Electrical Hazard Risk Assessment

Paul Campbell, 10/7/14

Everything contained in this document is my opinion and mine alone. I have given reference to several standards and technical papers as supporting documentation. I wrote this piece starting originally as an update to a pervious position paper on risk assessment of electrical work but with the introduction of 70E-2015 and considering other documents, it has expanded considerably to complete documentation of a methodology for performing risk assessments of electrical tasks utilizing existing standards with the best known information I have at this time. Note that my approach is different from that specified in NFPA 70E and grew out of dissatisfaction with particularly glaring issues with that standard. These are discussed at length in a critique. However unlike a critique, I have also supported the critique by giving a detailed alternative.

This opinion is offered as a straw man argument. That is, the issues with NFPA 70E are illustrated and an alternative methodology is given which is based on standards but is not itself a standard. This document is intended to further discussion on and to eventually develop a more complete standard for considering risk assessments for electrical hazards.

Introduction

NFPA 70E-2015 is significantly changed from the 2012 edition. New terminology is in use. For instance Article 130.4(A) says this about shock hazards:

> A shock ***risk assessment*** shall determine the voltage to which personnel will be exposed, the boundary requirements, and the PPE necessary in order to minimize the possibility of electric shock to personnel.

Similarly, Article 130.5 states:

> An arc flash ***risk assessment*** shall be performed, and shall:
>
> 1. Determine if an arc flash hazard exists. If an arc flash hazard exists, the risk assessment shall determine:
>   a. Appropriate safety-related work practices.
>   b. The arc flash boundary.
>   c. The PPE to be used within the arc flash boundary.

It is the intention of this opinion paper to provide some guidance and background on doing risk assessments. The author has been trained in the past on performing risk assessments for production lines (moving equipment) as well as for the chemical process industry, and has facilitated numerous teams in performing these functions.

Risk Assessment Origins

Although this appears to be a new term, it has hardly new. OSHA has required risk assessments for a long time such as 1910.132(d)(1):

The employer shall assess the workplace to determine if hazards are present, or are ***likely*** to be present, which necessitate the use of personal protective equipment (PPE).

The key word here is likely, and this is all that a risk assessment is. Risk is the combination of both the magnitude of the hazard itself (electrocution or burns in this case), and the likelihood. Neither by itself is very helpful. For instance an EKG (electrocardiogram) actually operates by measuring a small amount of current passing through a person's body. The person is definitely being shocked by the process but the electrical current is so small that no injury occurs. Here we have a case of 100% likelihood of shock, but no injury. Similarly, although being struck by lightning in most cases results in extensive injuries including death, it is also unlikely to occur if reasonable precautions are taken. In this case, the likelihood of being struck by lightning is extremely low but the injury magnitude is enormous.

What is required in the 2015 edition is to perform a similar analysis of all electrical tasks. OSHA 1910.132(d)(1) and similar regulatory requirements in Subchapter R and S have always made risk assessments mandatory. The only change from the 2012 edition to the 2015 edition of 70E is to both make this fact clear and offer further guidance.

In the past, the other issue with arc flash is knee-jerk reactions. This attitude is even promoted by the wording that OSHA and NFPA 70E use. For instance nowhere in 1910.132 does it define how to assess the word "likely". Instead, it immediately promotes the use of PPE by the very next sentence in 1910.132(d)(1):

If such hazards are present, or ***likely*** to be present, the employer shall...Select and have each affected employee use the types of PPE that will protect the affected employee from the hazards identified in the hazard assessment.

70E-2012 was similar. Article 130.5 states:

An arc flash hazard analysis shall determine the arc flash boundary, the incident energy at the working distance, and the personal protective equipment that people within the arc flash boundary shall use.

The definition of an arc flash hazard (in both the 2012 and 2015 editions) is similar:

A dangerous condition associated with the possible release of energy caused by an electric arc.

It is not until we get into the informational notes that are explanatory and not actually part of the standard itself that the likelihood requirement becomes slightly more clear. Informational Note No. 1 under the definition states this:

An arc flash hazard may exist when energized electrical conductors or circuit parts are exposed or when they are within equipment in a guarded or enclosed condition, provided a person is interacting with the equipment in such a manner that could cause an electric arc. Under normal conditions, enclosed energized equipment that has been properly installed and maintained is ***not likely*** to pose an arc flash hazard.

So how does one actually determine what hazards are not likely? NFPA 70E-2012 provided guidance in two places, first, there was a very enlightening informational note in 130.7(A) (the PPE section), which is used verbatim in the 2015 edition:

It is the collective experience of the Technical Committee on Electrical Safety in the Workplace that normal operation of enclosed electrical equipment, operating at 600 volts or less, that has been properly installed and maintained by qualified persons is ***not likely*** to expose the employee to an electrical hazard.

Second, the 2012 (and 2015) editions refer to the arc flash hazard tables in a second informational note under the arc flash hazard definition:

See Table 130.7(C)(15)(A)(a) for examples of activities that could pose an arc flash hazard.

The major difference is that in 70E-2015, the table that is referenced contains a list of tasks and equipment conditions followed by a column that states "Arc Flash PPE Required". A second table then gives specific PPE levels corresponding to generic estimates of the incident energy. Finally, the same table entitled "Protective Clothing and Personal Protective Equipment" (PPE) gives the PPE based on the "level". In comparison 70E-2012 and earlier versions contained a single task table which combined the hazard and likelihood but contained several entries where the likelihood of the hazard was reduced but not the severity. However it still recommended a reduction in PPE despite no reduction in hazard severity. By treating severity and likelihood separately, the new 70E-2015 table sidesteps this issue. However to add confusion, every task in 70E-2012 had an H/RC rating. There were no entries that stated that no PPE was required. Thus it seemed that every task from landing wiring onto live terminals to "…fused switch operation with covers on" had an H/RC rating from 0 to 4. Only the severity changed, although clearly this is nonsense.

Risk Assessment Approaches

There are generally three major approaches to risk assessments: prescriptive approaches, qualitative risk assessments, and quantitative risk assessments. The prescriptive approach relies on a panel of industry experts which develops a recommendation. For instance the approach to shock hazards specified in 70E is a prescriptive approach where specific PPE and/or tools are required depending on the approach distance.

The qualitative approach generally uses a panel of experts. The recommended list of experts includes subject matter experts (electrical engineers, safety engineers), site specific experts (operators, electricians, mechanics), and management representation on a team that collectively makes qualitative decisions on hazards using a company-specific risk ranking matrix. The risk ranking matrix consists of a consensus opinion of the severity of the injury, and the likelihood that an injury would occur, and whether or not the risk (severity and likelihood) are acceptable according to the matrix. The risk ranking would for example allow minor first aid cases to occur as long as they are infrequent but require multiple fatalities only under extremely unlikely conditions ("almost never"). Common techniques for identification of hazards include HAZOP, What-If, and Structured What-If (SWIFT) methods.

The quantitative approach generally consists of a similar panel of experts and the same risk ranking table. However the quantitative approach relies more heavily on specific quantitative results such as a calculated likelihood. Quantitative methods include Layers of Protection Analysis (LOPA), ANSI B11.TR3, ANSI RIA R15.06, Fault/Event Trees, and Markov Modeling. The basis behind these methods is borrowed from quantitative equipment reliability analysis techniques such as FMEA. These methods are ideally suited when the event frequency is rare but the consequences are severe since human judgment is less accurate and for complex systems such as interlocks with multiple redundant components.

Shock Hazard Risk Assessment

Shock hazards are the easier risk to assess. Any time that conductors are suitably guarded, insulated, or isolated, there is no shock hazard. Second if the voltage is less than a threshold (50 VAC or 100 VDC), there is no shock hazard. Finally if for a given available fault current the time of exposure is short enough, there is no hazard or the type of hazard may be something other than a fatality. In all other cases, conductors are considered exposed. Direct contact is not necessary to cause a shock. When a conductor is approached closer than the dielectric strength of the air surrounding the conductor, a flashover is very likely to occur through the air and a shock will occur. The prescriptive risk assessment method given in NFPA 70E for shock hazards is based on the assumption that a shock will occur with 100% certainty, although the shock distances include a buffer for inadvertent movement of the worker.

Thus risk assessment consists of a four step process:

1. *Determining whether all conductors are guarded, insulated, or isolated. If not, they are exposed.*
2. *Determining whether or not the voltage or current and exposure time is sufficient to cause a hazard.*
3. *Determining the minimum safe distance from the exposed conductors.*
4. *Determining based on the task whether or not the safe distance will be crossed.*

Likelihood in this case is assumed to be 100% if the task requires crossing the minimum safe distance, if a shock hazard (step 1 and 2) exists.

