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An Evaluation of the Fire Barrier System Thermo-Lag 330-1

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An Evaluation of the Fire Barrier System Thermo-Lag 330-1

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Abstract

This report presents the results of three fire endurance tests and one ampacity derating test set (base line and clad ampacity testing) of the fire barrier system Thermo-Lag 330-1 Subliming Coating. Each test was performed using cable tray specimens protected by a nominal three-hour fire barrier envelope comprised of two layers of nominal 1/2" thick material. The fire barrier systems for two of the three fire endurance test articles and for the ampacity derating test article were installed in accordance with the manufacturer's installations procedures, Thermal Science Inc. Technical Note 20684, Revision V. The barrier system for the third fire endurance test article was a full reproduction of one of the original manufacturer's qualification test articles. This final test article included certain installation enhancements not considered typical of current nuclear power plant installations. The primary criteria for fire endurance performance evaluation was based on cable circuit integrity testing. Secondary consideration was also given to the temperature rise limits set forth in the ASTM E119 standard fire barrier test procedure. All three of the fire endurance specimens failed prematurely. Circuit integrity failures for the two fire endurance test articles with procedures-based installations were recorded at approximately 76 and 59 minutes into the exposures for a 6" wide and 12" wide cable tray respectively. Temperature excursion failures (single point) for these two test articles were noted at approximately 65 and 56 minutes respectively. The first circuit integrity failure for the full reproduction test article was recorded approximately 119 minutes into the exposure, and the first temperature excursion failure for this test article was recorded approximately 110 minutes into the exposure. In all three cases, the protected cables were eventually subjected to direct fire exposure, and in each case large sections of the fire barrier system were observed to fall away from the test articles during the fire exposures. Extensive regions of full fire barrier material burn-through were also noted. The ampacity test specimen produced an ampacity derating factor ranging from approximately 36% to 46% depending on the individual cables considered.

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EXECUTIVE SUMMARY

The tests described in this report were undertaken by Sandia National Laboratories (SNL) under the sponsorship of the U.S. Nuclear Regulatory Commission (USNRC) Office of Nuclear Reactor Regulation (NRR). The fire barrier cladding system evaluated is Thermo-Lag 330-1, manufactured by Thermal Science Inc. (TSI). The purpose of the tests described here was to provide independent fire endurance and ampacity derating test data and results.

Testing involved the evaluation of four test articles. Each of the test articles was based on a "U"-shaped section of cable tray protected by a nominal three-hour protective envelope comprised of two layers of nominal 1/2" thick prefabricated panel sections. Three of these test articles, Test Articles 1, 2 and 3, were designed to be subjected to fire endurance testing using the three-hour ASTM E119 time-temperature profile (as noted below, two of the tests were terminated after periods of less than three hours). The fourth, Test Article 4, was subjected to an ampacity derating test set (one base line test with no cladding and a second test with the cladding in place).

In each case, the test articles were intended to reproduce the physical characteristics and attributes of certain of the original manufacturers qualification test articles. That is, the base test articles were constructed using physical specifications typical of past manufacturer qualification test articles, and in fact, modeled on certain specific manufacturer test articles. This included the physical dimensions, orientation, cable loading, and instrumentation. Table ES.1 provides a summary description of each of the four test articles.

As noted in Table ES.1, two different installation methods were used in the protection of the test articles. The fire barrier systems for Test Articles 1, 2 and 4 were installed in accordance with the manufacturer's installation procedures as presented in TSI Technical Note 20684, Revision V, November 1985 [4]. These installations included pre-buttering of all material joints during assembly, off-setting of joints between the two layers of material, and the use of 18ga stainless steel tie wires to secure the panels to the test article.

In contrast, Test Article 3 was a full reproduction of one of the original manufacturer's fire endurance qualification test articles. This installation included a number of enhancements not considered typical of nuclear plant applications. In particular, all of the material joints in each layer were secured and reinforced using bolts and/or stainless steel wire stitching (based on examination of photographs of the original manufacturer's test article). In addition, a final overcoat of trowel-grade material approximately 1/10" thickness was applied to the outside of the outer layer of the barrier system.

Installation of the fire barriers was performed by union certified insulation contractors. Prior to the initiation of the installations efforts, all of the involved personnel were provided with installation training by a former TSI field representative and installation

trainer. Two such training sessions were conducted, one exclusively for the SNL project staff and a second for the fire barrier installers.

Table ES.1: Summary of Test Article Characteristics			
SNL Test Article	Test Type	Barrier Installation Basis	Description
TA 1	3-Hr Fire Endurance	Revision V Procedures	Six inch, solid bottom cable tray in "U"-shaped configuration with a light cable loading (Based on TSI test report #82-5-355B, [1])
TA 2	3-Hr Fire Endurance	Revision V Procedures	Twelve inch, ladder-back cable tray in "U"-shaped configuration with a light cable loading (Based on TSI test report #82-11-81, Test Article #4, [2])
TA 3	3-Hr Fire Endurance	Full Reproduction	Identical to TA2 with exception of barrier installation basis
TA 4	Ampacity Derating	Revision V Procedures	Twelve inch, ladder-back cable tray in "U"-shaped configuration with approximately 50% cable loading, three sizes of cables installed in three separate power circuits (Based on TSI test report #82-5-355F, [3])

Summary of Fire Endurance Test Results

In testing, each of the three fire endurance test specimens failed prematurely. As in the original manufacturer's testing, the principal failure criteria for the fire endurance tests was based on certain cable electrical performance circuit tests incorporated into each of the test articles. Four such circuits, similar to those used in the original manufacturer tests, were installed in each of the test articles. Failure of any one of these four circuits would constitute an overall test failure. These circuit performance tests were configured so as to be consistent with the original manufacturer's test articles.

Each of the test articles experienced circuit integrity failures during the fire exposure in three of the four circuit tests. These failures occurred in each of the two circuit-to-circuit (or conductor-to-conductor) and in the single circuit-to-ground (conductor-to-ground) test circuits for each test article (test circuits 2-4). The first circuit failures were observed as follows (failure times given in the format of hrs:min:sec):

Procedures Based Test Articles:

Test Article 1: First Circuit Failure at 1:15:39

Test Article 2: First Circuit Failure at 0:58:32

Full Reproduction Test Article:

Test Article 3: First Circuit Failure at 1:58:52

In general, failure on all three of the normally open circuit tests was observed within 15 minutes of the first such failure. All of these failures occurred well short of the nominal three-hour fire endurance rating associated with the installed fire barrier systems.

As discussed below, the final circuit integrity test, test circuit 1, was a circuit-to-system test in which breaking of the copper conductor was expected to result in a detectable open circuit condition. However, because of the electrical configuration used by the manufacturer, and hence by SNL, quite extraordinary conditions would be required to actually detect failures on this circuit (see Appendix A for further discussion). While no failures were detected on this circuit during testing, no conclusions can be drawn based on these results. Post-test inspection of each of the test articles did reveal both broken and extremely brittle conductors.

In addition to the cable circuit performance, consideration has also been given to the temperature rise limits established in the ASTM E119 general fire barrier performance testing standards. In accordance with these criteria, a fire barrier test would be considered a failure if:

1. Any single point temperature measurement within the protected envelope rises more than 325°F (181°C) above ambient temperature observed at the start of the test; or
2. The average of all temperature measurement points within the protected envelope rises more than 250°F (139°C) above ambient.

In comparison to these temperature rise limits, Test Articles 1 and 2, the procedures-based installations, experienced their first failures at approximately 65 and 55 minutes respectively, well short of the nominal manufacturer's rating of 3 hours (180 minutes). Test Article 3, the enhanced full reproduction test article, experienced its first failure at approximately 1 hour, 50 minutes, again well short of the nominal 3 hour rating. In each case, the first failure observed was associated with a single point measurement exceeding the allowable temperature rise criteria (as per criterion 1 above).

Each of the three fire endurance test articles eventually suffered a structural collapse of the protected envelope. That is, during each test it was observed that large sections of the fire barrier system fell away from the test article and that sections of the cable tray comprising the test specimen itself were eventually exposed directly to the furnace flames (based on observation through furnace viewing ports and the visibility of the cable tray itself). For each test article, virtually all of the insulation and jacketing material on the protected cables was consumed by fire during the exposure. Upon post-test examination,

only bare and embrittled copper conductors remained in most regions of each test article. The only exception to this observation was in the regions immediately adjacent to and outside of the furnace interface bulkhead penetrations where the insulation and jacketing materials had not fully burned, but did soften and/or melt so that upon cooling the individual cables had fused into a single mass. The fire exposures for Test Articles 1 and 2 were terminated after 2½ and 2 hours respectively because gross structural failure of the barrier system had already been observed, and temperatures throughout the test article were in excess of the single point high temperature failure criteria. Test Article 3 was exposed to the full three-hour fire exposure duration, although gross structural failure of the fire barrier system had been observed by 2½ hours.

Another aspect of the fire endurance test is the application of a post-exposure hose stream test. None of the three fire endurance test articles was actually subjected to the full hose stream test as specified in the ASTM E119 test standard. That is, each of the three test articles showed extensive levels of damage upon removal from the test furnace, and so, the hose stream was simply used to extinguish and cool the test article (upon removal from the furnace, each of the three fire endurance test articles continued to burn freely). In each case the hose stream pressure used was the nominal water main available line pressure and was below that specified in the standard exposure. The duration of the exposure was simply that required to fully extinguish burning in the test article, and was typically less than the standard hose stream duration.

Nonetheless, in each case, the fire barrier system was utterly destroyed wherever it was directly contacted by the hose stream. In the case of Test Articles 1 and 2 the hose stream was applied to the test article immediately upon removal from the test furnace. In the case of Test Article 3, initial attempts were made to cool the test article by applying a light water mist. However, the test article had become so hot during the exposure that this proved impractical, and the test article repeatedly reignited upon removal of the mist spray. The full hose stream was applied to extinguish the test article approximately 10-15 minutes after removal from the test furnace.

Summary of Ampacity Derating Test Results

Table ES.2 summarizes the ampacity derating test results in comparison to the original manufacturer's results. The ampacity derating test set performed by SNL on Test Article 4 revealed ampacity derating factors of 46.4%, 36.2%, and 35.6% for the 8AWG, 4AWG and 2/0 cables respectively. (Note that all three cable sizes were contained within the single test article.) This compared to the original manufacturers published values of 16.15%, 16.86% and 17.68% respectively.

However, a systematic mistake in the calculation of ampacity derating factors by the manufacturer has previously been noted involving the correction of experimental ampacity values to standard conditions (see USNRC Information Notice 92-46). When this error is corrected values of 31.8%, 32.4%, and 33.1%, respectively, are obtained based on the manufacturer's data and analysis methodology.

Table ES.2: Summary of Ampacity Derating Results			
Data Source	Ampacity Derating Factors (%)		
	8 AWG	4 AWG	2/0
TSI Data, Published Values	16.15	16.86	17.68
TSI Data, Initial Error Corrected	31.84	32.43	33.10
TSI Data, Fully Corrected	38.10	32.43	35.55
SNL Test Article 4	46.4	36.2	35.6

During the course of the current work, a further mistake in the original analysis performed by the manufacturer was identified in that the manufacturer failed to correct for the fact that each of the three conductors in the test article were brought to widely varying steady state temperatures. Only the single hottest cable measurement point was used to correct all three cables, and the cable to cable variations were ignored. When this further error is corrected, ampacity derating factors of 38.1%, 32.4% and 35.5%, respectively are obtained based on the manufacturer's original data.

In the final analysis, the SNL ampacity derating results indicate a somewhat more severe ampacity derating effect than do the manufacturer's original results, even when those original results have been fully corrected. However, the differences which remain could be accounted for by any one of a number of factors. In particular, the differences could be the result of inherent shortcomings in the original manufacturers test procedures and/or complications which arose due to the extremely complex nature of the test article itself (both geometric complexity and cable-to-cable control interactions). In particular, the manufacturer's failure to achieve a uniform cable-to-cable hot-spot temperature condition would be expected to significantly impact the final results. It should also be noted that due to these shortcomings and complications, the ampacity derating factors determined here should not be considered a reliable indication of the ampacity derating performance to be expected in real applications.

1.0 INTRODUCTION AND OVERVIEW

1.1 Purpose

The purpose of this project was to assess the performance of the fire barrier system Thermo-Lag 330-1 in a three-hour, double layer configuration. This included an assessment of both fire endurance performance and the associated ampacity derating impact. The project was sponsored by the U. S. Nuclear Regulatory Commission (USNRC) Office of Nuclear Reactor Regulation (NRR). The fire barrier system Thermo-Lag 330-1 is manufactured by Thermal Science Inc. (TSI). The tests performed by SNL reproduced the physical characteristics, instrumentation, and cable loadings of test specimens used in certain of the original qualification tests performed by the manufacturer. These tests included three three-hour fire endurance tests and one set of ampacity derating tests (one base line and one clad ampacity test).

1.2 Background

Thermo-Lag is one of a number of available products intended for use as a localized fire barrier. That is, this and other products are used to form a protective barrier around individual pieces of equipment in order to protect that equipment from the damaging effects of a fire. In nuclear power plants, the most important application is in the protection of electrical equipment including cable trays, conduits, and junction boxes. In many situations, such fire barrier systems were installed as a 10CFR50, Appendix R fire safety regulations compliance measure.

Appendix R requires that in the event of a fire "where cables or equipment ... of redundant trains of systems necessary to achieve and maintain hot shutdown conditions are located within the same fire area ... means of ensuring that one of the redundant trains is free of fire damage shall be provided" (section III.G.2). One acceptable means of meeting this requirement specifically identified in the regulations is to protect the components of at least one system with a fire barrier which has a fire endurance rating of either one- or three-hours. (The choice of rating duration depends on the availability of fire detection and suppression systems in the fire area.) This endurance rating is determined by qualification tests in which a mock-up of the barrier system is exposed to the ASTM E119 standard time-temperature curve [5] for the time period associated with the barrier rating.

In the current project, the concern is focussed on the protection of cables in cable trays. For the manufacturer's tests considered here, the criteria used to assess the performance of the barrier system was based on an American Nuclear Insurer's (ANI) standard [8] in which cables housed within the fire barrier system are monitored for electrical performance. That is, the test is declared a failure if any one of the electrical test circuits fails or faults during either the fire exposure or hose stream test. The configuration of each of the original manufacturer's circuit integrity tests was reproduced, to the extent possible based on the original test reports, and the primary criterion for the assessment of barrier performance was these circuit integrity tests.

However, in addition to the ANI circuit integrity criteria, the current evaluations have also considered the temperature rise limits established in the general ASTM E119 fire barrier qualification test standard [5]. This ASTM standard was intended primarily to serve as a test method for general building construction elements such as walls, floors, ceilings, and doors. It was not specifically written for application to more localized cable tray fire barrier systems such as that considered here. Nonetheless, it is common practice to compare the fire barrier temperature performance for cable tray fire barrier system tests to the temperature rise limits established in the ASTM test. In particular, the ASTM E119 test is passed if temperatures measured on the unexposed surface of the barrier system do not rise above certain threshold levels for the average of all measurements and for any single point temperature measurement. These criteria are based on the temperature rise above the ambient temperature at the start of the test, and are 250°F and 325°F for the average and single point responses respectively.

In the case of cable tray fire barrier systems, it has been common practice to assess the temperature performance based on the measurement of cable and cable tray response temperatures, rather than the inside barrier surface temperature. Such assessments were provided in the original manufacturer's reports. The data analysis performed here included the evaluation of the cable and cable tray temperature responses consistent with this general practice. However, for information purposes, thermocouples were included to measure the temperature on the unexposed surface of the fire barrier system.

Following the fire exposure, the test article is subjected to a direct water hose stream test. The barrier system should remain intact during this final exposure. (As will be discussed further below, none of the fire endurance test articles was actually subjected to the full hose stream exposure test due to the extensive levels of damage observed during the actual fire exposure.)

However, in addition to the fire endurance rating and certification, the impact of the protective envelope on the allowable performance limits of the protected equipment must also be considered. That is, the fire barrier system represents an insulating envelope surrounding the protected equipment which is in place even under normal operating conditions. For example, electrical cables under load (with current flowing) will inevitably experience an electrical self-heating effect proportional to the amperage carried by the cables due to the inherent internal resistance of the conductor. This internally-generated heat must be dissipated to the environment in order to maintain the cables below their specified operating temperature limits (typically 90°C for modern cable types). The insulating effect of the fire barrier system represents an additional impediment to this heat transfer process, and hence, the electrical carrying capacity of the protected cables must be reduced accordingly. Failure to adequately account for this insulating effect could lead to premature aging of the protected components. This is the process of ampacity derating.

Initial uncertainty regarding the ability of Thermo-Lag to meet the requirements of the applicable standards associated with fire barrier qualification were raised as a result of the failure of such systems in certain utility sponsored fire-endurance tests (see, for

example, reference 6). Upon review by the USNRC, it was also found that a wide range of ampacity derating factors for nominally identical applications had been identified. The tests performed in the current program are intended to provide an independent assessment of the Thermo-Lag's performance as a fire barrier system, including both fire endurance performance and ampacity derating.

1.3 Overview of the Test Program

All of the tests performed under this program involved cable tray test specimens protected by a nominal three-hour fire barrier system. Each barrier system was formed using two layers of nominal 1/2" thick Thermo-Lag 330-1 preformed panels. A total of four test articles were evaluated including three fire endurance test articles and one ampacity derating test article. In each case, the test articles were intended to reproduce the physical characteristics and attributes of certain of the original manufacturers qualification test articles. That is, each of the test articles constructed for use in this program reproduced, as closely as possible, the dimensions, physical layout, instrumentation, and cable loadings of typical manufacturer qualification test articles. In particular, the following TSI test articles were used as the model for the test articles evaluated in this program:

Fire Endurance Test Articles*:

SNL Test Article #1	TSI test report #82-5-355B, Test Article #2 [1]: Three hour fire endurance test for a 6-inch square solid bottom cable tray, light cable loading, Revision V procedure-based barrier application.
SNL Test Article #2	TSI test report #82-11-81, Test Article #4 [2]: Three hour fire endurance test for a 12-inch ladder-back type cable tray, light cable loading, Revision V procedure-based barrier application.
SNL Test Article #3	TSI test report #82-11-81, Test Article #4: Three hour fire endurance test for a 12-inch ladder-back type cable tray, light cable loading, full reproduction of manufacturers barrier installation.

Ampacity Derating Test Article*:

SNL Test Article #4	TSI test report #82-5-355F [3]: Ampacity derating test of a 12" cable tray protected by a 3 hour fire barrier, Revision V procedure-based barrier application.
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(* In all subsequent discussions, the test articles will be identified by the SNL test article number as identified here)

Note that in the case of Test Articles 1, 2 and 4 , the fire barrier installations were based on the manufacturer's installation procedures as presented in TSI Technical Note 20684, Revision V dated November 1985 [4]. These installations were based on the

use of nominal 1/2" thick pre-formed panels. To form the three-hour barrier, two layers were used. Each layer protecting each section of the cable tray was generally formed by four individual pieces; namely, a top, a bottom, and two side pieces. In each case, both the top and bottom panels were cut so that the reinforcing ribs which are formed in the panel during the manufacturing process were oriented so as to run across the width of the cable tray. The Thermo-Lag panels were secured to the test article using external stainless steel 18ga tie wires around each layer of the barrier system at nominal 12" intervals throughout, and within 2" of the end of any panel and any panel joints. All joints were "pre-buttered" with trowel grade material during the assembly process. That is, trowel grade material was applied in a thick bead along the line of the each joint between individual panel sections prior to assembly of the joint (similar to the practice of mortaring bricks). These installation procedures are discussed in greater detail below (see Section 2.1.3).

In the case of Test Article 3, the fire barrier installation was intended to reproduce, as closely as possible, the original manufacturer's installation. The cable tray system which formed the basis of this test article was identical to that of Test Article 2. Information taken from the published test report [2], the associated daily work sheets, unpublished photographs of the original test article, and unpublished photographs of similar test articles constructed during the same time period by TSI were all used to insure that the SNL installation matched that of the original manufacturer's test as closely as possible. This installation was again based on the use of a double layer of nominal 1/2" thick panels, but the panels were secured to the test article using a combination of bolts and wire stitching. All joints in the barrier system were both pre-buttered and wire stitched. In addition, the primary outer layer joints were also bolted. This installation is described in greater detail below (see Section 2.3.3).

In each case, the actual installation of the fire barriers was performed by union certified insulation contractors. Prior to the initiation of the installation efforts, all of the involved personnel were provided with installation training by a former TSI field representative and trainer. Two such training sessions were conducted, one exclusively for the SNL project staff and a second for the union insulators (also attended by SNL project staff). All installation work was performed under the direct observation of at least one representative of the SNL project staff. The on-site SNL project representative retained the authority to accept the installation work performed.

1.4 Overview of Instrumentation Usage

The data gathered during the three fire endurance tests included cable, cable tray, fire barrier surface, and exposure environment temperature response as well as cable circuit integrity data. For the ampacity derating test set, the measured data included cable, cable tray, fire barrier surface, and environmental temperatures, and cable circuit amperage data. All of the data gathered during these tests was recorded using calibrated instrumentation systems.

Primary data recording was performed by SNL personnel using SNL equipment. That is, all of the instruments which were attached to the test articles themselves were

installed by SNL personnel (this includes all of the test article thermocouples and the circuit integrity wiring for the fire endurance test articles). Full quality assurance inspection was implemented to insure the integrity of the installed instruments. The data from these installations was gathered using SNL provided equipment.

Supplemental data was also gathered using certain UL instruments. The fire endurance furnace exposure temperature profile was monitored using the UL equipment normally associated with the exposure furnace utilized in testing. For the ampacity derating test set, the individual cable amperage levels were monitored using equipment provided by UL. SNL personnel observed the operation of these systems during testing, and records of the data gathered were provided to SNL immediately upon completion of each individual test.

Both the SNL and UL data recording instruments are subject to periodic calibration recall systems utilizing calibration standards traceable to the National Institute for Standards and Technology (NIST). The current calibration of all instruments utilized for the measurement of test data was verified prior to testing. Appendix A provides additional detail on the individual data logging equipment used in this program and documentation of the current calibration of each measurement device.

1.5 Limitations of Temperature Data Validity

All of the thermocouples used in the instrumentation of the test articles were unshielded, Type K, Chromel-Alumel thermocouples with welded junction beads. The thermocouples were formed by stripping back approximately 1/2" of insulation from the ends of the lead wires, forming the exposed conductors into a diamond shape, and spot-welding a junction bead into the outer tip of this diamond. The integrity of each weld junction was verified mechanically. The thermocouple bead was then installed at the desired location using methods described in Appendix A.

All of the thermocouples were formed from normal accuracy Thermocouple-Grade wire (as opposed to high-accuracy Thermocouple-Grade wire or lower grade Extension wire). In general, Type K thermocouples are capable of measuring temperatures in the range of -200 to 1250°C (-328 to 2282°F). For operation from 0-293°C (32-559°F) normal Thermocouple-Grade type K thermocouples, such as those used here, will provide an accuracy limit of $\pm 2.2^{\circ}\text{C}$ ($\pm 4^{\circ}\text{F}$) [9].

However, it should be noted that the thermocouple lead wires used in this effort were insulated with a teflon-based insulation. (Teflon insulation was chosen to provide a high level of moisture resistance.) In thermocouple applications, the manufacture recommends that Teflon insulation will provide reliable results in continuous use applications up to temperatures of 260°C (500°F) and in single reading applications

up to 316°C (600°F).¹ Beyond this level, unreliable results should be anticipated. In particular, as the teflon insulation exceeds these levels, thermal breakdown of the insulation is expected. This can lead to the formation of "false junctions" along the length of the thermocouple lead wires, and renders the location of the temperature measurement point uncertain. (If a false junction forms, then the measurement would be made at the location of the false junction rather than at the location of the original bead.)

In reviewing the test data associated with the temperature response of the fire endurance test articles, it should be noted that temperature measurements in excess of 316°C (600°F) are considered unreliable (in this case, the single reading temperature limits are applicable). In particular, it can be concluded that a thermocouple which measured temperatures in excess of these values was, in fact, exposed to such temperatures at some point along its length; however, the exact location of that exposure would be considered uncertain. These limits are well in excess of the limits on temperature which are established in the relevant ASTM fire endurance test standard. Hence, the data gathered will provide an accurate and reliable measure of the temperature response in comparison to these temperature rise criteria. (Note that this limitation does not impact the furnace exposure profile measurements because a different grade of thermocouples is used in that application.)

¹Based on information provided by the manufacturer of the thermocouple wire, Watlow Gordon, in its 1991/92 catalog of "Temperature Measurement Products," PC9192, pages 189 and 219 for the type 508 insulation used in this program.

2.0 DESCRIPTION OF TEST ARTICLES

2.1 Test Article 1

2.1.1 Physical Description

Test Article 1 was a fire endurance test article, and was built around a 6" square, solid bottom cable tray with internal rungs spaced at 6" intervals along the bottom of the tray. The cable tray assembly itself was constructed from two 48" straight sections, one down-turning elbow section, and one up-turning elbow section mutually secured by bolts and bolting plates. Each of these cable tray sections was constructed from 10ga galvanized steel, and were custom made for use in this program. These sections were bolted together to form a single "U"-shaped assembly. This cable tray assembly was then welded into place onto an overall external support frame. This support frame also provided for the interface between the test article and the fire endurance furnace. The cable tray materials, configuration, orientation, and construction were all consistent with the original manufacturer's test article. In fact, cable tray sections were specially constructed for use in this program using the descriptions and specifications provided in the original test report. Dimensional drawings of the test article are provided in Appendix A.

A single layer of cables was installed in the test article consistent with the placement of cables in the original manufacturer's test. A listing of the cables used and the specific arrangement of cables within the cable tray is discussed in detail in Appendix A. Based on the actual diameters of the cables used, and on a nominal total cable tray area of 36 square inches (6"x6") the percentage fill for this cable tray was approximately 4%.

2.1.2 Instrumentation

Instrumentation of Test Article 1 consisted of a reproduction of the original manufacturer's instrumentation installations with certain additional SNL instrumentation supplements. The manufacturer's original installation included 8 type K thermocouples located at 12" intervals along one of the cable segments located in the center of the cable tray. No other thermocouple instrumentation of the original test article was documented. This placement of thermocouples was fully reproduced. The SNL supplemental thermocouples installed included the following:

- The centrally located instrumented cable was provided with a total of 10 thermocouples rather than 8 as in the original manufacturers test (spacing was maintained at 12" intervals).
- Ten additional thermocouples were installed on each of two additional cables, one on each side of the cable tray (left and right of center), at locations consistent with those of the centrally located instrumented cable.

