A Review of the Revised Millstone Nuclear Power Station Fire Barrier Ampacity Derating Analyses

A Letter Report to the USNRC

Revision 0

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ATTACHMENT 2

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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 third and final report in a series of reports assessing the licensee implementation of fire barrier system ampacity derating analyses for cables installed at the Millstone Nuclear Power Station (MNPS). The current report documents the results of a SNL review of a submittal from the licensee provided in response to an USNRC Request for Additional Information (RAI) of 5/13/97. This work was performed as Task Order 6 of USNRC JCN J2503.

1.0 OVERVIEW AND OBJECTIVE

1.1 Objective

The objective of the current report is to document SNL's findings and recommendations resulting from a review of a revised licensee submittal from the Millstone Nuclear Power Station (MNPS). The subject submittal was forwarded to the USNRC in response to a Request for Additional Information (RAI) dated May 13, 1997, and deals exclusively with the question of ampacity derating of cables protected by Thermo-Lag fire barrier systems.

It should be noted that this review specifically assumes that no further licensee interactions will take place as a part of the current review process. This is a departure from previous review efforts associated with MNPS in that previous reviews have assumed that a supplemental RAI might be issued to resolve any identified technical concerns. In this review, technical findings have not been couched in the terms of a recommended RAI to the licensee. Rather, it is assumed that any follow-up would be performed under the normal USNRC inspection and enforcement processes. This review is intended to identify potential issues of technical concern that remain unresolved.

1.2 Background

The current review is the third and final report in a series of SNL review reports for MNPS. The USNRC review efforts on this subject now spans a period of over five years. The questions of concern relate to ampacity derating assessments for cables protected by Thermo-Lag fire barrier systems as originally documented in USNRC Generic Letter 92-08. The history of the review/resolution effort for MNPS is summarized as follows:

- Sept. 19, 1994: A USNRC letter to MNPS cites that "unresolved technical issues remain regarding ampacity derating."

- Nov. 3, 1995: MNPS provides it's initial response to the ampacity concerns raised in GL 92-08 including two specific case examples, one for a conduit and one for an air drop, to illustrate the licensee's ampacity assessment methodology.

- May 16, 1996: SNL forwarded to the USNRC a letter report documenting the findings and recommendations resulting from a review of 11/95 licensee submittal.

- August 12, 1996: Based in part on the SNL findings, the USNRC forwarded to the licensee a second RAI requesting resolution of several technical concerns regarding the licensee analyses.

- Dec. 13, 1996: The licensee response to the 8/96 RAI was submitted. Included were the supporting calculations not included in the 11/95 submittal. A supplemental assessment of certain unique installations was also submitted by MNPS on Dec. 27, 1996.

- March 27, 1997: SNL completes its review of the 12/96 submittals, and forwards a second letter report to the USNRC. A number of unresolved technical concerns are identified.

- May 13, 1997: The USNRC forwards a third RAI to the licensee requesting resolution of the remaining technical concerns identified in the SNL report of 3/97.

- July 11, 1997: MNPS provides a preliminary response to the 5/97 RAI. This response commits the licensee to revise its ampacity calculations for both Unit 1 and Unit 2 and identifies the intended approach to resolution of the technical concerns without specifically resolving those concerns.

- March 1998: The licensee provides the USNRC with a draft RAI response providing more specific proposed answers to the identified technical concerns. SNL is asked to review these draft responses.

- March 19, 1998: SNL provides a letter to the USNRC citing certain areas in which the licensee draft response may not fully resolve the identified technical issues.

- Feb. 17, 1999: MNPS provides its official response to the USNRC RAI of 5/97. The submittal cites that all issues have been resolved, but does not provide the updated calculations for review.

- Feb 26, 1999: SNL requests (via e-mail) that the revised calculations be provided so that issue resolution can be confirmed.

- May 25, 1999: The licensee completes is updating of the subject calculations and forwards an informational copy to the USNRC. SNL is provided with a copy in July 1999.

- September 30, 1999: SNL completes the current review effort.

1.3 Overview of the Licensee Submittal

The licensee revised calculation 96-ENG-01528-E2 provides an entirely new set of ampacity derating calculations for MNPS as compared to those documented in earlier licensee submittals. Further, the revised calculation is based an entirely new approach to the ampacity calculations as compared to those earlier analyses. It would appear that this new calculation fully supercedes the previous calculations.

As such, the revised calculation effectively **resolves or renders moot all of the technical concerns identified in previous reviews**. This is not to say that no technical concerns remain. Rather, the technical concerns identified for the new calculations bear no relationship to those identified in previous reviews.

It should be noted at the outset that the revised calculation represent a tremendous improvement in the licensee's ampacity assessments. Both the technical merit and quality of the calculations has improved substantially. In addition, the calculations are far more complete and scrutable. In particular, the thermal model is well documented as are the actual case examples. It is largely on this basis that, as noted above, SNL finds that all of the previous technical concerns raised in the RAIs of 8/96 and 5/97 have been either resolved or rendered moot.

The calculation itself is ultimately presented in three parts; namely, calculations for cable trays, conduits, and unique configurations. Similar techniques of analysis are used for each application, but the methods are tailored to the cases under study. The chapters which follow will consider each of these general application classes.

1.4 Report Organization

Chapters 2 provides an overview of the licensee's new calculations for cable trays and identifies potential points of technical concern regarding these calculations and the associated case examinations. Chapters 3 and 4 provide similar discussions for the licensee's conduit and unique configuration analyses respectively. Chapter 5 summarizes the review findings.

2.0 THE LICENSEE'S REVISED CABLE TRAY CALCULATIONS

2.1 Overall Approach

The licensee's overall approach for cable trays is based entirely on thermal modeling. The only application of test data is in the validation of the thermal model estimates of ampacity derating factors.

As is usual, the calculation is performed in two parts: an analysis of the baseline (or unprotected) case and an analysis of the clad (or protected) case. The ampacity limits for each case are compared to determine the fire barrier derating factor.

