AN ASSESSMENT OF CABLE FUNCTIONALITY PERFORMANCE ISSUES FOR THE TUE COMANCHE PEAK UNIT 1 THERMO-LAG FIRE ENDURANCE TESTS

ENCLOSURE 2

An Assessment of Cable Functionality Performance Issues for the TUE Comanche Peak Unit 1 Thermo-Lag Fire Endurance Tests

A Technical Evaluation Report to the USNRC

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1.0 Introduction

1.1 Overview

The work described in this Technical Evaluation Report (TER) was performed by Sandia National Laboratories (SNL) under USNRC contract JCN J2017, Task Order 2. The objective of this task order is to provide support to the USNRC in the evaluation of the acceptability of the Texas Utilities Electric (TUE) fire endurance tests performed on the fire barrier material Thermo-Lag 330-1 as applied at Comanche Peak Unit 1 (CPSES-1). Several test reports have been submitted by TUE for USNRC consideration. A list of those reports which remain under consideration, and which were evaluated as a part of the current work, is provided in Section 2.

This document represents the second review report prepared by SNL. The first was submitted for USNRC consideration on March 15, 1994 [1]. In that initial review, a number of questions and issues were raised. Based in part on this initial SNL review, the USNRC prepared a Request for Additional Information (RAI) which was submitted to TUE [2]. TUE has responded to this RAI through a submittal under a cover letter from W.J. Cahill Jr. to the USNRC dated August 8, 1994 [3] and through a second submittal under a cover letter from C.L. Terry to the USRNC dated November 9, 1994 [4]. These TUE submittals and the original test reports [5-10] form the basis for the SNL review documented here.

1.2 Scope of the Current Review

The scope of the current review includes two primary objectives. The first is to determine whether or not the questions raised in the RAI have been resolved. The second objective was to assess cable functionality performance during the TUE tests. In initial reviews of the TUE response, it was determined that the utility had not adequately addressed the questions raised by the USNRC in this regard (this position was communicated to TUE by the USNRC in a public meeting August 30, 1994). Hence, at the request of the USNRC, SNL has performed cable functionality analyses using the test data reported by TUE. SNL has also provided a recommended procedure and acceptance criteria for the ultimate evaluation of cable performance acceptability during the TUE tests which is based on these SNL analyses.

1.3 Report Organization

Section 2 of this report identifies those specific test articles which are considered in this review. It is the understanding of SNL that TUE has withdrawn its request for approval of the remainder of the Unit 1 test articles. Hence, this TER is limited only to those test articles for which approval is still being sought by TUE. Section 3 provides a direct assessment of the adequacy of the TUE response to the USNRC RAI on a question by question basis. Section 4 of this report describes the basis for the SNL cable functionality analyses and presents the SNL analysis results. Section 5 presents a recommended test acceptance criteria which is based on the ultimate

performance limits of power, control, and instrument cables. Section 6 of this report provides a summary of SNL's findings regarding cable IR performance during the TUE tests and provides recommendations regarding the acceptability of each of the TUE test articles. Section 7 provides a listing of the documents referenced in this report.

2.0 Identification of Tests Considered

In this review SNL has considered only a sub-set of the test articles which have been submitted by TUE for USNRC consideration. Note that in general each of the TUE test reports deals with multiple test articles which were tested simultaneously. Hence, the current reviews often include only a portion, or portions, of a given TUE test report. The test articles considered in this review are:

Scheme 9-3 1½" and 2" conduits only [5].

Scheme 11-2 1½" and 2" air drops [6].

Scheme 11-4 Box assembly [7].

Scheme 11-5 24" center cable tray assembly only [8].

Scheme 13-2 12" cable tray and 2" conduit [9].

Scheme 15-2 Individual power cable wraps [10].

It is the understanding of SNL that TUE has withdrawn its request for consideration of the balance of the CPSES-1 test articles. No further consideration of the "withdrawn" test articles, or of the sections of those test reports dealing with these test articles, has been given here.

3.0 Adequacy of the Utility RAI Response

3.1 Overview

On June 15, 1994, the USNRC forwarded a Request for Additional Information (RAI) to TUE [2]. The TUE response was transmitted to the USNRC on August 8, 1994 [3] with additional supplemental analyses provided under separate cover November 8, 1994 [4]. Section 3.2 below specifically assesses the adequacy of the utility RAI response on a question by question basis. In particular, this section focusses primarily on the responses presented in [3] with reference to the analyses of [4] as appropriate. The analyses presented in [4] are discussed in greater detail in Section 3.3 below.

In general, the responses which were obtained were either adequate or, for those cases in which the responses were inadequate, SNL has, at the direction of the USNRC, performed supplemental calculations to provide the needed information (See Section 4 below). SNL finds that sufficient information has been provided by TUE to resolve all of the critical questions regarding cable functionality in its fire endurance tests. The following subsections address each of the questions asked in the RAI and the adequacy of the utility response.

3.2 TUE Responses to Specific Questions

3.2.1 Question 1: Special Application Instrumentation Wires

The utility response appears adequate for this question. The mineral insulated cables cited by the utility as the only such cables relied upon in a fire scenario, and the assessment that these cables are qualified to temperatures higher than those experienced in the fire tests is reasonable. Mineral insulated cables are very rugged and would not likely be damaged from the exposures experienced in the TUE tests.

3.2.2 Question 2: Bonded Jacket Cables

The utility does note that bonded jacket cables are housed in Thermo-Lag protected envelopes, and in fact, that some of these cables were included in the tests. The utility response did not adequately address the issue of aged cable performance citing this as a "new or different staff position." In general, this is a very difficult question to address as the current state of knowledge regarding this issue remains poor. SNL had noted this particular case as an exception to the general arguments made by TUE regarding cable jacket swelling, and SNL stands by the finding that this is, indeed, a potential exception to TUE's arguments. However, given the current state of knowledge it is not reasonable to expect the utility to be able to fully assess this question at the current time. Despite the fact that the utility response does not fully address the question, it is not recommended that any follow-up questions on this issue be raised at the current time.

3.2.3 Question 3: Stone and Webster Calculation

The calculation has been provided as requested. The utility response is fully adequate.

3.2.4 Question 4: NRC Acceptance Requirements

The utility response to this question is not considered adequate. The questions raised by the USNRC regarding the inadequacy of the pre- and post-test "megger" tests remain valid and the utility argument in this regards is not considered appropriate. The issue of barrier burn-through remains a significant potential concern. SNL does agree with the utility approach to this second issue involving a case by case examination of the barrier performance. SNL efforts have included the performance of supplemental calculations as presented in Section 3 of this report which will address the cable operability questions raised in this question for the TUE tests. The issue of barrier burn-through is addressed on a case by case basis as a part of the SNL review. It is not recommended that any follow up question be submitted to the utility in this regards.

For the record it should be noted that the utility appears to be citing an April 1993 letter from the USNRC as the basis for the acceptability of its pre- and post-test megger testing. However, this letter was associated with the fact that TUE had indicated that it had not taken the low-voltage circuit integrity tests, which were normally performed, during Test Scheme 15-1. SNL had previously been asked to review the utility procedures in this regards and had written a letter to the USNRC [11] which was strongly critical of both the low voltage and the pre- and post-test megger tests citing that neither of these tests would represent an adequate assessment of cable performance during the fire exposures. The 4/93 USNRC letter clearly states a position consistent with this early SNL recommendation and indicates that the TUE low voltage measurements were not an adequate test to demonstrate cable performance.

Based on this finding the letter went on to state that it was not concerned with the omission of the low voltage test from the test protocol. However, the letter does not endorse the concept of pre- and post-test megger testing as an adequate basis for cable performance assessments. It simply states that if such measurements are to be made then the post test measurements should be made as soon as possible after the test. TUE had, at that time, indicated quite strongly that due to safety concerns it would not perform megger tests during the exposure (the SNL recommended approach). Taken in this context, the USNRC letter of April 1993 merely expresses that the tests which are to be performed should be performed promptly after completion of the exposure and does not endorse the TUE pre- and post test measurements as adequate to demonstrate cable performance.

3.2.5 Question 5: Transmitter Circuit Model

The utility has concurred with the staff position as cited in the RAI and has used the SNL recommended model as the basis for its subsequent calculations. This response is fully adequate.

3.2.6 Question 6: Use of Inappropriate EQ Test Data

The utility response disagreed with certain minor aspect of the RAI, but did agree to utilize the suggested set of Rockbestos IR vs. Temperature data in lieu of the data set used in the original TUE submittals. This response is fully adequate.

