Electric Fire Pump Controller Inspection, Test & Maintenance Arc Flash Hazard White Paper

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Arc Flash Description

The occurrence of an arc flash involves the rapid release of energy through an arcing fault between a phase bus bar and another phase bus bar, neutral, or a ground. Initiation of such an event can be caused by contamination or tracking over insulated surfaces, dust, dropping tools, accidental touching, condensation, material failure, corrosion, or faulty installation, among others means. An arc fault causes an ionization of the air and resultant formation of highly conductive plasma through which a sustained arc is established and maintained until such time that the current is interrupted. As the temperature of the arc increases, the resistance of the plasma path decreases causing an increasing current flow and resultant increase in temperature, quickly elevating the severity of the event. The temperature of the arc flash can reach as high as 35,000°F. These temperatures can cause severe burns to human skin, the ignition of nearby combustibles, and even liquefy or vaporize metal parts in the vicinity of the event, including copper, aluminum, and steel. The resultant rapid volumetric expansion of material (conservatively estimated as up to 40,000 to 1 – vaporing copper expands 67,000 times its mass) in transitioning from a solid to a vapor creates an explosive pressure with sufficient concussive force to cause physical damage to equipment and severe injury to personnel within the area. The blast pressure can exceed 2000 lb/ft^2 with a pressure wave velocity exceeding 700 mph. Damaging sound waves (as high as 140-160 dB) and flash injuries can occur resulting in loss of hearing and vision. These injuries can be very severe including death of the exposed individual.

Arc Flash Hazard

The provisions of NFPA 25 (2017 Edition), Sections 4.9.6 and 8.3.3.11 provide that legally required precautions must be taken when testing or maintaining electric controllers for motor-driven fire pumps. The provisions of NFPA 25, Sections A.8.3.3.11 and A.4.9.6 further provide a reference for the user to NFPA 70E (2015 Edition) for additional safety guidance. NFPA 25, Section A.4.9.6 also provides warning of the unusual hazard associated with electric fire pump installations that installed in accordance with NFPA 20 which discourages the installation of a disconnect in the power supply connection. In the United States the provisions of 29 CFR 1910.333(c) provide that individuals working on exposed live parts must be qualified and must be familiar with the proper use of special precautionary techniques, personal protective equipment (PPE), insulating and shielding materials, and insulated tools. Furthermore, the provisions of the General Duty Clause of 29 U.S.C. §654(a)(1) provide an overarching requirement that employers shall furnish to each of his/her employees a place of employment, which is free from recognized hazards that cause, or are likely to cause, death or serious physical harm to the employee. This provides a baseline statement that marks the utmost importance of safety in the conduct of work and sets a basis of such in requiring that safety be paramount in the conduct of any work application.

The provisions of NFPA 70E (2015 Edition), Section 130.5 require that an arc flash risk assessment be performed to determine if an arc flash hazard exists for any electrical installation. Where an arc flash hazard is found to exist, the risk assessment shall also determine the appropriate safety related work practices required, the arc flash boundary distances (location at which the incident energy equals 1.2 cal/cm^2), and the required PPE necessary for work conducted within such boundary distances. The results of this assessment must be documented as provided by NFPA 70E, Section 130.5(3)(A). The electrical equipment itself must include labeling that specifically indicates 1) the nominal system voltage, 2) the arc flash boundary, and 3) at least one of the following: a) the available incident energy and corresponding working distance or the arc flash PPE category needed for work on the equipment (but not both), b) the minimum arc rating of clothing, or c) site-specific level of PPE as provided by NFPA 70E, Section 130.5(3)(D). The owner of the electrical equipment is responsible for the documentation, installation and maintenance of this field-marked labeling.

Unfortunately, the application of such labeling and availability of risk assessment documentation has been found to be virtually nonexistent in current fire pump installations. Where an inspector is faced with conducting work inside an energized unlabeled electric fire pump controller without proper documentation they have no means to determine what specific level of PPE is necessary for the safe completion of such work and as such should not engage in the activity.

