SANDIA REPORT
SAND2008-4820
Unlimited Release
Printed February 2009

High Energy Arcing Fault Fires in Switchgear Equipment, A Literature Review

Jason W. Brown, Steven P. Nowlen, and Francis J. Wyant

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of Energy's
National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2008-4820
Unlimited Release
Printed October 2008

High Energy Arcing Fault Fires in Switchgear Equipment, A Literature Review

Jason W. Brown, Steven P. Nowlen, and Francis J. Wyant

Risk and Reliability Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0748

Abstract

In power generating plants, switchgear provide a means to isolate and de-energize specific electrical components and buses in order to clear downstream faults, perform routine maintenance, and replace necessary electrical equipment. These protective devices may be categorized by the insulating medium, such as air or oil, and are typically specified by voltage classes, i.e. low, medium, and high voltage. Given their high energy content, catastrophic failure of switchgear by means of a high energy arcing fault (HEAF) may occur. An incident such as this may lead to an explosion and fire within the switchgear, directly impact adjacent components, and possibly render dependent electrical equipment inoperable. Historically, HEAF events have been poorly documented and discussed in little detail. Recent incidents involving switchgear components at nuclear power plants, however, were scrupulously investigated. The phenomena itself is only understood on a very elementary level from preliminary experiments and theories; though many have argued that these early experiments were inaccurate due to primitive instrumentation or poorly justified methodologies and thus require re-evaluation. Within the past two decades, however, there has been a resurgence of research that analyzes previous work and modern technology. Developing a greater understanding of the HEAF phenomena, in particular the affects on switchgear equipment and other associated switching components, would allow power generating industries to minimize and possibly prevent future occurrences, thereby reducing costs associated with repair and downtime. This report presents the findings of a literature review focused on arc fault studies for electrical switching equipment. The specific objective of this review was to assess the availability of the types of information needed to support development of improved treatment methods in fire Probabilistic Risk Assessment (PRA) for nuclear power plant applications.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to J.S. Hyslop, Gabriel Taylor and Jason Dreisbach of the U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research. Without their support this work would not have been possible.

CONTENTS

NOMENCLATURE

Acronyms

10 CFR	Title 10 of the *Code of Federal Regulations*
AIRS	Advanced Incident Reporting System
AMF	Axial Magnetic Field
ANSI	American National Standards Institute
CFD	Computational Fluid Dynamics
CSA/EEMAC	Canada Standards Association/Electrical and Electronic Manufacturers Association of Canada
DOE	Department of Energy
EMTP	Electromagnetic Transient Program
EPRI	Electrical Power Research Institute
GCB	Gas Circuit Breaker
GE	General Electric
GIS	Gas Insulated Switchgear
HEAF	High Energy Arcing Fault
HVL	High Voltage Laboratory of Darmstadt University of Technology
IEC	International Electromechanical Commission
IEEE	Institute of Electrical and Electronics Engineers
IPH	Institut Pruffeld fur elektrische Hockleistungstechnik of Germany
LCE	Local Chemical Equilibrium
LER	Licensee Event Report
LTE	Local Thermal Equilibrium
MCC	Motor Control Center
MCB	Miniature Circuit Breaker
MOV	Motor Operated Valve
MV	Medium Voltage
NEMA	National Electrical Manufacturers Association
NFIRS	National Fire Incident Reporting System
NFPA	National Fire Protection Association
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NRCC	National Research Council Canada
OCPD	Overcurrent Protection Device
PC	Personal Computer
PRA	Probabilistic Risk Assessment
RES	Office of Nuclear Regulatory Research
RHR	Residual Heat Removal
SONGS	San Onofre Nuclear Generation Station
TMF	Transverse Magnetic Field
UK	United Kingdom
UL	Underwriters' Laboratory

Symbols

A	Ampere
A	Material Constant (eq. 1)
AC	Alternating Current
DC	Direct Current
ºC	Celsius
ºF	Fahrenheit
ft	Feet
Hz	Hertz
I_{arc}	Arc Current (eq. 1)
K	Kelvin
lbf	Pound force
m	Meter
Pa	Pascal
s	Second
t	Arc Duration (eq. 1)
V	Volt
W	Watt
Y	Burning (eq.1)
Ω	Ohm

Chemical Symbols

Al	Aluminum
CO_2	Carbon Dioxide
O_2	Oxygen
SF_6	Sulfur Hexafluoride

1. INTRODUCTION AND OBJECTIVES

The purpose of this report is to document the findings obtained from an extensive literature review on the subject of arc faults. As described below, high energy arc fault (HEAF) events have been recognized as a hazard since the earliest days of electrical use. Hence, the literature review identified papers dating back as far as the early 1900s. This paper will describe the existing literature on HEAF-type events focusing in particular on electrical switching equipment (e.g., as opposed to electrical transformers). The ultimate objective of this review is to assess the extent to which the existing literature might support improvements in current fire probabilistic risk assessment (PRA) methods for treating the HEAF-initiated fire events. This work seeks to identify gaps in the existing knowledge base that adversely impact our ability to quantify the risk associated with such events. These efforts were sponsored by the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES).

The ability to disconnect a particular component from its power supply provides a greater amount of protection for those working in the area and allows a higher assurance towards the continuity of operation. In order to isolate and de-energize specific components used in the power generation industry, switchgear may be utilized to clear downstream faults, maintain equipment, and replace malfunctioning devices. Typically, they are categorized by construction type, insulating medium, and/or voltage classes. Characterizing switchgear by the latter, the Institute of Electrical and Electronic Engineers (IEEE)[1] defines the power circuit breakers as low, medium, and high voltage which corresponds to less than 1,000 VAC, from 1,000 to 35,000 VAC, and greater than 35,000 VAC, respectively. Failure of these devices, as well as any associated equipment, may be catastrophic for the equipment, personnel and operations.

A massive electrical discharge, the HEAF itself, may cause a catastrophic failure to electrical switchgear. The fault typically involves a short circuit from one, or more, of the bus bar connections to a ground or between phases of the power source through the surrounding medium, such as air or an insulating fluid. The surrounding medium becomes ionized and an electric discharge travels along the path of least resistance. HEAF have been noted to occur from poor physical connection between the equipment and the bus bars (often following maintenance), environmental conditions such as excessive dust or salt fog, failure of the internal insulation, or the introduction of a conductive instrument or foreign object while the switchgear is energized (e.g., a metal wrench or screwdriver used during maintenance).

The electric fault may lead to massive localized pressure and temperature increases, metal vaporization, equipment failure, explosions, and an enduring fire. Each of these could develop into great losses to the power system, operation time, and nearby equipment. These events also pose a serious threat to workers in the vicinity of the incident. There has been limited research, primarily by equipment manufacturers, looking at preventing HEAF incidents from occurring and controlling them when they occur. The studies that have been performed varied greatly in analysis and complexity but have led to the introduction of new equipment designs and protective features such as arc flash detectors and circuit interrupters.

[1] IEEE Standard 1584, "IEEE Guide for Performing Arc-Flash Hazard Calculations," 2002

In order for an arc to initiate, there must be an ionized path for it to travel along. The ionization may occur from metal vaporization of electrodes, poor (high resistance) connection to bus bars in switchgear equipment, decayed and cracked electrical wiring, failure of the insulation, or introduction of metal instruments or conductive debris. Initial experiments used straightened paper clips to initiate arc faults on single-phase systems. In industrial settings, the introduction of conductive objects, such as a maintenance worker's wrench, rodents, or excessive dust, may contribute to the occurrence of fault events. Environmental conditions, e.g. humidity or wind, affect the arc instability and contribute to its random nature. Even though it has been shown that arcs tend to travel away from the ignition source seeking a ground or interruption, they still possess an element of randomness.