3.2.7 Question 7: Reconsideration of Sample Cases

TUE has provided for a reassessment of its example cases. The submittal also acknowledges that the sample cases did not envelope the 3/4" conduit test of Scheme 9-3. However, the utility has withdrawn its request for the approval of this particular test article, and hence, this response is adequate within the context of this question.

3.2.8 Question 8: Basis for Assessment of Cable Performance Temperatures

The utility response to this question was not fully adequate. While TUE has utilized the recommended SNL analysis methodology to assess the performance of certain of the cables from its tests, the analyses were incomplete and did not consider all of the cables in each test. SNL has performed supplemental analyses to support the final assessment of cable performance during the TUE tests. These analyses provide an adequate basis to assess the ultimate performance of the TUE test cables, and hence, it is not recommended that any addition questions be submitted to the utility in this regards.

For the record, it should be noted that SNL disagrees with the utility arguments regarding the usefulness of the average cable temperature as an indication of cable performance. The utility argument in this regards is "comparing apples to oranges." It is noted by the utility that the cable insulation will not be at a uniform temperature <u>through its thickness</u> due to heat transfer delays. This is cited as the justification for using a <u>length-wise average</u> cable temperature as the basis for analysis. Variations through the thickness can not be equated to length-wise variations. This argument ignores the critical importance of localized hot-spots to overall cable performance. Any assessment of cable performance based on temperature must recognize the logarithmic decline in IR with increasing temperature. A simple linear temperature average such as that used in the original TUE calculations fails to account for this important effect. A length-wise averaging of temperature "washes out" the hot-spots, and hence, should never be used as the basis for assessing cable performance.

3.2.9 Question 9:

Question 9 was similar to Question 5 above with regards to a specific TUE calculation. The utility response to this question was fully adequate.

3.2.10 Question 10:

Question 10 was similar to Question 6 above with regards to a specific TUE calculation. The utility response to this question was fully adequate.

3.2.11 Question 11: Direct Comparison of Cable Performance to Acceptance Criteria

The utility response to this question was not adequate. TUE did provide analyses of the cable IR's using the SNL recommended composite cable analysis methodology as documented in [4], but the utility failed to provide a direct comparison of the analysis results to the USNRC acceptance criteria. In addition, as discussed in Section 3.3 below, the utility made a number of numerical errors in the MATHCAD (a computer mathematical analysis software package) implementation of its analyses. However, SNL has performed supplemental calculations which provide the needed comparisons. Hence, SNL does not recommend that follow-up questions be submitted to the utility at this time.

3.2.12 Question 12: Use of Differing Analysis Methods for Different Tests

The utility response to this question cites its response to Question 8. While this response was not adequate, the supplemental calculations performed by SNL eliminate the need for an additional RAI to the utility regarding this issue.

3.2.13 Question 13: Temperature Rating of the TUE Cables

TUE has confirmed that for ampacity purposes it cables are rated for an ambient of 50°C. This response is fully adequate. Note that SNL has used this information in its supplemental analyses of power cable performance. In particular, the SNL analyses assume that the maximum possible cable temperature increment due to at-power operation would be 40°C, the difference between the cable rating temperature of 90°C and the ambient temperature of 50°C. (For many other plants use of a 50°C increment would be appropriate because typical cable analyses assume a 40°C ambient temperature.)

3.2.14 Question 14: Temperature Conversion Error

The utility acknowledges the error but notes that the calculatic :n question was superseded by a subsequent calculation. Hence, TUE apparently does not anticipate a correction to the cited analysis. This response is adequate.

3.2.15 Question 15: Failure to Consider Power and Control Circuits

The utility response takes exception to the power cable fault analogy offered by SNL and the USNRC, and does not address the larger question of assessing the performance of power cables while in operation. While this response was not adequate, the supplemental calculations performed by SNL eliminate the need for an additional RAI to the utility. In particular, SNL's analyses have considered the performance of power cables by including an at-power temperature increment as discussed in 3.2.13 above.

3.2.16 Questions 16, 17, 18, and 20:

These questions dealt with the need to compare the cable performance for each of the individual test articles to the USNRC acceptance criteria. While the utility response to these questions was not adequate, the supplemental calculations performed by SNL eliminate the need for an additional RAI to the utility.

3.2.17 Question 19: Scheme 11-5 Left Cable Tray Damage

The utility has withdrawn its request for approval of the upgrade scheme used on the left cable tray of Scheme 11-5. Hence, this question is no longer relevant.

3.3 Other Outstanding Issues

3.3.1 Overview

During it's previous review efforts, SNL had raised a number of points of concern regarding various aspects of the individual tests and test reports submitted by TUE. Many of the test articles initially reviewed by SNL are no longer being considered as a part of this final review process. Hence, many of the concerns raised are no longer relevant. This section outlines, in a more general technical issues oriented format, those issues which remain relevant given the modified list of tests being considered (see Section 2 above), and identifies the extent to which the identified concerns have been addressed or resolved by TUE. This section focusses primarily on the analyses provided by the utility in its supplemental submittal of November 9, 1994 [4].

3.3.2 Cable Performance Assessment Concerns

The major point of concern identified in the initial SNL review was the failure of the utility to provide test-specific analyses of cable performance acceptability. This concern applied uniformly to each of the individual test articles. In it's response to the USNRC RAI, TUE has provided estimates of the cable IR values from its fire endurance tests based on the SNL recommended "composite cable analysis methodology" [4]. However, these analyses contain certain errors and shortcoming, and hence, are not considered adequate to fully address the concerns raised.

With regards to the analysis errors, note that in implementing the calculations, the utility has apparently made errors in the manner in which the individual resistance

elements are summed. This error appears to affect all of the test cables for which more than 17 thermocouples were used during testing. In particular, for each cable with in excess of 17 thermocouples, resistance elements 14-17 are "double-summed." That is, in the calculation of the total resistance over the exposure length, elements 14-17 are counted twice. Since this calculation involves a summation of parallel resistance elements, the net result is the under-prediction of actual cable IR values. While this has a net conservative effect, and the errors which resulted were generally small, the presence of this error should be noted. (See for example the first case cited by TUE on page 2 of 3 of Enclosure 1 to TXX-94267 [2]. The error is found in the equations for "R_1" and "R_2" in which the terms for elements 14 through 17 are repeated in both expressions.)

Another shortcoming of the TUE analyses is that the final estimated cable IR values are not normalized to "ohms over 1000 feet of cable" (Ω-1000ft) as required for comparison to the USNRC acceptance criteria. Rather, the values are only reported as the effective IR over the actual exposure length of the cable in the test. Since the test cable exposure lengths were only 8-13 feet, the TUE calculated IR values would be approximately two orders of magnitude (a factor of 100) larger than would be the normalized Ω-1000ft values. The TUE results are not consistent with the need to assess performance in comparison to the USNRC acceptance criteria which requires a minimum IR of 1.0E6 Ω-1000ft. The calculated TUE values cannot be directly compared to the USNRC criteria until those values have been normalized for length.

Also noted in the TUE analysis is the fact that all of the cable IR analyses have been performed using only nominal values for the cable physical parameters. In particular, this involved the values assumed for the conductor diameter and the insulation thickness (which together imply an outer cable diameter). In fact, the values used in all cases by TUE are typical of instrument cables, and are not representative of either power or control cables. The actual physical parameters of the tested cables should be used for each analysis. In general the errors introduced by this difference would be relatively small because insulation thickness increases as cable size increases. Since these values appear in the calculations in the form of a ratio, and because the ratio changes only slightly for various cables (provided they are all rated at the same voltage as are the TUE test cables) the net effect on cable IR estimates due to changing cable sizes would be on the order of a factor of 2-3.

With regards to the cable functionality assessments themselves, there are two significant shortcomings to the utility analyses. First, the analyses only consider the performance of an single simulated instrument circuit as the basis for the assessment of performance for all of the tested cables. No consideration is provided for the performance of cables in either power or control circuits. The use of an instrument circuit analysis to assess the acceptability of power and control cable performance is not adequate. As a secondary aspect of this concern, the TUE analyses have not provided any consideration of the impact of power cable operating temperatures on cable performance. The USNRC acceptance criteria clearly indicate that power cable operating temperatures must be included in any cable functionality assessments.

One final shortcoming of the TUE analyses is that all of the circuit performance analyses are based on the cable exposure length which happened to be used in the fire endurance tests. This assumption has not been justified by TUE. In particular, It would be appropriate to perform circuit analyses based on the maximum credible cable exposure length, rather than on the very arbitrary test article cable exposure lengths. Given that the test exposure lengths were typically 8-13 feet, and that significantly longer exposure lengths could be postulated in actual plant applications, the circuit performance errors predicted could increase significantly.

