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Sep Rpt.

SUBJECT: Forwards summary of plant ampacity methodology,per NRC 951103 request.In accordance w/util 951220 ltr,methodology has been established & implemented as described in encl. Licensee currently scheduled to meet w/NRC on 970219.

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102-03854-WEI/SAB/NLT
January 24, 1997

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References: 1) Letter dated November 3, 1995, from Charles R. Thomas, Project Manager, Project Directorate IV-2, Office of Nuclear Reactor Regulation, USNRC to William L. Stewart, Executive Vice President, Nuclear, APS

2) Letter 102-03574-WLS/SAB/NLT dated December 20, 1995 from William L. Steward, Executive Vice President, Nuclear, APS, to USNRC

3) Letter dated 102-03833-JML/SAB/NLT December 31, 1996, from James M. Levine, Executive Vice President, Nuclear, APS to USNRC

Dear Sirs:

Subject: Palo Verde Nuclear Generating Station (PVNGS)
Units 1, 2, and 3
Docket Nos. STN 50-528/529/530
Ampacity Calculation Methodologies

By letter dated November 3, 1995 (Reference 1) the NRC requested that Arizona Public Service Company submit additional information to resolve open issues and concerns regarding the original analytical approach for ampacity derating determinations. In accordance with Reference 2, a methodology has been established and implemented as described in the enclosures to this letter.

Provided as Enclosure 1, "Summary of PVNGS Ampacity Methodology," is a description of the analytical methodology used by APS for performing ampacity calculations for PVNGS. Included in this summary are the standards and methodology used, and a description of the analysis performed for derating cables due to Thermo-Lag 330-1 enclosures.

Df01

Additionally, Enclosure 2, "Ampacity Sample Calculation," is provided to demonstrate how the methodology is applied to a cable tray. As described in Reference 3 this methodology has been applied to PVNGS cables to demonstrate that available ampacity margin exists for cables in PVNGS Unit 1.

Re-analysis of approximately 50 non-Class 1E cable tray sections enclosed with Thermo-lag 330-1 is in progress and is currently scheduled to be completed by January 30, 1997. One Class 1E circuit has been identified as having insufficient ampacity margin in that the circuit could operate at temperatures above its 90°C rating. This condition has been evaluated in all 3 PVNGS units and represents a cable life issue and poses no immediate operability concern. The Thermo-Lag enclosure for this circuit is no longer required to meet fire protection requirements and will be removed.

APS currently anticipates that the evaluation performed for Unit 1 will bound Units 2 and 3. APS will verify the applicability of the Unit 1 ampacity calculation to Units 2 and 3 by the end of the second quarter of 1997 as stated in Reference 3. If it is determined that the Unit 1 evaluation does not bound Units 2 and 3, unit-specific calculations will be performed following completion of this evaluation.

APS is currently schedule to meet with the NRC on February 19,1997, to provide a status of the resolution of Thermo-Lag 330-1 issues including information on the remaining work activities and a discussion on the ampacity methodologies which are being utilized at PVNGS.

Should you have any questions, please contact Scott A. Bauer at (602) 393-5978.

Sincerely,

WEI/SAB/NLT/rh

Enclosures

cc: L. J. Callan
K. E. Perkins
J. W. Clifford
K. E. Johnston

ENCLOSURE 1

SUMMARY OF PVNGS AMPACITY METHODOLOGY

9808190179

SUMMARY OF PVNGS AMPACITY METHODOLOGY

CABLE SELECTION AND SIZING STANDARDS

PVNGS utilizes cable selection and sizing criteria based on conventional methodologies described in ICEA P-46-426 and ICEA P-54-440. These methods verify that the cables will not overheat taking into account variables such as load current, cable size and type, ambient temperature, raceway type, and number of conductors in the raceway.

As part of the PVNGS design basis reconstitution effort, Unit 1 power cables were reevaluated with regard to ampacity margins and as-built conditions. This design basis reconstitution effort included a complete and thorough review of the factors that affect cable ampacity at PVNGS. Cable ampacity was determined based on the as-built physical installation and routing that exists for PVNGS. Consideration of Thermo-Lag 330-1 enclosures was only one of many parameters that determined the ampacity rating. This comprehensive evaluation/analysis of the PVNGS design provides assurances that the issues of importance regarding ampacity (including the necessary derating for the application of the Thermo-Lag 330-1 fire protective material) do not result in a cable installation that would result in adverse thermal conditions. The applicability of these evaluations to cables in Units 2 and 3 is currently under review and is scheduled to be complete by June 30, 1997. As stated in Reference 3 of the cover letter, the Unit 1 evaluation is expected to bound Units 2 and 3. If applicability cannot be confirmed, unit-specific calculations will be performed following completion of this evaluation.

In cases where it was determined that the standard sizing criteria are not met, individual detailed evaluations have been completed or are in process. In these limited cases, credit is taken for margins that exist in the standard methodology. Two examples of these margins are:

1. The PVNGS cable sizing criteria are based on 60° C ambient temperature for Class 1E cables and certain Non-1E cables, and 50° C for other Non-1E cables. In many cases it can be shown that the highest credible ambient temperature adjacent to the raceway is less than the assumed value and the calculated cable operating temperature can be reduced accordingly.

