

# **THERMO-LAG ELECTRICAL RACEWAY FIRE BARRIER SYSTEMS AMPACITY TESTS AND ANALYSIS**

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## **ABSTRACT**

In the early 1990s the Nuclear Regulatory Commission (NRC) determined there were potential deficiencies in the design, testing and installation of Thermo-Lag Electrical Raceway Fire Barrier Systems (ERFBS). Their two primary concerns were:

- The then currently installed Thermo-Lag ERFBS might not ensure the electrical cables were free from fire damage for the required time-rating and,
- The ampacity derating factors used at that time for Thermo-Lag ERFBS might not be correct.

Thermo-Lag had been utilized in the design of the Tennessee Valley Authority's (TVA) Watts Bar Nuclear Plant (WBN) to protect redundant cables required for safe shutdown of the reactor in the event of a fire. Such protection was a licensing requirement for WBN per Appendix R of the Code of Federal Regulations. After reviewing other available ERFBS options, TVA determined that redesign and qualification of the Thermo-Lag systems would provide the best available ERFBS and minimize cable replacement due to ampacity effects. The resulting fire and ampacity test program developed one-hour and three-hour rated Thermo-Lag ERFBS for a variety of conduit and cable tray applications. The improved designs and installation techniques for existing Thermo-Lag barriers sought to minimize the required ampacity deratings. These enhanced designs were used in initial installations at WBN and for upgrading other systems at other TVA nuclear plants. The TVA work also provided useful input to the IEEE P-848 standard then being developed which governed ERFBS ampacity testing. Results of ampacity tests performed by Texas Utilities Electric (TU, now TXU) and TVA were also compared to an existing mathematical model for cable trays which have an ERFBS installed. Modification to key parameters of that model were suggested which result in good correlation with the tests.

The results of both the fire and the ampacity testing conducted by TVA were initially published in a conference record not easily accessible by electrical engineers (Reference 1). Therefore those findings related to ampacity testing have been extracted and updated with the results of subsequent work and now made available to the minutes of the IEEE's Insulated Conductors Committee (ICC) to facilitate retrieval by those engaged in the efforts of Working Group D13 in the Station Cable Subcommittee of ICC.

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## **INTRODUCTION**

Electrical Raceway Fire Barrier Systems (ERFBS) have been used in nuclear plants in the United States to protect redundant electrical cables and equipment required for Fire Safe Shutdown (FSSD) of the reactor.

In accordance with the requirements of the Code of Federal Regulations (CFR), Title 10 Part 50, Appendix R (Reference 2), the fire barrier separating redundant FSSD cables and equipment must have a three-hour rating for areas without fixed automatic fire detection and suppression or a one-hour rating for areas with installed automatic fire detection and suppression.

When Appendix R was promulgated, the majority of the plants were operating or in final stages of construction. While redundant shutdown circuits were a part of their basic design, redundant FSSD circuits often did not have the required physical separation. The most cost effective backfit to meet the new requirements was to protect one of the installed redundant FSSD circuits. In addition to providing the necessary insulating properties to ensure survival of the cables, the barrier must also satisfy the conflicting requirement of not excessively impeding the release of internally generated ohmic heating under normal operating conditions.

One material which has been manufactured to satisfy the need for such a barrier system is Thermo-Lag, a proprietary material manufactured by Thermal Science Incorporated (TSI) of St. Louis, Missouri. The material is best characterized as a "subliming ablative" rather than an intumescent. When exposed to elevated temperatures the material transposes from a solid into a vapor which results in heat blockage (ablative-shielding/cooling). The material originated in the aerospace industry and was primarily used as a heat shield for vehicle re-entry into the atmosphere. A detailed discussion on the mechanics of Thermo-Lag can be found in Reference 3.

## **CONCERNS**

### **Fire Protection**

In 1989 Gulf States Utilities (GSU) River Bend Station performed a series of fire tests to evaluate their as-installed configurations where a subcontractor had removed the "stress skin" from the fire barrier material. Stress skin is a steel wire mesh installed by the vendor as part of the fabrication of the Thermo-Lag (one-hour Thermo-Lag has stress skin installed on the inside surface; three-hour Thermo-Lag has stress skin installed on both the inside and outside surfaces). During the tests, 30-inch wide trays protected with a 3-hour Thermo-Lag ERFBS exceeded pass/fail temperatures and lost circuit integrity within approximately 60 minutes. Catastrophic failure and collapse of the tray occurred within 90 minutes. Having experienced these failures GSU then repeated the fire test by constructing additional assemblies in accordance with the vendor's published installation manual. Similar failures occurred. These and other failures led the NRC to issue additional Information Notices (References 4 through 9).

TU, in support of the licensing of Comanche Peak Unit 2, also conducted additional fire endurance testing of one-hour Thermo-Lag ERFBS. Based upon test failures of small conduit and large cable trays during this program, the NRC issued Bulletin 92-01 (Reference 10) and supplement 1 (Reference 11) in June and August 1992. This Bulletin determined that Thermo-Lag, as then installed on conduits smaller than 4" and cable trays larger than 14" wide, was unable to meet its design basis testing requirements as a rated fire barrier.

This Bulletin was then followed by Generic Letter 92-08 (Reference 12) in December 1992. With all the concerns being raised by the independent testing performed by utilities and the NRC, it became clear that new tests and new test protocols would be required.

At the time this issue came to light, TVA was in the final stages of construction of WBN Unit 1 located near Spring City, Tennessee. The original design of WBN utilized an ERFBS manufactured by the 3M Company. Analysis of cables protected with the 3M system indicated that numerous replacements would be needed to accommodate its high ampacity derating. Consequently, WBN decided to switch to the Thermo-Lag product with its lower derating. Because WBN was quickly approaching its scheduled fuel load date, TVA could not wait for industry groups to resolve the issues and an aggressive program to determine both fire endurance and ampacity effects was undertaken.

### **Cable Ampacity**

The decision to apply Thermo-Lag at WBN occurred after the cables were installed in their raceways. Evaluation of the effect of the ERFBS on the installed cables was initially performed in the mid 1980s utilizing ampacity correction factors based on the results of tests conducted by or for its manufacturer. In June 1992 the NRC issued Information Notice 92-46 (Reference 6) which raised concerns regarding ampacity (as well as those related to fire endurance) based on a variety of tests whose results differed substantially from the published derating factors (see Table 1). Subsequent Notices, Bulletins and Generic Letters from the NRC and position papers from various industry groups identified additional potential problems with the original ampacity tests, with the most significant concerns in the area of protected trays (Reference 13).

A review of the tests reveals that there was little consistency between the various protocols used for the ampacity assessment. Differences existed in the length of the test specimens, the control of end-turn cooling effects, the method of ambient temperature control, the size and number of cables used, the size of raceway, the location of thermocouples and the definition of equilibrium conditions. Variances in such key parameters inevitably resulted in significant differences in the derived correction factors.