The overall analysis process involves (1) estimation of the baseline ampacity limit for each cable in a given tray, (2) estimation of the fire barrier ampacity derating factor for the tray, (3) calculation of the adjusted allowable ampacity limit for each cable, and (4) comparison of the actual in-plant ampacity load to the allowable ampacity limit. It should also be noted that the MNPS thermal model is inherently limited to single-layer fire barrier configurations with no air gaps between successive layers of fire wrap.

2.2 Analysis of the Baseline Cable Tray Cases

2.2.1 Baseline Modeling Basis

The baseline case analysis for cable trays relies on implementation of a Stolpe-based model.[1] Stolpe presented one of the pioneering studies on cable tray ampacity limits, and his method remains the primary basis for current cable tray ampacity limits accepted throughout industry.[2]

Stolpe's model is a relatively simple one-dimensional steady state heat transfer model. The cable mass is modeled as a homogeneous region with uniform heat generation. The model considers heat transfer through the cable mass by conduction, and heat transfer away from the cable mass by convection and radiation to the ambient environment.

The licensee baseline case thermal model is nominally consistent with the Stolpe method, and SNL identified no specific errors in the numerical implementation of the Stolpe model. However, as noted in Section 2.2.2 immediately below, the licensee has made one fundamental error in the interpretation and implementation of model results.

2.2.2 A Fundamental Oversight

In its implementation of the Stolpe cable tray thermal model, the licensee has failed to implement one critical check on the results. In particular, it is well known that the Stolpe approach can lead to unrealistic ampacity estimates in cases involving lightly loaded cable trays (i.e., relatively few cables in a given tray). This problem is particularly pronounced for cables with larger physical diameters The problem is manifested in cases where the diameter of any individual cable substantially exceeds the cable tray average fill depth, and indeed, many of the MNPS applications involve large cables in sparsely loaded trays.

The problem arises because Stolpe assumes that heat is generated uniformly throughout the mass of cables in the tray, and because the cable mass is modeled as a uniform thickness homogeneous mass spread across the full width of the tray. This is an idealization that works well in most cases. However, when there is a light cable load (i.e., less than a full layer of cables), or when there are one or more large cables in the tray, the average fill depth of the composite cable mass may be much less than the diameter of one or more of the individual cables. As a result, the heat transfer model may underestimate the temperature drop from the cable center to the cable surface for the larger cables. As a result, the method can grossly overestimate the allowable ampacity under these conditions.

Stolpe clearly recognized this problem in his original work. In fact, specifically to overcome this problem, Stolpe recommended that no cable in a random fill cable tray be allowed to carry more than 80% of its open air ampacity limit. That is, a cable with a nominal open air ampacity limit of 100 amps would be allowed to carry no more than 80 amps when installed in a random fill tray. The ICEA ampacity tables[2] directly incorporate this limit. The licensee assessment has failed to recognize this critical limit as a check on the estimated baseline ampacity limits. As a result, many of the estimated baseline ampacity limits are overestimated, in some cases grossly so. **This represents a fundamental oversight in the current licensee assessments that renders many of the cited results invalid.**

To illustrate more explicitly, the values in question are presented in several individual tables under "Attachment A - Ampacity Calculations for Cables in Thermo-Lag Wrapped Trays." For example, subsection 5.5 (see page A17 of A61) presents the baseline ampacity limits for a range of plant cables installed in a 12 inch cable tray under a variety of tray loading (depth of fill or percentage fill) conditions.

Consider, for example, the first column in the table on page A17. The cable in this case is a 750 MCM 3-1/C (triplex) power cable. The overall diameter of this cable is 3.39" (see page A5). This diameter is substantially larger than any of the fill depths analyzed which range from 0.4" to 1.5". As a result, the estimated baseline ampacity limits for this cable are excessive for five of the six cited fill conditions. The worst-case is the lowest fill condition (i.e., 10% fill or a 0.4" depth of fill). In this particular case, a baseline ampacity of 1120 amps is calculated. In comparison, the IPCEA standard[3] proscribes an open air ampacity limit (the most optimistic of any ampacity limits established for any cable) of 659-677 amps (depending on the voltage rating of the cable). Applying the 80% limit for random fill trays yields an absolute maximum tray ampacity of 527-540 amps (again depending on the cable's voltage rating). The licensee's estimates of the baseline ampacity for this cable are as much as twice the actual maximum allowable ampacity.

This problem is by no means limited to the one set of calculations used for illustration in the above discussion. Similar conditions exist for virtually all of the cable tray installed cables analyzed by MNPS. The failure of the licensee to place an upper bound limit on cable ampacity per the ICEA standard represents a serious and fundamental flaw in the licensee's analyses. Many of the licensee's calculated baseline ampacity limits grossly exceed actual upper bound ampacity limits for the subject cables. These estimates carry forward directly into the assessment of clad case ampacity limits as well.

2.3 Analysis of the Clad Case Ampacity Limits

2.3.1 Basis for Derating Analysis

The approach used to estimate clad case ampacity limits is based on use of the thermal model to estimate a fire barrier ampacity correction factor (ACF), which the licensee refers to as a derating factor (DF). (Note that the licensee is using a definition of derating factor that is not consistent with that generally applied to the term ampacity derating factor (ADF)). This value is applied to the estimated baseline ampacity to estimate the clad case ampacity limits. The DF (or ACF) is defined based on the ratio of the clad case and baseline case ampacity limits, or equivalently based on the square root of the clad and baseline heat load ratio, as follows:

$$DF \equiv \frac{I_{clad}}{I_{baseline}} = \sqrt{\frac{Q_{clad}}{Q_{baseline}}}$$

Note that using this definition, the DF is expressed as a fraction.

2.3.2 Estimation of the Derating Factor (DF)

In estimating a derating factor, it is critical that the baseline and clad case models be fully self-consistent. That is, if the two models use different assumptions, then the DF is based on a comparison between "apples and oranges" and may be invalid. This had been a significant point of concern regarding earlier versions of the licensee analyses. However, in the new calculation the thermal model used to analyze the clad case is fully consistent with the model used to analyze the baseline case. The licensee has fully resolved these concerns.

In general, the licensee DF model is well developed and appropriately executed. The licensee has presented some validation results that reflect well on the model. SNL found no specific points of technical concern regarding the licensee DF calculations.