2. The industry-standard sizing methods for cables in cable trays verify that overheating will not occur even when all conductors in the tray are

simultaneously loaded to their rated ampacities. In cases where a substantial portion of the conductors are deenergized or lightly loaded, the heat generated by cable losses is substantially lower than assumed in the standard methodology. In cases where the standard methodology indicates higher-than-desired operating temperatures of heavily-loaded conductors in such a tray, temperatures can be recalculated taking into account the reduced value of total heat in the tray. The methodology used to perform these calculations is described in "Sizing of Cables in Randomly Filled Trays with Consideration for Load Diversity" by H. C. Leake of APS, published in *IEEE Transactions on Power Delivery*, January 1997 and is provided as Attachment A. This methodology replaces the "watts-per-foot" methodology that was used in an earlier PVNGS calculation.

THERMO-LAG 330-1 AMPACITY DERATING

Application of Ampacity Testing

The evaluations performed under the design basis reconstitution effort also established new derating factors for cables in raceways enclosed in Thermo-Lag 330-1 protective envelopes (TPE). The PVNGS approach complies with the general methodology proposed in IEEE P848, *Procedure for the Determination of Ampacity Derating of Fire Protected Cables*, i.e., the ampacity of cables is multiplied by a derating correction factor to establish the ampacity of cables in Thermo-Lag 330-1 enclosed raceways.

The derating factors used in the PVNGS analyses are based on industry performed tests. Significant effort has been expended by the nuclear industry in performing empirical tests to quantify derating factors for various physical configurations. This test data has been utilized to derive derating factors which approximate the thermal performance of Thermo-Lag 330-1 enclosed trays and conduits at PVNGS.

Inconsistencies in these test results have not been precisely analyzed by the industry. As a result of test inconsistencies and in lieu of derating factors that were theoretically developed and confirmed through reproducible testing procedures, derating factors appropriate to PVNGS configurations were established from the results of industry testing and with qualitative evaluation of the applicability of these empirical test results to PVNGS. These values are determined by PVNGS to be reasonably representative of PVNGS configurations.

A review of industry test results revealed that the Tennessee Valley Authority (TVA) test results were quite different than those of Underwriters Laboratories (UL), Sandia National Laboratories (SNL), and Texas Utilities (TU) even though performed on similar test specimens. Therefore, PVNGS has disregarded the TVA results. Further review of the remaining tests determined that TU tested configurations (Test Report # 12340-94583,95165-95168, 95246) were most applicable to PVNGS installations. Excerpted pages from the applicable TU test report are provided as Attachment B. Additionally, the TU test results were relatively consistent with and representative of other industry test results obtained to date.

Derating of Cables in Cable Trays

Initial test reports from Thermal Sciences Inc. (TSI) established a derating factor of 12.5% for Thermo-Lag 330-1 cable tray enclosures. This value was utilized in the original PVNGS design basis calculations for cables in cable trays. More recent tests, based on the IEEE P848 methodology, have resulted in values in the range of approximately 28-36% for one ½" panel Thermo-Lag 330-1 installations and approximately 35-46% for one 1" panel or two ½" panel installations.

The PVNGS cable tray installation standard is a single ½" Thermo-Lag 330-1 pre-fabricated panel retained by wire, with trowel-grade material applied to fill panel joints to a level commensurate with the panel thickness. An additional skim-coat of trowel-grade material is then applied (approximately 3/16" to 1/4") over the entire enclosure such that the wire ties and stress skin are no longer visible. The nominal thickness of the resultant assembly is a uniform 3/4". All tray enclosures are of this single-panel design. There are no multiple tray enclosures at PVNGS nor are there any multi-layer installations on cable trays.

The PVNGS ampacity calculation currently utilizes a derating factor of 38.9% for cables in trays which exceeds the value derived from industry tests for a one-hour fire-rated installation design. This value was selected from the test results reported in Generic Letter 92-08 for three-hour fire-rated enclosures (per TSI Installation Specification consisting of either one 1" panel or two ½" panels) and was directly applied to the PVNGS one-hour fire rated enclosures (One-panel TPE). This was the largest reported derating factor that was empirically available for any tray configuration at the time the PVNGS design basis calculation reconstitution effort began. The derating factor for the 1" thick cable tray installations has been further substantiated by testing documented in Information Notice 94-22, "Fire Endurance and Ampacity Derating Test Results for 3-Hour Fire-Rated Thermo-Lag 330-1 Fire Barriers."

Additionally, APS reviewed TU installations for Thermo-Lag enclosed trays and determined they are representative in size, materials of construction, and configuration to the PVNGS tray installations. The applicable TU test specimen was a ½" pre-fabricated Thermo-Lag 330-1 panel with an approximate 1/4" over-coating of trowel-grade material on each side which extended onto the adjacent top and bottom surfaces for a distance of 5". All butt-joints between adjacent panel sections had a circumferential overcoat of ~1/4" Thermo-Lag 330-1 trowel-grade material. Therefore, the Thermo-Lag 330-1 material was approximately ½" thick on 50% of the test specimen and 3/4" thick on the remainder of the enclosure.

The derating factor selected for use at PVNGS is approximately 7% larger than the empirical test data developed in the TU test report for installations which are very similar to PVNGS cable tray enclosures. The use of the 38.9% derating factor, derived from the testing of 1" thick installations is considered to be conservative as applied to PVNGS' 3/4" thick installations.