The dielectric strength of air is approximately 3,000 Volts/mm, and human blood is an excellent conductor of electricity. Thus whenever a human approaches an electric circuit close enough, a flashover occurs and shock occurs even without direct contact. IEEE 516 is the definitive standard for work methods to avoid shock. This standard contains reference data and work methods used by NFPA 70E (all editions), IEEE C2 (National Electrical Safety Code), and OSHA 1910 Subchapters R (electrical distribution) and S (electrical utilization). IEEE 516 calculates a Minimum Approach Distance (MAD) which is a combination of both the flashover distance and an adjustment for inadvertent movement of the worker and (for overhead power lines) the conductor. NFPA 70E refers to this as the Restricted Approach Boundary whereas NESC and OSHA refer to this as the MAD. Beyond this distance, NFPA 70E defines a safe distance for unqualified workers called the Limited Approach Boundary. OSHA has a similar distance in the regulations but does not give it a name.

In all cases then the key question is whether or not the worker could approach too closely for safety reasons. For open, exposed conductors, this is the Restricted Approach Boundary or Minimum Approach Distance. Beyond this limit, the worker must use a combination of work methods, insulating tools, or insulating PPE for protection. This only applies though where conductors are exposed.

As a secondary precaution, electrical workers working on energized equipment are required to control access to the work area to warn other unqualified workers to remain outside of a minimum safe distance which although unnamed in OSHA regulations is referred to as the Limited Approach Boundary in NFPA 70E.

Arc Flash Risk Assessment

Unlike shock methods which are purely a distance consideration, arc flash hazards are more problematic. Specifically the likelihood of an arc flash is more difficult to determine and guidance within 70E is weak in this *regard. Arc flash incidents are rare which makes it difficult to assess the likelihood except with quantitative methods. The key requirements are in informational notes:*

An arc flash hazard may exist when energized electrical conductors or circuit parts are exposed or when they are within equipment in a guarded or enclosed condition, provided a person is ***interacting with the equipment in such a manner that could cause an electric arc***. Under ***normal conditions***, enclosed energized equipment that has been ***properly installed and maintained*** is not likely to pose an arc flash hazard.

Although the paragraph refers to "exposed", this is not a necessary condition to cause an arc flash. Instead, it depends on the type of work that is being performed ("normal" or "abnormal") and the condition of the equipment, as emphasized above. This latter requirement is also emphasized again in another informational note:

It is the collective experience of the Technical Committee on Electrical Safety in the Workplace that ***normal operation*** of enclosed electrical equipment, operating at 600 volts or less, that has been ***properly installed and maintained*** by qualified persons is not likely to expose the employee to an electrical hazard.

Unlike the 2012 edition, the 2015 edition actually defines the conditions for "normal operation" of equipment in 130.2(A)(2):

Normal operation of electrical equipment shall be permitted where all of the following conditions are satisfied:

(1) The equipment is properly installed.

(2) The equipment is properly maintained.

(3) The equipment doors are closed and secured.

(4) All equipment covers are in place and secured.

(5) There is no evidence of impending failure.

Unfortunately only the conditions for normal operation are defined. The tasks which are considered "normal operation" are still not defined. In fact perusal of the task list actually makes it more rather than less confusing as the above listed conditions are repeatedly used as a precedent for several tasks that do not appear related. The term "normal work" is defined but then never used in the task table itself. IEEE paper #ESW2011-22 gives "normal work" which involves interacting with equipment in such a way that could cause an electric arc as:

- *Opening hinged doors/covers without the use of tools.*
- *Switching operations such as operating circuit breakers, fused switches, or contactors for low voltage (<=1 kV) equipment.*

The conditions under which "normal work" would be likely to cause an arcing fault are given as:

- *Conductors are exposed.*
- *Installation is not compliant with applicable codes, standards, and manufacturer's instructions.*
- *Equipment state of maintenance not compliant with manufacturer's instructions.*

- *Equipment may not be free of electrical faults.*
- *Conductor insulation and isolation is suspect (deterioration due to contaminants or environmental conditions).*

A second category of work is interacting but is unlikely to cause an electric arc. These are also defined as “normal work” but indicate that with the absence of a likelihood to cause an electric arc, the equipment condition is immaterial. This group includes:

- *Testing control components <=120 V.*
- *Programming or reading a panel meter.*
- *Operating panel meter switches.*

The third category is called abnormal work. These are tasks which involve interacting with the equipment in such a way that it could cause an electric arc. This includes:

- *Work on energized conductors including voltage testing.*
- *Operating hinged covers or doors with the use of tools.*
- *Removal of bolted covers.*
- *Insertion or removal of individual MCC buckets, bus plug-in devices, or power circuit breakers.*
- *Installation of personal protective grounding equipment.*
- *Work of any kind on medium voltage equipment (> 1 kV).*

IEEE paper #ESW2011-22 did not include tasks which do not involve interacting with equipment at all such as thermography, and did not include tasks in which the worker is outside the arc flash boundary such as using remote controls.

If an incident energy engineering study is performed including calculating incident energy, then the tables in 70E are not supposed to be used. 70E-2015 makes it clear that the tables are “all or nothing”. However the task list could be at least used as a source of ideas for inclusion in an arc flash risk assessment performed to support the hazard assessment done as an engineering study. The tasks are summarized as follows:

1. *Reading a panel meter while operating a meter stick – no arc flash hazard.*
2. *Normal operation of a circuit breaker, fused switch, contactor, or starter – arc flash hazard depends on the “normal operation” conditions.*
3. *Normal operation of an outdoor medium voltage disconnect switch – arc flash hazard.*
4. *Work on AC energized electrical conductors and circuit parts including voltage testing – arc flash hazard.*
5. *Work on DC energized electrical conductors and circuit parts of series-connected battery cells including voltage testing – arc flash hazard.*
6. *Voltage testing on individual battery cells or multi-cell units – depends on “normal operation” conditions.*
7. *Work on exposed energized electrical conductors and circuit parts of utilization equipment directly supplied by a DC source – arc flash hazard.*
8. *Removal or installation of circuit breakers or switches – arc flash hazard.*
9. *Removal or installation of covers for equipment such as wireways, junction boxes, and cable trays that does not expose bare energized conductors and circuit parts – depends on “normal operation” conditions.*
10. *Removal of bolted covers – arc flash hazard.*
11. *Removal of battery intercell covers – depends on “normal operation” conditions.*

12. *Removal of hinged doors to expose bare energized conductors and circuit parts – arc flash hazard.*
13. *IR thermography or other noncontact inspections outside the restricted approach boundary – no arc flash hazard. Does not include opening/closing doors or panels.*
14. *Installing temporary protective grounds – arc flash hazard.*
15. *Work on control circuits with exposed energized electrical conductors and circuit parts, 120 V or below, without any other exposed energized equipment over 120 V including opening of hinged covers to gain access – no arc flash hazard.*
16. *Work on control circuits with exposed energized electrical conductors and circuit parts over 120 V – arc flash hazard.*
17. *Inserting or removing plug-in devices from bus ways, individual buckets from MCC's, circuit breakers or starters in drawout gear, individual DC cells or multi-cell units of a battery in an enclosure, or revenue meters – arc flash hazard.*
18. *Inserting or removing circuit breakers, ground and test devices, or voltage transformers in arc resistant gear – depends on "normal work conditions".*
19. *Inserting or removing or other maintenance work on individual cells or multi-cell units of a battery in an open rack – no arc flash hazard.*
20. *Insulated cable inspection with no manipulation of cable – no arc flash hazard.*
21. *Insulated cable inspection with manipulation of cable – arc flash hazard.*
22. *Work on exposed energized electrical conductors and circuit parts of equipment directly supplied by a panelboard or MCC – arc flash hazard.*

OSHA 1910.269 which is intended for distribution equipment gives a different list of examples of tasks. First, a similar list of equipment conditions is given:

- *Equipment is properly installed and maintained.*
- *There is no evidence of arcing or overheating.*
- *No parts are loose or sticking, or showing other signs of lack of maintenance.*

With those conditions satisfied, "normal operation" of enclosed equipment such as opening or closing a switch is not an arc flash hazard. A single task is considered to not be interacting with equipment in such a way that it could cause an electric arc: Inspection while not holding conductive objects and remaining outside the Minimum Approach Distance (MAD) with exposed, energized parts.

