This presentation reviews the typical protective relay methods used to reduce arc-flash hazards. Background information on arc flash is presented along with a review of the standards impacting arc-flash calculations. An exercise is included on how to calculate arc-flash energy.
Part one of this presentation discusses the topics listed on this slide.

- Background on arc flash
- Overview of arc-flash standards
- Methods to reduce arc-flash hazards
- Impact of CT location on protection
- Arc-flash tests
Part 2 Discussion Topics

- Arc-flash optical fiber installation examples
- Events with arc-flash detection (AFD)
- Special applications for AFD – arc chutes and hot-line tag
- Incident energy and instantaneous trip for maintenance mode settings calculations
- ARCPRO vs. Lee Equation

Part two discusses arc-flash optical fiber installation examples, events with arc-flash detection (AFD), special applications of AFD, and examples of how to calculate incident energy and settings for an instantaneous trip for maintenance mode. A comparison of ARCPRO calculation results to Lee Equation results is also shown.

Ulteig provided the ARCPRO calculations and results used in the examples discussed in this presentation. Minnesota Power provided the real-life system examples and verified the example results with third-party software.
An arc-flash hazard is a dangerous condition associated with the release of energy caused by an electric arc.

Arcs produce some of the highest temperatures on earth, up to 35,000°F (19,000°C) or more. For comparison, arc furnaces are approximately as hot as 3,000° to 5,000°F (1,600° to 3,000°C).

An arc flash produces the following:

- Dangerous levels of radiated energy—thermal and ultraviolet (UV).
- Flying shrapnel.
- Pressure waves.
- Sound waves.
Reducing arc-flash hazards is important. There is an average of ten Occupational Safety and Health Administration-reportable (OSHA-reportable) arc-flash incidents every day in the United States, resulting in at least one worker fatality.

The statistic on this slide is from “The Myths and Realities of Arc Flash Protection,” an article by Thomas E. Neal and Randell B. Hirschmann (available at http://www.electricenergyonline.com).
The main picture on this slide shows an arc-flash incident scene. The portable light was not in place during the incident.

This incident was caused by a mounting cover plate on the door of a 480 V circuit breaker cubicle. Two substation secondaries were tied together, so the available fault energy level was higher than normal. Circumstances suggest that the cubicle door was closed before the cover plate was secured. An estimated exposure of over 60 cal/cm² resulted in four workers being seriously injured.

The inset picture shows the damaged cubicle. Notice the following*:

- The top cover plate stud is intact.
- The bottom cover plate stud has melted away.
- Scorch marks indicating heat are visible from the top edge of the opening down.
- The chain mechanism is missing.

The fault started as a single-phase fault between the right-most phase and ground, and then it proceeded into a three-phase fault.

*This information is courtesy of the case history “Two Similar Incidents—Two Different Outcomes” by D. Doan and H. L. Floyd, which was presented at the 2006 IEEE IAS Electrical Safety Workshop.
The picture on this slide shows completely melted medium-voltage switchgear at a taconite mine.
Arcing faults produce the following severe worker hazards, which can have long-term effects:

- Infrared (IR) and UV radiation. IR, visible, and UV light levels are bright enough to cause corneal and retinal eye damage.

- Shrapnel. Arcs spray molten metal in a lethal mist at high-speed pressure. The high-momentum shrapnel can easily penetrate a body.

- Pressure. Blast pressure waves have thrown workers across rooms and knocked them from ladders, resulting in concussions and severe brain damage. Pressure on the chest can be higher than 2,000 lbs per square foot (100 kPa), which is sufficient to collapse a lung.

- Sound. Hearing loss can occur from a sound blast. The arc expands air rapidly, similar to thunder caused by lightning. Researchers have recorded magnitudes as great as 140 dB at a distance of 2 ft from the arc.

- Heat. Fatal burns can occur less than 3 ft from the arc. Serious burns are common at a distance of 10 ft. Staged tests show temperatures greater than 392°F (200°C) on the neck and hands for a person standing 2 ft from the arc. Clothing can be ignited from several feet away and can cause more severe burns than if the skin were exposed.

- Smoke. Toxic gases are formed by a chemical reaction between the molten copper dust and the atmosphere. Breathing these gases can result in thermal injury to the upper airway. Chemical injury to the lungs can cause narrowing of the airways and pneumonia.

- Psychological effects. Many workers report apprehension when they return to the work environment. Some require desensitization psychotherapy or reassignment to different jobs.
OSHA requires businesses to have a safety program, calculate arc-flash hazards, communicate the hazards, train workers on the hazards, and provide the personal protective equipment (PPE) and tools needed to work safely on energized equipment. The aim of OSHA compliance is to provide a “workplace free from recognized hazards.”
This slide lists some standards that address the issue of arc-flash protection and provide calculations and tables for determining incident energy.
The table on this slide shows the OSHA calculation requirements that became effective on July 10, 2014. The following table key is provided in OSHA 29 CFR 1910.269 Appendix E:

- 1Φ: Single-phase arc in open air.
- 3Φa: Three-phase arc in open air.
- 3Φb: Three-phase arc in an enclosure (box).
- Y: Acceptable; produces a reasonable estimate of incident heat energy from this type of electric arc.
- N: Not acceptable; does not produce a reasonable estimate of incident heat energy from this type of electric arc.
- Y-C: Acceptable; produces a reasonable, but conservative, estimate of incident heat energy from this type of electric arc.

The following footnotes are also provided with the table in the OSHA standard:

1. Although the Occupational Safety and Health Administration will consider these methods reasonable for enforcement purposes when employers use the methods in accordance with this table, employers should be aware that the listed methods do not necessarily result in estimates that will provide full protection from internal faults in transformers and similar equipment or from arcs in underground manholes or vaults.