Arc Flash Boundary

The determination of the arc flash boundary can be established by calculating the incident energy in accordance with Annex D of NFPA 70E, or through the use of NFPA 70E, Table 130.7(C)(15)(A)(b) for alternating current systems, but only where the specific designated provisions of the Table apply to the conditions being considered. A typical fire pump installation is considered a motor control center (MCC) with a voltage rating of 600V or less. For this type of equipment Table 130.7(C)(15)(b) includes two separate line entries. The first entry allows for a maximum available short circuit current of 65kA with a maximum fault clearing time of 0.03 seconds (2 cycles) and requires an arc-flash boundary of 5 ft. The second entry allows for a maximum available short circuit current of 42kA and the maximum fault clearing time of 0.33 seconds (20 cycles) and requires an arc-flash boundary of 14 ft. It is important to understand that these are just examples of the calculated arc flash boundary distance under those specific conditions indicated. Under any other conditions beyond these specific limits for short circuit current and clearing time indicated in Table 130.7(C)(15)(A)(b), the exact conditions must be individually assessed. A select number of recognized methods for such calculations are provided in Annex D of NFPA 70E.

Required Arc Flash PPE

Similarly, the determination of the required arc flash PPE can be established by conducting an incident energy analysis to determine the incident energy exposure level at the anticipated working distance of the employee's face and chest area from the prospective arc flash source for the specific task being performed, as provided in Annex D of NFPA 70E or it can be established using the PPE Category Method as included in NFPA 70E, Table 130.7(C)(15)(A)(b) for alternating current systems where the specific provisions of the Table apply to the conditions being considered. Again, a typical fire pump installation is considered a motor control center (MCC) with a voltage rating of 600V or less. For this type of equipment, Table 130.7(C)(15)(b) includes two separate line entries. The first entry allows for a maximum available short circuit current of 65kA with a maximum fault clearing time of 0.03 seconds (2 cycles) and requires Category 2 PPE arc-flash protection. The second entry allows for a maximum available short circuit current of 42kA and the maximum fault clearing time of 0.33 seconds (20 cycles) and requires Category 4 PPE arc-flash protection. An anticipated working distance of 18 in. is indicated in both cases. It is important to understand that these are just examples of the calculated arc flash incident energy and associated designation of required PPE under those specific conditions indicated. Under any other conditions beyond these specific limits for short circuit current and clearing time indicated in Table 130.7(C)(15)(A)(b), the exact conditions must be assessed individually to establish the specific incident energy for which the PPE must be then selected from NFPA 70E, Table 130.7(C)(16). A select number of recognized methods are provided in Annex D of NFPA 70. It is also important to note that the incident energy covered by the provisions of NFPA 70E, Table 130.7(C)(16) for Category 4 PPE is a minimum of 40 cal/cm^2. Beyond that limit, selection of appropriate PPE must be selected based on the actual incident energy protection afforded by the PPE and not the Category of PPE. Some manufacturers have PPE designated for incident energy levels significantly higher than 40 cal/cm^2. The protection afforded by the use of the designated PPE may not prevent all arc flash burn injuries but rather is intended to reduce potential burn injury and increase survivability. Additionally, arc rated PPE is not intended to address the resultant explosive physical impact trauma beyond the thermal effects of the arc flash whereas arc blast PPE (including hard hat, hearing protection, safety glasses, etc.) can include a degree of protection from physical impact. As the incident energy rises above 40 cal/cm^2, the concussive impact potential can exceed that protectable by conventional means.