That said, the licensee has generated what appear to be rather conservative estimates of the fire barrier derating impact. The licensee estimated DF impact ranged from 0.36 to 0.38. This would correspond to an ADF of 62%-64%. Nominally this appears to be a quite harsh penalty for a simple single layer Thermo-Lag fire barrier.

The MNPS barriers being analyzed are 1.5" thick (per the calculations). TVA/Watts Bar tested a somewhat thicker fire barrier system (TVA Test Item 7.2).[7] This was a 24" wide tray with a 1.25" base fire barrier system and two 3/8" upgrade layers for a total barrier thickness of about 2". In this test, TVA found the ADF to be 48% which would correspond to a DF (or ACF) of 0.52. A second similar test was performed by FPC/Crystal River.[8] In the FPC test a similar tray with a 3-hour single layer 1.125" thick barrier system was tested and found to have a 41.4% ADF (or a 0.586 DF). In comparison to these tests, the MNPS results appear quite conservative. One would nominally anticipate a DF that falls between these two experimental values.

The most likely source leading to this apparent conservatism is the fact that the licensee ignores heat transfer from the bottom surface of the tray/barrier for clad trays. SNL has made no specific attempts to verify this observation, nor to re-formulate the model.

2.3.3 Application of the DF

Once the value of the DF for a particular application has been established, the allowable ampacity limit for a given cable is estimated as follows:

$$I_{allowable} = I_{baseline} \times DF$$

Again observing the somewhat non-standard definition used by the licensee for its derating factor (DF), this is the correct expression to apply. Because the DF appears conservative, given an appropriate baseline ampacity, the clad case ampacity estimates would also be conservative. As noted in Section 2.2.2 above, many of the baseline ampacity limits have been over-estimated and in some cases substantially so.

2.4 Identification and Resolution of Nominally Overloaded Cables

On page 8 of 81 of the revised calculation body (section 2.2.1) the licensee identified four cables that they found to be nominally overloaded. If one assumes that the DF values have been appropriately estimated, then it would appear that the licensee has under-estimated the magnitude of the overload, and that certain other cables may also be overloaded. The problem derives directly from the over-estimated baseline ampacity limits as discussed in Section 2.2.2 above. The subsections that follow discuss and re-analyze the licensee identified overload cases, the general approach used by the licensee to argue away these overloads, and other potential cases that may also involve overloaded cables.

2.4.1 Licensee Identified Cases

As noted above, the licensee identifies four specific cables that are nominally overloaded based on their own analyses. However, these cases are impacted by the error described in Section 2.2.2 above. The specific cases cited by the licensee may be re-analyzed to compensate for the error as follows:

- Cables Z1B5105/A and Z1B5103/A: These two cables are cited as "BM code B09" which corresponds to triplex (3-1/C) 4/0 AWG power cable. The licensee calculation for the tray in question estimated a baseline ampacity limit of 322A. However, the open air ampacity limit for a 4/0 triplex cable is just 305-317A depending on the voltage rating of the cable (see IPCEA tables[3], page 259, correcting for a 50°C ambient and 90°C cable temperature). Given this range, the 80% of open air ampacity limit for random fill cable trays would then be 244-254A. These values represent the range in which the actual baseline ampacity must be assumed to fall (if the voltage rating of the cable were known, a single value could be derived). Applying the licensee estimated DF of 0.36 (which corresponds to an ADF of 64%) gives an allowable ampacity limit of 88-91A. This compares to the licensee cited allowable ampacity of 116A. The cited actual ampacity loads of 122A are well in excess of the revised ampacity limits. In this case, given the actual cable load, the cables would be able to withstand up to a 50% ADF (or 0.5 DF). A more realistic assessment of the actual fire barrier ADF might yield such a number, but this lies outside SNL's review scope.

- Cable 1B31A08/G and 2B41A16/A: These two cables are both cited as "BM code B03" which corresponds to a 3/C 8 AWG cable. The licensee estimated baseline ampacity limits for these cables are 48A and 55A, respectively. However, the open air ampacity limit for a 3/C 8 AWG cable is 54A, and 80% of this value is 43A. Hence, the cable tray baseline ampacity should not exceed 43A in either case. The licensee estimates and DF for the two trays in question is 0.36. Hence, the corrected allowable ampacity limit for each case is estimated as 43A*0.36=15.5A. Therefore, the cited actual cable load of 24A is well in excess of the nominal allowable ampacity limit. In this case, the cable would only be able to tolerate an ADF of 44% (a DF of 0.56).

Given this, SNL finds that the four cases identified by the licensee involving nominally overloaded cables have understated the extent of the cable overload assuming that the 0.36 DF value is accurate for the installed fire barriers. The cables in question do have some substantial margin available to accommodate the fire barrier. However, the licensee's estimate of the fire barrier derating impact exceeds the available margin substantially.

2.4.2 General Acceptability of the Licensee's Resolution Approach

The licensee's approach to resolution of the nominally overloaded cable conditions raises additional concerns. Basically, the licensee relies on the emergency overload rating of the cables to resolve the nominal overload. This approach is considered inappropriate.

The licensee cites that "these cables have thermosetting insulation, and can operate at 130°C for durations lasting no greater than 100 hours. This condition is very easily satisfied with these cables, with no sacrifice to their life." A reference is made to the IPCEA cable ampacity tables as the basis for these statements.

The reliance on cable emergency overload ratings for normally anticipated operating conditions is considered an inappropriate practice. The emergency overload conditions are intended only to provide a measure of the safety factor associated with potential emergency overloading conditions. These ratings are provided in the standard as a tool to be used in the design of circuit overload protection devices including breakers and fuses. Both the duration of any single overload event, and the total number of overload events that are allowed are severely limited by the standards. The factors allow for the design of appropriately coordinated circuit protection features (see, for example, IEEE 242[4]). They are not intended to excuse a cable that is otherwise overloaded given the normal anticipated design load on the basis of operating time.

Reliance on cable overload ratings as an indication of the normally anticipated load carrying capacity of a cable is considered inappropriate, and SNL recommends that such arguments be rejected by the USNRC.