Based on these errors and shortcomings, SNL finds that the TUE cable functionality assessments provided in [4] are inadequate to demonstrate the acceptability of the TUE fire endurance tests. Note that, at the request of the USNRC, SNL has provided supplemental analyses to support a final assessment of cable performance in these tests as documented in Section 3 above.

3.3.3 Test Scheme 9-3, 2" Conduit Test Article

For this test article it was noted by SNL that the post-test examinations revealed extensive regions of full material burn-through. This included a statement in the test report that "(n)o Thermo-Lag remained uncharred against the conduit in most areas." This condition was considered contrary to the criteria set for in [12]. The utility provided no significant response to this concern.

3.3.4 Test Scheme 15-2, Front and Rear Power Cables

In the initial review of this test report it was noted that several of the thermocouple lead wires within each of the two fire barrier envelopes tested had melted during the fire exposures. This was a significant concern because it potentially indicated that the thermocouple data was not valid for this test. The TUE response included a clarification that in both cases (both the front and rear power cable envelopes) the melted thermocouples were all associated with the bare 8AWG conductor which was placed in the envelope along with the power cable. None of the power cable thermocouples failed during the exposure. This is a credible explanation given the very massive size of the power cable. That is, the large thermal mass of the power cable could have easily absorbed enough heat so as to prevent damage to those thermocouples which were installed in intimate contact with the power cable itself, while those thermocouples installed on the much smaller 8AWG conductor would not have been afforded that same level of protection. Given this understanding, SNL recommends that the cable surface temperature data be accepted as indicative of the actual cable behavior.

However, this situation also illustrates the critical role played by the massive size of the power cable. The failure of the more exposed 8AWG thermocouples and the survival of the power cable thermocouples clearly indicates that the heat absorbing capacity of the power cable itself significantly influenced the results for these two test articles. That is, it is apparent that the power cables did, in fact, absorb very large quantities of heat during the exposure. Had the same barrier configuration been

installed on a cable of smaller diameter, much sharper rises in cable temperature would likely have been experienced. Hence, it is recommended that the results for these two test articles should in no case be extrapolated so as to justify the installation of a similar barrier system for the protection of cable sizes smaller than those tested; namely, 750 MCM. If this barrier system is to be applied to cables of smaller diameter, then these installations should be specifically validated by supplemental testing.

4.0 SNL Performance Evaluation Methods

4.1 Basis for Cable Functionality Concerns

The issue of cable performance during the TUE tests remains problematic because TUE did not make insulation resistance (IR) measurements during the actual fire exposures. Rather, only pre- and post-test cable IR measurements were made. SNL has previously cited that such pre- and post-test measurements provide no assurance of cable performance during the fire exposures [11]. Hence, these measurements should not be credited as a demonstration of test success in the light of other signs of potential cable degradation noted during the post-test examinations (jacket swelling and blistering, discoloration, charring, etc.).

This conclusions is based on the fact that the IR of a cable insulation material is a very strong function of temperature (IR decreases logarithmically with increasing temperature). This has been conclusively demonstrated through a variety of Equipment Qualification (EQ) tests performed by cable manufacturers, commercial test laboratories and by SNL under USNRC sponsorship. Hence, the post-test IR measurements made by TUE are insufficient to demonstrate cable performance during the fire exposures because significant cooling of the cables from their peak exposure temperatures occurred before the measurements were made. In particular, recall that the hose stream application preceded the post-test IR measurements.

This situation implies that cable functionality cannot be demonstrated based on the direct measured test data, but rather, must be assessed indirectly through analysis. Such supporting analyses were requested in the USNRC RAI, and an acceptable methodology for performing those analyses was provided (the SNL composite cable analysis method). TUE's response to the USNRC RAI failed to provide the requested cable IR analyses to support the evaluation of each of the cables in each of the TUE tests, failed to demonstrate that the tested cables met the cable IR acceptance criteria set forth in Suzanne Black's letter of 10/29/92 [12], and failed to provide alternate or supplemental cable functionality assessments. Hence, the USNRC has requested that SNL performed the needed analyses in order to provide a basis for the final determination of test acceptability by the USNRC.

Section 4.2 of this report provides the basis for the SNL analyses which have been performed and which are documented here. Section 4.3 provides the results of the SNL analyses. Section 4 provides a recommended procedure and criteria for assessing the ultimate acceptability of cable IR performance during the TUE tests.

4.2 SNL Cable Functionality Analysis Methodology

4.2.1 Overview

In order to assess cable functionality performance during the TUE tests, SNL has extrapolated Equipment Qualification (EQ) LOCA and Severe Accident test data to the

exposure temperatures experienced in the TUE tests. The analyses are based on Rockbestos EQ test reports [13] which provide experimentally determined analytical correlations for the IR of cross-linked polyethylene (XLPE) cable insulation as a function of temperature. This aspect of the analyses is consistent with the approach taken by TUE in those limited functionality analyses which the utility has performed.

The SNL analyses have been performed in two parts. The first part will be referred to as the "hot-spot analysis" and reflects the more conservative analysis approach. The second part of the analysis uses the "composite cable analysis method" described by SNL in its previous review submittal [1]. This second part of the analysis will be referred to as the "composite analysis." Each of these two analysis steps are described in the sections immediately below.

4.2.2 Part 1: Hot-Spot Performance Analysis

In this first part of the SNL analysis, the single-point "hot-spot" temperature for each cable in each test article was used to provide an initial assessment of cable IR performance. That is, in this initial analysis the only temperature measurement considered is the worst-case peak temperature measured along the length a given cable in the test article. This corresponds to the single highest temperature measured along the length of a given cable during the entire test. This value is used in conjunction with the EQ IR versus temperature correlation to estimate the cable IR at the measured hot-spot temperature. This is in contrast to other methods described elsewhere in this TER such as the original TUE method which used the simple average of all of the temperatures measured along the length of a given cable, or the SNL composite cable analysis methodology which uses each of the individual temperature measurements.

The use of this "hot-spot analysis method" would generally be considered the most conservative possible approach to an assessment of cable performance during the tests so long as the analysis is to be based on the measured cable surface temperatures. The only potential non-conservatisms in this analysis arise from uncertainty in the IR versus temperature correlations and from uncertainty as to whether or not these measured temperatures are truly representative of the actual hot-spot behavior (this second point is discussed in greater detail below).

Note that in presenting the results the IR values are normalized to "ohms over 1000 feet of cable" (Ω-1000ft). The effect of this normalization is simply to remove the cable's exposure length in a given test article as a parameter in the assessment. This normalization also allows for a direct comparison between each test and the USNRC acceptance criteria.

Note that in one respect the hot-spot analysis is also used as a screening tool. That is, the hot-spot analysis is much simpler to perform, being based on only one temperature, and is also the more conservative of the two analyses. Hence, if a given cable passes the USNRC IR acceptance criteria based on the conservative hot-spot analysis, then the more tedious composite analysis is not pursued for that case. Note however, that the hot-spot analysis also plays in integral role in SNL's final recommended

acceptance criteria for the subject CPSES-1 fire barriers (see further discussion in Section 4 below).

4.2.3 Part 2: Composite Cable Functionality Analysis

The second part of the SNL analysis utilizes the "composite cable method." In this analysis each of the individual temperature measurement points along the length of a cable or surface are used to assess cable IR performance over that individual segment of cable. For each measurement point the peak temperature value measured (typically the last recorded value) is used as the basis for analysis. That is, each temperature measurement is assumed to be representative of the cable temperature over a limited length of the subject cable. The characteristic length is taken as the actual distance between measurement points (typically 6" or 12"). Thus, each measurement point is used to estimate the local IR for that length of cable. All of the individual segment IR values are then summed as parallel resistance elements. This "composite" value provides an estimate of the cable IR over the full exposure length of the test cable. It is this value which can be considered an accurate analytical estimate of the actual cable IR which might have been measured had such measurements been made at the peak of the fire exposure <u>provided that no evidence exists which indicates that a cable was subjected to localized heating which might not have been accurately characterized by the test data</u> (this caveat is discussed at length below and, for example, involves cases in which post-test observations noted "char" at locations between cable thermocouples). As in the "hot-spot analysis" the "composite" IR results are normalized to Ω-1000ft.

4.2.4 Analysis Temperature Selection Bases

In each of the two parts of the SNL analysis, the "hot-spot" and "composite" analyses, the calculations were repeated for either two or three cases as follows:

Case 1: Each part of the analysis is performed using the highest temperature(s) measured along the surface of each individual cable. That is, for Case 1 the analysis is based on the actual measured cable surface temperatures.

Case 2: FOR THE POWER CABLES ONLY each part of the analysis is repeated using the highest measured cable surface temperature(s) <u>plus</u> an increment of 40°C. Case 2 is intended to provide for an assessment of power cable self heating effects on cable performance during a fire.

