Template NRR-092

March 1, 2000

Mr. Daniel G. Malone
Acting Director, Licensing
Palisades Plant
27780 Blue Star Memorial Highway
Covert, MI 49043

SUBJECT: PALISADES PLANT - CABLE AMPACITY ADJUSTMENT METHODOLOGY (TAC NO. MA3808)

Dear Mr. Malone:

By letter dated November 3, 1998, Consumers Energy Company responded to questions raised by the NRC staff during an October 22, 1998, telephone call regarding the cable ampacity adjustment methodology used for the Palisades Plant. Consumers Energy Company also provided relevant information by earlier letters dated July 10, 1997, and June 25, 1998. The NRC staff, with assistance from its contractor, Sandia National Laboratories (SNL), has completed a review of your ampacity methodology and finds it to be acceptable. In view of certain restrictions you have applied regarding application of the alternate ampacity methodology, we have no further questions or concerns. The results of the review are presented in the enclosed staff evaluation report and its associated Letter Report, "A Review of the Harshe/Black Diversity Based Ampacity Method as Published and as Applied at the Palisades Nuclear Plant," dated December 19, 1997, by SNL.

This completes our review efforts under TAC No. MA3808. If you have any questions regarding this matter, please contact me at (301) 415-3049 or by e-mail at *dsh@nrc.gov*.

Sincerely,

/RA/

Darl S. Hood, Senior Project Manager, Section 1
Project Directorate III
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Docket No. 50-255

Enclosure: Staff Evaluation Report

cc w/encl: See next page

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

March 1, 2000

Mr. Daniel G. Malone
Acting Director, Licensing
Palisades Plant
27780 Blue Star Memorial Highway
Covert, MI 49043

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Darl S. Hood

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Project Directorate III
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Docket No. 50-255

Enclosure: Staff Evaluation Report

cc w/encl: See next page

Palisades Plant

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

STAFF EVALUATION REPORT BY THE OFFICE OF NUCLEAR REACTOR REGULATION

REGARDING CABLE AMPACITY METHODOLOGY

CONSUMERS ENERGY COMPANY

PALISADES PLANT

DOCKET NO. 50-255

1.0 INTRODUCTION

On July 11, 1996, Consumers Energy Company (the licensee) determined that a number of cables at the Palisades Plant did not meet the ampacity design basis stated in Section 8.5.2 of the Palisades Final Safety Analysis Report (FSAR). Specifically, the licensee had not analyzed or dispositioned power cables in overfilled cable trays (with greater than 30 percent physical fill) to confirm the acceptability of existing ampacity limits.

The licensee analyzed and documented a sample of overfilled cable tray sections that could potentially exceed the Insulated Power Cable Engineers Association (IPCEA)/Insulated Cable Engineers Association (ICEA) method (References 3 and 4 of the attached Letter Report) and made adjustments based upon field conditions using the Harshe-Black methodology. As described in the Institute of Electrical and Electronic Engineers' (IEEE's) paper entitled "Ampacity of Cables in Single Open-Top Cable Trays" by B. L. Harshe and W. Z. Black (IEEE Transaction on Power Delivery, Vol. 9, No. 1, pp. 1733-1739, October 1994), the Harshe-Black ampacity methodology is a mathematical thermal model that can be used to predict the operating temperatures for cables when there is load diversity (i.e., cable trays do not have all cables loaded simultaneously to their maximum allowable levels) in a single, horizontal, open-top cable tray.

NRC Headquarters staff assisted Region III with its overview of the licensee's resolution of the ampacity issue by assessing the Harshe-Black methodology used at Palisades. During the course of this review, the licensee responded to the NRC staff's written requests for additional information regarding this methodology by letters dated July 10, 1997, and June 25, 1998. By letter dated November 3, 1998, the licensee responded to the NRC staff's questions raised during an October 22, 1998, telephone call regarding the implementation of the licensee's ampacity adjustment methodology. The NRC staff, with assistance from its contractor, Sandia National Laboratories (SNL), has completed a review of the licensee's ampacity methodology. The results of the review are presented in the remainder of this staff evaluation and in SNL's Letter Report, "A Review of the Harshe/Black Diversity Based Ampacity Method as Published and as Applied at the Palisades Nuclear Plant," dated December 19, 1997 (Attachment).

ENCLOSURE

2.0 EVALUATION

After reviewing the licensee's submittals and SNL's Letter Report, the NRC staff agrees with the SNL analyses and conclusions. The ampacity adjustment analysis review and a discussion of the application of the ampacity adjustment methodology follows.

2.1 Ampacity Adjustment Analysis Review

2.1.1 Potential Nonconservative Aspects of the Harshe-Black Model:

As discussed in Sections 2.1, 2.2, and 2.3 of the attached Letter Report, the NRC staff and SNL identified two potential nonconservative aspects of the Harsche-Black model. The first of these is that localized heating effects of the power cables may be inappropriately "diluted" if one were to analyze a relatively wide tray with a very small number of power cables. Consider, for example, a case involving a single-powered cable in a larger mass of cables. Using the as-published Harshe-Black approach, the single cable would be modeled as a very thin layer stretching across the full width of the tray. This would be a very unrealistic model for this situation and it overemphasizes the importance of tray width. In such a case, those portions of the tray remote from the powered cable (more than a few cable diameters away) will have little real effect on the behavior of the cable of interest. The as-published Harshe-Black model would over-credit the heat dissipating effects of the surrounding cables, and could very easily result in overly optimistic ampacity estimates.

The second potential nonconservative aspect is that the Harshe-Black model might overestimate cable ampacity limits under certain conditions. In particular, if several powered cables happen to be clustered in close proximity to each other, then the localized heating effects may be more pronounced than will be estimated by Harshe-Black. SNL finds the original arguments regarding this aspect of the model put forth by Harshe-Black to be unconvincing.

In light of the specific SNL findings and the thermal modeling concerns identified above, the NRC staff requested that the licensee reconsider its unqualified endorsement of the Harshe-Black ampacity methodology or, alternatively, provide additional technical justification. In its June 25, 1998, letter, the licensee replied that it recognizes that the Harshe-Black ampacity adjustment methodology contains limitations, and as a result, the Harshe-Black methodology is not endorsed on an unqualified basis. The analytical models used in the licensee's analysis from the Harshe-Black methodology only utilize the concept of "layering" cables based upon the cable's thermal loading. The licensee's approach also develops layer parameters and tray thermal models based upon a conservative representation of the cable configuration. Specifically, on the thinning and clustering issues, the Palisades model reduces the width of the cable tray analytically for those cases when there are a very small number of power cables in the cable tray in order to adjust for localized heating effects of the cables and to avoid underestimating the heat sources.

The information provided by the licensee resolved the NRC staff's concerns regarding these potential nonconservative aspects of the Harsche-Black model.

2.1.2 SNL's Recommended Restrictions

SNL found that the Palisades-modified Harshe-Black method does have a nominal ability to provide realistic and reasonable estimates of cable ampacity limits or cable operating temperatures under a range of diverse load conditions. However, the validation studies performed by SNL also identified certain conditions under which unreasonable results might be obtained through this method. These undesirable results relate to cases where a number of very large cables are grouped together. Given these concerns, SNL recommended (see Section 4.2 of the attachment) that the application of the modified Palisades ampacity determination methodology be subject to the following two restrictions:

a. That the Palisades modified diversity method not be applied to any tray that includes two or more cables that: (1) are powered to at least 80 percent of the nominal ICEA cable tray ampacity limit; and (2) has a diameter exceeding the tray fill depth when calculated using the ICEA definitions of depth of fill. For this case, as noted by Stolpe (see J. Stolpe, "Ampacities for Cables in Randomly Filled Trays," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-90, part I, pages 962-974, 1971), a potential for a severe localized hot spot exists that would make it unwise to credit diversity in the ampacity assessment.

b. That a lower bound be established on the thickness of the combined hot and warm zones in the diversity thermal model. This would: (1) prevent excessive "thinning" of the more heavily loaded cables; (2) more accurately reflect the presence of larger diameter cables in the hot group; and (3) ensure a conservative treatment of potential clustering effects. SNL recommended that the combined thickness of the hot and warm zones should equal or exceed 80 percent of the diameter of the largest cable in these two groups. If the condition is not met by the nominal model formulation, then the width of the analyzed section may be adjusted (reduced) so as to increase the hot/warm zone thickness until the restriction is met, provided that the overall heat load for each cable group is maintained at their correct values.

The NRC staff requested that the licensee consider the two restrictions as recommended by SNL for the Palisades-modified Harshe-Black methodology in terms of their acceptability and to verify whether the existing analysis performed for the applicable raceways requiring adjustment according to the Palisades FSAR, Section 8.5.2, were bounded for the two application restrictions. Alternatively, the licensee could provide comprehensive validation data sufficient to address the technical shortcomings of the modified Harshe-Black methodology as cited by the SNL findings. (See Sections 2.4 through 2.6 of the attachment).

In its letter dated June 25, 1998, the licensee agreed with the NRC staff concept that a potential exists for a localized hot spot to exist if the two conditions cited in Restriction a are present. The licensee reviewed the analyzed cable trays at Palisades for these conditions and determined that there are no cases in which the two conditions exist. The licensee also verified that 80 percent of the allowable ICEA open air ampacity is not exceeded by the installed plant configurations.

In its June 25, 1998, letter, the licensee also agreed to investigate the impact of a lower bound. The licensee's review of the ampacity analysis for Palisades indicates that the margin that exists in the maximum calculated cable trays' temperatures is sufficient to account for any slight increases that may occur due to the lower bound. The licensee stated that it would continue the analysis for every cable tray with a combined thickness of the hot and warm zones less than 80 percent of the diameter of the largest cable in the subject zones.

The information provided by the licensee resolved the NRC staff's concerns for the potential for undesirable results for the conditions discussed in Restriction a above. The licensee indicated that results were still pending regarding the impact of a lower bound as discussed in Restriction b above. Thus, the resolution of this issue is based upon a later licensee response that is discussed in Section 2.2 of this staff evaluation report.

2.1.3 NRC Staff's Requested Clarifications

Although SNL observed that there are no specific errors in the implementation of the Palisades-modified ampacity example calculation provided by the licensee, several points required additional clarification:

a. The basis for the licensee's assessment of the assumed plant ampacity loads was not clear. The NRC staff requested that the licensee explain how the cable load ampacity values were obtained, and confirm that this practice bounded the most conservative possible configuration for each tray analyzed, including consideration of all possible modes of plant operation.

b. The example case provided by the licensee had assumed an emissivity of the top surface of the cable mass of 0.95. The NRC staff requested that the licensee clarify this value as it was not consistent with either typical practice or the measured Palisades emissivity values cited in the Harshe-Black paper.

c. In the licensee model, the emissivity of the lower surface of the cable tray was cited as 0.65. The NRC staff asked the licensee to explain and justify the chosen value of 0.65 for the bottom surface of the cable mass. If any of the cable trays under analysis were solid-bottom type trays, then the licensee was requested to explain whether the cables were installed in direct and continuous contact with this bottom surface, or were laid on internal rungs within the tray, and whether the bottom surface was ventilated. If the cables are not in intimate contact with the bottom plate, and the bottom plate is not ventilated, then the NRC staff asked the licensee to explain how the model was adjusted to account for the additional air gap between the bottom of the cables and the tray bottom. The NRC staff and SNL noted that the Harshe-Black thermal model does not inherently allow for any such gap, but rather, inherently assumes either direct cable-to-bottom plate contact or installation in an open ladder-type tray.

In its letter dated June 25, 1998, the licensee provided the following clarifications:

> The basis for the Palisades ampacity analysis was to determine the maximum expected cable tray temperature. To determine this maximum temperature, the continuously energized power cables which could contribute to the overall heat intensity in a given cable tray section were identified. A continuously energized cable is defined as a cable which is energized during any plant condition long enough to generate a significant amount of heat. Control cables and intermittent or infrequent loads such as motor operated valves, emergency equipment, test equipment, and cranes were not

considered continuously energized. The analysis conservatively assumed that continuous loads are energized at the same time and did not take credit for the diversity of safety-related loads (i.e., loads from redundant divisions are considered energized).