2. At these voltages, the presumption is that the arc is three-phase unless the employer can demonstrate that only one phase is present or that the spacing of the phases is sufficient to prevent a multiphase arc from occurring.
3. Although the Occupational Safety and Health Administration will consider this method acceptable for purposes of assessing whether incident energy exceeds 2.0 cal/cm², the results at voltages of more than 15 kilovolts are extremely conservative and unrealistic.

4. The Occupational Safety and Health Administration will deem the results of this method reasonable when the employer adjusts them using the conversion factors for three-phase arcs in open air or in an enclosure, as indicated in the program’s instructions.
NFPA 70E Changes in 2015 Edition

- Hazard/Risk Category (HRC) is now called PPE Category
- HRC 0 has been eliminated
- Hazard analysis is now risk assessment
- Other changes were made as well – always review latest standards
This and the following slide show the Hazard/Risk Category (HRC) table in previous editions of the National Fire Protection Association (NFPA) 70E standard. This table was updated in the 2015 edition of the standard.

<table>
<thead>
<tr>
<th>HRC</th>
<th>Clothing Description (number of layers)</th>
<th>PPE Required Minimum Arc Rating (cal/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Nonmelting, flammable materials; heavy cotton (1)</td>
<td>NA</td>
</tr>
<tr>
<td>1</td>
<td>Fire-retardant (FR) shirt and pants or FR coverall (1)</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Cotton undergarments plus FR shirt and pants (1 or 2)</td>
<td>8</td>
</tr>
<tr>
<td>HRC</td>
<td>Clothing Description (number of layers)</td>
<td>PPE Required Minimum Arc Rating (cal/cm²)</td>
</tr>
<tr>
<td>-----</td>
<td>-----------------------------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>3</td>
<td>Cotton undergarments, FR shirt and pants plus 1 FR coveralls, or 2 FR coveralls (2 or 3)</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>Cotton undergarments and FR shirt and pants plus multilayer flash suit (3 or more)</td>
<td>40</td>
</tr>
</tbody>
</table>
The updated NFPA 70E standard requires the PPE shown on this slide. In addition to the required protective clothing, each PPE category also requires that workers wear additional protective equipment.

For PPE Categories 1 and 2, this includes the following:

- Hard hat.
- Safety glasses or goggles (as needed [AN]).
- Hearing protection (ear canal inserts).
- Heavy duty leather gloves.
- Leather footwear (AN).

For PPE Categories 3 and 4, this includes the following:

- Hard hat.
- Safety glasses or safety goggles (selection required [SR]).
- Hearing protection (ear canal inserts).
- Leather footwear.
The terms shown on this slide are some of the main terms used when discussing arc flash. The definitions of these terms, which are taken from NFPA 70E and IEEE 1584, are reviewed on the following slides.

- Incident energy
- Arc-flash boundary
- Working distance
Incident Energy

- Amount of thermal energy impressed on surface at certain distance from source that is generated during electrical arc event
- Typically expressed in cal/cm$^2$
- Defined in IEEE 1584 as J/cm$^2$
- $1.2 \text{ cal/cm}^2 = 5 \text{ J/cm}^2$
A flash-protection boundary, referred to as an arc-flash boundary in NFPA 70E, is an approach limit at a distance from live parts that are insulated or exposed within which a person could receive a second-degree burn.
The working distance is the dimension between the possible arc point and the head and body of the worker positioned in place to perform the assigned task.
Arc-Flash Risk Assessment Steps
Assessment Review Interval Not to Exceed 5 Years

• Collect system data and operation modes
• Calculate bolted-fault and arc-fault currents
• Determine protective relay operate times
• Document system voltages, equipment classes, and working distances
• Determine incident energy and flash-protection boundary

Arc-flash calculation steps include the following:

• Collect the system data and modes of operation. In short, an accurate one-line diagram that includes the system source, line, and transformer impedances is needed. Operators also need to know the modes of operation, as well as whether additional feeders and generators may be in service and how that impacts fault currents and trip times. The goal is to establish conditions that produce the maximum fault currents.

• Determine the bolted-fault currents. Calculate the maximum three-phase fault current based on short-circuit programs or fault studies.

• Determine the arc-fault currents. The arc-fault current is typically slightly less than the bolted-fault current because of arc impedance.

• Determine the protective relay or device operate times. One subtle aspect of calculating arc-flash incident energy is that a lower fault current (e.g., a farther downstream fault) may not decrease the energy if the protection used is an inverse-time overcurrent characteristic (e.g., a fuse or 51 device). The lower fault current could (and often does) result in increased energy because of the increased trip times. Incident energy analysis is typically performed at 100 percent and 85 percent of maximum arcing current. Also, if no intentional time delay is used, the operate time for instantaneous relaying is still taken into account. Thus, breaker operate times must always be considered.

• Document system voltages, equipment classes, and working distances. IEEE 1584 includes tables that provide the typical bus gaps and working distances for 15 kV, 5 kV, and low-voltage switchgear; low-voltage motor control centers; panel boards; and cables.

• Determine the incident energy. IEEE 1584 includes equations and reference spreadsheets that can be used for this task.

• Determine the flash-protection boundary. Based on the incident energy, a flash-protection boundary can be calculated.
Methods of Limiting Arc-Flash Hazards
The best way to minimize arc-flash danger is to avoid the hazard area. Do not work on energized equipment.
If configurations and processes allow for equipment to be de-energized before personnel are in the hazard area, that eliminates the risk of injury to personnel. In many cases, however, the infrastructure is not in place to allow for switching equipment out while maintaining service to customers or avoiding process interruption.