## **TVA APPROACH TO RESOLUTION**

A survey of available guidance revealed the existence of two ampacity test protocols which were applicable to protected raceways. The first was UL 1712 (Reference 14). The second was a new standard under preparation within the Insulated Conductors Committee of the IEEE, known as IEEE P-848, (Reference 15).

A comparison of the two documents showed that many of the parameters thought to have been the source of lab-to-lab inconsistencies during earlier Thermo-Lag tests were controlled in the draft P-848 document. The issued UL Subject 1712 was silent on many of these same points. A comparison of those key parameters is provided in Table 2. Thus, TVA elected to follow IEEE P-848 (then on draft 11) in its tests.

## CONDUIT TESTING AND ANALYSIS

At the same time that TVA was evaluating various methodologies; TU was conducting fire tests and preparing to perform ampacity tests. The two utilities agreed to share results. TU also permitted TVA to witness their tests at Omega Point Laboratories, (OPL now Intertek Testing Services, Inc) in San Antonio, TX. The exposure to the TU program proved very beneficial.

P-848 had called for ampacity tests to include the determination of both baseline and wrapped ampacities using 1" and 4" conduits. The conduits were to contain 1-3/c No. 6 AWG and 3-1/c 750 kcmil cables, respectively. The intent was to provide conduits filled to approximately 40% with a cable typically used in 3-phase power circuits in power plant applications. The draft document called for the conductors to be connected in series and powered single phase. This latter provision was a concession to the knowledge that few facilities would have a laboratory grade "ganged" three-phase power supply necessary to keep the currents uniform within specification in all three conductors, an issue totally eliminated by the use of the series arrangement. However, when the TU tests began it became apparent that the magnitude of conduit heating produced by the magnetic imbalance was significant and could suppress the equilibrium currents.

With this conductor arrangement, conduit surface temperatures were approximately 80°C. When a fourth conductor was later added, the equilibrium currents rose substantially and the conduit surface temperature dropped to 60°C or less. From this, TVA concluded that tests with three conductors powered single-phase could produce inconclusive results since the non-realistic surface temperature would change the effective thermal resistivity from the conduit surface to the surrounding air and the conduit losses would impact the effective conductor resistance.

At the conclusion of these tests, TVA performed a detailed review of the TU conduit configurations and found that they differed in a significant way from TVA

designs. Both used the same Thermo-Lag preformed sections, however TVA procedures dictated that the interior of the barrier have a complete layer of trowel grade Thermo-Lag applied prior to installation. TU used a more conventional method, employing only pre-buttered joints. Because of the resulting difference in fit, TVA believed that both fire and ampacity tests might yield distinct results and thus determined to perform its own tests on 1" and 4" conduits.

As permitted by P-848, separate conduits were used for each of the TVA assemblies. The utilization of different conduit segments for each configuration allowed the test program to proceed at a much faster pace than if they had been conducted sequentially on the same segment, due to the 30 day cure time (for the trowel grade material) between each test. Given that the thermal resistivity of water is fairly low, its elimination from the seams and interior prior to ampacity testing is required in order to obtain results which are indicative of installed raceways.

Because of the conduit heating anomalies TU had experienced, TVA determined to repeat the tests with three conductors fed single-phase at its Chattanooga laboratory. This would confirm the TU findings and keep a plant commitment to be in compliance with the draft P-848. Having demonstrated that the effects of the conduit heating were understood and reproducible, TVA planned to then proceed to 4/c testing.

TVA's three conductor single-phase tests, performed in conformance the then current draft of P-848, produced the expected suppressed baseline currents. For the 3/c # 6 AWG and the 3-1/c 750 kcmil, the measured baseline currents were 54 and 234 amps, respectively, at 90°C (versus 69 and 598 amps as given in P-46-426, Reference 166). As with earlier TU tests, high conduit surface temperatures (80°C) were noted. The ampacity correction factors were scattered, reflecting the dependency upon the particular conduit segments utilized. Results are as shown in Table 3. TU and TVA observations would subsequently result in modifications to the conductor arrangements specified in P-848.

Having observed the excessive conduit losses during both the TU and in-house testing and identified likely mechanisms, TVA then re-performed the tests with four conductors per conduit. In the one-inch conduit, a 4/c #6 AWG cable was used. In the four-inch conduit, a fourth 1/c 750 kcmil conductor was added. In order to assess the repeatability of the tests, additional runs were performed using different baseline (bare) 4" conduit

segments. The tests, with results designated ACF1 and ACF2 in Table 4, produced the anticipated reduction in conduit temperature from 80°C to 60°C. The equilibrium currents substantially increased even though an additional heat producing conductor was in the conduit. There was also a reduction in the span of ACFs, indicating less dependence on the conduit characteristics. That span closely mirrored an analysis performed using classical Neher-McGrath methodologies (Reference 17). Yet, the correction factors were still well above that expected based on TSI and TU tests, especially the ACFs in excess of unity for the four-inch conduit.

Because of the high correction factors observed, TVA decided to perform additional single-phase tests with a higher number of conductors in the four-inch conduit and a series of three-phase tests on both the one and four-inch conduits. These tests would confirm that significant conduit heating effects had been eliminated and substantiate the high correction factors. One 3/c #6 AWG cable was used in the three-phase testing of the one-inch conduit. Eight 3/c #6 AWG cables were utilized in the four-inch tests, with only the end-turn connections being changed to accommodate the desired power supply arrangement. As before, two baseline conduits were used in an attempt to confirm repeatability. The results of the 24/c single phase tests are given in Table 5. For ease of comparison, the ACFs based on the 4/c tests have been included. The results of the three-phase tests are shown in Table 6. The correction factors for the earlier 4/c tests using the first set of baseline conduits have been included to facilitate comparison.

Good correlation was obtained between the two sets of tests, with the differences likely attributable to the changes in the test cable construction which had altered the distribution of the thermal resistance attributable to the insulation and jacket.

Based on the confirmation provided by the additional tests, TVA concluded that ACFs at or near unity were indeed possible for its specific configurations. In general, the correlation between the 4/c, 24/c and three-phase testing was good. However, the difference between the two baseline conduits was greater than is desirable for test repeatability and seemed to indicate that some conduit specific effects were still being seen.

Observations - First, it was noted that the results of tests performed with three conductors connected in series and powered single phase (as was required by both

drafts 11 and 12 of P-848), were dependent on the particular conduits utilized. During the test specimen fabrication stage, TVA had assumed the choice of test conduits would make little difference in the determination of the final correction factor. Thus, there was no effort made to "match" conduit segments (i.e. select all from the same vendor). A literature review found that the conduit losses are a function of the magnetic permeability and electrical resistivity of the steel used in its manufacture. Since neither property was controlled by industry standards such as NEMA C80.1 (Reference 18), the magnitude of the losses (and thus the equilibrium currents and ACFs) were dependent upon the specific conduit segments. This represented a direct challenge to test repeatability (which had been one of the primary objectives of the P-848 effort).