The licensee stated that these assumptions provide bounding results for the analyses. The resulting calculation yields the maximum expected heat generated by the cables in each analyzed tray section.

The emissivity value of the top surface of the cable mass and the bottom cable and tray surface used in the ampacity analysis was obtained from Appendix B of ICEA P-54-440 (Third Edition), WC-51, "Ampacities of Cable in Open Top Cable Trays." This standard identifies the effective thermal emissivity of the cable surface as 0.95 and the steel tray surface as 0.33. Based upon this standard, the top cable surface was assigned the value of 0.95.

The cable trays installed at Palisades are ladder type open-bottom trays. The bottom surface was assigned the arithmetic average of (0.95 + 0.33)/2 or 0.65 for emissivity. This conservatively assumes that there is an equal amount of cable surface and tray surface along the bottom of the tray. The spacing of the bottom rails for cable trays at Palisades provides for a larger amount of cable surface than tray surface, and therefore this emissivity value is conservative.

Additional justification for the emissivity values used for the Palisades analysis was provided in Omega Point Laboratories Report No. 14540-100770, "Ampacity Derating of Fire Protected Cables," dated December 5, 1996. Omega Point Laboratories conducted a test for Illinois Power Company (Clinton Station) to determine the ampacity derating of cables when an Electrical Raceway Fire Barrier System is installed on the cable system. The test was conducted on a 24" wide by 4" deep steel ladder back cable tray assembly, clad with 3M Interam fire protection materials. The test was performed in accordance with Draft 16 of IEEE Standard P848, "Standard Procedure for the Determination of the Ampacity Derating of Fire Protected Cables."

One of the measurements made during the test was the surface emissivity of the cable jacket and the cable tray (galvanized steel). All emissivity measurements were made with the test article at its equilibrium temperature. The surface emissivity of the test article was measured at nine points on each different surface type. The average emissivity of the nine locations was as follows:

Test Article	Surface Type	Measured Emissivity
24" Cable Tray	Galvanized Steel Tray	0.38
24" Cable Tray	Cable Jacket Surface	0.99

Overall, the emissivity values used for the Palisades cable ampacity calculation (0.95 for the cable surface and 0.33 for the steel cable tray) provide for conservative results since lower emissivity will result in lower cable temperature.

The NRC staff finds the information provided by the licensee to be acceptable and responsive the NRC staff's need for clarifications.

2.2 Application of Ampacity Adjustment Methodology

The NRC staff agrees with the SNL finding (see e.g., Appendix B of the attachment) that both the basic Harsh-Black method and the licensee's modified version of the method (in which the width of the analyzed section may be limited) can result in very significant increases in cable ampacity limits as compared to the industry standards (i.e., ICEA methods) that do not credit diversity. For example, some of the cases calculated by SNL resulted in the tripling of the estimated ampacity limit. Thus, load diversity can significantly impact cable operating temperatures under realistic installation conditions.

Further, supplemental validation studies performed by SNL did reveal at least one potential weakness of the method. That is, when the cable load includes very large power cables that are heavily loaded, then the method may underestimate cable temperature increases. This weakness is caused by the way in which the heavily loaded cables are modeled as a relatively thin layer across the width of the section analyzed by the thermal model. Therefore, the model may not adequately treat the localized heating effects associated with power cables that are large in comparison to either the overall tray fill depth, or to other heavily loaded cables that are physically smaller. The most significant potential limitations are:

- The Harshe-Black method may overstate the role of heat dissipation across the width of the tray when only a very few powered cables are present. The licensee's modifications adequately address this point of concern.
- Ampacity limits for large cables may be overstated. The NRC staff notes that the licensee has implemented a limitation in its own assessments for large cables.
- If some subset of the powered cables are located in close proximity to one or more large heavily loaded cables, then ampacity limits may be overstated. The licensee's modification to the Harshe-Black method reduces the potential magnitude of the error, but does not entirely eliminate it. Some constraints on the application of the method are needed to prevent this potential for error from being realized in ampacity analyses.

Overall, the Harshe-Black methodology as originally published is deficient for two main reasons: (1) it may allow an overly optimistic treatment of potential localized heating effects under certain circumstances, and (2) it will overstate the role of heat dissipation within the cable mass for cases involving a small number of powered cables. For these reasons, the NRC staff agrees with SNL that the Harshe-Black methodology should not be accepted for unqualified use in cable ampacity limit assessments.

With regard to the modified Harshe-Black method, the NRC staff stipulates that the following restrictions should be used in the Palisades assessments:

- The method should not be applied to any tray that includes two or more cables that are (1) powered to at least 80 percent of the nominal ICEA cable tray ampacity limit, and (2) whose diameter exceeds the tray fill depth when calculated using the ICEA definitions.
- In formulating the thermal model, a lower bound should be established on the combined thickness of the central high-intensity or "hot" and "warm" cable layers to prevent

excessive "thinning" of this layer and to more accurately reflect the presence of larger cables in this group. These two groups will likely represent the total heating source for the thermal model. The NRC staff recommends that this lower bound be no less than 80 percent of the diameter of the largest cable in the hot and warm groups.

The first restriction is specifically intended to address the Stolpe test results (see Section B.3.2, Appendix B of the attachment) and the concerns expressed in his pioneering work on cable tray ampacity. It would disallow use of the diversity method in cases where the potential exists for a smaller cable to be "sandwiched" between two larger, heavily loaded power cables. The second restriction is intended to address the potential clustering of a number of smaller cables in close proximity to a larger powered cable. By placing a lower bound on the combined thickness of the "hot" and warm cable layers, this approach will ensure that the heating zone is modeled with a thickness that is at least nominally consistent with that of the larger cables.

By letter dated November 3, 1998, the licensee responded to questions raised by the NRC staff during a telephone call on October 22, 1998, to discuss the implementation of the licensee's ampacity adjustment methodology. The licensee confirmed that its reevaluation of the 367 open air cable trays had been completed and identified 87 trays that met the condition where the hot and warm zones do not exceed 80 percent of the diameter of the largest cable in these two zones. The licensee re-evaluated these 87 cable trays, along with 34 cable trays that pass through fire stops, using the revised computer model. The results of this re-evaluation indicated that the calculated tray temperatures will remain below the insulation temperature rating of the cables in the trays. The NRC staff finds this response to be acceptable and it resolves the NRC staff's concerns for the licensee's ampacity adjustment methodology.

In summary, the NRC staff agrees with SNL's finding that, given the lack of rigorous model validation and the potential for misapplication of nonconservative results, the Harshe-Black method, as originally published, is not acceptable for use. However, the use of modified Harshe-Black methodology as implemented, given the restrictions cited herein, is acceptable for use at Palisades. The licensee has provided sufficient information for the application of an ampacity adjustment methodology, consistent with appropriate and conservative engineering practices.

3.0 CONCLUSION

On the basis of the above evaluation, the NRC staff concludes that the relevant concerns associated with the Harshe/Black ampacity adjustment methodology have been resolved and the licensee has provided an adequate technical basis to assure that the modified Harshe-Black methodology is acceptable for use at Palisades. Given the restrictions described herein regarding the application of this methodology, the NRC staff has no outstanding safety concerns regarding the cable ampacity methodology used at Palisades.

Attachment: Letter Report

Principal Contributor: R. Jenkins

Date: March 1, 2000

A Review of the Harshe/Black Diversity Based Ampacity Method as Published and as Applied at the Palisades Nuclear Plant

A Letter Report to the USNRC

Revision 0

December 19, 1997

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USNRC JCN J-2503, Task Order 5

ATTACHMENT

TABLE OF CONTENTS:

FORWARD

The United States Nuclear Regulatory Commission (USNRC) has solicited the support of Sandia National Laboratories (SNL) in the review of utility submittals associated with fire protection and electrical engineering. This report represents the first in an anticipated series of reports associated with the Palisades Nuclear Plant (PNP). The report documents a SNL technical review of a licensee submittal involving a new method of ampacity assessment for random fill cable trays. In particular, the submittal documents a method that explicitly credits load diversity. The standard approaches to ampacity assessment for cable trays provide no provisions for crediting load diversity. Hence, this new method represents a departure from previously accepted methodologies. The current report documents an initial review by SNL of the licensee submittal and, in particular, the diversity crediting methodology both in its base as-published form and as modified by PNP for the actual licensee applications. This effort has been conducted under USNRC JCN J-2503, Task Order 5.

1.0 INTRODUCTION

1.1 Objective

In response to USNRC Generic Letter 92-08 and a subsequent USNRC Request for Additional Information (RAI), in July 1997 the Palisades Nuclear Plant (PNP) provided documentation of the utility position regarding the acceptability of ampacity loads for fire barrier clad cables. SNL was requested to review portions of this submittal under the terms of Task Order 5 of the General Technical Support contract USNRC JCN J-2503.

The objective of the current review as stated in the Task Order Statement of Work is to "Review and evaluate the submittals from Consumer Power Company regarding its alternative ampacity determination methodology (denoted Harshe-Black method) and determine its acceptability and appropriateness to meet the regulatory requirements as cited in the Palisades Final Safety Analysis Report (FSAR). Evaluate the Harshe-Black methodology as used by the licensee against other previous findings derived from work performed under JCN J-2018 and J-2017 including applicable industry standards."

The licensee submittal in question was submitted to the USNRC as follows:

- Letter, July 10, 1997, Thomas C. Bordine, Consumers Energy, to the USNRC Document Control Desk, licensee reference Docket 50-255 - License DPR-20 with one attachment (including 4 cited enclosures).

Note that in addition to the Harshe-Black based analyses, the full submittal deals with a number of other applications and analysis methods. These include assessments for open air conduits, duct banks, and cable trays traversing fire stops. SNL has not reviewed these other ampacity assessments, but rather, has limited our review to those portions directly related to the Harshe-Black method consistent with the statement of work cited above. These calculations are documented in Enclosure 1 of the licensee submittal.

1.2 Overview of the Utility Approach

The licensee has taken a unique approach to the assessment of ampacity loads. In particular, the assessments are based on application of a "modified" Harshe-Black approach to analysis. The original Harshe-Black method was documented in an *IEEE Transactions* paper [1]. The licensee has applied a modified version of the base method in order to explicitly address certain limitations and potential pitfalls of the methodology, and these modifications will weigh heavily in SNL's evaluation as will be discussed in Chapter 2 below.

In summary, the Harshe-Black methodology is intended to explicitly credit cable ampacity load diversity in the analysis. In this sense, the method does depart from the standardized approaches of Stolpe [2] or IPCEA/ICEA [3,4]. The standard methods, and in particular the standard cable tray methods, allow no credit for load diversity. The standard methods conservatively assume that all cables are loaded to their full ampacity limits. In actual applications only a subset of the installed cables will actually carry continuos power loads while others will be normally de-energized (such as control cables or intermittent power cables). Hence, the overall heat load on the system may be lower than that assumed in the standard ampacity tables, and some additional ampacity margin will be realized. The explicit intent of the Harshe-Black method is to relax the no-diversity assumption in a systematic manner and to allow higher ampacity limits on the basis of diversity. Indeed, the ampacity limits derived using the Harshe-Black method may significantly exceed the standard ampacity limits.

1.3 Organization of Report

This review has focused on a general assessment of the licensee ampacity assessments. This review has included a specific assessment of the acceptability of both the base as-published and the licensee applied modified Harshe-Black ampacity analysis methodologies. Section 2 presents an overview of the diversity-based analysis methodology including the modified method proposed by the licensee. Section 3 provides a brief review of the individual licensee sample calculations. Section 4 summarizes the SNL recommendations regarding the need for additional information to support the final assessment of the utility analyses. Appendix A presents a listing of a simplified implementation of the Harshe-Black method used by SNL to support parts of this review. Appendix B provides a more detailed examination of the Harshe-Black method, including some supplemental validation studies performed by SNL.