2.4.3 Other Potential Cases of Ampacity Overload

In addition to the four applications already identified by the licensee, there are at least three additional trays where cables are apparently overloaded. This is based on correcting the baseline ampacity limits to reflect the 80% of open air limit, and retaining the licensee's estimates of the fire barrier derating impact. The cases identified by SNL that may warrant further review are:

- Cable Z1B5105/A in Tray Z14FM20;
- Cables Z2B0606/A, Z2B0606/B, Z2B0610/A, and Z2B0610/B, in Tray Z23GE10; and
- Cables Z2B0610/A and Z2B0610/B, in Tray Z23HB10.

In each of these cases, it would appear that a more realistic estimate of the fire barrier derating impact may show the cables to be operating within acceptable ampacity limits.

2.5 Use of a Finite Element Model

The licensee does make reference to use of the finite element model HEATING6 as a part of the submittal. The licensee presents numerous results to show that, in effect, the finite element model yields the same results as the simplified Stolpe model. This would imply that the finite element model is being employed in a highly simplistic manner. In effect, the licensee appears to be using the finite element code as a numerical solver for a very simplistic heat transfer problem. Given this specific context, this is found to be an acceptable approach to the problem solution.

In a more general context, the use of detailed finite element modeling of a cable tray heating would raise numerous questions. In particular, finite element models are primarily designed to allow for two- and three-dimensional modeling of transient heat transfer problems. To the knowledge of the author, only very limited scope applications of such models have yet been employed, and these have been subject to only modest validation.

It would appear that MNPS is not, in fact, using any sophisticated modeling approaches; but rather, is using a very sophisticated heat transfer program to solve an almost trivial one-dimensional steady state heat transfer problem. Hence, it is not surprising that by using the same heat transfer assumptions and correlations, the sophisticated model yields essentially identical answers as does the simple hand calculation model. In the context of the current calculations, the use of the finite element code has little or no significance beyond its service as a mathematical solver.

This should not, however, be taken as a general validation of finite element modeling of individual cable ampacity conditions. That is, should the licensee choose to implement its finite element model in a more sophisticated format, such as a "true" two-dimensional model of a particular tray with different ampacity loads imposed on individual cables, then SNL recommends that the NRC seek additional validation of the model in this mode of operation. This is a purely speculative comment intended to direct future NRC staff reviewers towards potential points of concern regarding this particular model.

2.6 Use of the Harshe/Black Method

The licensee makes reference to the method of Harshe and Black (licensee reference 3.1.10). In particular, the flow chart presented on page 81 of 81 of the calculation cites use of "Harshe & Black for covered raceways." The calculation reviewed by SNL presents no such applications. Indeed, it would not appear that any covered raceways have been included in the applications cited in this licensee submittal.

The Harshe/Black method is an approach that allows some credit for cable load diversity in estimating cable tray ampacity limits. That is, the Stolpe method used to generate the current industry standard cable tray ampacity tables assumes that every cable in a given tray is fully loaded to its rated ampacity limit. In reality, cables will carry a "diversity" of cable loads. It has been shown that under certain conditions, the existence of diversity in the cable loading can lead to higher ampacity limits for those cables that are loaded.

The Harshe/Black method was successfully applied by one licensee; namely, Palisades. However, in accepting the Palisades analyses, the USNRC requested that certain restrictions be placed on the method to ensure that potentially optimistic results are not credited.[6] Hence, should MNPS implement the Harshe/Black method in the analysis of any of its cable trays, it would be appropriate for the USNRC to ensure that the cited restrictions on the method have been appropriately considered. Again, in this review, none of the calculations has utilized the Harshe/Black diversity method. Hence, this is a purely speculative finding intended to identify potential areas of technical concern that might warrant USNRC attention during future inspection/enforcement activities.

2.7 Summary of Licensee Cable Tray Calculation and Results.

The MNPS ampacity derating calculations for cable trays as represented in licensee calculation 96-ENG-01528E2 Revision 2 are substantially improved in both quality and technical competence as compared to earlier licensee submittals on the same topic. Positive aspects of the approach include the following points:

- The licensee thermal model for both the baseline and clad cases is well thought out and well executed.
- The clad and baseline models are fully self-consistent, and are consistent with currently accepted industry practice.
- The clad case model is conservative.

- No errors of execution were noted in the thermal model itself, although one error was noted in the application of the model results to baseline ampacity limit estimation as noted below.

- The model is well documented and easy to follow.

The licensee estimates of the fire barrier derating impact appear quite conservative. In particular, the licensee reports ADF impacts of 62%-64% (corresponding to an ACF or DF of 0.36-0.38). Derating tests by TVA and FPC appear to provide upper and lower bounds, respectively, for the anticipated derating impact of the MNPS fire barriers. Those results suggest that the actual derating impact should be expected to fall in the 42-48% range. Hence, the licensee thermal model appears to contain substantial conservatism, although SNL has not specifically attempted to identify the source of this conservatism.

There was one fundamental flaw noted in the licensee's interpretation and application of the modeling results. In estimating the baseline ampacity, the licensee has failed to limit cable ampacities to 80% of the open air ampacity limit (per the ICEA standard). As a result, baseline ampacity limits in some cases are grossly overstated (those cases where the cable diameter substantially exceeds the average cable tray fill depth). This potential in the Stolpe/ICEA model is well known. The global limitation that cable tray ampacity not exceed 80% of the cable's open air limit was implemented specifically to mitigate this problem. SNL finds that this oversight seriously compromises the licensee's assessment of both baseline and clad case ampacity limits, and potential overloads.

SNL has reviewed the other cases cited in Licensee Attachment D, the results for fire barrier clad ladder type cable trays without covers. Based on this review, it would appear that at least three additional trays may include nominally overloaded cables if one assumes that the licensee estimates of the fire barrier impact are correct. In all cases a substantial margin is available to accommodate the fire barrier's derating impact, and more realistic assessments of the fire barrier impact may resolve the apparent overloads.

In addition to these findings, SNL has identified three areas for potential attention during future inspection/enforcement activities. These findings should be viewed as being purely speculative in nature in that they do not impact the calculations reviewed by SNL. They identify potential areas where changes in the licensee's approach to analysis might result in new areas of potential technical concern. These areas are as follows:

- The thermal model used for the analysis of clad cable trays assumed a single layer fire barrier system with no imbedded air gaps. It may be appropriate to ensure that fire barrier upgrade activities have not introduced imbedded air gaps through the installation of either additional layers of material or through over-wraps.

