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DOCUMENT TITLE: Duke Power Cure Time Fire Test Analysis

PROJECT NAME: Cure Time Fire Test

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This is the initial issue of this document. This document evaluates the results of the Duke Power Penetration Seal Fire Test conducted on March 2, 2000. Contained within this evaluation are discussions related to the performance of each tested seal assembly, as well as a "failure modes analysis" for those penetrations which allowed the passage of flame during the fire test.

* This Technical Document contains this cover sheet (page i) and pages 1-30 (for a total of 31 pages).

DESIGN VERIFICATION METHOD:

- ☒ Design Review
- ☐ Alternate Calculation
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Duke Power Company
Corporate Fire Protection

Duke Power Cure Time
Fire Test Analysis

Technical Document:
00003-23-0084-F16-005
Revision 0

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1.0 INTRODUCTION

On March 2, 2000, at Omega Point Laboratories (OPL), Duke Power Company conducted an experimental 3-hour fire endurance test of several penetration seal designs. Following the completion of the 3-hour fire endurance portion of the test, a hose-stream test was conducted in accordance with the requirements of IEEE-634 (Reference 7.1) for nuclear generating stations. The results of the test were mixed in that many of the configurations tested were successful and a few of the assemblies failed. This document is being prepared to perform a detailed analysis of the test data to determine individual seal performance, as well as failure modes associated with penetration seal assemblies that allowed passage of flame during the fire endurance test.

In addition, this document contains supplemental information associated with construction of the test assembly and post-test examination. All supplemental information was collected by Duke Engineering & Services (DE&S) as part of DE&S' management of this testing scope for Duke Power Company.

2.0 TEST OBJECTIVES

As indicated in the test plan for OPL Project No. 14980-106206 (Reference 7.2), the intent of the fire test was to obtain performance data related to various penetration seal assemblies sealed with silicone foam (Dow Corning® 3-6548 Silicone RTV Foam) that was installed and allowed to cure for varying times. The pre-established cure times included both baseline seals (i.e., seals allowed to cure for at least 24-hours) and seals with "reduced" cure times (i.e., seals with cure times less than the manufacturer's recommended 24-hour period). The various cure times tested included the following:

- > 24-hour cure time (complete seals only)
- ~ 6-hour cure time (both complete seals and seal repairs)
- ~ 4-hour cure time (both complete seals and seal repairs)
- ~ 2-hour cure time (both complete seals and seal repairs)
- < 30-minute cure time (seal repairs only)

In addition to cure time, an objective of this test was to confirm the results of the 1999 Duke Power fire test (Reference 7.3) with respect to the ability of silicone foam with non-optimal cell structure to perform as well as silicone foam with optimal cell structure.

The final objective of this test was to assess the performance of seals installed with a portion of the material inside sleeve extensions (i.e., outside the plane of the barrier).

3.0 TEST ASSEMBLIES

The following section contains a brief description of each of the tested penetration seal assemblies. More complete descriptions of each test penetration, including "as-built" construction drawings is contained in the final test report prepared by OPL (Reference 7.11). Information provided in this report includes analyses based on raw thermocouple data (provided by OPL) and information collected by DE&S during DE&S' management of this testing scope. The information contained in this document should be used in conjunction with the OPL test plan (Reference 7.2) and the final fire test report (Reference 7.11) to obtain a greater understanding of the actual fire tested configurations.

Note: Throughout this document "reduced" cure times will be referred to as either being ~ 6-hour, ~ 4-hour, ~ 2-hour or < 30-minutes in duration. This designation applies to the time period between the last layer or lift of silicone foam material installed and the beginning of the 3-hour fire endurance test. Because most seals and repairs required multiple lifts (generally 4 to 6 lifts depending upon seal depth), the initial lift may have been installed up to 2 hours before the last lift due to the minimum 15 minute minimum wait time between installation of lifts.

3.1 Penetrations 1, 2, 4 and 5

Each of these penetrations was a 12" diameter x 8" long schedule 40 steel sleeve cast in place through the 8" thick concrete test slab. Each penetration contained a single 2" diameter schedule 40 carbon steel pipe that extended 12" below the slab and 36" above the slab with the a pipe capped installed on the exposed end. Each penetration seal consisted of an 8" depth silicone foam installed between 1" thick ceramic fiber damming boards (Fiberfrax® Duraboard® LD). The damming boards were approximately 16" x 16" and installed such that they overlapped the 12" round opening by at least 2". Both top and bottom side damming boards were secured in place with four (4) mechanical fasteners placed at the corners of the damming boards (1/4" Hilti® HDI Drop-In-Anchors). The only difference between these penetrations was the cure time allowed for each seal. The actual cure times for these penetrations were as follows:

- Penetration 1: ~ 2-hour cure time for the entire seal
- Penetration 2: ~ 6-hour cure time for the entire seal
- Penetration 4: ~ 4-hour cure time for the entire seal
- Penetration 5: > 24-hour cure time for the baseline seal with a repair area adjacent to one side of the pipe (completely through the seal) repaired with silicone foam with ~ 4-hour cure time

3.2 Penetrations 3 and 6

Both of these penetrations were 12" diameter x 8" long schedule 40 steel sleeves cast in place through the 8" thick concrete test slab. Both penetrations contained a cable bundle comprised of jacketed and non-jacketed armored cable supplied by Duke Power Company (see Reference 7.11 for exact cable fill information). The cable bundles extended 12" below the slab and 36" above the slab. Both penetration seals consisted of a 6" depth silicone foam installed between 1" thick ceramic fiber damming boards (Fiberfrax® Duraboard® LD). The damming boards were compression fit into the sleeves such that the outer surface of the damming board was flush with the face of the test slab on both sides of the barrier. The only difference between these penetrations was the cure time allowed for each seal. The actual cure times for these penetrations were as follows:

- Penetration 3: ~ 4-hour cure time for the entire seal
- Penetration 6: > 24-hour cure time for the entire seal

3.3 Penetrations 7 and 8

Both of these penetrations were 12" x 24" unlined blockouts cast in the 8" thick concrete test slab. Both penetrations contained a single 6" x 12" galvanized steel ladder-back cable tray supplied by Duke Power Company. The cable loading for each tray was comprised of jacketed and non-jacketed armored cable supplied by Duke Power Company (see Reference 7.11). The cable trays and associated cables extended 12" below the slab and 28" above the slab (see Appendix E of Reference ?? for a discussion regarding cable and tray length for these penetrations). Both penetration seals consisted of an 8" depth silicone foam installed between 1" thick ceramic fiber damming boards (Fiberfrax® Duraboard® LD). The damming boards were approximately 16" x 28" and installed such that they overlapped the opening by at least 2" on all sides. Both top and bottom side damming boards were secured in place with a combination of mechanical fasteners (both 1/4" Hilti® HDI Drop-In-Anchors and 2-1/4" long Tapcon® Screws with steel washers were used). The only difference between these penetrations was the cure time allowed for each seal. The actual cure times for these penetrations were as follows:

- Penetration 7: > 24-hour cure time for the baseline seal with a repair area inside the tray above the cables (completely through the seal) repaired with silicone foam with ~ 2-hour cure time. Additionally, this seal contained an area sealed with foam exhibiting non-optimal cell structure as described below.
- Penetration 8: > 24-hour cure time for the baseline seal with a repair area inside the tray above the cables (completely through the seal) repaired with silicone foam with < 30-minute cure time

A portion of **Penetration 7** was sealed with silicone foam having non-optimal cell structure. The non-optimal cell structure foam was created by intentionally hand mixing batches of silicone foam with a 1:3 part A to part B ratio. The area sealed with the non-optimal foam was below the cable trays and extended the entire width and depth of the seal (approximately 3" x 24" x 8" deep).

3.4 Penetrations 9, 10, 12 and 13

Each of these penetrations was a 12" diameter x 12" long schedule 40 steel sleeve cast in place through the 8" thick concrete test slab such that the sleeve extended 2" beyond the barrier on both sides. Each penetration contained a single 2" diameter schedule 40 carbon steel pipe that extended 12" below the slab and 36 " above the slab. Two different basic seal designs were used to seal these penetrations as described below.

Penetrations 9 and 12 were each sealed with a 12" depth silicone foam installed without any form of permanent damming. The only difference between these penetrations was the cure time allowed for each seal. The actual cure times for these penetrations were as follows:

- Penetration 9: > 24-hour cure time for the baseline seal with a repair area adjacent to one side of the pipe (approximately 10-1/2" through the seal) repaired with silicone foam with < 30-minute cure time
- Penetration 12: ~ 2-hour cure time for the entire seal

Penetrations 10 and 13 were each sealed with a 10" depth of silicone foam installed between 1" thick ceramic fiber damming boards (Fiberfrax® Duraboard® LD). The damming boards were compression fit into the sleeves such that the outer surface of the damming board was flush with the end of the 12" long sleeve on both sides of the barrier. The only difference between these penetrations was the cure time allowed for each seal. The actual cure times for these penetrations were as follows:

- Penetration 10: > 24-hour cure time for the baseline seal with a repair area adjacent to one side of the pipe (completely through the seal) repaired with silicone foam with ~ 6-hour cure time
- Penetration 13: ~ 6-hour cure time for the entire seal

3.5 Penetrations 11 and 14

Both of these penetrations were 12" diameter x 12" long schedule 40 steel sleeves cast in place through the 8" thick concrete test slab such that the sleeve extended 2" beyond the barrier on both sides. Both penetrations contained a cable bundle comprised of jacketed and non-jacketed armored cable supplied by Duke Power Company. The cable bundles extended 12" below the slab and 36" above the slab. Both penetration seals consisted of a 10" depth of silicone foam installed between 1" thick ceramic fiber damming boards (Fiberfrax® Duraboard® LD). The damming boards were compression fit into the sleeves such that the outer surface of the damming board was flush with the end of the 12" long sleeve on both sides of the barrier. The only difference between these penetrations was the cure time allowed for each seal. The actual cure times for these penetrations were as follows:

- Penetration 11: > 24-hour cure time for the entire seal
- Penetration 14: > 24-hour cure time for the baseline seal with a repair area adjacent to one side of the cable bundle (completely through the seal) repaired with silicone foam with < 30-minute cure time

4.0 SEAL PERFORMANCE

This section contains a detailed analysis of the performance for each individual seal assembly tested. Since certain penetrations were designed to collect data for multiple conditions (e.g., effects of cure time as well as performance of silicone foam with non-optimal cell structure), some analyses may contain multiple discussions, each related to a smaller portion of the larger overall penetration seal.