2.0 THE HARSHE-BLACK METHODOLOGY

2.1 Overview and Background

As noted in Section 1.2 above, the specific intent of the of Harshe-Black method is to credit diversity in cable power loads as a part of the ampacity assessment process. The original method was documented in an *IEEE Transactions* paper [1]. As the paper cites, the widely accepted ICEA P-54-440 method [3], which derives from the work of Stolpe [2], assumes no diversity in its cable ampacity assessments. This is, recognizably, a conservative approach to analysis because in practice it is unlikely that every cable in a tray will be loaded to its full ampacity limit. The explicit intent of the Harshe-Black method is to relax the "no-diversity" assumption in a systematic manner.

The discussions that follow in this chapter will begin with a brief review of the diversity issue (Section 2.2)[1]. A description of the base as-published Harshe-Black methodology will be provided in Section 2.3. Next, the modifications implemented by the licensee in their own applications will be discussed (Section 2.4). In section 2.5 SNL will consider the relative impact of the method on tray ampacity limits. Section 2.6 will take up the question of model validation, and will explore some additional validation comparisons.

Note that the discussions of this chapter are supported by the information provided in both Appendices A and B. Appendix A provides a listing of the program used by SNL to develop the numerical results discussed here. Appendix B provides a more detailed and explicit discussion of the method, its impact on ampacity limits, its validation, and its limitations.

2.2 Some Words of Caution From Stolpe

It must be recognized that diversity in cable loads and the potential for crediting diversity is by no means a new subject. The current standardized method for cable tray ampacity assessment [3] is based on the work of Stolpe [2], and it bears repeating here that Stolpe had clear and significant reservations regarding any methodology which attempted to systematically or generically credit load diversity in ampacity assessments.

As a basis for his concerns, Stolpe cites his own testing that did include one very limited test of a diverse load case. As a part of his tests, Stolpe had assembled one cable tray containing eight different wire gauges, and for one wire gauge (12 AWG) both a single-conductor and multi-conductor cable. In one particular test, Stolpe applied power to just three of the nine different cable groups. Each group was powered to the ampacity that his own model (assuming no diversity) predicted would lead to a 50°C temperature rise in the conductors (90°C cable hot spot and 40°C ambient). Stolpe made the following observations regarding the results of this test:

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[1]The discussion in Section 2.2 is excerpted largely from a SNL letter report of 8/14/97 related to the Palo Verde ampacity assessments and a SNL review of the alternate Leake diversity analysis methods. The same observations are relevant to any diversity-based ampacity method, and are noted again here for clarity and consistency.

"The No. 6 (AWG) cables ran about 15°C cooler than when all cables were energized but the 4/0 cabl: ..ly an 1°C cooler. It is from this experimental finding that it appears to be unwise to increase cable ampacities on the basis of diversity. The cables in the above diversity test were separated by about 6-inches of "dead" cable, but it is conceivable that the No. 6 cables could be placed adjacent to, or between, some 4/0 cables. If the cables in this configuration had increased ampacities based on assumed diversity, there would undoubtedly be a local hot spot in the cable tray. Thus, it seems impossible to apply a general increase in the ampacities of smaller cables due to diversity because there is no general way to assure that small cables would remain separated from large cables in randomly filled trays."

It is quite clear from this passage that any method for crediting diversity will be controversial. Clearly, diversity is a real phenomena common to most actual nuclear plant applications. The Stolpe method is conservative in that it allows no credit for diversity. When significant levels of diversity can be demonstrated, it may be appropriate to relax this conservatism. Ultimately, there are two critical questions to be answered:

(1) What methods of credit are appropriate?

(2) Under what circumstances should credit for diversity be allowed?

Note that the two questions are related. That is, the method by which diversity is credited will impact the decision as to when that methodology is appropriate for use. The current topic of discussion is the Harshe-Black methodology, and hence, the observations and recommendations made here are limited to that method.

2.3 The Base As-Published Harshe-Black Method

The Harshe-Black analysis method is based on a fairly simple modification of Stolpe's method for the analysis of cable tray ampacity. The only difference between the models lies in the treatment of heat transfer effects within the cable mass itself which, in turn, impacts the assumed overall heat load on the thermal system. The changes may appear minor, but they can have a quite substantial impact on the estimated ampacity limits of the cables. This will be discussed further in Section 2.5 below.

In the original Stolpe/ICEA method, all of the cables are assumed to be powered to an equal level and the cable mass is treated as a single homogeneous region with a uniform rate of volumetric heat generation throughout. This is, in practice, expressed as the rate of heat generation per unit cross-section of the cable mass, or the heat intensity. The model then treats heat transfer within this cable mass using a simplified one-dimensional solution, and treats heat transfer between the surface of the cable mass and the ambient using simple convection and radiation correlations.

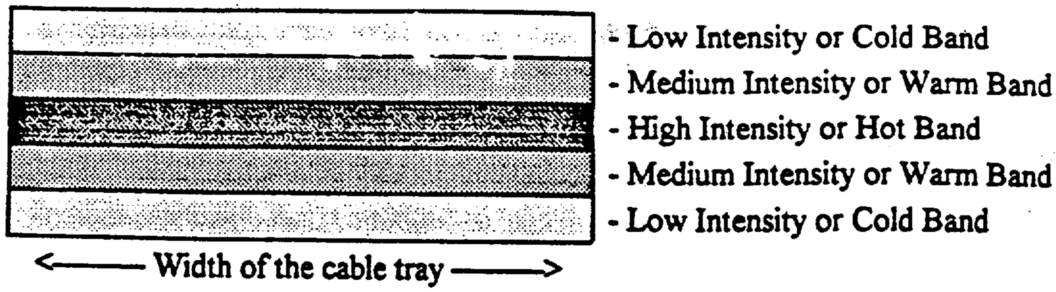

Figure 1: Schematic of the Harshe-Black cable mass thermal model for conduction heat transfer analysis with the layered cable sections.

In contrast, the Harshe-Black method separates the cables in the tray into as many as three groups according to their actual in-service heat intensity loads; namely, the hot, warm, and cold (or high, medium, and low intensity) cable groups. A layered thermal conduction model is then assembled with the highest intensity cables in the center, and the lowest intensity cables at the top and bottom surfaces as illustrated in Figure 1. In the analysis it is clearly the high-intensity cable that are of primary concern. If these cables are operating at acceptable temperatures, then the other lower intensity cables will also be acceptable.

One other aspect of this change is also very important. That is, the heat generation rate for each layer is based on the sum of the actual heating rates for the individual cables in that group. This is will substantially reduce the overall system heat load in comparison to the Stolpe model in which all cables are assumed to be powered to the code limit ampacity.

The overall thermal model is based on a conduction analysis of the layered cable mass coupled with a standard treatment of the cable surface to ambient convection and radiation behavior. Significant increases in the estimated allowable ampacity limits are realized because (1) the zone of highest heating is limited in size as compared to Stolpe's model, and (2) the overall heat load on the system is reduced compared to Stolpe. Both factors contribute to lower temperature drops for a given situation, or equivalently, higher maximum heat intensity limits for a given set of temperature conditions.

The Harshe-Black model is clearly less conservative than the Stolpe/ICEA model, a fact acknowledged by PNP. Indeed, it can result in substantially higher ampacity limits in comparison to the Stolpe assumptions. This is discussed in more detail in Appendix B below. Some of the inherent conservatisms associated with the Harshe-Black method are:

- The highest intensity cables are assumed to be located along the horizontal centerline of the cable mass so that the insulating effect of the surrounding cables is nominally maximized. In reality, cables may be located anywhere in the tray, including at the surface of the cable mass.

- Heat transfer from the sides of the cable tray system are not credited. This is consistent with Stolpe's method. This is nominally conservative, but is especially appropriate for a diversity case where a cable may be located remote from the edges of the tray. Any credit for heat transfer from the sides may be excessive under these conditions

The primary sources of potential non-conservatism in the method derive from the following factors and situations:

- If one is analyzing a relatively wide tray with a very small number of power cables, the localized heating effects of the power cables may be inappropriately "diluted." Consider, for example, a case involving a single powered cable in a larger mass of cables. Using the as-published Harshe-Black approach, the single cable would be modeled as a very thin layer stretching across the full width of the tray. This would be a very un-realistic model for this situation and over-emphasizes the importance of tray width. In such a case those portions of the tray remote from the powered cable (more than a few cable diameters away) will have little real effect on the behavior of the cable of interest. The as-published Harshe-Black model would over-credit the heat dissipating effects of the surrounding cables, and could very easily result in overly optimistic ampacity estimates.

- There is a potential that the Harshe-Black model might overestimate cable ampacity limits under certain conditions. In particular, if several powered cables happen to be clustered in close proximity to each other, then the localized heating effects may be more pronounced than will be estimated by Harshe-Black. SNL finds the original arguments regarding this aspect of the model put forth by Harshe-Black to be unconvincing.

  The original paper by Harshe-Black does cites that the validation field measurements did include some assessment of clustering effects. One of the measured trays included one group of three powered cables each with an ampacity load "almost twice the code ampacity limit" and two clusters of 3 and 6 cables respectively for which the cables were loaded to about 60% of the code ampacity. The results are cited as indicating a "weak influence of mutual heating between cables and the strong correlation with the electrical current." The implication being that clustering of the cables is not as important as one might expect.

  These results appear to be contradicted to some extent by the authors Figure 4. Here the effect of cable groupings appears to be quite significant. Further, in the discussion the authors state that clustering appeared to have little or no impact when the cable loading was 60% or less than the code limit. This would indicate that the previous conclusions regarding the relative impact of clustering based on comparisons between a heavily loaded cable cluster and two lightly loaded cable clusters were inappropriate.

  Note that in Appendix B SNL has documented some limited validation results that appear to indicate that some level of conservatism is retained even given some clustering of the powered cables. However, the cases available for experimental validation are quite limited, and do not explore the full range of potential applications. This is considered a serious potential shortcoming of the as-published method that has not been adequately addressed.

- If a particular case involves an especially large power cable whose diameter approaches the fill depth, then the Harshe-Black method may overestimate the ampacity limit for this cable. This is actually also a problem for the Stolpe method. Hence, Stolpe recommended that no cable ampacity should exceed 80% of the open air limit. Harshe-Black endorses this constraint as well, and this should mitigate the concern for the larger cables themselves.

- A concern related to that immediately above is that if the tray contains two or more very large power cables that are both powered at or near their ICEA ampacity limits, then a smaller cable that is sandwiched between these two cables may be subjected to a severe localized hot spot, and increasing the ampacity limit of the smaller cable based on diversity elsewhere in the tray may be inappropriate. This is the concern raised by Stolpe, and SNL finds that this concern has not been adequately addressed in the Harshe-Black method. As discussed further in Appendix B below, SNL recommends that diversity should not be credited when this potential exists.

As a final point, it should be noted that the Harshe-Black paper retains the upper bound ampacity limit of 80% of the open air ampacity for all cables in a random fill cable tray. This was one element of the ICEA tables as well. The paper points out that under the Harshe-Black method there is no theoretical limit to a cables potential ampacity. That is, any cable could be found to have an infinite ampacity limit provided that the tray was infinitely wide. Clearly, unrealistic results are quite possible, again, due largely to the overstating of the width effect in the thermal model. The 80% limit provides some nominal assurance that absurd answers are not credited in an analysis. PNP has specifically stated that the 80% limit was also retained in their own analyses.

Appendix B provides a more detailed review of the as-published Harshe-Black method including certain supplemental validation studies performed by SNL. On the basis of this review, SNL finds that the as-published Harshe-Black methodology may significantly overestimate cable ampacity loads. Hence, SNL recommends that this version of the method should not be accepted for use in nuclear power plant applications.

2.4 The PNP Modified Method

PNP has made one very critical modification in its own application of the Harshe-Black methodology. This modification does make the licensee analyses somewhat more conservative than would be obtained using the base as-published Harshe-Black methodology, especially as applied to cases with only a small number of powered cables. This modification impacts to some extent all of the items identified by SNL in Section 2.3 above as potential sources of modeling non-conservatism. Hence, an understanding of the licensee modification and its impact is critical to SNL's assessment of the PNP submittal.