Desborough[2] described the electric currents flowing during the fault as non-symmetric causing unbalanced magnetic forces to act on the arc. If the current is large enough, the arc may be driven by these magnetic forces in the axial and azimuth directions. For a period of time, the arc is in motion along the conductor and inner surface of the equipment until it stabilizes at the insulation partition. Desborough also points out that minimal damage will occur while the arc is moving, but substantial damage occurs when it stabilizes. Considering that arc temperatures have been known to exceed four times the sun's surface temperature, the incident may be catastrophic to anyone or anything in the path of, or in line with, the stabilized electrical discharge.

The rapid heating of the air within the switchgear enclosure (e.g., the cabinet it is housed in) or transformer equipment causes a dramatic pressure and temperature increase. In the preliminary studies of the arc fault phenomenon in compartments, the internal gases were assumed to be ideal. This assumption did not account for compression of the insulating gases. In the 1990s, pressure models were further developed through both theoretical and historical exploration.

Arc duration was found to be dependent on the supply current and breaking capabilities. Using devices that would limit the current or break the circuit, an arc could be extinguished quickly and with minimal damage. Insulating materials located around the bus bars or along the interior walls of the compartment also helped quench the arcing fault. However, when over-current devices did not activate, or did not respond quickly enough, these insulating materials, which are commonly a type of plastic composite, could ignite and lead to a fire event.

The mechanical and thermal stresses leading to compartment and equipment failure have been a concern of equipment manufacturers. Topics like pressure and shock waves in the compartments have been minimally studied. Other issues, like the radial temperature of an arc, need further investigation. In general, HEAF events have been minimally explored but improvements in the early quantitative results have been made. Further improvement and refinement of this research would provide greater understanding and more accurate insight into this phenomenon.

[2] Desborough, M., "Pressure Rise and Burn Through Predictions and the Principles of Pressure Relief Device Design," IEE Colloquium on Risk Reduction: Internal Faults in T&D Switchgear, 1997.

2. LITERATURE REVIEW FINDINGS

The Literature Review Findings section details previous HEAF research. This includes initial experiments designed to investigate the phenomenological effects of arc events, incident summaries, and areas for applicable research.

2.1 General Observations

The earliest research identified in our literature search dates to the early 1900s. These efforts were generally limited to attempts to establish an initial understanding of the HEAF phenomena. These early studies were also focused primarily on equipment design and manufacturing questions; that is, the primary focus was to design better switching equipment that would be less vulnerable to arc fault failures. By the mid-1950s, as indicated by Wilson[3], approximately 1,500 investigations had been conducted for electrical contacts, but very few were published for high-currents (i.e., currents of 5,000 amperes and over). Experiments during this time were basic and typically executed on low voltage models. Primitive data acquisition tools, poorly described experimental procedures, and a lack of detailed assumptions limits the usefulness of the research conducted during this time period. Although explosions and fires were noted as a possible consequence of HEAFs, they were not extensively investigated.

More recent studies have further developed the understanding of the HEAF phenomena through experimentation and re-evaluation of previous theories. Specific components, such as transformers, overhead power lines, and switchgear, have been identified as vulnerable to arc events. Another perspective is that much of the more recent research has emphasized worker safety and the investigation of methods for both preventing incidents in the different electrical equipment and protecting personnel from the effects of an HEAF event. The personnel safety investigations in particular have led to more detailed characterization of the effects of a HEAF event on its surroundings (e.g., ignition of worker clothing and the potential for flash-burns to a workers exposed skin). These studies are available through IEEE and from various conferences and journals.

For the nuclear power industry, interest in HEAF-initiated fire events has been peaked by recent events. One key event took place at the San Onofre Nuclear Generating Station (SONGS) and is described further in Section 2.2. As noted above, one specific application of interest to nuclear power plants (NPPs) is fire PRA. PRA methods are used to assess the potential risk of severe accident events as the result of upsets to normal NPP operations, including the potential impact of fires. The incident at SONGS and other similar events clearly illustrate the need to investigate the HEAF phenomena in the context of plant risk. The SONGS event formed the primary basis for the current guidance[4] used in fire PRAs to assess the potential risk implications of HEAF events for NPPs. This event and a similar event at the Maanshan plant in Taiwan (with a different root cause) also led the NRC to initiate an investigation of NPP HEAF events in 2001.

---

[3] Wilson, W. R., "High-Current Arc Erosion of Electric Contact Materials," AIEE Transactions, Vol. 74, No. III, pp. 657 – 663, August 1955.
[4] See Volume 2, Appendix M of NUREG/CR-6850, *EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities*, September 2005.

This NRC study is discussed further in Section 2.7. That investigation identified a number of other similar events.

Fundamentally, the literature review performed here is focused on identifying information and insights from the public literature that could support improvements to the existing PRA assessment methods for HEAF-initiated fire events. As will be noted in the sections which follow, while significant research has been undertaken, the focus of that research has generally been limited to the behaviors of the initiating equipment and the initial arc flash itself. The needs of a fire PRA tend to focus on the enduring fire and its potential impact on nearby equipment. Unfortunately, very little research has focused on these aspects of the HEAF event. It is primarily from the reviews of past events that we can gain relevant insights.

2.2 The San Onofre Nuclear Generating Station HEAF Event

Since switchgear control the electricity to other components in a power generating plant, failures to one or more switchgear may result in extensive equipment outages, which could ultimately interfere with the continuity of operation or the safe shutdown of the plant. Because deviations from full power production levels may be costly, maintaining operational stability remains a major objective for the industry. In the context of a nuclear power plant, such events may also initiate a plant transient leading to a potential challenge of maintaining core integrity. Historic HEAF events, such as the occurrence at the SONGS[5], provide insight into the effects and potential severity of such incidents.

The SONGS HEAF event occurred in a 4.16 kV non-safety (one that does not power safety equipment) switchgear when a main breaker contact (one phase of the connector between the back of the switchgear breaker unit and the source power bus bar) failed to close fully following routine maintenance activity. The event resulted in ionized products (vaporized metal) that led to additional shorts in an adjacent switchgear bay and a catastrophic HEAF failure in that second switchgear unit. Offsite power was lost when this conductive smoke shorted out the energized incoming terminals of the reserve auxiliary transformer. As a result, the AC powered lubrication pumps for the turbine bearings failed to operate. The back-up DC power supply did not function on demand due to a defect in the trip setting device in the standby power supply breaker. The enduring fire initiated by the HEAF would ultimately last for three hours causing extensive damage to several electrical components including cables in overhead cable trays. This event demonstrated that even with redundancies built into a plant design, catastrophic failures resulting from collateral damage may still occur.

2.3 Equipment Vulnerable to Electrical Arcing Events

The processing and distribution of energy through the power system requires the use of specialized components to safely and efficiently supply electricity. The equipment that is primarily susceptible to HEAF events includes overhead power distribution lines, transformers, and switchgear. Other types of electrical switching equipment similar to switchgear (i.e., other types of open-contact switching equipment handling high electrical power loads) may also be

[5] NRC Information Notice 2002-27, Recent Fires at Commercial Nuclear Power Plants in the United States, September 20, 2002.

subject to HEAF. These components each face unique electrical and fire challenges. Such equipment may include electrical load centers and certain type of motor control centers.

Power distribution lines carry large amounts of current at high voltage and must deal with environmental effects. The casing that surrounds the overhead wires must be robust enough to weather various conditions such as sun exposure, winds, or snow and ice. If the insulation on the distribution lines were to fail, arcing may occur and surrounding structures could ignite. There have also been cases where arcing faults in power distribution lines have been induced by environmental conditions such as smoke from a forest or large grass fire, including an event that impacted off-site power feeds to the Diablo Canyon Nuclear Plant in 2001[6].

