Fire-Induced Failure Mode Testing for dc-Powered Control Circuits[1]

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Abstract: The U.S. Nuclear Regulatory Commission, in concert with industry, continues to explore the effects of fire on electrical cable and control circuit performance. The latest efforts, which are currently underway, are exploring issues related to fire-induced cable failure modes and effects for direct current (dc) powered electrical control circuits. An extensive series of small and intermediate scale fire tests has been performed. Each test induced electrical failure in copper conductor cables of various types typical of those used by the U.S. commercial nuclear power industry. The cables in each test were connected to one of several surrogate dc control circuits designed to monitor and detect cable electrical failure modes and effects. The tested dc control circuits included two sets of reversing dc motor starters typical of those used in motor-operated valve (MOV) circuits, two small solenoid-operated valves (SOV), one intermediate size (1-inch (25.4mm) diameter) SOV, a very large direct-acting valve coil, and a switchgear/breaker unit. Also included was a specialized test circuit designed specifically to monitor for electrical shorts between two cables (inter-cable shorting). Each of these circuits was powered from a nominal 125V battery bank comprised of 60 individual battery cells (nominal 2V lead-acid type cells with plates made from a lead-cadmium alloy). The total available short circuit current at the terminals of the battery bank was estimated at 13,000A. All of the planned tests have been completed with the data analysis and reporting currently being completed. This paper will briefly describe the test program, some of the preliminary test insights, and planned follow-on activities.

Keywords: Fire PRA, Electrical Circuits, Cable Failure Mode and Effects, Spurious Actuation.

1. INTRODUCTION

One of the fire protection issues identified as a result of the 1975 cable fire at the Browns Ferry Nuclear Power Plant (NPP) was the potential that fire-induced cable failures could lead to the spurious operation of plant systems and equipment. Efforts to resolve this issue continue at both the Nuclear Regulatory Commission (NRC) and among NRC licensees. In 2000-2001, the Nuclear Energy Institute (NEI) along with the Electric Power Research Institute (EPRI) and in collaboration with the NRC Office of Nuclear Regulatory Research (RES) conducted a preliminary series of experiments investigating cable failure modes and effects [1,2]. Follow-on studies were undertaken by RES in 2005-2006 to further investigate these behaviors [3]. Both of these investigations utilized alternating current (AC) powered control circuits only. In 2006, Duke Energy performed a series of similar tests focusing on the behavior of armored cables, a cable configuration utilized widely at the Duke plants. The Duke Energy tests again included AC-powered control circuits, but also included a limited set of tests on direct current (dc) powered control circuits.

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DC-powered control circuits play an important role in the safety strategy for most U.S. nuclear power plants. DC systems provide a diverse and independent backup to the primary AC-powered systems and are relied upon under conditions when AC power is lost (e.g., station blackout). The dc systems provide an additional level of safety and protection against plant accidents and are unique in that they are powered entirely by on-site power sources (banks of station batteries).

The proprietary Duke Energy test results provided indications that in some regards the behavior of dc-powered circuits is unique in comparison to corresponding AC-powered circuits. In particular, all of the tests conducted to date involving AC control circuits have observed that, following the initial fire-induced cable failures, protective fuses in the surrogate control circuits would typically clear after a relatively short period of time (ranging from less than one second to a maximum of roughly 20 minutes). In contrast, in several of the dc tests, the protective fuses never cleared despite obvious and extensive cable damage. The Duke Energy test set was limited in scope and utilized experimental systems that were not entirely representative of typical plant practice. In particular, the Duke Energy tests utilized a dc battery bank made up from automotive type lead-acid batteries. The total available short circuit fault current was much lower than would be typical of an actual power plant station battery bank (some hundreds of amperes for the test system as compared to on the order of 20,000A or more for a typical Class 1E station battery bank). As a result, the test results were considered inconclusive.

Given the results of the Duke tests and the relative importance of dc-powered control circuits to plant safety and post-fire safe shutdown, the Office of Nuclear Reactor Regulation (NRR) determined that a more complete and representative investigation of dc-powered circuit/cable failure modes and effects was needed. Based on an NRR request a testing program to address this need was initiated by RES at Sandia National Laboratories (SNL) during the summer of 2008. Shortly after the program's inception, the U.S. commercial nuclear power industry, through the Electric Power Research Institute (EPRI), requested that the investigation be performed as a collaborative effort under the terms of an existing memorandum of understanding between RES and EPRI. NRC accepted this proposal and work on the effort began in earnest during the fall of 2008.