Three specific tasks which could cause an arcing fault are:

- *Inspection of electric equipment with exposed, energized parts while holding a conductive object such as a flash light that could fall or otherwise contact energized parts irrespective of MAD.*
- *Inspection of electrical equipment with exposed, energized parts while closer than the MAD without consideration of any PPE being worn such as rubber gloves.*
- *Using open flames for example in wiping cable splice sleeves.*

Risk Assessment Standards

There are a number of risk assessment standards. Among them are:

- *ANSI B11.TR3-2000 – Risk Assessment and Risk Reduction (for machine tools)*

- *ANSI/RIA R15.06-1999 – For Industrial Robots and Robot Systems – Safety Requirements*
- *ANSI/PMMI B155.1-2011 – Standard for Packaging Machinery and Packaging-Related Converting Machinery – Safety Requirements for Construction, Care, and Use*
- *SEMI S10-0307 – Safety Guideline for Risk Assessment and Risk Evaluation Process*
- *ISO 12100:2010 – Safety of Machinery – General Principles for design – Risk assessment and risk reduction*
- *IEC 61508 – Functional Safety*
- *IEC 61511 – Functional Safety*
- *LOPA – Layers of Protection Analysis*
- *NFPA 70E-Annex F.*

When evaluating the various risk assessment procedures, a fundamental criterion is whether or not they are complete. In other words if the specifics of the severity ranking for injuries or the specific likelihood values for timing are not given in concrete terms, then the results are similarly vague and meaningless. Most risk assessment standards give vague terms for evaluation of hazard severity and likelihood, and no guidance on acceptable risk. For instance 70E gives the following categories for the probability of occurrence for the hazard: “very high, likely, possible, rare, negligible”. No further guidance defining these terms is given. After giving information for determination of the likelihood and severity of the hazard, 70E Annex F simply ends. There is no guidance on how to determine risk. Some standards such as IEC 61508 or ANSI B11.TR3 seem to suggest that acceptable risk is “company and industry specific”. While true to some degree, leaving it completely undefined makes the standard incomplete and reference to further documentation is a necessity. There are standards out there for acceptable risk. Eliminating risk assessment procedures which are not “complete” or vague eliminates most risk assessment procedures except RIA, PMMI, and LOPA.

The second consideration is time frames. The vast majority of risk assessment standards are concerned with injuries from moving machinery. They are designed to analyze hazards that may occur every few minutes or hours such as operators and maintenance personnel working on an assembly line. Arc flash hazards on the other hand are rare events. OSHA investigates only a small number of arc flash incidents per year. Thus we can immediately exclude risk assessment procedures that do not consider an appropriate time frame including the various machine safety standards and NFPA 70E Annex F that appears to be based on ANSI B11.TR3. This requirement is only met by LOPA and IEC 61511.

A final requirement is that the risk assessment procedure should be general enough to accommodate electrical hazards of shock and arc flash. In this respect only LOPA and RIA is generalized enough to support this. However LOPA has a defined table of hazards. Electrical hazards are not in the list of incident rates. Incident rate data must be determined from another source.

All of these various standards have the same 10 step procedure. It is merely necessary to follow the same general procedure with arc flash hazards but substituting severity and likelihood information from known information about arc flash:

1. *Identify the process (task and equipment).*
2. *Collect information.*
3. *Gather personnel. Recommended personnel include safety managers, operators, maintenance personnel, engineers, electricians, and production managers.*

4. *Identify the hazards by taking each task in turn and considering the hazards of the specific task. Do not get this backwards. Starting from generic hazards and working backwards tends to miss details and/or "find" hazards that don't exist.*
5. *For each hazard, determine the magnitude of the hazard with no safeguards (PPE, protective barriers, etc.). This is to determine worst case.*
6. *Identify whether or not the severity of the hazard is acceptable. For instance if a shock could occur but the voltage is under 50 V and thus no injury is likely, this is considered acceptable.*
7. *Determine the likelihood that the hazard will occur.*
8. *Using the two factors (hazard severity, and likelihood), determine the risk and whether the risk is acceptable or not.*
9. *Determine the severity and/or likelihood that the hazard will occur with the safeguards in place.*
10. *Re-evaluate the risk again and determine whether or not it is acceptable.*

The identification process is typically done using a subprocedure. These procedures begin with a written step-by-step procedure for a batch process, process diagram, flow diagram, or some other documentation showing the process in its intended operational condition. Each part of the process is considered in turn along with a series of possibly predetermined questions and/or key words to consider the consequences of failures in the process such as "what if the tank overflows". For electrical equipment the above task lists from existing standards provides an ideal set of "key words" and the single line diagram that forms of the basis of all engineering analysis procedures provides an outline of the equipment to be considered. The hazard identification procedures are generic enough that they can be mixed with the risk assessment procedures. Of those procedures, HAZOP is specific to chemical plants. What-If is almost too generic as it asks the panel of experts to both ask questions and answer them. The SWIFT ("Beyond FMEA: the structured what-if technique (SWIFT)", J. Healthcare Risk Management, 2012, Vol 31, pp. 23-29) method lends itself very well to identification of electrical hazards. SWIFT is a generalization of HAZOP and starts with a fixed list of conditions or criteria and looks at each piece of equipment in turn, generating a list of potential hazards for analysis. A version tailored specifically to electrical hazards is described below.

Safeguards are grouped into 6 categories, and implementation should pick from the highest category first because these have the greatest effectiveness:

1. *Designing out the hazard by eliminating it. For example, remote racking mechanisms move personnel completely out of the area where the hazard would occur.*
2. *Substituting something to change the severity or likelihood, or the possibility of avoiding or limiting the harm. For example dividing up transformers, adding current limiting fuses or breakers, using remote operators or "sticks" to increase working distance, and similar means all eliminate the hazard or substitute it for a less severe or likely one.*
3. *Engineering controls. These are safety technologies or protective devices that limit the harm in many or most circumstances such as adjusting breaker settings, using smaller fuses, or adding arc flash relays.*
4. *Awareness. This includes either active signs such as indicators showing the presence of voltage or passive indicators such as arc flash or shock hazard labels indicating the presence of a hazard. These do not decrease severity but can decrease likelihood. Statistical analysis of the impact of signage has shown that in some cases it can have a benefit but improvements are often modest at best.*
5. *Administative controls. These include procedures to minimize exposures such as requiring an electrical work permit for energized work. There is no impact on severity but it can reduce likelihood.*

6. *PPE. This is the lowest level of control. PPE does nothing to prevent the hazard from occurring. It only reduces the degree of harm to the worker, assuming that the PPE work. No PPE is 100% effective, and normally comes with additional risks such as heat exhaustion, limited visibility, potential undetected damage, and limited dexterity.*

Hazard Severity

This author collected data on arc flash incidents from January 1, 2007 to September 13, 2012., approximately a 5 year period. Data was summarized for only cases involving electrical burns, not cases involving electrocution unless there was clear evidence from the investigation summary that there was a separate arc flash injury. A total of 10 fatalities, 115 serious injuries requiring hospitalization, and 21 minor injuries where the victim was treated and released were cataloged. Thus the range of injuries spans the gamut and there are approximately 10 serious injuries for every fatality. Cawley (Occupational Electrical Injuries in the U.S., 2003-2009, IEEE Paper #ESW-2012-24) reported 7,350 burn injuries and 11,110 shock injuries over that time period. Cawley and others have reported fairly consistent electrical burn injury rates of 0.1 injuries per 10,000 workers, but this was automatically collected data and did not drill down to verify the specific circumstances of the burn injury. The Bureau of Labor Statistics does not have a specific category for "arc flash" or "shock".

Wellman (OSHA Arc-Flash Injury Data Analysis, IEEE Paper #ESW-2012-28) looked at specific circumstances surrounding arc flash injuries. Injuries due to burns were reported at every voltage down to 120 V but all fatalities were for 480 V and higher. 11% of injuries at 480 V were fatalities. This rose to 12% for medium voltage (1 kV to 35 kV).The single case at 120 V occurred when a computer hardware technician unplugged a multiple-receptacle power strip. As the technician was unplugging the power strip, the metal cover plate over the receptacle came loose and fell onto the blades of the plug on the strip's cord. The employee received both an electric shock and burns to the hand. Thus this is a case of damage due to high currents directly burning tissue, not arc flash.

Alicia Stoll and Maria Chantia performed a number of tests to determine the threshold for a 2nd degree burn as reported in "Method and Rating System for Evaluation of Thermal Protection", Aerospace Medicine, Vol. 40, 1969, pp. 1232-1238. This information shows that at 1 second, the 2nd degree burn threshold is 1.2 cal/cm^2. At 2 seconds it increases to 1.5 cal/cm^2. It continues to rise to a maximum of about 2 cal/cm^2. The rate of survival for burns goes down substantially for 2nd degree or greater burns to the face and chest. Thus NFPA 70E chose 1.2 cal/cm^2 as a safety threshold while NESC-2012 uses a 2.0 cal/cm^2 threshold.

Thus it is clear from this data that for any voltage over a lower threshold of somewhere around 120 VAC, a burn injury requiring hospitalization is possible. And for any voltage over 277 V, a fatality is possible. Burns and fatalities can occur if the incident energy exceeds 1.2 cal/cm^2.

Likelihood

Again as reported by Cawley among others, the electrical burn injury rate in the U.S. is approximately 1 in 100,000 workers per year. This includes burns that are not necessarily due to arc flash. Data from both Cawley and Wellman indicates that fatalities (for over 277 V) account for approximately 11% of all injuries up to 35 kV.

There are three root causes of an arcing fault:

A. *Equipment inherent unreliability causes an arc flash, likelihood as P(A)*

B. *External environment and condition causes an arc flash likelihood P(B).*

C. Human error likelihood, P(C).

These can be expressed as a probability of successful task completion without an arc flash so that we have P(no arc flash) = (100%-P(A))(100%-P(B))(100%-P(C)). It is more convenient to view this formula as the probability of an arc flash but the calculation is still cumbersome to use as the formula becomes P(A)+P(B)+P(C)-P(A given B) –P(A given C) – P(B given C) + P(A)P(B)P(C). However if it can be assumed that the arcing fault likelihoods are all very small and that the likelihood of a "double fault" (two causes occur simultaneously) is exceedingly low then the equation can be approximated by a very satisfying and simple result that P(arc flash) = P(A) + P(B) + P(C).