The modification made by PNP imposes a limit on the width assumed for the cable tray section analyzed by the thermal model. That is, in the as-published method, the width of the modeled section is always the actual tray width. In the PNP applications, under certain circumstances the width of the modeled section may be less than the full tray width. The actual section width is defined as a part of the model formulation process. PNP follows the same process outlined by Harshe-Black for grouping the cables into hot, warm, and cold groups and then proceeds to "build up" a section of the cable tray for thermal analysis, the "modeled section".

Initially, all of the "hot" cables are taken as a group, and the width of the modeled section is limited to the sum of the hot cable diameters plus one-half the actual cable tray depth of fill. If this value is equal to or greater than the tray width, then the method defaults back to the base as-published method, and the tray width is used as the width of the modeled section. If there are only a few powered cables, the width of the modeled section may be much less than the full width of the tray.

In practice, this restriction will be relaxed to at least some minor extent once the warm and cold regions have been defined to complete the modeled section. To define the complete model, cables are added from the warm and cold groups one at a time beginning with those cables with the next highest ampacity loads. At some point the addition of just one more cable will result in the modeled section's depth of fill exceeding that of the actual tray. At this point, the model is considered complete, and the width of the modeled section is adjusted (upwards) to obtain a match to the actual tray fill depth (as the modeled section gets wider, the depth of fill is reduced so that the modeled section's cross sectional area equals the total cross sectional area of the included cables). In the example case provided in the submittal, this final adjustment resulted in a 10% increase in the analyzed section width for a case involving three powered 1/C #4/0 cables.

This modification ensures that the cable section modeled will more realistically reflect the potential localized heating effects. The difference is quite important. The primary impact of this modification is realized through the following factors:

- Under the as-published Harshe-Black method, the thickness of the hot cable group at the center of the thermal model can become arbitrarily small. Consider an extreme example: a single 1" diameter cable in a 24" wide tray would be modeled as a thin strip 1/24" thick through the center of the tray (depth of fill is not a consideration here for the base method). This is clearly not a realistic thermal model for this one powered cable. Under the PNP modified method, this is not allowed to happen to as significant a degree. If the same 1" cable is assumed to be in a tray with a 3" fill, then the cable would initially be modeled as a strip 2.5" wide and 0.4" high (the width is based on the 1" diameter plus 1.5" for ½ the fill depth, the height is then chosen so that $h*w=d^2$) (some relaxation of this width may occur in the final steps). While still an idealization, this is much closer to reality, and a much more reasonable thermal model. This is a far more realistic approach to modeling, especially for cases involving a small number of energized cables.

- Given the modified method, the high intensity region will generally represent a larger fraction of the modeled section than would be the case for the as-published Harshe-Black method. To illustrate, in the above example if we assume both cases involve a 3" fill, then the basic method would have assumed just 1.4% of the analyzed cable mass (that is, 1/24" out of the full 3" depth) was being heated by electric current. In the PNP modified approach about 13% of the analyzed mass (0.4" of the full 3" depth) would be producing heat. This will results in somewhat more conservative ampacity limits when this condition is invoked.

- For cases in which a very limited number of cable are powered, the PNP modification will ensure that the width effects are not grossly overstated. Consider again the case of a single powered 1" cable in a 24" tray with a 3" overall fill depth. Under the as-published methodology, this cable is assumed to communicate with the ambient with equal efficiency over the full top and bottom surface of the tray. For this case this would be quite unrealistic. In reality, heat transfer will actually be concentrated in the area immediately surrounding the cable; what one might call the "zone of thermal influence." Beyond this zone, the heat transfer rates would fall off sharply. The PNP approach would limit the ambient exchange to just 2.5" of the top and bottom surface; the 1" diameter of the cable plus one-half of our assumed 3" fill. In reality, this is a much more reasonable model of the "zone of thermal influence" that this cable might actually experience.

- Finally, the process by which cables are added to the modeled section ensures that a more conservative modeling configuration is obtained. The procedure is somewhat complex, and includes consideration of both cable size and heating loads. For the warm group, those cables loaded to 80%-100% of their ICEA ampacity limits, the largest highest intensity cables are added first. For the cold group, all the remaining cables the smallest, lowest intensity (typically the unpowered cables) are added first. The practice with regard to the warm group in particular is conservative and ensures that potential clustering effects are treated more reasonably than they are under the base as-published method. As will be discussed in Section 3 below, this appears to have had a significant impact on the example case cited in the licensee submittal.

There is also a second aspect of the PNP implementation that could be classified as a modification to the base method. Recall that the heating rate for each layer is based on the simple sum of the individual heating loads for the cables that make up that layer (a simple sum of the I^2R products for each cable). Hence, the predicted temperature rise is an "average" value. A cable with a higher heat intensity may experience a higher temperature rise, and a cable with a lower heat intensity may experience a lower temperature rise. The as-published method provided no discussion of this effect and appears to make no adjustments for relative ampacity levels. In contrast, the licensee has implemented a final step in which the estimated temperature rise for each cable is adjusted either up or down to reflect the actual ampacity load of that cable. This would appear to be a prudent and well reasoned approach to a problem not addressed in the original publication.

In summary, the PNP modifications to the basic Harshe-Black model are quite important. The modifications will in particular, impact those cases where the number of powered cables is small (high diversity cases). Indeed, SNL finds that the PNP implementation is far more realistic and will curb certain tendencies in the base method that might lead to unreasonable estimates of the cable ampacity limits. The PNP modifications will be critical to SNL's evaluation of the method as will be discussed further below. Appendix B provides a more detailed examination of how this change impacts the estimated ampacity limits.

2.5 Exercising the Model

SNL has explored to a limited extent the results obtained using the both the basic Harshe-Black model and the PNP modified version, including a modest exploration of certain sensitivities in the model input parameters. These analyses are documented in detail in Appendix B below.

The first effect explored was the general impact of the Harshe-Black model on estimated ampacity limits for diversity cases. For all of the cases explored both the as-published Harshe-Black and modified Harshe-Black methods allow more generous ampacity limits depending on the number of cables present. The credit given for diversity in either the base or modified Harshe-Black methodology can be very significant. The calculated ampacity limit was as much as tripled in comparison to the nominal ICEA limits for a non-diverse tray. Indeed, for certain of the cases, the "global" 80% of open air ampacity limit would be the only active limit. As was noted above, the diversity methods are clearly less conservative than are the standard methods of analysis. Again, the question remains are the more generous ampacity limits reasonable.

The second feature explored by SNL was the impact of the cable tray width on the estimated ampacity limits. This is especially important because of the change introduced in this behavior by the PNP modifications of the Harshe-Black method. The results show that the as-published Harshe-Black methodology is prone to the prediction of absurdly high ampacity limits for cases with only a few powered cables. Under these conditions, the as-published Harshe-Black methodology is clearly unrealistic, and places an undue emphasis on the role of cable tray width in the assessment of localized cable heating behavior. While the "global" ampacity limit of 80% of the open air ampacity will provide a nominal check on this behavior, under certain circumstances, reliance on the 80% limit may be excessive. Based on these results, SNL makes the following finding and recommendation:

- SNL finds that the excessive weighting of the cable tray width provided by the as-published Harshe-Black method represents a serious and unreasonable flaw. Based on this observation SNL recommends that the as-published Harshe-Black methodology should not be accepted for use in the assessment of nuclear power plant cable ampacity limits.

In contrast, the PNP implemented modification to the basic methodology sharply curtailed this behavior. Recall that the PNP modification limits the width of the tray section analyzed; hence, the localized heating effects are more realistically modeled. This was indeed quite encouraging and offered significant hope that the modified method as implemented by PNP might be acceptable. The review then turned to the topic of model validation, and this is taken up in Section 2.6 immediately below.

2.6 Validation

One critical aspect of any thermal model is validation through comparison to measured data. The licensee, PNP, has provided no direct validation results of its own upon which to judge the model. In the original publication of Harshe-Black, only a limited set of validation results were presented, and the conditions under which the cited measurements were obtained is not fully explained. It should be noted that PNP was apparently directly involved in the development of the method, and the field measurements cited in the original paper were made at PNP. However, the cited results leave many questions unanswered. In an attempt to further validate the method, SNL performed some comparisons of both the base as-published and PNP modified Harshe-Black method to the available experiments on diverse load trays. These comparisons are discussed in detail in Appendix B below.

Unfortunately, the range of data available for this type of validation is rather limited. Most of the laboratory tests performed to date have not involved load diversity. The measurements cited by Harshe/Black in their original work were based on actual cable installations at the Palisades Plant, but have only been presented in a very limited context. The detail available is not sufficient to fully assess the reliability and completeness of these results. Only two other sources of diversity data are known, and neither was apparently considered in the development of the Harshe-Black method. One source is Stolpe's original tests that included just one diversity experiment (Harshe-Black do discuss Stolpe's non-diversity experiments, but do not discuss his one diversity test). To SNL's knowledge, the only other set of diversity-based testing was a set of seven tests performed by TVA for the Browns Ferry plant in the late 1980's.[2] As discussed in Appendix B, SNL's own validation results illustrated both strengths and weaknesses of the Harshe-Black method.

When the model was validated against the Stolpe diversity test, the base as-published method under-estimated the measured cable temperature rise for <u>all three</u> of the powered cable groups. This is a somewhat unexpected and disturbing result. For the largest cables, the measured temperature rise exceeded the predicted temperature rise by 84% (47°C measured versus 25.5°C predicted rise). SNL attributes this, again, to the overly optimistic treatment of cable width effects, and the lack of adequate consideration of potential cable clustering effects. This poor performance reinforces SNL's recommendation that the base method should not be accepted for use in nuclear power plant analyses.

In contrast, the PNP modified method performed much better on the Stolpe validation case. For two of the three cable groups the estimated temperature rise conservatively bounded the measured temperature rise. For the third group, the six #4/0 1/C cables that

[2]SNL has access to this data by virtue of our participation in the USNRC review of the TVA analyses. A more complete citation is provided in Appendix B.

were the largest cables in the test, the measured temperature rise exceeded the predicted temperature rise by about 20%. This indicates some remaining potential for the method to underestimate actual cable operating temperatures. In this case, it would appear that even the modified method gave an overly optimistic treatment of the large cable behavior. SNL attributes this to the modeling of these large cables as a thin layer that was much smaller in thickness than the physical diameter of the larger cables. The 4/0 cables had a physical diameter of 0.8 inches in comparison to a tray fill of 0.764" (using the ICEA definition of fill depth), and to a hot layer thickness in the thermal model of just 0.58". Hence, the thickness of the hot zone in the thermal model was about 72% of the diameter of the largest high-intensity cable in the tray. This apparently led to an overly optimistic treatment of the localized heating effects for these relatively large cables. For the second largest cables, the six #1/0 1/C cables, the predicted temperature rise was conservative. In comparison to these cables, the thickness of the modeled hot zone was equal to about 89% of the cable diameter. Based on this result, some constraint on the application of the method to prevent this problem from being manifested appears appropriate. This will be taken up in Section 4 below.

When considering the TVA validation case results, note that there is no difference at all between the base and modified methods for these tests. This is because the highest load group (the hot zone group) always included a sufficient number of cables to ensure that the tray width was used as the modeled section width under both approaches. Hence, the modeling results are identical. The validations against these tests did demonstrate a nominal ability of the diversity method to conservatively predict cable operating temperatures. In this case, the tests involved 120 identical cables, hence, the potential impact of cable size variations are not included in the tests. In all cases 25% of the cables were powered in excess of the ICEA ampacity (up to 150% of those limits), and 25-50% were powered to some fraction of the ICEA ampacity (60% to 100%). The remaining cables were unpowered. For all of these cases the model did conservatively estimate the cable temperature rise values as reported by TVA. The primary shortcoming of this comparison is that TVA did not systematically attempt to measure the actual hot-spot temperature, hence, the measured temperatures may be somewhat optimistic.