Derating of Cables in Conduits

Initial test reports from TSI established a derating factor of 9% for Thermo-Lag 330-1 conduit enclosures. More recent tests, based on the IEEE P848 concept, have resulted in values in the range of approximately 5-10% for ½" thick Thermo-Lag 330-1 installations and 9-20% for 3/4" thick installations.

The physical installation details for PVNGS have been previously provided to the NRC in PVNGS letter dated December 22, 1994, and generally consists of a box configuration constructed of Thermo-Lag 330-1 pre-fabricated panels as compared to pre-formed, half-round Thermo-Lag 330-1 material utilized in industry tests.

There are three basic configurations of conduit Thermo-Lag 330-1 installations at PVNGS.

1. One-panel TPE consisting of one layer of ½" nominal thickness pre-fabricated Thermo-Lag 330-1 panels externally covered by an over-layer of 1/4" Thermo-Lag 330-1 trowel-grade material.

2. One-panel Upgraded TPE consisting of one layer of ½" nominal thickness pre-fabricated Thermo-Lag 330-1 panels externally covered by 2 over-layers of 1/4" Thermo-Lag 330-1 trowel-grade material (upgraded Appendix R 1-Hour barriers

will be the future installation where required to meet Appendix R fire endurance requirements).

3. Two-panel TPE consisting of two layers of ½" nominal thickness pre-fabricated Thermo-Lag 330-1 panels each externally covered by an over-layer of 1/4" Thermo-Lag 330-1 trowel-grade material (previously 3-Hour Appendix R barriers).

Derating factors have been established by comparing the three basic PVNGS configurations to the TU test specimens. A qualitative analysis was performed to address the differences in barrier construction techniques and thickness. The process for determining the appropriate TPE derating factors for each type TPE is as follows:

One-panel TPE

The TU conduit specimens utilized Thermo-Lag 330-1 pre-formed conduit sections of ½" nominal thickness to construct protective envelopes for ¾", 2", and 5" conduits. An additional ¼" nominal thickness pre-shaped conduit section was installed as an overlay on the ¾" and 2" conduits. The resultant Thermo-Lag 330-1 thickness for the specimens were ¾" nominal for the ¾" and 2" conduits, and ½" nominal for the 5" conduit. The maximum derating value established in these tests was 10.7%.

An additional derating allowance of approximately 10% was applied to the largest derate factor obtained from empirical testing yielding a derate factor of 21% to address variations in test samples, potential air gaps associated with the additional ¼" Thermo-Lag 330-1 overlay, and hysteresis losses in the test case.

The PVNGS physical installations differ from the tested configuration in that a box configuration constructed of 1/2" Thermo-Lag 330-1 pre-fabricated panel material is used at PVNGS as compared to Thermo-Lag 330-1 pre-formed conduit sections used for the industry test specimens. However, due to the large margins in the sizing of PVNGS cables, the effects of these differences on the derating factor do not invalidate the conclusion that the PVNGS cables operate within their thermal ratings.

PVNGS has concluded that an appropriate derating factor for the One-panel TPE is the 21% value established by the TU testing for the following reasons:

1. Commonality in the relative thickness of the Thermo-Lag 330-1 enclosure of the TU test specimens (¾") and the PVNGS One-panel ¾" TPE enclosures.

2. Additional allowances have already been included to address variations in test samples, potential air gaps associated with the additional ¼" Thermo-Lag 330-1 overlay, and hysteresis losses in the test cases.

3. Class 1E cables enclosed in One-panel TPE conduit could accept a Thermo-Lag 330-1 derating factor in excess of 45% without impact on cable thermal ratings (90 °C/40 year life). Most non-1E cables could accept a derating factor value in excess of 36%. A few non-1E cables have been identified that that could accept a derating factor value in the range of 25 to 28%.

One-panel Upgraded TPE

As discussed previously, the One-panel Upgraded TPE installations are simply a One-panel TPE, with an additional 1/4" layer of Thermo-Lag 330-1 trowel grade material. The resultant total thickness is (½" + ¼" + ¼") nominally 1". This configuration was not specifically tested by either TU or TVA.

The variation from the tested configuration stems from the additional ¼" trowel grade layer. Applying generalized heat transfer principles, the allowable current flow in a give conductor with a fixed temperature of operation is inversely proportional to the square root of the thickness of the insulating material in which it is installed. Applying this relationship to the 21% derating factor developed for the One-panel TPE above yields a derating factor of 32%.

It should be noted that a comparison of the derating factors determined from the TU test for the 5" conduit (½" Thermo-Lag 330-1 pre-formed conduit sections) and the 2" conduit (¾" pre-formed conduit sections) resulted in lower derating factors for the thicker sections instead of higher as assumed above. Additionally, the calculated increase in the derating factor is approaching the values measured for cable tray installations, which have always been substantially larger than conduit installations.

Therefore, APS has concluded that a 32% derate factor is appropriate for One-panel Upgraded TPE conduit installations at PVNGS. Please note that it has been determined that considerable excess available ampacity margin exists for these TPE installations. Cables enclosed in One-panel TPE conduit installations could accept a Thermo-Lag 330-1 derating factor in excess of 50% and still operate within their thermal ratings (90 °C/40 year life).