Case 3: For each cable, each part of the analysis is repeated using the maximum temperature(s) measured on the metal surfaces enclosed within the fire barrier system. For cable tray test articles this would be the cable tray side rail temperatures. For conduit test articles the conduit surface temperature is used. For

air drops and individually wrapped cables the temperatures measured on the bare 8AWG wire segment are used.

As further clarification, note that Case 1 is the base-case in that it utilizes the surface temperature of the cables exactly as measured during the test. In particular, the Case 1 "composite" analysis provides a best-estimate of the actual cable IR which would have been measured for each of the test cables had such measurements been made during the peak exposure period. It would not, however, include any consideration of power cable self heating effects (note that <u>none</u> of the test cables were subjected to an imposed electrical current during the fire exposures).

Case 2 represents a conservative assessment of power cable self-heating effects on cable performance. In the case of the TUE tests, a temperature increment of 40°C was chosen because TUE has sized its cables using an assumed cable operating temperature of 90°C and an ambient temperature of 50°C for a net ambient-to-cable increment of 40°C (see JCN J2017 Task Order 1 cable ampacity assessment efforts). The need for these assessments arises from the requirements set forth in [12].

Case 3 addresses additional concerns and requirements expressed by the USNRC in [12] and the USNRC position as stated in Supplement 1 to Generic Letter 92-08. One of the issues raised in these documents was the need for fire barrier performance assessments to include the consideration of cable tray raceway and external conduit temperatures. It should, however, be noted that the final recommendations made regarding the TUE test acceptability do not include the consideration of this case.

4.2.5 Assumed Cable Properties

In performing the analyses described here certain assumptions regarding the physical characteristics of the cables had to be made. This included assumptions regarding both the composition of the cable insulation materials and the physical dimensions of the cable conductors and insulation.

The information provided by TUE identified Rockbestos cross-linked polyethylene (XLPE) as the predominant insulation material in use at CPSES-1. Hence, all of the SNL analyses have been performed assuming this as the insulation material. The correlation for IR versus temperature cited by SNL in its previous reviews were used throughout in this analysis. (Note that the TUE response included an agreement that the correlation cited by SNL in its review was an appropriate basis for analysis.)

The TUE information provided in the various test reports also identified the gross physical characteristics of the cables used in testing. However, the specific details of cable insulation thickness and conductor diameters was not provided. Hence, SNL has made assumptions regarding these parameters based on available product literature for Rockbestos cables. In particular, TUE has used cables of 5 different gages; namely, 16AWG, 12AWG, 8AWG, 6AWG, and 750MCM. All of the cables are cited as being rated for 600V. In SNL's previous review, only nominal values for the cable physical parameters were used in order to demonstrate the methods and concerns. For more

accurate assessments it is important that more realistic parameters be used in the analysis.

Table 4.1 enumerates the values provided by TUE for both the stranded wire dimensions and insulation thicknesses for the cables used in its test program. However, SNL notes that the TUE values are not entirely self-consistent. In particular, the diameter of the insulated conductor (column 5 of Table 4.1) should be equal to the sum of the wire diameter (column 3) plus twice the insulation thickness (column 4). For the two smaller cable sizes (16 and 12 AWG) the match is exact.

Table 4.1: Assumed values for physical dimensions of TUE cables.

Cable Size	Applicable TUE Cable Types[1]	d_{cu} Stranded Wire Diameter	t_{insul} Insulation Thickness[2]	D_o Diameter of Insulated Conductor[3]
16 AWG	W-063 W-071	0.060"	0.030"	0.120"
12 AWG	W-046 W-047 W-048	0.092"	0.030"	0.152"
8 AWG	W-023	0.146"	0.045"	0.266" * 0.236" *
6 AWG	W-020	0.184"	0.045"	0.334" * 0.274" *
750 MCM	W-008	0.998"	0.080"	1.288" * 1.158" *

1. Cable types as identified in TUE test reports.
2. This value ignores any secondary jacket which might be applied to the individual conductors and represents only the primary insulation thickness.
3. This value is not the same as overall cable diameter. The first number provided is the cable outer diameter value provided by TUE. The second number, if one is shown, (presented in the format * #.### *) is the value used by SNL in this analysis and is based on the sum of the conductor diameter plus twice the insulation thickness. The TUE values for the larger power cables are assumed to vary due to inclusion of an overall jacket in the measurement of outside cable diameter.

However, for the three larger cables (8 AWG, 6AWG and 750 MCM) significant deviations are noted (the TUE insulated conductor diameters are too large). It is presumed that in addition to the insulation on these cables there is also an over-jacket present which adds to the outside diameter of the cable. This would be quite typical

of a large, single conductor cable. It is inappropriate to credit this additional jacket thickness in an IR calculation. The jackets are present only to serve as a physical protection for the insulation and are not generally credited with providing additional electrical insulation. Hence, the diameter of the insulated conductor which has been used by SNL in these analyses is the sum of the wire diameter (column 3) plus twice the insulation thickness (column 4) as provided by TUE. Note that column 5 of Table 4.1 provides both the TUE values and the values actually used by SNL.

4.3 SNL Cable Functionality Analysis Results

The results of the initial Part 1 hot-spot analyses are summarized in Table 4.2. Recall that in this step, the single point hot-spot temperature is used to estimate the IR value, with this value normalized to "ohms over 1000ft of cable" (Ω-1000'). The results of the Part 2 composite analyses are summarized in Table 4.3. Recall that this analysis is only performed for those cables and cases in which the hot-spot analysis (from Table 4.2) showed a local IR value of less than 1.0×10^6 Ω-1000' (the balance of the cases are identified in Table 4.3 as "screened").

The initial performance screening value, as noted above, is 1×10^6 Ω-1000' as specified in the [12]. It was intended that this criteria be applied to the actual cable IR values measured during the fire exposures had such measurements been made. This would correspond most closely to the SNL Case 1 analyses presented in Table 4.3. Test cables which exceed this acceptance criteria would be considered to have "passed" the test, provided that no other indications of test failure were noted (such as significant burn-through or severe localized cable damage). The results of the SNL Case 1 composite analysis in comparison to this initial acceptance criteria are summarized in Table 4.4.

Note that for those cases in which a failure is indicated, supplemental cable performance assessments are required. Section 4 below provides a recommended basis for the ultimate assessment of cable performance during the TUE tests. Section 6 summarizes SNL final recommendations regarding the acceptability of each of the TUE tests.

Table 4.2: Results of the part 1 hot-spot cable performance analysis.

Test Scheme	Cable Type	Cable IR (Ω-1000')		
		Case 1: Peak Cable Surface Temp.	Case 2: Peak Cable Surface Temp. +40°C	Case 3: Peak Exposed Metal Surface Temp.
9-3; 1½" Conduit	P (W-023)	1.13 E 3	4.80 E 1	7.33 E -9
	C (W-048)	1.58 E 4	-	7.67 E -9
	I (W-071)	1.06 E 5	-	1.06 E -8
9-3; 2" Conduit	P (W-020)	1.05 E 4	4.45 E 2	4.70 E -5
	C (W-047)	2.10 E 5	-	5.93 E -5
	I (W-071)	1.15 E 5	-	8.18 E -5
11-2; 1½" Air Drop	P (W-023)	9.15 E 6	3.88 E 5	4.05 E 5
	C (W-048)	3.06 E 6	-	4.24 E 5
	I (W-071)	1.23 E 6	-	5.85 E 5
11-2; 2" Air Drop	P (W-020)	5.20 E 3	2.21 E 2	3.36 E 5
	C (W-048)	1.42 E 7	-	4.24 E 5
	I (W-071)	4.71 E 7	-	5.85 E 5
11-4 Box Assem. (upper and lower trays)	P_u (W-020)	2.65 E 6	1.12 E 5	1.37 E 6
	C_u (W-048)	1.77 E 7	-	1.73 E 6
	I_u (W-071)	2.05 E 7	-	2.38 E 5
	P_l (W-020)	1.43 E 6	6.07 E 4	4.99 E 5
	C_l (W-048)	4.95 E 6	-	6.29 E 5
	I_l (W-071)	4.81 E 6	-	8.69 E 5
11-5; 24" Center Tray	P (W-020)	1.53 E 5	6.47 E 3	1.46 E 3
	C (W-048)	1.96 E 4	-	1.83 E 3
	I (W-071)	4.80 E 4	-	2.53 E 3
13-2; 12" Tray	P (W-023)	3.88 E 5	1.65 E 4	4.41 E 3
	C (W-046)	1.84 E 5	-	4.61 E 3
	I (W-071)	5.97 E 4	-	6.37 E 3
13-2; 2" Conduit	P (W-020)	2.47 E 5	1.05 E 4	4.75 E 1
	C (W-048)	2.68 E 6	-	5.98 E 1
	I (W-071)	2.84 E 6	-	8.26 E 1
15-2; 750MCM Cables	P_F (W-008)	1.32 E 7	5.85 E 5	1.00 E -2
	P_R (W-008)	2.95 E 4	1.25 E 3	3.06 E 0