The additional testing performed by TVA, with alternate conductor/power supply configurations, reduced the conduit losses as evidenced by the drop in conduit surface temperatures from 80°C to 60°C. Ideally, both the baseline and wrapped tests would be performed on the same physical conduit specimen. However, when the fire barrier system contains components with long cure times (such as Thermo-Lag's trowel grade material), this may not be practical. In that case, the conduits should be "matched" (i.e. from the same vendor and lot).

TVA learned that ACFs at or near unity were possible even when an ERFBS was applied. The ACFs in excess of 1.0 were unexpected, based on existing data (the original TSI ACF was 0.91 and the recent TU tests produced ACFs in the range of 0.89 to 0.94). TVA believes that a significant contributor to this improvement was the elimination of the annular air space between the conduit outer surface and the inner surface of the Thermo-Lag. This was accomplished by the complete pre-buttering of the interior of the preformed sections of Thermo-Lag prior to placing them over the conduit. The effect of such an air gap can be seen from Equation 1 which is based on Reference 17.

If the above relationship is evaluated for Thermo-Lag, with pre-buttered joints only, installed on a 1" conduit containing a single 3/c #6 AWG cable, approximately 4.6 thermal ohms are added to the circuit for each 0.05" of air gap. Given that the total thermal resistance of the above configuration is approximately 20 thermal ohms, the effect of the gap can be significant (an approximate additional 10% derating per 0.05" length of gap).

Next, having eliminated the air gap as described above, the additional thermal resistance from installation of the Thermo-Lag appears to have been offset by the significant increase in the overall surface area and by the increased surface emissivity of the Thermo-Lag compared to bare conduit.

The Neher-McGrath expression for the thermal resistance from a cylindrical surface to the surrounding air is shown in Equation 2 below. As can be seen, the thermal resistance decreases as a function of the greater surface area presented by the wrapped conduit. The change in surface area is most dramatic for the smaller diameter conduits. For example, the application of a 5/8" layer of Thermo-Lag (at its maximum tolerance) to a one-inch conduit results in an approximate 2.8 times increase in surface area. The thermal resistance to the surrounding air also decreases with increasing emissivity.

The application of the dull white Thermo-Lag results in a surface emissivity of approximately 0.9. As will be shown, this is well above that of bare conduit. During the literature search noted above, it was observed that the recommended value for conduit emissivity had changed significantly over the last few decades. When the Neher-McGrath work was performed in 1957, a value of 0.95 was utilized. In 1962, when ICEA P-46-426 was generated, a value of 0.82 was applied. More recently, work undertaken by the Insulated Conductors Committee to produce IEEE 835 (Reference 19) to update P-46-426 has utilized a value of 0.50. Conversations with those involved in the 835 project and those familiar with the conduit manufacturing process, revealed that the change was driven by improvements in the hot-dip process and by a trend towards the use of electro-galvanized intermediate metal conduit (IMC) and electrical metallic tubing (EMT) in lieu of hot-dipped rigid steel conduits. In the hot-dip process, zinc coating is applied in a bath at about 850°F, whereas electrogalvanizing is carried out around 200°F. The shorter cooling time for the latter process results in a smaller zinc grain structure and therefore a smoother, shinier surface and hence a lower emissivity. Changes to the hot-dip process since the 1950s have resulted in shorter dwell times within the zinc bath and consequent shorter cooling times and shinier surfaces (i.e. lower emissivities).

Because there was no attempt to "match" the conduits used in the TVA tests, it is believed that the difference observed between ACF1 and ACF2 was a function of the surface emissivities of the various segments used in

making the baseline measurements. Since manufacturing standards did not specify an acceptable range of conduit emissivity, P-848 drafts were revised to include guidance on this parameter to ensure reproducibility of test results.

Finally, during the three-phase tests the adjustments necessary to keep three individual single phase supplies in equilibrium were found to be cumbersome. A change in the current in one phase produced a temperature change (and thus a current change) in the other two phases. In contrast, the currents were always the same in every conductor during the series-connected tests. As a result, the definition of "equilibrium" had to be somewhat relaxed for the three-phase tests. TVA believed that the majority of the difference between the single and three-phase results stemmed from this change. Thus, it appears that the 4/c and 24/c tests both yielded acceptable results without the complexity introduced by trying to keep the currents from three individual supplies constant. Given the greater ease of working with the 3/c #6 AWG cables as compared to the 750 kcmil conductors, the former size appears to be the better choice for further laboratory work.

Emissivity - Since the conclusion of the above series of tests, TVA has undertaken three other efforts to determine the range of conduit emissivities. The first was a special review conducted in the warehouse at the Sequoyah Nuclear Plant (SQN) by TVA personnel. The second set of data was accumulated at a TVA lab in conjunction with an evaluation of the derating effects of a 3M fire barrier system. The third set was developed during the TVA Thermo-Lag program at OPL. Each data set was taken with a Mikron Infrared thermometer. Readings at TVA were taken at four locations on each specimen. Those at OPL were taken at nine locations per specimen. Results of those efforts are shown in Table 7. As was noted in above, lower values of emissivity result in increased values of ACF.

Selection of TVA ACFs - In choosing ACFs for inclusion in TVA's internal design standards, the worst case ACF was identified for one and four inch conduits for each thickness of Thermo-Lag from the 4/c and 24/c tests. Those factors were further reduced by 5% to account for possible variations in the surface emissivities of installed conduits. The final values are shown in Table 8.

### **Non-Standard Conduit Configurations**

Multiple conduits within common enclosures - The

program also included assemblies to evaluate multiple conduits encased within common Thermo-Lag panel enclosures. Two types of such enclosures may be utilized at TVA plants. The first type consists of Thermo-Lag panels mounted directly on the surface of the conduits, with no intentional peripheral air gap. This construction is used on all three- and four-sided boxes (the additional side of the three-sided box being provided by a concrete wall or ceiling).

The second enclosure type consists of flat Thermo-Lag panels attached to a Unistrut frame installed around (but not touching) the conduits. This construction is used where the conduits to be protected are routed such that only two sides of the box will be Thermo-Lag, the other sides being concrete walls or a wall and the ceiling. The substantial heat capacity of the concrete and rebar, coupled with its low thermal resistivity (compared to Thermo-Lag), will ensure that such two- and three-sided enclosures are not the limiting cases and may be represented during testing through the use of four-sided assemblies.

