a solution that matches all of the specified conditions and equations. This typically involves simply matching the cable heating rate to the rate of heat flow through each of the thermal elements and interfaces. This eliminates the need to iterate manually to a solution, and ensures highly accurate results.

The model has been exercised for a two case examples to illustrate the impact of various parameters and assumptions. These are two of the cited validation cases, the Tennessee Valley Authority (TVA) 1" and 4" conduit tests. In the licensee submittal these cases appear in Tables A.4, A.6 and A.7 of the supporting DE&S report. These cases in particular have been used to explore various features and sensitivities of the model, and to further validate the model.

A.2 The TVA 1" and 4" Conduit Tests, The Test Conditions

The TVA test simulated in these two examples are taken from the results for TVA test articles 7.6a and 7.6b. The tests articles are described as follows:

> Test Article 7a involved a 1" galvanized steel conduit with a single 4/C #10 AWG cable installed. The measured baseline ampacity for this cable (corrected to standard temperature conditions) was 32.7A, and the clad ampacity was 29.66A. The fire barrier was comprised of a 3-hour 330-1 initial installation (1.25" thick pre-formed conduit sections, no pre-buttering) plus two 3/8" layers of a Thermo-Lag 770 upgrade material. The measured conduit emissivity for this test was 0.48 as reported by TVA.
>
> Test Article 7.6b involved a 4" galvanized steel conduit with 12 passes of a 3/C #6 AWG cable installed. The fire barrier was identical to that used for the corresponding 1" conduit as described above; again, no pre-buttering of the conduit sections was employed. The measured baseline ampacity for this cable (corrected to standard temperature conditions) was 29.21A, and the clad ampacity was 25.56A. The measured conduit emissivity for this test was 0.69 as reported by TVA.

A.3 Initial Simulation Results

SNL was successful at reproducing the licensee's calculations. Attached to this appendix is a printout of the SNL thermal model. The case shown is the analysis of the 1" conduit as per the exact licensee implementation. The numerical results match well within a small error. The minor discrepancies can be attributed to round off errors, and the fact that the DE&S cases were apparently performed using a manual iteration procedure. Manual iteration can never achieve the same level of accuracy as that obtained using a simultaneous equation solver such as that used by SNL.

A.4 Incomplete Analysis for Validation Study

DE&S did provide a detailed analysis of these two cases (plus two TUE test cases) as a part of its validation study. However, SNL finds that the DE&S analysis did not represent an adequate or complete validation basis. In particular, the DE&S has mixed "apples and oranges" for their case analysis in that a mixture of test measured baseline ampacity values and IPCEA based emissivity values was used. DE&S did not illustrate a full as-applied implementation in which the IPCEA baseline ampacities were used; hence, they did not exercise the model in its actual intended manner. Hence, SNL has reexamined these cases using a more complete approach. The approach taken by SNL is described further below. As will be noted below, the results reflect favorably on the approach and model.

As noted above, SNL found that the licensee/DE&S analyses of the TVA cases are neither fully consistent with the experimental conditions nor consistent with the intended actual application practice. Instead, a mixture of test and application conditions have been used. Hence, SNL does not consider the results to be an accurate reflection of how the model would work in practice, nor how the model would perform in a direct simulation of the tests.

In particular, DE&S used and emissivity of 0.8 to analyze the baseline case and the measured emissivity in the clad case analysis. Further, the licensee has changed the convection correlation to a more conservative estimate for the clad case. Each of these factors is nominally consistent with the actual application practice. However, the baseline ampacity assumed in the analysis was that actually measured in the test. In actual practice, the licensee would utilize a tabulated ampacity limit. Hence, SNL's finding that the licensee has mixed experimental and application factors inappropriately.

There are two possible ways to look as these data sets to validate the model more appropriately. The first is to directly re-analyze the test data using the thermal model. In this case, the analysis should be performed so as to model the tests as accurately and as consistently as possible. Hence, the simulation should be based on use of the both the measured baseline ampacity and the measured surface emissivity to estimate internal thermal resistance. Further, a true simulation of the tests would utilize both the exact same emissivity and convection correlations for both the baseline and clad analyses because these conditions do not change in the test. The objective would then be to accurately predict the clad ampacity and hence the ADF.