IEEE Standard 493-2007 contains a wealth of information specific to equipment reliability. The following table gives a wealth of overall failure rate information, combining both data from IEEE:

Equipment	IEEE 493, Table 10-2	IEEE 493, Table 10-4
Liquid Transformer	0.0062	0.00289
Fixed circuit breakers	0.0052	
0-600 V	0.0042	0.0000338
Above 600 V	0.0176	
0-600 A	0.0035	
>600 A	0.0096	
Draw out circuit breakers	0.0030	
0-600 V	0.0027	0.000509
Above 600 V	0.0036	
0-600 A	0.0023	
>600 A	0.0030	
Starters 0-600 V	0.0139	0.00180
Starters 600-15 kV	0.0153	0.00313
Disconnects	0.0061	0.00015
Insulated bus	0.001129	0.00303
Bare bus 600 V	0.000802	0.00949
Bare bus > 600 V	0.001917	0.00215
Cable in conduit aboveground/1k ft	0.049180	0.000054
Aerial cable/mile	0.014370	0.01169
600 V cable aboveground	0.001410	0.000096
601-15 kV aboveground cable	0.014100	0.000538
Buried cable 0-600 V	0.003880	0.00199
Buried cable 600-15 kV	0.006170	0.0201
Buried cable > 15 kV	0.003360	
Cable terminations above ground 0-600 V	0.000127	
Cable terminations above ground 600-15 kV	0.000879	
Aerial cable terminations	0.001848	
Underground	0.000303	

terminations		

The following excerpt from Table 10-32 (from 1974 data) breaks down the specific failure modes:

Equipment	*L-G arcing fault*	*Other arcing fault*	*Other electric defects*	*Other mechanical defects*	*Other*
Circuit breakers	*33%*	*10*	*19*	*11*	*27*
Starters	*14*	*20*	*55*	*11*	*0*
Disconnects	*15*	*4*	*47*	*14*	*20*
Open wire	*34*	*23*	*25*	*6*	*12*
Cable	*73*	*1*	*7*	*5*	*14*
Cable joints	*70*	*9*	*20*	*0*	*0*
Terminations	*55*	*4*	*37*	*4*	*0*

Finally, the following Table 10-29 gives failure types for circuit breakers (again, 1970's vintage data):

Failure mode	*Draw-out types*	*Fixed types*
Failed to close when it should	*5*	*6*
Failed while opening	*12*	*2*
Opened when it should not	*58*	*4*
Damaged while successfully opening	*6*	*4*
Damaged while closing	*1*	*4*
Failed while in service (not opening or closing)	*16*	*73*
Failed during maintenance	*0*	*2*
Damage found during maint.	*2*	*0*
Other	*0*	*5*

Table 10-30, taken from a CIGRE study from the mid 1990's gives an indication of when circuit breakers failed:

Test Result	*Electromechanical*	*Solid State*
Trip unit failed to operate	*7.7%*	*3.0*
Trip unit out of specification	*5.7*	*2.6*
Mechanical issues	*2.5*	*2.0*
Issues with power contacts	*2.4*	*2.0*
Arc chute problem	*0.6*	*0.7*
Aux contact issue	*0.4*	*0.0*
Percent passing inspection	*80.6%*	*89.3%*

Table 10-33 gives characteristics of when failures occurred for equipment other than circuit breakers:

Equipment	*Failed in Service*	*Failed during maintenance or testing*	*Damage found in PM*	*Partial Failure*	*Other*
Starters	*37*	*6*	*36*	*20*	*2*
Disconnects	*72*	*3*	*18*	*6*	*1*
Open wire	*68*	*2*	*1*	*6*	*23*
Cable	*92*	*2*	*2*	*3*	*1*
Terminations	*80*	*2*	*12*	*6*	*0*

Ideally one would like to know what the arcing fault rate is (Table 10-2 or 10-4 multiplied by Table 10-32) during maintenance or operating activities. Unfortunately Table 10-33 does not state values in these terms but failures *during maintenance are listed at a rate of 2-6%. Further, Table 10-33 does not indicate any information about the distribution of arcing faults (whether primarily during service while not operating or performing maintenance, or otherwise). Thus a constant estimate that 10% of arcing faults occur during maintenance or operations will be used as a "typical" case. A very conservative case would be to assume that 100% of arcing faults occur during work activities only. The conservative estimate will be reviewed again in a later section.*

In the table below, Table 10-2 or 10-4 is multiplied by the percentage In Table 10-32, and then by 10%. Table 10-4 values are taken whenever available as they represent more recent data. Rates given below show both line-to-ground arcing faults and other arcing faults as well as the total because in some conditions such as with high resistance grounding the likelihood of an line-to-ground arc is reduced substantially as follows:

Equipment	*L-G arcing fault*	*Other arcing fault*	*Total arcing rate*
Fixed circuit breakers	*0.0002*	*0.00005*	*0.0002*
0-600 V	*0.0001*	*0.00004*	*0.0002*
Above 600 V	*0.0006*	*0.0002*	*0.0008*
0-600 A	*0.0001*	*0.00004*	*0.0002*
>600 A	*0.0003*	*0.0001*	*0.0004*
Draw out circuit breakers	*0.0001*	*0.00003*	*0.0001*
0-600 V	*0.00009*	*0.00003*	*0.0001*
Above 600 V	*0.0001*	*0.00004*	*0.0002*
0-600 A	*0.00008*	*0.00002*	*0.0001*
>600 A	*0.0001*	*0.00003*	*0.00001*
Starters 0-600 V	*0.00004*	*0.00006*	*0.0001*
Starters 600-15 kV	*0.00004*	*0.00006*	*0.0001*
Disconnects	*0.000002*	*0.0000006*	*0.000003*
Aerial cable/mile	*0.0004*	*0.0003*	*0.0006*
600 V cable above ground	*0.000007*	*0.000001*	*0.000008*
601-15 kV aboveground cable	*0.00004*	*0.0000005*	*0.00004*
Cable terminations above ground 0-600 V	*0.000007*	*0.0000005*	*0.000008*
Cable terminations above ground 600-15 kV	*0.00005*	*0.000004*	*0.00005*

With respect to environmental conditions, there is very little information regarding electrical equipment reliability in any conditions other than those specified by codes and standards. Thus just as with NFPA 70E it will be assumed that equipment is installed and maintained according to requirements of standards and manufacturer requirements.

An analysis by this author on BLS injury data from January 1, 2007 to September 13, 2012 indicates that approximately 80% of all arc flash incidents were due to human error as the primary cause, not equipment failure. With respect to human error probability, there are a variety of models that have been developed. Regardless of the model, human error rates under stressful (emergency) situations are typically 30-40%. In unstressed situations they *can vary from approximately 1% to 10%. HEART for instance gives error rates for incidents such as a dropped screwdriver of 6-13%.*

Thus when the least reliable equipment arcing rate is 0.0008 arcing faults/year and the most reliable human reliability rates are 0.01, human reliability dominates the result whenever human performance is even a small factor in causing an arc flash. It is only when human reliability is essentially nonexistent such as while operating a breaker or opening or closing a hinged panel that equipment reliability becomes the dominant concern.

Acceptable Risk

Acceptable risk is difficult to determine. Heavily populated countries such as United Kingdom, Netherlands, and Australia have very specific requirements. The minimum tolerable risk for the United Kingdom (HSE 2001) is 1,000 in a million injuries per year while the minimum acceptable risk for which no specific action needs to be taken is 1 in 1 million. U.S. FDA regulations also give a 1 in 1 million limit, as do many U.S. EPA standards including the rate for carcinogens in drinking water. OSHA standards for benzene start at 1 in 10,000. The minimum HSE limit of 1 in 1,000 was determined by considering the risk experienced by high risk groups in mining, demolition, and deep sea fishing (HSE 1992). Major Industrial Accidents Council of Canada (MIACC) recommends a minimum tolerable risk level for land use from all sources where there is no nearby public exposure of 100 in a million, dropping down to 1 in a million for high density residential areas. Many acceptable risk criteria set a much weaker acceptable risk threshold for risks to company workers compared to risk requirements for "the public". "Public" risk is frequently to 1 in a million while worker acceptable risk is generally 1-2 orders of magnitude less.