3.0 THE LICENSEE EXAMPLE CALCULATION

3.1 Overview

The licensee has documented only one case example of an application of the modified Harshe-Black methodology for random fill cable trays in the submittal. This case is presented in Appendix A to Attachment 1 of the licensee submittal.

3.2 General Observations

The licensee implementation of the modified Harshe-Black method is quite complicated, and in many ways fairly sophisticated. It is dependent on accessing certain data from other licensee electrical service documentation, in particular, in the definition of cable tray characteristics, cable fills, cable characteristics, and cable ampacity loads. This did make it somewhat difficult for us to follow and understand the model. This was not, however, an insurmountable problem.

The submittal includes the calculation results for just one cable tray case. The case involves a tray with just three relatively large conductors in the high-intensity group, each loaded to about 108% of the nominal ICEA limit. The tray does have a very significant load diversity with about half of the cables carrying no load at all and nearly one-third carrying 80% or more of the ICEA limit. Hence, this is a good example case that includes a substantial hot zone and a substantial warm zone as well. The final result of the calculation is an estimated hot-spot temperature of 89.7°C. Given the level of load diversity, this appears to be a very conservative estimate of the hot-spot temperature.

SNL would attribute the apparent conservatism in this case to the number and nature of the cables that were included in the warm zone of the thermal model. That is, there are a total of 14 conductors that fall within the definition of the warm zone (ampacity loads of 80-100% of the ICEA limits), and these cables are also relatively large. Hence, in formulating the thermal model it would appear that large heavily loaded cables dominated the thermal model for both the warm and hot zones. The combined thickness of the hot and warm zones represented 1.4" of the overall 1.7" fill depth. Hence, the PNP practice for this case has resulted in a thermal model that effectively assumed a very conservative clustering of the heavily loaded cables. Hence, only a minimal, and probably conservative, ampacity credit was realized.

The cited example case is one that appears to have maximized the level of conservatism for the licensee model. It is unclear whether or not this example would be typical of other applications at PNP. In particular, if the "warm" group had been less populated (by either smaller cables or by fewer cables) then the estimated ampacity limits for the high intensity group might have increased sharply. Note that the high intensity or hot group was modeled as a fill layer just 0.46" in thickness when the actual hot group cables each had a diameter of 0.71". If it were not for the added effect of the warm zone, the ampacity estimates may have been overly optimistic. Recall the results for the validation against the Stolpe test discussed above. In that case the temperature rise for the larger cables was under-estimated, and this was attributed to an excessive thinning of the hot layer in comparison to diameter of the largest cables.

This result when viewed in context with the earlier SNL validation studies indicates that one measure of the acceptability and conservatism of the model would be to look at the combined thickness of the hot and warm zones. Recall that these two zones will be made up exclusively of cables loaded to 80% or more of the ICEA limits. Hence, it is in these two zones that most, if not all, of the heat will be generated. In order to ensure that the thermal effects for larger cables are properly captured, it would be prudent to establish a lower limit on the thickness of this heat generating band. In particular, if the heat producing band is much smaller than the diameter of the largest of the heat producing cables, then unrealistic results might be obtained. In this particular example, this was clearly not a problem, but in other cases it may be. Of most likely concern would be cases that involve few if any warm zone cables. A recommendation to implement such a modeling limitation is stated in detail in Section 4 below.

As a final note, SNL observed no specific errors in the implementation of the thermal model. It appears to have been implemented fully consistent with the text descriptions, and has employed reasonably modern and widely accepted heat transfer correlations.

3.3 Specific Areas of Uncertainty

There were only a very limited number of items identified by SNL for which some uncertainty remained. These are:

- It is unclear on what basis the licensee assumed in-plant ampacity loads have been assessed. In particular, it is unclear if the assumed configuration represents a typical plant ampacity load for a given mode of plant operation, or whether the licensee has assessed the worst-case configuration for relatively long-term loads for the subject cables. The most conservative approach would be to assume that each cable is powered to its worst-case <u>continuous</u> design load (where continuous implies operation for a sufficient period of time that steady state temperature conditions might be achieved). It would appear that this is indeed the basis used in the licensee assessments. If an alternate basis has been used, then the results may not bound all modes of plant operation.

  For example, if a given tray houses power cables to the residual heat removal system, then the ampacity load configuration during shutdown might be more severe than that typical of power operations. If the assumed ampacity loads were based on an assumption that the plant was at power, then the results may not adequately bound the configuration.

  It is recommended that the licensee be asked to explain the basis upon which the cable continuos operation load ampacity values were obtained, and to confirm that this practice has bounded the most conservative possible configuration for each tray analyzed.

- The example case provided by the licensee assumes an emissivity of the top surface of the cable mass of 0.95. This is somewhat high in comparison to typical values. Indeed, the original Harshe-Black paper that documents the method states that field measurements of the cables, presumably made at Palisades in conjunction with the field temperature measurements, indicated that the cable emissivity was 0.6 to 0.7 (see the paragraph immediately proceeding the section of the paper entitled "Thermal Model Applications").

It is recommended that the USNRC ask the licensee to explain and justify its use of a cable mass top-surface emissivity of 0.95 in the cited calculations.

- The licensee model cites the emissivity of the lower surface of the cable tray as 0.65. It is unclear what the basis for this value is. It is suspected that this value is intended to represent the emissivity of a galvanized steel plate. This raises two questions:
  - It is recommended that the USNRC ask the licensee to explain and justify the chosen value of 0.65 for the bottom surface of the cable mass.
  - It is further recommended that the USNRC ask the licensee the following questions: Are any of the cable trays under analysis solid-bottom type trays? If yes, (1) are the cables installed in direct and continuous contact with this bottom surface, or are they laid on internal rungs within the tray, and (2) is the bottom surface ventilated? If the cables are not in intimate contact with the bottom plate, and the bottom plate is not ventilated, then how has the model been adjusted to account for the additional air gap between the bottom of the cables and the tray bottom? Note that the Harshe-Black thermal model does not inherently allow for any such gap, but rather, inherently assumes either direct cable-to-bottom plate contact or installation in an open ladder-type tray.

4.0 FINDINGS AND RECOMMENDED APPLICATION LIMITATIONS

4.1 The Base As-Published Harshe-Black Method

SNL finds that the as-published Harshe-Black method can result in unreasonable and excessive estimates of ampacity limits under a wide range of application conditions. When validated against Stolpe's one diversity test, the base method under-estimated the measured temperature rises for all three of the powered cable groups by a significant margin. Based on this and other observations documented above, SNL recommends that the as-published method not be accepted for use in the assessment of nuclear power plant cable loads.

4.2 The Modified PNP Diversity Method

SNL finds that the PNP modified Harshe-Black method does have a nominal ability to provide realistic and reasonable estimates of cable ampacity limits or cable operating temperatures under a range of diverse load conditions. However, the validation studies performed by SNL also identified certain conditions under which unreasonable results might be obtained. These are related to cases where there are some number of very large cables included in the high-intensity or hot group.

SNL does recommend that the modified PNP method be accepted for use in nuclear plant ampacity assessments, subject to two restrictions (detailed below). It is important to note that in making these recommendations two aspects of the licensee modified modeling practice are of critical importance to our conclusion that the method provides a reasonable assurance that appropriate results will be obtained. These are (1) the licensee practice of limiting the width of the analyzed tray section, and (2) the licensee adherence to the definition of warm zone cables as those loaded in excess of 80% of the ICEA limits and the practice of adding the most conservative of the warm zone cables to the model first. These two licensee modifications are very important to the performance of the model.

Given these discussions, SNL recommends that application of the modified PNP diversity method be subject to the following two constraints:

- SNL recommends that the PNP modified diversity method not be applied to any tray that includes two or more cables that (1) are powered to at least 80% of the nominal ICEA cable tray ampacity limit, and (2) whose diameter exceeds the tray fill depth when calculated using the ICEA definitions of depth of fill. For this case, as noted by Stolpe, a potential for a severe localized hot spot exists that would make it unwise to credit diversity in the ampacity assessment.

- SNL recommends that a lower bound be established on the thickness of the combined hot and warm zones in the diversity thermal model. This will (1) prevent excessive "thinning" of the more heavily loaded cables, (2) more accurately reflect the presence of larger diameter cables in the hot group, and (3) ensure a conservative treatment of potential clustering effects. SNL recommends that the combined thickness of the hot and warm zones should equal or exceed 80% of the diameter of the largest cable in these two groups. If the condition is not met by the nominal model formulation, then the width of the analyzed section may be adjusted (reduced) so as to increase the hot/warm zone thickness until the restriction is met provided that the overall heat load for each cable group is maintained at their correct values.

The first restriction will require a simple check of the licensee cable/ampacity tables to establish a general applicability of the method to each tray. The second constraint is somewhat more complex, and will require that an additional application check be placed into the model. Using the licensee method, the hot zone will include all cables with ampacity loads in excess of 100% of the ICEA ampacity, and the warm zone will be made up of cables loaded to 80%-100% of their ICEA limits. It is most likely that this restriction will impact cases where there are few or no cables in the 80-100% warm group.

Both of these constraints are intended to address limitations of the model when applied to cable trays that include a mixture of both large and small heavily loaded cables. This includes consideration of the Stolpe test results, and his expressed concerns. The first constraint is intended to eliminate the potential that a smaller cable might be located between two large, heavily loaded cables in direct recognition of Stolpe's concern. The second is intended to address the more subtle potential that the impact of larger cables on localized heating effects might be excessively diluted by use of an arbitrarily thin hot-zone model using the Harshe-Black approach. Given the inclusion of these two constraints, SNL finds that the modified PNP method should provide reasonable estimates of diverse case ampacity limits, and recommends its acceptance by the USNRC.

It is further recommended that the licensee, PNP, be asked to review its own calculations to ensure compliance with these two application restrictions.

4.3 The Licensee Example Calculation

SNL observed no specific errors in the implementation of the thermal model. SNL finds that the thermal model has apparently been implemented fully consistent with the text descriptions, and has employed reasonably modern and widely accepted heat transfer correlations. There were a very limited number of specific point of uncertainty identified by SNL for which some uncertainty remained. These are:

- It is unclear on what basis the licensee assumed in-plant ampacity loads have been assessed. It is recommended that the licensee be asked to explain the basis upon which the cable load ampacity values were obtained, and to confirm that this practice has bounded the most conservative possible configuration for each tray analyzed including consideration of all possible modes of plant operation.

- The example case provided by the licensee assumes an emissivity of the top surface of the cable mass of 0.95. This value is not consistent with either typical practice, nor the measured PNP emissivity values cited in the Harshe-

Black paper. It is recommended that the USNRC ask the licensee to explain and justify this value.

- The licensee model cites the emissivity of the lower surface of the cable tray as 0.65. Regarding this assumption:
  - It is recommended that the USNRC ask the licensee to explain and justify the chosen value of 0.65 for the bottom surface of the cable mass.
  - It is further recommended that the USNRC ask the licensee the following questions: Are any of the cable trays under analysis solid-bottom type trays? If yes, (1) are the cables installed in direct and continuous contact with this bottom surface, or are they laid on internal rungs within the tray, and (2) is the bottom surface ventilated? If the cables are not in intimate contact with the bottom plate, and the bottom plate is not ventilated, then how has the model been adjusted to account for the additional air gap between the bottom of the cables and the tray bottom? Note that the Harshe-Black thermal model does not inherently allow for any such gap, but rather, inherently assumes either direct cable-to-bottom plate contact or installation in an open ladder-type tray.

5.0 REFERENCES

1. B. L. Harshe and W. Z. Black, "Ampacity of Cables in Single Open-Top Cable Trays," *IEEE Transaction on Power Delivery*, Vol. 9, No. 1, pp. 1733-1739, Oct. 1994.

2. J. Stolpe, "Ampacities for Cables in Randomly Filled Trays," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-90, Pt. I, PP 962-974, 1971.