Fire Pump Disconnect/Overcurrent Design

For fire pump installations, the provisions of NFPA 20, Chapter 9 and NEC, Article 695 permit the installation of a single disconnecting means between the source of power and the fire pump controller/transfer switch under the following conditions:

- The disconnecting means must be identified as being suitable as service entrance equipment
- The disconnecting means must be lockable in both the closed and open position
- The disconnecting means must be located remote from other building and other fire pump disconnecting means
- The disconnecting means must be marked "Fire Pump Disconnecting Means"
- A placard must be installed adjacent to the controller indicating the location of the disconnecting means and location of any keys needed to unlock such
- The disconnecting means must be supervised in the closed position by (1) central station, proprietary station or remote station signaling device, (2) local signaling service that sounds an audible alarm at a constantly attended location, (3) locking of the disconnecting means in the open position, or (4) sealing of the disconnecting means in the open position where located within a fenced enclosure or building under control of the owner with weekly inspections

While a single disconnecting means is permitted under the above conditions, the installation of a disconnecting means is not required under the provisions of either NFPA 20 or the NEC. As a result, it is rare to find the installation of such within the power feed to the fire pump controller due to the increased cost of installing such devices. This typical lack of disconnecting means limits the ability to de-energize the fire pump controller, requiring that work be completed on an energized controller.

For fire pump installations, the provisions of NFPA 20, Chapters 9 and 10 and NEC, Article 695 provide that the only overcurrent protection required for squirrel cage or wound-rotor induction motors shall be within the fire pump controller and shall have a time delay of between 8 and 20 seconds at locked rotor current, and 3 minutes at 300 percent of the motor full-load current. Other means of overcurrent protection, while not recommended by NFPA 20 and the NEC, would have to be rated higher than that specified above to limit the opportunity for tripping of other overcurrent protection prior to that located within the controller. If installed, the overcurrent protection device must be sized in accordance with either of the following:

- Sized to carry the locked rotor current of the fire pump plus the full-load current of all other connected loads for an indefinite period of time
- The overcurrent protection device must not be field adjustable and must not open:
    - Within 2 minutes at 600 percent of the full-load current,
    - With a restart transient of 24 times the full-load current, or
    - Within 10 minutes at 300 percent of full-load current

This is intended to ensure continuity of power to the fire pump under certain adverse overload conditions to keep the fire pump operational regardless of risk to the conductors. As a result, it is rare to find the installation of such within the power feed to the fire pump controller due to the increased cost of installing such devices. The only other overcurrent protection typical for a fire pump installation would be the primary fuse found in the transformer supplying power to the installation. Both the rating and associated operating time delay [typically beyond that indicated in NFPA 70E, Table 130.7(C)(15)(A)(b)] associated with these device cause an increase in the exposure to an electric arc flash incident energy beyond that normally anticipated for typical motor control centers. As a result, each installation condition must be individually assessed to determine the incident energy associated with the specifics of that installation. The determination of the appropriate PPE must then be selected based on such a determination.

The provisions of NFPA 25, Section A.4.9.6 further emphasizes the increased hazard typically associated with an electric fire pump installation by reiterating the discouragement of the installation of disconnects and presumably overcurrent protection in the power supply by NFPA 20.

Calculation of Incident Energy

The calculation of the incident energy in accordance with NFPA 70E, Annex D requires a thorough knowledge and understanding of the operating conditions at hand as well as the principals and limitations of the various calculation methods presented.

The provisions of NFPA 70E, Annex D include four suggested methods for determination of incident energy, each with associated limitations as summarized on NFPA 70E, Table D.1 as follows:

Table D.1 Limitation of Calculation Methods

Section	Source	Limitations/Parameters
D.2	Lee, "The Other Electrical Hazard: Electrical Arc Flash Burns"	Calculates incident energy and arc flash boundary for arc in open air; conservative over 600 V and becomes more conservative as voltage increases
D.3	Doughty, et al., "Predicting Incident Energy to Better Manage the Electrical Arc Hazard on 600 V Power Distribution Systems"	Calculates incident energy for three-phase arc on systems rated 600 V and below; applies to short-circuit currents between 16 kA and 50 kA
D.4	IEEE 1584, *Guide for Performing Arc Flash Calculations*	Calculates incident energy and arc flash boundary for: 208 V to 15 kV; three-phase; 50 Hz to 60 Hz; 700 A to 106,000 A short-circuit current; and 13 mm to 152 mm conductor gaps
D.5	Doan, "Arc Flash Calculations for Exposure to DC Systems"	Calculates incident energy for dc systems rated up to 1000 V dc

The utilization of any of these methods requires a thorough understanding of the methods and limitations thereof for proper determination of incident energy associated with a specific installation and should only be undertaken by qualified individuals.