Since there was no specific guidance in P-848 for evaluating multiple conduits within a common enclosure, TVA first performed modeling to identify the key attributes regarding such arrangements. Parameters identified were conduit size, number of conduits and their arrangement into rows and/or columns, conduit spacing (where multiple conduits are used) and box size (in the case of two-sided boxes on Unistrut frames). These attributes were selected in a manner as to ensure conservative results as described below.

Enclosures constructed of panels mounted directly to the conduit - Air gaps (between adjacent conduits) tend to vary in accordance with the enclosed conduit size. With small conduits, the correspondingly small air gaps result in the heat transfer across the gap being a function of radiation and conduction only, rather than a combination of radiation, convection and conduction. Thus, the ACF derived using "small" conduits would tend to be conservative. In keeping with the P-848 philosophy, TVA chose to utilize 1" conduits since they are the smallest conduits in which power circuits are typically routed.

For such enclosures, surface area is lowest for low numbers of small conduits. A single conduit would provide for the lowest surface area but does not include any internal air gap since TVA's method of application is to utilize preformed sections coated with trowel grade material. While a two conduit encasement would result

in such an air gap, each conduit would have an adjacent "end wall" from which to radiate. Thus, a set of three conduits in a row provides the least surface area, while still including a conduit which is not adjacent to one of the enclosure end walls. Such an arrangement, using 1" conduits, was included.

When conduits are banked in multiple rows, an additional air gap is injected between the rows. In order to assess that effect, TVA included a test assembly which had a double row of three 1" conduits. The presence of multiple conduits in close proximity to one another (even without a barrier) results in mutual heating and the introduction of what Neher and McGrath described as an "interference temperature rise". This effect is typically accounted for through the use of a grouping factor, such as is given in P-46-426. The tendency of the effect to dominate the overall correction factor contributed to TVA's decision to use small conduit banks (1x3 and 2x3) as described above in order to best isolate the impact of the ERFBS.

A separation between conduits of one-half their nominal diameter was utilized. Lesser separations would result in a greater interference temperature rise effect, as described above (and thus appear to minimize the effect of the barrier) but are not feasible below one-fourth of the nominal diameter because of the physical interference of couplings and supports and as a result of the need for tool clearances. Larger separations would also generally support individual wrapping of the conduits.

Based on the above, the tested configurations included:

- A single row of three 1" steel conduits in free air.
  - Same as above, with a one-hour enclosure made of 5/8" Thermo-Lag 330-1.
- Two rows of three 1" steel conduits in free air.
  - Same as above, with a one-hour enclosure made of 5/8" Thermo-Lag 330-1.

Enclosures constructed of panels mounted on a Unistrut frame - In contrast to the boxes formed by Thermo-Lag panels in direct contact with multiple conduits, this arrangement potentially results in a large gap between the conduit surface and the inner wall of the panels. In such an arrangement, free air exchange exists between that larger space and the small conduit-to-conduit gaps, rendering the latter insignificant. Tests to assess the effect of the large gap and the Thermo-Lag enclosure were conducted using a single 1" conduit (thus avoiding the concern for "interference temperature rise" mentioned above).

Tests were conducted using 1" conduits, given that its thermal resistance to the surrounding air is higher than that of a 4" (due to the smaller surface area of the former). As noted earlier, this is the smallest size conduit in which power circuits are typically routed.

For a given size conduit, the minimum box size (and therefore the minimum air gap thickness) is established by the diameter of the conduit, the thickness of the Unistrut and the gap between the conduit and the Unistrut. For a single 1" conduit with Thermo-Lag mounted over 1.625" P1000 Unistrut, the smallest possible box would be approximately 4.75" by 4.75" (as measured over the Unistrut).

It is expected that the largest box (regardless of conduit size or numbers of conduits) will be approximately 36" by 36". A test assembly was constructed to evaluate this large box, however, due to a transcription error on the part of an OPL employee, the 3'0" by 3'0" box became a 30" by 30" box. Following the logic presented in the preceding paragraphs, the larger enclosure more readily supports convection and presents a larger surface area to the enclosing room and would thus be expected to have a lesser impact than the 4.75" by 4.75" box. This expectation was borne out by the tests as can be seen from the results given in Table 9 below.

A supplemental test was performed in the 30" by 30" enclosure using the 2x3 assembly to evaluate the grouping effect in a large enclosure. Results are also given in Table 9.

Selection of the final ACF - Based on the above tests, TVA standards now require the use of an ACF of 0.88 for multiple conduits installed in Thermo-Lag enclosures mounted on Unistrut frames and an ACF of 0.74 for multiple conduits installed in Thermo-Lag enclosures which do not use Unistrut frames. These ACFs will be applied to the base ampacities of the TVA standards. Those ampacities already include a 0.86 adjustment for grouping factor based upon the assumption of a 1x6 bank. TVA standards require that the arrangement be confirmed in the field and if the resulting configuration requires a more severe ACF than 0.86, that the ampacity be adjusted accordingly.

Based on the above, the tested configurations included:

- A single 1" rigid steel conduit in free air.
  - Same as above, with a one-hour Thermo-Lag 330-1 ERFBS mounted on a 4.75" by 4.75" Unistrut frame.
  - Same as above, with a one-hour Thermo-Lag

330-1 ERFBS mounted on a 30" by 30" Unistrut frame.

- Two rows of three 1" steel conduits in free air.
  - Same as above, with a one-hour Thermo-Lag 330-1 ERFBS mounted on a 30" by 30" Unistrut frame.

### **Conduits with a Three-Hour Upgrade System**

The three-hour upgrade system is comprised of TSI 1.25" 330-1 pre-formed sections and two layers of the 3/8" 770-1 flexible wrap material. The TVA plan, following draft 14 of P-848, required that derating factor tests be conducted using both a single one-inch conduit containing one four-conductor #10 AWG cable, insulated with cross-linked-polyethylene and having an overall jacket of chlorosulfonated polyethylene and a single four inch conduit containing twelve 3/c #6 AWG cables, the latter constructed from the same materials as noted above. In both tests, the conductors were arranged in series and powered from a single-phase source. The results of the tests are shown in Table 10, with the 4" conduit producing a more significant derating.

The 330-1/770-1 fire barrier system was applied by TVA personnel in accordance with TSI instructions. In an attempt to eliminate air gaps between the various layers of the barrier system, trowel grade material was applied between the 330-1 and the first layer of 770-1 and between the two layers of 770-1. Post-test inspection showed that in spite of the pre-buttering and the use of tie wires, air gaps were induced between the layers by the sagging of the 770-1 mat material. The total thickness of the barrier system and the size of the gaps are tabulated in Table 11. It is likely that the air gaps contribute significantly to the reduced ACF (as compared to the one hour system).