Two-Panel TPE

The Two-panel TPE configuration consists of two layers of ½" nominal pre-fabricated panels each with approximately 1/4" skin coat over-layer of Thermo-Lag 330-1 trowel grade material. There is an air gap approximately equal to the depth of the pre-fabricated panel ribs between the inner and outer panels. The total combined Thermo-Lag 330-1 material thickness is (1/2" + 1/4" + 1/2" + 1/4") nominally 1.5". There is currently no known industry test for this configuration.

Applying the heat transfer principles utilized for the One-panel Upgraded derating factor as described above, a derating factor of 45% was obtained. Therefore, APS has concluded that a 45% derate factor is appropriate for Two-panel TPE installations at PVNGS. Please note that it has been determined that considerable excess available ampacity margin exists for most cables in these TPE installations. Most cables enclosed in Two-panel TPE conduit installations could accept a Thermo-Lag 330-1 derating factor in excess of 80% and still operate within their thermal ratings (90 °C/40 year life). The exception to this is the cable discussed in the cover letter and the following summary.

PVNGS AMPACITY CALCULATION RESULTS

Overview

PVNGS cables enclosed in Thermo-Lag 330-1 fire protective materials generally have a large margin of ampacity even after accounting for the postulated impact of Thermo-Lag 330-1. The excess in available ampacity remaining after the cables have been derated to account for all factors (e.g. temperature, raceway fill, Thermo-Lag 330-1, etc.) provides sufficient design margin to assure that the subject cables will not operate with conductor temperatures in excess of design limitations.

Summary of Cable Tray Calculation Results

PVNGS calculation 01-EC-ZA-300 addresses cable ampacity for cables installed in trays in Unit One. As-built design data was extracted from the Plant Data Management System Cable and Raceway Tracking System regarding configuration details for each tray section as to physical location, tray fill, presence of Thermo-Lag 330-1, tray covers,

and fire stops. Fire stop deratings were applied, as a minimum, to trays without Thermo-Lag 330-1 or tray covers. Specific details regarding the actual cable loading was obtained from other plant/project databases, plant drawings, vendor drawings, and other approved engineering documentation. The results of this calculation demonstrates that the ampacity of class 1E and safe shutdown circuits is acceptable, and the 90°C 40 year cable rated operating temperature will not be exceeded.

Approximately 175 cables in Non-Class 1E cable trays have been identified in the calculation as having marginal ampacity. A small percentage of these cables are in trays enclosed in Thermo-Lag 330-1. These anomalies are due primarily to overly conservative assumptions made in the establishment of actual cable loads, based on problem resolutions completed to date. It is expected that most, if not all of these cables will be found acceptable as well. This activity is currently scheduled to be completed by January 30, 1997.

Since the Thermo-Lag 330-1 derating factor assumed for the PVNGS One-panel TPE tray enclosures (¾" uniform thickness) is obtained from type testing of TSI 3-Hour rated 1" nominal thickness enclosures, the results of the calculation are considered appropriate and conservative. The test results of the three-hour barriers bound the PVNGS design.

Summary Conduit Calculation Results

PVNGS calculations 01-EC-ZA-301 and 13-EC-ZA-302 address cable ampacity for circuits installed in Thermo-Lag 330-1 enclosed conduit. Derating factors utilized in these calculations were obtained directly from TU test experience including the additional margins as recommended by the USNRC for the One-panel TPE .

Derating factors were analytically derived by extrapolation of the 21% factor selected for use at PVNGS to the One-panel Upgraded TPE (32%) and the Two-panel TPE (45%). It is concluded that the magnitudes of ampacity margin for most installations are more than sufficient to account for any derating associated with these enclosures. The calculations clearly demonstrate that the impact of the Thermo-Lag 330 -1 TPE installations will not credibly impact cable life or exceed the cable's thermal ratings over the 40-year life of the facility. As an example, the ampacity margin after derating for most circuits enclosed in Two-panel TPE enclosures is greater than 65%.

Based on the PVNGS ampacity calculation results, it is concluded that the magnitudes of ampacity margin are more than sufficient to account for any derating associated with these enclosures with additional margin remaining with one exception.

One conduit assembly has been identified that has no excess available ampacity margin. The conduit assembly, enclosed in Two-panel TPE, is located in the Control Building Train B Remote Shutdown Panel Room. The cables in question serve as the power feed from Emergency Diesel Generator "A" to the 4.16 kv switchgear 1E-PBA-S03. Calculation 01-EC-ZA-301 has revealed that, at design basis or worst-case room ambient temperatures (PVNGS calculation 13-EC-HJ-003), under forced shutdown and Loss-of-Coolant Accident loading conditions, a cable operating temperature in excess of 90° C could be achieved. This increased temperature of operation remains well under the thermal limits for operation of the cable insulating material but does impact cable life. Given the non-continuous nature of the Emergency Diesel Generator (EDG) duty cycle over a 40-year period, cable accelerated aging while on-line has been determined to be more than compensated for by the significant period of time the cable is at room ambient temperature while the EDG is off-line. Evaluation of this problem concluded that the cable life expended to-date is significantly less than its installed life, and the risk of premature cable failure is not considered credible. Consequently, the operability of the A Train Emergency Diesel Generator as a source of essential on-site power is not challenged. This specific Thermo-Lag 330-1 installation is scheduled to be removed on or before the next refueling outage of each of the 3 units as it is no longer required to meet Appendix R requirements.