The second way to look at these tests is to attempt to predict the actual ADF using the approach essentially as it would be implemented in practice but while at the same time reflecting the actual conditions of the tests. To achieve this, the baseline ampacity is taken from the standard IPCEA tables, the first major change in this analysis as compared to the DE&S cases. An emissivity of 0.8 is used in the baseline analysis as per the DE&S analyses. The second major change is that for the clad analysis, the same emissivity, 0.8, is used to reflect the presence of the exact same conduit in the clad and baseline tests. Finally, the exact same convection correlation and coefficients (a=0.27) are used in both the baseline and clad conditions, again, to reflect the fact that in the test the convection conditions would have remained constant.

It is important to note that these examples are not intended to reflect the licensee applications, nor to imply some problem with the licensee customizing its analyses of clad cases to suit as-installed conditions. These examples are simply intended to more closely reproduce the conditions that were present in the TVA tests for the purposed of validation for the approach in general. Indeed, the licensee approach will provide an additional level of conservatism in comparison to these validation results.

A.5 Direct Re-Analysis of the Test Data

Consistent with the above discussions, SNL has re-analyzed the direct test data. The results are illustrated in Table A.1.

Table A.1: Summary of results for analysis of the TVA 1" and 4" conduits using the as-measured test conditions in all aspects of the model as compared to the DE&S analyses.

Case	Baseline Analysis		Clad Case Analysis		Estimated ADF (%)
	Conduit Emissivity	Convection Factor 'a'	Conduit Emissivity	Convection Factor 'a'	
1" Conduit					
1	0.8	0.27	0.48	0.20	19.4*
2	0.48	0.27	0.48	0.27	17.64
4" Conduit					
3	0.8	0.27	0.48	0.20	21.3
4	0.48	0.27	0.48	0.27	20.5

* Note this is the value reported by DE&S. SNL obtained a very slightly different result in its own implementation of 19.5%.

Note that cases 1 and 3 correspond directly to the DE&S analyses. Cases 2 and 4 represent the modified SNL assessments. Note that the differences are significant, but not excessively large. The SNL simulations, as expected, more closely match the experimental results of 10% ADF for the 1" and 13% for the 4" conduits. This lends some added level of validation for the thermal model, and shows that some conservatism exists in comparison to the tests even when the best possible simulation of the data is employed.

The remaining conservatism can be attributed to the conservative treatment of the air gap. That is, recall that the thermal model assumes a perfectly isolating annular air gap between the fire barrier inner surface and the conduit. In reality while some air gap will exist unless steps are taken to specifically eliminate it, the barrier and conduit will, at the very least, make some intermittent contact. Hence, the actual heat transfer will be enhanced by conduction through the contact points, and this is not treated in the thermal model. Instead, a conservative model assuming no contact whatsoever is applied.

A.6 Using the IPCEA Tables

In actual applications of the method, the initial baseline condition would utilize a roughly equivalent cable loading (matching the percentage fill of the actual case) and begin by assuming the IPCEA ampacity limits as the baseline case. As noted above, DE&S did not execute this full approach in its validations. Hence, SNL has done so here.

One aspect of these analyses is that the use of the IPCEA tables requires that the cables analyzed actually be covered by a case in the tables. For the 1" conduit, the actual test configuration, a 4/C #10 AWG cable is not covered by the tables. Hence, SNL has assumed the following as the nearest equivalent cable load that is covered by the tables:

> For the 1" conduit, SNL has assumed that the conduit houses a single 3/C #8AWG cable. This is the smallest multi-conductor cable included in the IPCEA conduit ampacity tables. Indeed the cited diameter of the 3/C #8 AWG cable from the IPCEA tables was 0.708" versus the 4/C #10 AWG cable used by TVA with its 0.603" diameter. This is as close as we can reasonably get for the test case versus a case from the standard tables. Given this, the baseline ampacity taken from the ampacity tables is 52A (see tables pg 313).

For the 4" conduit, the situation is somewhat different:

> There is no pressing need to substitute an alternate cable load into the 4" conduit in lieu of the actual tested cable load. Instead, one can simply use the IPCEA tabulated ampacity limit of 69A for a single 3/C #6 AWG cable in conduit (see page 313 of the standard), and apply an NEC correction factor of 0.40 to allow for the 36 conductors present in the 12 cables. Note that this correction factor assumes no load diversity, and applies to 31 to 40 conductors. Hence, a baseline ampacity of 27.6A with the same cable load can be assumed.