2. OVERVIEW OF ELECTRICAL TESTING APPROACH

The program tested five different dc control circuits commonly found in NPP applications; namely, dc reversing motor starters such as those used to control a motor operated valve (MOV), a small (pilot) solenoid-operated valve (SOV), a medium sized (1 inch (25.4mm) diameter) direct-acting vent-type SOV, a large (8 inch) direct acting valve coil, and a large (15kV) switchgear breaker assembly. Surrogate test circuits were constructed to simulate and monitor the performance of each of these circuit types. In the case of the MOV and the small pilot SOV, two each of the surrogate circuits were constructed. Each surrogate circuit is integrated with an actual end-device of the type described (i.e., a motor starter, solenoid valve, valve coil or switchgear unit). The EPRI collaboration made available the motor starters for the MOV circuits, both the medium and large SOV valve/coil, and the switchgear unit. The pilot SOVs were procured based on typical industry specifications.

Figure 1: Photograph of the 60-cell battery bank used in testing.

The various control circuits were powered from a relatively large 60-cell lead-acid dc battery bank providing fault currents that are of the same order as typical station batteries (13,000A maximum fault current). The battery cells were made available to the test program through the EPRI collaboration. Figure 1 provides a photograph of the 60-cell battery bank.

The focus of the testing is on cable failure modes and effects, so each of the surrogate control circuits is connected to an electrical cable in the same way as it would be connected to control cables in an actual NPP application. The connected cable is then exposed to a fire environment, either in a well controlled small scale radiant heating apparatus or in actual fire compartment with a gas burner and burning cables. The voltage and current signals for each conductor in each circuit are then monitored throughout the thermal exposure. Analysis of the test data can determine how the circuit behaved once fire-induced cable shorting was observed. Of particular interest is the potential for spurious activation of the control circuit functions. The control circuits are not actively exercised during the test, but if certain short circuits occur, the circuits can experience spurious actuations (motor operators can close, valves can change position, the breaker can close or trip open, etc.)

Also constructed was a specialized circuit designed to monitor explicitly for cable-to-cable (or inter-cable) shorting between a number of source cables and a single target cable. This inter-cable circuit was specifically looking for a "smart" dc short; i.e., a short circuit that involves at least one conductor in the target cable shorting to the positive side of the battery bank and at least one other conductor in the same target cable shorting to the negative side of the battery bank. For certain types of dc control circuits a smart-short of this type is required to actuate the system.

The final test circuit of interest is a ground fault detection circuit for the overall battery bank. The battery bank is operated in an ungrounded mode reflecting common practice in NPP dc systems (i.e., neither the positive nor negative sides of the battery bank are connected to the local earth ground). However, the first short circuit between an energized cable and any of the grounded test structures holds the potential to ground the battery bank. For example, if a conductor connected to the positive side of the battery bank shorts to a grounded cable tray or conduit, then the battery bank as a whole becomes grounded. The grounding status of the battery bank can change over the course of a test as various short circuits are observed and as circuit protective fuses clear. A separate circuit is provided to monitor the status of the battery bank grounding through the course of the test. This data is vital to interpreting the other behaviors that occur during the test.

3. FIRE EXPOSURE CONDITIONS

The testing involved both small- and intermediate-scale tests. The overall approach paralleled that of the earlier CAROLFIRE project and both test facilities are described in detail in the project report [3]. The small-scale testing apparatus is known as Penlight. Test samples, in this case the control cables, are placed in the center of a cylindrical steel (inconel) shroud that measures approximately 20 inches (0.51m) in diameter and 32 inches (0.81m) long. The outside of the shroud is heated by a set of computer-controlled quartz lamps to a desired set-point temperature. The shroud is painted flat-black on both the inner and outer surfaces and acts as an intermediate radiant heating surface between the lamps and the test sample. That is, the lamps heat the shroud and the shroud, in turn, heats the test sample. The radiant exposure intensity is easily calculated based on grey-body radiant heating equations.

For this program, as in the previous CAROLFIRE testing, the cables were routed through Penlight either in open ladder-style cable trays or in rigid metal conduit. Figure 2 provides a photograph of Penlight in the cable tray configuration. Note that for testing, the ends of the exposure shroud are closed off with insulating board material to minimize air flow through the exposure region during testing. Penlight tests generally involved two energized sample cables (one cable connected to each of two dc circuits) plus a third cable monitored for temperature response. One goal of the small-scale tests was to verify the proper operation of each of the dc surrogate circuits and to ensure that the failure modes and effects behavior could be elicited from the test data. The second primary goal was to provide an initial exploration of the dc failure modes and effects behaviors for various thermoset and thermoplastic cable types.