- The licensee analysis document cites the Harshe/Black method of analysis (licensee reference 3.1.10) and notes in the process flow chart (see page 81 of the calculation) that this method may be used for the analysis of covered raceways. However, the documents reviewed by SNL contained no such calculations. The Harshe/Black method can lead to unreasonable results if certain restrictions are not observed. These restrictions were documented during USNRC/SNL review of the Palisades ampacity derating submittals (see for example reference 6). If MNPS actually implements the Harshe/Black method in any of its cable tray applications, some attention to the proper implementation of the recommended method restrictions may be warranted.

- MNPS has illustrated results obtained using a finite element code called HEATING6. The mode of application illustrated in the documents reviewed by SNL is obviously quite simplistic. The applications appear to simply mimic the one-dimensional steady state heat transfer model of Stolpe. In this very limited context, the model is found to be adequate and appropriate. However, if in future applications the licensee were to employ the model's more sophisticated two-dimensional modeling capabilities, then some additional scrutiny and validation of the results may be warranted. This is because only very limited experience with finite element modeling of cable trays is currently available.

- SNL finds that the licensee's argument as to why the nominally overloaded cables were acceptable is inappropriate. The licensee cited reliance on the cable's emergency overload temperature ratings as the basis for accepting the nominal overload conditions. SNL recommends rejection of the proposal that emergency overload ratings may be used to justify normally anticipated operating loads.

3.0 CONDUITS CALCULATIONS

3.1 Approach to Analysis

The approach to the analysis of fire barrier clad conduits is similar to that taken for cable trays. The licensee first calculates the baseline ampacity, then estimates and ampacity correction factor (ACF), and then estimates the clad case ampacity as the product of the ACF and baseline ampacity. This is then compared to the actual load ampacity to determine case acceptability.

3.2 Thermal Model Basis

The underlying thermal model used by MNPS is nominally that recommended by Neher and McGrath[5] for the estimation of conduit ampacity limits. This same model has also been used in the development of the currently accepted industry ampacity standards[3].

However, in order to implement the model for the specific cases at MNPS, the licensee has made certain assumptions, and certain of these have not been justified. In particular, the Neher/McGrath method assumes that all of the cables in a given conduit will be of the same size and physical characteristics. In the MNPS cases, a mixture of cable types and sizes may be contained in a single conduit. To deal with this difference, the licensee has made the following assumptions:

- One of the critical parameters is the effective diameter of the cable bundle within the conduit. Neher/McGrath provide a method for estimating this value for up to three cables of like size. The licensee has extended this model to apply to an unlimited number of cables of random size. The licensee approach to this problem appears reasonable and appears to yield modestly more conservative results than would the Neher/McGrath approach.

- The Neher/McGrath method is based on estimating the total allowable heat load for the conduit as a whole and then partitioning that heat load to individual cables. However, as noted above the base method assumes that all cables are of a like size. In MNPS cables of different sizes may be housed in the same conduit. In order to partition the heat load to individual cables, the licensee has used the cross-sectional area of the cables. That is, the portion of the total heat load for an individual cable is weighted according to the fraction of that given cable's area to the total cross-section of all cables. This is similar to the approach taken by Stolpe in his model of cable trays, but is inconsistent with the Neher/McGrath approach and can lead to anomalous results. The licensee has provided no justification for this approach.

3.3 Errors in Thermal Model Implementation

3.3.1 Cable Surface to Conduit Thermal Resistance

It was noted in this review that the licensee has made certain mistakes in its implementation of the Neher/McGrath model. The first such mistake is in the estimation of the cable surface to conduit thermal resistance term. In particular, Neher/McGrath cite the following equation for this term:

$$R_{sd} = \frac{n'A}{1+(B+CT_m)D_s'}$$

where A, B, and C are constants, T_m is a mean temperature, and D_s' is the equivalent diameter of the cable bundle (this is equation 41 in the Neher/McGrath paper). The licensee's error occurs when the value of the term n' is set. This value is defined by Neher/McGrath as "the number of conductors contained within D_s'." That means that n' is the total number of conductors within the cable bundle being modeled which is also the total conductor count for the entire conduit since all the cables are modeled as a single bundle.

In contrast, the licensee has set n' to the maximum number of conductors in any one cable, and this value is typically three. In some applications the total conductor count is substantially higher. For example, in Section 5 of licensee Attachment B, the number n' is assumed to be 3 (see page B18) when the total conductor count is actually 44. Hence, the thermal resistance between the cable surface and conduit wall has been underestimated by over one order of magnitude.

Note that this term is only one of a series of thermal resistance terms. Hence, its impact on the calculated ampacity limits is somewhat moderated in the overall calculation. The very strong dependence on conductor count may appear odd at first glance. However, the term is not simply estimating thermal resistance to the outer surface of the cable bundle, but rather, estimates the worst case resistance to the surface of any individual cable within that bundle. That is, the method attempts to bound the worst case conditions that will be encountered within the conduit; namely, a cable that is located at the center of the cable bundle.

SNL finds that this is a serious mistake in the current licensee calculations. The result of this error taken alone would be to under-estimate the cable bundle to conduit temperature drop. In turn, this would result in estimated ampacity limits being overly optimistic.