Table 4.3: Results of part 2 composite cable functionality analysis.				
Test Scheme	Cable Type	Cable IR (Ω-1000')		
		Case 1: Measured Cable Surface Temp's[1]	Case 2: Measured Cable Surface Temp's +40C	Case 3: Exposed Metal Surface Temp's[2,3]
9-3; 1½" Conduit	P (W-023)	2.92 E 4	1.24 E 3	8.79 E -8
	C (W-048)	1.87 E 5	-	DNC
	I (W-071)	9.64 E 5	-	DNC
9-3; 2" Conduit	P (W-020)	1.11 E 5	4.73 E 3	5.26 E -4
	C (W-047)	2.18 E 6	-	DNC
	I (W-071)	7.09 E 5	-	DNC
11-2; 1½" Air Drop	P (W-023)	Screened	2.08 E 6	3.05 E 6
	C (W-048)	Screened	-	3.19 E 6
	I (W-071)	Screened	-	4.40 E 6
11-2; 2" Air Drop	P (W-020)	8.78 E 4	3.73 E 3	1.19 E 7
	C (W-048)	Screened	-	1.50 E 7
	I (W-071)	Screened	-	2.07 E 7
11-4 Box Assem. (upper and lower trays)	P_u (W-020)	Screened	7.55 E 5	Screened
	C_u (W-048)	Screened	-	Screened
	I_u (W-071)	Screened	-	Screened
	P_l (W-020)	Screened	4.23 E 5	4.03 E 6
	C_l (W-048)	Screened	-	5.61 E 6
	I_l (W-071)	Screened	-	7.02 E 6
11-5; 24" Center Tray	P (W-020)	7.08 E 5	3.00 E 4	1.18 E 4
	C (W-048)	2.23 E 5	-	1.49 E 4
	I (W-071)	2.31 E 5	-	2.06 E 4
13-2; 12" Tray	P (W-023)	1.61 E 6	6.84 E 4	2.53 E 4
	C (W-046)	1.04 E 6	-	3.19 E 4
	I (W-071)	5.23 E 5	-	4.40 E 4
13-2; 2" Conduit	P (W-020)	3.40 E 6	1.44 E 5	6.95 E 2
	C (W-048)	Screened	-	8.76 E 2
	I (W-071)	Screened	-	1.21 E 3
15-2; 750MCM Cables	P_F (W-008)	Screened	1.45 E 6	DNC
	P_R (W-008)	4.54 E 5	1.93 E 4	DNC

1. "Screened" indicates case passed screening criteria in part 1 analysis and was not recalculated.
2. DNC = Did Not Calculate either because gross failure would clearly be indicated or because of temperature measurement problems (failed TC's and/or failed TC lead wires).
3. Exposed metal temperature used was either cable tray side rail, conduit surface, or bare 8AWG conductor as appropriate to a given test.

Table 4.4: Summary of cable functionality analysis results in comparison to initial USNRC IR acceptance criteria of 1.0×10^6 Ω-1000'.

Test Scheme	Cable Type	Is Composite Cable IR Greater Than 1.0×10^6 Ω-1000' ? (Based on Case 1: Measured Cable Surface Temp's only)*	Overall Test Performance in Comparison to USNRC Acceptance Criteria
9-3; 1½" Conduit	P (W-023)	Fail	Fail
	C (W-048)	Fail	
	I (W-071)	Fail	
9-3; 2" Conduit	P (W-020)	Fail	Fail
	C (W-047)	Pass	
	I (W-071)	Fail	
11-2; 1½" Air Drop	P (W-023)	Pass	Pass
	C (W-048)	Pass	
	I (W-071)	Pass	
11-2; 2" Air Drop	P (W-020)	Fail	Fail
	C (W-048)	Pass	
	I (W-071)	Pass	
11-4 Box Assem. (upper and lower trays)	P_u (W-020)	Pass	Pass
	C_u (W-048)	Pass	
	I_u (W-071)	Pass	
	P_l (W-020)	Pass	
	C_l (W-048)	Pass	
	I_l (W-071)	Pass	
11-5; 24" Center Tray	P (W-020)	Fail	Fail
	C (W-048)	Fail	
	I (W-071)	Fail	
13-2; 12" Tray	P (W-023)	Pass	Fail
	C (W-046)	Pass	
	I (W-071)	Fail	
13-2; 2" Conduit	P (W-020)	Pass	Pass
	C (W-048)	Pass	
	I (W-071)	Pass	
15-2; 750MCM Cables	P_F (W-008)	Pass	Pass
	P_R (W-008)	Fail	Fail

* This assessment only includes consideration of the Case 1 analyses. That is, consistent with the USNRC criteria, this assessment is based on the composite cable analysis criteria which most closely approximates the cable IR values which might have been measured had such measurements been made at the peak of the fire exposure.

5.0 SNL Recommended Basis for Test Performance Assessment

5.1 Overview

Based on the results of the SNL analyses presented above, several of the TUE tests failed to achieve the nominal USNRC cable IR acceptance criteria of 1.0E6 Ω-1000'. Hence, the ultimate determination of acceptability for these tests becomes problematic. SNL finds that utility has not provided a sufficient basis for accepting these tests because TUE has not demonstrated, on a case-by-case basis, that each of those test cables which failed to achieve the USNRC nominal IR acceptance criteria would be capable of performing its design function (as per the USNRC position as stated in a public meeting on August 30, 1994).

The following sections document a recommended cable functionality acceptance procedure and criteria for the ultimate evaluation of the TUE tests. This recommendation is based on SNL's best professional judgement regarding the likely failure mechanisms and ultimate performance limits of electrical cables. This includes consideration of both EQ and fire safety research results.

5.2 General Basis for Recommended Criteria

It is the recommendation of SNL that a final determination of acceptability for those tests which fail to meet the USNRC nominal IR performance criteria be based on an assessment of cable IR performance <u>at the measured cable hot-spot</u>. This recommendation is based on past cable testing experience in both EQ and fire safety which indicates that the failure of an electrical cable due to high temperature exposures is likely to occur at a localized point rather than along the full length of an exposed cable (see, for example, [14]). Thus, the evaluation of the cable performance at the hot-spot location during the fire exposure tests would most accurately reflect this experience.

Note that this acceptance criteria differs significantly from that set forth by the USNRC in [12]. The nominal USNRC criteria considers the cable IR which would be measured along the full exposure length of the test. Hence, the USNRC acceptance criteria is based on a composite IR which, to some extent, is averaged along the full exposure length (although it is not a simple linear average value). Hence, if the hot-spot analysis is used to assess ultimate cable performance, then it is also appropriate to reconsider the acceptance threshold.

Note also that, as illustrated in Table 4.2 and 4.3, the hot-spot analysis is more conservative than the composite analysis. In general, the hot-spot analysis predicts IR values approximately one order of magnitude lower than the predicted composite values, although the differences will be strongly dependent on the extent to which temperatures vary along the length of the cable.

Barring any independent indications of test failure (see further discussion in Section 5.3 below) SNL's recommended test evaluation criteria are as follows:

- It is recommended that a test be accepted if all of the cables meet the USNRC cable IR acceptance criteria of 1.0E6 Ω-1000ft when calculated using the SNL composite cable analysis method. This calculation should be based, in this case, on the actual measured cable surface temperatures. This is consistent with the original USNRC acceptance criteria set forth in [12]. If the calculated cable IRs exceed this criteria, then the effects of power cable operation would be bounded by the margin which is inherent in this criteria.

- In the event that the nominal USNRC IR acceptance criteria is not met, it is recommended that an analysis of the measured hot-spot IR performance be made using a single-point hot-spot analysis such as the analyses presented above as the Part 1 Hot-Spot Analyses (see Table 4.2).