The intermediate-scale tests were also essentially identical to the test configuration used in the previous CAROLFIRE test program. The test setup involves a propylene gas burner placed under a partially-enclosed metal framework with cable trays and raceways passing through the upper part of the framework. The upper portion of the framework is enclosed on the top and all four sides down 4 feet (1.2m) from the top. The lower portion of the framework is open on all four sides. The intent of the framework is to capture hot gasses from the fire and to create a damaging hot gas layer condition. This framework is enclosed within a larger test facility. Figure 3 provides a general schematic of the intermediate-scale test apparatus. Note that the test framework is scaled to match the overall dimensions of an ASTM E603 standard test enclosure.

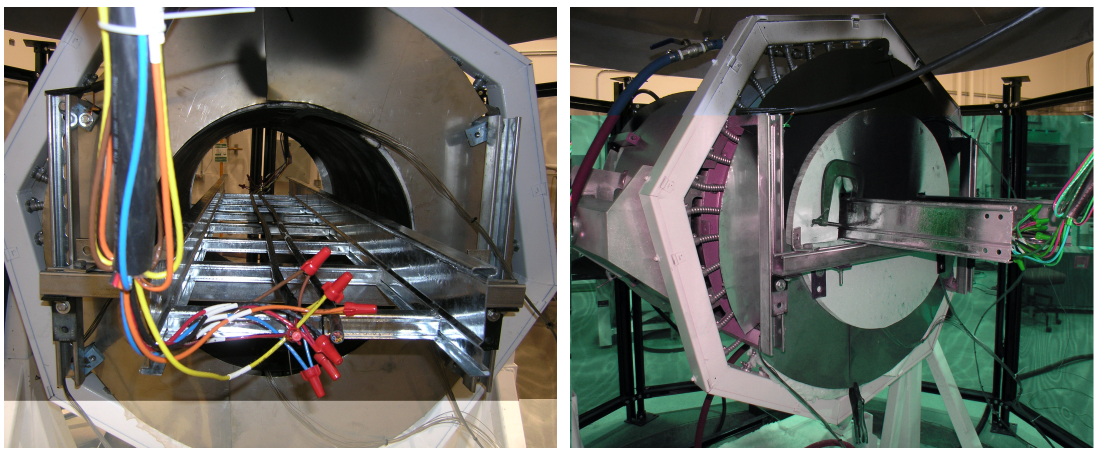

Figure 2: Penlight testing apparatus shown with a cable tray in an open configuration (left) and with the cylinder ends covered by an insulating board and ready for testing (right).

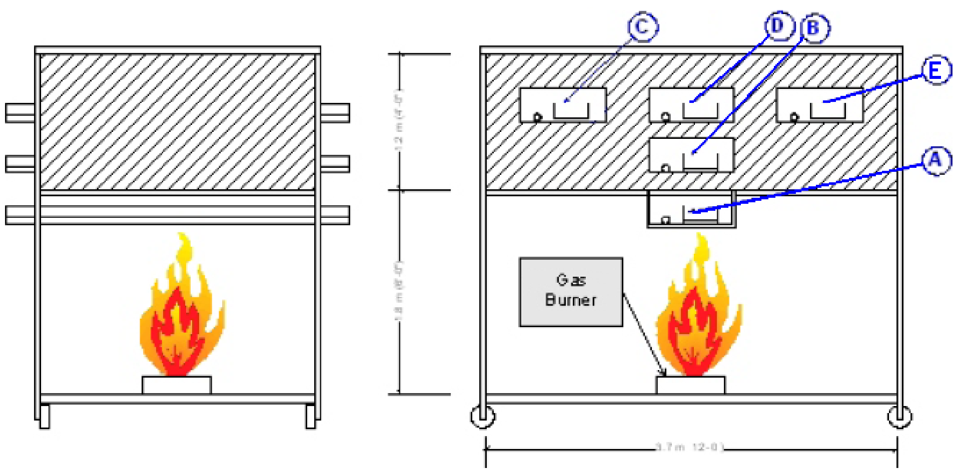

Figure 3: Intermediate-scale test framework.

The objective of the intermediate-scale tests was to assess the circuit failure modes and effects behaviors under more realistic conditions. Tests in the intermediate scale generally involved energized cables embedded in a random-fill cable tray arrangement. In some cases, especially for the trays located in positions 'A' and 'B' as shown in Figure 3, trays were fully loaded with cables. For trays in other (side) locations, only a partial fill was used. The trays used in testing are standard 12 inch (300mm) wide galvanized steel trays. A typical partial fill tray would have cables only in the central 1/3 of the cable tray (across the tray width) with a roughly 3-inch (76mm) deep fill. This typically meant 3-4 layers of cable. The energized sample cables would be embedded within this cable mass. Each such cable mass was typically comprised of 16-20 individual cable lengths typically including two energized cables. Figure 4 is a photograph showing cable trays of both types (fully loaded and partial fill) being prepared for testing.