3.3.2 Temperature Drop Through Cable Insulation and Jacket

The second mistake noted is in the estimation of the temperature drop through the individual cable insulation and jacketing layers. Neher/McGrath recommend two different correlations for this term depending on whether the cable is single- or multi-conductor. However, the licensee has used an expression that does not match these recommendations. Further, the licensee expression is either incomplete or simply incorrect. The equation is first presented in Section 6.3.5 of the body of the calculation (page 43) and is implemented in subsection x.2.6 of each conduit calculation (for example, in Section 5.2.6, page B20) of Attachment B. The licensee calculates the "maximum cable operating temperature" using the expression (this is the form used in Attachment B):

$$T_m = T_c + \frac{Q_o}{(4 \cdot \pi \cdot k_c)}$$

where T_m is the peak cable temperature, T_c is the cable surface temperature, Q_o is the heat flow for the cable, and k_c is thermal conductivity. However, the expression is clearly incomplete. This term bears a striking resemblance to typical expressions involving heat transfer through an annulus which would be appropriate for modeling of single conductor cables. The presence of the term (π) in the denominator, in particular, is an indication of a circular geometry problem. If this is the case, the correct expression should read as follows:

$$T_m = T_c + \frac{Q_o}{(2 \cdot \pi \cdot k_c)} \ln\left(\frac{r_o}{r_i}\right)$$

Note the replacement of (4) in the denominator with a (2). The presence of a (4) in this expression generally is associated with a spherical annulus whereas a (2) is generally associated with a tubular or linear annulus. In this case, the geometry is clearly that of a tube.

Also note the addition of the natural logarithm term (where r_o is the cable outer radius and r_i is the cable insulation inner radius). Given the thickness of a typical cable insulation layer in comparison to the conductor size, the natural logarithm term would be on the order of 0.1 or less. Hence, the licensee appears to have overstated the temperature drop for the cable insulation by a factor of on the order of 10 or more.

The above discussion addresses the apparent base error in implementation. However, there is also the question of whether or not an annular model is appropriate to the cables under study. In general, heat transfer in a single conductor cable is appropriately treated as heat transfer in an annulus. However, the licensee is dealing, in general, with triplex and multi-conductor cables. Neher/McGrath recommend an alternate expression for multi-conductor cables (see Neher/McGrath equation 39). This alternate expression is more conservative because the heat transfer in a multi-conductor cable is more complex and more restrictive than is simple conduction in a single conductor cable. In this regard, even if the gross error of implementation is corrected, the assumption of annular heat transfer for multi-conductor cables would be optimistic.

SNL finds the licensee treatment of heat flow within the individual cables appears to be in error. The net effect of this error would appear to be over-estimation of the cable insulation temperature drop. Hence, the mistake taken alone would result in reducing the estimated ampacity limits.

3.3.3 Apportioning the Heat Load to Individual Cables

As noted above, the licensee has apportioned the total heat load for the conduit to individual cables based on the cross-sectional area of each cable. This is somewhat similar to Stolpe's approach for cable trays, but may have more severe and unanticipated implications when applied to conduits. The licensee has provided no specific basis for this approach, and the approach may result in anomalous and non-conservative results for some conductors.

In general, the number of cables in a conduit will be less than the number of cables in a cable tray. Hence, the implications of size variations may be more pronounced for the conduits. To illustrate, Section 5 of the licensee Attachment B describes a conduit with a total of 15 cables installed. Of these, there are four different types of 3-conductor 14 AWG cable installed. The estimated ampacity limits for these four cable types range from 4.8 to 9.1 amps. Those cables with the thickest insulation and hence the largest cross-sections are assigned the highest ampacity limits. This result is counter-intuitive, and the range of results appears overly broad for cables of the same basic wire gage.

For a given cable ampacity, the heat load depends only on the conductor size (14 AWG in this case) and conductor count (in this case 3 per cable). For this given heat load, the thicker the insulation/jacket layer, the higher the temperature rise from the outer surface through the insulation/jacket would be. Hence, the cables with the thicker insulation would likely operate hotter for a given ampacity load than those cables with a thinner insulation/jacket layer. This would imply that the ampacity limits for the cables with thicker insulation/jacket layers should be lower than the ampacity limits for cables with a thinner insulation/jacket layer. However, the licensee approach results in just the opposite effect. Cables with thicker insulation/jacket layers are assigned higher ampacity limits. It would appear that some additional thought into partitioning of the heat load to individual cables is in order.

3.4 Specific Applications

SNL has not reviewed the specific application results in detail. The compounding effect of the identified model implementation errors makes it difficult to determine what the final answers "should be." That is, both the baseline ampacity limits and the ampacity derating factors are impacted.

However, it was noted that none of the cables cited in Attachment E carry a substantial ampacity load. This, in itself, raises potential questions as to how these in-plant loads were estimated. In particular, the analysis may not have considered all modes of plant operation. For example, a cable that is only powered during shutdown would have no load during power operations, but might carry substantial loads during other modes of operation. It may be appropriate to ensure that all modes of plant operation have been considered.

Given the ampacity loads cited in Attachment E, it appears unlikely that any of these cables will ultimately be found to be unacceptable. Each of the cited loads is quite small, and is likely well within acceptable ampacity limits.

3.5 Summary of Findings for Conduit Analyses

SNL finds that the general approach taken by the licensee in the analysis of conduit and single cable wrap applications is appropriate. However, the review has also identified at least two significant errors in the model implmentation, and has called into potential question one of the underlying analysis assumptions. These areas of technical concern are summarized as follows:

- In the implementation of Neher/McGrath equation 41, the thermal resistance between the surface of the cables and the inner surface of the conduit, the licensee has mis-interpreted the definition of the conductor count term (n'). The correct value should be the total conductor count for the entire cable bundle but the licensee has used the maximum conductor count for any single cable in the bundle. This error taken alone would result in modestly optimistic ampacity results.

- In the calculation of heat transfer within an individual cable, the licensee has implemented an incomplete and/or erroneous expression. This error taken alone would result in conservative estimates of the ampacity limit. However, the annular region heat transfer model that was presumably intended is not appropriate to the analysis of multi-conductor cables. Use of the annular region model for multi-conductor applications, taken alone, would result in optimistic ampacity results.

- The licensee practice of partitioning the total heat load to individual cables based only on the cable cross-sectional area has not been justified and appears to have led to anomalous results.

The net effect of the implementation errors noted here cannot be fully assessed. For some cases it appears that the net results of the improperly implemented model were conservative. However, the errors are all inter-related, and are serious in nature.

Ultimately, given the cable ampacity loads cited in Attachment E, none of the cited cables appears to be potentially overloaded. It may, however, be appropriate to verify that the cited cable loads have considered all possible modes of plant operation.