4.1 Penetrations 1, 2, 4 and 5

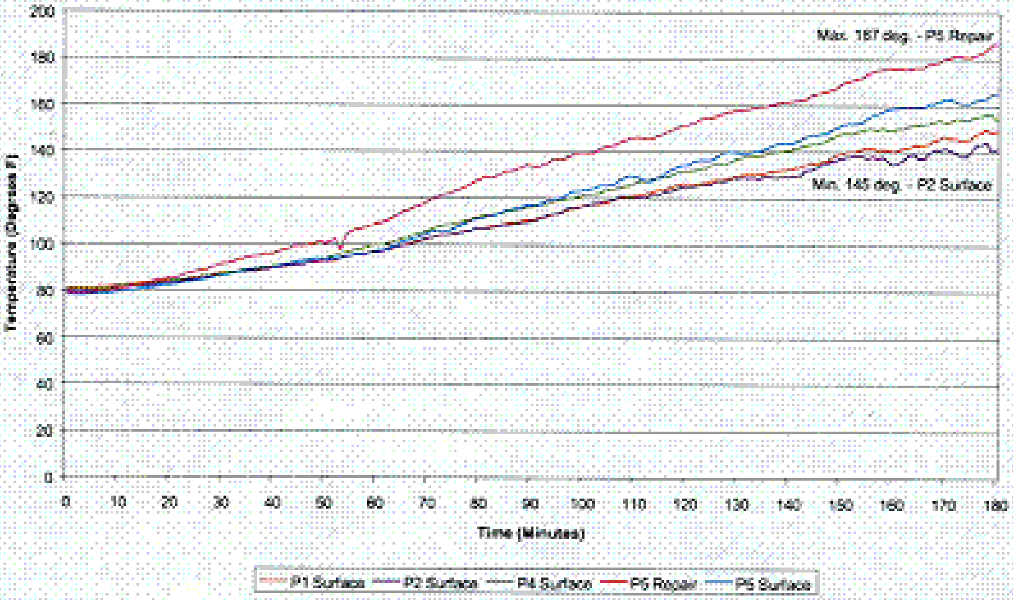
General Seal Performance

Each of these penetrations successfully withstood both the 3-hour fire endurance and hose stream portions of the test. Throughout the fire endurance portion of the test, thermocouple readings for these penetrations trended in a similar manner for temperature readings taken at similar locations for each seal. No significant observations were noted for any of these penetrations during the fire endurance test or subsequent hose stream.

Unexposed Side Temperatures

The performance of all unexposed side temperatures for each of these penetrations was below the Duke Power acceptance criteria for both mechanical (680°F) and electrical (700°F) penetration seals. Additionally, these temperatures were well below the unexposed side seal surface limitation for Catawba electrical penetration seals (325°F plus ambient or ~400°F). A graph depicting the unexposed side temperature profile associated with seal surface temperatures for each of these penetrations is provided below (see Figure 4.1-1).

Figure 4.1-1
Seal Surface Temperatures (Pens. 1, 2, 4 and 5)

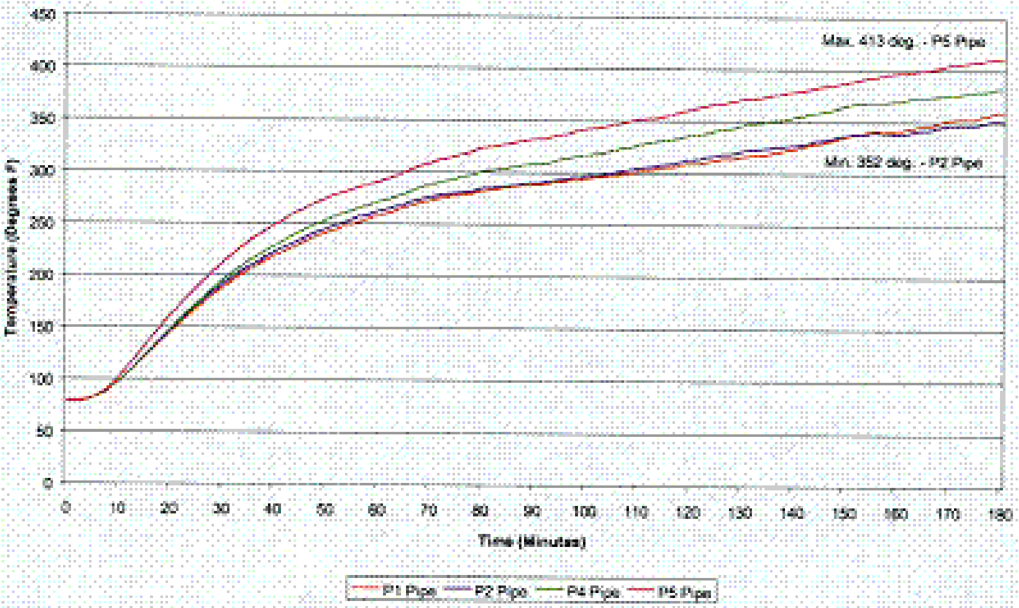


C1

This graph clearly shows that the temperature on the unexposed seal surface of each of the seal assemblies increased gradually throughout the test. The fact that the temperature recorded for the repair area of Penetration 5 was slightly higher than the other seal surface temperatures (187°F as compared to the range of 145°F-166°F) is attributed to the thermocouple's proximity to the pipe. The seal surface thermocouples for Penetrations 1, 2, 4 and 5 were placed at the midpoint between the pipe and edge of the sleeve. This placement resulted in the thermocouples being located about 2-1/2" away from the pipe. The thermocouple over the surface of the repair area was placed near the center of the repair. Since the repair was approximately 3" in diameter and extended out from the pipe, the repair area thermocouple was located about 1-1/2" from the pipe. This determination is further supported by a comparison of this thermocouple (187°F) to the temperature recorded at the interface of the pipe for Penetration 5 which was monitored on the seal surface 1" away from the pipe (194°F for TC#16).

A comparison of penetrating item temperatures (monitored on the pipe at a point 1" above the seal surface) for these penetrations yielded similar results. Throughout the 3-hour test, temperatures monitored on the penetrating pipe for each of these penetrations gradually increased and were in the same general range (see Figure 4.1-2).

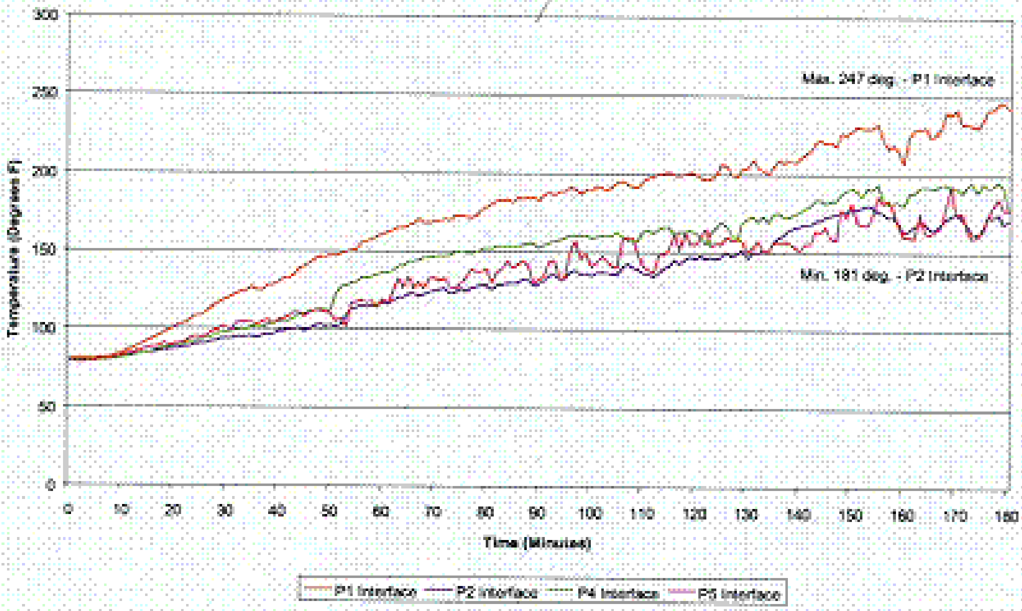
Figure 4.1-2
Pipe Temperatures (Pens. 1, 2, 4 and 5)



C2

Interface temperatures (monitored on the seal surface at a point 1" away from the penetrating item) were also consistent for these penetrations as indicated in Figure 4.1-3 below.