4. SUMMARY OF THE TEST CONDITIONS AND VARIABLES

The small-scale tests focused primarily on cable type, circuit type, and routing configuration as the primary tests variables. The exposure intensity (i.e., shroud temperature) was also varied but to a limited degree. Once a reasonable exposure temperature for a given cable was determined, one leading to failure in roughly 10-20 minutes, subsequent tests of that cable tended to use the same exposure temperature. The desired exposure temperature was different for each of the different cable types tested, but once determined, was generally held constant across the testing of each cable type. The cable types included essentially all of the cable types tested in CAROLFIRE, plus a sample of armored cables and Kerite™ insulated cable provided by industry. Cables included both thermoset and thermoplastic insulation types. Most of the tested cables were of a 7- or 8-conductor configuration and typically had 12AWG conductors. Routing conditions included both cable trays and conduits. No air-drop (no raceway) tests were performed for the dc circuits.

Figure 4: Photograph of full-fill (left) and partial-fill (right) cable trays being prepared for testing.

As in the Penlight test, the intermediate scale tests varied the cable type used on each circuit. The intermediate scale tests also varied the location of the cables in the facility. Generally, each test location (‘A’ through ‘E’ as shown in Figure 4) contained two-to-four energized cables, and all of the dc circuits were utilized in every intermediate scale test. Locations A and B are typically within the gas burner’s flame zone and represent the most severe exposure conditions. Location D is typically outside the flame zone of the burner itself but within the burner plume. Cables at Location D will experience flame impingement as the cables at Locations A and B burn. Locations C and E are outside the plume and outside the flame zone so these locations experience only hot gas layer exposure conditions.

5. PRELIMINARY TEST INSIGHTS

The analysis of test data is currently ongoing so only preliminary insights have been developed. However, those preliminary insights do confirm certain observations made during the Duke Energy tests and highlight that the dc cable faulting behaviors are unique in comparison to corresponding AC circuits.

One of the first behavioral differences noted during testing was the fact that the dc faults were generally more energetic than were the faults observed with the AC circuits in previous testing. In the case of the AC circuits, cable electrical failure is typically accompanied by minor arcs followed relatively quickly by a fuse-blow which de-energizes the circuit. These arcs were readily observed and sufficient to ignite the cables in most cases. The dc cable failures also generated arcs, but by comparison, the arcs generated by the dc cable failures are far more energetic. The arcs also tended to be short-lived and, in the case of the larger fuses (15A and 35A) generally were not of sufficient duration to cause the protective fuses to activate (blow to an open circuit condition). In the case of the dc cables, the arcing behavior is not only sufficient to ignite the heated cables, but was also sustained for a longer period of time and often times was sufficient to actually melt the conductors. Figure 5 illustrates typical post-test conditions observed. This illustration is taken from a Penlight test, but similar behavior was also noted in the intermediate scale tests. Note that some of the conductors have been broken (melted) and that pieces of copper conductor and copper slag are evident laying on the inside-bottom of the Penlight exposure shroud. These faults were also sufficient in many cases to either weld a conductor to the metal rungs of the cable tray and/or to burn holes into the tray rungs.

Figure 5: Photograph of a typical case where arcing faults resulted in conductors being severed during testing (note the cable on the left in this photo).

A second observation is relative to fuse clearing. In practice, dc circuits are often fused at a higher level than are corresponding AC circuits. For example, a typical AC MOV circuit would typically be fused at about 3A whereas a typical dc MOV circuit would be fused at 10A. The largest fuses in use in this test program are those associated with the switchgear trip circuit (the switchgear close and trip/open circuits are fused separately). This circuit uses 35A fuses. In testing, it was quite common for the 5A and 10A fuses to clear during each test. However, in the case of the 35A fuses clearing of a fuse due to cable faulting was actually a rare event despite post-test conditions such as those illustrated in Figure 5 (i.e., extensive cable damage often including broken conductors). In many cases, the broken conductors would actually remain energized until the battery disconnect was opened to isolate the test cables from the battery bank. In previous testing with the AC systems no case was ever observed where an open circuit conductor failure occurred (i.e., the conductor was severed or melted during testing) and yet the conductor remained energized.