It is important to note that where the fire pump is fed from both a utility connection and an emergency generator, each of the connections would need to be evaluated for incident energy associated with the arc flash hazard.

Example Incident Energy Determination – Duke University

As an illustration of the calculated incident energy for a typical installation, information provided by Paul Westray, Electrical Engineer with Duke University, regarding the following ten installed electric fire pumps located on campus is presented below.

DUKE UNIVERSITY - FIRE PUMP MITIGATION SUMMARY									
Fire Pump	Rating	Flow	Pressure	Utility Source	Utility Voltage	Before Mitigations		After Mitigations	
						Utility	Generator	Utility	Generator
Bell Tower	40 hp	750 gpm	65 psi	1000 kVA	480V	9.82 cal/cm2	4.40 cal/cm2	9.82 cal/cm2	0.07 cal/cm2
Perkins	100 hp	1,500 gpm	95 psi	2500 kVA	480V	112.23 cal/cm2	19.3 cal/cm2	0.86 cal/cm2	0.11 cal/cm2
CIEMAS	75 hp	1,250 gpm	70 psi	3000 kVA	480V	131.88 cal/cm2	15.9 cal/cm2	0.67 cal/cm2	0.68 cal/cm2
FFSC	100 hp	1,250 gpm	105 psi	3000 kVA	480V	95.28 cal/cm2	0.60 cal/cm2	2.54 cal/cm2	0.60 cal/cm2
Schwartz-Butters	75 hp	1,000 gpm	100 psi	500 kVA	480V	40.08 cal/cm2	5.63 cal/cm2	0.81 cal/cm2	3.01 cal/cm2
Fuqua	150 hp	1,250 gpm	120 psi	1500 kVA	480V	64.14 cal/cm2	10.71 cal/cm2	1.69 cal/cm2	0.32 cal/cm2
LSRC	150 hp	2,500 gpm	75 psi	2000 kVA	480V	110.37 cal/cm2	N/A	1.96 cal/cm2	N/A
Aquatics	50 hp	1,000 gpm	65 psi	1000 kVA	480V	41.89 cal/cm2	13.53 cal/cm2	2.30 cal/cm2	0.41 cal/cm2
Keohane	75 hp	1,000 gpm	100 psi	500 kVA	480V	19.14 cal/cm2	12.14 cal/cm2	0.41 cal/cm2	0.13 cal/cm2
WDI	60 hp	1,000 gpm	75 psi	1500 kVA	480V	56.31 cal/cm2	0.13 cal/cm2	1.13 cal/cm2	0.13 cal/cm2

As can be seen eight of the 10 installations included incident energy levels associated with the fire pump installation connection to the public utility in excess of 40 cal/cm^2 making work on an energized controller even with appropriately rated PPE and increasingly dangerous undertaking. It should be further noted that the calculated incident energy is not controlled simply by the pump size but is set by the size of the utility connection and associated clearing time of the available overcurrent protection. In the case of these installations, additional overcurrent/disconnect protective measures were added to decrease the incident energy level to more manageable limits as indicated in the After Mitigations columns of the summary table; however, it should be noted that these additional measures are not typical of electric fire pump controller installed in accordance with the provisions of NFPA 20 and the NEC as indicated above.

NFPA 25 Requirements for Work Inside the Fire Pump Controller

A number of activities are included in NFPA 25 that require the inspector to access the interior of the fire pump controller while the panel may be energized. Where the controller is not provided with a separate disconnect, the controller would generally remain continuously energized unless power is pulled at the suppling transformer.