Transformers, commonly those that are oil-filled, may experience arcs that propagate through the fluid. Zalosh[7] describes this type of event as involving the formation of air bubbles that get larger with time as more arcs occur. Finally, catastrophic failure takes place, typically from over-pressurization causing a rupture of the transformer casing, and the fluid being discharged. The transformer fluid may ignite as either a pool or spray fire. This issue has been explored to a much larger extent than other types of HEAF events, and the resulting fire is conceptually easier to quantify because the knowledge base on oil pool and spray fires is relatively robust.

High voltages and currents along with normal equipment degradation have been linked to arc initiation in switchgear. Routine maintenance and servicing along with improvements in component materials and grounding devices have not eliminated the concerns associated with HEAFs in switchgear. These events, however, have not been studied to a great extent even though there have been recent occurrences. This is particularly apparent when it comes to understanding the behavior of the resulting or enduring fire. The switchgear research has focused on arc development, sustainability, mechanical and thermal impacts from temperature and pressure increases, equipment design, personnel hazards/safety, and the use of composite materials within the actual compartment. Most of the work is preliminary. Also, it has been shown statistically that switchgear equipment has been as vulnerable to HEAF incidents as transformers and thus warrants additional studies.

For the remainder of this report, switchgear and other electrical switching equipment will be the particular focus. While power transmission lines are vulnerable to arc fault failures, the potential impact on a nuclear power plant from such incidents is not unique to fire events and would be characterized by the general treatment of loss of off-site power events. In the case of transformers, as noted, the existing knowledge base is relatively robust with respect to both the arc-fault phenomena and the treatment of the enduring oil fires. It is the case of electrical switching equipment such as switchgear where the knowledge base remains relatively poor, especially with regard to the enduring fire behaviors and effects.

2.4 Switchgear Effects after HEAF Incident

A HEAF results in a large pressure and temperature increase in the confined switchgear housing space. These pressure rises have been known to expel molten metals and hot gases

[6] See NRC Special Inspection Report 50-275/01-10; 50-323/01-10, dated June 6, 2001.
[7] Zalosh, Robert G., "Industrial Fire Protection," Wiley, 2003

throughout the vicinity of the HEAF blast. The high energy arc itself has been noted to reach temperatures of more than 20,000°C[8], instantly vaporizing bare metal and materials used to compartmentalize the interior electronics. Arc duration has been found to play a significant role in flame initiation. When an arc is able to burn without interruption, more hot gases and molten metals are created and ignition of the switchgear components becomes more likely.

Enduring fires within the switching equipment (i.e., fires lasting beyond the arc fault itself) have been reported in previous events. The combustible materials in the switchgear may ignite under specific conditions, such as prolonged arc exposure. The ensuing fire may not necessarily be contained within the electrical cabinet, but rather, may spread to cables or other equipment. An incident of this magnitude may have a great impact on the system operation if important plant equipment is impacted.

Beyond the effects to the equipment caused by the arc, secondary failures of dependent components have been documented[5]. The pressure produced by a HEAF has the potential to cause catastrophic failure of the physical containment unit (e.g., the cabinet in which the equipment is housed), potentially throwing molten metals or housing shrapnel in the vicinity of the blast. The dispersal of heated materials may lead to secondary fires of combustible materials that impact vital system components or cause injury. As demonstrated by both testing and experience, the effects of the HEAF in switchgear clearly have the ability to physically interfere with the surroundings.

Vaporized metal and the hot gases expelled from the switchgear equipment could lead to additional short circuits and secondary arcing. These vaporized metals could significantly impact and damage electronic and computer equipment. Soot production, in general, is a topic that has been studied to an extent, but remains rather conceptual with numerous assumptions.

Extinguishing a fire in energized equipment and venting the products of combustion are other important aspects to investigate. The application of water to energized switchgear has the potential to electrically shock the responders. Other extinguishing agents, such as carbon dioxide (CO_2), may not completely remove the heat from the equipment and thus lead to reignition. Ventilation of the smoke must also be addressed. As described previously, soot and smoke may lead to additional shorts and secondary arcing within the facility.

Halon fire suppression systems have been largely phased out of industrial use because of environmental concerns. Other means to suppress fires resulting from a HEAF must be considered. There has only been a limited amount of research performed on Halon alternatives, such as water mist. Mawhinney[9] analyzed the effectiveness of these systems for switchgear applications. From the experiments, he was able to show that water mist systems outside of equipment did not greatly impact the fire event and ultimately caused water damage. It was shown that water mist systems would operate best if the nozzles were directly over the housing of the faulting components. If a system was designed inside of the actual switchgear, a HEAF

---

[8] Lee, Ralph H., "The Other Electrical Hazard: Electric Blast Burns," IEEE Transactions on Industry Applications, Vol 1A-18, No. 3, May/June, 1982.
[9] Mawhinney, J. R., "Findings of Experiments Using Water Mist for Fire Suppression in an Electronic Equipment Room," Proceedings: Halon Options Technical Working Conference, 1996.

could render it useless by repositioning discharge nozzles or severing the delivery system. Experiments on other suppression methods have been limited.

2.5 A Summary of Pre-1980 Publications

Research on arcing faults found in the IEEE database spanned a wide range of studies over the years. Important aspects that were analyzed included the ignition, extinction, and reignition of an arc. When the subject was initially being theorized, contemporary authors commonly criticized the lack of experimental data to support the various hypotheses. Addressing the issue, Attwood[10] et al. developed experiments to investigate the effects of different electrode materials, geometries, and spacing on the reignition of metallic arcs in air. At the time, this work was commended for the oscillograms showing the current and voltage effects on a time axis during a zero current period. This work also addressed the glow-to-arc transition for the different experimental models. The development of these fundamental arcing characteristics provided insights into the phenomena itself.

Upon the publication of the preliminary research, it was contended that a major gap existed between low and high voltage theories and experiments. According to Wilson[3], very few of the 1,500 references were published for high-currents of 5,000 amperes and over. He also emphasized that the conclusions established "from experience at low current could not be applied at high current without specific verification." The report primarily focused on the erosion rates of different materials and alloys at high currents in addition to subsequent comparison between the electrodes. It was assumed that all of the electric power went into the melting and vaporization of the contact material. The information from Wilson's work was used to directly improve the electrode reliability in circuit breaking devices.

After the number of reports of low voltage arcing faults increased throughout the power industry, research on these systems expanded. Kaufmann[11] initiated the discussion on arc events in power distribution systems by describing incidents involving AC electrical equipment. Even though the failure rate of these devices was low, he explained, serious injuries and massive damages may occur. The author concluded that it was better to overprotect a system and suffer the nuisance tripping rather than risk total burnout.

Other researchers, such as Shields[12] and Dunki-Jacobs[13], further reviewed arcing faults on low-voltage systems and offered insights into preventing these occurrences. Shields provided interesting accounts of severe damage to electrical components resulting from high energy discharges, which were then referred to as "burndown." Both authors suggested that standardized maintenance, improving equipment designs by compartmentalization, and the use of ground-sensor relaying or ground fault protection would reduce catastrophic arcing events.

---

[10] Attwood, S. S., W. G. Dow, and W. Krausnick, "Reignition of Metallic A-C Arcs in Air," Middle Eastern District Meeting for the A.I.E.E., pp. 854 – 870, March 11 – 13, 1931.

[11] Kaufmann, R. H., Page, J. C., "Arcing Fault Protection for Low-Voltage Power Distribution Systems - Nature of the Problem," Transactions of the American Institute of Electrical Engineers, Vol. 79, p. 160 – 167, 1960.

[12] Shields, Francis J., "The Problem of Arcing Faults in Low-Voltage Power Distribution Systems," IEEE Transactions on Industry and General Application, Vol. 1GA-3, No. 1, pp. 15 – 25, Jan/Feb 1967.