Often, arc-flash events occur when the switching of equipment is taking place. Manual breaker racking in and out is a particularly hazardous time for personnel to be exposed to an arc flash. There are methods available that allow personnel to perform breaker racking from a safe distance.

Personnel can also be protected by adding communications to protection devices. This allows information to be retrieved, settings groups to be changed, protection functions to be enabled or disabled (maintenance mode is discussed later in this presentation), and other tasks to be completed that personnel would normally have to be in front of the relay to perform. Remote communication allows personnel to do these tasks well-removed from the danger area. It also makes it more likely that the full functionality of the relays will be used because items such as load profiling, metering, breaker monitoring, and so on can be accessed at any time without risk to personnel.

Building on the communications aspect of hazard avoidance, functions such as event retrieval can be automated by adding a communications processor and a computer to the network so that the data are gathered on demand or at a regularly scheduled interval. Supervisory control and data acquisition (SCADA) features can be gained as well with the human-machine interface (HMI) function of communications processors. These systems provide full visibility and control of many devices that can be in the hazard zone and can minimize the time personnel need to work in the hazard area.

In power plant and industrial applications, distributed control systems (DCSs) and/or programmable logic controllers (PLCs) perform similar functions to that of the SCADA system. They allow for the remote operation of equipment and for workers to avoid exposure to potentially hazardous equipment operation.
There are many ways to remotely operate a control switch. This slide shows a remotely operated switch. In the picture on the left, the worker is holding the control switch and is away from the front of the breaker door. The worker appears to be wearing natural fiber and/or fire-retardant (FR) clothing and glasses, but no other PPE. In some cases, the worker may still be required to wear the same kind of PPE as he would if he were in front of the door.
As discussed later in this presentation, microprocessor-based relays with programmable logic can be used to customize protection in order to improve tripping times and reduce arc-flash incident energy. Additionally, with the logic available in the relays, personnel can be more selective when applying the faster tripping times. For instance, using the maintenance mode scheme (enabling instantaneous overcurrent during maintenance) minimizes tripping times, but sacrifices coordination. So, it is best in this case to have personnel select to enable this feature only when work is being done on equipment.

When the ability to detect the light from an arc-flash event is added to a relay, the relay is able to more accurately differentiate an arc-flash event from a downline fault. In other words, another factor of authentication for this detection is added. This feature allows personnel to always have the protection enabled because two separate pieces of information are required to act. Additionally, AFD helps improve protection speed and security because the protection requires two distinct identifiers of an arc-flash event to occur together. Personnel do not have to wait to qualify the overcurrent, as is typically done in standalone overcurrent applications.
In most applications, the 51 relay on the main breaker has a slow curve to coordinate with the slowest of the feeder 51 relays. Improving (minimizing) the coordination time between the main relay and the feeder relays can help reduce the incident energy from arc faults. However, in general, the improved coordination time is still a long time delay when compared with the other options discussed in this presentation.
The basic theory of a fast bus trip scheme (also called a zone interlocking scheme) is that the relay on the main breaker has a definite-time element set for approximately 3 cycles. If a fault occurs on one of the feeders, the respective feeder relay sees the fault and sends a blocking signal to the main relay, preventing operation. For a fault on the bus, only the main relay sees the fault and a blocking signal is not sent to the main relay. As a result, the main relay clears the fault with a small time delay. Note that both the feeder and main relays can be configured with inverse-time overcurrent elements for the coordination of feeder faults, while still providing fast clearing times for bus faults.

This slide shows the feeder current transformers (CTs) on the bus side of each feeder breaker. When applying the fast bus trip scheme, the CT location is important. In this case, the scheme would actually block the high-speed tripping for an internal breaker fault because the feeder instantaneous overcurrent (50) elements would see the internal breaker fault as a feeder fault.

The fast bus trip scheme covers internal breaker faults when the CTs are located on the load side of the breaker, which is typically how bus differential relaying CTs are applied. CT location is discussed in more detail later in this presentation.
The table on this slide shows the advantages and disadvantages of the fast bus trip scheme. The benefits are that it provides fast and secure protection for minimal additional cost. However, added complexity (wiring and settings) is required to implement a fast bus trip scheme. This can make testing more difficult, but with a good test plan, this scheme can be properly tested. Note that it is essential that the scheme be tested as a whole rather than simply testing each relay individually.

The relay operate time is 3 cycles due to the intentional delay on the definite-time element in the main relay. This allows time for the relay to receive the blocking signal from the feeder breakers.
Traditional bus differential relaying is faster than the fast bus tripping scheme because there is no intentional time delay. If bus differential relaying is designed as shown in the figure on this slide, the CTs overlap the breaker, providing protection for faults within the breaker. The feeder relays in this design are on the bus side of the breaker, so they also provide protection for faults within the breaker.
The table on this slide shows the advantages and disadvantages of the bus differential relaying scheme. The timing shown is for a high-impedance differential. A low-impedance differential can be slightly faster.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Trip Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast</td>
<td>More relay settings</td>
<td>&lt;28 ms</td>
</tr>
<tr>
<td>Secure</td>
<td>Extra cost for CTs</td>
<td>(high-impedance differential)</td>
</tr>
<tr>
<td>Dependable</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In order to improve safety while working near energized equipment, protection engineers have implemented an instantaneous setting in relays that is used when personnel are within the hazard zone.

The presence of personnel can be indicated with a pushbutton on the relay, a separate switch, or via remote communication. While activated, this change in settings disables the time coordination and allows the breaker to trip without any delay. Instantaneous trip during maintenance scheme can be added to new or old installations without much expense. This special protection scheme is only activated when personnel are in the proximity of the energized circuit(s).