96 SM 372-3 PWRD

Sizing of Cables in Randomly-Filled Trays With Consideration for Load Diversity

H. C. Leake
Arizona Public Service Company
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Abstract—Method for demonstrating increased ampacity of cables in trays with loading diversity. Ampacity tables for sizing cables in randomly-filled cable trays are provided in NEMA WC 51-1986 [1] based on a model developed by J. Stolpe which ensures that the maximum cable temperature does not exceed the insulation rating (typically 90°C) under worst-case conditions [2]. The Stolpe model intentionally disregards the reduced heating effect of deenergized or lightly-loaded cables to ensure that all possible hot spot conditions are enveloped. In recent years other methods have been proposed to credit loading diversity in order to justify increased ampacity. However, since they involve certain assumptions about the heat distribution within the cable mass, these methods may fail to identify individual overloaded conductors. This paper describes a simple method which considers the performance of individual conductors while providing a means of increasing ampacity as a result of loading diversity.

I. INTRODUCTION

Maximum operating temperature is one of the criteria which must be considered when sizing power cables. A number of factors can cause significant temperature rise in power cables routed through trays, including concentrated heat due to I^2r losses in a number of heavily-loaded cables and lack of ventilation due to tight packing of the cables. Excessive temperatures reduce cable life.

Various thermal models are used to predict maximum operating temperatures within cable trays. Some of the more rigorous ones, such as the "Finite Difference Model" developed by A. Hiranandani [3], utilize detailed design information such as the position of each cable in the tray and the current through each of its conductors during the worst-case heating scenario. In randomly-filled trays, however, this information is often not available and a simpler sizing methodology is most often used.

The conventional methodology utilizes a model developed by J. Stolpe [2] which calculates the intensity of dissipated heat that would cause the hottest conductors in a tray to just reach their rated maximum temperature. It conservatively assumes uniform heat intensity throughout the cable mass equal to that of the most heavily-loaded conductor. By limiting the number of variables to just a few, it can be used to derive generic ampacity tables such as those in NEMA WC 51-1986 [1]. However, due to its conservatisms, predicted temperatures may be unrealistically high in trays in which significant loading diversity exists.

It is sometimes advantageous to justify loading of cables in excess of standard ampacities. Design modifications can create thermal effects more adverse than originally anticipated and cause deviations from conventional cable sizing criteria. Examples include increased current in feeder cables due to added loads, increased depth of tray fill, higher ambient temperatures, and derating due to tray covers or fire-resistant protective wrap (see IEEE Design Guide 666-1991 [4] for typical derating factors). In such cases, identification of design conservatisms can eliminate the need for costly temperature monitoring or cable replacement projects. This reanalysis often focuses on reduced heat dissipation in the cable mass due to loading diversity.

In most power cable trays, all conductors do not operate simultaneously at their rated ampacities, and it is often the case that actual heat dissipation is only a small percentage of the value assumed in the Stolpe model. For example, control circuits and power feeds to motor operated valves and other intermittent or seldom-used equipment may constitute much of the bulk of the tray fill while producing very little heat. Experimental results described in [5] and [6] indicate that the Stolpe method is conservative for such conditions.

However, Stolpe explicitly warns against using diversity as a basis for increased ampacity. "It seems that better judgment would dictate general ampacities assuming that diversity does not generally exist, because 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", he states [2]. It is evident, then, that alternative sizing methodologies which modify the Stolpe model to reduce its conservatisms on the basis of diversity must ensure that potential hot-spot conditions are addressed. The methods which have been proposed to date do not always fulfill this objective.

Use of the conservative Stolpe assumption for total heat dissipation is a prudent means of addressing worst-case temperature rise within the cable mass, but a more realistic value is often justified when calculating the rise in the air surrounding the cable mass.

96 SM 372-3 PWRD A paper recommended and approved by the IEEE Insulated Conductors Committee of the IEEE Power Engineering Society for presentation at the 1996 IEEE/PES Summer Meeting, July 28 - August 1, 1996, in Denver, Colorado. Manuscript submitted January 2, 1996; made available for printing June 3, 1996.

II. ANALYTICAL MODELS

A. General Modelling Techniques

Basic parameters used to calculate temperatures in randomly-filled power cable trays are shown in Fig. 1. The conventional Stolpe method treats the cable mass as a rectangular object which generates heat uniformly and dissipates it across its top and bottom surfaces. Simplifying assumptions are discussed in [2]. Two heat transfer equations are used to determine the heat intensity that would cause a maximum temperature (T_m) equal to the cable rating:

1) Temperature Rise Within Cable Mass: Heat is transferred from the current-carrying conductors to the cable mass surface through conduction as described in [7]:

$$T_m - T_c = \frac{W \cdot \rho \cdot d}{8w} \qquad (1)$$

where

- d = depth of cable mass (in)
- T_c = average cable mass surface temperature (°C)
- T_m = maximum temperature within cable mass (°C)
- W = heat dissipated in cable mass per unit length (w/ft)
- w = width of cable mass (in)
- ρ = effective thermal resistivity of cable mass (°C-ft/w)