[13] Dunki-Jacobs, J. R., "The Effects of Arcing Ground Faults on Low-Voltage System Design," IEEE Transactions on Industry and General Application, Vol. 1A-8, No. 3, pp. 223 – 230, May/June 1972.

In the late 1970s, Stanback Jr.[14] performed laboratory experiments on 277 V single phase systems. One of the observations from the experiments was that a stable arc was difficult to establish with increased spacing between the bus bar and enclosure, an increase in available current, and with an increase in the number of bus bars. The experiments also illustrated the random nature of arcing faults. Other researchers calculated that arcs having less than 38 percent of the available fault current will self-extinguish. Stanback Jr.'s experiments showed that many arcs did indeed extinguish with less than the 38 percent but also that arcs may not necessarily be self-sustaining with greater fault currents.

The author hypothesized "a formula for the approximate prediction of maximum probable burning damage," given in units of cubic inches, relating it to the arc duration and current.

$$Y = AI_{arc}^{1.5}t \qquad \text{(Equation 1)}$$

For Equation 1, the burning damage was represented by Y, a material constant was given as A, and the arc current and arc duration were given as I_{arc} and t, respectively. This equation could be used to evaluate the cost differences between possible equipment options and with damages and the interruption of operation. The author stressed that this equation was only verified for 277/480 V systems and should not be applied to other voltages. This research provided comprehensive experiments that identified some interesting aspects of arcing faults.

There were other significant pieces of work that addressed the safety concerns with electrical hazards. Lee[8] provided a comprehensive study on the effects of HEAF on workers. He presented the nature of this phenomenon, which included the voltage reaction through an electrical system during an incident. Though Lee provided stabilization distances, he warned that higher voltages could potentially lead to longer arcs. When addressing the intense radiative heat produced during a HEAF event, he developed tables of temperature and human skin relationships to show the effects of tissue tolerance. Lee determined that fatal burns and major burns may occur at five and 10 feet away, respectively. Lee's research provided a valuable insight into the hazards and consequences of arc exposure. Many of the correlations used in his work would provide the framework to various electrical safety standards.

Some of the arc events that took place throughout facilities within the United States led to extensive damage, injuries to staff, and high costs associated with repairs and lack of operation continuity. Preliminary research focused on identifying the arc fault problem and suggesting methods to aid in preventing such occurrences. Various theories were discussed and experiments were developed to test the working hypotheses. These studies involved identifying some of the vulnerable equipment and an initial understanding of the phenomena and physics of the arc. This work allowed for the development of rudimentary solutions to some of the HEAF problems. The experiments provided a valuable baseline for research; however, it has been shown that some of the initial studies may need to be revisited due to poorly defined experimental methodologies, a lack of detailed justification to assumptions, and insufficient data acquisition techniques.

[14] Stanback Jr., Harris I., "Predicting Damage from 277-V Single Phase to Ground Arcing Faults," IEEE Transactions on Industry Applications, Vol. 1A-13, No. 4, pp. 307 – 314, 1978.

Nevertheless, these researchers provided the framework for continuing the study of HEAF events.

2.6 A Summary of Post-1980 Publications

When researchers started to analyze arcing faults, assumptions were made to simplify the problems they were facing. This was true for both the qualitative and quantitative results. Recent arc fault research has been focused on refining these original findings and developing new methods for calculating some of the desired event information. Statistics were also being gathered from power distribution centers and other facilities to more adequately address the issues with the incident type, effected equipment, severity, causes, and frequency. Fire incidents in industrial settings were rarely discussed in detail.

In order to gain a greater understanding of the problem, researchers began devising more applicable and elaborate experiments with better data acquisition equipment. Since the majority of preliminary experiments seemed to be focused on low-voltage, single-phase systems (in order to understand the basic phenomena), full scale, medium and high voltage tests were being performed worldwide to investigate some issues like temperature increases within a compartment, metal vaporization of electrodes and compartment walls, pressure wave formation, and the thermal and mechanical stresses on the equipment. More complex experiments were now being conducted on HEAF events in three-phase systems. It was noted that the arcs occurring on three-phase systems were easier to sustain than on single-phase due to the higher magnetic forces. This being said, these systems reasonably deserved a more in depth analysis.

One of the major issues, however, that was not adequately addressed by the researchers conducting the experiments was the limitations of the instrumentation. The arc event occurs so rapidly that the actual conditions may not be adequately represented by the recorded data from instruments, e.g. pressure probes and thermocouples. Several investigations into the preliminary research have refined many of the initial findings.

An example of a reinvestigation of previous work may be found in a study by Terzija et al.[15]. Here, this paper tested the validity of the Warrington formula method used to calculate arc resistance. The authors analyzed the original experiments used to develop the method in question and noted that "bad" results were removed from the experiments without explanation. They found that the equipment used in the original research was fairly crude and inaccurate. The authors, after discounting the Warrington formula, developed a different approach to arc resistance calculations that would greatly assist future work.

To further the investigation on HEAF, equipment manufacturers analyzed various composite materials, insulating gases, and compartment geometry. Additionally, producers of arc suppressing and current-limiting devices were conducting research to determine the effectiveness of their particular instruments in different scenarios. Meanwhile, there was a growing concern for personnel and worker safety in locations where arc fault events have historically taken place. This was, in part, due to the initiation of arcing faults resulting from accidental arc initiation (from a tool, for example), inadequate training, and poor maintenance.

[15] Terzija, V. V., H. J. Koglin, "New Approach to Arc Resistance Calculation," Electrical Engineering, Archiv fur Elektrontechnik, Vol. 83, Issue 4, pp. 193 – 201, 2001.

Standards, such as IEEE 1584 and NFPA 70E, were developed to provide guidelines for installing, maintaining, and servicing high powered equipment.

One particularly interesting topic that was investigated was the effect of dielectric mediums on standard compliance. In order to comply with specific standards, manufacturers had to show that specific equipment could withstand mechanical stresses after an arc event. It was noted that Sulfur Hexafluoride (SF_6) and air, two acceptable gases used for compliance, showed dramatic differences in pressure characteristics. Other insulating materials, such as hydrocarbon fluids, were analyzed for their arc quenching characteristics. These research initiatives helped build upon the preliminary studies and thus offered a better perspective on HEAF events.

Equipment was being manufactured to be less susceptible to arc faults and workers were being more cautious and cognizant of arcing potential. This was through the addition of insulating gases, such as SF_6, improved interior materials, and devices that would limit the current being introduced to the system after an arc fault initiated. The studies were particularly focused on the mechanical and thermal stresses of the system, worker safety, and the potential for upstream fault occurrences. The concern regarding a fire incident after an arc fault event was mentioned, but hardly elaborated upon in any great depth.

Gammon[16] puts arcing faults into perspective as she describes arc faults in relation to short circuits. "…(T)he magnitude," she says, "of the current is limited by the resistance of the arc and may also be limited by the impedance of a ground path. This lower level fault current is often insufficient to immediately trip overcurrent devices, resulting in the escalation of the arcing fault, increased system damage, tremendous release of energy, and threat to human life."

Computers have recently been used in analysis of electrical systems. Some programs have been developed to look at current increases and the potential for an arcing event. The major goal of this particular research is to identify conditions leading up to a high energy release and then attempt to prevent the event from occurring. Finite element analysis was used to look at the mechanical stresses in switchgear and transformers[15].

Computational fluid dynamics (CFD) have been used to measure the pressure and temperature increase[17]. The initial results seemed comparable to experimental results, but the limitations were not discussed in any significant detail. However, the time it takes to run simulations is much longer than simpler calculations. As computer technology improves and more applicable software programs are developed, computational simulation times may decrease.