4.0 UNIQUE CONFIGURATION CALCULATIONS

4.1 Approach to Analysis

MNPS has four applications that do not fit neatly within the context of either the single tray or conduit calculations. These are referred to by the licensee as "unique Thermo-Lag configurations." The analyses for these cases are presented in Attachment C to the calculation, with the results summarized in Attachment F.

The four applications involve (1) a two-tiered wire-way, (2) a cable tray with one individual cable wrapped with conduit sections of Thermo-Lag fire barrier material, (3) a cable tray that has one individual wrapped cable plus a fire barrier installed over the tray as a whole, and (4) a tray with two triplex power cables that are wrapped together in a common conduit section envelope. For these applications the licensee has applied a somewhat unique set of modeling tools to estimate the clad case ampacity limits. The licensee analyses of these four cases is discussed in the sub-sections which follow.

4.2 Analysis of Raceway Z25XA10

4.2.1 Raceway Configuration

A schematic diagram of this raceway appears on page C3 of the licensee calculation. The case involves a two wire-ways mounted against a wall, one above the other. Both raceways are protected on the three exposed sides with a Thermo-Lag fire barrier system. A fire barrier panel is also placed between the two raceways. The upper raceway contains light power cables (16-10 AWG), while the lower raceway contains instrumentation only. The objective is to estimate the ampacity limits for the power cables.

The installed fire barrier has a stated thickness of 3 inches. It would appear that the barrier is comprised of two layers of 1.5" Thermo-Lag. It should be noted that no known ampacity test has involved a Thermo-Lag fire barrier of this thickness.

4.2.2 Baseline Case Analysis

The baseline ampacity is estimated using the Stolpe/ICEA thermal model as if the wire-way were a simple cable tray. The calculations appear appropriate to this case, and no implementation errors were noted. In particular, the cables are all of relatively small size, and the error noted in Section 2.2.2 does not impact this particular raceway analysis.

4.2.3 Clad Case Analysis

The clad case model is virtually identical to the model used for the analysis of other cable trays. One optimistic assumption was noted in the application of this model to this raceway. That is, the thermal model has not considered the impact of an air gap between the two barrier layers. Neglecting the air gap between layers is nominally an optimistic assumption.

However, a number of pessimistic (conservative) assumptions have also been made. The most substantial of these is that the thermal model only considers heat transfer through the top panel of the fire barrier system. This neglects heat transfer to the wall to which it is attached. In reality, the (presumably concrete) wall will act as a substantial heat sink and would moderate cable temperatures substantially.

In balance, it would appear that the licensee model contains substantial net conservatism. Hence, SNL finds its application in this case to be acceptable.

4.2.4 Assessment of Derating Factor and Cable Loads

The licensee estimates the derating factor (DF or ACF) to be 0.31. This corresponds to an ADF of 69%. This is likely a very conservative estimate of the derating impact for this particular application.

In assessing the ampacity loads of the installed cables, it is noted that all of the cables carry only very modest current loads. The highest load cited is 1.5A. In the final assessment the licensee determines that all cable loads are acceptable.

4.2.5 Summary of Findings

SNL finds that the licensee analysis of raceway Z25ZA10 is conservative, and has adequately demonstrated that the subject cables are operating within acceptable ampacity limits.

4.3 Analysis of Raceway Z23FA25

4.3.1 Raceway Configuration

Raceway Z23FA25 is a cable tray in which one cable has been clad in a fire barrier made from pre-formed conduit sections. The balance of the tray contains a number of other unclad cables. All of the cables in this raceway are relatively large power cables (250-500 MCM triplex cables). There are a total of six cables present, of which only one is wrapped. The cited thickness of the fire barrier is 1.5" and it is apparently a single layer barrier system.

4.3.2 Baseline Case Analysis

The baseline case ampacity is estimated for all of the cables in the tray that are not clad in the fire barrier. This is accomplished using the Stolpe/ICEA cable tray thermal model. To compensate for the presence of the one clad cable, the tray width is adjusted from the actual width of 24" to 18". This would appear to be an appropriate basis for analysis of this case.

In this case, because of the relatively substantial cable fill, all of the cable ampacity estimates do comply with the overall limit of 80% of open air ampacity for random fill cable trays. Hence, the concern raised in Section 2.2.2 is not relevant to this particular application. SNL finds that the cited ampacity limits for non-clad cables are appropriately estimated.

4.3.3 Clad Case Analysis

The clad case analysis involves only an analysis of the one clad cable. For the remaining unclad cables, the baseline ampacity is assumed to apply. SNL finds this to be an appropriate assumption for this case.

In effect, the licensee is estimating the actual cable ampacity limit assuming that the cable is in a conduit that is made of Thermo-Lag. The licensee applies the Neher/McGrath model to this case. SNL finds that this is an appropriate approach to analysis.

To compensate for the fact that the "Thermo-Lag conduit" is located in a cable tray, the licensee increases the assumed ambient temperature to reflect the proximity to the other cables in the tray. SNL finds this to be a reasonable and prudent approach.

The licensee implementation of the Neher/McGrath model does contain one substantial error. The error is identical to one of the errors noted in Section 3.3.2 above. That is, the licensee equation used to estimate the temperature drop through from the surface of the cable to the conductor is either incomplete or in error. Further, the apparent intent of the licensee model was to apply an annular ring model to the cable. This model is not appropriate for a triplex cable, and the licensee should apply the more conservative model for multi-conductor cables recommended by Neher/McGrath.

Overall, the net effect of the licensee's analysis has likely overestimated the insulation cable surface to conductor temperature rise because of the dominating impact of the error involving the incomplete or erroneous equation. Further, the cable in question does have substantial margin. Hence, SNL finds that, despite the modeling errors, there is an adequate basis available to conclude that the cable is operating within acceptable ampacity limits. It is recommended that the modeling error be brought to the attention of the licensee.

4.3.4 Assessment of Derating Factor and Cable Loads

For this application the derating factor is not estimated. Rather the actual ampacity limit of the one clad cable is assessed directly as discussed in Section 4.3.4 above.

4.3.5 Summary of Findings

SNL finds the licensee assessment of the un-wrapped cables in this tray is appropriate. No implementation errors were noted.