Utilities have been using this type of scheme as a hot-line tag setting for many years.
Modern relays have programmable front panels and pushbuttons. The pushbuttons are used to enable the instantaneous trip during maintenance scheme. The {TRIP} and {CLOSE} pushbuttons can also be programmed with a time delay. For example, if the pushbuttons are programmed with a 10-second delay, the LED begins to flash once one of the buttons is pressed and the worker has 10 seconds to leave the area before a trip or close action takes place.
This slide shows a manually operated maintenance switch. When the switch is rotated to the maintenance (MAINT.) position, its contact closes and is connected to an input on a modern relay. The input of the modern relay then activates the instantaneous maintenance mode and sends a signal to active the blue Maintenance Mode light shown on the panel.
The main benefit of adding a maintenance mode scheme to a relay is faster tripping, which yields safer work conditions. An additional benefit is the low cost involved in implementing this scheme. Only a switch and a little wiring or logic are required. However, there are disadvantages as well. The main disadvantage is that coordination is lost and the differential may operate for an out-of-zone fault. Also, accounting for human error, the switch may be left on, which increases the time that the system is vulnerable to a misoperation.

Note that the table on this slide also indicates the operate time for this scheme. This is the relay operate time and does not include the breaker time. The breaker time must be accounted for when determining the incident energy of an arc-flash event.
In this example, the maintenance mode scheme is enabled in Relay M1 by Breaker M1 when working on either Feeder F1 or Feeder F2. This scheme can be activated via the methods previously discussed, and it can be activated at the feeder or main locations. If work is being done downstream on Feeder F1 from Breaker F1, then an instantaneous trip would be enabled in Relay F1 and not Relay M1. The instantaneous trip during maintenance scheme is always enabled in the next relay upstream from the device that the worker is working on.
When setting the 50 element, consider what the maximum expected load current is and set the 50 pickup above that. In some cases, the arcing current is high enough that the 50 pickup can be set above the bus rating of the equipment and still be well below the arcing current. Motor starting can cause the current to increase above the equipment rating for short periods of time. The effect of this needs to be considered if there is a large motor that could be started while work is being done on an adjacent circuit not related to the motor.
This slide shows that on some distribution circuits it is possible to have a 50 element enabled all the time that covers most of the circuit. This is different than enabling an instantaneous trip during maintenance scheme, but it is another option that can be used for arc-flash protection. This option is mainly used on overhead distribution circuits where within the 80 percent instantaneous reach there are manually operated field switches.

The current settings for the Relay B 50 element are typically required to be 125 percent (or larger) of the remote bus fault current ($I_{BUS}$).
Combining AFD and high-speed overcurrent sensing provides fast tripping and security. The combination of overcurrent and arc sensors provides independent fault detection with two separate technologies, thereby eliminating false trips from lighting.
The light algorithm adds a level of security to the detection of light flashes. This function reduces false-positive indications of light from photo-flash devices and also filters out any single high-energy particle hitting the optical sensors.
AFD-based protection can act on the circuit breaker in a few milliseconds (2 to 5 ms). This fast response can reduce or prevent injury to personnel and limit or eliminate equipment damage by limiting the arc-flash energy.

Arc-flash protection, in general, requires both the measurement of an overcurrent element (50PAF) and the detection of light. The output logic should, in most cases, combine (the AND result of) the 50PAF and light outputs.

Arc-flash overcurrent detection compares current samples with the pickup setting. The security counter requires two consecutive samples above the setting threshold before acting.

The 50PAF element is shown in the figure on this slide. The 50NAF element, which is similar to the 50PAF element, is used to cover ground faults.
This slide shows the logic for a relay that has four fiber-optic AFD inputs and protection elements. Each channel has a fiber-optic receiver and an LED-sourced fiber-optic transmitter, which is used for continuous self-testing and monitoring of the optical circuit.

Each of the four fiber-optic light sensor inputs is associated with one inverse light element, offering enhanced security coupled with exceptionally fast operation.

The inverse-time characteristic is fixed, offering robust rejection of unrelated light events.

The relay trips if both overcurrent (50PAF) and light detection conditions assert.
Some feeder protection relays include light analog quantities in their event reports, allowing operators to plot the light intensity of an arc flash along with the current. The figure on this slide illustrates the operating speed of the AFD element. If the relay has high-speed output contacts, the trip coil will be energized in 2 ms. If not, the operate time of the output contacts must be included in the total operate time.
The disadvantages of an overcurrent and flash detection scheme are very minimal and are to be expected when adding sensors to the system.

Do not use a conductor when adding sensors to the system; use fiber optics.
The arc-flash overcurrent elements use raw analog-to-digital (A/D) converter samples and require that two samples in a row are above the setting threshold in order to declare an overcurrent condition. Fast overcurrent detectors like these are susceptible to high harmonics. The phase threshold should be set to at least twice the expected maximum load to avoid unintended pickup. The neutral threshold should be set like a normal neutral overcurrent element, plus margin. For example, set it to half of the available ground fault current but no less than the natural ground current produced by the load or system unbalance.

The overcurrent elements will pick up temporarily during inrush, but the supervision of the light-based element will keep the relay from declaring an arc-flash condition.
To be secure, the arc-flash light element must be set according to the guidelines listed on this slide.

**Arc-Flash Light Elements**

- Elements continuously measure ambient light
- Pickups must be above highest normal light intensity expected at each light sensor installation
- Relay command measures ambient light at each sensor
The graphs on this slide provide a comparison between the previously discussed schemes on the basis of incident energy and the resulting flash boundary. Note that the dedicated bus protection schemes are included in the Instantaneous Trip category. As can be seen, AFD provides the best protection and the safest work environment.
The location of the CTs can impact arc-flash protection. This slide shows the inside of a medium-voltage switchgear cubicle with the circuit breaker removed. The CTs are placed around the insulator tubes and can be located on the load side, bus side, or both sides.
The diagram on this slide shows that the breaker stab, or connection point to the outgoing feeder, is not covered by the bus differential relaying scheme because it is past the location of the CT. This would be an out-of-section fault for the bus differential relaying scheme, and the scheme would not trip. As a result, the fault detection and tripping for this fault would be up to the bus time-overcurrent and/or transformer time-overcurrent protection scheme, which is much slower than the bus differential relaying scheme. An arcing fault in this location could lead to significant equipment damage and hazard exposure to personnel.