A more detailed recommended practice is given in the CCPS-LOPA risk assessment standard, an excerpt of which from Appendix E is given in the table below:

Generalized USA Industry Data	*Likelihood for workforce from all scenarios/year*
High risk (e.g mining, heavy construction)	*0.0001*
Low risk (e.g. engineering, services)	*0.00001*
General industry (checmical, manufacturing, rail, trucking)	*0.0001*
Driving accidents	*0.0001*
Airline accidents	*0.0000005*
Work-related accidents in U.S. industry	*0.000019*
All accidents in U.S. (work and nonwork)	*0.00035*

CCPS-LOPA lists some regulations and major companies that have set risk tolerance criteria:

Agency	*Maximum tolerable risk from all scenarios*	*Negligible risk from all scenarios*
UK Health and Safety Executive	*0.001*	*0.000001*

Shell (onshore and offshore)	*0.001*	*0.000001*
BP (onshore and offshore)	*0.001*	*0.0001*
ICI (onshore)	*0.000033*	*N/A*
Rohm and Haas	*0.000025 (single employee)*	*N/A*
Typical criteria for LOPA for all scenarios affecting an individual	*0.001*	*0.00001*
For any one scenario affecting an individual (most useful for LOPA)	*0.0001*	*0.000001*

There are risk criteria for conditions other than fatalities but they are not very well defined. In absence of clear criteria, frequently an appeal is made to the Heinrich risk triangle that suggests that for approximately every fatality, there are 10 major injuries, 100 minor injuries, and 1000 near-misses. As previously reported data is that about 1 out of every electrical burn injuries (11%) are fatalities. Thus applying the Heinrich risk triangle to arc flash hazards, the average rate of occurrence of an arc flash which may result in an injury should be approximately 10 times the acceptable rate for a fatality.

Based on Cawley's analysis of BLS statistics, the measured risk rate for arc flash is 0.00001 injuries/worker/year (1 in 100,000). Of those, approximately 10% as stated previously are fatalities or approximately 1 in a million. Thus the actual injury rate is identical to the "negligible risk" recommendation of LOPA for any one scenario affecting a single individual as well as a variety of other risk criteria. The maximum tolerable risk for a fatality from the LOPA standard is 0.0001/worker/year. Factoring in that only about 1 in 10 arc flash injuries results in a fatality raises this criteria to 0.001 arcing faults/unit/year. Thus the maximum tolerable risk for arc flash hazards should be 1 in 1,000 per year.

Analysis

Armed with the criteria of arc flash likelihood less than 1 incidents per 1,000 unit-years and finally combining all the results together, we can arrive at the following conclusions:

1. *For all tasks in which human error is a concern such as using a screw driver with exposed conductors exposed beneath the working area, the minimum error rate of even 6% is simply unacceptable. All tasks where human reliability is the major contributing factor have unacceptably high arc flash potential and PPE must be worn.*

2. *When equipment is in poor condition although the risk is small, arc flash PPE should be required.*

3. *For tasks in which equipment failure rates are the key concern, equipment which operates at an arcing fault failure rate of 0.001 or better would be considered tolerable and not require arc flash PPE.*

The above likelihood table is repeated again here. All equipment meets the 0.001 arcing faults/unit-year criteria. Further as alluded to earlier this table is based upon an estimate that 10% of all arcing faults occur where a worker is interacting with the equipment. A very conservative estimate would be to assume that arcing faults occur only during interaction with the equipment and not at any other time. Those cases which fail to meet the more conservative requirement are highlighted:

Equipment	L-G arcing fault	Other arcing fault	Total arcing rate
Fixed circuit breakers	0.0002	0.00005	0.0002
0-600 V	0.0001	0.00004	0.0002
Above 600 V	0.0006	0.0002	0.0008
0-600 A	0.0001	0.00004	0.0002
>600 A	0.0003	0.0001	0.0004
Draw out circuit breakers	0.0001	0.00003	0.0001
0-600 V	0.00009	0.00003	0.0001
Above 600 V	0.0001	0.00004	0.0002
0-600 A	0.00008	0.00002	0.0001
>600 A	0.0001	0.00003	0.00001
Starters 0-600 V	0.00004	0.00006	0.0001
Starters 600-15 kV	0.00004	0.00006	0.0001
Disconnects	0.000002	0.0000006	0.000003
Aerial cable/mile	0.0004	0.0003	0.0006
600 V cable above ground	0.000007	0.000001	0.000008
601-15 kV aboveground cable	0.00004	0.0000005	0.00004
Cable terminations above ground 0-600 V	0.000007	0.0000005	0.000008
Cable terminations above ground 600-15 kV	0.00005	0.000004	0.00005

Two categories of equipment would appear marginal with the “conservative” requirement: fixed circuit breakers, and medium voltage circuit breakers. A third specific case that bears mentioning is equipment that can be installed or removed from an energized bus such as draw-out switchgear. Each of these conditions will be considered separately.

Medium Voltage Equipment

Technically, there are several differences between the construction of medium voltage and low voltage equipment. Larger spaces are required to avoid flash overs. Energized equipment must be made inaccessible to unqualified personnel as per NEC. Grounded or insulated panels or separate compartments are common to avoid the need for more expensive insulation to meet requirements that all cable in a given compartment meets the insulation requirements of the highest voltage. High resistance grounding is common and in some cases, mandated by regulation. These all contribute to lowering the risk of a shock hazard. Thus at first blush it would seem odd that medium voltage equipment has a higher failure rate compared to low voltage equipment.

Tt must be kept in mind that this data comes from 1974, over 40 years ago. There have been several significant technological advancements since that time:

- *In the 1970's vacuum interrupter technology was very unreliable. Air or oil interrupters which are more susceptible to contamination and have much shorter allowable cycles between maintenance activities were dominant whereas vacuum interrupters become the dominant technology 20 years later. However statistical data on vacuum interrupter performance compared to competing technologies is obscure. CIGRE report "The Impact of the Application of Vacuum Switchgear at Transmission Voltages", CIGRE WG A3.27 details the scant information that is available and estimates failure rates at 0.00003. One manufacturer (Powell) claims failure rates of about 1 in 100,000 during the expected life of the vacuum breaker. Although this claim appears to be very low, it is within an order of magnitude of 0.000509 from IEEE 493-2007, Table 10-4.*

- *Polymeric insulation systems for cable including an understanding of the phenomena of partial discharge failures has reached a point where the predominant medium voltage cable technology (PILC) has all but disappeared from use. Similarly cycloalaphatic epoxy insulators have all but displaced ceramic insulators due to their improved mechanical and electrical characteristics.*

Rather than looking further for answers, this specific issue has already been tackled by the Mine Safety and Health Administration (MSHA) for mining equipment. Until very recently, medium voltage equipment was not even allowed to be used in an underground mine except with by requesting a special exception to the regulation. MSHA's view on medium voltage at the time of the survey data in IEEE 493 can best be described by a report, "History of Coal Mine Electrical Fatalities Since 1970" by Richard R. Reynolds, which examined fatalities from 1970 through 1983. The report showed that the overwhelming majority of surface fatalities (almost 75%) involved medium voltage. The vast majority involved contact with overhead power lines with trucks, cranes, and drill rigs. In every case the operator was preoccupied with some other task and simply forgot the power line was there. Another 40% of the reported cases involved working on medium voltage equipment while it was energized. The implication is clear that at that time medium voltage equipment was much more hazardous compared to low voltage.

> *Side note for the reader: MSHA defines "low voltage" as under 600 V, "medium voltage" 601-1 kV, and "high voltage" as 1 kV to 5 kV. IEEE uses the term "low voltage" up to 1 kV, and "medium voltage" as 1 kV to 35 kV. NEC mixes terms and sometimes refers to "high voltage" as over 600 V and sometimes as over 1 kV. This paper uses the international (IEEE) terminology.*

From 1970 through 1983, MSHA had not allowed medium voltage equipment for underground coal mining. In time as motor sizes grew, medium voltage had become necessary for underground operations. From 1983 onwards, MSHA had approved over 100 site-specific permits to operate mining equipment underground over 1 kV. In 2010, MSHA published a final rule, Federal Register Volume 75, Number 65, pages 17529-17553, revising 30 CFR Parts 18 and 75 for coal mines, following granting 52 petitions for modification from 1997 to 2010 for 5 kV equipment. In the revision, "MSHA determined that the methods the mine operator proposed to follow when using the high voltage equipment would at all times guarantee no less than the same measure of protection afforded the miners by the existing standards." Similar language is repeated throughout the publication in the federal register.

Arc flash hazard likelihood is not only likely to be reduced but contrary to popular myth, the magnitude with medium voltage equipment is reduced as well. For example with a 2500 kVA, 3 phase transformer with ANSI standard impedance (5.5% for 2400 V and above, 5.75% for 480 V), and an infinite source on the primary side, the *short circuit current is 6.3 kA for 4160 V, and 52 kA for 480 V. Using IEEE 1584 empirical equation with switchgear and assuming a dead short across the transformer leads, the incident energy for 4160 V is 2.8 cal/cm^2 with a 0.5 second arc. Under the exact same conditions, arc gap, and time for the 480 V arc, the incident energy increases to 28 cal/cm^2. This is a 10 fold increase in incident energy by using the lower system voltage.*

NFPA 70E and Roberts treat medium voltage as more hazardous than low voltage equipment. It appears that historically medium voltage equipment was much more hazardous especially at a time when most substations were of the open air/overhead variety. However the technology and overall design of medium voltage equipment has changed in the 40 years that have elapsed since the survey that is documented in IEEE 493 to the point where medium voltage equipment should no longer be treated differently.