## **TRAY TESTING AND ANALYSIS**

### **Analysis of TU Tray Tests**

The Thermo-Lag protected cable tray configuration tested by TU was identical to that intended for use at WBN. Therefore, TVA chose to utilize the correction factors determined by TU rather than duplicate this work.

TU had also determined that the P-848 draft provided the best available guidance for the tests and had utilized draft 11. That document required the use of a 4" by 24" tray filled 126-3/c #6 AWG 600 volt copper cables arranged in four layers. The wrapped tray utilized a single 5/8" layer of the Thermo-Lag panels. TU barrier designs also called for a single layer of a flexible silica

blanket to be placed over the top of the cable mass. According to TU, the blanket was added to provide additional protection for cables in highly filled trays from the heat transmitted through the barrier. The thermal resistivity of the material (Reference 20) is about twice that of the cable mass itself and could therefore result in some additional derating. In order to ensure that the effect of the silica blanket was accounted for, a layer was included in the TU tests. The tests demonstrated that a ACF of 0.682 was appropriate. While, TVA designs do not utilize the silica blanket, the configurations are otherwise identical. The TU results were thus deemed representative and conservative when applied to WBN's single wrapped trays.

#### **TVA Non-Standard Tray Configurations**

Following review of the TU work, TVA began a further series of tests at OPL for tray configurations which were not enveloped by the earlier program. These included one-hour rated tray assemblies which deviated from the TU/IEEE P-848 configuration and several three-hour assemblies. The test plan utilized P-848 guidance for the tests, with adaptations as required.

Tray with a removable sheet steel cover - The tests at OPL addressed the enclosure of ladder type trays having a sheet steel top cover. Consistent with P-848, a baseline test was first conducted for the single open top 24" by 4" ladder back tray in free air. A solid sheet steel top cover was then added and the assembly was wrapped with 5/8" of Thermo-Lag 330-1. During application of trowel grade material, the cover sagged. As more material was added to ensure that no air gap would exist between the bowed cover and the flat 330-1 panel, the cover sagged further. The end result was that the total barrier thickness greatly exceeded the nominal 0.625", with a maximum reading of 1.81" taken at the center of the sagging cover. The ACF of 0.60 (Table 11) is thus regarded as conservative for WBN where most trays are 18" wide. With this narrower width, less sag would be anticipated and therefore less trowel grade material would be required.

Vertical stacked trays - The tests at OPL addressed the common enclosure with Thermo-Lag of a vertical stack of trays. The stack included two power trays and one control tray, with the latter tray on the bottom. The ACF developed for this latter arrangement will also be used for cases where two power trays are in the common enclosure without the control tray and when one power tray and one non-power tray (in a vertical stack) are in a common enclosure. The application of this ACF is

conservative since the two tray arrangement affords more direct heat dissipation for the power tray(s) than the tested three tray enclosure. The tray specimens tested were as follows:

- Three open top 24" by 4" ladder back trays in free air.
- Same as above within a common enclosure made of 5/8" Thermo-Lag 330-1.

Results of that testing are also shown in Table 11. It should be noted that an ACF of 0.64 was determined using the measured baseline (26.19 amps) for the triple tray stack. However, TVA standards stipulate an ACF of 0.59 using the baseline for a single tray in free air (29.48 amps). This selection maintains a consistency in the method of determining ACF for wrapped trays but it raised the concern that standards might not adequately address mutual heating effects for unwrapped trays.

TVA's tray ampacities are based on ICEA standard P-54-440 (Reference 21) which are derived from the mathematical model first proposed by John Stolpe (Reference 22). Each of the referenced documents assumes that the trays under consideration are oriented horizontally and isolated from other significant heat sources, including power trays, whether located beside, above or below the tray of interest. TVA, like many utilities, does not invoke any special derating for trays in a vertical stack though such arrangements are common.

In his seminal work, Stolpe suggested that such an arrangement may result in mutual heating and that one approach for the prevention of overheating could be to utilize an ambient temperature, elevated 5 to 10°C above the general ambient for the room under consideration (for "moderate" and "extreme" cases, respectively as described by Stolpe).

The TVA tests established that the baseline current for a vertical stack of three horizontal trays (power, power and control, top-to-bottom, respectively) was 11.2 percent below that of the single tray in free air. The depth of fill used in those tests was 2.16", based on three layers of 0.735" cable, 32 cables per layer in a 24" wide tray. Using this information, the standard ICEA ampacity for a 3/c #6 cable was used along with figure 4 of the Stolpe paper and the diameters of the test and ICEA cables to determine an allowable ampacity of 26.4 amps for the TVA cable. This is within 1% of the measured 26.19 amps and shows that the ICEA standards for cables in tray are conservative and that the available conservatism is sufficient to offset the mutual heating effects of

multiple stacked trays.

Trays wrapped with a three-hour upgrade system – As a part of the TVA program, TSI's three hour tray upgrade system was also tested. The three-hour TSI system is comprised of 1.25" thick 330-1 panels and two layers of 3/8" 770-1 material. The assembly was constructed so as to be in compliance with the configuration required by draft 14 of IEEE P-848.

The 330-1/770-1 fire barrier system was applied by TVA personnel in accordance with TSI instructions. In an attempt to eliminate air gaps between the various layers of the barrier system, trowel grade material was applied between the 330-1 and the first layer of 770-1 and between the two layers of 770-1. Post-test inspection showed that in spite of the pre-buttering and the use of banding, air gaps (as large as 1.75") were induced on the bottom side of the tray between the layers by the sagging of the 770-1 mat material. It is likely that the air gaps contribute significantly to the reduced ACF (as compared to the one hour system). Results of the tests are shown in Table 11.

#### **Mathematical Analysis of Wrapped Trays**

TVA determined that alternate tray configurations would be required. A literature search was conducted to determine if a proven mathematical model existed which could be used to extend the TU results in lieu of additional testing. The search revealed that such a model for the ampacity of fire protected cable trays had been offered by Phil Save and Gary Engmann (Reference 23). Following their review of other models, Save and Engmann proposed that the wrapped system could be divided into seven regions (proceeding from the bottom of the enclosure upward through the tray);

- The outside surface of the wrap below the bottom of the tray.
- The fire wrap below the bottom of the tray.
- The lower portion of the cable mass
- The upper portion of the cable mass.
- The air space between the top of the cable mass and the fire wrap.
- The fire wrap over the top of the tray.
- The outside surface of the fire wrap over the top of the tray.

As noted above, the vendor sponsored results had been brought into question since publication of the paper in 1988. Since there was an absence of confirmatory tests, TVA's efforts turned to identification of acceptable test

methodologies. However, after completion of the TU tray tests, the knowledge that additional tray configurations were likely to be encountered as the fire barrier installation process progressed at WBN, led TVA to revisit the Save-Engmann analysis. With a cable depth of 2.95" in the TU tests, the ACF can readily be compared to the 3.0" computation in the Save-Engmann paper. The initial review, Table 12, indicated that there was a significant discrepancy between the model and the TU results.