- Eight thermocouples were installed on each of the two side rails of the cable tray. These thermocouples were installed at, nominally, 18" intervals along each side rail.
- Five thermocouples were installed at, nominally, 24 inch intervals for measurement of the air temperature inside the envelope.
- Three thermocouples were installed to measure the fire barrier panel inside surface temperature. In particular, thermocouples were attached to the following panels:
 - the center of the top-most panel on the inner layer protecting the upper straight leg of the cable tray assembly,
 - the center of the lower-most panel on the inner layer protecting the lower straight leg of the cable tray assembly, and
 - the center of the inner layer, outer radius protective panel, just above the joint between the up-turning and down turning elbow sections.

The specific placement and installation details for these thermocouples are described further in Appendix A.

In addition to the temperature data, for both the original manufacturer's test and the SNL test, certain individual cables were subjected to low-voltage excitation in order to provide a nominal measure of the performance of these cables during the fire exposure. Three types of circuit integrity tests were conducted, namely, circuit-to-circuit (or conductor-to-conductor), circuit-to-ground (or conductor-to-ground), and circuit-to-system (or conductor continuity). It was not possible to determine the exact configuration of the manufacturer's cable integrity circuits from the information provided in the original test report. The test report does identify several instrumented cables and provides "typical" circuit configurations, but fails to identify the exact wiring configuration used for each cable. The SNL circuit integrity tests were based on the information which was provided, and were configured using a best-practice approach based on prior SNL cable functionality testing experience.

In each of the three SNL fire endurance test articles, four individual cables (either multi-conductor or single conductor) were connected to separate circuits for integrity testing (2 cables for circuit-to-circuit and one cable each circuit-to-ground and circuit-to-system). In each case, the energizing voltage was 28VDC with no baseline current imposed on the conductors. Appendix A provides specific circuit configuration information for each of these circuits.

2.1.3 Fire Barrier System

The fire barrier system for Test Article 1 was installed in accordance with the TSI procedures as presented in Technical Note 20684, Revision V. The three-hour barrier system was constructed from two layers of nominal 1/2" thick panels. The first layer was constructed with the stress skin facing inward (towards the cable tray), and the second layer was constructed with the stress skin facing outward. In both cases, the

top and bottom panels for each section were cut so that the reinforcing ribs formed in the panel during manufacture were oriented so as to run across the width of the cable tray. In the case of the inner layer, the ends of these top and bottom panel ribs were flattened using a hammer from the outer edge in about $\frac{3}{4}$ " from each edge of the panel. This flattening of the ribs to the thickness of the rest of the panel allowed for a tight and uninterrupted joint between the top/bottom panels and the two side panels. This procedure is consistent with the manufacturer's installation procedures and with the installation training received by the installers.

In the formation of each layer of the barrier system, panels were initially cut to size and then "dry fit." That is, prior to final assembly, the cut panels were secured in place on the test article using temporary holding straps. The quality of each of the seams and joints between abutting panels was carefully inspected to ensure that a tight final fit had been achieved. Only upon the achievement of a tight dry fit was the final assembly undertaken, and the panels secured in place.

During the final assembly of each section, all of the seams and joints between panels within a single layer were "pre-buttered" with trowel grade Thermo-Lag 330-1 material. That is, a thick bead of the trowel grade material (typically $\frac{1}{2}$ - $\frac{3}{4}$ " wide and $\frac{1}{2}$ " deep) was placed along the line of the seam or joint prior to assembly of the pieces. (Note that Figure 2.2(b) illustrates the formation of such a bead during the assembly of a typical joint.) During assembly, the formation of these seams and joints was closely observed to insure that (1) a tight and uninterrupted fit between panels was observed, and (2) that the seam or joint formed was completely filled with trowel grade material.

In the formation of the elbow sections, the "flats" across the width of the tray (the inside and outside radii) were formed by large panels cut to size, scored, and bent to form the curve. In the formation of these pieces, the score lines were inspected to insure that the stress skin itself was not cut. Here again, the panels were cut so that the ribs ran across the width of the tray. In all cases the score-and-bend lines were repeatedly filled with trowel grade material to restore the full original panel thickness upon curing. The sides of the elbow sections were formed from single piece "C"-shaped sections.

All panels were secured to the test article using 18ga stainless steel tie wires installed over the outside of each layer. Tie wires were placed within two inches (on each side) of any butt joint between material panels, and at no greater than 12" intervals throughout. In many cases, particularly on the elbow sections, closer spacing was employed to ensure a tight and secure fit. During the assembly process it was often necessary to install temporary wires to support, typically, the side panels forming a given section while the top and bottom panels were prepared for installation. In all cases, such intermediate wires were removed during the final assembly process so as to insure that no wires penetrated either layer of the protective envelope. During the installation of the second layer, panel butt joints were offset from those of the first layer by a minimum distance of 2".

The support strut under the front of the test article (the "nose support" at the bottom of the elbow section) was also protected consistent with the manufacturers procedure. That is, layers of material were installed and secured with tie wires at, typically, 6" intervals. These support structures were completely protected with a double layer of cut Thermo-Lag panels all the way out to the base support frame, including the angled support riser pieces. In addition, the long angled riser pieces which support the furnace interface structure at the rear of the test articles were also provided with partial protection by a single layer of the Thermo-Lag material even though these risers did not penetrate the protected envelope. (These risers were also protected by a 2" thick layer of ceramic insulating blanket during the fire test.)

Figure 2.1 illustrates the general placement of panels in each layer of the envelope for Test Article 1. Figure 2.2 provides photographs of the test article before, during, and after installation of the barrier.

2.2 Test Article 2

2.2.1 Physical Description

Test Article 2 was a fire endurance test article and was built around a "U"-shaped 12", ladder back cable tray assembly with 6" rung spacing. The cable tray assembly itself was constructed from two 48" straight sections, one down-turning elbow section, and one up-turning elbow section mutually secured by use of bolts and bolting plates. The straight sections of the cable tray were constructed from 10ga galvanized steel for the side rails and 3/4" galvanized conduit for the rungs, and were custom made for use in this program. The elbow sections were constructed of 14ga galvanized steel and were acquired off-the-shelf. The cable tray materials, configuration, orientation, and construction were all consistent with the original manufacturer's test article. The completed cable tray assembly was mounted into an overall external support frame by welding to fixed support struts. This support frame also provided for the interface between the test article and the fire endurance furnace. Dimensional drawings of the test article are provided in Appendix A.

Cables were installed in the test article consistent with the placement of cables in the original manufacturer's test. A discussion of the cables used and the specific arrangement of cables within the tray is presented in Appendix A. Based on the actual diameter of each cable, and on a nominal total available cable tray cross-section of 48 square inches (12"x4") this represents a cable fill of approximately 15%.

2.2.2 Instrumentation

Instrumentation of Test Article 2 consisted of a reproduction of the original manufacturer's instrumentation installations with supplements. The manufacturer's original installation included 8 type K thermocouples located at 12" intervals along each of three of the cable segments (a total of 24 cable temperature measurements). These cables were located in the center and along each side of the cable tray. This

placement of thermocouples was fully reproduced. The supplemental instrumentation installed included the following:

- Each of the instrumented cables was equipped with ten, rather than eight, thermocouples (spacing was maintained at 12 inch intervals).
- Eight thermocouples were installed on each of the two side rails of the cable tray. These thermocouples were installed at, nominally, 18 inch intervals along each side rail.
- Five thermocouples were installed at, nominally, 24 inch intervals for measurement of the air temperature inside the envelope.
- Three thermocouples were installed to measure the fire barrier panel inside surface temperature (see description of placement in Section 2.1.2 above).

Appendix A provides detailed information on the specific placement and methods of installation for these thermocouples.

In addition to the temperature data, certain of the individual cables were subjected to low-voltage excitation in order to provide a nominal measure of the performance of these cables during the fire exposure. The general configuration of these circuit integrity tests were identical to those described in Section 2.1.2 above, however, the individual cables selected for instrumentation in Test Article 2 differed. Appendix A provides detailed information on the circuit integrity configurations and wiring for Test Article 2.

2.2.3 Fire Barrier System

The fire barrier system for Test Article 2 was installed in accordance with the TSI procedures as presented in Technical Note 20684, Revision V [4]. The, nominal, three hour barrier system was constructed from two layers of nominal 1/2" thick panels. The procedures used in this installation were identical to those described above in Section 2.1.3 for Test Article 1. Figure 2.1 illustrates the typical placement of pieces in each layer of the protective envelope (the placement of pieces in Test Article 2 was essentially identical to that of Test Article 1). Figure 2.3 provides photographs of Test Article 2 before, during and after barrier installation.

2.3 Test Article 3

2.3.1 Physical Description

The physical configuration and construction of Test Article 3 was identical in all ways to that of Test Article 2. Refer to Section 2.2.1 above.

2.3.2 Instrumentation

The configuration and installation of instrumentation for Test Article 3 was identical in all ways to that of Test Article 2. Refer to Section 2.2.2 above.

2.3.3 Fire Barrier System

In the case of Test Article 3, the fire barrier system was installed so as to reproduce the manufacturer's original installation as closely as possible based on the available information. This information included the full TSI test report including the daily work sheets, and unpublished photographs of this and other similar test articles constructed by TSI during the same time period. The installation procedure referenced in the subject test report was not identified as a specific TSI Technical Note as were later versions, but was provided with the full test report.

The fire barrier system for Test Article 3 was, again, comprised of two layers of nominal 1/2" thick panels. All material joints and seams were pre-buttered with Thermo-Lag 330-1 trowel grade material during assembly. In all cases, the joints and seams were also reinforced with 18ga stainless steel wire stitching, and in the case of the outer layer, 1/4"x2" machine screws were also employed to reinforce all of the panel joints and seams. The installation procedures included the following provisions:

General Provisions:

- Wire Stitching: All joints and seams between material panels which did not incorporate a continuous section of un-cut stress skin (including all flat butt joints and all corner joints) were "laced" or "stitched" using 18ga stainless steel wire. (Note that "stitching" implies the use of several individual loops of wire across a joint whereas "lacing" implies the use of a single continuous strand of wire repeatedly looped through a joint along its length.) Figures 2.4, 2.5 and 2.6 illustrate various aspects of this procedure. (Figure 2.10, described below, provides photographs to illustrate the results of this procedure.)
- Back-filling: Stitching or lacing was accomplished by drilling a small hole (approximately 1/16" diameter) through the panel at the appropriate location and feeding the wire through the resulting hole. The drilled hole was then back-filled as fully as possible by pressing trowel grade material into the openings. This procedure was closely monitored during the filling of some of the more accessible such holes. It was noted that by pressing trowel grade material into the hole with the flat of a trowel, material could be forced fully through the hole so as to protrude from the other side of the panel.
- Bolting: In addition to stitching, machine screws (1/4"-20 x 2") and hex-nuts were used to secure the corners and butt joint seams between panels in the outer layer. (The bolting procedure is illustrated in Figure 2.5). Bolting flanges approximately 1 1/2" wide were formed in the panel sections which cover the sides of the cable tray and at all butt-joint locations by scoring and folding the panel

edges as shown (note that in no case did the scoring cut through the stress skin). The open corners created were then filled with ½"x½" cut strips of panel material and trowel grade material to restore the full panel thickness throughout the corner. Prior to assembly, all of the flange mating surfaces were pre-buttered. Machine screws were then used to secure the matching bolting flanges on adjoining panels at intervals of no more than 6" and within 2" of each end of any such bolting flange pair. As described above, wire lacing was then installed along the full length of all such joints through the bolting flange sections. (Figure 2.10, described below, illustrates the results of this procedure.)

- Flange Corner Filling: Upon completion of the bolting and lacing of the outer layer, trowel grade material was used to cover both ends of the machine screws and to further fill the inside corners of each flange's score and fold line (based on inspection of the unpublished manufacturer photographs). (Figure 2.10, described below, illustrates the results of this procedure.)
- Final Overcoat: Upon completion of the outer layer installation, a final over-coating of the test article with 330-1 trowel grade material was performed. A damp paint brush was used to provide an initial coating of trowel grade material over the entire surface of the test article to a depth of approximately 1/10". This surface was then smoothed using a damp paint roller. (Figure 2.10, described below, illustrates the results of this procedure.)
- Nose Support: The horizontal support under the "nose" of the cable tray assembly was also fully protected. For each of the two layers, the two panels which butted up against the nose support, the outer radius protective panel and the panel protecting the lower surface of the lower leg of the cable tray assembly were secured to the corresponding panels protecting the nose support using the same stitching procedure as described above. In addition, individual tie wires were placed around each layer of the nose support protection at, nominally, 6" intervals. This protection was extended to the full length of the support including the angled riser pieces.

Inner Layer Installation:

- General Piece Pattern: A total of seven pieces were used to form the inner layer of the protective envelope around the cable tray. Figure 2.7 illustrates the general placement of these pieces.
- Protection of the Elbow Section: In particular note that the inner layer protecting the two elbows which comprise the bottom of the "U" was formed using just three pieces. The curved surface forming the inner radius was protected by a single panel cut to size, and then "scored" at 4-6 inch intervals to allow for bending of the panel to form this inside curve. The outer radius and the side rails were protected by two panel sections, one panel covering the upper elbow and one covering the lower elbow as far as the horizontal "nose" support structure. Note that in each case, the panel was cut so that the sides of the

elbow were protected by polygon shaped flaps which fold over at the outside corner of each elbow. In this way, a continuous layer of the stress skin covers the outer corners of the envelope. All of the joints between the polygon-shaped side flaps were also wire stitched. Figure 2.8 illustrates the construction of these pieces.

- Joints: All joints, including both flat panel butt joints and corner joints, on the inner layer were laced with individual loops of wire every three inches binding the panels across the joint as described above. In addition, all joints were pre-buttered during the assembly process. All of the score-and-bend lines were repeatedly filled after installation with trowel grade material as required to restore the full panel thickness throughout. (Figure 2.10, described below, illustrates this procedure.)

Outer Layer Installation:

- Joint Placement: All joints in the outer layer were offset from those in the inner layer by no less than 2 inches.
- Joint Bolting and Lacing: As noted above, every joint in the outside layer was secured using a combination of bolting and wire lacing.
- General Layout: The outer layer on Test Article 3 was made up of 12 individual pieces. Figure 2.9 illustrates the general placement of these outer layer pieces. Note that the primary difference between the inner and outer layers is that in the outer layer, the envelope protecting each section of cable tray is formed from four rather than two pieces.

Figure 2.10 provides photographs of Test Article 3 before, during, and after installation of the fire barrier system which illustrate the various steps in the installation process.

2.4 Test Article 4

2.4.1 Physical Description

The physical configuration of Test Article 4 was much simpler because this test article was not designed for fire endurance testing, and hence, no furnace interface provisions were required. The cable tray assembly comprising the core of the test article was identical to that used in Test Articles 2 and 3 (see description in Section 2.2.1 above), however, the support structure was considerably simplified, and the cable loading was quite different. Appendix A provides additional detail on the construction of Test Article 4.

The cable tray assembly was loaded with three sizes of cables. All of the cables of a given cable size were tied together electrically into a single electrical loop. Appendix A provides a detailed description of each of these cables and the arrangement of cables within the cable tray. Based on the actual diameter of each cable, and on a nominal

total available cable cross-section of 48 square inches (12"x4") this represents a cable fill of approximately 28%. Note that due to the inherent inefficiency of cable packing (i.e., packing of round cables into a rectangular space will inevitably lead to some empty space between the individual cables) this fill of cables represented approximately 60% of the full available tray depth of 4". That is, once installed, the depth of fill was approximately 1½-2". With this depth of fill, the cables were easily arranged so that no significant air gaps through the cable mass were present.

The installation of the cables in the test article is described in detail in Appendix A. In general, the cables were installed in five sections (two sections each of the 8AWG and 2/0 cables and a single section of the 4AWG cable). Each of the five cable sections was formed by looping a single length of cable repeatedly back through the cable tray. In addition, for four of the five sections a single separate length of cable instrumented for temperature was also installed (see further discussion in Section 2.4.2 below). In this way, the number of connections required to complete each of the three cable electrical loops was minimized.

2.4.2 Instrumentation

Instrumentation of Test Article 4 included a reproduction of all of the original manufacturer's installation with SNL supplements. The manufacturer's original instrumentation included thermocouples on three lengths of cable. However, note that the original test report includes a discrepancy in this regard. The text describes thermocouples installed on one length of each size cable whereas the figures show no thermocouples installed in the 2/0 cable section. The instrumentation for Test Article 4 reproduces both interpretations so that in all, four lengths of cable were instrumented.

Each of the four instrumented cables was equipped with six 24ga. bare bead type K thermocouples with welded junctions. Appendix A provides a description of the specific placement and method of installation of these thermocouples.

In addition, supplemental instrumentation was installed to fully characterize one specific section of the cable tray (Section 2 as identified in Appendix A). That is, at a specific location on the upper part of the elbow section of the cable tray, thermocouples were installed:

- on the both of the cable tray side rails,
- on the inner surface of each of the four panels forming the inner layer of the fire barrier around that section, and
- on the outer surface of each of the four panels forming the outer layer of the fire barrier system.

One additional thermocouple was installed on each of the two side rails at the location corresponding to cable section 5 as identified in Appendix A. Finally, three thermocouples were installed for the measurement of the external ambient temperature.

2.4.3 Fire Barrier System

The fire barrier system for Test Article 4 was installed in accordance with the TSI procedures as presented in Technical Note 20684, Revision V [4]. The three hour barrier system was constructed from two layers of nominal 1/2" panels. The procedures used in this installation were identical to those described above in Section 2.1.3 for Test Article 1.

Note that in certain specific aspects, the same level of rigor was not applied to the construction of the fire barrier system for this test article as had been applied to Test Articles 1-3 because it was known that this test article would not be subjected to fire endurance testing. For example, the two horizontal support bars were only nominally protected by a double layer of the fire barrier material. It was determined that the formation of a sealed double layer protective envelope which was installed in nominal accordance with the manufacturer's installation procedures was the primary objective with regards to the ampacity derating test. Figure 2.11 provides photographs of Test Article 4 before, during, and after barrier installation.

- A total of 12 Pieces are Used to Form Each Layer of the Barrier System.
- Note that Each surface of Each Section of the Cable Tray Assembly is Protected by a Single Panel.
- Panel Joints of the Outer Layer are Offset From Those of the Inner Layer by a Minimum of 3".

Figure 2.1: General Layout of Individual Panels for Both the Inner and Outer Layers of the Fire Barrier System Protecting Test Articles 1 and 2.

(a) Test Article 1 Before Installation.

(b): Installing Elbow Section Panels

Figure 2.2: Barrier Installation Process for Test Article 1.

(c) Elbow Section Inner Layer Complete.

(d): Fitting Lower Leg Panels, Note Pre-Buttering Bead at Panel Edge
Figure 2.2: Barrier Installation Process for Test Article 1.

(e) Lower Leg Inner Layer Complete

(f): Inner Layer Complete

Figure 2.2: Barrier Installation Process for Test Article 1.

(g) Outer Layer Elbow Section Side Panels.

(h): Elbow Section Outer Layer Complete.

Figure 2.2: Barrier Installation Process for Test Article 1.

(i) Initial Dry Fitting of Upper Leg Top Panel.

(j): Upper Leg Panels Held by Bands for Temporary Support.

Figure 2.2: Barrier Installation Process for Test Article 1.

(k): Checking Joint Fill on Upper Leg Panels.

(l): Test Article 1 Complete, Cured, and Ready for Testing.
Figure 2.2: Barrier Installation Process for Test Article 1.

(a): Test Article 2 Prior to Installation of Fire Barrier System.

Figure 2.3: Barrier Installation Process for Test Article 1.

(b): Fitting Lower Leg Panels, Note Pre-Buttering Bead on Lower Panel.

(c): Checking Wire Tie Spacing on Lower Leg Section.

Figure 2.3: Barrier Installation Process for Test Article 2.

(d): Fitting Side Panels to Elbow Section with Temporary Ties.

(e): Attaching Inner Surface Thermocouple to Outer Radius Panel.

Figure 2.3: Barrier Installation Process for Test Article 2.

(f): Temporary Supports for Elbow Inner and Outer Radius Panels.

(g): Checking Joint and Score/Fold Fills.

Figure 2.3: Barrier Installation Process for Test Article 2.

(h): Inner Layer Installation Complete.

(i): Fitting Lower Leg Outer Layer Side Panels.

Figure 2.3: Barrier Installation Process for Test Article 2.

(j): Fitting Lower Leg Outer Layer Top and Bottom Panels.

(k): Installation and Curing Complete, Test Article Ready for Testing.
Figure 2.3: Barrier Installation Process for Test Article 2.

Figure 2.4: Test Article 3 Inner Layer Stitching Procedure.

Figure 2.5: Test Article 3 Outer Layer Flange Bolting Procedure.

Figure 2.6: Test Article 3 Outer Layer Lacing Procedure.

- Note that Pieces 1 and 2 are scored and folded so that outer and side surface of cable tray section are protected by a single panel.
- Pieces 3 and 4 each protect the outer surface and sides of the upper and lower elbow sections respectively.
- Piece 7 protects the inner radius of both the upper and lower radius sections.

Figure 2.7: General Pattern Pieces for Test Article 3 Inner Layer.

Step 1:
Raw Panels are cut and scored
to allow formation of outer
radius and side rail protection:

..... Score and Fold Line. Do Not
Cut Through Stress Skin
—— Full Material Cut-Through Line

Step 2:
The Polygon-Shaped Side Flaps
Are Folded Over at the Score
Lines to Form Side Protection.
These Side Flaps are Then
Mutually Secured with Wire Ties.
Flap Joints are also Filled With
Trowel Grade 330-1 Material.

Step 3:
Outer radius pieces are
installed onto the Cable
Tray Elbow Sections.

Step 4:
The Outer Radius Pieces Are Secured
to the Single Inner Radius Panel
Using Pre-Buttering of the Joint and
Wire Ties at 3" Intervals. The Two
Outer Radius Pieces are also Tied
Together Using Wire Ties at all
Joints.

Figure 2.8: Formation of Test Article 3 Inner Layer Elbow Pieces.

Note Formation of Bolting
Flange From Side Panel Sections
By Scoring and Folding

- A total of 12 Pieces are Used to Form the Outer Layer of the Barrier System.
- Note that Each surface of Each Section of the Cable Tray Assembly is Protected by a Single Panel.
- Panel Joints of the Outer Layer are Offset From Those of the Inner Layer by a Minimum of 3".

Figure 2.9: General Piece Pattern for Test Article 3 Outer Layer.

(a): Forming the Inner Layer Outer Radius and Elbow Panel Section.

(b): Inner Layer Panels Attached to Elbow Section.

Figure 2.10: Barrier Installation Process for Test Article 3.

(c): Initial Lacing of Inner Radius and Side Panel Sections.

(d): Inner Layer Elbow Section Complete and Filled.

Figure 2.10: Barrier Installation Process for Test Article 3.

(e): Initial Lacing of Upper Leg Inner Layer Panels.

(f): Pre-Buttering of Upper Leg Inner Layer Panels.

Figure 2.10: Barrier Installation Process for Test Article 3..

(h): Dry Fitting the Lower Leg Bottom/Side Panel.
Figure 2.10: Barrier Installation Process for Test Article 3.

(g): Tightening the Upper Leg Inner Layer Lacing.

(i): Lacing the Lower Leg Top to the Side and Inner Radius Panels.

(j): Preparing the Nose Support Outer Layer Lacing.

Figure 2.10: Barrier Installation Process for Test Article 3.

(k): Attaching the Outer Layer Elbow Side Panels, Note Flange Formation.

(l): Detail at Side Panel to Nose Support Junction.

Figure 2.10: Barrier Installation Process for Test Article 3.

(m): Fitting Cut Strips to the Bolting Flange Inside Corner.

(n): Remaining Side Panels Installed, Inside Flange Corners Filled.
Figure 2.10: Barrier Installation Process for Test Article 3.

(o): Pre-Filling the Outer Layer Inner Radius Score/Fold Lines.

(p): Inner Radius Panel Installed, Note use of Bolts at Flange Matings.

Figure 2.10: Barrier Installation Process for Test Article 3.

(q): Fitting the Upper Leg Outer Layer Bottom Panel, Note Flange Pre-Buttering.

(r): Detail of Outer Layer Flange Lacing Procedure.
Figure 2.10: Barrier Installation Process for Test Article 3.

(s): Outer Layer Base Installation Complete, Final Overcoat Not Yet Applied.

(t): Final Overcoat Detail, Note Exposed Flange Corners Filled.

Figure 2.10: Barrier Installation Process for Test Article 3.

(a): Initial Assembly of Inner Layer Pieces.

(b): Inner Layer Complete.

Figure 2.11: Fire Barrier Installation Process for Test Article 4.

(c): Right Side of Test Article, Barrier Complete.

(d): Left Side of Test Article, Barrier Complete.

Figure 2.11: Fire Barrier Installation Process for Test Article 4.

3.0 SUMMARY OF TEST RESULTS

3.1 Fire Endurance Test Articles

3.1.1 Basis for Performance Evaluation

The fire exposure time-temperature profile used in testing is based on the ASTM E119 general fire barrier standard time-temperature exposure [5]. However, the primary performance evaluation criteria used by the manufacturer are based on American Nuclear Insurers (ANI) Bulletin #5(79) [8]. This bulletin states that the test shall be "declared a failure" if any of the instrumented cable circuits "fail or fault" during the fire exposure or post-exposure hose stream test. This criteria was also used here as the primary basis for consideration of fire barrier performance. Note that in the current evaluation, circuit failure was assumed only when dead-shortening on a particular test cable was noted. That is, no consideration was given to lesser levels of degradation observed prior to dead-shortening.

In addition to consideration of the ANI criteria, this report has included consideration of the average and single point peak temperature measurements made during the fire tests. These measurements are evaluated in comparison to the general fire barrier performance evaluation criteria established in the ASTM E119 standard which requires that the average temperature on the unexposed surface of the fire barrier system not increase above the initial temperature by more than 250°F, and that no single point temperature measurement increase above the initial temperature by more than 325°F. The comparison of actual temperature response to these ASTM temperature rise limits is common practice in fire endurance tests of this type. However, in the case of cable tray fire barrier systems it has also been more common that temperature comparisons are based on measurements of the cable and cable tray response temperatures rather than the fire barrier unexposed surface temperature. The original manufacturers test reports did include the maximum average and maximum single point temperatures measured on both the cables and cable tray, although the specific ASTM temperature rise criteria are never considered explicitly.

In the SNL tests, the evaluation of internal fire barrier temperature response has been performed based only on the cable and cable tray side rail thermocouples. This approach is essentially consistent with the temperature reporting of the original test reports in that the manufacturer's temperature measurements were based only on cable temperature measurements. In evaluating the internal temperature rise behavior of the SNL test articles for comparison to the ASTM temperature rise limits, the supplemental internal barrier surface thermocouples and internal envelope air temperature thermocouples installed on the Sandia test articles have been eliminated from the analysis. That is, internal temperature response analysis is based on only those thermocouples located on the cable tray side rails and on the cables themselves. In the case of the average temperature response, all of the cable and cable tray side rail measurements are averaged as a single group.