Draw-out vs. Fixed Breakers and Similar Equipment that Allows Inserting/Removing

In 1974, draw-out switchgear designs differed significantly from fixed breaker designs. Equipment is designed according to either UL 489 standards or ANSI C37 standards. There is a major difference in philosophy between them. The characteristics of UL 489 (fixed) equipment are:

- *Sealed, molded case breakers*
- *Little or no maintenance*
- *No user replaceable parts*
- *Good performance and reliability*
- *Long life*

In contrast, the C37 design philosophy includes:

- *Iron frame. Older designs are "open" while newer designs are enclosed.*
- *Maintainable for a long service life*
- *Most parts can be replaced in the field*
- *High performance and reliability*
- *High maintenance costs*

Since that time circuit breaker designs have drastically improved. To drive down cost of ownership, ANSI C37 equipment (drawout) has moved towards the same minimal maintenance philosophy as UL 489 equipment. By stocking parts that are common to both designs, ANSI C37 equipment can take advantage of the much larger installed base on UL 489 equipment. In many cases today, the exact same circuit breakers for instance are used in both designs. Thus the actual circuit breakers in drawout switchgear may in fact be a molded case circuit breaker where no service or maintenance can be done aside from cleaning, exericising, and testing.

Technology has also changed over the last 40 years. Vacuum interrupters are now the norm especially for large, medium voltage, or draw-out breakers. For instance in 1974 the oil in greases that were in use at the time would evaporate. Greases would harden in ANSI C37 beakers causing them to operate slowly or seize up after only 1-2 *years of operation. Annual maintenance was an absolute requirement. Today, fluoropolymer greases and improved mechanical designs have reached a point where greasing schedules can be extended to between 8 and 30 years (lifetime). In some recent circuit breaker models from multiple manufacturers, a bistable magnetic actuator with a single moving and sliding bearings part has replaced prior mechanisms with 20-30 movable parts. Several manufacturers now offer circuit breakers for underground vaults that are designed to operate indefinitely even while submerged in water with no maintenance. As an example, the S&C Vista series of switchgear consists of a vacuum circuit breaker and a switch mounted in a stainless steel box that is filled with SF-6 gas and then plug-welded shut.*

Thus we are at a point where the only reliability difference with respect to UL 489 and ANSI C37 designs is with the housing of the circuit breaker and not the circuit breaker itself, at least with current equipment. Older equipment may tend to provide performance closer to that predicted by IEEE 493 data. However this is only a part of the consideration that should be given.

Notwithstanding breaker reliability, the activities surrounding the actual "inserting" or "removing" function needs to be considered in not only circuit breakers but all similar devices such as watt-hour meters, plug-in devices on busway, MCC buckets, and drawout switchgear. Equipment such as circuit breakers, contactors, and load breaking disconnect switches use a variety of mechanisms to safely make or break the arc such as an over centered cam, arc chutes, puffer devices, or arc quenching media (oil, SF-6, vacuum). None of these mechanisms are in use in "draw out" equipment. Spring loaded "fingers" or "stabs" are pushed together to maintain an electrical connection via the use of spring pressure alone. Any human errors that are made during the insertion or removal itself such as misalignment, misjudging bent or damaged stabs, or shutters that fail to open and jam or cock the device can lead to overheating at the joint and subsequent arcing faults, or in the worst case a stab can bend over during insertion and turn into a line-to-line fault. MCC buckets in particular are not designed for live insertion and the flimsy mechanical design easily results in misalignment of bus stabs. Any grounds left behind, test leads, screwdrivers, or wrenches can all lead to catastrophic results. Thus this particular class of tasks which seemingly has little to do with human performance errors is very susceptible to the small fraction of errors that do occur. One manufacturer (ABB) claims in a presentation entitled "Safety Aspect of Low Voltage Switchgear" that the root cause of nearly 80% of switchgear arcing faults is human errors.

A further special mention needs to be made for meter sockets. Certain specific types of watthour meters and similar devices are designed in such a way that the bus bars at the connection are laying in a horizontal plane from the back to the front of the cabinet. Testing by EPRI has shown that in this configuration the incident energy is much higher than predicted by IEEE 1584. Thus 70E and NESC both arc flash PPE to be worn while inserting or removing these devices, and NESC elevates the incident energy rating higher than for other equipment.

Thus Roberts and NFPA 70E both specifically require the use of PPE during insertion/removal activities specifically because of the elevated hazards involved due to human error. However for operations and maintenance on circuit breakers themselves, the age of the equipment should be considered as equipment constructed in the last 10-15 years is equally reliable regardless of whether it is designed under UL 489 or C37 standards as far as the non-drawout mechanism is concerned.

Equipment Condition

None of the conclusions so far provide any support for not maintaining equipment, and certainly in most cases not for operation following a fault. Rather they point to PPE requirements when working on equipment that has been *damaged, or suspected of damage. Data from IEEE Standard 493-1997 is based on "average" or "typical" maintenance. If equipment is not maintained properly, Article 130.5 and 130.7 are very clear that an incident energy analysis does not apply because the arc flash hazards can be significantly higher than predicted. NEMA AB-4 which is the standard referenced by all molded case circuit breaker manufacturers specifically requires a visual inspection to verify integrity of the breaker prior to re-energization. In order to comply with NFPA 70E, proper maintenance (as outlined in Chapter 2) is required.*

In a similar fashion to concerns over the lack of maintenance, some tasks can still be performed with equipment where the hazard exceeds the available PPE. Any task which does not require arc flash PPE could be performed safely. Any task where arc flash PPE is required and the available PPE is exceeded cannot be performed safely. This allows a fairly broad list of tasks to be performed even on equipment with excessively high incident energy.

The condition of the equipment does not make it impossible to perform maintenance. Lack of maintenance does not invalidate safe work. Incident energy (hazard) analysis assumes that protective devices operate properly. However the devices are located closer to the power source than the location of the potential arcing fault. Improper functioning of those devices can invalidate the hazard analysis. Improper functioning of the equipment being worked on can increase the likelihood of an arcing fault but is not likely to increase the severity of the hazard. Thus as long as upstream equipment is working properly, proper PPE can be selected in order to perform maintenance on equipment which may have a high likelihood of an arcing fault. Robert Brown ("Failure Rate Modeling Using Equipment Inspection Data") has attempted to quantify equipment reliability even under poor equipment condition. However just as with mechanical reliability data this method is fraught with errors. Fortunately it is possible to sidestep the controversy altogether. Just as with considering the possibility of human errors as a potential cause for an arc flash hazard, equipment condition can be handled in a similar manner. It will be assumed that if equipment condition is unknown or suspect that the risk of an arc flash is not acceptable and arc flash PPE is required to mitigate the hazard.

Thus an arc flash risk assessment need not preclude any and/or all work from being performed due to the uncertain condition or status of the equipment. Arc flash PPE can be safely determined if upstream equipment is in good working condition.

As an alternative when the condition of the equipment is unknown, a second method can be employed. Arc flash PPE must be worn when equipment is in an unknown condition. IEEE 1584 can only be applied when the system voltage, short circuit current, equipment design, working distance, gap length, and opening times are known. However some simplifying assumptions can be made. Working distances and gap lengths are given for most equipment. A maximum arcing time of 2 seconds is suggested. The ANSI/IEEE 141 short circuit calculation method provides a conservative (over-estimated) value, is relatively simple to apply and requires minimal knowledge of the system. Thus a table can be developed to be utilized where relatively little is known about the equipment or its condition by assuming that all over current protection devices may not work. The available fault current is extremely limited but the end result gives usable boundaries even with little available information. The procedure is then:

1. *Estimate short circuit current using an available method such as ANSI/IEEE 141 or IEC 60909 (comprehensive method).*
2. *Look up the results on the table below to determine required PPE which assumes 2 seconds opening time for overcurrent protective devices.*

Equipment Type	*System Voltage*	*kA for 1.2 cal/cm^2*	*kA for 4 cal/cm^2*	*kA for 40 cal/cm^2*
Open Air	*480-600*	*0.15*	*0.5*	*5.6*
	1-15 kV	*0.1*	*0.3*	*2.5*
Switchgear	*480-600*	*0.1*	*0.4*	*5.3*
	1-15 kV	*0.1*	*0.3*	*2.7*
MCC's and panelboards	*480-600*	*0.07*	*0.25*	*3.1*