2.7 Research Insights Derived from Event Review Publications

HEAF events were occurring and being reported more readily because of aging electrical equipment and the increasing electricity demands[10]. As a result, researching HEAF events occurring in different power distribution systems gained momentum. The power industry and

[16] Gammon, Tammy; Matthews, John; "Arcing-Fault Models for Low-Voltage Power Systems," Industrial and Commercial Power Systems Technical Conference, p. 119 – 126, 2000.
[17] Friberg, G., Pietsch, G. J., "Calculation of Pressure Rise Due to Arcing Faults," IEEE Transactions on Power Delivery, Vol. 14, No. 2, p. 365 – 370, April 1999.

equipment manufacturers had an interest in preventing these accidents from taking place because of public safety and the high costs associated with losses in operation continuity and repairs.

Though attempts to recover the original citation were unsuccessful, Shields[12] provided a description of some major incidents. The first such report he discussed was about a huge New York City apartment complex where "two main 480Y/277 volt switchboards were completely destroyed, and two 5000-ampere service entrance buses were burned-off right back to the utility vault" by an arc that burned for over an hour. The 10,000 residents lost service to building water pumps, hallway and stairway lighting, elevators, appliances, and apartment lighting. Several days would pass before temporary electricity was supplied. Shields also reported another catastrophic arc event in the Midwest, where a HEAF burned for more than 15 minutes causing fires in two transformers and a switchboard service entrance. He also cited several incidents taking place in government buildings, many separate occurrences in the same manufacturing facility, and an arc that burned for eight minutes causing burndown in low-voltage switchgear equipment in an industrial processing plant. These events helped illustrate the concern that the power industries and the device manufacturers were experiencing at the time.

The nuclear industry documents various accidental events in Licensee Event Reports (LERs) which may impact proper plant operations. The reporting guidelines may be found in Title 10 of the *Code of Federal Regulations* (10 CFR) Section 50.73. By investigating numerous events throughout many different plants, it becomes apparent that the number of HEAF events in switching gear equipment may warrant additional research.

A HEAF incident at SONGS[18], occurring on March 12, 1968, caused several different alarms in the control room. Operators observed smoke, blue arcing, and a fire in three cable trays above the switchgear. The events led to a reactor trip and shutdown procedures. A local fire department was contacted for assistance with the incident. As a result from the event, the following devices were inoperable due to cable failure:

- safety injection recirculation valves
- west recirculation pump and discharge valves
- electric auxiliary feedwater pump
- safety injection train valves
- refueling water pump discharge valves to the recirculation system

From the bus failure the following equipment was lost:

- west Residual Heat Removal (RHR) pump
- south transfer pump
- boric acid injection pump
- boric acid storage tank heaters and boric acid system heat tracing
- south primary plant makeup pump
- flash tank bypass valve

[18] San Onofre Nuclear Generating Station Unit 1, Report on Cable Failures – 1968, Southern California Edison Company, San Diego Gas & Electric Company, circa 1968.

- east and west flash tank discharge pumps
- center component cooling water pump
- and several motor operated valves (MOV)

Fortunately, the HEAF event occurring at SONGS did not lead to a complete loss of the core cooling capability, core damage, or a radiological release. This incident emphasizes the point that switchgear may lead to major events within power plants. There were other HEAF occurrences that illustrate this issue further.

On January 3, 1989, at Oconee Nuclear Station[19] a 6.9 kV switchgear failure led to an explosion and a subsequent fire, which caused the main turbine and two reactor coolant pumps to trip. The fire brigade was activated, but attempts to use CO_2 and dry chemical extinguishers proved to be an insufficient means of fire suppression. A fog nozzle was then used and, in about an hour, the fire was extinguished. Smoke was reported in the control room, however, there was no further elaboration made in the report.

At the Waterford Generating System, on June 10, 1995, an electrical fault occurred on a 4.16 kV bus bar which led to a fire in the switchgear that propagated to the above cables and resulted in a reactor trip. A worker reported heavy smoke within the turbine building; however, rather than activating the fire brigade, the shift supervisor requested that two auxiliary operators, dressed in personal protective equipment, investigate and visually confirm the presence of a fire. After the field verification, the shift supervisor activated the brigade who attempted to use portable CO_2, dry chemical, and halon extinguishers for suppression. When this failed, operators requested assistance from an offsite fire department. Upon arrival, the fire brigade leader would not allow the offsite crew to use water for about 20 minutes. When other methods were exhausted, the fire department used water and suppressed the event in approximately four minutes. From the Waterford event, it was shown that the fire indication alarms and the lack of visual notification in the control room caused the crew to be unaware of a fire incident. And finally, the attempts to use portable extinguishers rather than water further delayed the suppression of the fire. The incident at the Waterford Generating Station showed that improper fire response in handling a HEAF fire could lead to a prolonged fire event.

A phase-to-phase electrical fault, that lasted four to eight seconds, occurred in a 12 kV electrical bus duct at the Diablo Canyon[20] nuclear power plant on May 15, 2000. This bus supplied the reactor coolant and water circulating pumps, thus resulting in a turbine trip and consequent reactor trip. The fault in the 12 kV bus occurred below a separate 4 kV bus from the startup transformer, and smoke resulting from the HEAF caused an additional failure. When the circuit breaker tripped, there was a loss of power to all 4 kV vital and non-vital buses and a 480 V power supply to a switchyard control building, which caused a loss of power to the charger for the switchyard batteries. After 33 hours, plant personnel were able to energize the 4 kV and 480 V non-vital buses. This event was initiated due to the center bus overheating causing the polyvinyl chloride (PVC) insulation to smoke, which lead to a failure of the adjacent bus

[19] Licensee Event Report 26989002, "Fire in 1TA Switchgear Due to Unknown Cause," Oconee Nuclear Station, Unit 1, January 3, 1989.
[20] NRC Information Notice 2000-14, Non-Vital Bus Fault Leads to Fire and Loss of Offsite Power, September 27, 2000.

insulation. Having only a thin layer of silver plating on the electrodes, noticeably flaking off in areas not directly affected by the arc, contributed to the HEAF event. Other factors that caused the failure were heavy bus loading and splice joint configurations, torque relaxation, and undetected damage from a 1995 transformer explosion. Photos of this failure are located in Appendix A.

On August 3, 2001, a breaker from the main auxiliary transformer to a 4 kV Bus 12 failed at Prairie Island Nuclear Generating Plant[21,22] initiating a fire in a cubicle. This was caused by poor electrical connection between the primary disconnect assembly and the bus stab, thus resulting in overheating and failure in the breaker. The arcing led to a turbine and reactor trip. An adjacent bus was de-energized and the supporting firefighting efforts extinguished the fire in approximately an hour and a half. This event demonstrated successful organization and coordination by those involved.

Another event at SONGS[23, 24, 25] occurred on February 3, 2001. There was a failure of the main contacts of a 25 year old 4.16 kV breaker to close fully causing a HEAF event. Thick, black, ionized smoke dispersed through conduit penetrations in the cubicles, which shorted incoming terminals of the offsite power supply from the reserve auxiliary transformer. As a result of the failure, neither of the AC turbine lube pumps started. This should have automatically initiated the backup DC emergency turbine lube oil pump; however, this failed due to a defective trip-setting device. The fault current continued even though the breaker was tripped. Efforts by the onsite brigade and offsite fire department to extinguish the flames by introducing portable dry chemical extinguishers proved futile since heat continued to reignite the internal components. The fire persisted to burn for three hours until water was applied. These effects may be seen in Appendix B. This event calls the estimated heat release rate of electrical cabinets, suggested by the Electrical Power Research Institute (EPRI), into question since a subsequent study showed that the estimate may be a factor of 1,000 higher for energized electrical equipment.