NFPA 25, Section 8.3.3.7(2)(a) requires that electric motor voltage and current levels be recorded on all lines at each of the required flow conditions during the annual performance test of the fire pump. This would normally include churn, rated and 150% flows. With variable speed controllers, additional flow point readings would be needed. Additionally, NFPA 25, Section 8.3.3.9(3) requires that the electric motor voltage and current levels be taken with the pump operating at peak operating load after transfer of power to the alternate power source for installations that include an automatic transfer switch. These recorded voltage and current levels must be evaluated under NFPA 25, Sections 8.3.7.2.5 through 8.3.7.2.9 to ensure the following:

- that the voltage readings do not fall more than 5% below, or extend more than 10% above, the rated (nameplate) voltage for the motor,
- that the recorded amperage does not exceed the full load current multiplied by the motor service factor, and
- that the product of the recorded voltage and current does not exceed the product of the rated voltage and full load current multiplied by the motor service factor.

For older fire pump controllers, inspection personnel must conduct work inside the energized fire pump controller. With the advent of a requirement in NFPA 20 to include voltage and current meters from the exterior of fire pump controllers, inspection personnel would no longer be required to open the fire pump controller to take the necessary readings. This was initially included in the 1999 Edition of NFPA 20 as follows: "Means shall be provided on the exterior of the controller to read all line currents and all line voltages." The committee substantiation included with the modification is as follows, "This is to eliminate a recognizable hazard, i.e., high available fault current. A fire pump controller enclosure serves to contain such a fault and is tested to verify its integrity." The current language in the 2016 Edition of NFPA 20 has been tweaked slightly over the years to include accuracy criteria for the installed meters and reads as follows, "10.3.4.3 Means shall be provided on the exterior of the controller to read all line currents and all line voltages with an accuracy within +/-5 percent of motor nameplate voltage and current."

Interestingly, the provisions of NFPA 25, Table A.8.1.1.2 provides that the installed voltmeters and ammeters on the face of the controller be inspected for accuracy (5%) annually. If checked in place, this would require that inspection personnel must conduct work inside the energized fire pump controller to complete the task of verifying accuracy of the installed voltmeter and ammeter. It should also be noted that the inclusion of this task as an inspection activity would not appear to be correct but should likely have been included as a test activity. Alternatively, the voltmeter and ammeter could be removed and bench tested and then reinstalled; however, this work would also likely require work inside the energized fire pump controller. Inclusion of this provision within NFPA 25 appears to be contrary to the original intent of the change made to NFPA 20 in 1999 to minimize the exposure to personnel to the hazards associated with work inside of an energized fire pump controller.

The provisions of NFPA 25, Table A.8.1.1.2 also includes additional provisions for the following activities that need to be completed which would appear to also involve internal access to the fire pump controller:

- Tighten electrical connections as necessary (It is assumed that this is an inspection of loose electrical connections) – Annually
- Calibrate pressure switch settings – Annually
- Inspect for any corrosion on printed circuit boards (PCB's – Annually)
- Inspect for any cracked cable/wire insulation – Annually
- Inspect for any leaks in plumbing parts – Annually
- Inspect for any signs of water on electrical parts – Annually

Similar provisions are also included in NFPA 25, Table 8.1.1.2 with corresponding references to specific provisions of the code as follows:

- NFPA 25, Section 8.1.1.2.2 – Electrical connections shall be checked annually and repaired as necessary.
- NFPA 25, Section 8.1.1.2.4 – Printed circuit boards (PCB's) shall be checked annually for corrosion.
- NFPA 25, Section 8.1.1.2.5 – Cable and/or wire insulation shall be checked annually for cracking.
- NFPA 25, Section 8.1.1.2.6 – Plumbing parts, both inside and outside of electrical panels, shall be checked annually for any leaks.
- NFPA 25, Section 8.1.1.2.16 – All controls and power wiring connections shall be checked annually and repaired as necessary.
- NFPA 25, Section 8.1.1.2.21 – The accuracy of pressure gauges and sensors shall be inspected annually and replaced or recalibrated when more than 5 percent out of calibration.

NFPA 25, Section 8.3.2.8(2) requires that during the weekly/monthly churn tests on controllers that include electronic pressure sensors, that the inspector record the current pressure and the highest and lowest on the controller event log. This work may involve inspection personnel making internal access to an energized fire pump controller.