A review of the parameters used in the Save-Engmann analysis indicated two potential sources of this variance. The first was the value of thermal conductivity for the barrier material. Their analysis was performed using a value of 0.430 W/m\*°C (as provided by TSI). Subsequent TSI sponsored evaluation by Washington University revealed a fairly strong temperature dependency for this parameter (Reference 24). For an average barrier temperature of 65°C, the new data suggests a value of 0.233 W/m\*°C for thermal conductivity.

The second major parameter which adversely impacted the original analysis was barrier thickness. One-hour rated Thermo-Lag 330-1 material is sold as being a minimum 0.5" thick. This is the value utilized in the Save-Engmann work. Minimum thickness is critical for fire performance but its use is non-conservative for ampacity analysis. Actual factory and field measurements by TVA have repeatedly shown that the material is manufactured 'thick'. That data indicates that 0.625" is an appropriate number for the present evaluation.

The only other modification to the Save-Engmann model necessary for comparison with the TU tests was to include consideration for the silica blanket. The basic model was reduced by Save and Engmann to a system of two equations with two unknowns (Equations 3 and 4). The system can be solved iteratively by first guessing value for the unknowns,  $a$  and  $s$ , the asymmetry of the cable mass and heat intensity, respectively.

In order to account for the effect of the silica blanket (present in the TU tests) on  $a$ ,  $s$  and  $km$ , an additional equation (Equation 5) and unknown were added and the parameter  $km$  in Equation 4 was changed to  $km^3$ . As before, the equations are solved by guessing values for the unknown and iterating until the system converges. With these changes and using a baseline value of  $s$  which corresponds to the actual baseline test current

(rather than a nominal value from P-54-440) the model correlates very well with the TU tests (see Table 12) and validates its fundamental soundness.

Using these adjustments, the ACFs shown in Table 1 of the Save-Engmann paper can be recalculated. For these standard configurations (i.e. no silica blanket) the revisions to include *km3* are not required. The results are shown in Table 13.

### Application

The benefit of such a model is that cable sizing for a variety of configurations can be evaluated without the time and expense of testing per IEEE 848. Such alternate configurations could include barriers with non-standard panel thicknesses or trays with raised side rails (to clear underlying cables which extend above the rails) and trays with sheet metal top covers under the Thermo-Lag. Each case requires only simple modification of the input parameters.

In the case of "3" hour barriers, the thickness of the Thermo-Lag, *zb* and *zt*, must be adjusted. Where raised side rails exist, the parameter *d* is adjusted. Application of a cover would require adjustment of the parameter *eu*.

### SUMMARY

The history of TVA's Thermo-Lag ampacity test program and its results have been reviewed. Resultant suggestions were provided for enhancement of the emerging draft IEEE standard governing such work. Ampacity tests conducted on cables in tray by TU were analyzed and compared with an existing thermal model. Modifications to that model were proposed which provided good correlation with the TU results.

### ACKNOWLEDGEMENTS

The author would like to acknowledge the contributions made to the ampacity portion of the Thermo-Lag project by the other TVA team members at the time the work was performed: Mark Henry Salley (the TVA Corporate Fire Protection Specialist at the time, now with the Nuclear Regulatory Commission) and J. J. Pierce, the Appendix R Manager at WBN (retired). Thanks are also extended to John White, of TU at the time the work was performed for permitting TVA to witness his tests and for graciously sharing the results. Special thanks are extended to Gary Engmann, of Black and Veatch (at the time the work was performed) for his time and patience in the discussion of his work.

### REFERENCES

1. *Fire Endurance and Ampacity Testing of One- and Three-Hour Rated Thermo-Lag Electrical Raceway Fire Barrier Systems*, M. H. Salley, K. W. Brown, presented at the 1995 International Joint Power Generation Conference in Minneapolis, MN
2. Code of Federal Regulations (CFR), Title 10 Part 50, Appendix R, paragraph III.G.2.
3. NRC/NRR Official Transcript of Proceedings *Meeting with Thermal Science, Inc., to Discuss Issues Involving Thermo-Lag 330*, dated October 17, 1991. NRC Public Document Room Accession Number 920205305.
4. NRC Information Notice 91-47, *Failure of Thermo-Lag Fire Barrier Material to Pass Fire Endurance Test*, August 6, 1991.
5. NRC Information Notice 91-79, *Deficiencies in the Procedure for Installing Thermo-Lag Materials*, December 6, 1991.
6. NRC Information Notice 92-46, *Thermo-Lag Fire Barrier Materials Special Review Team Report Findings, Current Fire Endurance Testing, and Ampacity Calculation Errors*, June 23, 1992.
7. NRC Information Notice 92-55, *Current Fire Endurance Test Results for Thermo-Lag Fire Barrier Material*, July 27, 1992.
8. NRC Information Notice 92-82, *Results of Thermo-Lag 330-1 Combustibility Testing*
9. NRC Information Notice 93-40, *Results of Thermo-Lag 330-1 Combustibility Testing*, December 15, 1992.
10. NRC Bulletin No. 92-01, *Failure of Thermo-Lag 330 Fire Barrier Systems to Maintain Cabling in Wide Cable Trays and Small Conduits Free from Fire Damage*, June 24, 1992.
11. NRC Bulletin No. 92-01, Supplement 1, *Failure of Thermo-Lag 330 Fire Barrier Systems to Perform its Specified Fire Endurance Function*, August 28, 1992.
12. NRC Generic Letter 92-08, *Thermo-Lag 330-1 Fire Barriers*, December 17, 1992.
13. NRC Information Notice 94-22, *Fire Endurance and Ampacity Derating Test Results for 3-Hour Fire-Rated Thermo-Lag 330-1 Fire Barrier*", March 16, 1994.
14. Underwriters Laboratory Subject 1712-1984, entitled, *Outline of Investigation Tests for Ampacity of Electrical Conductors Installed in Fire Protective Systems*.
15. IEEE P-848, Draft IEEE Standard entitled, *Procedure for the Determination of the Ampacity*

*Derating of Fire Protected Cables*, under preparation by Task Force 12-45 of the Tests and Measurements Subcommittee of the Insulated Conductors Committee of the IEEE. TVA testing began when the document was at draft 11. Later segments of the program utilized subsequent drafts. The document was ultimately published as IEEE 848-1996.