What scheme would work in this situation? AFD with light and overcurrent detection, or the maintenance mode scheme would work.
Applying a bus differential relay and instantaneous trip during maintenance mode in the feeder relay covers most possible fault scenarios when working on the breaker shown on this slide.
Feeder protection relays can protect mains and feeders with a variety of loop and point sensors. Each arc-flash board in the relays contains inputs for four arc-flash sensors, which can be either loop or point sensors.
A bare-fiber sensor (not shown) is just a bare-fiber cable.

A point sensor (shown on this slide) contains transmit (TX) and receive (RX) fiber-optic cables that meet at the sensor. The sensor can easily be snapped into a standard-sized hole in the switchgear.

Sensor diagnostics are performed automatically every 10 minutes by the relay. The diagnostics raise an alarm if there is too much attenuation in the loopback test, indicating a damaged or disconnected fiber. Sensor diagnostics also raise an alarm if the ambient light level is too high, causing the light sensor element to pick up continuously.

The sensor diagnostics, or loopback test, do not interfere with AFD in any way.

Arc-flash diagnostics can be manually initiated.
Point Sensor Assembly

Dual V-Pin Latch

V-Pin Terminators

Jacketed-Fiber Zipcord Duplex

Sensor

Length Is Limited
Bare-Fiber Sensor Assembly

- Dual V-Pin Latch
- V-Pin or ST® Splice Connector
- Jacketed Fiber
- V-Pin Terminators
- Bare Fiber

“B” meters

“A” meters

Total loop length = 2 • A + B
Current-limiting fuses are used in many applications to reduce arc-flash hazards. When using any type of fuse, it is important to always have spares in stock and, when necessary, to replace damaged fuses with the same type of fuse.

Current-limiting fuses and current-limiting protector devices such as the Is-limiter are not discussed in detail in this presentation.
Arc-Flash Tests
The pictures on this slide show the air-magnetic switchgear used for the test videos on the following slides.
This 46-cycle arc-fault video shows the damage that can occur without AFD. Notice the arc blast venting through the top vents on the cabinet. The breaker truck was heavily damaged by this arc-flash event.

PPE Category 3 (formerly known as HRC 3) requires that personnel wear PPE with a minimum arc thermal performance exposure value rating of 25 cal/cm². This is commonly known as a “moon suit.” It can be very difficult to work in this type of PPE.
The 5-cycle arc-flash event shown in the video on this slide demonstrates that sending a trip signal to the breaker in less than 4 ms from the onset of current significantly reduces the incident energy of the arc-flash event. The 5-cycle arc flash corresponds to a breaker with a 5-cycle fault-clearing time. The breaker truck and cubicle were undamaged by this relatively short arc-flash event.

PPE Category 1 (formerly known as HRC 1) requires that personnel wear PPE with a minimum arc thermal performance exposure value rating of 4 cal/cm². This can be met using single-layer FR cotton clothing and appropriate face, head, and neck protection. This type of PPE is much easier to work in than the PPE Category 3 moon suit.
The insulators shown on this slide are part of the air-magnetic breaker truck. The picture on the left shows an undamaged insulator. The picture on the right shows the insulator damage resulting from the 46-cycle arc flash shown in the video on the previous slide. Part of the porcelain insulator material is missing.
The video on this slide shows a test without AFD. The arc fault was allowed to continue for 46 cycles.

The test mannequin is wearing arc-flash PPE. This PPE is not rated for the arc-flash PPE category of this test. Subsequent inspection of the test mannequin showed that the front of the shirt was extensively burned. Merely touching the burned fabric caused it to fall away.
The video on this slide shows a test with AFD.

The test mannequin is wearing HRC 0 arc-flash PPE. (Note that HRC 0 does not have an equivalent PPE category in the updated NFPA 70E standard.) The electrodes are 36 inches from the face of the mannequin. As with all of the tests, the relay immediately detected this arc flash and provided a trip output. The arc fault was allowed to continue for 5 cycles, corresponding to the fault-clearing time of a typical breaker. Subsequent inspection of the test mannequin showed no damage to the FR shirt or the face shield. Compare this with what can happen without AFD, as shown in the 46-cycle fault PPE test video.
The graph on this slide shows the relative reduction in incident energy corresponding to the switchgear and PPE videos that show tests performed without AFD and with AFD. AFD achieves a significant reduction in arc-flash incident energy and the corresponding PPE category.
A 20- x 20- x 40-inch arc-flash test box was used for 26 of the 28 high-current tests. This box is equipped with 0.75-inch solid copper electrodes connected to a high-current source.

The arc flash was triggered by a 28 AWG fuse wire connected across the electrodes.
This slide shows a high-current test performed on three relays with AFD (three relays were tested simultaneously to increase the amount of test data). The relays performed flawlessly.

The trip time from the onset of current ranged from 3.1 to 3.6 ms. In this test, it took 1.5 ms from the application of current to the appearance of light. This was measured using a 1,000 frames-per-second (fps) high-speed video camera. The trip time from the first appearance of light was calculated by subtracting 1.5 ms from the onset of current results.
In the test event report shown on this slide, the relay took 3.1 ms to trip, as measured from the application of current. When measured from the appearance of light, it took 1.6 ms to trip.