2) Temperature Rise in Air Surrounding Cable Mass: Heat is transmitted from the cable mass surface to the surrounding air through convection and radiation as described in [8]:

$$W = hA_s(T_c - T_a) + \sigma A_s \varepsilon (T_{cK}^4 - T_{aK}^4) \qquad (2)$$

where

- A_s = area of top and bottom of cable mass surface per unit length (ft²/ft)
- h = overall convection heat transfer coefficient of the cable mass to surrounding air (w/ft²-°C)
- T_a = ambient temperature (°C)
- T_{aK} = ambient temperature (°K)
- T_c = average cable mass surface temperature (°C)
- T_{cK} = average cable mass surface temperature (°K)
- W = heat dissipated in cable mass per unit length (w/ft)
- ε = thermal emissivity coefficient of cable mass and tray surface (dimensionless)
- σ = Stefan-Boltzmann constant (w/ft²-°K⁴)

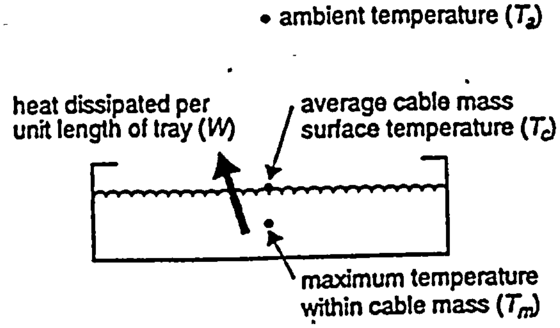

Fig. 1. Thermal Model of Tray Cross-Section

B. Comparison of Methods

For the purpose of comparison, the Stolpe method and several variations which credit diversity are designated as follows:

Method	Description
A	Stolpe model as described in [2]. Postulates total heat equal to the heat intensity of the most heavily loaded cable multiplied by the cross-sectional area of the cable mass. Most conservative method. Diversity not considered.
B	"Uniform Method" described in [5]. Postulates total heat equal to the sum of conductor I^2R losses. Heat is averaged over the cross-sectional area of the cable mass. Least conservative method.
C	Method described in [6] using a "Configuration Diversity Factor" of 1.0. Same results as Method B.
D	"Layered Method" described in [5]. Similar to Method B, but accommodates non-uniform heat distribution by postulating most heavily loaded cables in layer at center of tray and least heavily loaded cables adjacent to surface. Calculated ampacities are lower than Method B.
E	Same as Method C, except accommodates non-uniform heat distribution by applying a "Configuration Diversity Factor" of 2.0 which was determined in [6] by testing. Results in lower ampacities than Method C.
F	As proposed by this paper. Temperature rise within cable mass is calculated in accordance with Method A, but temperature rise through the air surrounding the cable mass is based on the realistic total heat loss in accordance with Method B.

The most fundamental difference between Method A and all of the other methods is the value of dissipated heat used in (1) and (2) to calculate temperature rise. The value used in Method A is considerably higher than in the others in cases where significant loading diversity exists.

Method A uses a value which is often conservative:

$$q_m = I_c^2 \cdot r_c \tag{3}$$

$$Q_m = \frac{q_m \cdot n}{D_m^2} \tag{4}$$

$$A_m = \sum D^2 \tag{5}$$

$$W_c = Q_m \cdot A_m \tag{6}$$

where

- I_c = current through most heavily-loaded conductor (A)
- r_c = electrical resistance of most heavily-loaded conductor per unit length (Ω/ft)
- q_m = heat dissipated by most heavily-loaded conductor per unit length (w/ft)
- n = number of conductors in most heavily-loaded cable
- D_m = diameter of most heavily-loaded cable (in)
- Q_m = heat intensity of most heavily-loaded cable per unit length (w/in^2-ft)
- D = diameter of cable (in)
- A_m = cross-sectional area of cable mass (in^2)
- W_c = conservative value of heat dissipated in cable mass per unit length (w/ft)

Formulas (4) and (5) use cable D^2 to calculate cross-sectional area rather than $\pi D^2/4$ to account for interstices.

Methods B, C, D, and E use a realistic value of dissipated heat based on the highest steady-state losses that would be expected at any time:

$$W_r = \sum I^2 r \tag{7}$$

where

- I = actual current through conductor (A)
- r = electrical resistance of conductor per unit length (Ω/ft)
- W_r = realistic value of heat dissipated in cable mass per unit length (w/ft)

Methods B and C use W_r for W in (1) and (2), assuming that the dissipated heat is distributed evenly throughout the cable mass. Method D also uses W_r, but postulates that the highest heat intensity occurs in a layer at the center of the cable mass. This assumption reduces the ampacities below those calculated by Methods B and C. Method E applies a factor to W_r which reduces the calculated ampacities to account for non-uniform heat distribution.

Method F uses W_c for W in (1) and W_r for W in (2). Equation (1) is a simplified representation which neglects the distribution of heat-producing cables within the cable mass. This model is usually justified since the actual heat distribution is difficult to quantify and its consideration would be incompatible with the concept of standardized ampacity tables. The use of W_c is a concession to the simplified model and provides assurance that individual overloaded conductors are identified. Method F adopts this approach, consistent with Method A, for calculation of temperature rise within the cable mass. Method F differs from Method A only in its use of to W_r, rather than W_c, to calculate temperature rise in the air surrounding the cable mass.