Figure 4.1-3
Interface Temperatures (Pens. 1, 2, 4 and 5)



Post-Test Examination

Post-test examination of these penetrations revealed that each of these seals displayed similar characteristics. In all cases both top and bottom side damming boards were intact with 2"-3" of resilient foam remaining. Consistent throughout each of these seals was the fact that slightly more foam was charred along the pipe interface than the sleeve interface.

Summation for Penetrations 1, 2, 4 and 5

Overall the temperatures recorded on the unexposed side of these penetrations were significantly below Duke Power's acceptance criteria of 700°F for electrical seals and 680°F for mechanical seals. Additionally, the unexposed side seal surface temperature was well below Catawba's acceptance criteria of 325°F + ambient (~400°F) for electrical seal surface temperatures. Based on the comparisons provided above for both thermal and physical performance of these seal assemblies, varying the cure time had no adverse affects on the performance of these penetration seals.

4.2 Penetrations 3 and 6

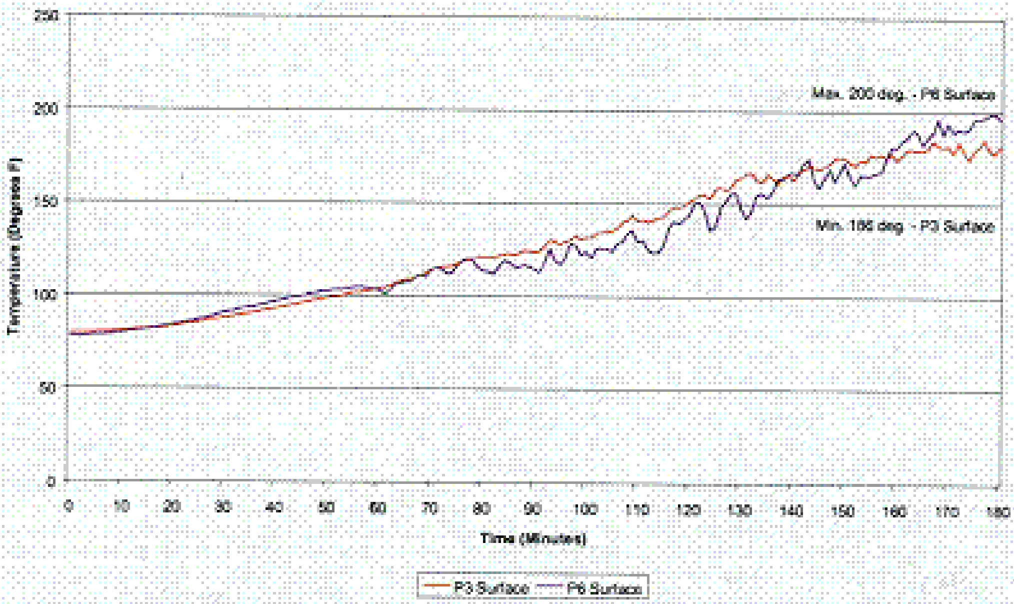
General Seal Performance

Both of these penetrations successfully withstood both the 3-hour fire endurance and hose stream portions of the test. Throughout the fire endurance portion of the test, thermocouple readings for these penetrations trended in a similar manner for temperature readings taken at similar locations for each seal. No significant observations were noted for either of these penetrations during the fire endurance test or subsequent hose stream.

Unexposed Side Temperatures

The performance of all unexposed side temperatures for both of these penetrations was below the Duke Power acceptance criteria for both mechanical (680°F) and electrical (700°F) penetration seals. Additionally, these temperatures were well below the unexposed side seal surface limitation for Catawba electrical penetration seals (325°F plus ambient or ~400°F). A graph depicting the unexposed side temperature profile associated with seal surface temperatures for both of these penetrations is provided below (see Figure 4.2-1).

Figure 4.2-1
Seal Surface Temperatures (Pens. 3 and 6)

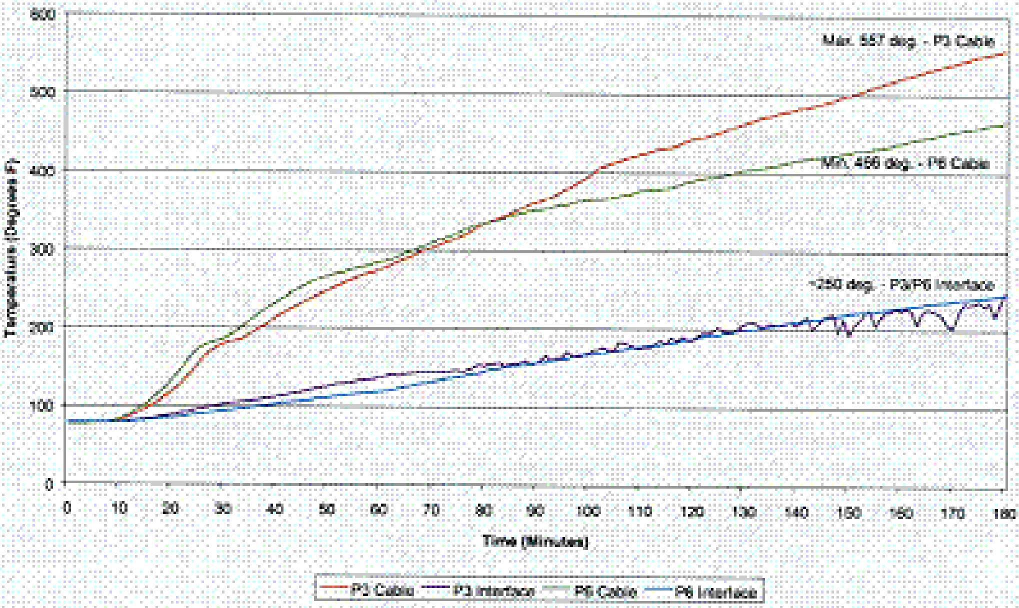


This graph clearly shows that the temperature on the unexposed seal surface of both of the seal assemblies increased gradually throughout the test and remained well below the acceptance limits.

C4

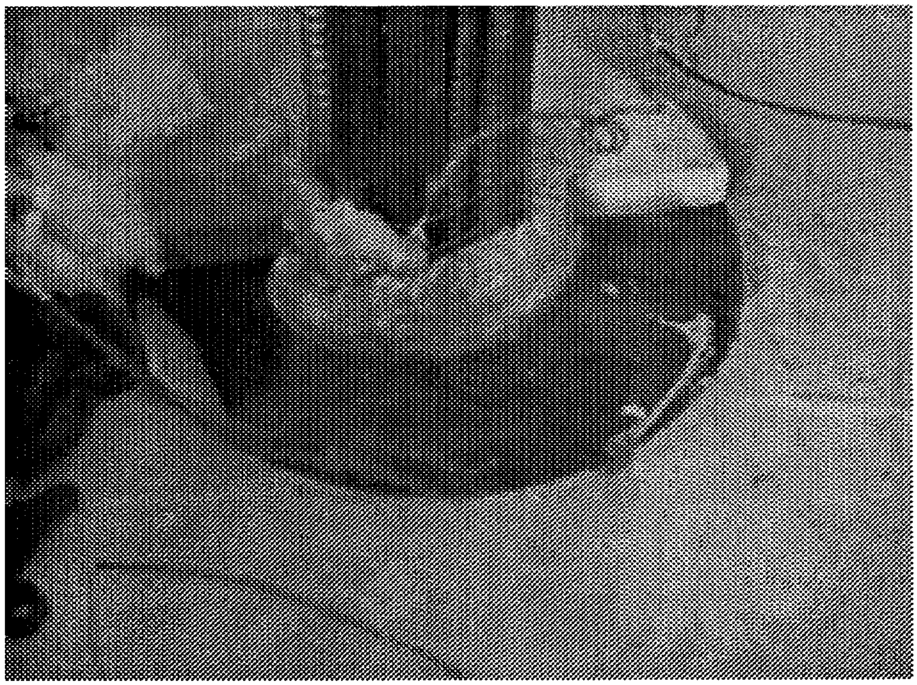
A comparison of penetrating item temperatures (monitored on the largest diameter cable at a point 1" above the seal surface) and interface temperatures (monitored on the seal surface at a point 1" away from the penetrating item) were also consistent for these penetrations as indicated in Figure 4.2-2 below.