3.1.2 Test Article 1

Test Article 1 was tested on December 8, 1993. The prevailing ambient temperature at the initiation of the test was 19°C (66°F). The test furnace temperature profile during the test was well within the allowable ASTM E119 limits. Appendix B provides a detailed examination of the test data, a description of observations made during and after testing, and photographs of the test article before, during, and after exposure.

The primary failure criteria, as discussed above, was failure of any one of the circuit integrity tests. At 1:15:39 into the exposure the first cable circuit failure was noted, and by 1:30:39 all three of the normally open circuit integrity tests, circuits 2-4, had failed. This included the circuit-to-ground test and the two circuit-to-circuit tests. (As noted in Appendix A, the circuit 1 circuit-to-system circuit integrity test was configured such that it was not expected that failure would be detectable except under quite extraordinary and unlikely circumstances. While no failures on this circuit were detected, no conclusions can be drawn on the basis of this data.)

In addition, the ASTM general fire barrier temperature rise criteria have been considered. Based on the prevailing ambient conditions, the temperature rise limits corresponding to the ASTM E119 test standard for this test article were (1) a single point temperature measurement in excess of 200°C (391°F), or (2) an average temperature for all thermocouples inside the envelope of 158°C (316°F). (As discussed above, the supplemental thermocouples were excluded from this evaluation).

The first temperature excursion in excess of these limits observed for Test Article 1 occurred after 1 hour, 4 minutes and 39 seconds (1:04:39) and was associated with a single point temperature measurement exceeding the specified single point temperature rise limits. The measurement point was Channel 36, an upper leg, centrally located cable tray side rail thermocouple.

At 1:19:39 after ignition, the average temperature of all the cable and cable tray side rail measurement points was in excess of the average temperature rise limit. By the time the test exposure was terminated, all of the temperatures measured throughout the test article were in excess of the single point temperature rise limit.

The fire exposure was terminated 2:30:00 after ignition. At this point, the upper leg and upper elbow section of the cable tray were fully exposed and clearly visible from the furnace viewing ports. (Pieces of the barrier material were observed to fall away from the test article at various times during the exposure, eventually exposing the tray itself.) Appendix B provides photographs of the test article as it was removed from the test furnace. Note that the upper leg of the cable tray is fully exposed and literally "glowing red hot."

As noted previously, the fire barrier system was in a severely degraded condition upon removal from the furnace. Hence, the procedures established in the ASTM E119 test standard for conduct of the post-exposure hose stream test were not fully implemented.

In particular, the actual nozzle discharge pressure was less than that specified in the ASTM standard, and the hose stream was not maintained for the full required duration, but rather, was maintained only long enough to extinguish and cool the test article.

Upon exposure to the hose stream the remaining pieces of the fire barrier system were dislodged from the test article wherever the hose stream directly impacted the test article. The lower leg of the cable tray was protected from direct hose stream impact by the balance of the cable tray, and hence, post-test examination of this section was possible. The outer layer of the barrier system for this section had completely fallen away. A large pile of debris from the upper leg panels had accumulated on top of the lower leg top panels. Some limited virgin Thermo-Lag material was found in the following locations:

- adjacent to the back wall bulkhead penetrations,
- adjacent to the nose support structure (under the front base of the tray assembly) and on the horizontal section of the nose support itself,
- on the central regions of the inner layer pieces protecting the sides of the lower elbow section, and
- in the central region of the lower leg, inner layer, top panel.

The remainder of the Thermo-Lag material had been burned away during the fire exposure. Extensive areas of complete burn-through were noted on the lower leg panels examined after the test. In fact, the lower leg, inner layer, bottom surface panel was completely consumed with the exception of where it penetrated the back wall bulkhead and where it met the horizontal nose support structure. Appendix B provides photographs of the test article taken the following day and illustrates the condition of the cables which had been located in the cable tray. Note that virtually all of the cable insulation and jacketing materials were consumed by fire, and that only bare and embrittled copper conductors remained (only a limited amount of melted insulation remained adjacent to and outside of the furnace interface bulkhead penetrations).

3.1.3 Test Article 2

Test Article 2 was tested on December 7, 1993. The prevailing ambient temperature at the initiation of the test was 19°C (66°F). The test furnace temperature profile during the test was well within the allowable ASTM E119 limits. Appendix C provides a detailed examination of the test data, a description of observations made during and after testing, and photographs of the test article before, during, and after exposure.

The primary failure criteria, as discussed above, was failure of any one of the circuit integrity tests. At 0:58:32 into the exposure the first cable circuit failure was noted, and by 1:06:32 all three of the normally open circuit integrity tests, circuits 2-4, had failed. This included the circuit-to-ground test and the two circuit-to-circuit tests. (As noted in Appendix A, the circuit 1 circuit-to-system circuit integrity test was configured such that it had not been expected that failure would be detectable except

under quite extraordinary and unlikely circumstances. While no failures were detected on this circuit, no conclusions can be drawn based on this data.)

In addition, the ASTM general fire barrier temperature rise criteria were considered. Based on the prevailing ambient conditions, the temperature rise limits for this test article were (1) a single point temperature measurement in excess of 200°C (391°F), or (2) an average temperature for all thermocouples inside the envelope of 158°C (316°F). (As discussed above, the supplemental internal air and barrier inner surface thermocouples were excluded from this evaluation).

The first temperature excursion in excess of these limits observed for Test Article 2 occurred after 54 minutes 32 seconds (0:54:32) and was associated with a single point temperature measurement exceeding the specified single point temperature rise limit. At this time both Channels 19 and 29 had exceeded this limit. These two channels were cable measurements on the center and right cables near the upper leg bulkhead penetration.

At 1:02:32 after ignition, the average temperature of all the cable and cable tray side rail measurement points was in excess of the average temperature rise limit. By the time the fire exposure was terminated, only two temperature measurement points remained below the single point temperature rise limit. Each of these measurements was a cable tray side rail temperature in the lower leg adjacent to the lower furnace bulkhead penetration.

The fire exposure was terminated 2:00:00 after ignition. At this point, the upper leg and upper elbow section of the cable tray were clearly visible from the furnace viewing ports. (Pieces of the barrier material were observed to fall away from the test article at various times during the exposure, eventually exposing the tray itself.) Appendix C provides photographs of the test article as it was removed from the test furnace. Note that the upper leg of the cable tray is fully exposed and literally "glowing red hot."

The condition of Test Article 2 after testing was quite similar to that of Test Article 1 described above. Extensive regions of material burn through were noted. Appendix C provides photographs of the test article taken the following day and illustrates the condition of the cables which had been located in the cable tray. Note that virtually all of the cable insulation and jacketing materials were consumed by fire, and that only bare and embrittled copper conductors remained (only a limited amount of melted insulation remained in the areas adjacent to and outside of the furnace interface bulkhead penetrations).

3.1.4 Test Article 3

Test Article 3 was tested on December 6, 1993. The prevailing ambient temperature at the initiation of the test was 20°C (68°F). The test furnace temperature profile during the test was well within the allowable ASTM E119 limits. Appendix D provides a detailed examination of the test data, a description of observations made

during and after testing, and photographs of the test article before, during, and after exposure.

As noted above, the primary criteria for failure of the fire barrier system was failure of any one of the circuit integrity tests. At 1:58:52 into the exposure the first cable circuit failure was noted, and by 2:07:52 all three of the normally open circuit integrity tests, circuits 2-4, had failed. This included the circuit-to-ground test and the two circuit-to-circuit tests. (As noted in Appendix A, the circuit 1 circuit-to-system circuit integrity was configured such that it had not been expected that failure would be detectable except under quite extraordinary and unlikely circumstances. While no failures were detected on this circuit, no conclusions can be drawn based on this data.)

In addition, the ASTM general fire barrier temperature rise criteria were considered. Based on the prevailing ambient conditions, the temperature rise limits for this test article were (1) a single point temperature measurement in excess of 201°C (393°F), or (2) an average temperature for all thermocouples inside the envelope of 159°C (318°F). (As discussed above, the supplemental internal air and barrier inner surface thermocouples were excluded from this evaluation).

The first temperature excursion in excess of these limits for Test Article 3 occurred after 1 hour, 49 minutes and 52 seconds (1:49:52) and was associated with a single point temperature measurement exceeding the specified single point temperature rise limit. The measurement point was Channel 28, a cable temperature measurement on the right side of the upper leg near the upper furnace bulkhead penetration.

At 1:57:52 after ignition, the average temperature of all the cable and cable tray side rail measurement points was in excess of the average temperature rise limit. By the time the fire exposure was terminated, only two temperature measurement points remained below the single point temperature rise limit. Each of these measurements was a cable tray side rail temperature in the lower leg adjacent to the lower furnace bulkhead penetration.

The fire exposure was terminated after the full three-hour exposure. At this point, the upper leg and upper elbow section of the cable tray were clearly visible from the furnace viewing ports through the fully burned through inner layer panels and stress skin (although the stress skin remained in place). Appendix D provides photographs of the test article as it was removed from the furnace. Note that the upper leg of the cable tray is fully exposed and is literally "glowing red hot."

Because of the severely degraded condition of the test article upon removal from the test furnace, the full post-exposure hose stream test was not applied to this test article. Rather, a light mist hose application was initially applied in an attempt to extinguish and cool the test article so as to allow for a detailed inspection of the condition of the test article. However, upon removal of the mist application, the test article repeatedly "reflashed" reigniting the fire. Hence, this approach was abandoned, and the full hose stream finally applied. However, even this final hose stream application was not performed in full compliance with the standard hose stream exposure specifications.

In particular, the hose stream application was both lower in nozzle pressure and shorter in duration than specified in the standard.

In the case of Test Article 3, post-mortem examination revealed extensive regions of full material burn-through. In fact, only limited sections of virgin material remained. Most of the inner layer stress skin remained in its original locations on the test article, including the wire stitching. However, in general, this stress skin was devoid of any remaining unburned material, consisting of only the bare stress skin itself. The only exceptions were virgin material found (1) on the side panels protecting the lower elbow section, (2) on the top panel protecting the lower leg section, (3) at each of the two furnace bulkhead penetrations, and (4) adjacent to and around the horizontal cable tray nose support structure. Appendix D provides photographs of the test article taken the following day during a detailed post-mortem examination of the test article. Note that virtually all of the cable insulation and jacketing materials were consumed by fire (only limited amounts of melted but un-burned insulation remained in areas adjacent to and outside of the furnace interface bulkhead penetrations).

3.2 Ampacity Derating Test Article 4

Appendix E provides a detailed examination of the test results for both the base line (unprotected tray) and protected tray ampacity tests which comprise the SNL Test Article 4 ampacity derating test set. The base line test was performed on October 14-15, 1993 and the protected tray test was performed on December 9-10, 1993. In each case, the tests were performed in the same test facility, a "High Ambient" environmental test chamber located in the UL primary electrical testing laboratory. The final ampacity derating factors indicated by the SNL test set were 46.4%, 36.0%, and 35.3% for the 8AWG, 4AWG, and 2/0 cables respectively.

In considering the comparison between the SNL and TSI test results one must recognize that in the original TSI report mistakes were made in the calculation of the ampacity adjustment factors used to correct actual base line and protected cable ampacities. That is, the standard test protocol calls for the test article to be housed in an environment at 40°C. The current flowing through the cable loop(s) is then adjusted such that the cable conductor temperature(s) is(are) brought to a stable temperature of 90°C. In practice, the environment and cable temperatures cannot be maintained at the exact desired temperature, and so, a correction procedure is provided by which the ampacity values can be adjusted to account for minor differences between the ideal and the actual experimental environment and cable temperatures. The TSI analysis of the original experimental data involved two series of errors in the calculation and application of these ampacity adjustment factors as follows:

- The first series of errors was made in the application of an ICEA P-46-426 equation which is designed to compensate for variations in the tested versus standard ambient and conductor temperatures. The TSI analysis inverted the roles of the actual and desired cable and ambient temperatures. This appears to be a systematic error common to a number of the original TSI test reports. The net result of this error was to severely under-estimate the ampacity derating

factors. (The existence of this error has been noted previously. See, for example, reference 6.)

- A second series of mistakes was identified in the TSI calculations having to do with the application of the cable conductor temperature data. In particular, in its analysis TSI used only the hottest single conductor temperature as the basis for the calculation of ampacity adjustment factors for all three cables sizes when in fact, two of the three cables were well below the desired experimental temperature of 90°C. In the TSI analysis, this variation between cable sizes is ignored. The net effect of this error was a further under-estimation of the ampacity derating factors for both the 8AWG and 2/0 cables.

Appendix E, Section E.4 provides a detailed examination of these errors and provides a two-step re-examination of the original tests data. Table 3.1 provides a comparison between the SNL test data and the original manufacturers test data including the results of this re-examination. In addition to the SNL test results, values of ampacity derating are presented for the TSI test data based on three levels of error correction as follows:

- TSI (1): Data taken from TSI original report data analysis tables without correction.
- TSI (2): Values based on correction of the amperage adjustment factor calculation but still using the single highest cable temperature as the basis for correction of all cable amperages as in the original report.
- TSI (3): Values of the ampacity adjustment factor were based on use of each of the individual cable conductor temperatures to correct the experimental ampacity of each individual cable.
- SNL: This is the data for SNL Test Article 4. In each case, individual conductor temperatures were used to adjust individual conductor ampacities prior to calculation of the Ampacity Derating Factor.

As can be seen from this table, the original manufacturer's analysis severely underestimated the ampacity correction factors. The initial correction of the TSI analysis, as represented by TSI(2) raised the derating factors by a factor of approximately 2. The final values, as represented by TSI(3), further increase the derating factor for both the 8AWG and 2/0 cables. The 4AWG cable is unaffected by this final correction because in both the TSI base line and protected tray tests the 4AWG cable happened to be the hottest of the three cables. Hence, in each case, the 4AWG cable temperature was used by TSI as the basis for the ampacity corrections. In general, the SNL test results most closely correspond to the fully corrected TSI(3) values.

In the case of the 8AWG cable, a significantly larger ampacity derating factor was found than for the other cable sizes. This was an unexpected result. It was initially

Table 3.1: Ampacity Derating Factors				
Cable Size	Data Source*	Corrected Base Line Ampacity	Corrected Protected Ampacity	Ampacity Derating Factor (%)
8 AWG	TSI (1)	17.46	14.64	16.15
	TSI (2)	20.38	13.89	31.84
	TSI (3)	23.96	14.83	38.10
	SNL	23.7	12.7	46.4
4 AWG	TSI (1)	35.77	29.74	16.86
	TSI (2)	41.75	28.21	32.43
	TSI (3)	41.75	28.21	32.43
	SNL	37.8	24.2	36.0
2/0	TSI (1)	105.91	87.18	17.68
	TSI (2)	123.6	82.69	33.10
	TSI (3)	131.6	84.82	35.55
	SNL	113.6	73.5	35.3
* See text for explanation of data sources				

suspected that this might have been an indication that the 8AWG cable had not come into full equilibrium prior to the termination of the protected tray test. However, the results were confirmed through an examination of the data from the final hour of the over-night settling period. This analysis is presented in detail in Appendix E. The results obtained from this alternate data set, which were obtained after a settling period of approximately 15 hours, confirmed the results presented above. Hence, this result is not considered anomalous. Rather, it is suspected that this difference results from the "U"-shaped cable tray configuration and from the complex cable loading.

It must be emphasized that the configuration used in the original manufacturer's tests, and hence by SNL, is quite poor from an experimental control standpoint. In this configuration, the experimenter must simultaneously control the temperature response of three separate cable circuits. However, the temperature of each cable is dependent on that of the other cables. Achieving a stable and representative final ampacity condition is unnecessarily complicated (a single cable circuit would achieve the desired end without these unnecessary complications). In the SNL tests, a relatively self consistent stability was achieved because the test protocol specifically sought to bring all three conductor hot spots to a similar temperature. This is clearly an improvement over the original manufacturer's protocol in which wide variations between cable hot spot temperatures were tolerated and then not accounted for in the

data analysis. However, achieving this level of consistent stability for this configuration, particularly for the protected tray, was a long and tedious process.

In the final analysis, the SNL ampacity derating factors are somewhat higher than fully the corrected manufacturer's results. However, given the inherent weaknesses of this test configuration, the difficulties encountered in achieving a uniform cable-to-cable final hot spot temperature condition for each test in the test set, and the differences in the test protocol utilized, the differences in derating factor are not considered significant. Far more significant are the oversights and errors made in the original manufacturer's data analysis; namely, the failure to account for the variation in cable hot spot temperatures and the error made in the application of the temperature-ampacity correction factor.

It should be noted that because of these experimental shortcomings, SNL does not consider the ampacity derating test results reported here to represent a reliable assessment of the ampacity derating factors which would be encountered in actual applications. It is recommended that ampacity derating assessments be based on alternative tests utilizing test articles which are geometrically more simplistic (e.g. simple straight runs of cable tray), and for which a less inter-dependent temperature control is possible (e.g. using a single cable power circuit).

4.0 CONCLUSIONS

4.1 Fire Endurance Tests

4.1.1 Procedures-Based Installations

The fire barrier systems for Test Articles 1 and 2 were installed in accordance with the TSI installation procedures as documented in TSI Technical Note 20684 Revision 5 [Reference 4]. Each test article was provided with a nominal three-hour fire barrier system comprised of two layers of nominal 1/2" thick preformed Thermo-Lag 330-1 panels. In each case during the fire endurance exposure, the fire barrier system failed well short of the three-hour rating period.

The primary criteria for assessing the performance of the fire barrier system was the performance of the circuit integrity tests. For Test Article 1, the first cable circuit failure was noted at 1:15:39 into the exposure, and by 1:30:39 all three of the normally open circuit integrity tests, circuits 2-4, had failed. This included the circuit-to-ground test and the two circuit-to-circuit tests. For Test Article 2, the first cable circuit failure was noted at 0:58:32 into the exposure, and by 1:05:32 all three of the normally open circuit integrity tests, circuits 2-4, had failed.

In addition, the current evaluation considered the performance of the test articles in comparison to the temperature rise limits established in the general ASTM E119 fire barrier qualification test. For Test Article 1, the first temperature excursion in excess of these limits occurred after 1 hour, 4 minutes and 39 seconds (1:04:39) and was associated with a single point temperature measurement exceeding the specified single point temperature rise limit. At 1:19:39 after ignition, the average temperature of all the cable and cable tray side rail measurement points was in excess of the average temperature rise limits.

For Test Article 2, the first temperature excursion in excess of these limits occurred after 54 minutes and 32 seconds (0:54:32) and was associated with a single point temperature measurement exceeding the specified single point temperature rise limit. At 1:02:32 after ignition, the average temperature of all the cable and cable tray side rail measurement points was in excess of the average temperature rise limit.

In each case, the fire endurance exposure was terminated prematurely because gross structural failure of the barrier system had been noted. The tests were terminated after 2½ hours and 2 hours for Test Articles 1 and 2 respectively. In each case, at the time of test termination the Thermo-lag panels protecting the upper leg section of the cable tray had fallen away, and the cable tray itself was fully exposed.

The mode of barrier failure was similar for the two test articles. In each case, a two-step process of degradation was noted. First, quite early into the exposure, within several minutes, the seams between panels in the outer layer were observed to open in the regions between the tie wires used to secure the panels to the test articles (recall that the installation procedures call for spacing of such tie wires at no greater than 12"

intervals.) This appeared to allow flames to penetrate the protective layer. Secondly, the tie wires themselves were observed to stretch upon heating allowing the protective panels to sag. Eventually, the tie wires weakened to the point that they could no longer support the Thermo-Lag panels. The tie wires then broke allowing the panels to fall away from the test article. Upon the demise of the outer layer, the process was repeated for the inner layer.

Post-mortem examination of each of the test articles revealed extensive regions of full material burn-through. That is, there were large sections of the inner layer panel stress skin which were found devoid of virgin unburned Thermo-Lag material. The insulation on the cables located in each of the cable trays were completely consumed by fire, and only bare copper conductors remained.

4.1.2 Full Reproduction Test Article

Test Article 3 was a full reproduction of one of the original manufacturer's qualification test articles. The fire barrier installation included certain installation "upgrades" not considered typical of current nuclear plant installations. These included (a) wire stitching of all inner layer seams and joints, (b) bolting and lacing of all outer layer seams and joints, and (c) addition of a final 1/10" thick layer of trowel grade material on the outside of the second layer panels. This test article was also observed to fail well short of the three-hour rating of the barrier system.

The primary criteria for assessing the performance of the fire barrier system was based on the performance of the circuit integrity tests. In the case of Test Article 3, the first cable circuit failure was noted at 1:58:52 into the exposure, and by 2:07:52 all three of the normally open circuit integrity tests, circuits 2-4, had failed. This included the circuit-to-ground test and the two circuit-to-circuit tests.

In addition, the current evaluation considered the performance of the fire barrier system in comparison to the temperature rise limits established in the ASTM E119 general fire barrier qualification standard. For Test Article 3, the first temperature excursion in excess of these limits occurred after 1 hour, 49 minutes and 52 seconds (1:49:52) and was associated with a single point temperature measurement exceeding the specified single point temperature rise limit. At 1:57:52 after ignition, the average temperature of all the cable and cable tray side rail measurement points was in excess of the average temperature limit.

In this case, the fire endurance exposure was maintained for the full three-hour time period. However, by the end of the exposure period, the outer layer Thermo-lag panels protecting the upper leg section of the cable tray had fallen away, and the inner layer panels had completely burned through. The cable tray itself was fully visible through the inner layer stress skin which remained attached to the test article.

The mode of failure for Test Article 3 was significantly different than that for Test Articles 1 and 2. In the case of Test Article 3, the bolting and stitching procedure appeared to prevent the opening of panel seams. However, as the test progressed, the

Thermo-Lag panels protecting the downward-facing sections of the cable tray were observed to soften and sag. Eventually, the stress skin itself tore and gave way in a line parallel to the material seams, presumably due to a loss of strength at high temperatures. This allowed the bulk of the outer layer panels to fall away from the test article, fully exposing the inner layer panels. It then appears that the inner layer panels simply burned through as post-mortem examination found that the inner layer stress skin was still in place on the test article, although only bare stress skin remained in most locations.

Post-mortem examination also revealed that the insulation and jacketing materials on the cables located in the cable tray were completely consumed by fire, and only bare copper conductors remained.

4.2 Ampacity Test Set

The final ampacity derating factors determined based on the SNL test set were 46.4%, 36.0%, and 35.3% for the 8AWG, 4AWG and 2/0 cables respectively. This is in comparison to the original TSI published values of 16.15%, 16.86%, and 17.68% respectively. However, the TSI published values were improperly calculated. When the original TSI data are fully corrected, the derived ampacity derating factors are 38.1%, 32.4%, and 35.6% respectively. (Note that the relatively high derating factor for the 8AWG cable in the SNL tests was confirmed by the analysis of two separate temperature/ampage data sets from the SNL protected tray test.)

In general, it must be noted that the TSI test protocol was quite poor. The greatest inherent difficulty derives from the complex nature of the test article which uses three different cable circuits in a single test specimen. Further complications are introduced because of the "U"-shaped cable tray. With three inputs (the power for each cable circuit) and three interrelated output parameters (the hot-spot temperature of each cable) it is quite difficult to achieve a good balanced condition of cable equilibrium.

Further difficulties arose in that the TSI test protocol led to wide variations in conductor temperature between the three cable sizes and then ignored this variation in its data analysis. The published TSI ampacity derating factors ranged from 16.15% to 17.68%. When the initial ampacity adjustment factor errors (which have been previously noted, see reference 6) were corrected the derating factors were found to range from 31.84% to 33.10%. When further corrections were made for the low individual cable conductor temperatures observed in the 8 AWG and 2/0 cables, the derating factors for these two cables rose to 38.10% and 35.55%, respectively, yielding a final ampacity derating factor range of 32.43% to 38.10%. In the final analysis, the SNL ampacity derating factors are somewhat higher than those indicated by the corrected TSI data.

Note that in the SNL tests the 8AWG cable ampacity derating factor was significantly higher than that of the other two cables. This result was confirmed, and is not considered anomalous. In fact, the fully corrected TSI values also show a significantly greater derating factor for the 8AWG cable than for the other two cables. Even these

fully corrected values are considered suspect because the SNL correction procedure does not fully account for the fact that the temperature of each of the individual cables is highly dependent on that of its neighbors. Clearly, to ignore these temperature variations is inconsistent with the intent of the standard and distorts the results significantly, but even the SNL applied corrections do not fully compensate for this oversight.

In general it has been assumed that ampacity derating factors would not be significantly affected by factors such as cable size. These results are in apparent contradiction to this assumption. No definitive explanation for why the 8AWG derating factor is significantly higher than that for the two larger cables has been identified. However, it is suspected that the configuration of the cable tray test article and the complex arrangement of cables within the cable tray may have had a significant impact on the ampacity values. That is, the complex configuration used by TSI, and hence by SNL also, introduces quite complicated radiative exchange behaviors between the upper and lower legs of the tray which are inconsistent from cable to cable. It is suspected that this had a significant impact on the results.

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Appendix A:
Test Instrumentation Configuration and Calibration

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A.1 General Construction and Instrumentation of Test Articles

A.1.1 Test Article 1

A.1.1.1 Base Construction

Test Article 1 was comprised of a "U"-shaped cable tray assembly mounted into an external support frame. The cable tray assembly itself was formed from 4 sections of 6"x6" solid bottom steel tray. In particular, a horizontal "U"-shaped assembly was formed using two straight 48" long sections connected to each other using one up-turning and one down-turning elbow section. Note that on an up-turning elbow section the bottom of the tray is along the outside radius of the elbow whereas on a down-turning elbow the bottom of the tray is along the inside radius of the elbow. These four individual sections were connected to form the overall cable tray assembly using steel bolting plates, bolts, nuts, and lock washers (as is typical practice in the assembly of cable tray sections).

Each of these cable tray sections was specially constructed for use in this program to specifications based on the original manufacturers test article. Each section was formed from 10ga galvanized steel with rungs welded to the bottom of the tray at 6" intervals. Note that the original manufacturers test article on which the SNL test article was based was constructed using slightly thinner 11ga steel cable trays of the same dimensions. SNL's use of slightly thicker material implies that the overall mass of the cable tray was somewhat greater in the SNL test than in the original manufacturer's test. The increased mass in the SNL test would moderate the internal protected envelope temperature response due to the increased thermal mass. That is, temperatures using a 10ga steel tray, as in the SNL test, would tend to be lower than those obtained using a thinner 11ga steel given that all other factors remained fixed.

The external support structure was formed using, primarily, 2"x2" structural steel square stock welded into the desired configuration. This external support frame included a furnace interface bulkhead structure which formed a vertical wall at one end of the support frame. This bulkhead structure was constructed of 2"x2" steel framing members and was covered with 1/16" sheet steel. In addition, steel studs were welded to the exposure side of the bulkhead plating to allow for the attachment of thermal insulation during the fire exposure test. This bulkhead structure represents the boundary between the fire exposure side of the test article and the unexposed side of the test article. The structure was designed to allow for the introduction of the test article into a side-entry furnace for testing, consistent with the original manufacturer's test configuration.