- In performing this analysis, the hot-spot temperature should be used to estimate cable IR with the result normalized to "Ω-1000ft" so as to provide a consistent basis for comparison. It is further recommended that a value of 1.0E3 Ω-1000ft be utilized as the minimum acceptable IR limit for the predicted hot-spot behavior. This IR threshold is based on the following:

  - One of the concerns regarding cable performance is that as power cable leakage currents increase (due to IR breakdown) an added heat load is introduced due to resistance heating in the insulation itself. As this heating effect increases, a progressive and accelerating breakdown of the cable insulation at a localized point will occur. Given a hot-spot IR of 1.0E3 Ω-1000ft, the localized heating effect due to leakage currents for a cable energized to 480V (typical upper end voltage applied to a 600V rated cable) would amount to 0.23 Watts per foot of cable (based on simple V=IR and $Q=I^2R$ calculations where R would equal 1.0E3 Ω-1000ft or equivalently 1.0E6 Ω-1ft). A typical power cable could absorb this much heat with only a minor impact on cable temperature (on the order of 5°C increase after a full hour of such leakage based on scoping calculations for a 3-conductor 8AWG power cable). Hence, this level of degradation would not be expected to trigger localized cable breakdown.

  - If the IR were reduced locally by one additional order of magnitude (to 1.0E2 Ω-1000ft) then localized heating would increase by an order of magnitude to 2.3 W/ft for the same voltage. While a power cable might survive localized heating of this magnitude for a limited period (i.e., on the order of a few minutes), sustained exposure would likely lead to progressive thermal breakdown of the cable.

  - When cable thermal damage limits determined in fire exposure testing have been compared to the IR measurements made during severe accident steam exposures, a good correlation between results has been found [15].

This correlation indicates that cable IR values in the range of approximately 32-320 Ω-1000ft (1.0E2 - 1.0E3 Ω-100m) would be indicative of failure in a fire environment. Hence using an IR acceptance limit of 1.0E3 Ω-1000ft will provide a modest margin in evaluating cable IR performance in the absence of actual performance data. This margin is considered appropriate given the uncertainty associated with how well the actual cable hot-spot has been characterized in the tests (see further discussion in Section 5.3 below).

- For instrument cables with an IR of 1.0E3 Ω-1000ft, the error introduced into a typical 4-20ma circuit would be only a small fraction of the full scale output for reasonable cable exposure lengths. For example, a 50V instrument circuit (a relatively high voltage for such circuits) would experience just 0.1 mA leakage currents, or 0.5% of full scale output, assuming a 20 foot exposure length of cable. With a 100ft exposure length, a very conservative upper bound given the nature of power plant installations, the error would increase to just 2.5% of full scale. The level of circuit degradation associated with these instrument cable IR values would be considered acceptable.

- For control cables, the arguments are much the same as those presented above with regard to power cables. That is, for the time during which the control cables operate, they behave in the same manner as would a light power cable. The one significant difference is that for control cables the cable self heating effect due to normal current flow would be insignificant due to the very short times such cables are typically energized.

- The hot-spot analysis <u>must include</u> the consideration of cable self-heating effects for power cable applications (e.g. the case 2 analyses). The recommended SNL acceptance limit of 1.0E3 Ω-1000ft is based on including such cable self-heating effects as a part of the calculation. If cable self-heating is not accounted for, then a more stringent requirement would be appropriate (e.g., the general USNRC acceptance criteria of 1.0E6 Ω-1000ft).

5.3 Limitations to the SNL Recommendations

The failure of TUE to perform cable IR measurements during the test exposures has made the problem of determining the acceptability of the TUE tests much more difficult and uncertain. SNL disagrees with TUE regarding the general ability of a test laboratory to make such measurements during the fire exposures. That is, TUE has cited safety concerns as the basis for its not having performed IR measurements as requested by the USNRC. However, extensive experience in LOCA, Severe Accident, Fire, and Hydrogen Burn testing have clearly demonstrated that such measurements can be made without compromising safety.

It is strongly recommended that cable IR measurements should be made during the fire exposure portion of the fire endurance testing protocol if cable functionality is to be used as the basis for test acceptance. While periodic IR measurements are preferred,

at the very least a single-point measurement should be made at the height of the fire exposure before the termination of the flame exposure and before removal of the test article from the test cell. In the case of TUE, temperatures have been used to estimate cable performance factors. However, SNL does not recommend that these analysis procedures should be considered an acceptable alternative for general test evaluation in the future. Reliance on calculations of the type performed here as the basis for test evaluation cannot be justified given the relative ease with which cable IR measurements can be made during these fire tests.

The procedure and recommended acceptance criteria outlined above are considered to include a modest level of conservatism. SNL's best judgement is that this methodology will provide a level of conservatism equivalent to between one and two orders of magnitude in the ultimate local cable IR performance. This conservatism arises primarily from conservatism which appears to exist in the cable IR versus temperature correlation cited by the manufacturer (based on comparisons to severe accident test data which indicate somewhat higher IR values than those calculated from the correlation, [16]), and from the SNL recommended hot-spot IR performance acceptance criteria of 1.0E3 Ω-1000ft. As discussed further below, this margin is considered necessary and appropriate in order to bound testing uncertainties.

In particular, in considering SNL's proposed evaluation criteria there is one fundamental concern that must be recognized. That is, the extent to which the true hot-spot behavior has been characterized is highly uncertain. In the case of the TUE tests, the cable surface temperature were measured at intervals of 6". The largest variations in measured temperatures between adjacent thermocouples noted in the TUE test reports were in excess of 200°F, and variations of 30-50°F were quite common in the areas near the cable hot-spots. With point-to-point variations this large, it must be concluded that the actual hot-spot exposure temperature is uncertain. This will lead directly to uncertainty in the cable IR performance estimates.

It should also be noted that certain of the TUE test reports identified localized spots of surface char on some of the protected cables after testing. Char inherently indicates that some combustion (smoldering or burning) of the cables took place during the test. Further, in the cases in which such damage was noted, it appears that the damage generally occurred at locations between cable surface thermocouples (i.e., in segments of the cable not covered by the fiberglass tape used to secure the thermocouples to the cable). These charred locations would almost certainly represent the true hot-spot for the cable. This indicates that there is no direct assurance that the actual hot-spot temperatures were measured, and hence, the true hot-spot temperature cannot be determined.

It was also noted as a part of these reviews that the issues of surface charring and excessive point-to-point temperature variation were closely linked. In particular, all of the tests in which surface charring of the protected cables was noted also experienced the highest point-to-point temperature variations. This is not overly surprising given that the presence of localized surface charring would be indicative of localized temperatures well in excess of the average temperatures experienced by the cables. As

will be noted below, for these tests acceptance is not recommended based on the high level of uncertainty inherent in the cable performance analyses.

The accurate characterization of the hot-spot behavior is considered critical to the appropriate assessment of cable performance. For tests in which charring damage to the protected cables is noted, or for which other evidence of very large point-to-point variations in measured cable temperature are found, no definitive assessment of cable performance can be made in the absence of actual IR measurements due to the large uncertainty in the actual hot-spot temperatures experienced. SNL's methodology is not intended to account for situations such as the subject tests where a very significant and demonstrated uncertainty regarding actual hot-spot exposure temperatures exists. A "hard and fast" limit on how large a variation would be considered excessive is difficult to identify. As a general rule, cases which display point-to-point variations of 75°F or more should be examined closely. In particular, for such cases the post-test examination results should be carefully reviewed for other evidence that significant uncertainty exists regarding the actual hot spot temperatures (such as charring between thermocouple locations).

Given this uncertainty it is considered appropriate to include a performance margin in these calculations. Note that a margin of one-to-two orders of magnitude in cable IR corresponds to a margin of about 50-100°F (28-56°C) in cable temperature given the IR versus temperature correlations cited by TUE. That is, the IR versus temperature correlation predicts a drop in cable IR by one order of magnitude for each 50°F increase in exposure temperature. As noted above, for most of the TUE tests point-to-point variations of 30-50°F were routinely noted. Hence, the margin inherent in the SNL methodology would encompass the implied uncertainty with regard to how accurately the true hot-spot temperatures were measured. This margin would not, however, encompass those cases for which evidence indicates that highly localized cable heating may have been experienced and was not fully characterized by the test data (such as local cable charring and/or very large point-to-point temperature variations).

6.0 Conclusions and Recommendations

6.1 Overview and Summary

The conclusions and recommendations provided below are based on a consideration of each individual test in light of the recommendations outlined in Section 4 above. In particular, Section 4 outlined a recommended procedure for determining the acceptability of the TUE tests in the absence of actual measured cable IR performance data. Each test article for which acceptance is being requested by TUE is evaluated separately below. In each case, a discussion of SNL's analysis findings is provided, and a final recommendation regarding acceptability of the test is given.