Figure 4.2-2
Cable & Interface Temperatures (Pens. 3 and 6)

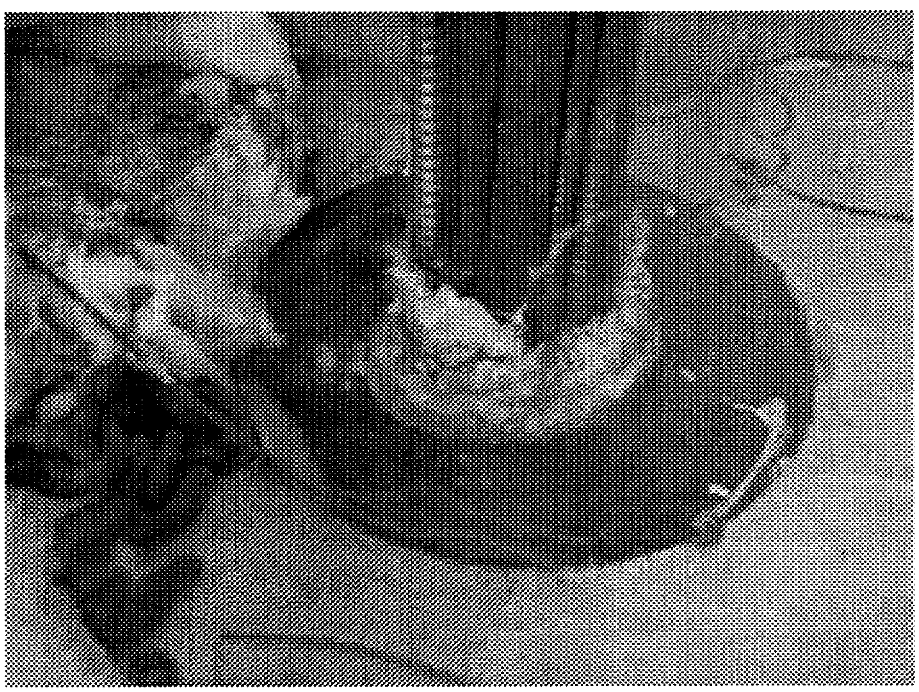


<u>Post-Test Examination</u>

Generally, a post-test examination is performed a few hours after the hose-stream test, once the test specimen has cooled slightly. The time-critical sequence associated with conducting this test necessitated that the fire endurance and hose-stream portions of the test be concluded in late afternoon. Because of this, the post-test examination was scheduled for the next morning. However, immediately following the hose-stream test, it was observed that Penetration 3 was emitting a significant amount of smoke. Because Penetration 3 was only a 6" thick silicone foam seal and a cable bundle was the only penetrating item through this seal, it was believed that if this specimen was allowed to smolder overnight, an accurate post-test examination might not be possible. With this in mind, the top side dam was removed from Penetration 3. With the dam removed it was visually confirmed by personnel from Duke Power, DE&S and Promatec Technologies that a thin layer of resilient foam did indeed remain intact beneath the damming board (see digital photos below taken at 4:34pm on 3/2/00).



Penetration 3 With Partial Top Side Dam Removed



Penetration 3 With All Top Side Damming Removed

Approximately 30 minutes later flaming occurred inside Penetration 3. Omega Point Laboratory personnel extinguished the fire by means of a dry chemical extinguisher. Upon returning to the lab the next morning, it was observed that no material was remaining inside Penetration 3.

The post-test examination conducted for Penetration 6 revealed that approximately ½"-1" of silicone foam remained intact beneath the top side damming board.

Summation for Penetrations 3 and 6

Overall the temperatures recorded on the unexposed side of both of these penetrations were significantly below Duke Power's acceptance criteria of 700°F for electrical seals and 680°F for mechanical seals. Additionally, the unexposed side seal surface temperature was well below Catawba's acceptance criteria of 325°F + ambient (~400°F) for electrical seal surface temperatures. Based on the comparisons provided above for both thermal and physical performance of these seal assemblies, varying the cure time had no adverse affects on the performance of these penetration seals.

4.3 Penetrations 7 and 8

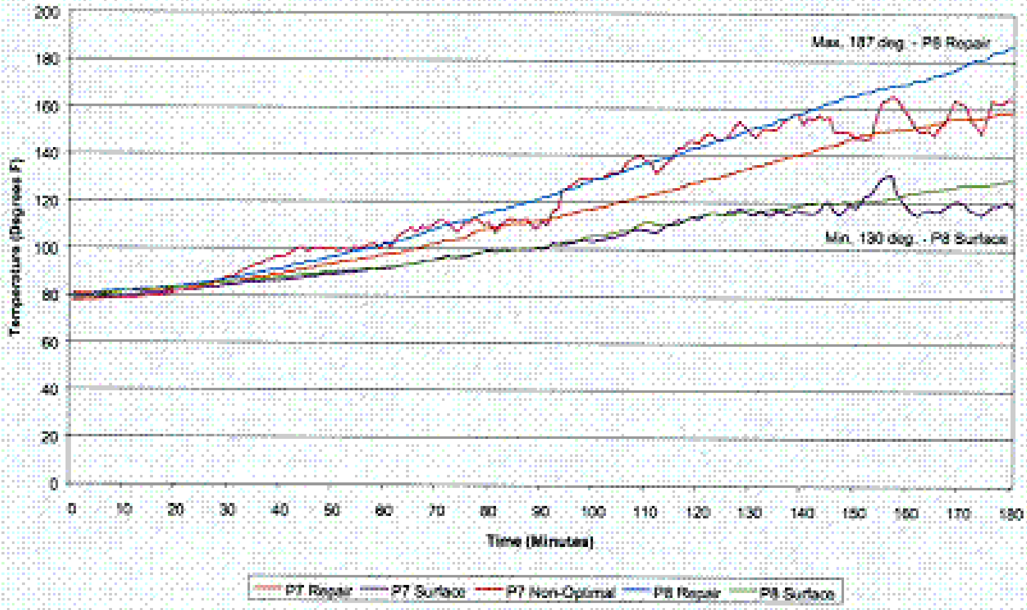
General Seal Performance

Both of these penetrations successfully withstood both the 3-hour fire endurance and hose stream portions of the test. Throughout the fire endurance portion of the test, thermocouple readings for these penetrations trended in a similar manner for temperature readings taken at similar locations for each seal. No significant observations were noted for either of these penetrations during the fire endurance test or subsequent hose stream.

Unexposed Side Temperatures

The performance of all unexposed side temperatures for both of these penetrations was below the Duke Power acceptance criteria for both mechanical (680°F) and electrical (700°F) penetration seals. Additionally, these temperatures were well below the unexposed side seal surface limitation for Catawba electrical penetration seals (325°F plus ambient or ~400°F). A graph depicting the unexposed side temperature profile associated with seal surface temperatures for both of these penetrations is provided in Figure 4.3-1.

Figure 4.3-1
Seal Surface Temperatures (Pens. 7 and 8)



This graph clearly shows that the temperature on the unexposed <u>seal surface</u> of both of the seal assemblies increased gradually throughout the test and remained well below the acceptance limits. Additionally, a review of these thermocouple readings confirms that non-optimal cell structure silicone foam performs thermally in a manner similar to silicone foam that exhibits optimal cell structure.

A comparison of penetrating item temperatures (monitored on the cable tray side rail and largest diameter cable at a point 1" above the seal surface) and interface temperatures (monitored on the seal surface at a point 1" away from the penetrating item) were also consistent for these penetrations as indicated in Table 4.3-2 below.

Table 4.3-2
Penetrating Item & Interface Temperatures

Thermocouple Location	Penetration 7	Penetration 8
Tray (1" above seal on side rail)	275°F	268°F
Tray Interface (1" from tray on seal)	210°F	185°F
Cable (1" above seal on largest OD cable)	405°F	317°F
Cable Interface (1" from cable on seal)	206°F	235°F
* *All temperatures listed are maximum temperatures reached during the 3-hour fire endurance test.*		

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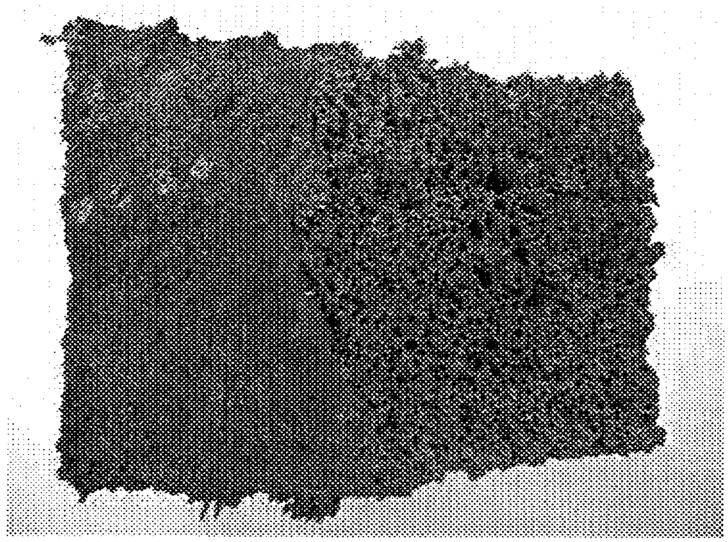
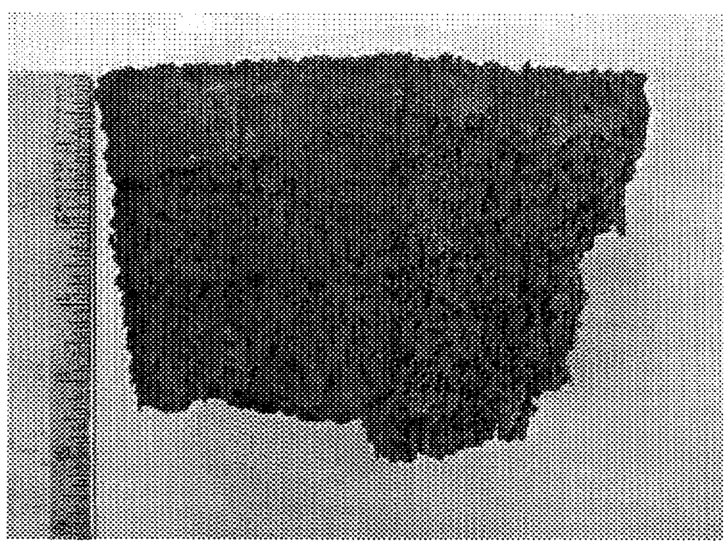
Post-Test Examination

Post-test examination of these penetrations revealed that each of these seals displayed similar characteristics. In both cases both top and bottom side damming boards were intact with 4"-5" of resilient foam remaining. Consistent throughout both of these seals was the fact that slightly more foam was charred along the cable interface than the blockout interface. The non-optimal cell structure foam contained in Penetration 7 appeared to char at the same rate as the silicone foam exhibiting optimal cell structure (see photographs below).