One assumption common to all models is uniformity of temperature across the cable mass top and bottom surfaces. On this basis, it is necessary only to calculate the average cable mass surface temperature (T_c) without regard for localized temperature variations. For methods which consider diversity, this approach implies the ability of the cable mass to evenly absorb and distribute the dissipated heat—a limitation of the model which is discussed later. Given this assumption, it is unnecessarily conservative to use W_c when calculating temperature rise in the surrounding air. Use of W_r for this portion of the calculation results in higher ampacities where trays include a significant number of unenergized or lightly loaded conductors.

C. Example

Results of the six methods can be compared by calculating the temperature rise for a hypothetical tray. The example is evaluated for a varying percentage of cables energized to a constant heat intensity, with the remaining cables deenergized. Constants are:

- W_c = 100 w/ft
- d = 3 in
- w = 24 in
- T_a = 40°C
- ε = 0.8
- ρ = 13.12°C-ft/w
- σ = 0.530×10^{-8} w/ft^2-°K^4

Results are calculated for various diversity factors (*df*) between 0.0 and 1.0 where:

$$df = \frac{W_r}{W_c} \tag{8}$$

The overall convection heat transfer coefficient (w/ft^2-°C) is calculated as recommended in [1]:

$$h = 0.101\,(T_c - T_a)^{1/4} \tag{9}$$

Results are shown in Fig. 2. It can be seen that, in this example, Method F is more conservative than the other methods which credit diversity. Since methods D and E were validated by testing, as discussed in [5] and [6], it can be concluded that these tests also support the results of Method F.

This example also reveals that Methods B through E may be non-conservative for trays with low diversity factors. The

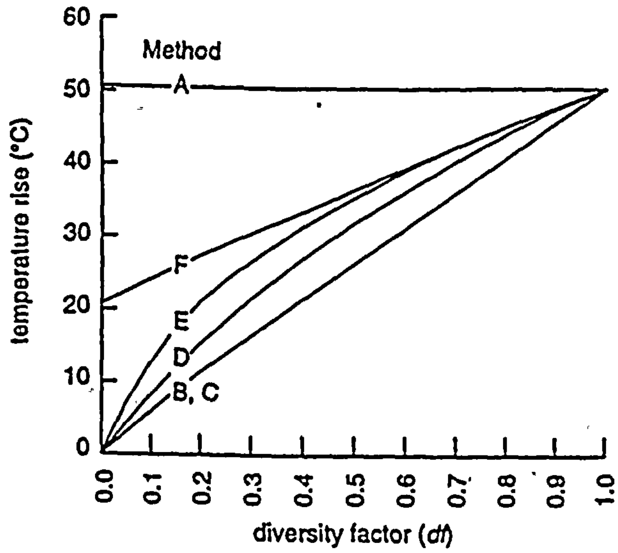

Fig. 2. Comparison of Example Results

temperature rise of a current-carrying cable would not approach zero with a decrease in diversity factor as suggested by these methods. This can be demonstrated by considering an example of a tray through which 100 equally-sized cables are routed, only one of which carries current. In this case the diversity factor would be 1/100 = 0.01. The current-carrying cable could get quite hot if overloaded, despite the large quantity of cables in the tray which generate no heat.

D. Limitations

Method A is conservative for any value of diversity factor or tray fill since it postulates a heat intensity throughout the cable mass that is greater or equal to the actual intensity at any point. However, individual conductors which are more heavily loaded than allowed by this method will not necessarily overheat, and plant modifications can often be avoided by considering other methods.

Methods B and C postulate a best-case scenario in which the heat is spread evenly throughout the cable mass. In many cases this assumption is optimistic and fails to identify individual overloaded conductors.

Method D is more conservative than Method B, but still involves the assumption that the heat is spread evenly across each layer. Therefore, the localized heating effect of an individual overloaded conductors within a layer may not be accounted for. Additional non-conservatism can result when the calculated thickness of a layer is less than the diameter of an individual cable in that layer. This can be demonstrated by the example of a 24" wide cable mass consisting of 3 layers of 1" diameter cables, with only cable dissipating heat. If modelled as a 1/24" thick x 24" wide heat-producing layer centered within two non heat-producing layers, each 1" wide slice would dissipate only 1/24 the heat of the actual 1" wide slice containing the current-carrying cable. It is unlikely that the results, when modelled in this manner, would accurately represent the physical condition. In order to ensure that Model D is properly applied, the heat intensity of a layer should equal the highest heat intensity of any cable within that layer, and the thickness of the layer should not be less than the diameter of the largest cable in the layer.

As noted above, methods B, C, D, and E may be non-conservative in cases where only a small proportion of the conductors dissipate heat. Under such conditions the applicability of these methods should be reviewed.