Table 6.1 below provides a summary comparison of the predicted cable IR values from the TUE tests to the generic USNRC acceptance criteria. It is SNL's recommendation that those test articles which pass in accordance with this criteria should be accepted. In particular, for those test articles which passed this initial criteria, no other evidence of significant potential cable operability concerns were noted (e.g., severe cable damage such as charring, significant burn-through of the barrier material, or indications of severe temperature gradients). For those test articles which failed to achieve this level of performance, additional analysis was performed. Table 6.2 summarizes the results of these additional analyses and provides a summary comparison of the performance in each test to the SNL recommended ultimate performance acceptance criteria. Recall that SNL's recommendation is based on an examination of the hot-spot cable IR behavior. Table 6.3 provides a summary of the SNL recommendations regarding the acceptability of the TUE tests. This summary includes consideration of both the USNRC general acceptance criteria (as per Table 6.1) and the SNL recommended ultimate cable performance acceptance criteria (as per Table 6.2).

6.2 Consideration of Specific Test Article Acceptability

6.2.1 Test Scheme 9-3, 1½" Conduit Test Article

None of the cables in this test article met the basic cable IR performance criteria set forth by the USNRC. Of particular concern is the rather poor performance of the power cable in this test article. The best-estimate of the composite power cable IR performance during the test, even neglecting cable self-heating effects, was 3.65E4 as compared to the USNRC acceptance criteria of 1.0E6. When the impact of cable self-heating effects are included in the analysis of power cable performance the predicted composite cable IR drops to 1.55E3.

Following the SNL recommended evaluation procedure, the single point hot-spot cable behavior is considered. An analysis of the hot-spot power cable behavior including cable self-heating effects (Case 2 from Table 4.2 for this test article) predicts a hot-spot IR of just 6.0E1 Ω-1000ft. This is well below the recommended SNL threshold value of 1.0E3 Ω-1000ft for the hot-spot IR.

Table 6.1: Summary of test performance results in comparison to generic USNRC IR acceptance criteria of 1.0×10^6 Ω-1000'.		
Test Scheme	Worst Case Cable Performance (Based on actual measured cable temp's)[1] (IR in Ω-1000')	Overall Test Performance in Comparison to USNRC Acceptance Criteria
9-3; 1½" Conduit	2.92 E 4	Fail
9-3; 2" Conduit	1.11 E 5	Fail
11-2; 1½" Air Drop[2]	(>) 1.23 E 6	Pass
11-2; 2" Air Drop	8.78 E 4	Fail
11-4 Box Assem.[2]	(>) 1.43 E 6	Pass
11-5; 24" Center Tray	2.23 E 5	Fail
13-2; 12" Tray	5.23 E 5	Fail
13-2; 2" Conduit	3.40 E 6	Pass
15-2; Front Cable[2]	(>) 1.32 E 7	Pass
15-2; Rear Cable	4.54 E 5	Fail

1 This assessment only includes consideration of the actual measured cable temperatures used in either a hot-spot or composite cable analysis as indicated in Tables 4.2 and 4.3.
2. These values are based on the initial hot-spot screening because the actual composite IR was never calculated. The composite value would be greater than the value indicated here.

Table 6.2: Comparison of cable performance results to SNL recommended ultimate hot-spot performance acceptance criteria.			
Test Scheme	Cable IR (Ω-1000')		Overall Performance in Comparison to SNL Ultimate Hot-Spot Performance Criteria of 1.0 E 3 Ω-1000'
	Worst Case Instrument and Control Cable Hot Spot IR	Power Cable Hot Spot IR (Including Temperature Increment for Power Operation)	
9-3; 1½" Conduit	1.58 E 4	4.80 E 1	Fail
9-3; 2" Conduit	1.15 E 5	4.45 E 2	Fail
11-2; 1½" Air Drop	1.23 E 6	3.88 E 5	Pass
11-2; 2" Air Drop	1.42 E 7	2.21 E 2	Fail
11-4 Box Assem.	4.81 E 6	6.07 E 4	Pass
11-5; 24" Center Tray	1.96 E 4	6.47 E 3	Pass
13-2; 12" Tray	5.97 E 4	1.65 E 4	Pass
13-2; 2" Conduit	2.68 E 6	1.05 E 4	Pass
15-2; Front Cables	N/A	5.85 E 5	Pass
15-2; Rear Cable	N/A	1.25 E 3	Pass

Table 6.3: Summary of SNL recommendations.	
Test Scheme 9-3, 1½" Conduit Test Article	Do not accept
Test Scheme 9-3, 2" Conduit Test Article	Do not accept
Test Scheme 11-2, 1½" Air Drop Test Article	Accept
Test Scheme 11-2, 2" Air Drop Test Article	Do not accept
Test Scheme 11-4, Box Assembly Test Article	Accept
Test Scheme 11-5, 24" Center Cable Tray Test Article	Accept
Test Scheme 13-2, 12" Cable Tray Test Article	Accept
Test Scheme 13-2, 2" Conduit Test Article	Accept
Test Scheme 15-2, Front Power Cable Test Article	Accept only for cables 750 MCM and larger
Test Scheme 15-2, Rear Power Cable Test Article	Accept only for cables 750 MCM and larger

It should also be noted that this test demonstrated vary large variations in point-to-point cable temperature measurements. In the area immediately surrounding the hot-spot, a point-to-point variation of as much as 158°F was noted for the power cable. Note that this range represents the variation in measured cable surface temperature over a 6" segment of the cable. Given this very large variation, the actual hot-spot temperature must be considered highly uncertain (higher temperatures than those measured may well have been experienced). Hence, a very large uncertainty regarding the hot-spot IR exists.

It is recommended that this test article should not be accepted. This recommendation is based on:

- Unacceptable composite cable IR values for all cables
- Unacceptable hot-spot cable IR values for all cables
- Excessive uncertainty regarding the adequacy of the hot-spot characterization

6.2.2 Test Scheme 9-3, 2" Conduit Test Article

The estimated composite performance of the control cable in this test exceeded the USNRC basic performance acceptance criteria of 1.0E6 Ω-1000ft. However, both the power and instrument cables in this test article failed to achieve this level of performance.

In considering the cable hot-spot behavior, the predicted IR values for both the control and instrumentation cables (see Case 1 analysis results in Table 4.2) were well above the SNL recommended acceptance criteria of 1.0E3 Ω-1000ft. However, the hot-spot performance analysis for the power cable, including the effects of cable self-heating, predicted an IR value of 5.61E2 (see Case 2 analysis in Table 4.2). This value fails to achieve the recommended SNL acceptance criteria.

It should also be noted that this test demonstrated a pronounced variation in point-to-point cable temperature measurements. In the vicinity of the hot-spot, a point-to-point variation of as much as 224°F over a length of just 6" was noted for the power cable (TC channels 96 and 97). Given this very large variation, the actual hot-spot temperature must be considered highly uncertain (higher temperatures than those measured may well have been experienced). Hence, the ultimate performance of the power cable cannot be accurately assessed.

Finally, as discussed in Section 5.3 above, the initial SNL reviews for this test article had noted that significant areas of full Thermo-Lag material burn-through were noted in the post-test inspections performed by Omega Point Laboratory as documented in the test report for this test article. This observation violated the acceptance criteria established by the USNRC in [12]. The implications of extensive material burn-through have not been addressed by TUE.

It is recommended that this test article should not be accepted. This recommendation is based on:

- Unacceptable composite cable IR values for all cables
- An unacceptable hot-spot cable IR value for the power cable when cable self-heating effects are considered
- Excessive uncertainty regarding the adequacy of the hot-spot characterization for the power cable in particular
- Extensive regions of full barrier material burn through noted during the post-test examinations

6.2.3 Test Scheme 11-2, 1½" Air Drop Test Article

The predicted composite performance of the cables in this article met the USNRC basic IR acceptance criteria of 1.0E6 Ω-1000ft. In fact, this finding included calculations based on the measured cable temperatures, power cable performance including self-heating effects, and the temperatures measured on the bare 8AWG conductor. While it was noted in the test report that certain of the thermocouple lead wires running through this section of the test assembly were melted during the exposure, no further evidence of any material burn-through nor excessive point-to-point temperature variation were noted.

It recommended that this test article should be accepted.

6.2.4 Test Scheme 11-2, 2" Air Drop Test Article

The estimated composite performance of the control and instrumentation cables met the USNRC IR acceptance criteria of 1.0E6 Ω-1000ft even when only the hot-spot behavior is considered. However, the estimated composite performance of the power cable in this article was close to an order of magnitude below the USNRC acceptance criteria even in the absence of cable self-heating effects. (the best-estimate of cable performance neglecting self-heating effects was 1.1E5 as compared to the USNRC acceptance criteria of 1.0E6).

In the consideration of the hot-spot IR behavior of the power cable an IR value of 2.78E2 was obtained when the effects of cable self-heating are included in the analysis (see Case 2 analysis in Table 4.2). This is well below the SNL recommended acceptance criteria of 1.0E3 Ω-1000ft.