Besides maintaining a comprehensive collection of incidents that have occurred in different plants, the nuclear industry also notes failure trends in switchgear equipment. A common finding was documented amongst five different arcing fault events in roughly a five year span. Incidents at Palo Verde, Kewaunee, Millstone, Sequoyah, and Browns Ferry were all associated with failures in the Noryl insulation that encapsulates the bus bar[26]. Debris and moisture were also attributed to faults in the switchgear and the arcing events resulted in electrical fires, under-voltage conditions, and reactor trips. Damaged bus bars were replaced as

[21] Preliminary Notification of Event or Unusual Occurrence, PNO-III-01-027, Electrical Panel Fire During Plant Startup, August 6, 2001.
[22] Licensee Event Report, 1-01-05, Fault and Fire in Non-Safeguards Circuit Breaker Results in Reactor Trip and Auxiliary Feedwater System Actuation, October 2, 2001.
[23] Licensee Event Report, 2001-001, Fire and RPS/ESF Actuation Caused by the Failure of a Non-Safety Related 4.16 kV Circuit Breaker, April 2, 2001.
[24] NRC Inspection Report 50-362/01-05, San Onofre Nuclear Generating Station NRC Special Team Inspection Report, April 20, 2001.
[25] NRC Information Notice 2001-01, Metalclad Switchgear Failures and Consequent Losses of Offsite Power, January 8, 2002.
[26] NRC Information Notice No. 89-64: Electrical Bus Bar Failures, September 7, 1989.

were the sections of defective insulation. Additional inspections and maintenance efforts were performed to prevent future incidents from taking place. By providing detailed documentation of failures in nuclear power plants, prevention methods were developed and implemented to mitigate other occurrences.

The Department of Energy (DOE) has developed an annual fire protection summary of events at different DOE facilities. Since 1999, these reports have been available electronically. A summary of HEAF events including specific site and dollar losses may be found in Appendix C.

The National Fire Protection Agency (NFPA) publishes large loss fire incidents within the United States. One reported incident occurred at an Ohio flammable liquids bulk storage plant[27]. An explosion originated in a switchgear area when a short circuit caused a HEAF that ignited flammable gas. One person was killed in the event and the reported dollar loss was greater than $5 million. This event shows that HEAF incidents are not limited to the nuclear industry.

The US Fire Administration collects fire incident data from every state. The National Fire Incident Reporting System, referred to as NFIRS, allows fire departments to report fires and thus contribute information for local and national trending. More than half of the annual fires in the US are reported through this method. However, this system contains inherent flaws that result from incomplete event summaries and findings, an incidental lack of detail, and inconsistent reporting structures across the different departments. There is neither publicly available nor interstate sharing of information. All data is collected and stored at the National Fire Data Center.

HEAF events occur throughout the world[28]. In French nuclear power plants (NPP), 28 fires have occurred in electrical cabinets and eight have taken place in control cabinets. In Japan, a short circuit caused a HEAF event in switchgear between the safety and non-safety class power. At the Greifswald NPP in Germany, in December 1975, a safety significant fire occurred when an electrician caused a triple-pole short circuit at the grounding switch between one of the exits of the stand-by transformer and the 6 kV bus bar of the 6 kV back-up distribution. A circuit breaker was defective and as a result the fault burned for seven and a half minutes until the breaker was manually activated. This caused a cable fire in the main cable duct, which led to a trip of the main coolant pump. A reactor trip and loss of all emergency feedwater pumps were caused by the incident, though no core damage occurred. The turbine building did not have fire detection or suppression systems installed and the well trained fire brigade was impaired due to the thick smoke. Additional arcing incidents have occurred in other components like transformers and overhead cables. These events illustrate that the US is not alone in the need to further understand the HEAF problem.

---

[27] NFPA Journal, Table 4: Large-Loss Fire Incidents of 2005, November/December 2006.

[28] NEA/CSNI/R(99)27, Nuclear Energy Agency, Committee on the Safety of Nuclear Installations, Fire Risk Analysis, Fire Simulations, Fire Spreading and Impact of Smoke and Heat on Instrumentation Electronics, March 10, 2000.

2.8 International Efforts

Many different countries seem to have a vested interest in the development of switchgear protection. This is due to the high cost of interruption and damages associated with an arc event and the ever increasing demand of energy. There are high power laboratories that have studied HEAF events all over the world. In particular, the NEFI High Power Laboratory in Skien, Norway, the British Short Testing Station in Hebburn, Great Britain, the High Voltage Laboratory of Darmstadt University of Technology in Germany, and the Paul Gubany High Power Laboratory in Ellisville, Missouri, USA have all participated in HEAF experiments. There are many other countries that have an interest as well. Japan, France, Finland, Sweden, Switzerland, Canada, and China in addition to many universities all performed research or gathered statistics regarding HEAF incidents. There is potential to develop international collaboration to analyze the various topics associated with arcing fault events.

3. IMPLICATIONS FOR RISK ANALYSIS

This section provides a brief discussion of the implications of the literature review findings organized by topical areas of interest to a fire Probabilistic Risk Assessment (PRA). The topical areas covered are fire frequency, impacts of the HEAF on nearby equipment, and fire suppression.

3.1 Implications for Fire Frequency Analysis

None of the publications reviewed specifically considered the issue of fire frequency analysis. The event reviews that were identified in the existing literature provided only qualitative insights into the nature of the HEAF events. Deriving quantitative insights, such as fire frequency estimates, has not been undertaken in any of the reviewed studies. As has been observed with other types of fire sources, the use of insights from the investigation of fire events in general industry presents certain key challenges that also apply to the HEAF-type events.

No review has provided a comprehensive compilation of HEAF fire events. All of the publications were dependent on voluntary reporting mechanisms (e.g., the National Fire Data Center databases) or on ad-hoc event reports (e.g., events reported in the mass media).

A second challenge is that the existing literature did not include any source that has characterized the population base of vulnerable equipment adequately. That is, the papers do indicate that general HEAF events are relevant to oil-filled transformers, high-voltage power transmission lines, bus bar-type power transport systems, and high energy electrical switching equipment. However, no specific population estimates for such components (e.g., equipment operating years encompassed by the event reviews) were identified. Further, the general category “high energy electrical switching equipment” is rather broad, but no specific study was identified that would allow for narrowing this category (e.g., perhaps eliminating specific types of switching equipment such as molded case circuit breakers, MCCs or load centers).

Based on the literature search, it would appear that continued reliance on the nuclear power plant experience base, while limited, still presents the most reliable source for HEAF fire frequency estimates. Additional reviews of the event databases would likely yield additional qualitative insights, but are unlikely to yield quantitative insights amenable to fire frequency calculations.

3.2 Implications for Fire Consequence Analysis

The second area of interest to fire PRA is the need to predict the damaging consequences of a HEAF event on plant equipment and cables in the vicinity of the faulting equipment. The existing approach documented in the RES/EPRI consensus methodology [NUREG/CR-6850, EPRI TR 1011989] is based on an empirical rule set derived from the SONGS event described earlier.

The existing literature provided only very limited insights of potential interest to estimating fire damage potential and behaviors. None of the studies reviewed included any investigation of the enduring fires that might be created as a result of the initial HEAF event. That is, all of the existing studies have focused on the arcing fault event itself, and no study has investigated the potential for ignitions of secondary fuels or the behavior of a more general electrical cabinet fire initiated by a HEAF equipment failure event. All of the identified experimental studies have involved the investigation of an initiating component (e.g., switchgear) that was housed in an otherwise empty electrical enclosure.

There are two aspects of the existing literature that do provide some insights and potential for further development. One is the characterization of the arc flash event itself. That is, correlations have been developed to characterize the arc-flash potential based on energizing voltage and phase separation distances. Given knowledge of a specific component's geometry, these correlations could be used to assess whether or not an arc flash event is plausible and further, to estimate the energy release potential associated with the initial arc flash.