The arc-flash event took 1.5 ms from the application of current to the appearance of light. This is measured from the 1,000 fps high-speed video.
The test shown on this slide used the largest current magnitude of any of the tests shown previously. In order to test the durability of the point and loop sensors, a point sensor and a loop sensor were installed in the arc-blast zone between the electrodes. The point sensor between the electrodes was externally damaged but still passed loopback light of 0.49 percent versus 14 percent before the arc blast. This sensor provided a 100 percent signal. The loop sensor was melted, but the event capture shows that both the point and the loop sensors reported (picked up) before they melted. This shows that AFD works properly even if the sensors are damaged by the arc blast.
In a sensor durability test, a point sensor and a loop sensor were placed right between the electrodes to test the durability of the sensors and to show that they detect the arc-flash light before being burned.

The point sensor, though darkened, was still functional after this test. It was used in a subsequent test to prove that it still worked.

The loop sensor was burned through but successfully reported the arc-flash light before being destroyed. The next slide shows the event report for these two sensors.
This slide shows the event report that corresponds to the two previous slides. Both the loop (green trace) and point (blue trace) sensors provided a 100 percent signal level. The two relays with the point and loop sensors in the arc-blast zone tripped in 2.62 ms and 2.72 ms from the onset of current. The breaker took 3 cycles to clear the fault.

The point and loop sensor levels stayed at 100 percent even after the fault was cleared. This is due to optical detector saturation in the relay because of the extremely high optical signal level (this is analogous to people seeing spots in front of their eyes after a camera flash). In AFD applications, signal saturation is a good thing—it provides some of the fastest trip times.
High-Current Test Findings

- 28 tests with 3 feeder protection relays each
- Average trip time
  - From current – 3.6 ms (measured)
  - From light – 2.1 ms (estimated), light follows current by about 1.5 ms
- Rugged sensors

AFD really works!
Part 1 Conclusions

- Arc flash is dangerous condition
- Standards aim to help reduce hazards
- If possible, work on de-energized equipment
- Use protective relaying methods to reduce arc-flash hazards
- CT location affects arc-flash protection
- Real-world tests show damage from arc-flash events
Part 2 Discussion Topics

- Arc-flash optical fiber installation examples
- Events with AFD
- Special applications for AFD – arc chutes and hot-line tag
- Incident energy and instantaneous trip for maintenance mode settings calculations
- ARCPRO vs. Lee Equation
Installation of Arc-Flash Point and Loop Sensors
Mounting Considerations

- Maintain 2-inch bend radius
- Use protection sleeves where sensors come in contact with sharp edges
- Do not route sensors over conductors – if they fall, dust, dirt, or moisture can contribute to fault path
- Avoid direct sunlight hitting sensors
The green highlighted areas in the figure on this slide show the preferred mounting locations for the arc-flash sensors. Using the four sensors, the switchgear can be broken into sections, each with its own tripping scheme.
Rear View of Switchgear

- **Breaker Compartments**
- **Bus Compartment**
- **Outgoing Line Compartments**

Loop bare-fiber sensor around bus section, away from breakers.

Mount outgoing line compartment sensors away from bus compartment.
Front View of Switchgear

- Breaker Compartments
- Bus Compartment
  - Mount breaker compartment sensors toward back of cell
  - Keep fiber cables away from breaker installation tracks
- Outgoing Line Compartments
A total of 12 sensors were installed for switchgear tests. In all of the tests, all 12 sensors detected enough arc-flash light for the associated light element to assert. This shows that arc-flash light is so bright that even poorly located sensors will detect enough light to assert.

The test data show that the best location for point sensors in a breaker cell is on the back wall, right above or below the shutter. In the picture on the left of this slide, the shutter has been manually raised to verify that the sensor view is not blocked when the shutter is in the operating position.

The next best location is on the rear-side wall, adjacent to the shutter.

A suboptimal location is on the middle of the side wall. The insulating panels of the breaker truck block the view of the arc flash from this sensor. Even in this suboptimal location, this sensor still asserted during the arc-flash event.
This slide shows a point sensor mounted in the breaker cubicle (note the suboptimal location).
Route the bare-fiber loop sensor through the main bus sections of the switchgear. Make a loop out of the route with one branch going high across the switchgear and the return branch passing below the bus sections. Do not mount the fiber-optic sensor on the bus or across the three phases of the bus. Make sure the bare-fiber loop sensor extends the entire length of the bus for complete coverage. A sensor in this area should trip the switchgear main breaker.
The picture on this slide shows that the line side of the breaker is typically a conversion section from switchgear bus to cable. Mount the sensors in this section where they have an unobstructed view of the cable tie point. Sensors in this cell should trip the individual feeder breaker for this section.
Mounting hardware, such as nylon push wing cable mounts, nylon cable ties, and point sensor grommets (as shown on this slide), is designed to use existing holes in the switchgear cabinets for routing the cable and mounting the sensors. If new holes are drilled in the switchgear, use extreme caution so that the electrical isolation and safety of the switchgear are not compromised. Consult the switchgear manufacturer for details on adding holes in the switchgear. Because the arc-flash sensors are very sensitive to light and the amount of light emitted during an arc-flash event is very high, mounting the sensors in existing holes is suitable in most cases. It is not recommended to modify the switchgear cabinet. Safety should always be of paramount concern.
Sensors should be affixed using available mounting grommets or permanent cable ties. The picture on this slide shows an example of a typical jacketed-fiber installation.
This slide shows the typical routing of a bare-fiber sensor in a breaker cabinet.
The bare-fiber sensor is optimized for monitoring large distributed resources, such as switchgear system bus enclosures. It is omnidirectional and can be mounted in close proximity to the switchgear enclosure walls. A bare-fiber sensor consists of the major components shown on this slide.