The "U"-shaped cable tray assembly was mounted into the external support frame such that the two open ends of the cable tray projected through this bulkhead. Consistent with the orientation of the original manufacturers test article, the cable tray assembly was mounted at a slight angle (about 15°) so that the "nose" of the assembly (that is, the bottom of the "U") was slightly lower than the "tails" of the assembly (that is, the legs of the "U"). The cable tray assembly was secured to the test article by welding

each side of the cable tray to steel support structures at three locations. The tail ends of both the upper and lower leg sections of the assembly were welded to horizontal support structures on the unexposed side of the furnace interface bulkhead. The "elbow section" of the cable tray assembly was welded to a "horizontal nose support" structure near the interface between the lower straight leg section and the up-turning elbow section.

Figure A.1 and A.2 provide general schematic representations of the Test Article 1 cable tray assembly and the full test article.

Note that in all cases, the left and right sides of the test article are defined as looking at the test article from the unexposed side of the furnace bulkhead interface section. That is, left and right are defined as if one were looking at the unexposed portion of the test article from outside the test furnace during testing. This convention is used uniformly throughout this report.

A.1.1.2 Cable Loading Arrangements

The loading of cables within Test Article 1 was comprised of a single layer of cables consistent with the loading used in the original manufacturer's test. Table A.1 identifies the specific cable products used. Figure A.3 illustrates the placement of cables within Test Article 1 using the item numbers provided in Table A.1. Note that based on the actual diameter of each of the individual cables, and an assumed total available cable tray cross-section of 36 square inches (6"x6") this loading represents a 4% fill of the cable tray. Figure A.4 identifies those individual cables which were monitored for both temperature and circuit integrity.

A.1.1.3 Circuit Integrity Test Configurations

Figure A.5 provides a schematic representation of the configuration of each of the four cable performance test circuits. Table A.2 identifies the specific configuration of each of the circuit integrity tests for Test Article 1. That is, each of the individual instrumented cables is identified, and the configuration of each circuit is described. This includes a description of the anticipated circuit failure indications. Note that the location of the instrumented cables within the cable tray is described in Figure A.4 as discussed above.

A.1.1.4 Placement of Thermocouples

The thermocouple instrumentation installed on Test Article 1 was comprised of:

- 10 thermocouples installed at 12" intervals on each of three specific cables,
- 8 thermocouples installed at 18" intervals on each of the two cable tray side rails,

Table A.1: Cable Types and Number Used in Test Article 1				
Item No. ¹	Cable Description ²	Cable Function ³	Number of Lengths	Outer Diameter (inches)
1	2/C, 10 AWG, PE/PVC	C	2	(.45" x.27") ⁴
2	8 Twisted Pairs (16/C), 18 AWG, PVC/PVC	C	1	0.475"
3	3/C, 14 AWG, EPR/Neoprene	C,I	1	0.535"
4	13/C, 20 AWG, PVC/PVC	C,I	1	0.39"
7	1 Twisted Triplet (3/C), 16 AWG w/Shield, EPR/Neoprene	I	1	0.39"
8	11/C, 20 AWG, PVC/PVC	I	1	0.34"
9A	1 Twisted Triplet (3/C), 14 AWG w/Shield, PVC/PVC	C,I	1	0.375"
10	9/C, 16 AWG, PVC/PVC	C,I	1	0.54"
11	1 pair (2/C), 16 AWG, PE/PVC	I	1	0.36"
<p>1 The item numbers are consistent with those of the original manufacturer's test report.</p> <p>2 All cables were 600V; Insulation/Jacket materials: PVC=Polyvinyl Chloride, PE=Polyethylene, EPR= Ethylene-Propylene Rubber.</p> <p>3 The functions are: C=Control, P=Power, I=Instrumentation</p> <p>4 This cable was flat rather than rounded as in the case of the other cables</p>				

- 5 thermocouples installed for the measurement of the internal envelope air temperature, and
- 3 thermocouples installed for the measurement of the surface temperature on the unexposed side of the fire barrier system.

The type of thermocouples used, and the methods of installation associated with each type of installation are provided in Section A.4 below.

The cable thermocouples were installed onto the cables prior to their installation into the cable tray. That is, the thermocouples were secured directly to the instrumented cables themselves at the desired 12" intervals using the methods described in Section A.4.1 below. These instrumented cables were then installed into the cable tray assembly at the desired location. For convenience, the individual thermocouple

Table A.2: Circuit Integrity Cable Configuration For Test Article 1

Item No. ¹	Cable Type	Circuit Test	Wiring Configuration ²	Failure Criteria ³
7	3/C, 16 AWG	Circuit 1: Circuit to System	One end of two of the three conductors were connected to each side of a 28VDC source, and the other ends of these same two conductors were joined to form a single closed circuit.	Indicator lamp voltage drop decreases to zero
9A	3/C, 14 AWG	Circuit 2: Circuit to Ground	The three conductors were joined at both ends and connected to one side of a 28VDC source. The other side of the DC source was grounded to the test article	Indicator lamp voltage drop increases to source voltage
10	9/C, 16 AWG	Circuit 3: Circuit to Circuit	The conductors were separated into three groups of three conductors each. One group was capped at both ends and isolated from the circuit. One end of each of the other two groups was hooked up to each side of the 28VDC source, with the other ends capped. This formed an open circuit between two groups of three cables each.	Indicator lamp voltage drop increased to source voltage
1	2/C, 10 AWG	Circuit 4: Circuit to Circuit	One end of each conductor was wired to one side of a 28VDC source, and the other end was capped to form an open circuit between conductors.	Indicator lamp voltage drop increases to source voltage
<p>1 Item numbers are consistent with Table 2.1.</p> <p>2 Note that four separate 28VDC sources were used in testing.</p> <p>3 This criteria corresponds to catastrophic cable failure (dead shorting or fully open circuit), no consideration was given to lesser levels of cable damage.</p>				

locations are identified as 12", 24", 36", ... , 108", 120". These identifications correspond to the nominal distance of the thermocouple from the open end of the upper leg of the cable tray assembly. In reality each cable was installed so that the thermocouples were located in a symmetric array along the upper and lower legs of the cable tray assembly. That is, the reference location for placement of the thermocouples was the joint between the up-turning and down-turning elbows at the bottom of the "U" as illustrated in Figure A.6, and the center of each cable was located congruent to this joint. Hence, the 60" location is actually located 6" above this joint, and the 72" location is 6" below this joint. All other locations are similarly located at progressive 12" intervals. Figure A.6 illustrates the location of the cable thermocouples along the length of the cable tray assembly for Test Article 1, and identifies the specific channel numbers for each measurement. Recall that Figure A.4 illustrates the location of the instrumented cables within the cable tray for Test Article 1.

In the case of the cable tray side rail thermocouples, a similar approach to placement and identification was taken as described immediately above for the cable thermocouples. That is, for convenience the side rail thermocouple are identified as 12", 30", 48", ... , 120", 138", and these identifiers correspond to the nominal distance of the thermocouple from the open end of the upper leg of the cable tray assembly. In reality this set of thermocouples was located in a symmetric array along the upper and lower legs of the cable tray assembly. That is, the reference location for placement of the thermocouples was the joint between the up-turning and down-turning elbows at the bottom of the "U" as illustrated in Figure A.7. Hence, the 66" location is actually located 9" above this joint. Also note that the distances from the reference point were measured along the outside radius of the cable tray assembly. The thermocouples were then located in the center of the side rail at the desired location. The methods of installation are described in Section A.4.3 below. Figure A.7 illustrates the placement of thermocouples on the side rails for Test Article 1 and identifies the specific channels associated with these measurements.

For the measurement of the internal protected envelope air temperature, thermocouples were located at 24" intervals along the cable tray. For convenience, the thermocouple locations are identified as 24", 48", 72", 96" and 120". However, as in the case of the cable and cable tray side rail thermocouples, the placement of air thermocouples was symmetric for the upper and lower legs of the cable tray. Hence, the 72" location actually corresponds to the junction between the up-turning and down-turning elbow sections at the bottom of the "U". The remaining locations are then relative to this reference location. Section A.4.5 provides a description of the installation methods used. Figure A.8 illustrates the location of the internal protected envelope air temperature measurements along the length of the cable tray.

Three thermocouples were installed on the unexposed surface of the fire barrier system. These thermocouples were placed (1) on the inner surface of the inner layer top panel protecting the upper leg of the cable tray, (2) on the inner surface of the inner layer panel protecting the outside radius of the elbow section, and (3) on the inner surface of the inner layer bottom panel protecting the lower leg of the cable tray.

The methods of installation used are described in Section A.4.4 below. The channel maps provided in Section A.5 identify the specific channels associated with each of these thermocouples.

A.1.2 Test Articles 2 and 3

A.1.2.1 Base Construction

The base construction and configuration of Test Articles 2 and 3 were identical. In general, Test Articles 2 and 3 were quite similar to Test Article 1 as described above. The construction of the cable tray assembly was similar, as was the external support structure and mounting arrangement. The principal difference in Test Articles 2 and 3 was that the cable tray was a 12" wide steel ladder back cable tray.

The cable tray used in the construction of Test Articles 2 and 3 was formed from a combination of off-the-shelf items and custom made items. In particular, each of the two cable tray assemblies was constructed using two elbow sections, one up-turning and one down-turning, obtained off-the-shelf, and using two 48" straight sections custom made for use in this program. In each case, these four cable tray sections were mutually secured to form the "U"-shaped cable tray assembly using steel bolting plates, bolts, nuts, and lock washers as is common practice in the assembly of cable trays.

The two elbow sections were constructed of 14ga galvanized steel. The two straight sections were constructed using 10ga galvanized steel for the side rails and ¾" galvanized conduit for the rungs. In comparison, the original manufacturer's test article upon which the SNL test articles are based was constructed using 11ga steel cable tray sections. Hence, the SNL test article used heavier straight sections and somewhat lighter elbow sections. In total, the SNL cable tray assembly was probably of quite similar overall mass as the original manufacturer's cable tray assembly, although the exact mass of the original manufacturer's test articles is unknown. Figure A.9 and A.10 provide general schematic representations of the Test Article 2 and 3 cable tray assemblies and the full test articles.

A.1.2.2 Cable Loading Arrangements

The loading of cables within Test Articles 2 and 3 were identical. This loading was comprised of, in general, a double layer of cables consistent with the loading used in the original manufacturer's test. Figure A.11 illustrates the placement of cables within Test Articles 2 and 3. Table A.3 identifies the specific cable products used. Note that based on the actual diameter of each of the individual cables, and an assumed total available cable tray cross-section of 48 square inches (4"x12") this loading represents a 15% fill of the cable tray. Figure A.12 identifies those individual cables which were monitored for temperature and circuit integrity.

Table A.3: Cable Types and Number Used in Test Articles 2 and 3				
Item No. ¹	Cable Description ²	Cable Function ³	Number of Lengths	Cable Diameter (inches)
1	1/C, 300 kCM, PVC	P	5	0.76"
2	7/C, 12 AWG, PVC/PVC	C	14	0.575"
3	2/C, 16 AWG, EPR/Hypalon	I	14	0.34"
<p>1 The item numbers are consistent with those of the original manufacturer's test report.</p> <p>2 All cables were 600V.</p> <p>3 The functions are: C=Control, P=Power, I=Instrumentation</p>				

A.1.2.3 Circuit Integrity Test Configurations

In the case of Test Articles 2 and 3, the configuration of the cable performance circuit integrity tests was identical. The configuration of each of the 4 circuits was quite similar to that of Test Article 1, and Figure A.5 provides schematic representations for each of these circuits. Table A.4 identifies the specific configuration of each of the circuit integrity tests for Test Articles 2 and 3. Note that for each test article the location of the instrumented cables within the cable tray is described in Figure A.12.

A.1.2.4 Placement of Thermocouples

The placement of thermocouples for each of the three fire endurance test articles (1-3), was essentially identical. The same number of thermocouples were used, and the distribution of thermocouples between the cables, cable tray side rails, the protected envelope air, and the inner surface of the fire barrier system was identical. Hence, the general discussions of thermocouple placement provided in Section A.1.1.4 above apply directly to Test Articles 2 and 3.

Figure A.13 illustrates the location of cable thermocouples along the length of the tray for Test Articles 2 and 3. The placement and numbering of side rail and internal protected envelope air temperature monitoring thermocouples for Test Articles 2 and 3 are identical to that of Test Article 1 as illustrated in Figures A.7 and A.8 respectively.

A.1.3 Test Article 4

A.1.3.1 Base Construction

Test Article 4 was comprised of a "U"-shaped cable tray assembly mounted horizontally into an external support frame. The overall construction of Test Article 4 was much simpler than that of Test Articles 1-3 in that the test article was not required

Table A.4: Circuit Integrity Cable Configuration For Test Articles 2 and 3

Item No. ¹	Cable Type ²	Circuit Test	Wiring Configuration ³	Failure Criteria ⁴
3	2/C, 16 AWG, center, bottom	Circuit 1: Circuit to System	One end of each of the two conductors were connected to each side of a 28VDC source, and the other ends were joined to form a single closed circuit.	Indicator lamp voltage drop decreases to zero
1	1/C, 300 kCM, right side	Circuit 2: Circuit to Ground	The conductor was connected to one side of a 28VDC source. The other side of the DC source was grounded to the test article	Indicator lamp voltage drop increases to source voltage
2	7/C, 12 AWG, left side, top	Circuit 3: Circuit to Circuit	The conductors were separated into three groups, two groups of three conductors each and one with just a single conductor. The single conductor was capped at both ends and isolated from the circuit. One end of each of the other two groups was hooked up to each side of the 28VDC source, with the other ends capped. This formed an open circuit between two groups of three conductors each.	Indicator lamp voltage drop increases to source voltage
3	2/C, 16 AWG, left side, bottom	Circuit 4: Circuit to Circuit	One end of each conductor was wired to one side of a 28VDC source, and the other end was capped to form an open circuit between conductors.	Indicator lamp voltage drop increases to source voltage

1 Item numbers are consistent with Table 2.2.

2 Cable locations are identified in Figure A.4.

3 Note that four separate 28VDC sources were used in testing.

4 These criteria are associated with catastrophic cable failure (dead shorting or fully open circuit), no consideration was given to lesser levels of cable degradation.

to interface with any other external structures. Hence, the external support frame was considerably simplified. The cable tray assembly used in Test Article 4 was identical to that used in Test Articles 2 and 3 described above (see section A.1.2.2 and Figures A.3 and A.9).

The external support frame for Test Article 4 was simply comprised of a framing structure made from 2"x2" steel square stock which included two horizontal support members. The cable tray assembly was mounted to this support structure by welding on each side of the tray to these two horizontal support structure. In addition, a "tail support" was welded into place on each side of the cable tray to support the upper leg at the open end of the "U"-shaped cable tray assembly. Figure A.14 provides a schematic representation of the overall test article.

A.1.3.2 Cable Loading Arrangement

The cable loading for Test Article 4 was comprised of three specific types of cables. Table A.5 provides a description of each of these three cables types. Figure A.15 illustrates the placement of these cables within the cable tray. Note that based on the actual diameter of the cables, and on an assumed total available cross-sectional cable tray area of 48 square inches (4"x12") this loading represents a 28% fill of the cable tray. In reality, the actual depth of cables was on the order of 1½-2".

Table A.5: Cable Types and Number Used in Test Article 4				
Item No. ¹	Cable Description	Cable Function ²	Number of Lengths ³	Cable Diameter (inches)
1	1/C, 2/0 AWG, 600V, PVC	P	20	0.52"
2	1/C, #4 AWG, 600V, PVC	P	58	0.33"
3	1/C, #8 AWG, 600V, PVC	P	99	0.23"
¹ The item numbers are consistent with those of the original manufacturer's test report. ² The functions are: C=Control, P=Power, I=Instrumentation ³ One length represents one pass through the cable tray.				

A.1.3.3 Placement of Thermocouples

In the case of Test Article 4, the ampacity derating test article, thermocouples were placed at 6 specific locations, or sections, of the cable tray. At each section, four individual cables were instrumented; namely, one 2/0 cable, one 4AWG cable and two 8AWG cables. (Note that the original manufacturer's test report contained a discrepancy with regards to placement of thermocouples in the test article. That is, the text of the report provided one description of the placement while the figures in the report presented a somewhat different placement. The Sandia test article reproduced

both interpretations, and hence, two of the 8AWG cable segments were actually instrumented.) Section A.4.2 provides a description of the thermocouple installation methods. Figure A.16 illustrates this placement of thermocouples.

In addition, thermocouples were installed on the cable tray side rails at the locations corresponding to both Sections 2 and 5 as indicated in Figure A.16. The methods used to install these thermocouples are described in Section A.4.3. Finally, 8 thermocouples were installed on the surfaces of the fire barrier system at the location corresponding to Section 2 as shown in Figure A.16. Four thermocouples were installed on the inner-most surface and four were installed on the outer-most surface of the fire barrier system. Thermocouples were installed on each of the two sides, the top, and the bottom of the cable tray barrier system. The methods of installation are described in Section A.4.4 below.

A.2 Overview of the Data Logging System

A.2.1 Primary Data Recording System

All four of the test articles were monitored during testing using a common primary data acquisition system. The primary acquisition system was comprised of a computer, hard and floppy disc drives, a printer, and a data logger. This equipment was supplied by SNL. All SNL data logging equipment is routinely calibrated through the SNL Calibration Recall System. This system provides calibration records in full compliance with DOE and DOD requirements, and utilizes calibration procedures traceable to NIST standards. Note that in this case, the only item in the primary data logging system requiring calibration is the data logger itself. The computer, disk drive units, and printer do not require calibration.

The data logger was a Hewlett-Packard Model 3497A computer controlled data acquisition system equipped with three 20-channel Type K thermocouple acquisition relay cards and one 20-channel DC voltage relay card. Each of these cards acts as a switching relay connecting a specific channel, on command, to the built-in data logger volt meter. In the case of the thermocouple cards, an electronic ice-point compensator is also included on each card. The computer was used to control the actions of the data logger, to store the measurements onto both a hard and floppy disc, and to echo the recorded data to a hard-copy printer after each scan.

A.2.2 Secondary Fire Endurance Data Systems

A.2.2.1 Circuit Integrity Monitoring Systems

The four 28VDC power supply systems were each comprised of a 28VDC/1amp power supply, a circuit status indicator lamp, a 0.5 ampere fuse, and the associated lead wires required to connect to the test article. In each case, one channel of the 3497 voltage card was connected so as to record the voltage across the circuit status lamp. In this manner, the status lamp acted as both a current limiting and load ballast resistor. That is, the voltage recorded across the lamp would be directly proportional to the current

flowing through each circuit. In addition, in the case of a closed circuit condition at the monitored cables, the lamps would simply experience the full 28VDC supply voltage and light up.

In the case of the circuit-to-system test, circuit 1, the cable circuit was normally closed meaning the indicator lamp would be normally lit. Failure of this test was nominally to be indicated by an open circuit condition indicated by the lamp for that circuit going out. However, the circuit configuration used by the manufacturer, and hence by SNL, was such the detection of failures on this circuit would require an extraordinary set of circumstances to occur. That is, this test is basically monitoring for breakage of the copper conductor which would, nominally, open the circuit. However, it must be recognized that actual breakage of the conductor would represent an extreme degree of damage as compared to shorting of the cable due to melting of the cable insulation. Thus, it is much more likely that the instrumented conductor would short to ground (the cable tray) well before breakage of the conductor would be observed. Thus, even if breakage were to eventually occur, it is almost a certainty that the conductor would have first shorted to ground. Hence, the ground itself would serve to complete the 28VDC circuit, and the lamp would remain lit with no measurable indication of failure. In order to detect failure, breakage of the copper conductor with the cable insulation was still intact would be required. This is unlikely to be observed in any fire test. Hence, no conclusions can be drawn on the basis of the data gathered from this particular circuit integrity test.

In the case of the circuit-to-circuit (conductor-to-conductor) and circuit-to-ground (conductor-to-ground) tests, the cable circuit would be normally open, and the indicator lamp normally dark. As damage to the cable occurred, the insulation resistance of the cable would degrade, and a current leakage path would be created. This would allow current to flow through the indicator lamp, and hence, cause an increase in the voltage drop across the lamp (the lamp acts like a simple resistor so that the basic equation $V=IR$ applies). Under dead-short conditions, the lamp would fully light, and the voltage drop across the lamp would rise to the full voltage of the power supply (28VDC). This system allowed for the nominal monitoring of the open circuit cable leakage currents, and hence, the cable insulation resistance. Because of the low voltage potential, the calculation of actual insulation resistance is not ideal, but none-the-less, the system does provide some measure of the progressive cable degradation in addition to the indication of dead-short conditions.

Prior to the initiation of testing, the actual power supply voltage and indicator lamp resistances for each circuit were measured using a calibrated multimeter. The multimeter used was a Hewlett-Packard Model 3478A, SNL Property Accounting ID #V803437, SNL Calibration File 2136A01669 2608, last calibrated 1/20/93, due for next calibration 4/20/94. The results are provided in Table A.6.

Table A.6: Circuit Integrity Circuit Parameters.				
Measurement	Circuit 1: Circuit-to-System	Circuit 2: Circuit-to-Circuit	Circuit 3: Circuit-to-Circuit	Circuit 4: Circuit-to-Ground
Supply Voltage (VDC)	28.52	28.48	28.94	28.14
Lamp Resistance* (Ohms)	71.5	69.2	70.1	68.8
* Resistance measurements were made using the four-wire ohm measurement mode.				

A.2.2.2 Furnace Monitoring and Control Systems

The furnace used in fire endurance testing was the UL "Column Furnace". This furnace normally provides flame exposure from all four sides, and is constructed so that two of the opposing sides can be opened for access to the furnace internals. For the purposes of the SNL tests, one of these two sides was left open, and a false wall was built in its place so that the furnace could accept the SNL side entry test specimens. (The manufacturers original tests had been performed in a side entry configuration and the SNL tests preserved this specimen orientation.) In this configuration, the SNL test articles were subjected to flame exposures on three sides. Figure A.17 provides photographs of the inside of the test furnace during construction of the wall, and of one of the SNL test articles inserted into the false wall in preparation for testing. This figure also illustrates the general configuration of the furnace burner jets and thermocouple installations. The furnace monitoring and control systems used in this test program are the standard set used by UL in the operation of the subject furnace. This system is comprised of:

- 6 ASTM Primary Furnace Thermocouples (for actual exposure monitoring)
- 4 ASTM Secondary Furnace Thermocouples (for furnace plenum status)
- 3 Magna-Helic Pressure Monitors
- 1 Strip Chart Recorder
- 2 Digital Clocks
- 1 Digital Temperature Meter/Switch
- 1 Auto Data Ten/30 Data Recorder

Each of these components is covered by the UL instrument calibration system and is subject to periodic routine calibration. The UL calibration system uses calibration standards traceable to NIST standards. The current calibration of all UL equipment was verified by SNL personnel prior to the initiation of testing. The primary data of importance to this program is the output of the 6 primary furnace thermocouples and their recording instruments. The other items are used to support the control of the furnace by the operators, but do not directly provide data relevant to the test analysis.

A.2.3 Secondary Ampacity Derating Data Systems

In the case of the ampacity test article secondary instrumentation was comprised of three low voltage power supplies and current measurement probes supplied by Underwriters Laboratories. Figure A.18 provides a schematic representation of the typical power supply circuit configurations. Typically, each system was comprised of a low voltage, variac controlled power supply, a current-to-voltage resistance shunt, and an external voltage meter. Current flow was monitored by measurement of the voltage drop across the current-to-voltage shunts.

In the case of the base line test, a slightly modified configuration was used for the 2/0 cable only. In this case, the power supply system was comprised of a low-voltage current source, an inductive current probe, and an analog amperage meter.

Equipment subject to calibration in this system was the three current-to-voltage shunts, the external volt meter, and the inductive current probe. Each of these items is covered by the UL instrument calibration system and is subject to periodic routine calibration. The UL calibration system uses calibration standards traceable to NIST standards. The current calibration of all UL equipment was verified by SNL personnel prior to the initiation of testing.

A.3 Specific Equipment Identification and Calibration

The specific equipment utilized in each of the primary and secondary data acquisition systems is identified in the following tables. Table A.7 identifies the SNL primary data logging system components. Table A.8 identifies the secondary furnace monitoring equipment utilized by UL. Table A.9 identifies the secondary ampacity derating power supply equipment utilized by UL. Information regarding the secondary cable circuit integrity test hardware used during the fire endurance exposures is presented above.

Table A.7: Identification and Calibration of Primary Data Acquisition System Hardware			
Component:	Manuf./Model:	Sandia I.D. #:	Calibration:
Computer	HP9216	N/A	N/A
Disc Drive	HP9153B	S605347	N/A
Printer	HP2225A	N/A	N/A
Data Logger	HP3497	V966026	File: 5394 Last: 6/17/93 Due: 3/17/94

A.4 Thermocouple Installation Methods

All of the thermocouples installed on each of the test articles were formed from unsheathed, teflon insulated, 24ga, normal accuracy, Thermocouple-Grade lead wires. Each thermocouple was formed by stripping back approximately 1/2" of the insulation from the ends of the individual lead conductors, forming the exposed conductors into a diamond shape, and spot-welding a junction at the exposed ends of the wires. The methods of installations used in each of the various applications are presented in the Sections which follow.

Teflon insulation was chosen to provide the highest possible level of moisture resistance. Thermo-Lag is a water based material, and hence, the release of moisture during the exposures was expected. Use of a porous insulation material, such as fiberglass, would render the thermocouples vulnerable to failure through partial shorting of the lead wires. Teflon is non-porous, and hence, is highly resistant to moisture intrusion.

It should be noted that the use of unshielded teflon insulation renders the temperature measurements unreliable above a peak temperature of 316°C (600°F) due to the anticipated thermal breakdown of the insulation (see Section 1.5 of the main text for a further discussion of this issue). The general accuracy of the thermocouples when operated in the range of 0-293°C (32-559°F) is certified by the manufacturer as $\pm 2.2^{\circ}\text{C}$ ($\pm 4^{\circ}\text{F}$) consistent with material and manufacturing control standards established by ASTM.

For each of the three fire endurance test articles (1-3), the installed thermocouple lead wires were routed along the cable tray and through the lower leg furnace bulk-head penetration. Each lead wire was then connected to a "plug-panel" mounted to stand-offs welded to the unexposed side of the furnace bulk-head. A layer of thermal insulation was used to protect these plug-panels during the fire exposures. Three, 20 pair, thermocouple extension trunk lines were then used to connect the thermocouples to the primary data logging system.

In the case of the ampacity test article (4) the thermocouple lead wires were routed along the individual instrumented cables and out along the upper leg of the tray. Again, the individual thermocouples were then wired into a plug panel mounted to the test article. The same extension trunks were used to provide connection to the primary data logging system.