The second aspect is that correlations have also been developed to estimate the flash heat flux level that would be experienced as a function of distance from the arc itself. These correlations derive primarily from those studies focused on personnel hazard. Various studies have, for example, examined the potential for induced flash burns to exposed skin and for igniting worker clothing. Unfortunately, none of the studies investigated the potential for igniting other types of secondary fuels that would be of interest to a nuclear plant fire PRA such as electrical cables. To utilize the flash heat flux correlations in the fire PRA context, an investigation of the ignition of potential secondary combustibles, and electrical cables in particular, under flash heating conditions (i.e., high intensity but very short duration heating) would be needed.

Overall, the existing literature provided no substantive information to support further refinement of the empirical rule set currently being used to characterize HEAF events.

3.3 Implications for Fire Suppression Analysis

The final aspect of fire PRA analysis is the question of fire detection and suppression analysis. Again, none of the identified studies in the existing literature included the testing of actual full mock-up electrical cabinets, but rather, they focused on the initial fault in the initiating component. Furthermore, the paper investigated in this study did not analyze the response time of smoke or heat detectors or fixed fire suppression systems during a HEAF event.

The research does indicate that when fuels are limited to the initiating component, the fires tend to be relatively small and either self-extinguishing or extinguished easily with hand-held extinguishers. This is likely because the fuels associated with the initiating equipment are both limited in quantity and not particularly flammable (i.e., the phenolic plastics and other rigid plastic materials used to manufacture the switching devices). Unfortunately, in practice fuels will likely not be limited to the initiating component, but rather, will include the other co-located control components (e.g., the control relays, small control power transformers, dial indicators, voltage and current monitoring devices, etc.) and both control and power cables. Hence, the insights relative to the past tests are of little or no interest to a more practical situation.

The reviews of actual HEAF fire events demonstrate that actual events tend to result in aggressive (i.e., intense and fast growing) fires that can be difficult to suppress. In many such events, electrical cabinets or electrical enclosures are breached either by the blast effects associated with the initial arc fault (e.g., access doors are blown open as in the SONGS event) or because the enduring fire is of sufficient intensity to burn through a cabinet's top panel and or panel penetrations (e.g., as in the Waterford event).

One aspect that has not been systematically investigated in any of the identified studies was the question of suppression timing and effectiveness. The best information in this area actually comes from those events that have occurred in the U.S. nuclear power industry (e.g., SONGS and Waterford), information that has already been factored into the existing fire PRA methodology.

4. CONCLUSIONS

When looking at the dynamic nature of HEAF, there are still many factors that are not well understood. The existing research is sharply limited in scope and has not addressed any of the key factors of interest to fire PRA in anything more than a preliminary and/or qualitative manner. While some aspects of the existing research could be applied to the fire PRA approaches, such as correlations for arc characterization and to estimate flash heat flux levels, other questions such as fire frequency, the behavior of an enduring fire initiated by a HEAF, and the effectiveness and timing of fire suppression, remain unaddressed. In order to improve the PRA approach, further research is needed.

Papers investigated in this work did not identify correlations between prolonged arcing within switchgear and the associated fire events. By studying this relationship, insights may be developed on topics such as fire conditions (e.g. temperature and pressure) within the compartment, flame spread to adjacent electrical components (e.g. cables, switchgear, or transient combustibles), and ionized soot production. The latter issue may have a significant impact on secondary arcing. These topics would aid in refining the fire PRA methods currently used by the nuclear industry.

One issue that may require special consideration is the design, effectiveness, and robustness of a suppression system for the HEAF application. It is recommended that additional research be focused on characterization of the enduring fire aspects of such events (e.g., ignition and burning behaviors) and the extinguishment of the fire event. A comparison between various suppression systems (e.g. CO_2, FM200, dry chemicals, and mist systems) in extinguishing energized switchgear fires would provide a stronger basis to perform the fire PRA.

The earliest of the HEAF-type studies were found to provide poorly defined methodologies, inadequate data acquisition equipment, and a lack of justified assumptions which lead to doubts in their credibility. More recent research has attempted to revisit some of the previous work while further refining the various unknown factors. Manufacturers have been continuously working to improve switchgear designs and to incorporate internal component partitioning, different insulating mediums, and alternative housing alloys meant to contain an arc more effectively. Studies supporting these design improvement activities have led to greater functionality and less occurrences for the power distribution industry. They have also contributed to the development of correlations that help to characterize the arc fault potential of a specific component based on voltage levels and phase separation distances.

Reviews of actual HEAF events had shown that these incidents are independent of the manufacturer. Hence, collaborative efforts to share previous experiences and engage in new research of the types already performed will likely continue, and will lead to a greater understanding of the HEAF phenomena, continuity of operation, and worker safety. However, to address the needs of fire PRA, the scope of the testing will need to expand as compared to past studies. In particular, fire PRA needs to assess the event behavior beyond the initial arc-fault event itself so as to encompass the issues related to the enduring fire. With the exception of those studies that have investigated actual HEAF events, the past research has focused exclusively on the initial arc fault event. Issues that go beyond the initial arc fault event include characterization of the potential for ignition of secondary combustibles (other than worker clothing), characterization of the fire growth and intensity following the enduring fire, and the effectiveness and timing of fire suppression efforts. None of the existing experimental studies has included the investigation of these post-arc fault event issues.