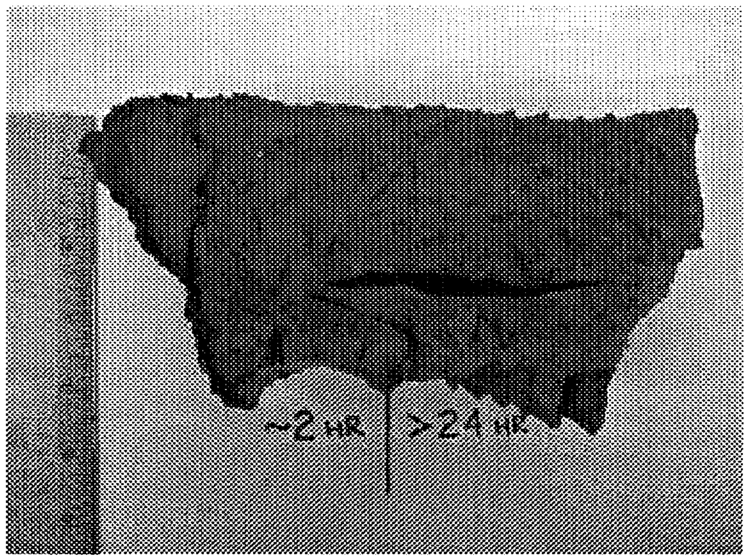


Penetration 7 - Plan View
(Optimal / Non-Optimal Interface)



Penetration 7 - Section View
(Optimal / Non-Optimal Char Depth)

Additionally, there appeared to be no difference in the char depth between the silicone foam that was allowed to cure for more than 24-hours and the reduced cure time foam (~ 2-hour cure for Penetration 7 and < 30-minute cure time for Penetration 8). The photograph below depicts a section of the material removed from Penetration 7. A similar char depth was observed in the corresponding area of Penetration 8.



Penetration 7 Section View
(~ 2-Hour Cure/ > 24-Hour Cure)

<u>Summation for Penetrations 7 and 8</u>

Overall the temperatures recorded on the unexposed side of both of these penetrations were significantly below Duke Power's acceptance criteria of 700°F for electrical seals and 680°F for mechanical seals. Additionally, the unexposed side <u>seal surface</u> temperature was well below Catawba's acceptance criteria of 325°F + ambient (~400°F) for electrical seal surface temperatures. Based on the comparisons provided above for both thermal and physical performance of these seal assemblies, varying the cure time had no adverse affects on the performance of these penetration seals. Additionally, silicone foam with non-optimal cell structure performed the same as silicone foam material installed with optimal cell structure. Thus confirming the conclusion drawn from the March 1999 Duke Power Fire Test and subsequent analysis (References 7.3 and 7.12).

4.4 Penetrations 9 and 12

A detailed analysis of the thermal performance of these penetrations was not conducted because both of these penetrations experienced flame-through during the fire endurance test. Refer to the failure mode analysis for Penetrations 9 and 12 (Section 5.1) for additional discussions related to these penetrations.

4.5 Penetrations 10 and 13

A detailed analysis of the thermal performance of these penetrations was not conducted because both of these penetrations experienced flame-through during the fire endurance test. Refer to the failure mode analysis for Penetrations 10 and 13 (Section 5.2) for additional discussions related to these penetrations.

4.6 Penetrations 11 and 14

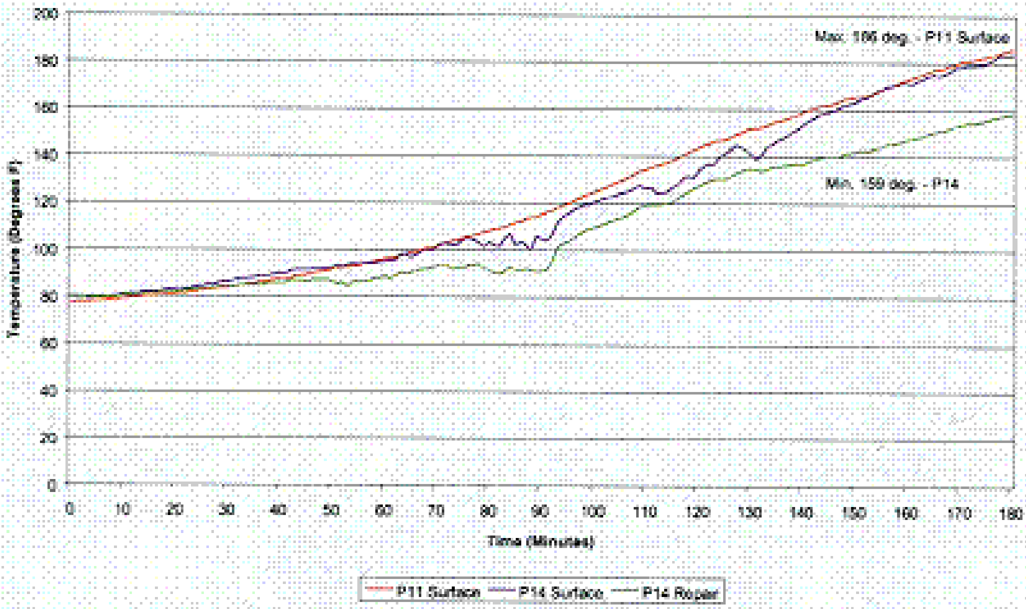
General Seal Performance

Both of these penetrations successfully withstood both the 3-hour fire endurance and hose stream portions of the test. Throughout the fire endurance portion of the test, thermocouple readings for these penetrations trended in a similar manner for temperature readings taken at similar locations for each seal. No significant observations were noted for either of these penetrations during the fire endurance test or subsequent hose stream.

Unexposed Side Temperatures

The performance of all unexposed side temperatures for both of these penetrations was below the Duke Power acceptance criteria for both mechanical (680°F) and electrical (700°F) penetration seals. Additionally, these temperatures were well below the unexposed side seal surface limitation for Catawba electrical penetration seals (325°F plus ambient or ~400°F). A graph depicting the unexposed side temperature profile associated with seal surface temperatures for both of these penetrations is provided below (see Figure 4.6-1).

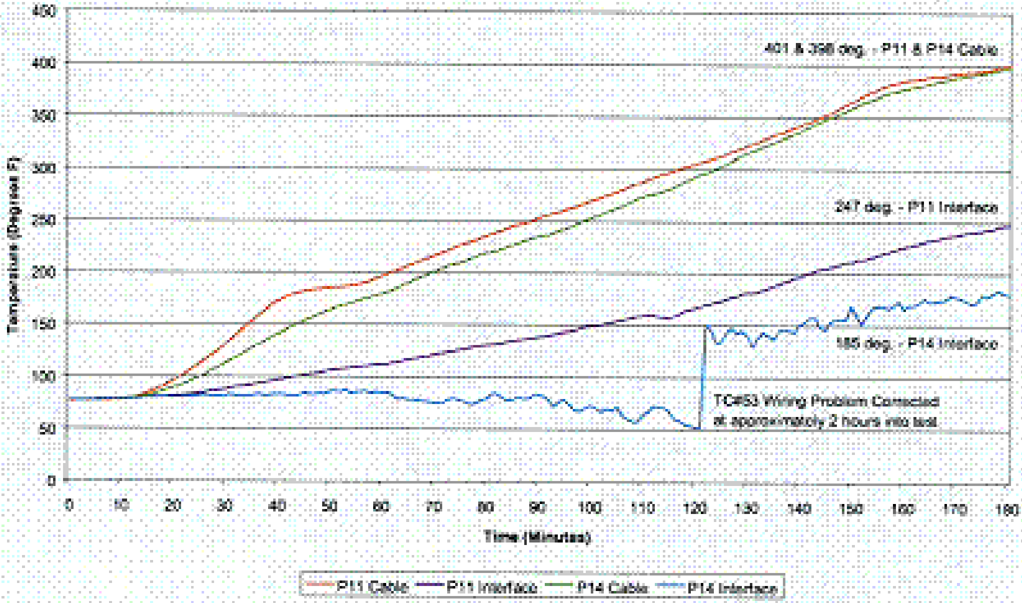
Figure 4.6-1
Seal Surface Temperatures (Pens. 11 and 13)



This graph clearly shows that the temperature on the unexposed seal surface of both of the seal assemblies increased gradually throughout the test and remained well below the acceptance limits. Additionally, the repair area of Penetration 14 (< 30-minute cure time) performed slightly better than the surrounding baseline seals, as evident by the lower endpoint temperature (159°F at 3-hours into the test).

A comparison of penetrating item temperatures (monitored on the largest diameter cable at a point 1" above the seal surface) and interface temperatures (monitored on the seal surface at a point 1" away from the largest penetrating cable) were also consistent for these penetrations as indicated in Figure 4.6-2 below.

Figure 4.6-2
Cable & Interface Temperatures (Pens. 11 and 14)



It should be noted that the thermocouple leads for TC #53 were inadvertently crossed. Omega Point Laboratory personnel identified this condition at approximately 2 hours into the fire endurance test. Upon correcting the wiring error, TC #53 began to record accurate data. Based on relatively low endpoint temperature for this thermocouple, and considering the temperature profile of the corresponding thermocouple for Penetration 11, there is no reason to believe that temperatures near the acceptance limits were approached at any time during this test at this location. Therefore, this error has no adverse impact on the validity of the test results.