A.4.1 Fire Endurance Cable Surface Thermocouples

For each of the cable surface thermocouples installed for the fire endurance test articles, a bare thermocouple bead was formed by arc welding the bared ends of the thermocouple lead wires. This bead was then placed in contact with the outer surface of the cable insulation at the desired location. A double wrap of overlapping fiberglass tape was used to secure the thermocouple in place. As progressive

thermocouples were installed, the thermocouple lead wires were periodically gathered together and secured to the cable itself using nylon cable ties.

A.4.2 Ampacity Derating Cable Conductor Thermocouples

For the measurement of cable temperatures for the ampacity derating test article, the thermocouple beads were placed below the cable insulation materials and in direct contact with the outer surface of the cable conductor. In each case, the insulation on the cable was slit so that the cable conductor could be exposed by "peeling back" a "V"-shaped flap of the insulation. The cut flap of insulation was then lifted, the thermocouple bead placed in direct contact with the conductor, and the flap pressed back into place over the junction. A double wrap of fiberglass tape was used to secure the flap and thermocouple in place.

Table A.8: Furnace Monitoring Hardware and Calibration			
Component:	Manuf./Model:	UL ID:	Calibration:
Pressure Monitors	Magna-Helic	3FB5MH; 18FB5MH; 48F65MH	last: 12/7/93 due: 12/7/94
Exposure Recording Thermocouples	UL/ASTM	80FB5DTM 150FB5DTM 213FB5DTM 221FB5DTM 222FB5DTM 233FB5DTM	last: 10/21/93 due: 10/21/94
Furnace Status Thermocouples	UL/ASTM	32FB5DTM; 33FB5DTM; 34FB5DTM; 35FB5DTM	last: 12/28/92 due: 12/28/93
Digital Clocks	(unknown)	13FB5CLK; 20FB5CLK	last: 12/1/92 due: 12/1/94
Data Logger	Auto Data Ten/30	23FBS0AS	last: 11/1/93 due: 11/1/94
Strip Chart	(unknown)	29FB5TR	last: 11/1/93 due: 5/1/94
Digital Temperature Switch	(unknown)	56F65DTM	last: 7/19/93 due: 7/19/94

A.4.3 Cable Tray Side Rail Thermocouples

In the case of the cable tray side rail thermocouples, each thermocouple bead was secured to the side rail using steel pop-rivets. After formation of the thermocouple bead, the lead wires immediately adjacent to the bead were spread to form a closed loop approximately $\frac{1}{8}$ " in diameter. A $\frac{1}{8}$ " hole through the cable tray side rail was then drilled. The thermocouple was secured to the side rail by installing a steel "pop rivet" through both the thermocouple end loop and the drilled hole. This installation method ensured a tight and secure bond between the thermocouple and the side rail while introducing a minimal disruption in the local thermal mass.

Table A.9: Current Source Hardware and Calibration				
Cable Size:	Component:	Manuf/ Model/Range	UL ID:	Calibration:
8AWG	Power Source	140V Variac	N/A	N/A
	Current Shunt	50A / 50mV	SH3124	Last: 7/1/93 Due: 7/1/94
	Multimeter	Fluke DVM	DMM8009	Last: 9/16/93 Due: 9/16/94
4AWG	Power Source	LVS 6.4V / 100A, (2 each)	N/A	N/A
	Current Shunt	100A / 50mV	SH3126	Last: 7/1/93 Due: 7/1/94
	Multimeter	same	same	same
2/0 (Base Line Test)	Power Source	L-V Transformer	N/A	N/A
	Inductive Current Probe	400 - 5 Ratio	CT 8004	Last: 9/30/93 Due: 9/30/94
	Amp Meter	5 Amp Range	AAM 5004	Last: 5/17/93 Due: 5/17/94
2/0 (Protected Tray Test)	Power Source	120 VAC Variac	84-0776	N/A
	Current Shunt	200A/50mV	SH5017	last: 5/10/93 due: 5/10/94
	Multimeter	same	same	same

A.4.4 Fire Barrier Surface Thermocouples

A number of thermocouples were installed for the measurement of the fire barrier panel surface temperatures. For each of the three fire endurance test articles, three such thermocouples were installed on the inner surface of the inner layer panels (i.e., the inner-most surface of the fire barrier system). For the ampacity test article, four thermocouples were installed on the inner surface of the inner layer panels and four thermocouples were installed on the outer surface of the outer layer panels.

In each case, the thermocouple lead wire was wire stapled to the surface of the fire barrier panel so that the thermocouple bead was in the desired position. In the case of those thermocouples located on the inside surface of the barrier system, this was done during the initial stages of the fire barrier installation process. For the outer surface thermocouples installed on the ampacity article the thermocouples were installed after completion of the fire barrier system. In each case, wire staples were installed over a total length of about 1-2" of the thermocouple lead wire, and to within 1/4" of the welded thermocouple bead. The bead itself and about one inch of the lead wire were then covered with a thin layer of the trowel grade material (approximately a 2" diameter, 1/10" thick coverage). This was done to ensure an intimate contact with the surface of the panels.

A.4.5 Internal Protected Envelope Air Thermocouples

For the internal air temperature measurements, each of the thermocouples was secured to a rung of the cable tray at the desired location. A 3-4 inch tab of the thermocouple lead wire including the bead at the end of the lead wire was bent so as to project between and above the level of the cables. In this manner, the thermocouple bead was located in the air gap between the cables and the inside surface of the fire barrier system top panels.

A.5 Specific Channel Maps

Table A.10 provides the mapping of specific data logger channels in the SNL data logging system to specific test article measurements for Test Articles 1-3. Table A.11 provides the same information for Test Article 4. (Note that as described above, the cable load currents were measured using independent hand-held probes and are not included in the SNL data logging system channel maps.)

Note that in these tables each measurement is identified by a slot and channel number. The channel number is the unique identifier which is associated with each measurement point as referenced throughout this report. The slot number is an indication of a particular data logger switching card. In particular, the SNL tests utilized 3 thermocouple channel switching cards (slots 0-2) and one analog DC voltage switching card (slot 3). Each of these individual cards can carry up to twenty channels of data.

Table A.10: Thermocouple and Circuit Integrity Data Acquisition Slot/Channel Map for Test Articles 1-3, the Fire Endurance Test Articles.

Slot	Channel	Description/Placement
0	0	Left Cable, TC1, 12"
	1	Left Cable, TC2, 24"
	2	Left Cable, TC3, 36"
	3	Left Cable, TC4, 48"
	4	Left Cable, TC5, 60"
	5	Left Cable, TC6, 72"
	6	Left Cable, TC7, 84"
	7	Left Cable, TC8, 96"
	8	Left Cable, TC9, 108"
	9	Left Cable, TC10, 120"
	10	Center Cable, TC1, 12"
	11	Center Cable, TC2, 24"
	12	Center Cable, TC3, 36"
	13	Center Cable, TC4, 48"
	14	Center Cable, TC5, 60"
	15	Center Cable, TC6, 72"
	16	Center Cable, TC7, 84"
	17	Center Cable, TC8, 96"
	18	Center Cable, TC9, 108"
	19	Center Cable, TC10, 120"

**Table A.10: Thermocouple and Circuit Integrity Data Acquisition
Slot/Channel Map for Test Articles 1-3, the Fire Endurance Test Articles
(Continued).**

Slot	Channel	Description/Placement
1	20	Right Cable, TC1, 12"
	21	Right Cable, TC2, 24"
	22	Right Cable, TC3, 36"
	23	Right Cable, TC4, 48"
	24	Right Cable, TC5, 60"
	25	Right Cable, TC6, 72"
	26	Right Cable, TC7, 84"
	27	Right Cable, TC8, 96"
	28	Right Cable, TC9, 108"
	29	Right Cable, TC10, 120"
	30	Left Side Rail, Outer Surface, TC1, 12"
	31	Left Side Rail, Outer Surface, TC2, 30"
	32	Left Side Rail, Outer Surface, TC3, 48"
	33	Left Side Rail, Outer Surface, TC4, 66"
	34	Left Side Rail, Outer Surface, TC5, 84"
	35	Left Side Rail, Outer Surface, TC6, 102"
	36	Left Side Rail, Outer Surface, TC7, 120"
	37	Left Side Rail, Outer Surface, TC8, 138"
	38	Right Side Rail, Outer Surface, TC1, 12"
	39	Right Side Rail, Outer Surface, TC2, 30"

**Table A.10: Thermocouple and Circuit Integrity Data Acquisition
Slot/Channel Map for Test Articles 1-3, the Fire Endurance Test Articles
(Continued).**

Slot	Channel	Description/Placement
2	40	Right Side Rail, Outer Surface, TC3, 48"
	41	Right Side Rail, Outer Surface, TC4, 66"
	42	Right Side Rail, Outer Surface, TC5, 84"
	43	Right Side Rail, Outer Surface, TC6, 102"
	44	Right Side Rail, Outer Surface, TC7, 120"
	45	Right Side Rail, Outer Surface, TC8, 138"
	46	Air Temp 1, 24", Inside Envelope
	47	Air Temp 2, 48", Inside Envelope
	48	Air Temp 3, 72", Inside Envelope
	49	Air Temp 4, 96", Inside Envelope
	50	Air Temp 5, 120", Inside Envelope
	51	T-Lag, Inner Surface, Center of Lower Leg Bottom Inside Layer Panel
	52	T-Lag, Inner Surface, Center of Outer Radius Inside Layer Panel
	53	T-Lag, Inner Surface, Center of Upper Leg Top Inside Layer Panel
	54	Unofficial Furnace Temp to Left of Test Article
	55	Unofficial Furnace Temp to Right of Test Article
3	56	Cable Integrity Circuit 1, conductor-to-system (data logger ch. 60)*
	57	Cable Integrity Circuit 2, conductor-to-conductor (data logger ch. 61)*
	58	Cable Integrity Circuit 3, conductor-to-conductor (data logger ch. 62)*
	59	Cable Integrity Circuit 4, conductor-to-ground (data logger ch. 63)*
<p>• The cable circuit integrity channels are referred to in all plots and analyses as channels 56-59 although in fact they were actually connected to data logger channels 60-63. This is simply a matter of convenience associated with the numbering of string characters in a computer variable array. This convention is observed throughout this report.</p>		

Table A.11: Thermocouple Slot/Channel Map for Test Article 4, the Ampacity Derating Test Article.

Slot	Channel	Description/Placement
0	0	Section 1, T1, 8AWG cable, side location
	1	Section 1, T2, 8AWG cable, central location
	2	Section 1, T3, 4AWG cable
	3	Section 1, Ts1, 2/0 cable
	4	Section 2, T4, 8AWG cable, side location
	5	Section 2, T5, 8AWG cable, central location
	6	Section 2, T6, 4AWG cable
	7	Section 2, Ts2, 2/0 cable
	8	Section 3, T7, 8AWG cable, side location
	9	Section 3, T8, 8AWG cable, central location
	10	Section 3, T9, 4AWG cable
	11	Section 3, Ts3, 2/0 cable
	12	Section 4, T10, 8AWG cable, side location
	13	Section 4, T11, 8AWG cable, central location
	14	Section 4, T12, 4AWG cable
	15	Section 4, Ts4, 2/0 cable
	16	Section 5, T13, 8AWG cable, side location
	17	Section 5, T14, 8AWG cable, central location
	18	Section 5, T15, 4AWG cable
	19	Section 5, Ts5, 2/0 cable

Table A.11: Thermocouple Slot/Channel Map for Test Article 4,
The Ampacity Derating Test Article (Continued).

Slot	Channel	Description/Placement
1	20	Section 6, T16, 8AWG cable, side location
	21	Section 6, T17, 8AWG cable, central location
	22	Section 6, T18, 4AWG cable
	23	Section 6, Ts6, 2/0 cable
	24	Section 2, Left Side Rail
	25	Section 2, Right Side Rail
	26	Section 5, Left Side Rail
	27	Section 5, Right Side Rail
	28	Section 2, T-Lag, Upper Panel, Inside Surface
	29	Section 2, T-Lag, Upper Panel, Outer Surface
	30	Section 2, T-Lag, Lower Panel, Inside Surface
	31	Section 2, T-Lag, Lower Panel, Outer Surface
	32	Section 2, T-Lag, Right Panel, Inside Surface
	33	Section 2, T-Lag, Right Panel, Outer Surface
	34	Section 2, T-Lag, Left Panel, Inside Surface
	35	Section 2, T-Lag, Left Panel, Outer Surface
	36	Ambient (in center of "U"-shaped test article between upper and lower legs)
	37	Ambient (above and to left side of test article)
	38	Ambient (above and to right side of test article)
	39	Unused

Tray Cross-Section

Exploded section view:

Figure A.1: Test Article 1 Cable Tray Assembly Details.

Figure A.2: Schematic Representation Test Article 1.

Location of Individual
Cables Within Test Article 1
(Cables Identified by Item
Number from Table)

Figure A.3: Placement of Cables in Test Article 1.

Location of Thermocouple Instrumented Cables

Location of Circuit Integrity Test Cables

Circuits

Circuit 1	Circuit to System 16AWG, 3 cond
Circuit 2	Circuit to Ground 14AWG, 3 cond
Circuit 3	Circuit to Circuit 16AWG, 9 cond
Circuit 4	Circuit to Circuit 10AWG, 2 cond

Note View as Seen from Open End
Of Cable Tray Assembly

Figure A.4: Identification of Test Article 1 Instrumented Cables.

Circuit 1: Circuit-to-System

Circuit 2: Circuit-to-Ground

Circuit 3: Circuit-to-Circuit

Circuit 4: Circuit-to-Circuit

Figure A.5: Configuration of Circuit Integrity Tests for Test Articles 1-3.

Location of Cable Thermocouples Along Length of Cable Tray

Section Views for Each Nominal Location Identifier with Thermocouple Channels

Figure A.6: Identification of Test Article 1 Cable Thermocouple Channels.

Location of Cable Tray Side Rail Thermocouples Along Length of Cable Tray

Section Views for Each Nominal Location Identifier with Thermocouple Channels

Figure A.7: Cable Tray Side Rail Thermocouple Channels for Test Articles 1-3.

Location of Protected Envelope Air Temperature Thermocouples Along Length of Cable Tray

Figure A.8: Location of Envelope Air Temperature Thermocouples
for Test Articles 1-3

Diagram of a beam with a rectangular cross-section. The total height is 5.25 inches, the total width is 12 inches, and the web thickness is 4 inches.

Nominal Mounting angle 15 deg.

15 deg.

48"

24"

Nominal location of Furnace Interface Bulkhead On External Support Frame

Down-Turning Elbow Section. Rung Along Inner Radius.

12"

Bolting Plates

Unexposed Side

Exposure Side

Horizontal Nose support

Up-Turning Elbow Section Rungs Along Outer Radius

55"

Nominal Total Exposure Length

A-33

Figure A.10: General Schematic of Test Articles 2 and 3.

Location of Individual
Cables Within Test
Articles 2 and 3.

Cable Sizes:

- - 16AWG, 2 cond.
- - 12AWG, 7 cond.
- - 300MCM, 1 cond.

Figure A.11: Placement of Cables For Test Articles 2 and 3.

Location of Thermocouple Instrumented Cables

Location of Circuit Integrity Test Cables

Circuits

Circuit 1	Circuit to System 16AWG, 2 cond
Circuit 2	Circuit to Ground 300MCM, 1 cond
Circuit 3	Circuit to Circuit 12AWG, 7 cond
Circuit 4	Circuit to Circuit 16AWG, 2 cond

Note View as Seen from Open End
Of Cable Tray Assembly

Figure A.12: Location of Instrumented Cables for Test Articles 2 and 3.

Location of Cable Thermocouples Along Length of Cable Tray

Section Views for Each Nominal Location Identifier with Thermocouple Channels

Figure A.13: Identification of Cable Thermocouple Channels
for Test Articles 2 and 3.

Figure A.14: General Schematic of Test Article 4.

Anpacity Test Article
Upper Leg Cable Arrangement

Anpacity Test Article
Lower Leg Cable Arrangement

Cable Sizes

8 AWG. 99 lengths
4 AWG. 58 lengths
2/0. 20 lengths

Note Section Views as Seen
From Open Ends of Cable
Tray Assembly

Figure A.15: Arrangement of Cables for Test Article 4.

Location of Cable Thermocouples Along Length of Cable Tray

Section Views for Each Nominal Section Identifier with Thermocouple Channels

Cable Sizes

Figure A.16: Identification of Cable Thermocouple Channels for Test Article 4.

(a): Furnace Interior During Construction of False Wall.

(b): Test Article in Furnace Ready for Testing, View From Unexposed Side.
Figure A.17: Photographs of Test Furnace.

- The power source is 110 or 240 VAC depending on power demand.
- The Variac provides a variable low AC voltage output to power the cables.
- The I/V Shunt provides a voltage drop proportional to current flow.
- The VAC meter measures the shunt voltage drop.

Figure A.18: Typical Configuration of Cable Current Monitoring Circuit.

Appendix B:
Test Article 1 Experimental Data and Analysis

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B.1 Basic Test Procedure

The furnace used for the fire exposure testing of Test Article 1 was an existing furnace at Underwriters Laboratories (UL) normally used for protected column exposures. This furnace was chosen because it was capable of receiving the side-entry test specimens being evaluated in this program. The furnace itself measures approximately 10'x10'x10', and provides fire exposure from all three sides not occupied by the test article itself. (Normally, the column furnace is operated with burners along the fourth side as well. However, for the purposes of this program, the fourth side of the furnace was removed, a false insulated partition was built in its place, and the test articles were inserted through an opening in this partition. Thus, one of the four walls was occupied by the test article rather than burners.)

In preparation for testing all of the open air passages between the fire exposure and the unexposed sides of the furnace interface bulkhead at the open ends of the "U"-shaped cable tray assembly were sealed using a flexible ceramic insulating blanket material. This included the spaces between the cables in the cable tray and the inner surface of the fire barrier system both above and below the cables themselves, the spaces between the cable tray side rails and the inner layer of the fire barrier envelope, and the space between the outer layer of the envelope and the edges of the cable tray bulkhead penetrations. The small gap between the two layers of Thermo-Lag forming the protective envelope at the open ends of the cable tray assembly (located on the unexposed side of the test article) was sealed using a silicone based fire barrier caulking compound.

The fire exposure side of the vertical wall section at the back of the test article was covered with a 2" thick layer of ceramic blanketing material. (Metal studs had been welded to this section during the assembly process for this purpose.) The two long angled support members extending from the back wall to the lower support members on each side of the test article were also protected by a 2" layer of the ceramic blanket material. A section of ceramic blanketing material was also used to shield the electrical and thermocouple plug boards mounted on the back of the test article.

Figure B.1 provides a photograph of Test Article 1 inside the furnace prior to the initiation of the exposure. The test article was placed through the partition wall and into the furnace. The back side of the furnace was kept open to allow access during this process. Once inserted into the furnace, the bottom members of the test article support structure were covered with a single layer of stiff ceramic fiber insulation panels, which were in turn covered with a thick layer of dry sand (approximately 2-3"). This protection fully covered all of the lower support structure members on the test article. The depth of sand was also sufficient to extend approximately 1" above the level where the Thermo-Lag panels protecting the angled riser pieces (which form a part of the nose support under the front of the cable tray assembly) began. The interface between the partition wall and the test article were also sealed using ceramic blanketing material.

Trunk lines were installed between the data logger system and the test article. These trunk lines were previously prepared and inspected for proper wiring. Each plug was identified for a given circuit or thermocouple channel. The proper installation of these trunk lines was verified by a second individual prior to testing. Operation of the data logging system was verified during a five minute pre-ignition data logging period.

Upon completion of the 5 minute pre-ignition data gathering, the test furnace was ignited. The test furnace temperature profile was both monitored and controlled by UL personnel using the standard set of UL equipment associated with the furnace. The nominal planned exposure duration was 3 hours. However, in the case of test Article 1, the fire exposure was terminated after 2½ hours. The fire exposure profile for the duration of the test was well within the allowable limits established for performance of ASTM E119 tests (see further discussion below).

B.2 Observations Made During Exposure

During testing, visual observations were made through viewing ports located in each wall of the furnace. The following summarizes the most significant observations made during the exposure:

Relative
Time

(hr:min): Observation:

0:00	Furnace ignition, ambient temperature approximately 19°C, Time 17:03:25
0:02	Charring of outer surface already beginning
0:05	Extensive blackening of outer surface right side, flames attached to panels
0:05	A section of stress skin ~6" long on the upper leg, lower panel delaminating from base material all the way across tray
0:18	Seam on upper leg, lower panel seam appears to be opening
0:30	Seam on upper leg, lower panel, left side definitely opening
0:31	Seam on upper leg, lower panel, left side opening in wide gap near bulkhead end; from unexposed side panel has not moved; the two tie wires nearest bulkhead on upper leg have broken; sagging in upper leg, lower panel has also opened butt-joint seam with upper end of inner radius panel
0:51	Inner elbow, outer layer, upper end of panel has fallen; upper left side of elbow outer layer also collapsing
0:53	Lower leg, outer layer, lower panel, left side seam has opening ~12"
0:55	Upper leg, inside layer, lower panel appears to have opened seam
0:59	Outer elbow, outer layer panel has fallen away from test article
1:01	Upper leg of cable tray is visible on left side
1:07	Upper leg, outer layer, right side panel has fallen away, large gap in inner layer seam visible
1:21	Upper leg, inner layer, right side panel has slipped and cable tray is fully exposed
1:22	Seam in outer elbow, inner layer opening just below elbow center

1:37	Only ragged remnants of barrier on upper leg remain; panels on elbow section inner layer still in place but large gaps visible; lower leg similar to elbow but with large pile of debris from upper leg pieces
1:57	Black smoke coming from around cables at upper bulkhead penetration
2:00	Remaining pieces of upper leg, inner layer, lower and side panels fallen away, tray fully exposed throughout upper leg
2:05	Lower leg, outer layer, bottom panel fallen away; inner layer fully open at lower seam
2:30	End Test

In summary, the test article suffered a catastrophic failure of the barrier system during the period from 67 to 81 minutes of the exposure. Figure B.2 provides a photograph of the upper leg, left side taken at 1:00. Note the large gap visible in the lower panel-side panel joint. Figure B.3 is a photograph of the same section taken at 1:13. Note that the upper leg, outer layer, lower panel has fallen, and the cable tray was visible through a gap in the inner layer. The protective barrier on the upper leg of the cable tray assembly literally fell apart, and the cable tray forming the upper leg of the "U" shaped cable tray section was fully exposed to the furnace fire at this time. The test was terminated prematurely, after 2½ hours, because catastrophic failure had been observed throughout the test article, and virtually all of the temperature measurements were exceeding the single-point temperature criteria for failure (200°C).

B.3 Post-Mortem Observations

Upon removal of the test article from the test furnace, extensive burning was observed in the remaining barrier material. Figure B.4 illustrates the condition of the test article as it was removed from the test furnace. The upper leg cable tray was fully exposed and was literally "glowing red hot." Only scattered pieces of the barrier material remained attached to the upper leg of the cable tray. This included the top panels on the upper leg and a large pile of debris on top of the lower leg which accumulated when the lower panels on the upper leg fell from the cable tray.

Figure B.5 shows the test article just prior to hose stream application. Upon application of the hose stream, any sections of material remaining on the test article which were directly impacted by the hose stream fell away immediately. Figure B.6 shows the test article during the hose stream application.

Post cooling examination of the test article was performed the next day. Figure B.7 shows the condition of the test article at this time. The insulation and jacketing material protecting the cables in the cable tray were fully burned away throughout the test article with the exception of the two bulkhead penetration areas. Even in the cables penetrating the bulkhead, and hence outside the furnace during the exposure were severely damaged. The remaining unburned insulation in these sections was charred and many of the cables were fused together into a single inseparable mass.

In the balance of the test article, all that remained of the tested cables was bare copper conductor. Upon initial examination, several of the smaller cable conductors were

found to have broken. Upon further examination it was found that all of the conductors were extremely brittle and broke easily when disturbed.

The lower leg of the test article was not subject to direct hose stream impact (due to the angle of application, the lower leg was shielded by the elbow section). A careful examination of this section was performed. The debris from the upper leg panels was removed from the top of the lower leg. The original stress skin from the lower leg, outer layer, upper panel was found resting in its original position. No virgin (unburned) Thermo-Lag material remained on this panel with the exception of that part of the panel which penetrated the furnace bulkhead. The remaining char from this panel was removed to expose the inner layer top panel. This panel was heavily charred. The Thermo-Lag material was fully burned through in a band extending along each edge of the panel to a width of about 2". The only remaining virgin material on this panel was in a 3-4" strip down the center of the panel.

The lower leg side rail panels and bottom panels were found to be fully burned through, although the stress skin remained in place on the test article. The only virgin material remaining on these panels was at the junction of the lower panel and the horizontal nose support, and at the bulkhead penetration.

The nose support structure was also examined in detail. Both the lower leg, inner layer, lower panel and the elbow section, inner layer, outer radius panel were found to still be firmly attached to the nose support protective panels with a band of virgin Thermo-Lag approximately 2" wide still evident. In addition, extensive virgin material remained on the inner layer protecting the horizontal support bar. Both layers of Thermo-Lag protecting the angled riser pieces which supported the horizontal support bar were fully burned through. A limited amount of virgin material was also noted in a strip along the center of the elbow section, inside layer, side pieces along the lower half of the elbow section.

B.4 Analysis of Critical Test Data

Figure B.8 provides a graphical representation of the actual and desired furnace temperature profiles. Note that the actual profile falls well within the ASTM E119 exposure profile acceptance criteria. (The ASTM acceptance criteria requires that for a test of three hours duration, the integrated actual time-temperature curve must be at least 95% of the integrated standard time-temperature curve.)

The primary failure criteria for the protective envelope was failure of any one of the four circuit integrity tests. Figure B.9 provides a graphical representation of the circuit integrity test data for Test Article 1. Note that this figure shows each of the three normally open circuits tests (the Circuit 2 circuit-to-ground test and the Circuits 3 and 4 circuit-to-circuit tests). In each case, so long as the cables remain fully functional, the measured open circuit voltage should stay fixed at zero. Failure would be indicated by an increase in the measured voltage, with catastrophic failure (dead-shortening) indicated by an increase in the measured voltage to the nominal supply voltage of 28VDC. All three of these circuits indicated total failure during the period

from 75-90 minutes after ignition. The first dead-short condition was noted on Circuit 3 at 75.65 minutes (1:15:39) after ignition. (Note that the power supplies were turned off at 100 minutes so that all circuit voltages returned to zero after that time.)

As discussed in Appendix A above, it was not expected that the configuration of the circuit-to-system circuit integrity test, Circuit 1, would allow for detection of the type of failure intended for this circuit test (breaking of the copper conductor itself). In practice, no failures were detected on this circuit. However, no conclusions can be drawn based on the performance of the circuit-to-system circuit test.