Two connector options (V-pin and ST® connectors) are available for transitioning from the jacketed-fiber to the bare-fiber section. A V-pin connector is shown on this slide.

For correct operation, a bare-fiber sensor must be located within 2 m of the arcing site, with at least 0.5 m of the fiber exposed to the light.
ST Connector Can Also Transition Jacketed-Fiber to Bare-Fiber Sections
The point sensor is optimized for monitoring confined switchgear spaces where the distance between sensors and the potential sources of arc (energized parts) can be kept below 2 m. Such spaces typically include breaker compartments, outgoing and incoming cable compartments, and potential transformer (PT) compartments.

The sensor is mounted flush on the switchgear cabinet wall using a standard 0.25-inch hole.

Point sensors are much more efficient light receivers than bare-fiber sensors. Point sensors are almost ten times more sensitive to light. Bare-fiber sensors are typically used over a wide area and do not absorb large amounts of light.
This slide shows an example relay light report that some relays can provide when they are equipped with AFD.
Arc-Flash Protection Saves Lives
Real-World Events
The real-world arc-flash incident shown on this slide involved a rat that caused a fault between two conductors in 6.6 kV switchgear. The AFD protection tripped quickly, resulting in only slight damage to the equipment after the event.
Looking at the event report shown on this slide, notice that the relay issued the trip 1 ms after the rat caused the fault. The circuit breaker opened 2.8 cycles after the start of the fault.
The event shown on this slide was from a bus arcing fault flashing into a switchgear circuit breaker cubicle. The event report shows that the light elements pick up first, followed by the overcurrent element. The time from light element assertion to circuit breaker opening is only 3.25 cycles.
Two special applications for arc flash are shown on this slide. The following slides discuss some challenges that these applications face.
Applying AFD Methods With Air-Magnetic Circuit Breakers
AFD faces a challenge when installed in switchgear that contains air-magnetic circuit breakers. When the contacts of an air-magnetic circuit breaker open during fault or load (non-arc-flash event), they generate arcs that can be sensed by arc-flash light elements. Arc is quenched by arc chutes and is not a problem worthy of AFD trip.
The AFD system does not have a way to differentiate light from an air-magnetic circuit breaker operation and light generated by an actual arc flash in the breaker compartment. Tests have shown that the light generated by air-magnetic breakers during normal switching and fault interruption can be enough to assert the light elements in the relay. This can cause the AFD elements in the relay to trip the bus when a feeder breaker trips for a downstream fault.
One way to solve air-magnetic circuit breaker problems involves sending trip signals from the individual feeder breakers to the AFD relay. If the AFD relay is able to detect the arcs generated by the feeder breakers, it should have a digital input wired to it that asserts when a feeder breaker is tripped by any protection.

The time that passes between the feeder relays issuing a trip and the feeder breaker actually opening (and the arc appearing) is at least 2 cycles, which is enough time to block the AFD logic.

When the AFD current pickups are set to the recommended value of two times the load, the input does not need to assert when the feeder breakers are manually opened during load conditions. Even though this operation generates an arc, typical load values are not enough to trigger an arc-flash trip in the AFD relay.
This slide shows a timing diagram of how this solution works with air-magnetic circuit breakers.
It can be argued that deliberately delaying the operation of the relay defeats the purpose of having
a high-speed AFD system. However, the added time delay is not always in effect. The elements are
only delayed when a feeder breaker is being tripped by a protective relay. If an arc flash occurs at
any other time, such as when the breaker truck is being racked in or out, the relay senses the arc
flash and sends a trip signal at its usual speed.

The main disadvantage of the outlined solution occurs when a normal breaker operation evolves
into an arc-flash event due to a mechanical failure. In this case, the delay is in effect and the AFD
relay needs to wait for the SV0xDO time before it can issue a trip for the arc-flash event. However,
the overall improvement in safety that is gained from having 3-ms protection for the vast majority
of the time is worth the added delay that is necessary during a switching operation on air-magnetic
circuit breakers.
What Is Hot-Line Tag?

- Hot-line tag is typically used for overhead distribution
- Worker enables hot-line tag
  - Reclosing is disabled and one trip is enabled
  - Trip is usually on fast curve but can still have time delay

Hot-line tagging is typically used on overhead distribution circuits to disable the reclosing feature after one trip (the fast trip) of the relay. In most cases, the first trip is usually on a fast curve, but even the fast curve can have built-in time delays. When using the hot-line tag feature for arc-flash protection, it is best to remove any intentional time delays from the fast curve.
Improving Hot-Line Tag for Arc Flash

- Still disables reclosing
- Enables instantaneous trip (no time delay on relay trip)
- Now reduces arc flash
Example 1
Implementing Instantaneous Settings for Maintenance Mode Scheme

See the hands-on exercise handout for more details.
Bolted-Fault Calculation

- Convert utility MVA and X/R to impedance
- Add transformer impedance
- Calculate fault current

\[ Z_{	ext{coarse}} = 100 \cdot \left( \frac{kV_u^2 \cdot MVA_t}{kV_i^2 \cdot MVA_u} \right) \angle \tan^{-1}(X/R) \]

\[ I_{\text{Base}} = \frac{MVA_t}{\sqrt{3} \cdot kV_i} \quad I_{\text{Fault}} = \frac{I_{\text{Base}}}{Z_{\text{total}}} \]