3. *Ampacities of Cables in Open-Top Cable Trays*, ICEA P-54-440, NEMA WC 51, 1986.

4. *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:

SNL MATHCAD Implementation of the Harsh-Black Diversity Model for Random Fill Cable Trays

Summary:

SNL has implemented a somewhat simplified version of the Harshe-Black model of diversity credit for random fill trays as described in the attached MATHCAD 4.0 workbook file. This file includes both the base as-published methodology and the PNP modified methodology in which the width of the section is limited in cases of few powered cables.

SNL's implementation is relatively simple and includes some simplifications and idealizations that make it unsuitable for actual applications. In particular, external convection is treated using a single heat transfer coefficient for both the top and bottom surfaces of the tray. This treatment is specifically intended to ensure consistency with Stolpe's thermal model. Second, there is no adjustment of cable electrical resistance for temperature. All values are taken as the resistance at 90°C. This is generally fine in the hot zone and as long as the hot-spot is 90°C, but will be conservative when estimating heat loads for the warm and cold zones, and for cases where the hot spot does not reach 90°C. The version that has been documented in this appendix is actually a two zone version (hot and cold). Incorporation of a third warm zone is relatively straight-forward. Indeed, certain of the validation results discussed in Appendix B did include some three zone cases. Finally, SNL has only exercised the model for cases where all of the cables in a given layer are powered to the same heat intensity. No adjustments to the temperature rise for individual cables are made.

The initial calculation assesses the temperature rise within the cable mass as per the simplified one-dimensional heat transfer model. This establishes the surface temperature of the cable mass. The second part of the model then calculates the rate of heat transfer away from the cable mass to the ambient by convection and radiation using the estimated cable surface temperature and the specified ambient as the driving thermal potential.

The limiting ampacity is derived by setting up a single solve block that automatically matches the specific temperatures, and the various heat flow rates in the thermal model. The model can also predict Stolpe/ICEA limits by simply matching the external heat transfer to the full non-diversity based cable heat load.

An implementation of the Harshe Bla.k Di. ersity-Based ampacity assessment method for cable trays. This version includes both the base methodology (as per the paper) and the method as modified by Palisades for actual applications. It also includes a nominal Stolpe/ICEA calculation at the end for reference purposes.

Programmed by: S. P. Nowlen, Sandia National Laboratories, November-December 1997

The base (stored) case involves the analysis of a given number or powered cables in a tray with a set fill depth. It is assumed that all other cables are not powered at all, so there are only two regions, the high intensity band and the low-intensity or unpowered bands.

Note that in this version, the ICEA definition of "square cables" is used throughout for both cross-section and for depth of fill assumptions.

"Mathcad 'trick': If you are using a version older than the 4.0 PC version, then you need to equate temperature to charge units since there was no fundamental temperature unit provided in these older versions of the program. Hence, you must insert a formula line that sets:

K:= 1 * coul (This is not a real equation in this implementation, only a text block)

Then use K as fundamental unit. For newer versions, this in not necessary because K (and R) is already defined as a fundamental unit. You do still need C to K and F to R conversions if you want to work in C or F. We are using 4.0, but will occassionally want temps in C so:

$$CtoK := 273.16 \cdot K$$

Set up initial parameters:

The Cables: In this case, we assume a fill of 3/C 6 AWG cables using the diameter given in ICEA P 54-440 Table 3-3:

$d_{cable} := 0.72 \cdot in$ $\quad R_{cable} := 5.15 \cdot 10^{-4} \cdot \frac{ohm}{ft}$ $\quad \rho_{cable} := 400 \cdot K \cdot \frac{cm}{watt}$

$n_{conductors} := 3$ $\quad \varepsilon_{cable} := 0.9$

The thermal conditions to meet:

$T_{hot} := 90 \cdot K + CtoK$ $\quad T_{amb} := (40 \cdot K + CtoK)$

The Tray:

$w_{tray} := 12 \cdot in$ $\quad d_{fill} := 3 \cdot in$

Set some Physical Constants:

$\varepsilon_{steel} := 0.7$ steel emissivity (not used in this example)

$\sigma := 0.530 \cdot 10^{-8} \cdot \frac{watt}{ft^2 \cdot K^4}$ Stephan-Boltzmann

Define The Power/diversity Loading:

If you want to simulate the Stolpe Answer, one way is to simply set all cables possible given the dfill above as powered (that is, no diversity at all). Recall that we use the ICEA definition of fill depth in this analysis so to do this use the following equation:

$n_{powered} := \frac{w_{tray} \cdot d_{fill}}{d_{cable}^2}$ $\quad n_{powered} = 69.444$

While this is a rather arbitrary and probably non-integer number, it will be internally self consistent. As an alternative, one can simp'y specify the number of powered cables as follows:

$$n_{powered} := 10$$

Recall that the last set value will be used below, so to use full fill, must delete the equation immediately above. This example continues with 10 powered cables.

Now we can calculate the dimensions of the high-intensity band for each method:

The base method:

$$w_{base} := w_{tray} \qquad w_{base} = 12 \cdot in$$

$$h_{base} := \frac{n_{powered} \cdot d_{cable}^2}{w_{base}} \qquad h_{base} = 0.432 \cdot in$$

The modified method:

$$w_{mod} := n_{powered} \cdot d_{cable} + 0.5 \cdot d_{fill} \qquad w_{mod} = 8.7 \cdot in$$

Cannot exceed tray width so do an upper bound check and reset if exceeded:

$$w_{mod} := if\left(w_{mod} > w_{tray}, w_{tray}, w_{mod}\right) \qquad w_{mod} = 8.7 \cdot in$$

Now get the corresponding band hieght for the modified method:

$$h_{mod} := \frac{n_{powered} \cdot d_{cable}^2}{w_{mod}} \qquad h_{mod} = 0.596 \cdot in$$

The solution will use a solve block so we first set up our callable functions for which we will later seek self-consistent solutions.

Cable Heating Rate:

$$Q_{cable}\left(I_{cable}, n\right) := I_{cable}^2 \cdot R_{cable} \cdot n_{conductors} \cdot n$$

Cable Zone Heat Intesity (NOT USED IN THIS EXAMPLE):

$$HI\left(I_{cable}, A_{zone}\right) := \frac{Q_{cable}\left(I_{cable}, n_{powered}\right)}{A_{zone}}$$

Cable mass Temperature Rise (recall we have just one heat zone at center):

$$dT_{mass}\left(Q, h_{hot}, w_{mass}\right) := \frac{Q \cdot \rho_{cable}}{4 \cdot w_{mass}} \cdot \left[\frac{h_{hot}}{2} + \left(d_{fill} - h_{hot}\right)\right]$$

Convection coefficient:

$$h_{surf}\left(T_{surf}\right) := 0.101 \cdot \frac{watt}{ft^2 \cdot K^{\frac{5}{4}}} \cdot \left(T_{surf} - T_{amb}\right)^{\frac{1}{4}}$$

Set up the overall external heat transfer expressions:

$$Q_{conv}(T_{surf}, A_{surf}) := h_{surf}(T_{surf}) \cdot A_{surf} \left(T_{surf} - T_{amb}\right)$$

$$Q_{rad}(T_{surf}, A_{surf}, \varepsilon_{surf}) := \sigma \cdot \varepsilon_{surf} A_{surf} \left(T_{surf}^{4} - T_{amb}^{4}\right)$$

$$Q_{external}(T_{surf}, A_{surf}, \varepsilon_{surf}) := Q_{conv}(T_{surf}, A_{surf}) + Q_{rad}(T_{surf}, A_{surf}, \varepsilon_{surf})$$

That is the "physics", now we just need a solution for our case. To do this we set up a solve block to get a simultaneous solution to a multiple equation set that will match temperatures and heat fluxes so that the full thermal model is self-consistent. This is a very simple case with two equations and two unknowns. In this implementation we need to match the external heat transfer to the internal generation rate, and find the surface temperature that provides this match.

For the base method:

First need to "seed" the answer

$$I_{base} := 10 \cdot amp$$

$$T_{surf} := 50 \cdot K + CtoK$$

Now we set up our solve block:

Given

$$Q_{external}(T_{surf}, 2 \cdot w_{base}, \varepsilon_{cable}) = Q_{cable}(I_{base}, n_{powered})$$

$$T_{surf} = T_{hot} - dT_{mass}\left(Q_{cable}(I_{base}, n_{powered}), h_{base}, w_{base}\right)$$

$$\begin{pmatrix} I_{base} \\ T_{surf} \end{pmatrix} := Find(I_{base}, T_{surf})$$

And the base method answer is:

$$I_{base} = 49.182 \cdot amp$$

$$T_{surf} - CtoK = 61.554 \cdot K$$

For the modified method:

Seed the solution:

$$I_{mod} := 10 \cdot amp$$

$$T_{surf} := 50 \cdot K + CtoK$$

Set up the Solve block

Given

$$Q_{external}(T_{surf}, 2 \cdot w_{mod}, \varepsilon_{cable}) = Q_{cable}(I_{mod}, n_{powered})$$

$$T_{surf} = T_{hot} - dT_{mass}\left(Q_{cable}(I_{mod}, n_{powered}), h_{mod}, w_{mod}\right)$$

$$\begin{pmatrix} I_{mod} \\ T_{surf} \end{pmatrix} := Find(I_{mod}, T_{surf})$$

And the Modified case answer is:

$I_{mod} = 42.252 \cdot amp$

$T_{surf} - CtoK = 61.894 \cdot K$

As a final step, we solve the same case using the nominal Stolpe/ICEA Method. Recall that in this case there is no credit for diversity.

First we calculate the number of cables making up a full fill of the specified cable and specified depth of fill for the specified cable tray width (using the ICEA definition)

$n_{Stolpe} := \frac{w_{tray} \cdot d_{fill}}{d_{cable}^2}$ $\quad n_{Stolpe} = 69.444$

Now we do our solution:

Seed the answer:

$I_{Stolpe} := 10 \cdot amp$

$T_{surf} := 50 \cdot K + CtoK$

Set up the Solve block:

Given

$Q_{external}(T_{surf}, 2 \cdot w_{tray}, \varepsilon_{cable}) = Q_{cable}(I_{Stolpe}, n_{Stolpe})$

$T_{surf} = T_{hot} - dT_{mass}(Q_{cable}(I_{Stolpe}, n_{Stolpe}), d_{fill}, w_{tray})$

$\begin{pmatrix} I_{Stolpe} \\ T_{surf} \end{pmatrix} := Find(I_{Stolpe}, T_{surf})$

And the "Stolpe" answer is:

$I_{Stolpe} = 22.005 \cdot amp$

$T_{surf} - CtoK = 68.694 \cdot K$

Let us recap our different solutions:

Recall the Case:

$w_{tray} = 12 \cdot in$ $\quad d_{fill} = 3 \cdot in$ $\quad n_{powered} = 10$

Recall the solutions:

$I_{base} = 49.182 \cdot amp$ The Basic Harshe-Black Solution

$I_{mod} = 42.252 \cdot amp$ The Modified Harshe-Black Solution

$I_{Stolpe} = 22.005 \cdot amp$ The Nominal Stolpe/ICEA Solution

Appendix B:

A Discussion of the SNL Sample Case Modeling Results

B.1 Introduction

As discussed in Section 2.4 of the text above, SNL has considered two nominal diversity analysis cases to illustrate the results of Harshe-Black diversity analysis method. For each case, SNL has explored both the basic method and the modified method as implemented by PNP. This Appendix provides a more complete discussion of the case results.

B.2 Nominal Case Examples to Illustrate Important Model Behaviors

Case example 1 involves a hypothetical cable tray assumed to be filled with either 6 AWG or 12 AWG 3/C cables. A number of sub-cases for were analyzed in which the following parameters were varied: the depth of fill, tray width, and the number of powered cables present in the overall mass. For each sub-case the limiting ampacity is calculated using three different methods of analysis. This case allows for a direct comparison of the diversity based ampacity results to those obtained using the Stolpe-ICEA standard methods.