The poor performance of the power cable can be attributed directly to the hot-spot behavior. The peak measured temperature for this cable was 439°F as compared to the next highest reading of 321°F for an adjacent thermocouple. This test article also demonstrated very high point-to-point variation in measured temperatures with a variation from the hot spot to the second adjacent measurement point (6" away) of 225°F. This wide variation implies that the hot-spot temperature may not have been well characterized and this rendered even the hot-spot analysis of questionable validity. It is not possible to provide an accurate estimate of the actual hot-spot temperature for this test given this very wide variability between adjacent measurement points.

Further evidence that the hot-spot was not well characterized was also demonstrated in the post-test examinations. For this test assembly it was noted by Omega Point Laboratory that 5 thermocouple lead wires were melted in the center section of this test article. In the photographs of these failed thermocouples provided in the test report, the thermocouple leads appear to have been charred over a short segment of their length (perhaps on the order of 2" or less). Further, the test report states that a "localized surface char" was identified on the power cable in this same area of the article. As noted previously, charring is an indication of actual combustion within the test article. Such evidence of combustion would appear to violate the intent of the ASTM testing standard, and represents a degree of damage beyond that nominally identified by the USNRC as potentially acceptable (e.g., jacket swelling, hardening, or discoloration). This localized charring also is indicative of the actual cable hot spot, and this charring appears to have occurred between two measurement points.

Based on these insights it appears that this test assembly likely suffered an actual or near burn-through of the fire barrier at a point adjacent to the power cable. Temperatures in the immediate vicinity of this location were high enough to melt, and possible char, the thermocouple lead wires, and to char (burn) the surface of the adjacent power cable. The power cable also experienced surface temperatures over a very localized segment well in excess of those experienced by the balance of the test article which leads to a very poor estimated cable IR performance.

It is recommended that this test article should not be accepted. This recommendation is based on:

- An unacceptable composite cable IR value for the power cable
- An unacceptable hot-spot cable IR value for the power cable
- Excessive uncertainty regarding the adequacy of the hot-spot characterization for the power cable
- Charring of the cable insulation in the immediate vicinity of the hot-spot

6.2.5 Test Scheme 11-4, Box Assembly Test Article

The estimated composite performance of all of the cables in both trays of this test article met the basic USNRC acceptance criteria of 1.0E6 Ω-1000ft. This estimate included calculations based on both the measured cable surface temperatures and the cable tray side rail temperatures. No other evidence of localized hot-spots or other barrier integrity problems were noted for this test article.

It is recommended that this test article should be accepted.

6.2.6 Test Scheme 11-5, 24" Center Cable Tray Test Article

None of the cables in this test article met the basic USNRC acceptance criteria when the composite cable performance assessments was considered (see Case 1 analyses in Table 4.3). However, when the hot-spot cable IR performance is considered, each of the three cables met the SNL recommended criteria (see the Case 1 and 2 analyses in Table 4.2). This assessment includes the consideration of cable self-heating effects for the power cable.

Note that no evidence of excessive point-to-point variation in temperatures was noted for this test article. Rather, the cable surface temperatures were relatively uniform, and only slightly in excess of values which would have yielded acceptable composite cable IR values.

It is recommended that this test article should be accepted.

6.2.7 Test Scheme 13-2, 12" Cable Tray Test Article

The composite analyses performed for both the power and control cables in this test article met the USNRC IR acceptance criteria based on measured cable surface temperatures (see the Case 1 analyses in Table 4.3). The instrument cable fell slightly below this criteria. When the hot-spot performance is considered, all of the cables performed in excess of the recommended SNL IR acceptance criteria (see the Case 1 and 2 analyses in Table 4.2). No evidence of pronounced localized cable heating effects were noted for this test article.

It is recommended that this test article should be accepted.

6.2.8 Test Scheme 13-2, 2" Conduit Test Article

All of the cables in this test article meet the USNRC cable IR performance criteria based on the actual measured cable temperatures. No other evidence of pronounced localized heating of the cables was noted for this test article.

It is recommended that this test article should be accepted.

6.2.9 Test Scheme 15-2, Front Power Cable Test Article

The composite IR performance of the power cable in this test article was acceptable in comparison to the USNRC acceptance criteria, even when the effects of cable self-heating were included in the analysis. However, SNL had previously raised concerns regarding the observation of melted thermocouples within this test article, and the resulting uncertainty regarding the accuracy of temperature measurements. As discussed in Section 5.4 above, these concerns have been addressed in part, but not in full. In particular, while the observations regarding melted thermocouples were not associated with the power cable surface temperature measurements, they do provide evidence that the very large size and large thermal mass of the power cable significantly influenced the test results. Hence, it is considered inappropriate to extrapolate the results of this test to similar configurations which involve cables of smaller size.

It is recommended that this test article should be accepted, but only for applications involving cables 750MCM and larger.

6.2.10 Test Scheme 15-2, Rear Power Cable Test Article

The estimated composite cable IR value for this power cable failed to meet the USNRC acceptance criteria, even in the absence of self-heating effects (the best-estimate IR performance during the test was 3.00E5 as compared to the acceptance value of 1E6). When the hot-spot cable IR performance was considered, an IR value of 1.68E3 Ω-1000ft is obtained including the effects of cable self heating. This value does meet the SNL recommended acceptance criteria.

One potential point of concern which does remain is that a significant variation in point-to-point cable temperatures was noted in the test data. The peak variation was about 90°F over a distance of 6" adjacent to the hot-spot. This variation is indicative of potentially marginal performance, especially given the very large size of the cable which would normally be expected to mitigate local heating effects through lateral heat conduction.

Also note that in prior reviews SNL had expressed concerns regarding the reliability of temperature measurements in light of the observed melting of certain of the thermocouple lead wires. The utility statements in this regard (see Section 5.4 above) are considered sufficient to justify reliance on the measured cable surface temperatures.

However, as discussed in Section 5.4 above, this test article should not be extrapolated so as to justify a similar installation for smaller cable sizes.

Of the tests reviewed, this is the one test article which is considered most difficult to judge. However, in the final analysis, SNL concluded that the combined conservatisms which arise as a result of the cable IR versus temperature correlation, the inherent nature of the hot-spot analysis method, and the recommended hot-spot IR acceptance criteria provides sufficient margin so as to justify acceptance of this test article based on the hot-spot analysis results.

It is recommended that this test article should be accepted, but only for applications involving power cables of 750MCM or larger.

7.0 References

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3. Letter: W.J. Cahill Jr., TUE, to the USNRC, August 8, 1994, TUE Log Number TXX-94173.

4. Letter: C.L. Terry, TUE, to the USRNC, November 9, 1994, TUE Log Number TXX-94267.

5. TUE Report No. 12340-94367j, "Fire Endurance Test of a Thermo-Lag® 330-1 Fire Protective Envelope (3/4 in., 1-1/2 in. & 2 in. Conduits)," 12/28/93.

6. TUE Report No. 12340-95766, "Fire Endurance Test of a Thermo-Lag 330-1 Fire Protective Envelope (24 in. Cable Tray with 2 in. Diameter and 1-1/2 in. Diameter Air Drops)," 8/27/93.

7. TUE Report No. 12340-95767, "Fire Endurance Test of a Thermo-Lag 330-1 Fire Protective Envelope (Box Design Air Drop From Two Nested 24 in. Cable Tray Assemblies)," 10/4/93.

8. TUE Report No. 12340-95768, "Fire Endurance Test of a Thermo-Lag 330-1 Fire Protective Envelope (Three 24 in. Cable Tray Assemblies)," 8/27/93.

9. TUE Report No. 12340-95769, "Fire Endurance Test of a Thermo-Lag 330-1 Fire Protective Envelope (12 in. Cable Tray & 2 in. Conduit)," 8/23/93.

10. TUE Report No. 12340-95770, "Fire Endurance Test of a Thermo-Lag 330-1 Fire Protective Envelope (Flexi-Blanket Wrapped Cables Laid in a 36 in. Cable Tray Assembly)," 10/4/93.

11. Letter: S. Nowlen, SNL, to P. Madden, USNRC, July 1, 1992.

12. Letter: S. Black, USNRC, to W. J. Cahill, Jr., TUE, October 29, 1992.

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15. "The Estimation of Electrical Cable Fire-Induced Damage Limits," SAND92-1404C, *Fire and Materials*, 1st International Conference and Exhibition, Sept. 24-25, 1992, Washington DC.

16. *Submergence and High Temperature Steam Testing of Class 1E Electrical Cables*, NUREG/CR-5655, SAND90-2629, Sandia National Laboratories, May 1991.