In these analyses the IPCEA baseline ampacity has been used to estimate the fire barrier ADF for a conduit whose properties are the same in the baseline and clad case. This corresponds to the test conditions in which the ADF is based on baseline and clad testing of the same conduit as in TVA's tests. For this approach, SNL has utilized exactly the same conduit emissivity, and exactly the same convection correlation for both the baseline and clad cases The results using this approach are illustrated in Table A.2. Note that the measured ADF and the value calculated by DE&A are included for comparison.

Table A.2: Summary of results for IPCEA based analysis of the 1" and 4" conduits assuming the same fire barrier as that tested by TVA. The DE&S analyses are included for comparison.	
Case	Estimated ADF (%)
1" Conduit	
Test Result	10
DE&S Analysis	19.4*
SNL Analysis	19.0
4" Conduit	
Test Result	13
DE&S Analysis	21.3
SNL Analysis	18.9
* Note this is the value reported by DE&S. SNL obtained a very slightly different result in its own implementation of 19.5%.	

Once again, the thermal model is conservative in comparison to the experimental results. This again, reflects well on the approach and on the model. The point illustrated by these results is that the modeling approach does provide some inherent level of conservatism even when the test conditions are simulated as nearly as is reasonably possible.

A.7 Summary

The SNL studies performed here has shown that the licensee approach is conservative and that it can provide reasonable estimates of the fire barrier ADF for conduits under a range of conditions. On this basis, SNL recommends that the approach is acceptable for the assessment of nuclear power plant cable ampacity loads.

A.8 SNL MATHCAD Program Listing

(Attached in the following five pages)

This file represents an SNL implementation of the Duke Engineering and Services method for the analysis of conduit ampacity limits as implemented for the Beaver Valley Nuclear Plant. The method is based on an analysis of the IPCEA nominal conduit ampacity limits to "back out" the internal cable-to-conduit thermal resistance. The external conduit-to-ambient resitance can then be modified to account for a fire barrier enclosure and a modified clad case ampacity limit derived. A comparison of the baseline ampacity from the tables and the modified clad ampacity yields a derating factor.

Programed by: Steve Nowlen, SNL, January 1998
Programed using: MATHCAD 4.0 (note that this version assumes availability of the fundamental temperature units of both K and R. Work is primarily in R.)

Note that the primary difference between this implementation and the licensee's is that we have taken a somewhat more direct approach to analysis of the heat transport equations. That is, the heat flux rate equations for each element of the system are set up as callable functions, and a solve block is used to obtain a simultaneous solution to these equations. This eliminates the need to perform manual iterations to a solution, and ensures a higher level of accuracy is obtained. SNL also does not directly utilize the heat transfer coefficient approach where q=UAdT except in the one case of the cable to conduit heat transport. This one 'U' value is a critical and major factor in the licensee approach, and is duplicated here for direct comparison. Instead, we use direct heat flux expressions such as q=hAdT or q=dT/R(thermal), and simply match the flux rates and temperatures. This difference is merely a matter of programming convienience, and has no impact whatsoever on the ultimate results. All other factors are exactly the same, and all of the exact same heat transfer correlations and assumptions are used. Hence, the reusits should be fully consistent, within some very narrow band of error, with those cited in the submittal.

The stored/default case is taken from the Duke/Beaver Valley validation case studies. The case is a simulation of one of the TVA tests. The example is taken from Table A.4 and A.6 of the Duke attachment and involves a 1" conduit with a single, 4/C, #10AWG cable.

Now set up physical parameters (all values are as per the Duke calculation)

The conduit

$d_{conduit} := 1.315 \cdot in$ $\quad d_{conduit} = 0.11 \cdot ft$ Conduit outer diameter

$t_{conduit} := 0.133 \cdot in$ Conduit wall thickness (not used)

$A_{conduit} := \pi \cdot d_{conduit}$ $\quad A_{conduit} = 0.344 \cdot \frac{ft^2}{ft}$ conduit outer surface area; Duke: 0.34

$\varepsilon_{conduit} := 0.48$ as per the Duke assumption for this case

The Cable:

$n_{cable} := 1$ number of cables

$n_{cond} := 4$ conductors per cable

$d_{cable} := 0.603 \cdot in$ Cable diameter (not used)

$Resist := 1.35 \cdot 10^{-3} \cdot \frac{ohm}{ft}$ conductor elec. resistance

$T_{cable} := (194 + 460) \cdot R$ Hot spot temperature in R

The Ambient:

$T_{ambient} := (104 + 460) \cdot R$

The Barrier:

$k_{barrier} := 0.122 \cdot \frac{BTU}{hr \cdot ft \cdot R}$ conductivity

$d_{barrier} := 6.52 \cdot in$ Outer diameter

$t_{barrier} := 2.4 \cdot in$ thickness

$\varepsilon_{barrier} := 0.99$ emissivity as per Duke calculations

The air gap

$t_{gap} := 0.2 \cdot in$ gap thickness

$k_{air} := 0.016 \cdot \frac{BTU}{hr \cdot ft \cdot R}$ air thermal conductivity

Physical constants:

$\sigma := 0.1714 \cdot 10^{-8} \cdot \frac{BTU}{hr \cdot ft^2 \cdot R^4}$ Stephan-Boltzmann

$\pi = 3.142$ verify Pi value is available via program

$FtoR := 460 \cdot R$ for convienence, conversion from F to R:

To actually do the calculations, we will set up a series of callable functions based on the licensee approach and correlations. We can then set up a simultaneous equation solve block below to give us the desired answer that matches the specified heat rates and temperature conditions.

The cable heating rate as a function of cable current load. The same expression applies to either the clad or baseline case, simply specify the current load:

$$q_{cable}(I) := n_{cable} \cdot n_{cond} \cdot I^2 \cdot Resist$$

Correlations for External Surface Heat Transfer to Ambient. This same set of expressions may be used for both the conduit in the baseline case and the barrier in the clad case. The values of temperature, emissivity and diameter n[illegible] be set accordingly.

External surface convection coefficient as a function of surface temperature and diameter as per licensee correlation (note that the validation studies use a leading coefficient of 0.27 whereas the actual application use 0.20)

$$h_{convext}(T_{surface}, d_{surface}, a) := a \cdot \left(\frac{BTU}{hr \cdot R^{\frac{5}{4}} \cdot ft^{\frac{7}{4}}} \right) \cdot \left(\frac{T_{surface} - T_{ambient}}{d_{surface}} \right)^{\frac{1}{4}}$$

External radiation coefficient as a function of temperature and emissivity:

$$h_{radext}(T_{surf}, \varepsilon) := \varepsilon \cdot \sigma \cdot \left[\left(T_{surf}^2 + T_{ambient}^2 \right) \cdot \left(T_{surf} + T_{ambient} \right) \right]$$

Total External heat flux as a function of surface temperature, emissivity, and diameter:

$$q_{external}(T_{surf}, \varepsilon, d, a) := \left(h_{convext}(T_{surf}, d, a) + h_{radext}(T_{surf}, \varepsilon)\right) \cdot d \cdot \pi \cdot (T_{surf} - T_{ambient})$$

Special correlations for the air gap region. Note that we use the Duke simplifications assuming the areas are about the same so use average diameter to get area and a view factor of 1.0. Hence:

For convection, we know gap is very small and as per Duke discussion we default to the conduction equation so:

$$h_{cgap} := \frac{k_{air}}{t_{gap}}$$

For the thermal radiation, the two surface expression is used where "in" is the conduit and "out" is the barrier inn– surface. Hence:

$$h_{radgap}(T_{in}, T_{out}, \varepsilon_{cond}) := \sigma \cdot \frac{\left(T_{out}^2 + T_{in}^2\right) \cdot (T_{out} + T_{in})}{\left(\frac{1}{\varepsilon_{cond}} + \frac{1}{\varepsilon_{barrier}} - 1\right)}$$

Total heat transport through the gap, note that we use the conduit diameter as area basis, as per the DE&S practice.

$$q_{gap}(T_{in}, T_{out}, \varepsilon_{cond}) := \left(h_{cgap} + h_{radgap}(T_{in}, T_{out}, \varepsilon_{cond})\right) \cdot \pi \cdot d_{conduit} \cdot (T_{in} - T_{out})$$

Conduction expression for the annular ring of fire barrier material:

$$q_{barrier}(T_{in}, T_{out}) := \frac{2 \cdot \pi \cdot k_{barrier}}{\ln\left(\frac{d_{barrier}}{d_{barrier} - 2 \cdot t_{barrier}}\right)} \cdot (T_{in} - T_{out})$$

Now we start the case calculations. The first step is to get the heat transfer coefficient for the cable bundle to conduit outer surface based on the baseline ampacity. In this case, we use the value measure in the test. Normally, we would use the tabulated ampacity limit for an actual analysis.

$$I_{base} := 32.7 \cdot amp$$

For the Baseline case we must match the internal and external heat transport by setting the surface temperature of the conduit. This implies that there is really only one unknown, the conduit temperature. Hence, we set up a one-equation solve block. Also note use of a=0.27 in convection correlation.