The first effect to be illustrated is the impact of the Harshe-Black model on estimated ampacity limits for diversity cases. This effect is illustrated by the results in Table B.1. Note that for all of the cases shown in this table, the ICEA and Stolpe methods yield exactly the same ampacity regardless of the number of cable assumed to be powered. This is inherent in these methods because they do not credit load diversity.

In contrast, both the basic Harshe-Black and modified Harshe-Black methods allow more generous ampacity limits depending on the number of cables present. Also note that as the assumed number of powered cables increases, the basic and modified versions of the Harsh-Black method converge to the same estimated ampacity limits. The point of actual convergence occurs as the sum of the diameters of the powered cables approaches the width of the tray. For higher numbers of powered cables, the results are identical. For lower numbers of powered cables, the two methods yield significantly different results, the PNP modified method being significantly more conservative.

The primary point to be taken from these results is that the credit given for diversity in either the basic or modified Harshe-Black methodology can be very significant. Indeed, for certain of the cases, the "global" 80% of open air ampacity limit would be the only active limit. Hence, the calculated ampacity limit for these cases was as much as tripled in comparison to the nominal ICEA limits for a non-diverse tray (63 A based on 80% of the open air ampacity versus the nominal limit of 21 A). The question which remains unanswered by these examples is "is this realistic?". This question will be taken up further in Section B.3 below as regards validation of the method.

Table B.1: Sub-case examples to illustrate how m... credit might be taken for diversity using either the basic or PNP modified Harshe-Black method. Each case assumes a 24" wide cable tray filled to a 3" depth of fill (based on the ICEA definition of fill depth) with 3/C 6 AWG cables. For each case the number of cables assumed to be powered is varied. This has no impact on the ICEA or Stolpe results, but does impact the Harshe-Black results. All predicted ampacity limits which exceed the 80% of open air ampacity (from column 2) are shaded, and in these cases the 80% limit would be invoked by all methods.

Number of Powered Cables[4]	80% of Open Air Limit[1]	ICEA Tray Limit[2]	Stolpe Method Limit[3]	Basic Harshe-Black	Modified Harshe-Black
1	63.2	21	22.0	215	66.2
10				68.8	42.3
20				49.2	40.5
100				24.4	24.4

1. This value is based on the IPCEA P-46-426 Tables
2. This value is taken directly from the ICEA P-54-440 tables assuming a 3" fill.
3. This value is calculated by SNL using the same basic thermal model under conditions of no load diversity. The results illustrate nominal consistency of the thermal model with the ICEA tables.
4. A 3" fill of this cable in a 24" trays would imply a total fill of approximately 139 cables.

The second feature to be illustrated is the impact of the cable tray width on the estimated ampacity limits. This is shown in Table B.2, and is especially important because of the change introduced in this behavior by the PNP modifications of the Harshe-Black method. The results show that the basic Harshe-Black methodology is more to the prediction of absurdly high ampacity limits for cases with only a few powered cables. Note that the meaning of "few" in this context depends on the cable diameter and tray width but is generally related to cases where the sum of the diameters of the powered cables is less than the width of the tray. For these cases, the 80% of open air limit would be invoked, but even this limit may be excessive under certain of these circumstances. The basic Harshe-Black methodology for these cases is clearly unrealistic, and places an undue emphasis on the role of cable tray width in the assessment of localized cable heating behavior. Based on these results, SNL makes the following finding and recommendation:

- SNL finds that the excessive weighting of the cable tray width provided by the basic Harshe-Black method represents a serious and unreasonable flaw. Based on this observation SNL recommends that the basic Harshe-Black methodology should <u>not be accepted</u> for use in the assessment of nuclear power plant cable ampacity limits.

In contrast, the PNP implemented modification to the basic methodology has a significant moderating impact on this behavior. Recall that the PNP modification limits the width of the tray section analyzed; hence, the localized heating effects are more realistically modeled. One can also note that for the cases with only a few powered cables (in this case this applies to the cases with either 1 or 10 powered cables) the modified PNP method yields the same ampacity limit regardless of tray width. This is because the "width" of the powered cables has not yet reached the width of the tray in either case, a 12" or 24" tray. Hence, the estimated ampacity limit is the same for both. This is indeed quite encouraging and offers some hope that the modified method as implemented by PNP might be acceptable. Unfortunately, the cases illustrated here are arbitrarily chosen, and there is no experimental data against which to validate the predictions. The issue of method validation is taken up in Section B.3 below.

Table B.1: Sub-case example to illustrate how cable tray width can impact the estimated cable tray ampacity under various method of analysis. Each case assumes a cable tray filled to a 3" depth of fill (based on the ICEA definition of fill depth) with 3/C 6 AWG cables. For each case the number of cables assumed to be powered is varied. This has no impact on the ICEA or Stolpe results, but does impact the Harshe-Black results. Again, the shaded entries indicate ampacity limits that exceed the "global" 80% of open air ampacity limit (from column 2).

Number of Powered Cables[3]	80% of Open Air Limit[4]	ICEA Tray Limit[1]	Stolpe Method Limit[2]	Basic Harshe-Black	Modified Harshe-Black
Results with 1 Powered Cable:					
12" Tray	63.2	21	22	152	66.2
24" Tray				215	66.2
Results with 10 Powered Cable:					
12" Tray	63.2	21	22	49.2	42.3
24" Tray				68.8	42.3
Results with 20 Powered Cables					
12" Tray	63.2	21	22	35.6	35.6
24" Tray				49.2	40.5
Results with 40 Powered Cables:					
12" Tray	63.2	21	22	26.5	26.5
24" Tray				24.4	24.4

Notes:
1. This value is taken directly from ICEA P-54-440 table 3-3.
2. This value is calculated by SNL using the same basic thermal model with no diversity assumed to illustrate nominal consistency of the model with the ICEA tables.
3. A 3" fill of this cable using the ICEA definition would imply a total of approximately 69 cables present in the 12" tray and 139 in the 24" tray.
4. The IPCEA P-46-426 open air limit for a 6 AWG 3/C cable is 79A.

B.3 Validation of the Harshe-Black Method

B.3.1 Validation by the Original Authors and the Licensee

PNP has provided no direct validation of its analysis methodology in its own submittal. Hence, they are inherently dependent on the validation provided in the original work by Harshe and Black. However, that work provided only very limited comparative validation of the basic method, and SNL finds that this comparison was not adequately discussed to determine its overall acceptability.

In particular, the original Harshe-Black paper does include one figure (figure 2) in which field measured cable temperatures were compared to estimated cable temperatures obtained using the base as-published diversity method. The values are uniformly conservative, indicating a nominally conservative model. However, there are many points that would be of interest that are not adequately documented in the paper. For example, how the field measurements were performed has not been adequately explained. It would appear that all of the measured cable temperatures are based on the cable surface temperature rather than conductor temperature. Ampacity limits should be based on the conductor temperature and these will be higher than the cable surface temperature. It is also unclear how the thermal model was implemented to simulate the measured trays (for example, whether the cable ampacities at the time of the testing were measured or simply assumed). It is also unclear how wide of a selection of cable trays was examined and whether or not the selection is sufficient to validate all applications (a single table citing a range of certain tray parameters is provided). Finally, the authors cite that some of the data was not presented because it is considered suspect. If this data indicated some cases of non-conservative performance, then explicit explanations of the presumed discrepancies and a review of the authors conclusions of non-applicability would be appropriate.

As noted above, the validation results presented in the original paper show no cases where the results are non-conservative. Surely there must be some cases where the method would be inappropriate, and the validation study would be expected to explore these cases as well. It would then be appropriate to ensure that the adequate limitations on the application of the method are established to ensure that inappropriate results are not credited. A proper validation should verify that the model can accurately or conservatively predict operating temperatures given the actual conditions at the time of the measurements. Given the results of our own case studies, as discussed in Section B.2 above, SNL remains skeptical of the adequacy of the model validation. Of particular concern is the obviously questionable treatment of tray width effects and localized heating provided in the base as-published model, and the concerns raised by Stolpe's one diversity test.

Unfortunately, there are only a limited selection of tests currently available upon which this type of validation might be reasonably based. One is Stolpe's diverse cable tray test as reported in his original paper. The second is a series of six diversity tests performed by TVA for the Browns Ferry plant. SNL will take up each of these two cases in the subsections that follow.

B.3.2 The Stolpe Diversity Test

As a part of his original work, Stolpe ran one test involving a diverse load cable tray. The tested tray included nine different types and sizes of cables. In his first test all of the cables in the tray were powered to an equal level of heat intensity, that value that his model predicted would result in a 50°C hot-spot temperature rise (90°C cable temperature). In a second test of this same tray only three of the nine cable groups were powered, and each was powered to the same ampacity as in the first test. Hence, for both cases, the heat intensity of the powered cables is constant. This makes the analysis much simpler.

Note that there does appear to be a discrepancy regarding the actual ampacity of the 6 AWG cable in these two tests. In particular, Stolpe's Table II indicates that the predicted ampacity limit for the 6AWG cable in a 20% fill should be 51 A. This is the ampacity to which these cables should have been subjected in these tests. However, the data plot indicates that the actual test ampacity for this cable was somewhat less than 50 A (approximately 37A based on the plot). For all of the other cables, the plotted data are consistent with the table cited in Table II of the paper. In all likelihood the actual ampacity applied to this cable was 51 A as cited in the table, and the plot is in error. This conclusion is reenforced by the calculation of heat intensity for the various cables. For both the 1/0 and 4/0 cables, the tabulated and plotted ampacities are consistent, and indicate a heat intensity of about 8.4 W/in^2/ft. If one assumes 37 A was applied to the 6AWG cable a heat intensity of about 4.4 W/in^2/ft is obtained. Using an ampacity of 51 A, a heat intensity of about 8.4 W/in^2/ft is again obtained. In the calculations performed below, SNL has assumed the higher ampacity for the 6 AWG cables. This is actually the more generous treatment for this uncertainty because it will result in higher (more conservative) temperature rise predictions for the thermal model.

The results of this comparison are summarized in Table B-3. This table gives both the temperature rise measured for each cable by Stolpe, and the temperature rise predicted by both the base as-published and PNP modified versions of the Harshe-Black method. Note that the basic method under-predicts the measured temperature rise for all of the cables. In contrast, the modified method is conservative for two of the three cables and only under-predicts the temperature rise for the largest of the cables, the 4/0 cable.

Table B-3: Comparison of Stolpe diversity test measurements to predicted peak cable temperature predicted by both the base as-published and PNP modified Harshe-Black diversity models.

Cable	Stolpe Measured Temperature Rise	Base Harshe-Black Method Predicted Temperature Rise*	PNP Modified Method Predicted Temperature Rise*
6 AWG	27°C	25.5°C	39.3°C
1/0	32°C		
4/0	47°C		

*Note that since the cables are powered at the same heat intensity this is a two layer problem, hot and cold, and the Harshe-Black method predicts only one hot-spot temperature applicable to all cables.

Based on his own results, Stolpe concluded that any credit given for diversity could be overly optimistic. He concluded that "all it takes is two large conductor, heavily loaded circuits located side-by-side in a tray to produce a local hot spot in the tray cross-section." Indeed, his testing bears this out. The largest of the powered cables were the six 4/0 cables, each with a diameter of 0.8". Note that this diameter exceeds the nominal fill depth of the tray which was 0.6" using Stolpe's definition or 0.76" using the ICEA definitions of cable cross-section and fill depth. These cables clearly dominate the tray fill in this case, and hence, dominate the thermal behavior as well. The Harshe-Black model "spreads" these large cables out into a relatively thin layer; 0.33" for the as-published model and 0.58" using the PNP modified model (both values based on the ICEA definitions of fill depth).

Based on this result, it would appear prudent to place some limitations on the application of the methodology to ensure that such cases are accounted for. This topic is taken up in Section B.4 below.