Consideration has also been given to the maximum single point and average temperature response within the protected envelope. In particular, the ASTM fire barrier testing standard establishes limits on the allowable temperature rise for both single point temperature measurements and for the average of all measurements made on the unexposed surface of the fire barrier. These temperature rise limits are a rise above the prevailing ambient temperature of 139°C (250°F) for the average of all thermocouple measurements, and a rise above ambient of 181°C (325°F) for any single measurement. At the time of the test, the prevailing ambient temperature was 19°C (66°F). Hence, the respective temperature limits for Test Article 1 were 158°C (316°F) average temperature or 200°C (391°F) single point measurement.

Note that for cable tray fire barrier systems this comparison of test data to the ASTM temperature rise limits is typically based on the consideration of only the cable and cable tray side rail temperature response data. In general, the actual surface temperature of the unexposed side of the fire barrier system is rarely measured in such tests. While the SNL test articles did include measurement of the fire barrier unexposed surface temperature, the following analysis of the protected envelope temperature rise is based on consideration of thermocouple channels 0-45 only. This includes the thermocouples mounted on both the cables and on the side rails of the cable tray, and specifically excludes the thermocouples mounted on the inside surface of the inner barrier panels, and those measuring the air temperature within the envelope.

Figure B.10 presents the average, maximum and minimum temperature response data for Test Article 1 in graphical format. Table B.1 provides this same information in tabulated format. These curves were generated through processing of the original data files using a simple BASIC language computer program (a copy of this program is available in the project files). This program examined the data for channels 0-45 and determined the maximum, minimum and average temperature response for each data logging time step. These values were then written to an ASCII data file. The values were then plotted using a commercially available soft-ware package.

The first temperature excursion in excess of the temperature rise limits described above was violation of the single point temperature rise limit at 64.65 minutes (1:04:39) after ignition. At this time the temperature recorded on Channel 36, a centrally located, upper leg, cable tray side rail thermocouple, was 210°C (410°F), a rise above ambient of 191°C (344°F). By the time the test was terminated, after 2½

hours (2:30:00), even the point showing the lowest temperature within the protected envelope had exceeded the single point temperature rise failure criteria.

The average temperature rise limit was exceeded at 79.65 minutes (1:19:39) after ignition. At this time the average temperature measured on the cables and tray side rails, channels 0-45, was approximately 162°C (323°F).

In general, the visual observations made during the exposure are quite consistent with the behaviors noted in the temperature data. That is, as noted above, barrier panel physical failures were first observed to occur in the upper leg of the test assembly, then in the elbow section, and finally in the lower leg section. It was also noted that, based on post-mortem inspections, Thermo-Lag panel debris which fell from the upper leg section onto the lower leg section appeared to provide an additional level of protection for the lower leg section. This is also reflected in the temperature data. Figure B.11 provides additional temperature response data for three locations along the length of the center instrumented cable. In particular, one channel in the lower leg (Ch. 11), one channel in the elbow section (Ch. 15), and one channel in the upper leg (Ch. 18) are plotted. These data illustrate the differences in cable temperature response observed for the various sections of the cable tray assembly. These data clearly corroborate the visual observations regarding the progressions of test failures through the test article.

Also of interest is the temperature response measured on the inner surface of the fire barrier system. Figure B.12 illustrates the response of the inner layer, outer radius panel on the elbow section (Ch. 52) as compared to the response of the center instrumented cable near the same location (Ch. 15). Note that during the early stages of the exposure the fire barrier inner surface temperature leads that of the cables by approximately 30°C. This behavior was consistent with the other cable tray sections as well.

B.5 Summary of Test Results

Test Article 1 failed the fire exposure test well short of the nominal 3 hour rating expected of the barrier system. At 1:15:39 after ignition the first dead-short circuit integrity failure was noted (a circuit-to-circuit failure). By 1:29:39 after ignition, dead-short circuit failures had been observed on circuits 2-4, including both of the circuit-to-circuit test samples and the circuit-to-ground test sample.

Consideration was also given to the temperature rise limits established in the ASTM fire barrier testing standards. The SNL analysis in this regards included consideration of only the thermocouples installed on the cables and on the side rails of the cable tray. The first temperature excursion in excess of these limits was a single point temperature rise which exceeded the corresponding temperature rise limit (a rise above ambient of 181°C (325°F)). The first such temperature excursion occurred at 1 hour, 4 minutes, 39 seconds (1:04:39) after ignition. At 1:19:39 after ignition, the average temperature within the envelope reached 162°C (323°F), a rise above ambient of 143°C (257°F). This exceeded the average internal envelope temperature rise limit of 158°C (316°F) corresponding to a rise

above ambient of 139°C (250°F). (The analysis of system temperature rise was based on the cable and cable tray side rail temperature measurements only.)

The mode of barrier failure observed involved two processes. First, after a very short period (several minutes) the seams between individual panels in the outer layer were observed to open in short lengths between the supporting tie wires. This, presumably, allowed the fire to come into direct contact with the inner layer panels. Secondly, as the fire progressed, the tie wires holding the outer layer panels to the test article were observed to stretch due to the heating. It is a well known fact that most metals will lose strength at elevated temperatures. Hence, the tie wires eventually heated to the point where they would no longer support the weight of the Thermo-Lag panels and broke. This allowed the supported panels to fall away from the test article. A similar deterioration process then followed affecting the inner layer panels. Once any one of the inner layer seams was observed to open, thermal failure followed shortly.

The fire exposure was terminated 2:30:00 after ignition. At this time, even the lowest temperature measured within the test article was in excess of the single point temperature rise failure criteria. The upper leg and upper elbow sections of the cable tray itself were clearly visible from the furnace viewing ports, the Thermo-Lag panels having suffered catastrophic failure and fallen away from the cable tray. Upon removal from the furnace these exposed sections of the cable tray were observed to be literally "glowing red hot."

Hose stream application after the fire exposure was employed primarily to cool the test article as most sections of the Thermo-Lag were observed to have already suffered catastrophic failure. Post-mortem examination of the lower leg of the test article was performed in detail as this section was protected from the hose stream impact by the other sections of the cable tray assembly. This inspection revealed extensive regions in which the Thermo-Lag material had fully burned through. In fact, only limited areas of virgin, unburned, material were found (1) adjacent to and on the horizontal nose support, (2) at both the upper and lower furnace bulkheads, (3) on the central region of the inner layer side panels protecting the lower half of the elbow section, and (4) on the central region of the lower leg, inner layer, upper panel.

The insulation on the cables within the cable tray were completely consumed by fire, and only blackened bare copper conductors remained. These bare conductors were found to be very brittle, and broke easily when disturbed.

Table B.1: Test Article 1 Average, Maximum and Minimum Internal Envelope Temperatures (Based on Channels 0-45 only).*

Time (Min)	Average (C)	Maximum (C)	Minimum (C)	Time (Min)	Average (C)	Maximum (C)	Minimum (C)
-8.35	18.6	19.3	18.0	24.65	20.7	22.5	18.9
-7.35	18.6	19.3	18.0	25.65	21.0	23.0	19.0
-6.35	18.6	19.3	18.0	26.65	21.3	23.6	19.2
-5.35	18.6	19.3	18.0	27.65	21.7	24.3	19.3
-4.35	18.6	19.3	18.1	28.65	22.1	24.9	19.5
-3.35	18.6	19.3	18.1	29.65	22.6	25.7	19.8
-2.35	18.6	19.3	18.1	30.65	23.1	26.4	20.0
-1.35	18.6	19.3	18.1	31.65	23.6	27.2	20.2
-0.35	18.6	19.3	18.1	32.65	24.1	28.1	20.5
0.65	18.6	19.3	18.1	33.65	24.7	29.0	20.9
1.65	18.6	19.3	18.1	34.65	25.3	29.9	21.2
2.65	18.6	19.3	18.1	35.65	26.0	30.9	21.5
3.65	18.6	19.4	18.1	36.65	26.7	32.0	21.9
4.65	18.7	19.4	18.1	37.65	27.4	33.2	22.3
5.65	18.7	19.4	18.1	38.65	28.1	34.5	22.8
6.65	18.7	19.4	18.1	39.65	28.9	35.9	23.2
7.65	18.7	19.4	18.1	40.65	29.8	37.4	23.7
8.65	18.7	19.4	18.2	41.65	30.6	38.9	24.2
9.65	18.7	19.4	18.2	42.65	31.6	40.5	24.7
10.65	18.7	19.4	18.2	43.65	32.5	42.2	25.3
11.65	18.7	19.4	18.2	44.65	33.5	43.9	25.8
12.65	18.8	19.5	18.2	45.65	34.6	45.7	26.4
13.65	18.8	19.5	18.2	46.65	35.6	47.4	27.0
14.65	18.9	19.6	18.2	47.65	36.7	49.3	27.7
15.65	19.0	19.7	18.2	48.65	37.8	51.1	28.4
16.65	19.1	19.8	18.3	49.65	39.0	52.9	29.0
17.65	19.2	19.9	18.3	50.65	40.2	54.8	29.7
18.65	19.3	20.1	18.4	51.65	41.0	56.5	30.5
19.65	19.5	20.4	18.4	52.65	41.2	58.1	30.9
20.65	19.6	20.7	18.5	53.65	41.9	59.7	31.7
21.65	19.9	21.1	18.5	54.65	42.9	61.7	32.4
22.65	20.1	21.5	18.6	55.65	43.9	65.5	33.2
23.65	20.4	22.0	18.7	56.65	45.1	71.4	33.3

Table B.1 Continued

Time (min)	Average (C)	Maximum (C)	Minimum (C)	Time (min)	Average (C)	Maximum (C)	Minimum (C)
57.65	46.4	79.9	34.7	91.65	246.2	674.2	56.9
58.65	47.8	89.9	35.6	92.65	251.6	686.3	57.4
59.65	49.4	104.6	36.4	93.65	259.4	702.5	58.4
60.65	51.5	127.9	37.3	94.65	266.6	717.5	59.2
61.65	53.8	152.7	38.1	95.65	273.2	731.6	59.8
62.65	56.2	176.0	38.8	96.65	281.5	762.9	60.3
63.65	58.5	193.7	39.4	97.65	287.4	748.0	61.0
64.65	60.9	210.5	30.0	98.65	291.3	747.2	61.6
65.65	63.2	221.1	40.6	99.65	296.5	746.5	62.3
66.65	65.6	229.4	41.2	100.65	305.9	758.9	63.0
67.65	67.9	235.9	41.8	101.65	315.3	771.2	63.8
68.65	70.1	239.4	42.5	102.65	328.1	782.0	64.7
69.65	72.6	244.9	43.1	103.65	332.7	793.1	65.6
70.65	75.5	252.0	43.8	104.65	337.3	802.1	66.4
71.65	79.0	258.7	44.4	105.65	340.1	807.8	67.3
72.65	83.3	263.5	45.0	106.65	343.2	811.2	68.2
73.65	90.1	267.9	45.7	107.65	346.3	822.8	69.1
74.65	106.9	457.8	46.3	108.65	348.4	822.0	70.1
75.65	119.9	542.0	46.9	109.65	350.9	808.7	71.1
76.65	135.9	550.4	47.6	110.65	352.5	805.8	72.1
77.65	146.8	560.6	48.3	111.65	357.0	810.3	73.3
78.65	154.3	565.5	49.0	112.65	360.4	811.1	74.4
79.65	161.7	595.6	49.7	113.65	361.5	808.6	75.7
80.65	170.3	611.8	50.4	114.65	361.8	784.7	77.0
81.65	178.8	618.2	51.1	115.65	365.0	823.3	78.7
82.65	185.7	650.1	51.7	116.65	368.1	845.0	80.5
83.65	193.6	677.7	52.4	117.65	371.2	849.6	82.6
84.65	200.2	646.6	53.2	118.65	374.5	852.5	84.9
85.65	207.1	654.2	53.8	119.65	378.5	870.5	87.2
86.65	214.5	651.8	54.5	120.65	382.1	890.1	89.2
87.65	222.8	647.0	55.1	121.65	385.8	904.3	91.3
88.65	228.1	648.8	55.4	122.65	388.7	905.2	93.6
89.65	236.3	655.7	56.0	123.65	390.2	904.6	96.0
90.65	241.2	665.5	56.5	124.65	389.4	821.2	98.4

Table B.1 Continued.

Time (Min)	Average (C)	Maximum (C)	Minimum (C)	Time (Min)	Average (C)	Maximum (C)	Minimum (C)
125.65	394.6	894.7	99.5	138.65	416.2	771.2	124.8
126.65	393.7	830.0	100.7	139.65	419.1	761.6	127.6
127.65	390.2	807.2	101.9	140.65	423.5	771.0	130.9
128.65	390.3	766.3	103.2	141.65	429.4	762.7	135.2
129.65	393.7	784.4	104.7	142.65	436.0	768.0	140.7
130.65	398.5	790.8	106.4	143.65	457.1	860.6	148.3
131.65	400.0	784.1	108.3	144.65	459.5	791.6	156.2
132.65	401.3	775.1	110.5	145.65	477.8	799.3	164.4
133.65	406.1	795.1	112.8	146.65	477.2	796.5	172.5
134.65	409.6	805.1	115.2	147.65	498.7	798.9	178.4
135.65	413.6	822.5	117.4	148.65	540.8	822.2	190.3
136.65	415.3	788.3	119.7	149.65	552.5	1083.6	203.7
137.65	418.1	786.4	122.1				

- All times are in minutes relative to time of fire ignition, negative times are pre-ignition.

Special Note: Due to the nature of the thermocouples used in testing, temperature measurements in excess of 316°C must be considered unreliable due to the likelihood that false junctions would be created due to a breakdown in insulation resistance. See Section 1.5 of the main report for further discussion of the limits of thermocouple data validity.

Figure B.1: TA1 In Furnace Ready for Testing.

Figure B.2: TA1 at 1 Hour, Note Gap in Upper Leg Section Joints.

Figure B.3: TA1 at 1:13, Note Upper Leg Bottom Panel Falling Away.

Figure B.4: TA1 Being Removed From Furnace.

Figure B.5: TA1 Just Before Hose Stream Application.

Figure B.6: TA1 During Hose Stream Application.

Figure B.7: Post-Test Condition of TA1.

Figure B.8: ASTM E119 Furnace Profile (smooth curve) and SNL Maximum (upper jagged curve) and Average (lower jagged curve) Furnace Profile During Exposure Testing of Test Article 1.

Figure B.9: Test Article 1 Circuit Integrity Response Data for Normally Open Circuits 2-4.

Figure B.10: Test Article 1 Protected Envelope Maximum, Average, and Minimum Temperature Response Data (Based Cable and Cable Tray Side Rail Thermocouples only, Channels 0-45).

Figure B.11: Test Article 1 Center Instrumented Cable Response Data Versus Location in Cable Tray Assembly.

Figure B.12: Test Article 1 Comparison of Fire Barrier Inner Surface and Center Cable Temperature Response Data Taken from Elbow Section of Cable Tray Assembly.

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Appendix C:
Test Article 2 Experimental Data and Analysis

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C.1 Basic Test Procedure

The basic test procedure utilized for evaluation of Test Article 2 was identical to that described in Section B.1 for Test Article 1. The planned exposure duration was 3 hours. However, in the case of test Article 2, the fire exposure was terminated after 2 hours. The fire exposure profile for the duration of the test was well within the allowable limits established for performance of ASTM E119 tests (see further discussion below). Figure C.1 provides a photograph of Test Article 2 inside the furnace prior to the initiation of the exposure.

C.2 Observations Made During Exposure

During testing, visual observations were made through viewing ports located in each wall of the furnace. The following summarizes the most significant observations made during the exposure:

Relative
Time

(hr:min): Observation:

0:00	Furnace ignition, ambient temperature approximately 19°C, Time 17:44:00
0:03	Outer barrier surface is blackened throughout, top leg lower panel already bowing
0:08	Tie wires on elbow section have stretched and are no longer taught, flames attached to panels throughout.
0:14	Seam on top leg, left side panel-to-bottom panel joint opening.
0:15	A "flap" of material at the top of the outer layer, inside elbow panel has opened exposing inner layer panels.
0:17	Elbow section lower-middle outside elbow panel-to-right side panel seam opening, seam in upper leg bottom panel to left side panel seam fully opened.
0:22	Seam on lower leg bottom panel to right side panel has opened.
0:27	Intense flames coming from open upper leg left side joint.
0:46	Upper leg, inside layer bottom panel now visibly sagging between tie wires.
0:52	Upper leg outer layer lower panel is falling away in chunks near joint to elbow section.
0:54	Upper leg inner layer bottom panel-to-left side panel joint now visibly opened.
0:54	First circuit failure noted - circuit-to-ground
0:58	Second circuit failure noted - circuit 2 (circuit-to-circuit)
1:01	Barrier system falling apart throughout upper leg, tray visibly exposed, black smoke from cable burning visible.
1:06	Third circuit failure noted - circuit 3 (circuit-to-circuit)
1:07	Power cut to test circuits 2, 3, and 4.
1:10	A large pile of debris has collected on top of the lower leg (from pieces fallen away from upper leg)
1:20	Upper leg inner layer pieces have fallen away and tray is fully exposed.
1:38	First temperature failures (single point criteria) in lower leg section noted.

2:00 Test Terminated

In summary, the test article suffered a catastrophic failure of the barrier system during the period from 52 to 61 minutes into the exposure. Figure C.2 provides a photograph of the upper leg, left side taken 48 minutes into the exposure (0:48). Note that gaps are visible in the lower panel-to-side panel joint, and at the joint between the upper leg lower panel and the elbow section inner radius panel. Figure C.3 is a photograph of the upper leg section taken at 1:52. Note that the cable tray is fully exposed (the individual rungs of the cable tray can be seen clearly) because both the outer and inner layer bottom panels have fallen away. The protective barrier on the upper leg of the cable tray assembly had literally fallen apart. The test was terminated prematurely, after 2 hours, because catastrophic failure had been observed throughout the test article.

C.3 Post-Mortem Observations:

Upon removal of the test article from the test furnace, extensive burning was observed in the remaining barrier material. Figure C.4 illustrates the condition of the test article as it was removed from the test furnace. The upper leg cable tray was fully exposed and was literally "glowing red hot." Only scattered pieces of the barrier material remained attached to the upper leg of the cable tray.

Figure C.5 shows the test article just prior to hose stream application. Note that the remaining pieces of fire barrier material continued to burn with some vigor. Upon application of the hose stream, any sections of material remaining on the test article which were directly impacted by the hose stream fell away immediately. Figure C.6 shows the test article during the hose stream application.

Post cooling examination of the test article was performed the next day. Figure C.7 shows the condition of the test article at this time. The insulation and jacketing material protecting the cables in the cable tray were fully burned away throughout the test article leaving only bare and blackened copper conductors. It was found that all of the exposed conductors were extremely brittle and broke easily when disturbed.

The only insulation material found remaining was immediately at and outside of the two bulkhead penetration areas. Even in the cable lead sections penetrating the bulkhead, and hence outside the furnace during the exposure were severely damaged. The remaining unburned insulation in these sections was charred and many of the cables were fused together into a single inseparable mass.

The lower leg of the test article was not subject to direct hose stream impact (due to the angle of application, the lower leg was shielded by the elbow section). A careful examination of this section was performed.

The debris from the upper leg panels was removed from the top of the lower leg. The original stress skin from the lower leg, outer layer, top panel was found resting in its original position. No virgin (unburned) Thermo-Lag material remained on this panel

with the exception of that part of the panel which penetrated the furnace bulkhead. The remaining char from this panel was removed to expose the lower leg inner layer top panel. The central area of this panel appeared relatively intact. However, the remaining virgin Thermo-Lag material had crystallized during the exposure and subsequent cooling, and was found to be very hard. This panel was also heavily charred in a band extending along the each edge of the panel to a width of about 1".

The stress skin from the lower leg outer layer side rail panels and bottom panel were found largely detached from the test article except at the lower bulkhead penetration. The pieces were fully burned through and no virgin material in the outer layer was evident (again, except at the lower bulkhead penetration). The stress skin from the lower leg inner layer side and bottom panels was still in place on the test article. However, the only virgin Thermo-Lag material remaining on these panels was found to at the lower bulkhead penetration and at the area immediately adjacent to the horizontal nose support. That is, the lower leg, inner layer bottom panel was found still firmly attached at the junction with the nose support by a 2" band of virgin material. Upon further examination, the elbow section, inner layer, outer radius panel was also found to be firmly attached to the nose support by a similar band of virgin material, and the inner layer of material protecting the nose support itself was found largely intact.

C.4 Analysis of Critical Test Data

Figure C.8 provides a graphical representation of the actual and desired furnace temperature profiles. Note that the actual profile falls well within the ASTM E119 exposure profile acceptance criteria.

The primary failure criteria for the protective envelope was failure of any one of the four circuit integrity tests. Figure C.9 provides a graphical representation of the circuit integrity test data for Test Article 2. Note that this figure shows each of the three normally open circuits tests (two circuit-to-circuit tests and one circuit-to-ground test). In each case, while the cables remain fully functional, the measured open circuit voltage should stay fixed at zero. Failure would be indicated by an increase in the measured voltage, with catastrophic failure (dead-shortening) indicated by an increase in the measured voltage to the nominal supply voltage of 28VDC.

All three of the normally open circuits indicated total dead-shortening failures during the period from 58-66 minutes after ignition. This included the circuit-to-ground test and the two circuit-to-circuit tests. The first dead-short condition was noted on Circuit 4 at 58.53 minutes (0:58:32) after ignition. Circuits 2 and 3 failed to dead-shorts at 0:59:32 and 1:05:32 respectively. (Note that the power supplies were turned off at 1:06:32 so that the circuit voltages returned to zero after that time.)

As discussed in Appendix A above, it was not expected that the configuration of the circuit-to-system test, circuit 1, would allow for detection of the type of failure intended for this circuit test (breaking of the copper conductor itself). In practice, no

failures were detected on this fourth circuit. No conclusions can be drawn based on the performance of the circuit-to-system circuit test.

Consideration has also been given to the maximum single point and average temperature response within the protected envelope. In particular, the ASTM fire barrier testing standard establishes limits on the allowable temperature rise for both single point temperature measurements and for the average of all measurements made on the unexposed surface of the fire barrier. These temperature rise limits are a rise above the prevailing ambient temperature of 139°C (250°F) for the average of all thermocouple measurements, and a rise above ambient of 181°C (325°F) for any single measurement. At the time of the test, the prevailing ambient temperature was 19°C (66°F). Hence, the respective temperature limits for Test Article 2 were 158°C (316°F) average temperature or 200°C (391°F) single point measurement.

As described in Appendix B (see page B-6), the following analysis of the protected envelope temperature rise is based on consideration of thermocouple channels 0-45 only (the cable and tray side rail temperatures only). Figure C.10 presents the average, maximum and minimum temperature response data for Test Article 2 in graphical format. Table C.1 provides this same information in tabulated format.

The first temperature excursion in excess of the temperature rise limits described above was violation of the single point temperature rise limit at 54 minutes, 32 seconds after ignition (0:54:32). At this time, both channels 19 and 29, the "center" and "right side" cable temperatures at 120" (near the bulkhead end of the upper leg section), exceeded the temperature limit. The measured temperatures at that time were 280°C (536°F) and 304°C (579°F) respectively, well above the 200°C (391°F) limit. Within one additional minute, the third cable at this location (channel 9) had also exceeded the single point temperature limit with a measurement of 316°C (600°F). By the time the test was terminated after 2 hours (2:00:00), only two thermocouples, the two side rail thermocouples closest to the lower bulkhead penetration, remained below the single point failure criteria. All of the other thermocouples throughout the test article were recording temperatures in excess of 200°C.

The average temperature rise for the cable and cable tray side rail temperatures, channels 0-45, exceeded the average temperature rise limits at 62.53 minutes (1:02:32) after ignition. At this time the average temperature recorded was 159.5°C (319°F).

As in the case of the other test articles, the visual observations made during the exposure are quite consistent with the behaviors noted in the temperature data. Figure C.11 illustrate the differences in cable temperature response observed for the various sections of the cable tray assembly. These data clearly corroborate the visual observations regarding the progression of test failures through the test article.

Figure C.12 provides data on the response of the fire barrier inner surface as compared to that of the center instrumented cable. Note that in this case, the barrier inner surface leads the cable temperatures by approximately 40°C.

C.5 Summary of Test Results

Test Article 2 failed the fire exposure test well short of the 3 hour rating of the barrier system. At 0:58:32 after ignition the first dead-short circuit integrity failure was noted (a circuit-to-circuit failure). By 1:05:32 after ignition, dead-short circuit failures had been observed on circuits 2-4, including the circuit-to-ground and both of the circuit-to-circuit test samples.

Consideration was also given to the temperature rise limits established in the ASTM fire barrier testing standards. The SNL analysis in this regards included consideration of only the cable and tray side rail thermocouples. The first temperature excursion in excess of these limits was a single point temperature rise which exceeded the corresponding temperature limit (a rise above ambient of 181°C (325°F)). The first such temperature excursion occurred 54 minutes, 32 seconds (0:54:32) after ignition. At 1:02:32 after ignition, the average temperature within the envelope reached 159.5°C (319°F), a rise above ambient of 140.5°C (253°F). This exceeded the average internal envelope temperature limit of 158°C (316°F) corresponding to a rise above ambient of 139°C (250°F).

The mode of barrier failure observed was quite similar to that observed in the case of Test Article 1. That is, after a very short period (several minutes) the seams between individual panels in the outer layer were observed to open. This, presumably, allowed the fire to come into direct contact with the inner layer panels. As the fire progressed, the tie wires holding the outer layer panels to the test article were observed to stretch due to the heating. It is a well known fact that most metals will lose strength at elevated temperatures. Hence, the tie wires eventually heated to the point where they would no longer support the weight of the Thermo-Lag panels and broke. This allowed the supported panels to fall away from the test article. A similar process then followed affecting the inner layer panels. Once any one of the inner layer seams was observed to open, thermal failure followed shortly.

The fire exposure was terminated 2:00:00 after ignition. At this time, only two thermocouples were yielding temperature measurements below the single point temperature rise failure criteria (the two thermocouples on the lower leg side rail closest to the lower bulkhead penetration). The upper leg section of the cable tray itself was clearly visible from the furnace viewing ports, the Thermo-Lag panels having suffered catastrophic failure and fallen away from the cable tray. Upon removal from the furnace these exposed sections of the cable tray were observed to be literally "glowing red hot."

Hose stream application after the fire exposure was employed primarily to cool the test article as most sections of the Thermo-Lag were observed to have already suffered catastrophic failure. Post-mortem examination of the lower leg of the test article was performed in detail as this section was protected from the hose stream impact by the other sections of the cable tray assembly. This inspection revealed extensive regions in which the Thermo-Lag material had fully burned through on both the inner and outer layers of material. The lower leg materials were examined in detail, and both even the inner layer side rail and bottom panels were found to retain only limited amounts of virgin material in

those areas adjacent to the lower bulkhead penetration and to the horizontal nose support structure.