For the Baseline Case we set conduit emissivity to 0.8 to "match" IPCEA:

$$\varepsilon_{conduit} := 0.8$$

We first seed the solution with a guess:

$$T_{conduit} := T_{ambient} + 20 \cdot R$$

Now we set the solve block:

Given

$$q_{cable}(I_{base}) = q_{external}(T_{conduit}, \varepsilon_{conduit}, d_{conduit}, 0.27)$$

$$T_{conduit} := \mathrm{Find}(T_{conduit})$$

Thats all there is to the baseline analysis, and the answer in degrees F is:

$T_{cable} - FtoR = 194 \cdot R$ specified

$T_{conduit} - FtoR = 130.923 \cdot R$ calculated Duke: 130.9

$T_{ambient} - FtoR = 104 \cdot R$ specified

We will need the internal heat transfer coefficient as this carries forward to the clad analysis so:

$$U_{cb} := \frac{q_{cable}(I_{base})}{(T_{cable} - T_{conduit}) \cdot A_{conduit}}$$

$U_{cb} = 0.907 \cdot \dfrac{BTU}{hr \cdot ft^2 \cdot R}$ Duke: 0.90

Also for verification, note the heating rate of the cables at the specified ampacity

$q_{cable}(I_{base}) = 19.702 \cdot \dfrac{BTU}{hr \cdot ft}$ Duke: 19.64

$$q_{cable}(I_{base}) = 5.774 \cdot \frac{watt}{ft}$$

Now we set up the clad case. This case has more unknowns; hence, is more complicates. There is the unknown clad ampacity and three unknown temperatures (conduit, barrier inside, barrier outside). Hence, we need a set of four equations to solve. In this case we simply match the heating rate at each interface (cable-to-coduit, through the air gap, through the barrier, barrier-to-ambient) to the cable heating rate at a given clad ampacity. Also note use of a=0.20 in convection correlation.

For the clad case we set the conduit emissivity to the measured value of 0.48:

$$\varepsilon_{conduit} := 0.48$$

Again, we must first seed the answer:

$$I_{clad} := 20 \cdot amp$$

$$T_{conduit} := T_{cable} - 20 \cdot R$$

$$T_{barrierin} := T_{conduit} - 20 \cdot R$$

$$T_{barrierout} := T_{barrierin} - 20 \cdot R$$

Then we set up our four equation solve block. Note that in the first equation we carry forward our internal heat transfer coefficient from the baseline analysis case:

Given

$$q_{cable}(I_{clad}) = U_{cb} \cdot A_{conduit} \cdot (T_{cable} - T_{conduit})$$

$$q_{cable}(I_{clad}) = q_{gap}(T_{conduit}, T_{barrierin}, \varepsilon_{conduit})$$

$$q_{cable}(I_{clad}) = q_{barrier}(T_{barrierin}, T_{barrierout})$$

$$q_{cable}(I_{clad}) = q_{external}(T_{barrierout}, \varepsilon_{barrier}, d_{barrier}, 0.20)$$

$$\begin{bmatrix} I_{clad} \\ T_{conduit} \\ T_{barrierin} \\ T_{barrierout} \end{bmatrix} := \mathrm{Find}(I_{clad}, T_{conduit}, T_{barrierin}, T_{barrierout})$$

Thats it for the clad case, and the answers are (in degrees F):

$T_{cable} - FtoR = 194 \cdot R$ this is a specified temp.

$T_{conduit} - FtoR = 153.105 \cdot R$ Duke: 153.0

$T_{barrierin} - FtoR = 130.951 \cdot R$ the three solution temps Duke: 130.9

$T_{barrierout} - FtoR = 108.745 \cdot R$ Duke: 108.7

$T_{ambient} - FtoR = 104 \cdot R$ This is a specified temp

and for ampacity and derating factor:

$I_{clad} = 26.33 \cdot amp$ Duke: 26.3

$$ADF := \frac{I_{base} - I_{clad}}{I_{base}}$$

$ADF = 19.481 \cdot \%$ Duke: 19.4%

Clad heating rate:

$q_{cable}(I_{clad}) = 12.774 \cdot \frac{BTU}{hr \cdot ft}$ Duke: 12.8

$q_{cable}(I_{clad}) = 3.744 \cdot \frac{watt}{ft}$