Post-Test Examination

The post-test examination conducted for Penetrations 11 and 14 revealed that a similar amount of silicone foam (approximately 2"-3") remained intact beneath the top side damming board. Consistent throughout both of these seals was the fact that slightly more foam was charred along the cable interface (~2" remaining) than the sleeve interface (~3" remaining).

Summation for Penetrations 3 and 6

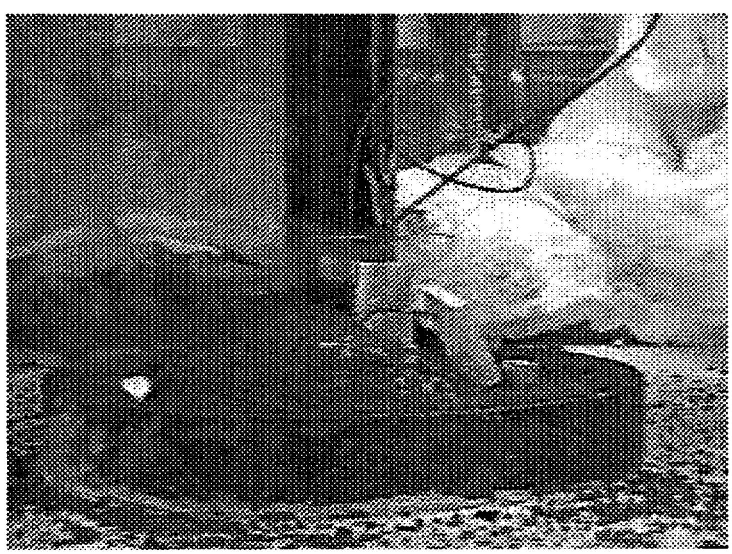
Overall the temperatures recorded on the unexposed side of both of these penetrations were significantly below Duke Power's acceptance criteria of 700°F for electrical seals and 680°F for mechanical seals. Additionally, the unexposed side seal surface temperature was well below Catawba's acceptance criteria of 325°F + ambient (~400°F) for electrical seal surface temperatures. Based on the comparisons provided above for both thermal and physical performance of these seal assemblies, varying the cure time had no adverse affects on the performance of these penetration seals.

5.0 FAILURE MODES ANALYSIS

Based on Section 4.0, Seal Performance, a failure mode analysis was performed for Penetrations 9, 10, 12 and 13. A failure mode analysis was not performed for any other tested penetrations, since all remaining penetrations did not fail during the fire endurance and hose stream tests.

5.1 Penetrations 9 and 12

Approximately 2-hours into the fire endurance test, it became obvious that Penetration 9 was going to fail due to passage of flame. The unexposed side of the seal had formed an inverted cone extending several inches above the original seal surface on the pipe (see photograph below).



Penetration 9
(Unexposed Side At ~2 Hours)

At 2-hours and 17-minutes the temperature monitored on the pipe exceeded the 680°F acceptance limit. Cracks had developed on the surface of the seal material, and an orange glow could be seen illuminating from the cracks. A few minutes later (approximately 2-hours and 20-minutes into the test), intermittent flaming occurred along the cracks in the seal surface. Penetration 9 was declared a failure. Fire resistant ceramic blanket material was placed over Penetration 9 to allow the fire test to continue.

Penetration 12 failed in a manner similar to Penetration 9 at approximately 2-hours and 30-minutes into the fire endurance test. This penetration was also covered with ceramic blanket material so that the fire test could continue.

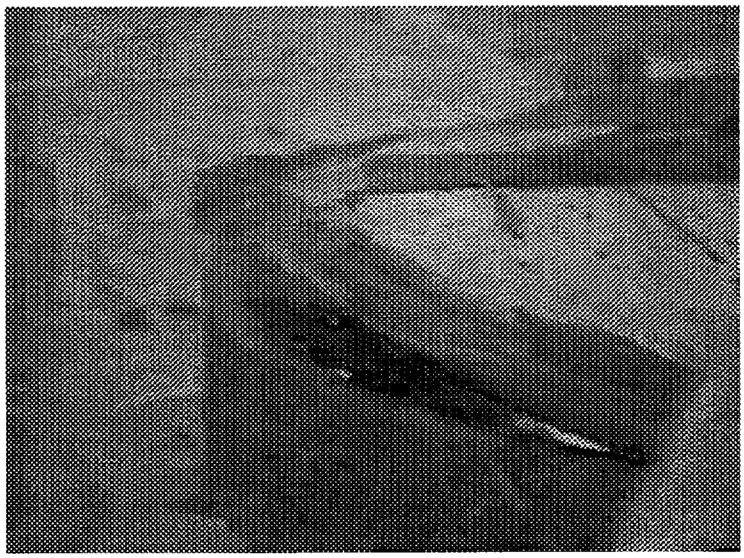
There were essentially two failure modes associated with Penetrations 9 and 12. First, the penetrating pipes exceeded the limiting endpoint temperature of 680°F at 2:13 (hr:min) for Penetration 12 and 2:17 (hr:min) for Penetration 9. The second failure mode associated with Penetrations 9 and 12 was the flaming which occurred on the unexposed side of the penetrations (~2:20 for Penetration 9 and ~2:30 for Penetration 12). The failure of these penetrations is attributed to two conditions; 1) the presence of seal material inside a sleeve extension immersed in the furnace, and 2) the fact that the fire test was conducted at positive pressure.

The 12" long schedule 40 steel pipe sleeves were cast in the 8" thick concrete test slab such that the sleeves extended 2" beyond the test slab on both sides of the barrier. The 12" thick silicone foam penetration seals were installed flush with each end of the sleeves. This resulted in 2" of the seal (and corresponding steel sleeve) extending inside the furnace. Therefore, throughout the fire endurance test, portions of both seals were subjected to flame impingement from the furnace on 5 sides, as opposed to seals installed completely within the barrier which are subjected to fire from only one side. Due to this, the initial 2" depth of the seal was consumed at a faster rate than normal. Once this occurred there was a greater amount of exposed steel sleeve, which resulted in a greater amount of heat being transferred into the seal. This scenario, combined with the adverse effects of the positive furnace pressure, as discussed in Section 5.3, ultimately lead to the silicone foam being consumed at a rate greater than previously observed in other industry fire tests.

5.2 Penetrations 10 and 13

Approximately 2-hours into the fire endurance test, it became obvious that Penetration 13 was going to fail due to passage of flame. The unexposed side damming board had lifted above the sleeve due to thermal expansion of the silicone foam material. At 2:06 (hr:min) into the test, the temperature monitored on the pipe exceeded the 680°F acceptance limit. A few minutes later (approximately 2-hours and 10-minutes into the test), intermittent flaming occurred beneath the top side damming board. Penetration 13 was declared a failure. Fire resistant ceramic blanket material was placed over Penetration 13 to allow the fire test to continue.

Penetration 10 failed in a manner similar to Penetration 13. At 2:38 (hr:min) into the test, the temperature monitored on the pipe exceeded the 680°F acceptance limit. At approximately 2-hours and 40-minutes into the fire endurance test, Penetration 10 was declared a failure (see photograph below). This penetration was also covered with ceramic blanket material so that the fire test could continue.



Penetration 13
(Unexposed Side At Failure ~2hrs. 40 mins.)

There were essentially two failure modes associated with Penetrations 10 and 13. First, the penetrating pipes exceeded the limiting endpoint temperature of 680°F at 2:06 (hr:min) for Penetration 13 and 2:38 (hr:min) for Penetration 10. The second failure mode associated with Penetrations 10 and 13 was the flaming which occurred on the unexposed side of the penetrations (~2:10 for Penetration 13 and ~2:40 for Penetration 10). The failure of these penetrations is attributed to three conditions; 1) the presence of seal material inside a sleeve extension immersed in the furnace, 2) premature catastrophic loss of the bottom side damming board, and 3) the fact that the fire test was conducted at positive pressure.

The 12" long schedule 40 steel pipe sleeves were cast in the 8" thick concrete test slab such that the sleeves extended 2" beyond the test slab on both sides of the barrier. The 10" thick silicone foam penetration seals were recessed 1" from the end of the sleeves to allow the permanent damming board to be installed flush with the sleeve ends. Both top and bottom side damming board was compression fit into the sleeves. This resulted in the bottom side damming board and initial 1" of the seal (and corresponding steel sleeve) extending inside the furnace. Therefore, throughout the fire endurance test portions of both seals were subjected to flame impingement from the furnace on 5 sides, as opposed to seals installed completely within the barrier which are subjected to fire from only one side. Due to this, the 1" depth of silicone foam beyond the barrier plane was consumed at a faster rate than normal. Once this occurred there was premature failure of the bottom side damming board and a greater amount of exposed steel sleeve, which resulted in a greater amount of heat being transferred into the seal. This scenario, combined with the adverse effects of the positive furnace pressure, as discussed in Section 5.3, ultimately lead to the silicone foam being consumed at a rate greater than previously observed in other industry fire tests.

Note: Had the bottom side damming board been mechanically fastened in place or otherwise attached in a more secure manner, it is believed that Penetrations 10 and 13 would have successfully withstood the fire endurance and hose-stream tests as evidence by the performance of Penetrations 11 and 14.