For the one clad cable, SNL finds that the licensee's approach to analysis is acceptable, but that the model implementation contains an error identical to the error discussed in Section 3.3.2. Ultimately, the licensee error has had a conservative impact on the analysis in this case.

Overall, SNL finds that the licensee has provided an adequate basis for concluding that the cables in raceway Z23FA25 are operating within acceptable ampacity limits. It is recommended that the modeling errors associated with the one clad cable be brought to the attention of the licensee.

4.4 Analysis of Raceway Z23FA30

4.4.1 Raceway Configuration

The raceway in this case is quite similar to raceway Z23FA25 (discussed in Section 4.3 above) except in that the entire raceway is also clad in a second fire barrier. That is, this case involves a cable tray with a total of four cables, one of which is wrapped with conduit sections of the fire barrier material. In addition, the entire tray is wrapped by a secondary barrier for a total length of 24" (see Section 2.2.3.3 of the licensee calculation).

4.4.2 Baseline Case Analysis

The baseline case analysis is identical to that performed for other cable trays with an adjustment made to the tray width to reflect the presence of the Thermo-Lag wrapped cable. The estimated ampacity limits do comply with the 80% of open air ampacity limit. SNL finds the estimated baseline ampacity limits to be acceptable.

4.4.3 Clad Case Analysis

In the clad case analysis the overall tray wrap is treated as a fire stop rather than as a cable tray wrap. The assumed ampacity derating impact is taken as 18% based on a recent IEEE publication. This is based on the very short coverage length (only 24"). SNL finds that this approach is acceptable in this particular application. The very short length presents a unique situation in that horizontal conduction down the length of the cables will moderate the cable temperatures as compared to a continuous fire wrap. This is especially true given that all of the cables in question are large diameter power cables.

For the one cable that is "double-clad", the treatment parallels that given to the individually wrapped cable in tray Z23FA25. An initial assessment is made of the ampacity limit for the cable in a "Thermo-Lag conduit." The same observations regarding this aspect of the analysis that were noted in the previous case, also apply to this tray as well. The same mistakes noted in the previous case also apply to this case as well. However, the same final observation regarding these mistakes also applies; that is, the net effect of the mistakes has been to reduce the estimated ampacity limit to a more conservative value. An additional 18% derate is also taken for this cable to reflect the short section of tray wrap. Again, SNL finds this to be a reasonable approach.

4.4.4 Assessment of Derating Factor and Cable Loads

The final estimates of the ampacity limits for the cables in this tray appear appropriate. The analysis does show that the cables have considerable margin even given the applied derating factors.

4.4.5 Summary of Findings

SNL finds that the licensee analysis has provided an adequate basis to conclude that the subject cables are operating within acceptable ampacity limits. It is recommended that the cited errors relating to the licensee treatment of heat transfer between the cable surface and conductor be brought to the attention of the licensee.

4.5 Analysis of Raceway Z23HA10

4.5.1 Raceway Configuration

Raceway Z23HA10 houses just two large triplex power cables. Both cables have been wrapped in a common barrier using pre-shaped conduit sections of Thermo-Lag. Again, the thickness is cited as 1.5".

4.5.2 Baseline Case Analysis

This case does not involve a baseline case analysis.

4.5.3 Clad Case Analysis

The clad case analysis is performed for the two cables as if the Thermo-Lag were a conduit. As noted in similar cases involving single cables, SNL finds this to be a reasonable approach.

The analysis suffers from the same problems as do the other conduit analyses performed by the licensee. In particular:

- The licensee has mis-interpreted the n′ factor in Stolpe Equation 41. In this case, the licensee assumes a value of 3 when the actual value should be 6, the total conductor count inside the "conduit".
- The analysis of temperature drop from the cable surface to the conductor is incomplete or incorrect.
- The model for a single conductor cable is apparently assumed when the cables are actually triplex or three conductor cables.

4.5.4 Assessment of Derating Factor and Cable Loads

No specific derating factor is estimated.

The licensee concludes that the actual cable loads are just below the acceptable cable loads (172A actual versus 175A allowable). Given the competing effects of the observed errors of analysis, it is not possible to assess whether or not the cables are actually operating within acceptable ampacity limits.

4.5.5 Summary of Findings

SNL finds that the licensee's approach to analysis of raceway Z23HA10 is acceptable. However, the licensee has made mistakes in the analysis. It is not possible to assess the net impact of these mistakes, and by the licensee's own analysis, the available margin is quite small. SNL finds that this case remains inconclusive. The licensee has not adequately demonstrated that the cables are operating within acceptable ampacity limits.

4.6 Summary of Findings for the Unique Configuration Analyses

SNL finds that the licensee's approach to the analysis of its unique configurations is generally acceptable. For each of the four cases, one or more errors were identified in the analyses. For three of the four cases, SNL finds that despite the errors, the licensee has provided a sufficient basis for concluding that the cables are operating within acceptable ampacity limits. The exception is raceway Z23HA10. In this one case, the acceptability of the ampacity loads has not been adequately demonstrated because the analysis contains at least three errors, and because the licensee's analysis has shown only a very minimal remaining margin. It is recommended that the analysis errors be brought to the attention of the licensee, and that the licensee be asked to re-examine its conclusions regarding raceway Z23HA10 once those errors have been corrected.

5.0 SUMMARY OF FINDINGS AND RECOMMENDATIONS

SNL has identified numerous errors in the licensee calculations. The errors impact all three classes of calculations; namely, the cable trays, conduits, and unique configurations. For several of the cable trays, all of the conduits, and three of the four unique configurations, the available information is sufficient to conclude that the cables are operating within acceptable ampacity limits. However, for at least seven of the cable trays and one of the four unique configurations, the acceptability of the actual plant ampacity loads remains indeterminate.

As a final note, the licensee itself did identify four cases involving cable trays where the cables were found to be nominally overloaded. SNL finds the licensee's approach to the resolution of these cases to be unacceptable. In particular, the licensee cites reliance on the cable emergency overload ratings as the basis for accepting the overload conditions. SNL recommends that the USNRC reject this approach, that is, SNL recommends that emergency overload ratings are an inappropriate basis for accepting anticipated ampacity loads under normal conditions of operation.

6.0 REFERENCES

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