NFPA 25, Table 8.1.1.2 and Section 8.3.3.10 provide that the fire pump alarm signals be tested annually. For an electric fire pump this would include pump running, loss of power, and phase reversal. For the first two items, such testing can be completed directly by operating the fire pump and by disengaging power on the controller; however, testing for phase reversal would be tested by simulating an alarm condition rather than an actual reversal of the electrical phase. This simulation can be accomplished by jumpering across the terminals within the fire pump controller, or by jumpering across the terminals at the monitor module installed outside the controller (where so equipped). Some controllers may include a test button inside the controller that simulates the same condition as jumpering the terminals. In any event, testing of this monitored condition may involve inspection personnel making internal access to an energized fire pump controller. NFPA 25, Section 8.3.3.10.1 further recognizes the hazard of conducting such work on an energized fire pump controller with a reinforcing mandate that such only be done by qualified personnel using appropriate PPE.

Fire Pump Performance Evaluation

Given the hazards associated with taking voltage and amperage readings inside the controller, a review of the benefit of taking such readings is in order. Voltage and amperage readings on a fire pump controller are taken to obtain information intended to verify the adequacy of the connected power feed and associated electrical "health" of the system. This information can allow for discovery of deteriorating operating conditions for the fire pump or the unacceptable fluctuations in electrical service and subsequent diagnosis of the issue. The stipulated measured voltage (measured voltage -5% to +10% of rated voltage) and amperage (measured voltage x measured amperage x motor service factor ≤ rated voltage x rated full-load amperage x motor service factor) variations provided by NFPA 25 are identical to those provided in NFPA 20 and the NEC for acceptance of a newly installed fire pump. Interestingly, motors designed for fire pumps in accordance with NEMA MG-1 allow for an increased range of operating voltages down to 90% of the rated voltage but is limited to usage by NFPA 20 and NFPA 25 to 95%.

Where such voltage and amperage measurements are not to be taken, consideration would need to be given to the objective of completion of annual testing for the fire pump. Completion of testing in accordance with NFPA 25 for a fire pump can be divided into two separate objectives. The first includes those intended to ensure that the performance of the installed fire pump meets that required to support the supplied demands that it is intend to serve. The second includes those intended to identify developing deterioration conditions that might be indicative of shortened service life or future performance issues. Of these two objectives, it should be clear that the paramount concern would be addressed by the former. The ability to supply the attached demands is the end of the day performance objective that is required. The latter of the two provides absolute benefit but to a lesser degree. A reduction or increase in voltage on an operating fire pump motor can have a number of operating impacts that can impact performance of the fire pump and that can service life of the motor.

- The torque on an electric motor varies as a square of the voltage. A small variation in voltage can have significant impact on the output torque available from the operating motor. A lower torque can manifest itself as a reduced ability to start and lower operating speed when under load. A measure of the adequacy torque output can be directly measured in the ability of the attached fire pump to start and produce the output pressures sufficient to meet the supported demands.
- The speed of the motor will change slightly with high or low voltage. At 110% of rated voltage, the driver speed will increase by 1% while at 90% of rated voltage the driver speed will by approximately 1.5%; however, the percent slip of the motor will decrease 17% and increase 23% at such voltage variations. Again, the output pressure of the attached fire pump can be used as a measure of adequacy of such conditions.
- The starting and full load current will also be impacted by variations in the voltage. At 110% of the rated voltage, the starting current will rise 10-12% while the full load current will go down 7%. At 90% of rated voltage, the starting current will go down by 10-12% and the full load current will rise up by 11%. Elevated current, will result in temperature rise in the conductors and windings for the motor. At 90% of rated voltage, the temperature rise will be around 6°C to 7°C (11°F to 13°F). The result of such an increase in operating temperature is a potential reduction in service life of the motor particularly when such operation is for extended periods of time that may accelerate the deterioration of the insulation system. With an anticipated service life of 20 years of continuous duty for a typical fire pump motor and the anticipated annual run time of a fire pump motor, even with weekly testing, of not more than 9 hours, the impact on actual service life is minimal.