B.3.3 The TVA Browns Ferry Diversity Tests

During 1988/89 the USNRC was engaged in the review of certain ampacity studies submitted by Tennessee Valley Authority (TVA) for the Browns Ferry Nuclear Plant.[3] During the course of that review the licensee provided a test report documenting the results of a study performed to validate TVA's own methods used to credit load diversity in ampacity assessments. The tests are quite unique and are readily applicable to a validation of the Harshe-Black method.

In brief, TVA assembled a single cable tray 18" wide and 4" tall that was filled to an overall fill depth of 2.16" (ICEA definition) using 120 lengths of a single-conductor #1/0 light power cable. The tray was first run to establish a nominal baseline ampacity limit with all cables powered as would normally be done today, for example, in an IEEE-848 ampacity tests. The 120 conductors were then re-connected into four separate cable groups of 30 cables each using a random selection of conductors to form each group. These groups were then powered independently to predetermined diverse ampacity values, and the resulting cable temperatures measured in a selection of locations.

Figure B-1 provides a simple schematic to illustrate the location of the cables in each of the four diversity groups. It is especially important to note that the groupings do include some significant clustering of the powered cable groups. For example note that at the left side of the tray, as seen in the figure, there is a cluster of group 1 and group 4 cables that is 4 cables wide by 4 cables high. Also, near the center of the tray there is a second clustering of group 1 and 4 cables. As discussed further below, in all of the tests both the group 1 and group 4 cables were powered during testing. This factor is important in interpreting the results as will be discussed below.

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[3]The original licensee submittal under review by the USNRC was documented under TVA cover to the USNRC Document Control Desk dated July 7, 1988. The review was coordinated by Mr. Hukam Garg, USNRC/NRR, and was supported by SNL under the terms of a general technical services contract for licensee and vendor Equipment Qualification inspections. This discussion is based on SNL records of this effort.

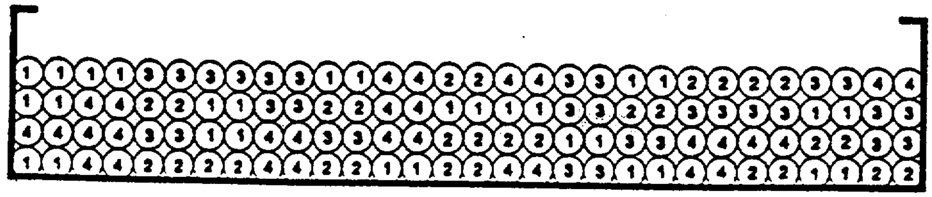

Figure B-1: Schematic representation of the TVA diversity test cable tray indicating the four cable power groups. Note that groups 1 and 4 were powered to some level in all tests.

There are some inherent limitations to this data. The most significant is that there was no systematic attempt to locate the actual hot spots in the tray. This is because not all of the cables in the tray were instrumented. Rather, a large number of preselected cables were instrumented prior to installation, many of these cables concentrated around the center of the tray with a more limited selection of thermocouples at the edges of the tray. The cable groupings were then chosen at random after installation. Hence, the actual hot spot temperatures may not have been truly captured. This is somewhat mitigated by the fact that several of the group 1 and 4 cables are present in a cluster near the center of the tray, and many of these cables were, in fact, instrumented. Hence, it can be concluded that the measured temperatures did characterize at least one of the two highest power density regions in the tray. However, the data should be viewed as somewhat suspect with the actual hot-spots somewhat uncertain. None-the-less some indication of the model behavior for these cases can be discerned.

A total of five diversity tests were performed. In each test at least one, and typically two, of the cable groups were not powered at all. The other cable groups were powered using from 60% to 150% of the nominal baseline ampacity measured during the original test with all cables powered. Table B-4 summarizes the conditions in each test.

Table B-4: Summary of TVA diversity test power loads

Test No.	Conductor Loading			
	Group 1	Group 2	Group 3	Group 4
211	120%	0%	100%	80%
212	120%	0%	0%	80%
213	130%	0%	0%	90%
214	110%	0%	0%	60%
215	150%	0%	0%	80%

All conductor loads are expressed as a percentage of the baseline ampacity measured in the original non-diverse load test of the same cable tray.

The reported test data includes the measured maximum cable temperature in each test. Given this data it is quite simple to simulate each test using the Harshe-Black methodology. In this case, the cables in each group represent one full layer of cables across the width of the tray. Hence, there will be no distinction between the base as-published method and the PNP modified method. Either would yield identical results.

To perform the validations, SNL implemented a simple version of the Harshe-Black method designed to simply estimate the maximum cable temperature rise given the set ampacity loads for each group of cables. The model is a slightly modified version of the printout presented in Appendix A above that incorporated the full three-zone temperature rise model for the cable mass as per the original Harshe-Black paper.

In the modeling, the choice of cable groupings for the thermal model was quite obvious. The cables were simply separated into three groups as follows: the hot cables were those with the highest loading (group 1), the cold cables were those with no load (group 2 for test 211 and both groups 2 and 3 for the other tests), and the warm cables were the remaining cables (groups 3 and 4 for test 211 and group 4 for the other tests). Note that for the warm group in test 211 there are two different ampacity loads applied in the test. Consistent with the Harshe-Black approach, the simulation used the actual heating load based on a summation of the individual cables. Also note that all electrical resistance values are taken as those at 90°C.

The results of this exercise are illustrated in Table B-5. Note that in each case the Harshe-Black method has conservatively estimated the maximum cable temperature as reported by TVA. That is, the predicted temperature rise is uniformly greater than the worst-case temperature rise reported in the tests. This is quite encouraging and provides a powerful basis for acceptance of the method under these conditions. One factor that is not accounted for by these tests is the mixing of very large heavily loaded cables with smaller power cables, the problem posed by the Stolpe test results.

Table B-5: Summary of Harshe-Black method simulation results for the TVA diversity tests.

Test No.	Measured Peak Cable Temperature Rise (C)	Calculated Peak Cable Temperature Rise (C)
211	35.38	47.1
212	27.38	35.1
213	32.19	41.6
214	20.58	27.3
215	39.13	48.3

B.4 Findings and Recommended Application Restrictions

SNL finds that the both the basic Harshe-Black method (as originally published by the authors) and the modified PNP version of the method (in which the width of the analyzed section may be limited) can result in very significant increases in cable ampacity limits as compared to the ICEA/Stolpe methods that do not credit diversity. Some of the example cases explored by SNL resulted in tripling of the estimated ampacity limit. Clearly, load diversity can significantly impact cable operating temperatures under realistic installations conditions. Whether or not the diversity credit allowed by this method is entirely warranted under all circumstances remains at least partially a matter of conjecture.

This is because only limited and sparsely documented validation of the basic methodology is available, and this validation has clearly not adequately explored the potential application limitations. Supplemental validation studies performed by SNL did reveal at least one potential weakness of the method. That is, when the cable load included very large power cables that are heavily loaded, then the method may underestimate cable temperature rises. This is an artifact of the way in which the heavily loaded cables are modeled as a relatively thin layer across the width of the section analyzed by the thermal model. This may not adequately treat the localized heating effects associated with power cables that are large in comparison to either the overall tray fill depth, or to other heavily loaded cables that are physically smaller.

Given this, the ultimate application limits of the methodology remain uncertain. The above discussions have identified some of the potential limitations, and in fact, the modifications implemented by PNP in its own applications directly address one of the most serious of these limitations. The most significant potential limitations are:

- The base (as published) method may over-state the role of heat dissipation across the width of the tray when there are only a very few powered cables present. The PNP modifications adequately address this point of concern.

- Ampacity limits for large cables may be overstated. To some extent this is also an inherent limitation of the Stolpe/ICEA methods as well. Imposition of a global limit of 80% of the open air ampacity provides one check on this possibility; hence, adequate recognition and proper application of this constraint in practice is necessary. Note that PNP has implemented this limitation in its own assessments, and SNL find no fault with the licensee applications in this specific regard.

- If some subset of the powered cables are located in close proximity to one or more large heavily loaded cables, then ampacity limits may be overstated. The PNP modification to the method reduces the potential magnitude of the error, but does not entirely eliminate it. It is this problem that was the primary basis for Stolpe's recommendation that diversity not be credited in cable tray ampacity assessments. Some constraints on the application of the method are needed to prevent this potential from being realized, and this is taken up further below.

Based on these findings, SNL makes the following recommendations regarding the acceptability of the base method as originally published by Harshe-Black:

- SNL finds that the base Harshe-Black methodology as originally published by the authors is deficient for two main reasons: (1) it may allow an overly optimistic treatment of potential localized heating effects under certain circumstances and (2) it will over-state the role of heat dissipation within the cable mass for cases involving a small number of powered cables. Hence, it is recommended that this version of the methodology should not be accepted for use in the assessment of nuclear power plant cable ampacity limits.

With regard to the modified Harshe-Black method used in the PNP assessments:

- SNL finds that PNP has implemented critical modifications that directly addresses the most serious shortcoming of the base Harshe-Black method (involving limitations placed on the width of the analyzed tray section). Validation cases examined by SNL indicate a nominal ability of the method to conservatively predict cable operating temperature for a range of conditions involving diverse cable loads. It can be anticipated that for most situations, the PNP modified method will result in reasonable-to-conservative estimates of the actual ampacity limits, or alternately cable operating temperatures, for diverse load cable trays.

  However, the validation also demonstrated that the method cannot adequately address cases that include relatively large, heavily loaded power cables. SNL recommends that some constraints be placed on the application of the method to ensure that inadvertent cable overloads do not occur. Specifically, SNL recommends that the modified PNP version of the Harshe-Black method be accepted for use subject to the following restrictions:

  - The method should not be applied to any tray that includes two or more cables that are (1) powered to at least 80% of the nominal ICEA cable tray ampacity limit, and (2) whose diameter exceeds the tray fill depth when calculated using the ICEA definitions.
  - In formulating the thermal model, a lower bound should be established on the combined thickness of the central high-intensity or "hot" and "warm" cable layers to prevent excessive "thinning" of this layer and to more accurately reflect the presence of larger cables in this group. These two groups will likely represent the total heating source for the thermal model. SNL recommends that this lower bound should be no less than 80% of the diameter of the largest cable in the hot and warm groups.

The first restriction is specifically intended to address the Stolpe test results and the concerns expressed in his pioneering work on cable tray ampacity. It would disallow use of the diversity method in cases where the potential for a smaller cable to be "sandwiched" between two larger heavily loaded power cables does exist. The second restriction is intended to address the potential clustering of a number of smaller cables in close proximity to a larger powered cable. By placing a lower bound on the combined thickness of the "hot" and warm cable layers, potential clustering effects will be more reasonably accounted for. This approach will ensure tha' the heating zone is modeled with a thickness that is at least nominally consistent with that of the larger cables.

The restrictions will require some modest changes to the thermal model for impacted cases. However, it is also likely that only a very limited subset of the licensee applications will be impacted. Indeed, it is possible that they will not impact any of the applications. It is recommended that the licensee be asked to review its applications against these restrictions.

SNL clearly acknowledges that these recommended restrictions are somewhat arbitrary. They are intended to address demonstrated limitations and shortcomings of the thermal model, but the cited numerical constraints are not well based in scientific evidence. There is simply not enough data available to fully assess the limitations of the method. At the same time, SNL also finds that the level of model validation that is available is not sufficient to warrant the unlimited applicability of the method. Indeed, our own validation efforts did illustrate that the model can underestimate cable operating temperatures under certain conditions, especially involving very large power cables. Hence, these restrictions are recommended pending the availability of more complete validation data sufficient to address the cited shortcomings of the model.

B.5 Summary of Findings and Recommendations

In summary, SNL recommends that the base Harshe-Black method as originally published should not be accepted for use in nuclear plant ampacity assessments. However, SNL also recommends the acceptance of the modified Harshe-Black methodology as implemented by PNP subject to two restrictions as cited in B.4 above. The recommended restrictions are intended to ensure that unreasonable ampacity limits are not obtained for cases involving a mixture or very large and smaller power cables. Including the recommended application restrictions, there is reasonable assurance that the PNP modified method can be used to demonstrate that actual cables are operating at or below their rated temperature limits.