The insulation on the cables within the cable tray were completely consumed by fire, and only blackened bare copper conductors remained. These bare conductors were found to be very brittle, and broke easily when disturbed. Even the cables lead sections penetrating the bulkhead were severely damaged and largely fused together into a single mass.

Table C.1: Test Article 2 Average, Maximum and Minimum Internal Envelope Temperatures (Based on Channels 0-45 only).*

Time (Min)	Average (C)	Maximum (C)	Minimum (C)	Time (Min)	Average (C)	Maximum (C)	Minimum (C)
-8.4667	18.5	19.1	17.9	24.533	22.3	27.4	19.7
-7.4667	18.5	19.1	17.9	25.533	23.0	29.4	20.0
-6.4667	18.5	19.1	18.0	26.533	23.6	31.0	20.2
-5.4667	18.5	19.2	18.0	27.533	24.4	32.8	20.5
-4.4667	18.5	19.2	18.0	28.533	25.1	34.5	20.9
-3.4667	18.5	19.2	18.0	29.533	25.9	36.2	21.2
-2.4667	18.6	19.3	18.0	30.533	26.8	37.9	21.5
-1.4667	18.6	19.3	18.0	31.533	27.7	39.7	21.9
-.4667	18.6	19.3	18.0	32.533	28.7	41.2	22.3
.5333	18.6	19.3	18.0	33.533	29.7	42.7	22.8
1.5333	18.6	19.3	18.0	34.533	30.8	44.4	23.2
2.5333	18.7	19.4	18.0	35.533	31.8	46.0	23.7
3.5333	18.7	19.4	18.0	36.533	32.9	48.0	24.3
4.5333	18.7	19.5	18.1	37.533	34.0	50.1	24.8
5.5333	18.7	19.5	18.1	38.533	35.2	52.2	25.3
6.5333	18.7	19.5	18.1	39.533	36.4	54.4	26.0
7.5333	18.8	19.6	18.1	40.533	37.6	56.7	26.5
8.5333	18.8	19.6	18.1	41.533	38.9	58.7	27.2
9.5333	18.8	19.7	18.1	42.533	40.1	60.6	27.9
10.533	18.9	19.7	18.2	43.533	41.4	62.0	28.6
11.533	18.9	19.8	18.2	44.533	42.7	63.9	29.4
12.533	19.0	19.9	18.2	45.533	44.0	65.9	30.1
13.533	19.0	20.1	18.3	46.533	45.4	68.2	30.9
14.533	19.1	20.2	18.3	47.533	46.7	69.9	31.8
15.533	19.3	20.5	18.4	48.533	48.1	71.7	32.6
16.533	19.4	20.8	18.5	49.533	49.5	74.0	33.5
17.533	19.6	21.2	18.5	50.533	50.9	75.9	34.4
18.533	19.8	21.7	18.6	51.533	52.2	77.9	35.4
19.533	20.1	22.2	18.8	52.533	53.7	79.9	36.4
20.533	20.5	22.7	18.9	53.533	55.1	81.6	37.3
21.533	20.8	23.4	19.1	54.533	57.5	107.8	38.3
22.533	21.3	24.1	19.3	55.533	71.0	304.5	39.4
23.533	21.8	25.7	19.5	56.533	79.8	397.5	40.4

Table C.1: Continued.

Time (Min)	Average (C)	Maximum (C)	Minimum (C)	Time (Min)	Average (C)	Maximum (C)	Minimum (C)
57.533	88.0	485.3	41.5	89.533	346.6	729.3	65.466
58.533	94.6	448.9	42.5	90.533	349.0	722.4	66.2
59.533	102.3	479.1	43.4	91.533	354.6	717.4	67.1
60.533	128.5	593.5	44.3	92.533	356.0	701.0	67.9
61.533	144.0	642.6	45.1	93.533	362.8	692.9	68.8
62.533	159.5	663.5	46.0	94.533	363.8	671.4	69.7
63.533	172.4	665.2	46.9	95.533	365.3	655.8	70.6
64.533	182.7	715.6	47.6	96.533	367.3	646.2	71.5
65.533	195.6	698.7	48.1	97.533	368.6	662.2	72.5
66.533	204.9	734.2	48.7	98.533	368.9	666.7	73.6
67.533	205.0	750.8	49.3	99.533	370.5	670.0	73.9
68.533	213.4	754.9	49.9	100.53	371.1	704.0	74.4
69.533	218.4	766.8	50.6	101.53	365.1	646.4	75.9
70.533	227.5	777.9	51.2	102.53	362.9	616.3	77.5
71.533	230.2	742.1	51.8	103.53	363.4	624.5	78.6
72.533	236.7	725.5	52.5	104.53	363.3	635.3	79.7
73.533	244.6	717.6	53.2	105.53	370.3	644.5	81.0
74.533	255.6	729.3	53.9	106.53	375.2	653.9	82.5
75.533	278.9	762.0	54.6	107.53	379.8	663.0	84.2
76.533	290.3	759.0	55.4	108.53	390.5	669.6	86.2
77.533	297.3	745.4	56.1	109.53	403.5	670.1	88.3
78.533	311.6	785.5	56.9	110.53	419.5	673.0	90.8
79.533	319.5	790.8	57.7	111.53	443.4	678.9	93.6
80.533	317.8	773.8	58.4	112.53	462.1	684.4	97.0
81.533	323.1	771.6	59.2	113.53	485.9	689.9	99.9
82.533	321.8	741.8	59.9	114.53	508.0	694.6	103.3
83.533	322.9	741.4	60.7	115.53	547.5	740.6	108.3
84.533	327.7	738.3	61.5	116.53	561.8	749.1	114.9
85.533	334.7	738.1	62.3	117.53	585.1	795.8	122.8
86.533	339.3	735.9	63.1	118.53	597.0	807.0	131.0
87.533	343.7	738.5	63.8	119.53	611.0	813.7	139.4
88.533	345.8	733.4	64.6				

* All times are relative to the time of fire ignition, negative times are pre-ignition.

Special Note: Due to the nature of the thermocouples used in testing, temperature measurements in excess of 316°C must be considered unreliable due to the likelihood that false junctions would be created due to a breakdown in insulation resistance. See Section 1.5 of the main report for further discussion of the limits of thermocouple data validity.

Figure C.1: TA2 In Furnace Ready for Testing.

Figure C.2: TA2 at 0:48, Note Gaps Panel Joints.

Figure C.3: TA2 Upper Leg at 1:52, Note That Cable Tray is Visible.

Figure C.4: TA2 Being Removed From Furnace.

Figure C.5: TA2 Just Before Hose Stream Application.

Figure C.6: TA2 During Hose Stream Application.

(a.): General View of Test Article.

(b.): Condition of Cables in Upper Leg Section.
Figure C.7: Post-Test Condition of TA2.

Figure C.8: ASTM E119 Furnace Profile (smooth curve) and SNL Maximum (upper jagged curve) and Average (lower jagged curve) Furnace Profile During Exposure Testing of Test Article 2.

Figure C.9: Test Article 2 Circuit Integrity Response Data for Normally Open Circuits 2-4.

Figure C.10: Test Article 2 Protected Envelope Maximum, Average, and Minimum Temperature Response Data (Based Cable and Cable Tray Side Rail Thermocouples only, Channels 0-45).

Figure C.11: Test Article 2 Center Instrumented Cable Response Data Versus Location in Cable Tray Assembly.

Figure C.12: Test Article 2 Comparison of Fire Barrier Inner Surface and Center Cable Temperature Response Data Taken from Elbow Section of Cable Tray Assembly.

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Appendix D:
Test Article 2 Experimental Data and Analysis

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D.1 Basic Test Procedure

The basic test procedure utilized for evaluation of Test Article 3 was identical to that described in Section B.1 for Test Article 1. The nominal planned exposure duration was 3 hours. In the case of test Article 3, the fire exposure was extended for the full 3 hour period. The fire exposure profile for the duration of the test was well within the allowable limits established for performance of ASTM E119 tests (see further discussion below). Figure D.1 provides a photograph of Test Article 3 inside the furnace prior to the initiation of the exposure.

D.2 Observations Made During Exposure

During testing, visual observations were made through viewing ports located in each wall of the furnace. The following summarizes some of the most significant observations made during the exposure:

Relative
Time

(hr:min): Observation:

0:00	Ignition, ambient temperature approximately 20°C, Time 19:10:08
0:03	Outer barrier surface shows some blackening.
0:07	Outer surface now blackened throughout.
0:13	Flames observed to be attached to surface of barrier panels throughout test article.
0:24	A "crack" is visible in the outer over-coat layer of material due to swelling of the over-coat, not at a seam location.
0:30	Outer overcoat material is flaking and loose in places.
0:31	Stress skin on elbow section upper half, inside radius outer layer panel is "sagging"/separating from panel.
0:35	Overcoat layer on upper leg sides has cracked due to swelling, (not at a seam though)
0:52	A large chunk of the over-coat char has fallen away from upper leg bottom panel.
0:52	Upper leg outer layer lower panel is falling away in chunks near joint to elbow section.
1:05	Upper leg outer layer bottom panel is bowing across width of tray, no opening of seam evident.
1:23	The upper leg, outer layer, bottom panel has fallen away from test article towards furnace bulkhead. The stress skin tore along length of seam, but the seam itself held.
1:25	Elbow section, outer layer, inner radius panel is falling away from test article, again, the stress skin tore but the joint did not give way.
1:35	Elbow section, outer layer, inner radius panel continuing to separate from test article.
1:38	The lacing on the joints for the outer elbow have stretched and are no longer tight, the bolts still appear to be holding well.
1:50	Single point temperature rise failure noted.

2:04 Elbow section, outer layer, outside radius visibly separated from side panels near center of section, bottom leg still looks relatively intact

2:11 Circuits 2-4 all failed, circuit power turned off.

2:14 Smoke coming through upper bulkhead penetration.

2:15 Smoke coming through lower bulkhead penetration also.

2:17 Smoke has stopped from penetrations.

2:27 Elbow section, outer layer, outer radius panel has fallen away from test article (starting at top), bottom still attached.

2:33 Lower leg, outer layer, bottom panel has fallen away from test article.

2:48 The bottom of the upper leg cable tray is fully exposed through inner layer panels.

3:00 End Test

In summary, the test article panels held together much better than had been observed with test articles 1 and 2, but nonetheless suffered failure well short of the nominal 3 hour rating of the barrier system. The lacing and bolting procedure used to secure the outer layer was quite effective at maintaining the integrity of the outer layer material joints. Rather than joint failures, it was observed that as the panels softened and sagged due to the high temperature exposure, the stress skin material simultaneously lost much of its strength (most metals loss strength at elevated temperatures). This eventually caused the stress skin itself to tear through, in turn allowing the bulk of the Thermo-Lag panels to fall away from the test article.

By the end of the test, the Thermo-Lag material covering the bottom of the upper leg section had completely burned through and only the stress skin remained. The cable tray forming the upper leg of the test article was fully exposed and visible through the stress skin. Figure D.2 provides a photograph of the test article as it was removed from the furnace.

D.3 Post-Mortem Observations

Upon removal of the test article from the test furnace, some burning was observed in the remaining barrier material, although this burning was not as energetic as had been noted in for Test Articles 1 and 2. The post-mortem examination revealed that relatively little un-burned Thermo-Lag material remained, presumably due to the relatively longer fire exposure time. This effectively reduced the amount of combustible material remaining, and hence, reduced the intensity of the resulting fire.

Upon removal from the furnace, initial attempts were made to cool the test article using a light mist water application. Because catastrophic failure had been observed, It was desired that an examination of the test article be made in its final condition prior to hose stream application. However, this proved impractical because the test article had become so hot, including the cables and cable tray, that upon removal of the mist, the test article would again burst into flames. Hence, a hose stream was eventually applied to fully cool the test article. Figure D.3 illustrates the pre-hose stream condition of the test article.

Prior to the final application of the hose stream, it was noted that most of the stress skin from the inner layer panels remained in place on the test article, although virtually no virgin un-burned Thermo-Lag material remained. In fact, the wire ties and lacing material used to secure the inner layer panels were also still intact, and still held the stress skin in place. This is illustrated in Figure D.4.

A crow-bar was used to remove the remaining stress skin in order to examine the cables. All that remained of the cables in the upper leg and elbow sections was bare copper conductor. In the lower leg section, some limited sections of badly charred and burned insulation material were evident, although large sections of bare conductor were also evident. At the completion of this inspection, the full hose stream was applied as described above.

A brief post-mortem inspection was also performed the following day. The condition of the test article at that time is illustrated in Figure D.5. No further significant findings were recorded at that time.

D.4 Analysis of Critical Test Data

Figure D.6 provides a graphical representation of the actual and desired furnace temperature profiles. Note that the actual profile falls well within the ASTM E119 exposure profile acceptance criteria.

The primary failure criteria for the protective envelope was failure of any one of the four circuit integrity tests. Figure D.7 provides a graphical representation of the circuit integrity test data for Test Article 3 for each of the three normally open circuits tests (the circuit-to-ground and two circuit-to-circuit tests). (Circuit degradation is indicated by non-zero voltages, with an increase to approximately 28VDC indicating dead shorting of the cables as discussed in Appendix B.)

The first dead-short circuit failure occurred on circuit 4 (circuit-to-circuit) at 1:58:52. Circuits 2 and 3 failed to dead-shorts at 2:07:52 and 2:04:52 respectively. (Note that the power supplies were turned off at 2:09:52 so that the circuit voltages returned to zero after that time.) As discussed in Appendix A above, it was not expected that the configuration of the fourth circuit test, the circuit-to-system test, would allow for detection of the nominal mode of circuit failure anticipated (e.g., breaking of the copper conductor itself). During testing, no failures were detected on this fourth circuit. No conclusions can be drawn based on the performance of the circuit-to-system circuit test.

As outlined in Appendix B, consideration has also been given to the maximum single point and average temperature response within the protected envelope. At the time of the test, the prevailing ambient temperature was 20°C (68°F). Hence, the respective temperature rise limits for Test Article 3 were a 159°C (318°F) average temperature or a 201°C (393°F) single point measurement. As for the other test articles, this analysis is based on consideration of thermocouple channels 0-45 only (the cable and tray side rail thermocouples only). Figure D.8 provides the average, maximum and

minimum temperature response plots for Test Article 3 (based on channels 0-45). Table D.1 provides the same information in tabulated form.

The first temperature excursion in excess of these limits was violation of the single point temperature rise limit at 1 hour 49 minutes, 52 seconds after ignition (1:49:52). At this time channel 28, the "right" cable temperatures at 108" (near the bulkhead end of the upper leg section), registered a temperature of 300°C (572°F), well above the 201°C (393°F) limit. By the time the test was terminated after 3 hours (3:00:00), only the two side rail thermocouples closest to the lower bulkhead penetration remained below the single point temperature limit. All of the other thermocouples throughout the test article were recording temperatures in excess of 200°C.

The average temperature rise of the cable and cable tray side rail temperatures, channels 0-45, first exceeded the corresponding temperature rise limit at 1:57:52 after ignition. At this time the average temperature recorded was approximately 165°C (329°F), which is in excess of the 159°C (318°F) temperature limit.

As in the case of the other test articles, the visual observations made during the exposure are quite consistent with the behaviors noted in the temperature data. Figure D.9 illustrate the differences in cable temperature response observed for the various sections of the cable tray assembly. These data clearly corroborate the visual observations regarding the progression of test failures through the test article.

Figure D.10 provides data on the response of the fire barrier inner surface as compared to that of the center instrumented cable. Note that in this case, the barrier inner surface leads the cable temperatures by approximately 50°C.

D.5 Comparison to Manufacturer Results

Test Article 3 was built as a full reproduction of one of the original manufacturer test articles; namely, TSI Test Article #4 from the report 82-11-81. This included both the base test article construction and installation of the fire barrier system. Hence, for this test article, direct comparison of the SNL and TSI test results is appropriate.

Figure D.11 compares the reported original TSI maximum cable temperature response data to the corresponding data gathered during testing of SNL Test Article 3. Figure D.12 provides a similar comparison for the average cable response data. In each case, the SNL data shows a much greater initial rate of temperature rise. Further, the TSI data indicates that all temperatures remained well below the relevant ASTM temperature rise limits, whereas the SNL test article exceeded these limits in less than 2 hours as discussed above.

(Note that the two TSI data plots were generated by SNL using the tabulated temperature response data presented in Appendix IV, Section 4 of the original TSI test report. An examination of the average temperature response data tabulated in Table 3 of the main body of the report revealed several discrepancies in comparison to the tabulated values presented in the Appendix, and the tabulated values were considered

to be the more reliable data set as they represented the "raw" unprocessed data. Also note that the SNL cable response plot is based only on the cable temperature measurement channels 0-29. All other data channels (cable tray side rail, internal envelope air, and fire barrier inner surface temperatures) have been excluded. This provides a consistent basis for comparison, that is, both curves are based only on the cable temperature responses measured.)

D.6 Summary of Test Results

Test Article 3 failed the fire exposure test well short of the nominal 3 hour rating expected of the barrier system. At 1:58:52 after ignition the first dead-short circuit integrity failure was noted (a circuit-to-circuit failure). By 2:07:52 after ignition, dead-short circuit failures had been observed on circuits 2-4, including the circuit-to-ground and both of the circuit-to-circuit test samples.

Consideration was also given to the temperature rise limits established in the ASTM fire barrier testing standards. The SNL analysis in this regards included consideration of only the cable and cable tray side rail thermocouples. The first temperature excursion in excess of these limits was a single point temperature rise which exceeded the corresponding failure criteria (a rise above ambient of 181°C (325°F)). The first such temperature excursion occurred at one hour, 49 minutes, 52 seconds (1:49:52) after ignition. At 1:57:52 after ignition, the average temperature within the envelope reached 165°C (329°F), a rise above ambient of 145°C (261°F). This exceeded the average internal envelope temperature limit of 159°C (318°F) corresponding to a rise above ambient of 139°C (250°F).

The mode of barrier failure was somewhat different for Test Article 3 than that observed for Test Articles 1 and 2. In the case of Test Articles 1 and 2, the failure mode observed typically involved a two step process in which seams between individual panel sections opened violating the envelope, and the supporting tie wires stretched and eventually broke allowing panels to fall away from the test article. In the case of Test Article 3, the outer layer seams had been secured using both bolts and wire lacing (recall that this was a full reproduction of an early manufacturer's test). These enhancements clearly reinforced these seams, and in practice, none of these seams appeared to open during testing. Rather, catastrophic failure of the outer layer panels was seen when the stress skin itself tore along a line parallel to such a seam, allowing the bulk of individual panels to fall away from the test article. It then appears that the inner layer panels simply burned through allowing penetration of the fire into the protected envelope. This was demonstrated in that during post-test examination of the test article the inner layer stress skin was found to be in place and still stitched together, but that these panels had burned down to bare stress skin with virtually no virgin Thermo-Lag material remaining.

The test was terminated after the full planned three hour exposure. At that time, only two thermocouples were yielding temperature measurements below the single point temperature rise failure criteria (the two thermocouples on the lower leg side rails closest to the lower bulkhead penetration). The upper leg section of the cable tray itself was clearly visible from the furnace viewing ports, the Thermo-Lag panels protecting the bottom of this

section having fully burned through. Upon removal from the furnace these exposed sections of the cable tray were observed to be literally "glowing red hot."

Initial attempts were made to cool the test article with a water mist application so that it might be inspected in detail. However, these attempts proved impractical as the test article repeatedly reignited after removal of the water mist, and continued to smolder even when open flaming did not reoccur. A limited inspection and dissection of the test article was performed during this period, and then a full hose stream application was made to fully cool the test article. The limited, pre-hose stream inspection revealed that virtually all of the Thermo-Lag material in the upper leg and elbow sections of the cable tray had been consumed during the fire. Extensive areas of full burn through were evident. As described above, only the inner layer stress skin remained in place. All of the cables within the cable tray were completely consumed by fire, and only blackened bare copper conductors remained. These bare conductors were found to be very brittle, and broke easily when disturbed.

**Table D.1: Average, Maximum and Minimum Temperature Response
for Test Article 3 (Based on Channels 0-45 only).**

Time (Min)	Average (C)	Maximum (C)	Minimum (C)	Time (Min)	Average (C)	Maximum (C)	Minimum (C)
-5.1333	20.0	20.7	19.3	27.867	21.9	24.5	20.1
-4.1333	20.0	20.6	19.3	28.867	22.2	25.1	20.2
-3.1333	20.0	20.7	19.4	29.867	22.5	25.7	20.3
-2.1333	20.0	20.7	19.4	30.867	22.9	26.4	20.5
-1.1333	20.0	20.7	19.4	31.867	23.2	27.1	20.6
-0.1333	20.0	20.7	19.4	32.867	23.6	27.8	20.8
0.8667	20.0	20.7	19.4	33.867	24.0	28.6	21.0
1.8667	20.0	20.7	19.4	34.867	24.4	29.4	21.2
2.8667	20.0	20.7	19.4	35.867	24.9	30.3	21.4
3.8667	20.0	20.7	19.4	36.867	25.4	31.1	21.7
4.8667	20.0	20.7	19.4	37.867	25.9	32.0	22.0
5.8667	20.0	20.6	19.4	38.867	26.4	32.9	22.2
6.8667	20.0	20.7	19.4	39.867	27.0	33.8	22.6
7.8667	20.0	20.7	19.4	40.867	27.6	34.8	22.7
8.8667	20.0	20.6	19.4	41.867	28.2	35.8	23.2
9.8667	20.0	20.7	19.4	42.867	28.8	36.8	23.6
10.867	20.1	20.7	19.4	43.867	29.5	37.8	24.0
11.867	20.0	20.7	19.2	44.867	30.1	38.8	24.4
12.867	20.1	20.7	19.4	45.867	30.8	39.8	24.8
13.867	20.1	20.8	19.4	46.867	31.6	40.9	25.2
14.867	20.1	20.9	19.4	47.867	32.3	41.9	25.7
15.867	20.2	21.1	19.4	48.867	33.0	43.0	26.2
16.867	20.2	21.2	19.4	49.867	33.8	44.1	26.7
17.867	20.3	21.4	19.4	50.867	34.6	45.2	27.2
18.867	20.4	21.6	19.5	51.867	35.4	46.3	27.7
19.867	20.5	21.8	19.5	52.867	36.3	47.5	28.2
20.867	20.6	22.1	19.6	53.867	37.1	48.6	28.7
21.867	20.7	22.3	19.6	54.867	37.9	49.8	29.3
22.867	20.9	22.7	19.7	55.867	38.8	50.9	29.8
23.867	21.0	23.0	19.8	56.867	39.7	52.1	30.4
24.867	21.2	23.4	19.8	57.867	40.6	53.3	31.0
25.867	21.4	23.7	19.9	58.867	41.5	54.4	31.6
26.867	21.7	24.0	20.0	59.867	42.4	55.6	32.2

Table D.1: Continued.

Time (Min)	Average (C)	Maximum (C)	Minimum (C)	Time (Min)	Average (C)	Maximum (C)	Minimum (C)
60.867	43.4	56.8	32.9	93.867	80.0	101.4	57.0
61.867	44.3	58.0	33.5	94.867	81.3	102.9	57.7
62.867	45.3	59.2	34.1	95.867	82.6	106.0	58.4
63.867	46.2	60.5	34.8	96.867	84.0	108.3	59.1
64.867	47.2	61.7	35.5	97.867	85.3	111.6	59.8
65.867	48.2	62.9	36.1	98.867	86.7	114.9	60.5
66.867	49.2	64.2	36.9	99.867	88.1	117.6	61.2
67.867	50.2	65.5	37.6	100.87	89.5	120.6	61.9
68.867	51.2	66.8	38.4	101.87	91.0	124.2	62.5
69.867	52.3	68.0	39.1	102.87	92.4	127.7	63.1
70.867	53.3	69.3	39.8	103.87	93.9	131.5	63.7
71.867	54.3	70.6	40.6	104.87	95.3	134.5	64.3
72.867	55.4	71.9	41.4	105.87	96.9	138.8	65.0
73.867	56.5	73.3	42.2	106.87	98.5	144.5	65.8
74.867	57.6	74.6	43.1	107.87	100.4	158.2	66.5
75.867	58.7	75.9	43.9	108.87	102.5	174.5	67.2
76.867	59.8	77.2	44.7	109.87	108.4	300.6	67.8
77.867	60.9	78.6	45.5	110.87	116.7	360.3	68.4
78.867	62.0	79.9	46.3	111.87	120.6	399.3	68.9
79.867	63.1	81.3	47.0	112.87	127.4	471.1	69.5
80.867	64.3	82.7	47.8	113.87	132.1	500.0	70.0
81.867	65.4	84.0	48.5	114.87	140.5	489.7	70.5
82.867	66.5	85.4	49.2	115.87	147.3	542.1	71.1
83.867	67.7	86.8	50.0	116.87	158.1	586.4	71.6
84.867	68.9	88.2	50.7	117.87	164.8	583.7	72.2
85.867	70.1	89.6	51.3	118.87	174.6	585.5	72.8
86.867	71.3	91.0	52.0	119.87	181.7	597.0	73.4
87.867	72.5	92.4	52.6	120.87	197.0	610.3	74.0
88.867	73.8	93.8	53.3	121.87	206.0	610.4	74.5
89.867	75.0	95.3	54.0	122.87	214.9	620.8	75.2
90.867	76.2	96.8	54.8	123.87	221.2	667.5	75.9
91.867	77.5	98.3	55.6	124.87	226.1	658.8	76.6
92.867	78.7	99.8	56.4	125.87	231.3	660.9	77.3

Table D.1: Continued.

Time (Min)	Average (C)	Maximum (C)	Minimum (C)	Time (Min)	Average (C)	Maximum (C)	Minimum (C)
126.87	234.6	684.2	78.1	153.87	359.0	712.8	106.0
127.87	236.2	660.0	79.0	154.87	365.7	721.2	107.3
128.87	237.9	659.4	79.9	155.87	364.3	750.1	107.2
129.87	239.4	672.7	80.9	156.87	366.2	797.8	107.4
130.87	241.5	671.5	82.2	157.87	366.2	784.9	107.6
131.87	247.5	645.1	83.6	158.87	365.8	799.2	107.9
132.87	254.0	637.0	85.2	159.87	367.2	802.7	108.2
133.87	260.2	647.8	87.3	160.87	370.5	804.8	108.5
134.87	263.9	644.5	90.1	161.87	375.8	801.6	108.9
135.87	265.6	641.5	91.9	162.87	380.3	785.7	109.6
136.87	268.4	650.4	93.1	163.87	386.6	782.4	109.9
137.87	273.6	658.1	94.7	164.87	395.4	779.5	110.7
138.87	275.8	639.7	96.2	165.87	413.6	773.3	111.4
139.87	278.4	637.1	97.2	166.87	404.1	779.6	112.1
140.87	283.0	649.3	98.2	167.87	405.4	799.6	112.7
141.87	294.3	665.7	99.5	168.87	427.9	803.5	113.8
142.87	297.7	666.5	100.8	169.87	419.9	808.0	114.5
143.87	300.6	661.9	101.8	170.87	421.7	808.3	115.0
144.87	305.2	672.6	103.4	171.87	427.0	813.7	115.7
145.87	308.0	670.1	104.3	172.87	425.6	818.2	117.5
146.87	314.2	703.5	104.9	173.87	449.0	821.6	122.8
147.87	323.2	730.3	104.9	174.87	457.5	822.6	131.2
148.87	327.2	735.5	105.0	175.87	456.9	823.5	138.1
149.87	333.1	751.7	105.1	176.87	479.5	816.6	146.4
150.87	338.4	753.3	105.1	177.87	490.1	804.7	154.7
151.87	344.4	730.1	105.3	178.87	513.7	808.6	163.4
152.87	355.1	703.3	105.5	179.87	527.8	807.0	172.6

* All times are relative to time of fire ignition, negative times are pre-ignition.