A complication to considering equipment condition is whether or not "proper maintenance" has been performed. "Proper maintenance" is defined in NFPA 70E, Chapter 2 by including a number of specific requirements such as keeping areas around equipment clear for accessibility, keeping single lines up to date, and using qualified persons for repair and maintenance. However, Chapter 2 references NFPA 70B and NETA-MTS for specific information on maintenance frequencies, methods, and tests. However, this guidance itself is not sufficient. Both standards contain a wealth of non-safety related procedures. Both contain recommendations such as torque testing fasteners, a maintenance test which has been thoroughly discredited in literature on fasteners. And both state that the maintenance frequencies given are generic and must be modified (increased or decreased) to suit the specific equipment and environment without giving guidance as to how this is done or what it would look like. Existing generic standards such as RCM allow for "run to failure" (no maintenance) conditions. Neither gives specific criteria to evaluate sufficient or "proper" maintenance such as targeted or measured failure rates, although this is difficult at best due to the relatively low frequency of failures of electrical equipment in general. Definitions of "average" or "acceptable" maintenance in the literature on failure rates as summarized in IEEE 493 similarly lacks a criteria for acceptable maintenance. Thus rather than an agreed-upon standard, we have opinions and ideas which run the gamut from liability-induced ultra-conservative standards to run-to-failure policies driven by a lack of standards providing a measure of credibility for what is unacceptable and knee-jerk reactions that span the entire spectrum from too much maintenance to too little. A few equipment specific standards exist but have similar problems. For instance all molded case circuit breakers reference NEMA AB-4 as the maintenance standard. NEMA AB-4 requires a visual inspection after every fault and at least once per year. The standard also requires exercising the breaker periodically and specifies a series of tests to verify functionality. It does not give frequencies for either activity, nor does it specify which tests should be applied to "critical" circuit breakers such as those providing a safety function (opening provides arc flash protection) compared to less critical equipment that can tolerate some level of failures.

PPE is not an iron clad guarantee

PPE specified according to ASTM 1959 and IEEE 1584 only reduces the likelihood of an injury requiring hospitalization due to arc flash in the face/chest area by 95%, as documented by numerical analysis in IEEE 1584. This test was done numerically and does not consider the condition of the PPE itself or whether or not the PPE is worn correctly. Doan and Neal in "Field Analysis of Arc Flash Incdients", IEEE IA Magazine, Vol. 16, Issue 3, showed that in many cases even when the correct PPE was specified, the end users modified it (cutting sleeves off) or wore it incorrectly and thus were injured in the areas that were exposed. Thus the 95% estimate may be optimistic but so far no cases have surfaced in which PPE specified by the IEEE 1584 standard has failed. Given the low incident rate *for arc flash injuries and the necessity of having a case where the PPE is very near the calculated incident energy rating (not over-rated), it may be decades before such a field failure actually occurs.*

Given that human error rates are 0.1/year, and the risk reduction from PPE is 0.05, the resulting residual risk from use of PPE alone assuming 100% compliance with rules and policies on wearing PPE, the likelihood of injury is reduced to 0.005. Appealing somewhat to the Heinrich risk conjecture, the fatality rate would thus be an order of magnitude lower or 0.0005/year. This exceeds the LOPA recommended average risk criteria for any one scenario affecting a single individual and would not be acceptable, and exceeds the average incident rates in many "high risk" occupations. Thus for instance using an uninsulated screwdriver to tighten a screw while landing a wire on an energized system with arc flash PPE alone would not be an acceptable risk.

Although the terminology changes depending on the standard, the concept of a hierarchy of protection is specified by several standards. For application to electrical work, the first step in reducing an unacceptable hazard is to either eliminate it or reduce it significantly. The second step is to apply administrative controls. The third step is to use PPE. Electrical examples of the first case would be to use an insulated screwdriver in the example just given where the exposed metal is less than the phase-to-phase distance. This eliminates the hazard of a screwdriver initiating an arc flash incident. An example of the second layer is use of an EEWP procedure to minimize or eliminate all energized tasks to the bare minimum that are absolutely necessary. The third and final layer is the use of PPE. Using the previous example, the first and second steps will significantly reduce the likelihood and possibly eliminate the likelihood of exposure in the first place and when used in conjunction with or in lieu of PPE would reduce the likelihood of an arc flash injury to an acceptable level.

Arc Flash Risk Assessment Procedure

The steps for the arc flash risk assessment are as follows:

1. *From the previous literature cited, determine an acceptable or tolerable risk for an arc flash hazard. As the tables give fatality rates, apply the Heinrich risk conjecture and multiply by 10 to arrive at a tolerable level of arc flash injuries requiring hospitalization per year for a single scenario involving one worker.*

2. *Prepare a list of tasks using the examples given in the various standards summarized earlier.*

3. *Begin with the single line diagram for the area to be analyzed. For each piece of equipment including any wireways, consider each task from the list previously generated, considering any special cases such as low voltage vs. high voltage compartments. Consider whether or not the task applies. If it does, perform the following analysis.*

   Note 1: Steps 1 & 2 are the SWIFT method for hazard identification.

   Note 2: Equipment commonalities can be taken into consideration but all equipment must be covered just as it is with an incident energy analysis. However overly broad categories (e.g. looking at opening doors on all equipment in all conditions) should be avoided as it will result in overly conservative results.

   a. *Is the likelihood of an arc flash for the task dependent on equipment condition, equipment reliability, or human error? If not, stop. No arc flash PPE required. Examples: performing visual inspections, checking or changing settings, or performing infrared scans without opening doors.*

   b. *Analyze the incident energy for the task. This may be determined for instance using IEEE Standard 1584. Is the incident energy equal to or less than 1.2 cal/cm^2? If so, only nonmeltable clothing is required.*

   c. *Is the likelihood of an arcing fault dependent on human error? If so, arc flash mitigation is required. Skip to step 4 with a likelihood of 0.1/year for the task considered. Examples: making circuit alterations to energized equipment; using uninsulated tools such as screwdrivers, pliers, or wrenches on or near exposed, energized equipment; opening covers held on by bolts that could fall into energized equipment; or inserting or removing equipment for an energized bus such as draw-out switchgear, plug-in bus devices, or MCC's.*

   d. *Is the equipment properly installed and maintained? If not, arc flash mitigation is required. Skip to step 4 with a likelihood of 1.0/year. Examples: not meeting standards in NFPA 70 (NEC) or NFPA 70E Chapter 2. Note that "properly maintained" is not strictly defined at this time.*

   e. *Equipment failure rate is defined using IEEE 493 data for an arcing fault. Refer to previous tables to determine likelihood of arcing fault (arc flash risk).*

4. *Perform a mitigation analysis two times. The first case assumes that no additional risk is detected in the field and uses the risk determined in step 3.The second case sets the probability of an arcing fault to 1.0/year if additional risk is detected in the field.*

   Note: "Double faults" are considered so rare that they are not checked.

   a. *Compare the hazard to 1.2 cal/cm^2. Compare likelihood to acceptable risk from step 1. If the likelihood is acceptable, no further mitigation is required. Otherwise, mitigation is determined using the following steps.*

   b. *For each case where mitigation is required, choose a specific arc flash mitigation to be used in the field to reduce arc flash hazard or risk to an acceptable level. This should be done in a hierarchy of controls fashion. Generic procedures (e.g. EEWP procedure) may exist but task specific procedures should include for instance the use of cover up, using hot sticks or remote operators to increase distance from the equipment, using upstream breakers or switches where incident energy is lower, use of "maintenance switches" or specific breaker settings to use to reduce incident energy, use of insulated tools and equipment, and finally specific PPE to use.*

   c. *For each case and mitigation technique, adjust either the hazard or the likelihood or both. For techniques which eliminate the hazard, the risk becomes zero. For those where the hazard is reduced, calculate the new incident energy level.*

   d. *Check the hazard to 1.2 cal/cm^2. If the hazard is sufficiently reduced, the case is complete. If the likelihood is reduced to an acceptable level, the case is complete. If the criteria are not met,, determine another mitigation technique and repeat as necessary.*

      For the case of PPE only if the PPE rating is high enough to meet the incident energy rating, then the hazard is acceptable. However, the likelihood will also be reduced by 95%. If the likelihood of injury is not acceptable then the PPE may still fail to provide sufficient protection and mitigation *must be repeated. As an example if a starter has previously faulted, donning PPE and opening a disconnect, and then opening the door would be acceptable whereas simply donning the PPE, bypassing the door interlock, and opening the door would not be acceptable whereas opening the disconnect before opening the door and then doing a visual inspection before attempting to close the disconnect to check voltages would be considered acceptable.*

   e. *Once all tasks and cases are analyzed, the analysis is complete. Move on to the next task and/or equipment until all tasks, equipment, and cases are analyzed.*

5. *After the analysis is complete, in the field before execution of every electrical of a task, the equipment should be visually inspected for potential indications that it may fail while the task is performed. If it may fail, then arc flash mitigation is required. Otherwise, no arc flash mitigation is required. Examples: evidence of arcing or overheating externally visible, doors blown loose or off, loose or sticking components, showing signs of contamination, or out of service due to a fault.*

This methodology stops short of providing a specific task list in similar fashion to 70E-2015. Several steps are equipment specific. As task and equipment specifics must be reviewed as part of the risk assessment, providing task lists similar to those that have already been published is not beneficial. Two examples are given as follows. Medium voltage switchgear is frequently (but not always) designed so that the low voltage control circuits are in an isolated compartment from the higher voltage power components. Aside from standards driven reasons the primary reason for doing so is because wiring in the same enclosure must be insulated to the same voltage class. Low voltage control wiring would become unacceptably expensive if designed to 5 kV standards. However some metal enclosed gear violates this principle. Second, some environments may significantly alter the likelihood of an arc flash. For instance in clean, dry electrical room with no ingress of dusts or flyings, opening and closing hinged doors can occur with negligible arc flash risk. The same activity performed when conductive dusts, metal shavings, or flyings are floating in the air and/or built up on top of equipment may create an arc flash when a hinged door is opened on a panel. The act of opening the door to a panel may trigger an arc flash. Thus opening a hinged door may or may not become an arc flash hazard, depending on equipment design and environmental conditions as an example. Both are counter-examples to the task list provided in NFPA 70E-2015.