Example calculates at 10.1 kA
Arc-Fault Current Calculation

- Calculation includes arc impedance
- Example calculates at 9.8 kA

\[
\log I_a = 0.00402 + 0.983 \cdot \log I_{bf}
\]

\[
I_a = 10^{\log I_a}
\]
## Relay Settings

<table>
<thead>
<tr>
<th>Setting</th>
<th>Relays F1 and F2</th>
<th>Relay M1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTR</td>
<td>120</td>
<td>200</td>
</tr>
<tr>
<td>51AP</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>51PIC</td>
<td>U3</td>
<td>U3</td>
</tr>
<tr>
<td>51P1TD</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>
Relay Operate Times

\[ T_p = TD \cdot \left( 0.0963 + \frac{3.88}{M^2 - 1} \right) \]

where:
- \( T_p \) is operating time in seconds
- \( TD \) is time-dial setting
- \( M \) is applied multiple of pickup current

\[ T_p(\text{Relay M1}) = 6 \cdot \left( 0.0963 + \frac{3.88}{9.8^2 - 1} \right) = 0.821 \text{ s} \]

Relay M1 + Breaker M1 = 0.821 s + 0.083 s = 0.904 s
Incident Energy Calculation

- 610-mm working distance and 0.2-second fault duration assumed for normalized energy
- 910-mm working distance and 0.9-second duration used in this example

\[
\log E_n = K_1 + K_2 + 1.081 \cdot \log I_a + 0.0011 \cdot G
\]

\[
E_n = 10^{\log E_n}
\]

\[
E = 4.184 \cdot C_f \cdot E_n \left( \frac{t}{0.2} \right) \left( \frac{610^x}{D^x} \right)
\]
Incident Energy Calculation

- Calculated energy is 18.6 J/cm² for open air (4.5 cal/cm² – PPE Category 2)
- Calculated energy is 47.6 J/cm² for switchgear (11.4 cal/cm² – PPE Category 3)
Current-limiting fuses and grounding methods can reduce fault currents.

**How to Reduce Incident Energy**

- Recall that arc-flash energy is proportional to $V \cdot I \cdot t$

  \[ E = 4.184 \cdot C_f \cdot E_n \cdot \left( \frac{t}{0.2} \right) \cdot \left( \frac{610^x}{D^x} \right) \]

- Reduce fault current
- Reduce fault-clearing time – we can control relay operating time
Implementing Instantaneous Settings

- Relay time from 0.8 to 0.025 seconds
- Total time from 0.9 to 0.108
- Energy reduction is $0.904 / 0.108 = 8.37$ times less energy

$$E_{\text{new}} = 4.184 \cdot 1 \cdot 3.73 \cdot \frac{0.108}{0.2} \cdot \frac{610^{0.973}}{910^{0.973}} = 5.73 \text{ J/cm}^2$$

$$E_{\text{new}} = 5.73 \cdot \frac{1.2}{5} = 1.37 \text{ cal/cm}^2$$
## Maintenance Mode Scheme Results

**We Can Now Wear Less PPE**

Requirements went from PPE Category 3 to 1

<table>
<thead>
<tr>
<th>Relay M1 Settings With Breaker M1 Time</th>
<th>Open Air (cal/cm²)</th>
<th>Switchgear (cal/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9-second delay</td>
<td>4.5</td>
<td>11.4</td>
</tr>
<tr>
<td>0.108-second delay (maintenance mode)</td>
<td>0.54</td>
<td>1.37</td>
</tr>
</tbody>
</table>
The flash boundary is an important calculation for arc-flash hazard analysis, and it is a number typically found on all arc-flash labels. For the example in the hands-on exercise, the arc-flash boundary calculation was not needed to show the important role that faster protective relays play in reducing the incident energy.

The flash boundary formula variables are as follows:

- $D_b =$ Distance of the boundary from the arcing point in millimeters.
- $E_b =$ Incident energy at the boundary in J/cm$^2$ (5.0 J/cm$^2$ for bare skin).
- $C_f =$ 1.0 for voltages above 1.0 kV.
- $t =$ Arcing time in seconds.
- $x =$ Distance exponent (see the IEEE 1584 Table 4 values).
- $E_n =$ Normalized incident energy in J/cm$^2$. 

\[
D_b = \left[ 4.184 \cdot C_f \cdot E_n \cdot \left( \frac{t}{0.2} \right) \cdot \left( \frac{610^x}{E_b} \right) \right]^{1/x}
\]
Example 2
ARCPRO vs. Lee
Equation for Voltages Above 15 kV

Utility
2,550 MVA
X/R = 15

230 / 34.5 kV
90 MVA
Z = 8.5%

Relay M1

M1

Relay F1
F1

Relay F2
F2
## ARCPRO vs. Lee Equation

<table>
<thead>
<tr>
<th>Power System Component</th>
<th>Lee Equation</th>
<th>ARCPRO</th>
</tr>
</thead>
<tbody>
<tr>
<td>System voltage</td>
<td>34.5 kV</td>
<td>34.5 kV</td>
</tr>
<tr>
<td>Fault current</td>
<td>12.5 kA</td>
<td>12.5 kA</td>
</tr>
<tr>
<td>Fault-clearing time</td>
<td>0.1 s</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Incident energy</td>
<td>26.5 cal/cm²</td>
<td>5.9 cal/cm²</td>
</tr>
</tbody>
</table>

Lee Equation is much more conservative
Part 2 Conclusions

- Where and how you mount sensors affects AFD protection
- Breakers with arc chutes are problem for AFD – use engineering judgement
- Hot-line tag for arc-flash reduction by making an instantaneous trip
- Maintenance mode scheme example demonstrates incident energy reduction
- Compare ARCPRO vs. Lee Equation results
Summary

- Provided background information on arc flash
- Discussed changes to standards
- Described relaying methods to reduce arc-flash hazards
- Calculated example incident energy for maintenance mode
- Compared ARCPRO to Lee Equation
Questions?