16. ICEA P46-426, 1962 edition, entitled, *Power Cable Ampacities*. Published by the Insulated Cable Engineers Association.
17. *The Calculation of the Temperature Rise and Load Capability of Cable Systems*, J. H. Neher and M. H. McGrath, AIEE Transactions, volume 76, October 1957, pp 752-773.
18. NEMA C80.1-2005, *Electrical Rigid Steel Conduit*
19. IEEE Standard 835-1994, entitled *Power Ampacity Cable Tables*.
20. *Ampacity of Wrapped Cables*, Keith A. Petty, IEEE paper 86 SM 398-2, IEEE Transactions on Power Delivery, volume 3, number 1, January 1988, pp 35-38.
21. ICEA P-54-440, *Ampacities of Cables in Open-Top Cable Trays*, Published by the Insulated Cable Engineers Association.
22. *Ampacities for Cables in Randomly Filled Trays*, John Stolpe, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-90, Pt. I, 1971, pages 962-974.
23. *Fire Protection Wrapped Cable Tray Ampacity*, Phil Save and Gary Engmann, IEEE Transactions on Energy Conversion, volume 4, number 4, December 1989, pp 575-584.
24. *Ampacity Analysis for Thermo-Lag Protected Trays*, James M. McKelvey, Washington University, St Louis, MO, July 28, 1992. Unpublished work performed under contract for TSI.

## SYMBOLS

### Neher-McGrath

Ds	the diameter of the conduit (or Thermo-Lag)
dT	the temperature difference between the surface of the conduit (or Thermo-Lag) and ambient air
$\epsilon$	the emissivity of the conduit (or Thermo-Lag)
n	number of enclosed conductors
OD	overall diameter of the conduit, in inches
gap	length of the gap, in inches
$\rho_{\text{air}}$	thermal resistivity of the air ( $^{\circ}\text{C}\text{-cm/watt}$ )
Re	the effective thermal resistance from the conduit (or Thermo-Lag) to the surrounding

air	
Rgap	thermal resistance of the of the gap, in thermal ohms
Tm	average surface temperature of the conduit (or Thermo-Lag) and the surrounding air

### Save-Engmann

a	distance from the bottom of the packed cable mass to a plane surface that is at the maximum temperature in the packed cable mass (meters)
d	loading depth of the cable tray (meters)
em	emissivity of the packed cable mass surfaces (dimensionless)
eob	emissivity of the outside of the wrap material on the bottom of the tray (dimensionless)
eot	emissivity of the outside of the wrap material on the top of the tray (dimensionless)
eu	emissivity of the inside of the material on top of the tray side rails - tray cover, wrap material, etc. (dimensionless)
km	thermal conductivity of the packed cable mass [watt/(meter-degree C)]
kzb	thermal conductivity of the wrap material on the bottom of the tray [watt/(meter-degree C)]
kzt	thermal conductivity of wrap material on the top of the tray [watt/(meter-degree C)]
k3	empirically derived equivalent thermal conductivity in the region between the top of the packed cable mass and the material on the top of the tray side rails - wrap, tray cover, etc. [watt/(meter-degree C)]
s	heat generation per unit volume of packed cable mass (watts/meter <sup>3</sup> )
sb	Stefan-Boltzman constant = $5.705 * 10^{-8}$ [watt/(meter <sup>2</sup> -degree K <sup>4</sup> )
t	thickness of the packed cable mass (meter)
Te	temperature of the environment (degrees C)
TKe	temperature of the environment (degrees K)
TKw	temperature of the packed cable mass (degrees K)
Tw	temperature of the packed cable mass (degrees C)
w	loading width of the cable tray (meters)
zb	thickness of the fire barrier material at the bottom of the tray (meters)
zt	thickness of the fire barrier material at the top of the tray (meters)

### Additional Parameters

kc	effective thermal conductivity of the silica cloth [watt/(meter-degree C)]
km3	effective thermal conductivity of the upper portion of the packed cable mass considering

the effect of the silica cloth [watt/(meter-degree C)]  
 tt total thickness of the cable mass and silica cloth (meters)  
 zc thickness of the silica cloth (meters)

Table 1  
 Pre-IEEE P-848 Ampacity Correction Factors

Configuration	Original TSI ACF <sup>1,2</sup>	Other Source ACF
Tray Wrapped with TSI 330-1 - 1 Hour	0.875	0.712
Conduit with TSI 330-1 - 1 Hour	0.91	0.987

Note 1 ACF = Wrapped Amps / Baseline Amps  
 Note 2 Based on TSI sponsored testing.

Table 2  
 Comparison of UL 1712 and IEEE P-848

Parameter	UL 1712	IEEE P-848
Tray Fill	not addressed	122 3/c #6 AWG
Conduit Fill	not addressed	see text
Conductor Size	not addressed	see text
Insulation/Jacket Type	not addressed	XLPE/CSPE <sup>1</sup>
T/C Size	22 AWG max	24 AWG only
T/C Layout	mid-point only	3 planes
Heat Breaks	not addressed	required
Length	6 ft minimum	12 ft minimum
Ambient	30, 40 and 50°C	40°C only
Conduit Size	not addressed	1" and 4"

Note 1 Cross-linked polyethylene insulation with a chlorosulfonated polyethylene jacket.

Table 3  
 3/c Single-Phase Test with TSI 330-1

Configuration	ACF
1" Conduit - 5/8"	0.97
1" Conduit - 3/8" + 3/8"	0.97
1" Conduit - 5/8" + 3/8"	0.96
4" Conduit - 5/8"	1.05
4" Conduit - 3/8" + 3/8"	0.92
4" Conduit - 5/8" + 3/8"	0.98

Table 4  
 4/c Tests with TSI 330-1

Configuration	ACF1	ACF2
1" Conduit - 5/8"	0.98	see note 1
1" Conduit - 3/8" + 3/8"	0.99	see note 1
1" Conduit - 5/8" + 3/8"	0.97	see note 1
4" Conduit - 5/8"	1.07	1.04
4" Conduit - 3/8" + 3/8"	1.01	0.98
4" Conduit - 5/8" + 3/8"	1.03	1

Note 1 An alternate 1" baseline conduit was not utilized until after this test.

Table 5  
 4/c versus 24/c - with TSI 330-1 - 4" Conduit Only

TSI	ACF1 4/c	ACF1 24/c	ACF2 4/c	ACF2 24/c
5/8"	1.07	1.07	1.04	1.03
3/8" + 3/8"	1.01	1.03	0.98	1.00
5/8" + 3/8"	1.03	1.04	1.00	1.01

Table 6  
1-Phase vs 3-Phase Testing with TSI 330-1

TSI Configuration	ACF 1φ 4/c	ACF1 3φ 8-3/c	ACF2 1φ 4/c	ACF2 3φ 8-3/c
1" with 5/8"	0.98	1.00	note 1	1.03
1" with 3/8"+3/8"	0.99	0.99	note 1	1.02
1" with 5/8"+3/8"	0.97	0.98	note 1	1.00
4" with 5/8"	1.07	1.05	1.04	1.02
4" with 3/8"+3/8"	1.01	0.98	0.98	0.95
4" with 5/8"+3/8"	1.03	1.04	1.00	1.01

Note 1 An alternate 1" baseline conduit was not used until after this test.