5.3 Effects of Furnace Pressure

Silicone foam undergoes a physical change when subjected to direct flame impingement from fire or is exposed to elevated temperatures (> 400°F) for an extended period of time. The physical change process results in the silicone foam material changing from a soft, resilient state to a hard, brittle state. This change in physical appearance is often referred to as "charring." While this change in physical properties results in a material that is no longer self-supporting, the charred silicone foam material does exhibit excellent insulating properties. Because of this, seal systems that require the use of permanent ceramic damming materials generally perform quite well during a fire endurance test despite the charred silicone foam material because the damming material keeps the charred silicone foam in place.

Through numerous reviews of industry related fire endurance tests, it has been observed that two variables significantly influence the rate at which silicone foam chars; 1) the presence of damming material, and 2) the thermal mass of through metallic components. First, the presence of permanent ceramic fiber damming material (board, blanket or bulk form) dramatically reduces the rate at which silicone foam chars by shielding the silicone foam from direct flame impingement. In addition to this, the permanent damming material slows the charring process by limiting the amount of oxygen available within the seal, and thus reducing the possibility of flaming internal to the seal assembly. As discussed above, an added benefit of the damming material is its ability to contain any charred silicone foam material in place, which enhances overall seal performance. The second parameter that substantially impacts silicone foam char rate is the thermal mass of through metallic components. Industry fire testing has demonstrated that as pipe size increases, so does the amount of heat transferred into and through the seal. This results in a greater char depth over a given period of time (i.e., a faster char rate) than a similar assembly containing a smaller sized pipe. Again, this is supported by numerous industry tests, including Duke Power Company's Slab 5 test (Reference 7.4) as summarized in Table 5.3-1.

Table 5.3-1
Duke Power Slab 5 Test Char Depth Comparison

Pen. No.	Sleeve Size	Pipe Size	Field Temp.	Interface Temp.	Pipe Temp.	Char Depth
14B	14"	10"	326°F	657°F	455°F	9"
12F	12"	8"	216°F	487°F	376°F	6"
12G	12"	4"	186°F	393°F	323°F	5"

In addition to the presence of damming material and the thermal mass of through metallic components, it is now believed that a third variable (furnace pressure) also significantly influences the rate at which silicone foam chars. Through careful analysis of performance data associated with Penetrations 9, 10, 12 and 13, it was observed that the time to failure (burn through) for these penetrations was significantly sooner than anticipated based on previous industry fire tests of silicone foam seals installed at the same depth. In an attempt to determine a reason why failure of these penetrations occurred so early, data from several previous tests of silicone foam penetrations was assembled for comparison. While information from a dozen or so tests was initially considered, commonality between basic designs tested, as well as the level of information provided in final test reports, ultimately lead to the following seven (7) fire tests being used for comparison.

Table 5.3-2
Industry Fire Tests

Fire Test Number	Fire Test Abbreviation	Reference Number
Dow Corning Test No. 1	DC1	Reference 7.5
ICMS Test NMP2-PSS7	PSS7	Reference 7.6
ICMS Test NMP2-PSS8	PSS8	Reference 7.7
ICMS Test NMP2-PSS9	PSS9	Reference 7.8
ICMS Test ICO1091035	ICMS1035	Reference 7.9
Duke Power Test from 1999	DP1999	Reference 7.3
Duke Power Test from 2000	DP2000	As discussed in this Report

From this set of fire tests, the following types of information were extracted; opening size; opening type; penetrating items; furnace pressure; test duration; minimum and maximum char depth. Test duration, minimum char depth and maximum char depth data was then used to approximate minimum and maximum char rates expressed in inches per hour.

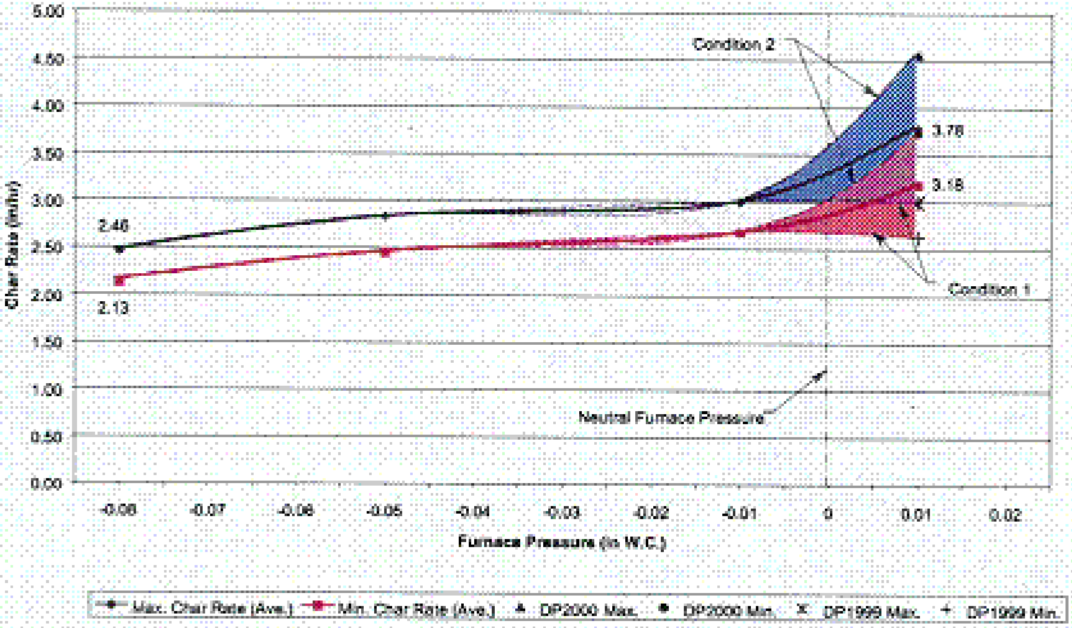
Table 5.3-3
Industry Fire Test Data Used for Comparison

Test ID Number*	Silicone Foam Seal Depth	Opening Size	Opening Type	Penetrating Items	Furnace Pressure	Tested Duration (Minutes)	Max. Char Depth (Inches)	*Max. Char Rate (Inches/hr.)*	Min. Char Depth (Inches)	*Min. Char Rate (Inches/hr)*
DC1-A1	9"	8"	Core-bore	None	-.08	180	7.75	*2.58*	7.25	*2.42*
DC1-A2	9"	8"	Core-bore	None	-.08	180	7.75	*2.58*	7.25	*2.42*
DC1-A3	9"	8"	Core-bore	None	-.08	180	7.125	*2.38*	6.625	*2.21*
DC1-A4	9"	8"	Core-bore	None	-.08	180	7	*2.33*	7	*2.33*
DC1-A5	9"	4"	Core-bore	None	-.08	180	7.25	*2.42*	7	*2.33*
DC1-A6	9"	4"	Core-bore	None	-.08	180	6	*2.00*	6	*2.00*
PSS7-1	12"	12"	Steel Sleeve	2" Pipe	-.08	180	9.75	*3.25*	6	*2.00*
PSS9-2	12"	6"	Steel Sleeve	None	-.08	180	8.5	*2.17*	4	*1.33*
PSS8-1	12"	8"	Steel Sleeve	4" Flex Cond.	-.05	180	7	*2.33*	5.5	*1.83*
PSS8-2	12"	6"	Steel Sleeve	Cable Bundle w/ Kellum Grip	-.05	180	8	*2.67*	7.25	*2.42*
PSS8-3	12"	6"	Steel Sleeve	Cable Bundle (25% fill)	-.05	180	10.5	*3.50*	8	*2.67*
PSS8-5	12"	6"	Steel Sleeve	Cable Bundle (50% fill)	-.05	180	9.25	*3.08*	8.25	*2.75*
PSS8-6	10"	6"	Steel Sleeve	Cable Bundle (50% fill)	-.05	180	7.75	*2.58*	7.75	*2.58*
ICMS1035-3	12"	12"	Steel Sleeve (Sch. 40)	None	-.01	180	9	*3.00*	8	*2.67*
DP1999-6	12"	12"	Steel Sleeve (Sch. 40)	None	> +.01	160	8	*3.00*	7	*2.63*
DP2000-9	12"	12"	Steel Sleeve (Sch. 40)	2" Pipe	> +.01	140	11	*4.71*	9	*3.86*
DP2000-12	12"	12"	Steel Sleeve (Sch. 40)	2" Pipe	> +.01	150	11	*4.40*	9	*3.60*

* Test ID Number is comprised of the fire test abbreviation from Table 5.3-2, followed by a dash "-" and the penetration number as identified in the associated fire test report.

Figure 5.3-4 depicts the relationship between silicone foam char rate and furnace pressure using minimum and maximum char rate profiles developed by normalizing the data from Table 5.3-3.

Figure 5.3-4
Char Rate vs. Furnace Pressure



From Figure 5.3-4 it is apparent that the rate at which silicone foam chars increases as furnace pressure increases. Because a majority of test data available within the industry was conducted in negative furnace pressure environments, the graph is clearly defined to the left of the neutral furnace pressure plane. However, only the Duke Power fire tests from 1999 and 2000 provide data points from tests exposed to positive furnace pressure environments, and each of these tests contained an anomaly. Therefore, the graph to the right of the neutral furnace pressure plane requires further explanation.