A third observation is relative to the duration of observed spurious actuations. Again, the data have not been fully analyzed at this time and, in this particular case, additional efforts are planned to review and assess the test data in the context of spurious actuation likelihood and duration (see discussion below) via an expert panel exercise. However, it can be stated that in general terms, longer duration spurious actuation were observed in the dc circuit testing than had been observed in the prior AC circuit testing. For example, in at least one case a dc MOV motor starter held a spurious actuation for in excess of one hour. As noted previously, the longest spurious actuation observed for any AC MOV test was on the order of 20 minutes. It is likely that fusing practices are a significant factor in this behavior.

6. PLANNED FOLLOW-ON ACTIVITIES

One of the key topics that must still be addressed is to assess the implications of the dc circuit testing results for fire Probabilistic Risk Assessment (PRA) applications. A modern fire PRA is expected to treat the potential for fire-induced spurious actuations as a part of the risk analysis. This is, for example, embodied directly into the recently developed PRA standards [4]. The RES/EPRI consensus fire PRA methodology [5] documents analysis methods for this aspect of the fire PRA. In general, the current methodology guidance was based on insights gained from the prior AC circuit testing efforts. As noted above, the dc testing has highlighted certain behavioral differences for dc circuits; hence, a review of the current methodology guidance in the context of dc circuits is appropriate.

The NRC's current plans call for the formation of an expert panel to address this topic. The panel will include two teams, one team made up of primarily electrical experts and a second team made up primarily of PRA and statistical analysis experts. Both teams will follow established NRC processes for Phenomena Identification and Ranking Table (PIRT) exercises in their deliberations. The PIRT process is, in effect, a structured and facilitated expert panel.

The electrical team will focus on the review and interpretation of the test data. The panel will attempt to develop consensus positions regarding exactly what occurred in each of the tests. The interpretation of the test data does require some considerable effort. The intent is that SNL will provide a preliminary and strictly factual assessment of the test data in its data report. Final interpretations of the test behaviors and implications will be developed by this first expert panel. For example, the expert panel will assess if and when spurious actuations did occur, and the corresponding duration of those spurious actuations signals. This first panel will also attempt to identify those key factors that should be considered when analyzing fire-induced failure modes and effects for dc circuits and will attempt to group circuits configurations based on these characteristics.

The intent is for the second team, the PRA and statistics experts, to utilize the output from the first expert panel and make recommendations as to how the data should be applied to fire PRA. This second panel will consider define the best-estimate values for spurious actuation likelihood and duration to be used in fire PRA. This second team will also engage in a PIRT exercise and will make recommendations what phenomena would be most important to explore further if additional testing is undertaken. NRC would utilize these results in the potential planning of future tests.

7. SUMMARY AND CONCLUSIONS

The issues related to fire-induced cable failure modes and effects, including the spurious actuation of equipment and systems, have been recognized since at least 1975. Efforts to address these issues for NPPs are ongoing. During past years efforts to investigate these issues were focused mainly on AC-powered control circuits. Quite recently an effort has been undertaken to investigate corresponding issues and behaviors for dc-powered control circuits. A series of small-scale and intermediate scale tests has been completed to investigate cable failure modes and effects for dc-powered control circuits. The results do confirm that in some regards, dc circuits are unique and that application of insights gained from the testing of AC circuits would not reflect these unique behaviors. Data processing is ongoing, and future efforts will include the convening of two expert panels to first interpret the available test data and then to assess the implication of the test results for fire PRA methods. Based on preliminary test insights, areas illustrating unique behaviors include the intensity of the arcing observed when cables short circuit, fusing practices and the implications for clearing of protective fuses, the potential for open-circuit conductor faults that leave conductors energized, and the potential duration of conductor-to-conductor hot shorts.

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9. REFERENCES

[1] D. Funk and E. Davis, *Characterization of Fire-Induced Circuit Faults,* EPRI, TR-1003326, December 2002.

[2] F.J. Wyant and S.P. Nowlen, *Cable Insulation Resistance Measurements Made During Cable Fire Tests*, NUREG/CR-6776, SAND2002-0447P, U.S. NRC, June 2002.

[3] S. P. Nowlen and F. J. Wyant, *Cable Response to Live Fire (CAROLFIRE),* NUREG/CR-6931, SAND2007-600, a report in 3 volumes, U.S. NRC, April 2008.
[4] *Addenda to ASME/ANS RA-S–2008 Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications*, ASME/ANS, Ra-Sa-2009, February 2009.
[5] S.P. Nowlen, B. Najafi, et.al., *EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, a joint publication of EPRI and the U.S. Nuclear Regulatory Commission*, EPRI TR-1011989, NUREG/CR-6850, a report in 2 volumes, September 2005.

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