Table 7  
Measured Conduit Emissivities

Location	Size	Material	No. of Specimens	Average Emissivity
SQN	0.5"	Alum	1	0.26
SQN	2.0"	Alum	4	0.18
SQN	0.5"	Steel	10	0.88
SQN	2.0"	Steel	10	0.86
CLSD	1.0	Steel	1	0.46
OPL	1.0"	Steel	11	0.47
OPL	4.0"	Steel	1	0.36

Table 8  
Selection of Final ACF, with Margin  
For Conduit with TSI 330-1

Configuration	Lowest ACF	TVA Standard
5/8"	0.98	0.93
3/8" + 3/8"	0.98	0.93
5/8" + 3/8"	0.97	0.92

Table 9  
Multiple Conduits in a Common Enclosure

Configuration	ACF
1 x 3 Bank of 1" Conduits w/ 5/8" 330-1	0.92
2 x 3 Bank of 1" Conduits w/ 5/8" 330-1	0.74
1" Conduit in a 4.75" by 4.75" Enclosure of 5/8" 330-1 on a Unistrut Frame	0.88
1" Conduit in a 30" by 30" Enclosure of 5/8" 330-1 on a Unistrut Frame	0.94
2 x 3 Bank of 1" Conduits in a 30" by 30" Enclosure of 5/8" 330-1 on a Unistrut Frame	0.91

Table 10  
Three-Hour Conduit Upgrade System

Configuration	ACF
1" Conduit w/ 1.25" 330-1 and Two Layers of 3/8" 770-1	0.90
4" Conduit w/ 1.25" 330-1 and Two Layers of 3/8" 770-1	0.87
Final ACF with Conservatism for Emissivity	0.82

Table 11  
Non-Standard Trays

Configuration	OPL ACF	TVA STD ACF
Single Tray with Top Cover and 1-Hour 330-1	0.60	0.60
Triple Tray with 1-Hour 330-1	0.64	0.59
Open Top Trays with 3-Hour, 1.25", 330-1 w/2 Layers of 3/8" 770-1	0.52	0.52

Table 12  
Mathematical Analysis of Wrapped-Trays

	Cable Depth (in)	Tray Depth (in)	ACF
Original Save-Engmann	3	4	0.77
TU Test	2.95	4	0.682
Modified Save-Engmann	2.95	4	0.673

Table 13  
Save/Engmann Thermo-Lag ACFs

Fill (in)	Height (in.)	TSI Barrier System				
		1-Hour Save/Engmann <sup>1</sup>	0.625" Modified Analysis <sup>2</sup>	3-Hour Save/Engmann <sup>3</sup>	1.25" Modified Analysis <sup>4</sup>	3-Hour Upgrade System <sup>5</sup>
1.0	3	0.75	0.67	0.70	0.58	0.51
	4	0.75	0.67	0.70	0.58	0.51
	5	0.75	0.67	0.70	0.58	0.51
1.5	3	0.76	0.68	0.71	0.59	0.52
	4	0.76	0.68	0.71	0.59	0.52
	5	0.76	0.68	0.71	0.59	0.52
2.0	3	0.76	0.70	0.71	0.62	0.54
	4	0.76	0.70	0.71	0.61	0.54
	5	0.76	0.69	0.71	0.61	0.54
2.5	3	0.76	0.71	0.72	0.63	0.55
	4	0.76	0.71	0.72	0.63	0.55
	5	0.77	0.70	0.72	0.62	0.55
3.0	4	0.78	0.72	0.73	0.64	0.57

Note 1 ACFs are based on a nominal 0.50" thickness and the original Thermo-Lag conductivity.

Note 2 ACFs are conservatively based the barrier maximum thickness (0.625") of the 1-hour system and the revised Thermo-Lag conductivity.

Note 3 ACFs are based on the original 3-hour design and the original Thermo-Lag conductivity.

Note 4 ACFs are conservatively based the barrier maximum thickness (1.25") of the 3-hour system and the revised Thermo-Lag conductivity.

Note 5 ACFs are based on the maximum thickness of the 3-hour upgrade system and the revised Thermo-Lag conductivity.

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**EQUATIONS**

**Equation 1 - Thermal Resistance of the Air Gap Under Preformed Thermo-Lag Sections**

$$R_{gap} = 0.012 * n * \rho_{air} * \log\left(\frac{OD + 2 * gap}{OD}\right)$$

**Equation 2 - Thermal Resistance between a Cylindrical Surface and the Surrounding Air**

$$Re = \frac{15.6 * n}{Ds * \left(\frac{dT}{Ds}\right)^{0.25} + 1.6 * \varepsilon * (1 + 0.0167 * Tm)}$$

**Equation 3 - Save/Engmann Equation 5**

$$s * a = \left[ \frac{1.917}{w^{0.25}} * \left( (T_w - \frac{s * a^2}{2 * km} - \frac{s * a * z_b}{kz_b}) - T_e \right)^{1.25} + s_b * eob * \left( (TK_w - \frac{s * a^2}{2 * km} - \frac{s * a * z_b}{kz_b})^4 - TK_e^4 \right) \right]$$

**Equation 4 - Modified Save/Engmann Equation 12**

$$s \cdot (t - a) = \frac{1.917}{w^{0.25}} \cdot \left[ \left[ T_w - T_e - \frac{s \cdot (t - a)^2}{2 \cdot km^3} - \frac{s \cdot (t - a)}{\left( \frac{k3}{d - t} \right) + 4 \cdot s_b \cdot \left( \frac{em \cdot eu}{em + eu - 0.462 \cdot em \cdot eu} \right) \cdot \left( \left( \frac{2 \cdot TK_w + TK_e}{3} \right)^3 \right)} \right] - \frac{s \cdot (t - a) \cdot z_t}{kz_t} \right]^{1.25} \dots$$

$$+ s_b \cdot eot \cdot \left[ \left[ TK_w - \frac{s \cdot (t - a)^2}{2 \cdot km^3} - \frac{s \cdot (t - a)}{\frac{k3}{d - t} + 4 \cdot s_b \cdot \left( \frac{em \cdot eu}{em + eu - 0.462 \cdot em \cdot eu} \right) \cdot \left( \left( \frac{2 \cdot TK_w + TK_e}{3} \right)^3 \right)} - \frac{s \cdot (t - a) \cdot z_t}{kz_t} \right]^4 - TK_e^4 \right]$$

**Equation 5 - Expression for Thermal Conductivity of the Cable Mass with the Silica Blanket**

$$km3 = \frac{(tt - a) * km + zc * kc}{tt + zc - a}$$