In cases where the depth of fill is close to the diameter of the largest cables, all of the methods which credit diversity may be non-conservative, and Method A is more appropriate. For example, in a tray containing a single layer of cables, the heat dissipated by a few current-carrying cables located side-by-side would not spread evenly to all of the unenergized cables, some of which could be a significant horizontal distance away. Hot spots could occur where the energized cables touch each other, and may not be identified by Methods B through F. This is illustrated in the test results shown in Fig. 8 of [2]. In a tray with a 0.76" calculated depth of fill, the temperature of an energized #4/0 cable, with a diameter 105% of the calculated depth of fill, dropped only 1° C when a number of the other cables were deenergized.

However, in the same test, the temperature of an energized #6 cable (with a diameter 52% of the calculated depth of fill) dropped 15° C when some of the other cables were deenergized. This supports the concept of reduced temperatures due to diversity in cases where unenergized cables are situated to act as a heat sink.

III. APPLICATION OF THEORY

Method F can be used to calculate the maximum allowable heat intensity (Q) for cables in a tray of known depth of fill, width, diversity factor, ambient temperature, and maximum rated temperature. Formulas (1) and (2) are used to calculate the value of W_c that will result in a maximum temperature within the cable mass equal to the cable rating. W_c is divided by the cross-sectional area of the cable mass to obtain Q. Q can then be used to calculate ampacity for particular cable types as a function of diameter, number of conductors, and resistivity in accordance with [1] and [2].

Using the same variables as Appendix B of [1], calculated Method F results are as shown in Fig. 3. Since the calculation is iterative, it is best performed on a computer. Computer code such as the following can be used to generate these results. This program initially postulates a total dissipated heat value (W_c) of 0 w/ft, then iteratively adjusts it until equality, within a specified accuracy level, is reached.

```
/* AMPACITY.C
 * C code for calculating maximum cable heat intensity
 * based on depth of fill and loading diversity */

#include <stdio.h>
#include <math.h>

#define TM       90       // maximum temperature
#define TA       40       // ambient temperature
#define ACC      0.01     // accuracy
#define E        0.8      // emissivity
#define SBC      5.3E-9   // Stefan-Boltzmann Constant
#define RHO      13.12    // thermal resistivity
#define W        24       // width of cable mass

main()
{
  float Tc, d, df, h, As, Wc = 0, Wr, result = 0;

  printf("Depth of Fill (inches): ");
  scanf("%f", &d);
  printf("Diversity Factor (0-1): ");
  scanf("%f", &df);

  As = W/12 * 2;    // surface area of top & bottom (sq ft / ft)

  do
  {
    Wc += result * 0.5;

    Wr = Wc * df;                              // see (8)

    Tc = TM - ((Wc * RHO * d) / (8 * W));      // see (1)

    h = 0.101 * pow(Tc - TA, 0.25);            // see (9)

    result = (h * As * (Tc - TA)) +
      (SBC * As * E * (pow(Tc + 273.15, 4) -
      pow(TA + 273.15, 4))) - Wr;              // see (2)

  } while (fabs(result) > ACC);

  printf("\nDo not exceed %2.3f watts/in%c-ft\n",
    Wc / d / W, 253);
}
```

IV. CONCLUSION

Method F provides a means of calculating reasonable cable loading limits as a function of diversity. Its validity is supported by the test results described in [5] and [6]. In cases where the diversity factor is low, it more accurately models the thermal effects than do Methods B, C, D, and E. Method F results in a maximum permissible heat intensity value which is used to ensure that individual cables are not overloaded. The only difference between Method F and Method A is the introduction of one additional variable (diversity factor) which affects the value of dissipated heat used to calculate temperature rise in the air surrounding the cable mass.

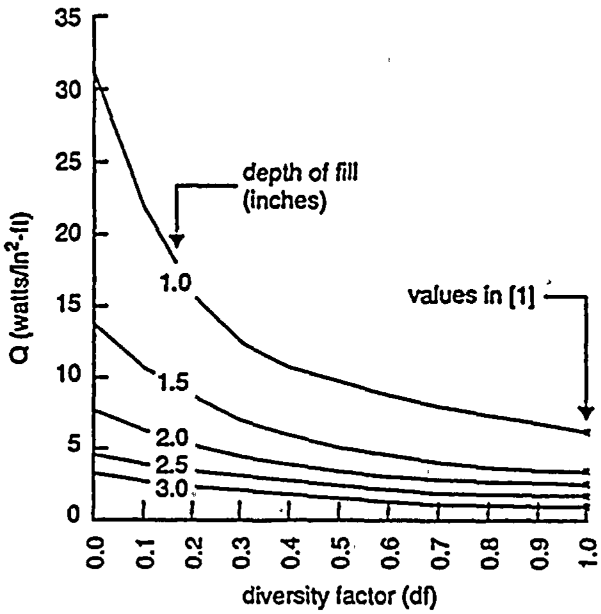

Fig. 3. Method F results for maximum allowable heat intensity per unit length as a function of diversity factor and depth of fill for 40° C Ambient

Since all of the alternative models assume that the heat is dissipated evenly across the top and bottom surfaces of the cable mass, they should be used with caution in cases where concentrated surface temperatures could exist, such as in a tray containing a single layer of cables.

Due to the limited number of input variables, Method F can be used to generate standardized results for a wide variety of configurations. Alternatively, a simple computer program can be used to generate results for specific configurations.

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ATTACHMENT B

Excerpts form Texas Utilities Ampacity Test Report Dated March 19, 1993