The Figure 5.3-4 lines associated with ***Condition 1*** represent the minimum and maximum char rate profiles if the data from the March 1999 Duke Power test is used. Char rate profiles following Condition 1 lines are known to be lower than actual char rates based on the fact that the 1999 Duke Power test was terminated at 2 hours and forty minutes. Actual char rates would be higher based on the intensity of an E-119 exposure during the final twenty minutes of a three-hour fire endurance test. Additionally, Penetration 6 from this test consisted of a 4" silicone foam build-out that overlapped the sleeve by a minimum of 4" in all directions on the exposed side of the test slab. This condition resulted in the steel sleeve being shielded from the furnace environment for a considerable portion of the fire endurance test, thereby slowing the silicone foam char rate. This condition was unlike any other configuration from the tests used to collect comparison data.

C9

The Figure 5.3-4 lines associated with ***Condition2*** represent the minimum and maximum char rate profiles if the data from the March 2000 Duke Power Test is used. Char rate profiles following Condition 2 are known to be higher than actual char rates based on the fact that a 2" portion of the seal was contained inside a 2" length of the steel sleeve that protruded into the furnace. This condition resulted in the initial 2" of the seal being subjected to the extreme furnace environment from essentially 5 sides as opposed to a seal within the plane of the test slab that is exposed to the furnace environment from 1 side only. Thereby accelerating the rate at which the initial 2" of the seal was consumed. Similar to Condition 1, this condition was unlike any other configuration from the test data used for comparison.

Ultimately, the portion of the Figure 5.3-4 graph to the right of the neutral furnace pressure plane was based on the mid-point between Condition 1 and Condition 2 data. Arbitrarily selecting the mid-point of each data set to complete the Figure 5.3-4 graphs only serves to show that char rates continue to increase as furnace pressure increases (at least through +.01" W.C.). The actual char rate profile would fall within the shaded areas of the graph. In fact, silicone foam char rates may actually increase dramatically when tested in a positive furnace pressure environment due to the positive furnace pressure continually fanning the char layer of the seal. The fanning phenomenon has been credited in recent testing of wooden fire doors as a probable factor in the failure of door assemblies tested at positive furnace pressure.

Note: The fire door industry is in the process of converting to standards that require positive furnace pressure testing. As a result some assemblies that were previously listed as rated assemblies (under negative furnace pressure conditions) have failed fire tests performed to the new positive pressure criteria.

5.4 Furnace Pressure vs. Differential Pressure

The results of varying furnace pressure as discussed above should not be confused with testing standard requirements, staff guidance or actual fire test results associated with penetration seals required to maintain differential pressure. Many of the Duke Power fire tests conducted in the 1978 timeframe were conducted under differential pressure conditions (Reference 7.4). Such tests were typically performed using a vacuum enclosure on the unexposed side of the test specimen. Differential pressure between the furnace and the unexposed side of the test specimen was then controlled by means of exhausting air from and occasionally forcing air into the vacuum enclosure. This method of testing is intended to simulate end use applications of penetration seals installed in barriers required to be pressure boundaries. Under such conditions it would be possible to expose a test specimen to a negative furnace pressure environment while maintaining a greater negative pressure inside the vacuum enclosure, thus establishing a positive differential pressure condition. While this method does simulate a penetration seal subjected to a fire under positive differential pressure conditions, it does not yield the same results as testing in a positive furnace pressure environment.

In 1984, the Division of Engineering Technology, Office of Nuclear Reactor Research (NRR), contracted Underwriter's Laboratories Inc. to conduct a series of small scale fire tests aimed at evaluating the effects of various fire test parameters (Reference 7.10). The affect of varying differential pressure was one of the test parameters evaluated by the project. Similar to the Duke Power testing, a vacuum enclosure was used on the unexposed side of the test slab to create many of the differential pressure environments. A total of twenty-four experiments were conducted on the parameter of differential pressure (only 23 are listed in Tables 1 and 2 of the report). Thirteen of the experiments were conducted on silicone foam seal assemblies installed without permanent damming. According to Tables 1 and 2 all except 1 of the experiments (experiment 20) were conducted under positive differential conditions (not necessarily a positive furnace pressure environment). Results of these experiments concluded that slight variations in the differential pressure did not significantly affect seal performance provided the differential pressure was positive.

Again, these conclusions should not be confused with the results of Section 5.3 above. Because the differential pressure was controlled by means of an enclosure on the unexposed side of the test specimen, the intensity of the fire was not changed. These conclusions demonstrate that positive differential pressures ranging from +.01" water column (W.C.) to +.50" W.C. do not significantly affect seal performance for the small scale designs tested. Obviously the results may not be the same for larger sized openings with greater spans of seal material. Section 5.3 conclusions suggest that varying the furnace pressure would result in a noticeable difference in seal performance.

6.0 CONCLUSIONS

Based upon the results of this report, the following conclusions can be made relative to the objectives of this test:

6.1 Silicone Foam Cure Time

Objective: Assess the impact of varying cure time on the performance of penetration seal designs comprised of silicone foam.

Conclusions: The manufacturer's recommended cure time for silicone foam is excessively conservative for installation of limited quantities of silicone foam similar to that represented in the fire test. Both complete seals and repairs to existing seals allowed to cure from as much as 6 hours and as little as ~25 minutes performed in a manner similar to identical seals allowed to cure in excess of 24 hours. This conclusion applies to configurations either with or without permanent damming material as the failure of Penetrations 9 and 12 (no damming material) are attributed to conditions other than seal material cure time.

6.2 Silicone Foam Cell Structure

Objective: Confirm the results of the 1999 Duke Power fire test with respect to the ability of silicone foam with non-optimal cell structure to perform as well as silicone foam with optimal cell structure.

Conclusions: The results of the this fire test, in conjunction with Duke Power's Experimental Penetration Seal Fire Resistance Test from May 12, 1999 (Reference 7.3), demonstrate the ability of silicone foam with non-optimal cell structure to perform similarly to optimal foam with respect to fire resistance. This applies to configurations that use permanent damming materials, since configurations without permanent damming have not been tested for this condition.

6.3 Sleeve Extensions

Objective: Assess the performance of seals installed with a portion of the material inside a sleeve extension (i.e., outside the plane of the barrier).

Conclusions: Seal designs that require permanent damming material (mechanically fastened or otherwise securely held in place) may have a portion of the seal installed inside a sleeve extension (outside the plane of the barrier) based on test Penetrations 11 and 14. The failure of Penetrations 10 and 13 are attributed to conditions other than the sleeve extension.

Sufficient data was not obtained to assess the impact of sleeve extensions for seal designs that do not require the use of permanent damming material based on the unexpected failure of Penetrations 9 and 12. The failure modes analysis for Penetrations 9, 10, 12 and 13 concluded that the adverse affects of positive furnace pressure contributed significantly to the failure of these penetrations. Therefore, the acceptability of sleeve extensions for seal designs without permanent damming material is indeterminate at this time.

7.0 REFERENCES

7.1 IEEE-634, "IEEE Standard Cable Penetration Fire Stop Qualification Test," 1978 Edition.

7.2 Omega Point Laboratories Test Plan for Project No. 14980-106206, "Experimental Three Hour Fire Resistance Test of Silicone Foam Penetration Seal Designs For Duke Power Company," revision 0, dated February 24, 2000 (a.k.a. DE&S Technical Document 00003-23-0084-F16-004).

7.3 Omega Point Laboratories Test Report for Project No. 14980-104516 "Experimental Penetration Fire Resistance Test," dated May 12, 1999 (a.k.a. DE&S Technical Document 00003-23-0065-F16-008).

7.4 Duke Power Company Slab No. 5, "Fire Qualification Test On Silicone Foam Floor Penetration Seals," September 20, 1978 (conducted at Southwest Research Institute, San Antonio, TX; SwRI Project No. 03-5656-001).

7.5 Dow Corning Fire Test No. 1, "Fire and Hose Stream Tests of Penetration Seals – Dow Test No. 1," October 1984 (conducted at Construction Technology Laboratories, Skokie, IL; CTL Project CR5465-4324 Doc. ID # 1191E).

7.6 ICMS Fire Test ICCO286016, "Fire and Hose-Stream Tests for Penetration Seal Systems (NMP2-PSS7)," March 1986 (conducted at Construction Technology Laboratories, Skokie, IL; CTL Project CR5853 / 4324 Doc. ID # 1613E).

7.7 ICMS Fire Test ICCO386017, "Fire and Hose Stream Tests for Penetration Seal Systems (NMP2-PSS8)," April 1986 (conducted at Construction Technology Laboratories, Skokie, IL; CTL Project CR5853 Doc. ID # 1619E).

7.8 ICMS Fire Test ICCO286018, "Fire and Hose Stream Tests for Penetration Seal Systems (NMP2-PSS9)," April 1986 (conducted at Construction Technology Laboratories, Skokie, IL; CTL Project CR5853 Doc. ID # 1617E).

7.9 ICMS Fire Test ICO1091035, "3 Hour Fire Resistance Evaluation of Ten Different Fire Penetration Seal Designs," November 11, 1991 (conducted at Omega Point Laboratories, Elmendorf, TX; OPL Project No. 11200-92180).

7.10 NUREG/CR-4112-V2, "Investigation of Cable and Cable System Fire Test Parameters. Task B: Firestop Test Method," January 1985 (conducted at Underwriter's Labs. Inc., Northbrook, IL).

7.11 Omega Point Laboratories Test Report for Project No. 14980-106206 "Experimental Penetration Fire Resistance Test," dated May 17, 2000 (a.k.a. DE&S Technical Document 00003-23-0084-F16-006).

7.12 DE&S Technical Document 00003-23-0065-F16-005, "Duke Power Penetration Seal Fire Test Analysis," revision 1, dated August 11, 1999.