Thus the procedure above should be executed for all tasks and all equipment on a case-by-case basis. Although this would seem to be even more time consuming and expensive than IEEE 1584 incident energy analysis, it need not be. Most equipment in most plants is expected to be similar. For instance although IEEE 1584 may need to be applied individually to every circuit breaker in a switchgear lineup in the same room, the task analysis may only need to be applied once when all breakers are of identical design, condition, and environment. The temptation (and danger) is to treat all equipment equally, as was done in the tables in NFPA 70E, folding in equipment and environments that are essentially "outliers" with safer equipment and environments.

Critique of 70E-2015

First, Annex F is insufficient. It addresses the wrong time frame for electrical hazards. The shortest duration is more than 10 minutes. Frequency of exposure is given but there is not enough data to estimate this. Likelihood is given as vague criteria rather than a definitive frequency of occurrence. And it gives a factor for considering whether the hazard can be "avoided" or not which is meaningless for arc flash and shock hazards. It does not give an acceptable risk criteria. In short it is just words on paper with no meaning. In short, the "core" portion of Annex F (the actual *risk analysis) is unusable. If Section F.2 is deleted and the above methodology substituted for F.2, Annex F would be a workable risk assessment method for arc flash hazards.*

Second as has already been stated, the list of conditions for normal operation should be clear and obvious so that personnel in the field can clearly understand it and do the evaluation. "No evidence of impending failure" is far too vague. Normal operation of an outdoor load break medium voltage disconnect switch which is mounted overhead and thus inherently has a much longer working distance, and has a rate of decrease of incident energy (exponent of 2 vs. 0.973) is clearly inherently much safer to operate than low voltage counterparts. For those operations where medium voltage motors are common (petrochemical, paper, mining), the equipment is often safer to work on since the low voltage and medium voltage compartments are isolated. Starting and stopping is just as common and should not be treated differently. If anything, the incident energies are typically much lower than 600 V class gear, and usually uses shielded wiring which inherently provides better protection against shock hazards compared to unshielded wiring. The task list for medium voltage gear seems to be generated out of fear of the unknown rather than out of any real safety concern.

Third, I applaud the inclusion of the term "normal operations". However the task list given by 70E-2015 is so contorted in its use that the term loses any meaning at all. Where it is used in papers by Roberts or by OSHA, it is clearly defined as switching tasks, and opening and closing doors. It does not refer to any other tasks. It is clear that the 70E Committee is making an attempt at recognizing tasks which are inherently dependent on human error rates, those which are inherently dependent on equipment reliability, tasks which are dependent on both, and tasks which are not dependent on either one. We can all agree to recognize this so just say so. The list itself just leads to more confusion. The list of "normal operations" and where this category is used in the task list is extremely arbitrary. Voltage testing cells on batteries and working on them should not be "normal operations" while doing the same task on AC equipment is treated differently. The battery case should not require arc flash PPE due to low voltages, not because of arbitrary conditions that do not apply. Similarly removal of doors on wireways, junction boxes, and cable trays follows the "normal operation" requirement but opening a hinged door on an MCC or panelboard even if it is attached to the same cable tray is considered an arc flash hazard.

Rather than attempting to further contort the definition of "normal work", it should be recognized for what it is. It is a list of criteria in terms of condition of the equipment and is used for those tasks where equipment reliability is the critical factor. This is a three part test. The first part is whether or not the equipment was designed and installed properly and can be verified by comparison to electrical codes. The second criteria is whether or not it is maintained properly, and can be verified by comparison of the maintenance program to the requirements in Chapter 2 of NFPA 70E. The final criterion is an inspection of conditions. The criteria can and should be visually field verifiable without opening the cabinet. This would include looking for physical damage, environmental contamination such as liquid running into or out of cabinet, and signs of blistering or charred paint, cracks, etc. Although the simple visual inspection may seem to be petty, consider that the failure rates for equipment in poor condition is still within an order of magnitude of equipment in good condition. The visual inspection cannot both be reasonable and practical, and still catch every defect.

Fourth, there are way too many categories and too many details to make the list easy to follow, with overlaps between various task definitions. An electrician in the field has no chance of memorizing or easily following the task list as it is written. It does not help that there are arbitrarily imposed limits such as treating medium voltage and low voltage equipment differently. I believe that this comes from a very simple issue. Many of the tasks are dependent on whether or not exposed, energized conductors are involved. Simply separating out those tasks that *are within the restricted approach boundary from those tasks that are outside the restricted approach boundary would greatly simplify the list.*

Finally, there is also a glaring omission from 70E-2015. Prior to this version there was always a minimum clothing standard (clothing is not PPE) which required nonmeltable fiber clothing for all electrical tasks regardless of whether PPE was required or not. PPE is required for arc flash hazards over 1.2 cal/cm^2. While performing tasks under 1.2 cal/cm^2 in the nude is perfectly acceptable from a hazard point of view, certain clothing (those that contain meltable fibers) can make a minor arc flash hazard much worse. I agree with dropping "H/RC 0" and making this the minimum requirement for all electrical tasks. But the standard should not have simply dropped it altogether. Any task which is considered safe simply because the incident energy is low (under 1.2 cal/cm^2) should still require nonmeltable clothing. Any task which does not require PPE by virtue of low likelihood of occurrence should not have a clothing requirement since if an arc flash hazard were to occur, survivability is already compromised.

Critique of the Risk Assessment in this paper

The risk assessment procedure outlined refers to the SWIFT technique for hazard identification, the LOPA method for risk analysis, and IEEE 1584 for hazard analysis. These three standards comprise the best available standards for implementation considering electrical risks. Documentation is provided for the inputs to these procedures where it can be given generically such as general failure rates for equipment and risk tolerance rates for a variety of industries and countries. In this respect, it is complete unlike Annex F in NFPA 70E.

The analysis methodology considers tasks in which the risk is always acceptable, tasks in which the hazard is always acceptable, and allows for analysis of all cases in between whereas for instance adherence to IEEE 1584 alone only considers cases where the hazard is acceptably low and adherence to NFPA 70E-2015 only considers tasks where the risk is acceptably low and even then only generically without consideration for equipment-specific cases.

The field assessment procedure is reduced to specific information which would be available to a technician working in the field. Task-specific hazard mitigation requirements as well as specific field inspection criteria are given. With this methodology, field personnel should not be left confused and unsure of what specific actions to take and what is acceptable and what is not.

Summary

NFPA 70E-2015 edition explicitly requires a risk assessment for electrical hazards. However a risk assessment was always required by OSHA. Shock hazard risk assessment has not changed from prior editions except in terminology. However arc flash standards in 70E-2012 and earlier editions implied that a risk assessment was required within the informational notes but these references were obscure at best. The guidance provided in 70E Annex F for risk assessments is not only poor but based on another standard that does not address infrequent, unlikely events such as arc flash.

Both shock and arc flash risk assessments were reviewed. Current standards recommend an absolute approach to shock hazards by controlling distance to energized equipment or by providing sufficient insulation to prevent lethal currents. Arc flash hazards are not entirely controllable and thus demand a probabilistic approach. Probabilistic risk assessment standards were reviewed and one standard was selected as the best fit to consider arc flash hazards.

Average equipment arcing fault incident rates and injury rates were considered as well as applicable existing industry and government-agency specific definitions of acceptable risk. It was shown that average arcing fault rates for electrical equipment does not exceed existing standards of acceptable or tolerable risk. As they are treated differently in the applicable standards, the perceived increased hazards in medium voltage and draw out equipment were specifically considered. It was shown that electrical equipment should not be considered inherently dangerous and where special PPE and other precautions must be taken at all times in order to perform work at an acceptable or tolerable level of risk.

It was also shown that specific tasks, specific equipment designs, and specific equipment conditions may deviate from the average and create conditions where the arc flash risk reaches an unacceptable level. However creating a generic one-size-fits-all procedure for all equipment, conditions, and tasks is not practical. Instead, a task-by-task, equipment-by-equipment procedure to address all tasks and all equipment is proposed using the SWIFT hazard identification technique coupled with LOPA as described previously for the risk assessment standard and IEEE 1584 for the hazard analysis. Thus a complete technique without any of the deficiencies in either the table method in the 70E-2015 standard nor with the deficiencies of the hazard analysis technique in Annex F is presented.