Special Note: Due to the nature of the thermocouples used in testing, temperature measurements in excess of 316°C must be considered unreliable due to the likelihood that false junctions would be created due to a breakdown in insulation resistance. See Section 1.5 of the main report for further discussion of the limits of thermocouple data validity.

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Figure D.1: TA3 In Furnace and Ready for Testing.

Figure D.2: TA3 As it was Removed from the Test Furnace.

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Figure D.4: Post-Test Examination of TA3.

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Appendix E:
Test Article 4 Experimental Data and Analysis

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E.1 Basic Test Procedure

In the performance of each of the two tests in the SNL ampacity derating test set (the base line and protected tray tests), the test article was placed into a large high-ambient environmental test chamber measuring approximately 12'x8'x8' (lwxhxh). This chamber was a self-contained, electrically heated, air circulating facility specifically designed for the testing of large electrical equipment at environmental temperatures up to about 80°C (176°F). Hence, it was ideally suited to the SNL tests which required a controlled ambient temperature of 40°C (104°F). Minimum clearances of 24" between the test article and the sides of the chamber were achieved. Instrumentation lead wires were then installed through built-in chamber penetrations to the data logging system which was located just outside the chamber. Power supply systems were connected to each of the three cable circuits through a second chamber penetration. Figure E.1 provides photographs of the test chamber and the test article.

The base line test of the cable tray article was performed on October 14-15, 1993. The fire barrier system was then installed on the test article. The protected tray test was performed on December 9-10, 1993 after a curing period in excess of 30 days. Note that the same test article was used for both the base line and protected tray tests.

In the case of the base line test, the cables were left un-insulated throughout. That is, no portion of the cables was protected by any form of insulating material. In the case of the protected tray test, the test article was, of course, protected by the Thermo-Lag fire barrier system. In addition, the open ends of the upper and lower leg sections were closed off using a ceramic blanket insulation material (on the sides between the cable tray and the fire barrier panels, and on the top and bottom between the cables and the fire barrier panels). The narrow gap between the panels forming the inner and outer layers of the fire barrier system were also sealed at the open ends of the system using a silicone caulking material. Also note that the cable tray extended out of the protected barrier system approximately 6-8" beyond the end of the fire barrier panels at both the upper and lower open ends of the "U"-shaped cable tray assembly (due to interference from the vertical cable tray "tail supports"). The cables in these two unprotected sections of the cable tray were also covered, top and bottom, with a 1" layer of ceramic blanketing material to minimize the excess conduction of heat along the length of the cables and out of the protective envelope.

Power was applied to each cable based on an initial estimate of the ampacity of each cable made prior to the start of each test. These initial estimates were based on the original manufacturer's test results. For approximately 4-6 hours, adjustments were made in the amperage of each cable until it appeared that a steady state hot-spot conductor temperature near 90°C for each cable size would be reached. The test article was then left to settle overnight (approximately 16 hours). Upon return the next morning, final ampacity adjustments were made, and the test article was again allowed to settle (typically 2-3 hours).

Two conditions were considered in determining when stable conditions at the desired final state had been achieved. First, it was required that the individual measurements

made at each time step for each of the three individual cable hot-spots (one location for each of the three cable sizes) must remain within $\pm 1^{\circ}\text{C}$ of the final average hot-spot temperature. This criteria was assessed by examining the printed temperature data record generated at the time of the test. Second, it was required that no apparent overall upward or downward trend in the cable temperature values be present. Compliance with this criteria was assessed by examining the graphical display of the hot-spot temperature data provided by the data logging program.

Upon observation of stable conditions having been attained, a one-hour final data logging period was initiated. Temperatures logged at ten minute intervals during this final hour were used as the basis for all calculations. Cable amperage readings were taken at the beginning and end of this period to verify the presence of stable source currents.

Note that this methodology is somewhat different than that employed by the manufacturer. In the original tests, the power delivered to each cable was based on a fixed percentage increment of the maximum allowable current from the ampacity tables for cables in cable trays. That is, in the base line test the final current supplied to each cable was nominally 120% of the table values. In the protected tray test this current was reduced to 90% of the table values. This approach, however, allowed each of the three cable sizes to seek its own equilibrium temperature, independent of the desired 90°C desired conductor temperature. Only one of the three cables ended up with its single hottest temperature measurement near the desired 90°C while the other cables had hot spot temperatures well below this value. Further, the manufacturer failed to bring the cable power levels to the desired levels with much accuracy. In reality the power levels in the base line test varied from 120.8%-122.2% of the table values, and for the protected tray tests the powers varied from 90.5%-92.0% of the table values. This also accounts for the variability in the final ampacity derating values obtained for the various cables. That is, if the test were actually performed as intended and the power levels were more accurately set, then each cable should have had an identical derating factor.

The intent of the ampacity derating tests is to achieve a steady state temperature condition for which the "hot spot" is at a temperature of 90°C . That is, the intent of the standard in this case would clearly be to bring each of the individual cables up to 90°C at the hot spot regardless of the relative power level required to obtain this value. As discussed further below, the experimental approach taken by the manufacturer fails to recognize the interdependency of each cable on its neighbors. The failure to obtain a uniform temperature condition in the manufacturers test was considered a serious flaw in the original testing. The SNL test procedure corrected this flaw by bringing each of the individual cables to a hot spot condition of 90°C .

E.2 Base Line Test Data and Analysis

Table E.1 presents the ten minute interval scan, hot spot and ambient data values used in the calculation process for the base line (unprotected tray) test of Test Article 4. (Use of 10 minute scanning intervals for the final hour is consistent with the

established UL procedure for performance of ampacity derating tests. Because data logging was performed at five minute intervals, every second scan was used in the final calculations.)

Table E.1: Base Line Test Cable Hot Spot and Ambient Temperature Data					
Time ¹	T _{a1} (ch. 37)	T _{a2} (ch. 38)	T _{c-8AWG} (ch. 9)	T _{c-4AWG} (ch. 18)	T _{c-2/0} (ch. 11)
129	40.4	39.9	90.8	91.7	92.2
139	41.2	40.6	91.0	90.8	91.7
149	41.0	40.4	91.0	91.3	92.0
159	41.2	40.3	91.1	91.1	91.9
169	40.7	39.8	91.1	91.5	92.2
179	40.7	39.8	91.2	91.3	92.1
189	40.8	39.8	91.4	90.9	92.0
Average	40.5		91.1	91.2	92.0
1. Time has been rounded to nearest minute; all temperature are (°C) and have been rounded to the nearest 0.1 degrees; calculation of averages was based on values rounded to 0.01 degrees to minimize cumulative round-off errors.					

The ampacity adjustment factor (AF) is calculated for each cable based on the formula presented in ICEA P-46-426:

$$I' = I \times AF = I \times \sqrt{\frac{T'_c - T'_a}{T_c - T_a} \times \frac{234.5 + T_c}{234.5 + T'_c}} \quad (E-1)$$

where the primes indicate the new desired condition and the values without the prime indicate the actual experimental values. In this case the values used are as follows:

$$\begin{array}{lll} T'_c = 90 & ; & T'_a = 40 & ; & T_a = 40.49 \\ T_{c-8AWG} = 91.9 & ; & T_{c-4AWG} = 91.2 & ; & T_{c-2/0} = 92.0 \end{array}$$

Note that in each case the individual conductor hot spot temperature averaged over the final hour of testing was used as the basis for calculation of the adjustment factor for that cable's current. Table E.2 provides the results of this calculation. Note that the

uniform nature of the amperage adjustment factors reflects the fact that all of the three cable hot spots were at quite similar temperatures.

Table E.2: Adjustment of Base Line Amperage Values			
Cable Size	Measured Amperage (I)	Adjustment Factor (AF)	Adjusted Amperage (I')
8 AWG	23.8	0.996	23.7
4 AWG	38.0	0.995	37.8
2/0	115	0.988	113.6

E.3 Protected Tray Test Data and Analysis

Table E.3 presents the ten minute interval scan, hot spot and ambient data values used in the calculation process for the protected tray test of Test Article 4.

Table E.3: Protected Tray Test Cable Hot Spot and Ambient Temperature Data					
Time ¹	T _{a1} (ch 37)	T _{a2} (ch 38)	T _{8AWG} (ch #)	T _{4AWG} (ch #)	T _{2/0} (ch #)
11:47	39.8	40.0	93.0	93.2	91.8
11:57	40.0	40.7	92.9	93.1	91.8
12:07	40.2	40.7	92.9	92.6	91.8
12:17	39.8	39.9	92.9	92.5	91.7
12:27	40.2	40.2	92.9	94.2	91.3
12:37	39.9	40.2	92.8	93.9	91.4
12:47	40.0	40.0	92.7	93.2	91.4
Average	40.1		92.9	93.2	91.6
1. Time has been rounded to nearest minute; all temperature are (°C) and are rounded to the nearest 0.1 degrees; averages were initially calculated based on use of temperatures rounded to 0.01 degrees to minimize cumulative round-off errors.					

The ampacity adjustment factor is calculated for each cable based on the formula presented in ICEA P-46-426 and as equation (E-1) above. In this case the values used are as follows:

$$\begin{array}{lll} T_c' = 90 & ; & T_a' = 40 & ; & T_a = 40.1 \\ T_{c-8AWG} = 92.9 & ; & T_{c-4AWG} = 93.2 & ; & T_{c-2/0} = 91.6 \end{array}$$

Table E.4 provides the results of this calculation. Note that the uniform nature of the ampereage adjustment factors reflects the fact that all of the three cable hot spots were at quite similar temperatures.

Table E.4: Adjustment of Protected Tray Ampereage Values			
Cable Size	Measured Ampereage (I)	Adjustment Factor (AF)	Adjusted Ampereage (I')
8 AWG	13.0	0.997	12.7
4 AWG	24.8	0.975	24.2
2/0	74.4	0.988	73.5

E.4 Analysis of Ampacity Derating Factor

The ampacity derating factor (ADF) is based on the ratio of the reduction in current carrying capacity to the original current carrying capacity:

$$ADF = \frac{I'_{base} - I'_{prot}}{I'_{base}} \times 100 \quad (E-2)$$

Note that in this format the ADF is expressed as a percentage drop in current carrying capacity. Table E.5 presents the final results for Test Article 4.

Note that the ampacity derating factor for the 8AWG cable was significantly higher than that of the other two cables. This was an unexpected result. Initially, it was suspected that this result might be anomalous. The suspected cause was that insufficient time for settling of the temperatures after the final current adjustments were made might have been allowed. However, further examination of the full data set confirmed the above results.

In order to confirm the results presented in Table E.5, and in particular that for the 8AWG cable, the data gathered during the final hour of the overnight settling period were examined in detail. Upon arrival at the test site the second day, the current values for each cable were measured and recorded prior to making the final

Table E.5: Ampacity Derating Factor for Test Article 4			
Cable Size	Corrected Base Line Amperage	Corrected Protected Tray Amperage	Ampacity Derating Factor (ADF %)
8 AWG	23.7	12.7	46.4 %
4 AWG	37.8	24.2	36.0 %
2/0	113.6	73.5	35.3 %

adjustments. Because the cables had settled at temperatures higher than the desired 90°C (93-96°C) it was decided to attempt to make one final adjustment to bring the cables nearer the desired temperature. However, because these data were recorded after a settling period in excess of 15 hours, they do represent a true and reliable condition of stability. Table E.6 summarizes the analysis of the data from the final hour of the over-night settling period. Table E.7 provides a comparison of the results from the final hour of the over-night settling period to those from the final hour of the test as a whole. Note that the final ampacity derating factors derived are virtually identical.

Table E.6: Adjustment of Protected Tray Amperage Values Based on the Final Hour of the Overnight Settling Period					
Cable Size	Measured Amperage (I)	Average Conductor Temp. (C)	Average Ambient Temp. (C)	Adjustment Factor (AF)	Adjusted Amperage (I')
8 AWG	13.4	96.0	40.1	0.955	12.8
4 AWG	25.4	95.7		0.957	24.3
2/0	74.4	93.2		0.976	72.6

This analysis confirms that the results presented in Table E.5 are not anomalous. Because the temperatures recorded during the final hour of the test as a whole are both more uniform from cable to cable, and closer to the desired 90°C goal, they are considered the more valid data set. Hence the results presented in Table E.5 will be used throughout the balance of the analysis.

E.5 Analysis of Original Manufacturer's Data

Note that the original manufacturer's test report contains certain very significant calculational and experimental errors. The analysis presented here provides for a two-

Table E.7: Comparison Between Ampacity Derating Factors Based on Final Hour of Overnight Settling Period and Based on Final Hour of Protected Tray Test as a Whole.				
Data Basis	Cable Size	Corrected Base Line Amperage	Corrected Protected Tray Amperage	Ampacity Derating Factor (ADF %)
Final Hour of Overnight Settling Period	8 AWG	23.7	12.8	46.0 %
	4 AWG	37.8	24.3	35.7 %
	2/0	114	72.6	36.3 %
Final Hour of Test as a Whole	8 AWG	23.7	12.7	46.4 %
	4 AWG	37.8	24.2	36.0 %
	2/0	113.6	73.5	35.3 %

step correction of these errors and provides a more realistic analysis of the original manufacturer's data than that presented in the original report.

The first series of errors noted was in the calculation of the ampacity adjustment factor (AF) as described in Sections E.1 and E.2 above. In the application of equation (E-1), which is designed to compensate for variations in the tested versus standard ambient and conductor temperatures, the TSI analysis inverted the roles of the actual and desired cable and ambient temperatures. In effect, the TSI analysis decreased the base line tray ampacities and increased the protected tray ampacities when the reverse should have been performed. The net effect of this error was to significantly underestimate the ampacity derating factors (by approximately a factor of 2).

A second series of mistakes was identified in the TSI calculations having to do with the application of the cable conductor temperature data. In particular, in its analysis TSI used only the hottest single conductor temperature as the basis for the calculation of ampacity adjustment factors for all three cables sizes when in fact, two of the three cables were well below the desired experimental temperature of 90°C. In the worst case, one of the cables was allowed to remain over 12°C below the desired 90°C target temperature. In the TSI analysis, this variation between cable sizes is completely ignored.

Table E.8 provides the results of a two-step re-analysis of the TSI data. The results identified in the table as TSI(1) are the original manufacturer published results. In the first correction step, the initial error associated with the inverting of the ampacity adjustment factor is corrected, but the single hottest cable temperature is still used as the basis for correction of all three ampacity values. These results are identified in the

table as TSI(2). In the second correction step, the actual individual conductor temperatures were used to calculate individual ampacity adjustment factors for each cable independently. These results are identified in the table as TSI(3). Table E.9 summarizes the ampacity derating test results.

Table E.8: Ampacity Derating Test Results									
		Base Line Tray Test				Protected Tray Test			
cable size	data source	T _c (°C)	T _a (°C)	I (A)	I _c (A)	T _c (°C)	T _a (°C)	I (A)	I _c (A)
8 AWG	SNL	91.1	40.5	23.8	23.7	92.9	40.1	13.0	12.7
	TSI (1)	90.87	47.95	18.87	17.46	91.7	38.67	14.26	14.64
	TSI (2)	90.87	47.95	18.87	20.38	91.7	38.67	14.26	13.89
	TSI (3)	77.8	47.95	18.87	23.96	84.4	38.67	14.26	14.83
4 AWG	SNL	91.2	40.5	38.0	37.8	93.2	40.1	24.8	24.2
	TSI (1)	90.87	47.95	38.66	35.77	91.7	38.67	28.96	29.74
	TSI (2)	90.87	47.95	38.66	41.75	91.7	38.67	28.96	28.21
	TSI (3)	90.87	47.95	38.66	41.75	91.7	38.67	28.96	28.21
2/0	SNL	92.0	40.5	115	113.6	91.6	40.1	74.4	73.5
	TSI (1)	90.87	47.95	114.46	105.91	91.7	38.67	84.90	87.18
	TSI (2)	90.87	47.95	114.46	123.6	91.7	38.67	84.90	82.69
	TSI (3)	85.2	47.95	114.46	131.6	88.6	38.67	84.90	84.82
<p>TSI (1): Data taken from TSI original report data analysis tables without correction. TSI (2): Values based on correction of the amperage adjustment factor calculation but still using of the single highest cable temperature as the basis for correction of all cable amperages as in the original report. TSI (3): Values of the ampacity adjustment factor were based on use of each of the individual cable conductor temperatures to correct the experimental ampacity of each individual cable. SNL: This is the data for SNL Test Article 4. In each case, individual conductor temperatures were used to adjust individual conductor ampacities prior to calculation of the Ampacity Correction Factor.</p>									

It should be recognized that in applying the second correction step, a significant extrapolation is being made which is not directly valid. That is, by correcting the individual cables separately, one is inherently assuming that each cable functions independently of the others. Due to the nature of the test article, this assumption is clearly flawed. However, to simply ignore the variations, as in the TSI analysis, is

Table E.9: Ampacity Derating Factors				
Cable Size	Data Source*	Corrected Base Line Ampacity	Corrected Protected Ampacity	Ampacity Derating Factor (%)
8 AWG	SNL	23.7	12.7	46.4
	TSI (1)	17.46	14.64	16.15
	TSI (2)	20.38	13.89	31.84
	TSI (3)	23.96	14.83	38.10
4 AWG	SNL	37.8	24.2	36.0
	TSI (1)	35.77	29.74	16.86
	TSI (2)	41.75	28.21	32.43
	TSI (3)	41.75	28.21	32.43
2/0	SNL	113.6	73.5	35.3
	TSI (1)	105.91	87.18	17.68
	TSI (2)	123.6	82.69	33.10
	TSI (3)	131.6	84.82	35.55
* See text for explanation of data sources				

clearly invalid as well. This effect must be accounted for in order to obtain a valid result. Ideally, all three of the cables should be driven to the same temperature before data is taken. In practice, the SNL tests attempted to do this.

E.6 Summary of Test Results

In summary, the SNL test results show that the ampacity derating factors would be 46.4%, 36.0%, and 35.3% for the 8AWG, 4AWG and 2/0 cables respectively. These values are in comparison to the original manufacturer's published values of 16.15%, 16.86% and 17.68% respectively. However, these manufacturer's published values were calculated incorrectly. When (1) the misapplication of the ICEA temperature/ampacity correction factor is corrected, and (2) the actual individual cable hot spot temperatures are considered, fully corrected ampacity derating factors of 38.10%, 32.43% and 35.55%, respectively, are obtained based on the original manufacturer's test results.

The SNL values are generally in agreement with the manufacturer's test data when that data is fully corrected. The remaining differences are fully attributed to the fact that the manufacturer made no attempt to obtain a uniform 90°C hot spot temperature for each individual cable, but rather, set the ampacity of each cable at uniform multiples

of the tabulated standard cable ampacity values. Because of the complex thermal interaction between the various cables, this approach significantly distorts the actual ampacity and ampacity derating values as evidenced by the wide variation in individual cable hot spot temperatures observed in the manufacturer's test.

The largest deviation is for the 8AWG cable in which the SNL result was significantly higher than even the fully corrected manufacturer result. Note, however, that even the manufacturer's data indicates that the derating factor for the 8AWG cable was significantly higher than that of the other cables. It should also be noted that for both the base line and protected tray tests performed by the manufacturer, the 8AWG cable was by far the lowest temperature cable. In the case of the manufacturer's base line test, the 8AWG peak conductor temperature was just 77.8°C, or 12.2°C lower than the desired 90°C value. For the manufacturer's protected tray test, the 8AWG peak conductor temperature was 84.4°C, or 5.6°C lower than the desired 90°C value. While the "fully corrected" manufacture values presented in the SNL analysis have included consideration of these temperatures, this consideration does not fully account for the complex nature of the cable-to-cable interactions present in this test article. Hence, even these "fully corrected" values must be considered suspect, and do not accurately reflect the true behavior of the test article.

No definitive explanation for why the 8AWG ampacity correction factor is significantly higher than that of the other two cables has been identified. The result is not considered anomalous because both the TSI and SNL experiments show significantly higher derating for this cable, and because the examination of two sets of data from the SNL tests eliminates thermal settling effects as a potential cause of anomalous final readings. It is suspected that the configuration of the test article as a "U"-shaped cable tray and the relatively complex nature of the cable loading arrangement introduced radiative heat exchange behaviors inconsistent between the various cable sections, and hence, resulted in different behaviors for each of the three cable sizes.

Figure E.1a: General View of Ampacity Test Chamber

Figure E.1b: Cable Current Supply and Monitoring Systems.

Figure E.1c: View of Left Side of Test Article While Positioned in Test Chamber for Protected Tray Test.

Figure E.1d: View of Right Side of Test Article and Location of "Right Side Ambient" Thermocouple.

Appendix F:
Quality Assurance

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F.1 GENERAL APPROACH TO QUALITY ASSURANCE

All activities performed as a part of this program were subject to Quality Assurance controls. These controls were codified in a written program specific Quality Assurance Plan (QAP). This QAP was developed in the spirit of an NQA1 Quality Assurance Procedures, although the specific quality level designations were modified to suit the needs of this program. In the QAP the level quality assurance controls applied to program activities was made dependent on its importance to the successful completion of the project and to the reliability of the results. The QAP was also developed consistent with the Sandia National Laboratories policy on Quality Assurance, and with the SNL Division 6000 Quality Policy. The following sections provide a brief summary of the Quality Assurance provisions exercised for certain specific aspects of the program.

F.2 PHOTOGRAPHIC DOCUMENTATION

All photographic documentation of project activities was controlled through the use of a "data-back" attachment to the cameras used. Each photographic negative was imprinted at the time of exposure with a 5-digit serial number reflecting (1) the task number, (2) the film roll number for that task, and (3) the specific photograph number for that roll. In addition, log sheets were kept to record the specific conditions being recorded in each photograph. These serial numbers are evident in the figures presented throughout the report.

F.3 MATERIAL CONTROL AND CHAIN OF CUSTODY

All materials used in this program were subject to both receipt inspection and access control. In addition, a full chain of custody was maintained and documented over all program materials, data, test articles, and equipment. These controls included the following:

- All purchased materials, including those not acquired off-the-shelf, were inspected upon receipt to insure compliance with purchase specifications. This included the Thermo-Lag materials themselves, which were obtained through a third party. In this case, a USNRC representative performed a source point inspection to insure that the third party supplier could document compliance with USNRC and manufacturer required quality control and storage procedures.
- Construction and instrumentation of the base test articles was performed by Sandia personnel at the Sandia Albuquerque facilities and under the direct supervision of a designated Sandia project representative. The work site was located within an access controlled building within the Sandia Technical Area I Security Area (a DOE classified access area) which is in turn located on Kirtland Air Force Base. Thus, three levels of security and access control were active.

- Shipment of the base test articles from Sandia to the Chicago area test site was performed through exclusive use of a closed tractor-trailer rig. Upon loading, each door to the trailer was secured by a Sandia project representative using numbered metal seals. The truck was then met at the test site by a Sandia project representative who inspected the seals prior to unloading.
- The Thermo-Lag panel materials were shipped under similar circumstances. That is, a Sandia project representative was present at the time of material pick-up, and at the point of material delivery to the test site. During transit, the trailer was sealed using numbered metal seals.
- The trowel grade Thermo-Lag materials were transported by car from the supplier directly to the test site by a Sandia project representative. During transport, a portable data logger was used to record the temperature history experienced by the material during shipment. Upon arrival at the test site, this temperature record was reviewed to insure that the manufacturer's specified temperature limits had not been violated.
- At the test site, Sandia was given exclusive access to a separate room in the immediate vicinity of the test furnace. All test articles and barrier materials were stored in this room throughout the installation and curing process. The temperature history of this room was recorded using an installed UL temperature monitoring system. At no time during installation and curing of the fire barrier system were the manufacturer's specified temperature limits violated.
- The doors to the Sandia work/storage area were sealed each night using numbered metal seals. A log book was maintained to record the application and removal of each individual seal. At no time during the installation and curing process were the seals broken by other than Sandia project representatives.
- All test activities were performed under the direct observation of Sandia project representatives. In addition, USNRC observers were present at all tests.

F.4 CONTROL OF BARRIER INSTALLATION

The installation of the fire barrier materials was performed by a team of 4 installers. This team included a crew chief (with prior experience as a quality assurance inspector for Thermo-Lag installation), an insulators union supervisor, and two union journeymen (one of which had significant prior experience as a Thermo-Lag installer). All members of the installation crew were provided with training in the installation of Thermo-Lag by a former TSI Technical Representative with extensive experience as a manufacturer installation trainer. This training included both a 3-hour classroom session, and hands-on examination and discussion of the specific Sandia test articles.

In addition, a Sandia project representative was present throughout the installation process. The Sandia project representative inspected and approved all aspects of the installation process and had sole authority to accept or reject installation work. Both of the Sandia project representatives who actively oversaw the installation activities were present at the training session for the installation crew. In addition, all of the Sandia personnel involved in the project were provided with Thermo-Lag installation training during a separate session with the same trainer.

A full curing period of no less than 30 days in a temperature controlled environment was allowed for all installations prior to testing. Again, the test articles were locked and sealed in the Sandia work/storage area throughout this process.

F.5 INSTRUMENTATION

All instrumentation utilized in this program for the recording of test data was calibrated using equipment traceable to NIST standards. This included both Sandia supplied data logging equipment and the UL furnace monitoring and control systems. Further information on instrument calibration is provided in Appendix A.

It should be noted that the thermocouples used for instrumentation of the test articles were insulated with teflon materials. The Type K thermocouples used have a nominal measurement range of -200 to +1250°C. However, the teflon insulation will break down well below this peak temperature, allowing the formation of a false junction at the breakdown point. The exact location of the thermocouple junction, and hence, the measurement point must be considered unreliable at temperatures in excess of 300°C. That is, while a higher thermocouple reading does indicate that the thermocouple has actually reached that temperature at some point along its length, the exact location at which that temperature occurs is indeterminate. This is well above the nominal failure threshold for interior envelope temperature during a fire endurance test.

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