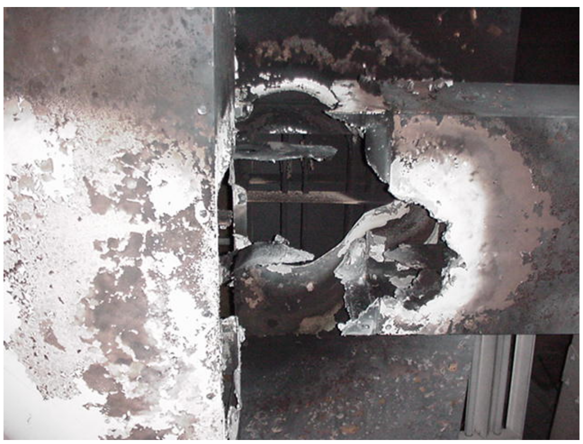
5. WORK CITED

1. Attwood, S. S., W. G. Dow, and W. Krausnick, "Reignition of Metallic A-C Arcs in Air," Middle Eastern District Meeting for the A.I.E.E., pp. 854 – 870, March 11 – 13, 1931.
2. Desborough, M., "Pressure Rise and Burn Through Predictions and the Principles of Pressure Relief Device Design," IEE Colloquium on Risk Reduction: Internal Faults in T&D Switchgear, 1997.
3. Dunki-Jacobs, J. R., "The Effects of Arcing Ground Faults on Low-Voltage System Design," IEEE Transactions on Industry and General Application, Vol. 1A-8, No. 3, pp. 223 – 230, May/June 1972.
4. Gammon, Tammy; Matthews, John; "Arcing-Fault Models for Low-Voltage Power Systems," Industrial and Commercial Power Systems Technical Conference, p. 119 – 126, 2000.
5. IEEE Standard 1584, "IEEE Guide for Performing Arc-Flash Hazard Calculations," 2002
6. Kaufmann, R. H., Page, J. C., "Arcing Fault Protection for Low-Voltage Power Distribution Systems - Nature of the Problem," Transactions of the American Institute of Electrical Engineers, Vol. 79, p. 160 – 167, 1960.
7. Lee, Ralph H., "The Other Electrical Hazard: Electric Arc Blast Burns," IEEE Transactions on Industry Applications, Vol. 1A-18, No. 3, May/June, 1982.
8. Licensee Event Report 26989002, "Fire in 1TA Switchgear Due to Unknown Cause," Oconee Nuclear Station, Unit 1, January 3, 1989.
9. Licensee Event Report, 1-01-05, Fault and Fire in Non-Safeguards Circuit Breaker Results in Reactor Trip and Auxiliary Feedwater System Actuation, October 2, 2001.
10. Licensee Event Report, 2001-001, Fire and RPS/ESF Actuation Caused by the Failure of a Non-Safety Related 4.16 kV Circuit Breaker, April 2, 2001.
11. Mawhinney, J. R., "Findings of Experiments Using Water Mist for Fire Suppression in an Electronic Equipment Room," Proceedings: Halon Options Technical Working Conference, 1996.
12. NEA/CSNI/R(99)27, Nuclear Energy Agency, Committee on the Safety of Nuclear Installations, Fire Risk Analysis, Fire Simulations, Fire Spreading and Impact of Smoke and Heat on Instrumentation Electronics, March 10, 2000.
13. NFPA Journal, Table 4: Large-Loss Fire Incidents of 2005, November/December 2006.
14. NRC Information Notice 2000-14, Non-Vital Bus Fault Leads to Fire and Loss of Offsite Power, September 27, 2000.
15. NRC Information Notice 2002-27, Recent Fires at Commercial Nuclear Power Plants in the United States, September 20, 2002.
16. NRC Inspection Report 50-362/01-05, San Onofre Nuclear Generating Station NRC Special Team Inspection Report, April 20, 2001.
17. NRC Information Notice 2001-01, Metalclad Switchgear Failures and Consequent Losses of Offsite Power, January 8, 2002.
18. NRC Information Notice No. 89-64: Electrical Bus Bar Failures, September 7, 1989.
19. Preliminary Notification of Event or Unusual Occurrence, PNO-III-01-027, Electrical Panel Fire During Plant Startup, August 6, 2001.
20. San Onofre Nuclear Generating Station Unit 1, Report on Cable Failures – 1968, Southern California Edison Company, San Diego Gas & Electric Company, circa 1968.

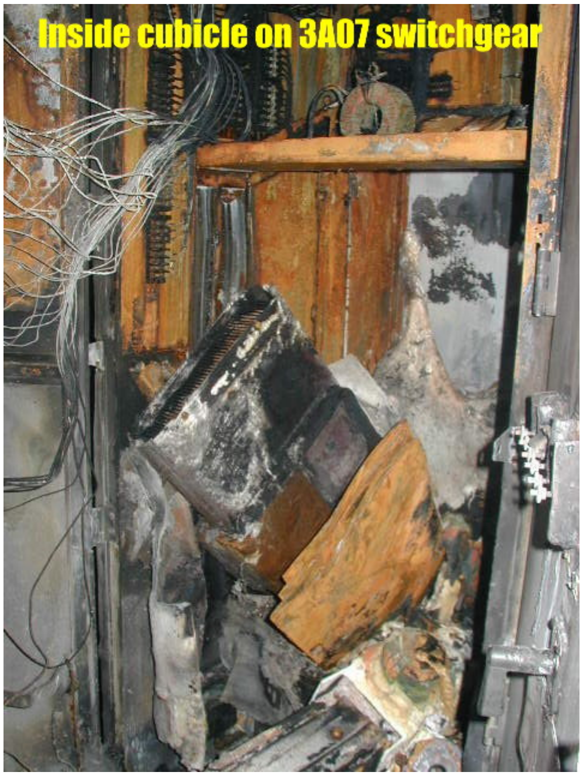
21. Shields, Francis J., “The Problem of Arcing Faults in Low-Voltage Power Distribution Systems,” IEEE Transactions on Industry and General Application, Vol. 1GA-3, No. 1, pp. 15 – 25, Jan/Feb 1967.
22. Stanback Jr., Harris I., “Predicting Damage from 277-V Single Phase to Ground Arcing Faults,” IEEE Transactions on Industry Applications, Vol. 1A-13, No. 4, pp. 307 – 314, 1978.
23. Terzija, V. V., H. J. Koglin, “New Approach to Arc Resistance Calculation,” Electrical Engineering, Archiv fur Elektrontechnik, Vol. 83, Issue 4, pp. 193 – 201, 2001.
24. Wilson, W. R., “High-Current Arc Erosion of Electric Contact Materials,” AIEE Transactions, Vol. 74, No. III, pp. 657 – 663, August 1955.
25. Zalosh, Robert G., “Industrial Fire Protection,” Wiley, 2003

APPENDIX A: PHOTOGRAPHS OF THE HEAF EVENT AT DIABLO CANYON






APPENDIX B: PHOTOS OF THE SAN ONOFRE HEAF EVENT


Inside cubicle on 3A07 switchgear


Burn mark inside Cubicle 3A0714
(Feeder from Reserve Aux Xfmr 3XR2)


Back panel doors of 3A0712 and adjacent cubicles


Bus bars in Cubicle 3A0711 (rear)


Bus bars in Cubicle 3A0712 (rear)


Front of 3B14 switchgear

APPENDIX C: ARCING FAULT INCIDENTS FROM DOE ANNUAL SUMMARY REPORTS

Table 1: Arcing fault incidents found in DOE Annual Summary reports

Year	Location	Description	Dollar Loss
1999	Chicago Operations/Brookhaven National Laboratory	High voltage electrical arcing across a plastic encased capacitor in a Pulsed Fired Network power supply resulted in a fire at the National Synchrotron Light Source (NSLS). Operations personnel first heard the electrical arcing and then saw flames within the power supply cabinet. After turning off the high voltage power to the equipment, they attempted to use fire extinguishers to put out the fire. Smoke detection above the area summoned the fire department. Damage was limited to the interior of the equipment cabinet. The National Synchrotron Light Source injector system was out of service for one week until the power supply used to provide the Klystron was repaired. As a result, the NSLS has filed a CAIRS report for the incident.	$95,000.00
2000	Richland Operations/Hanford Site	A 115 kV transformer failed internally causing a phase-to-ground fault. The unit exploded igniting the mineral oil contents and the fire department responded to the scene and extinguished the fire.	$37,734.00
2000	Carlsbad Area Office/Waste Isolation Pilot Plant	On October 23, 2000 a fire occurred at Substation #3 at the WIPP surface. The Facility Shift Manager has power isolated to the substation and the blaze extinguished. The fire occurred in a busway due to water migration from heavy rain causing arcing and meltdown of the copper busway bar.	$16,000.00
2000	Savannah River Operations/Savannah River Site	At 11:32, SRSFD personnel were dispatched to 105-K based on a call-in alarm from facility personnel. The fire was reported in Transformer Rm. #2. Upon arrival, facility personnel had extinguished the fire with an extinguisher. SRSFD firefighters investigated and found the cause of the fire to be an electrical short in Panel 26 E-1. There were no injuries and the estimate for damage is $10,000.	$10,000.00
2000	Richland Operations/Hanford Site	A 1500 kVA dry type outdoor transformer causing internal plastic components to ignite. The fire department responded and extinguished the fire.	$9,197.00
2000	Oakland Operations/Lawrence Berkeley National Laboratory	An electrician discovered a short and a fault might have caused the power to trip in a class room. Upon investigation, a fire was detected at the distribution panel.	$5,000.00
2001	Richland Operations/Hanford Site	A fire occurred in an electrical panel in room 235-B of building 234-5Z. The HFD responded to the scene and extinguished the fire. CAIRS No.: 2001061	$57,000.00
2002	Strategic Petroleum Reserve/Strategic Petroleum Reserve	Bryan Mound on-duty ERT responded to an on site transformer fire caused by lightning strike to a section of the air terminal on a lightning arrestor tower. The section then fell across the secondary 4160-volt bus and a phase-to-phase fault occurred. Site ERT's extinguished the remaining fire and then remained on scene until power was restored. (Occurrence Report BM-2002-0003)	$90,000.00

Year	Location	Description	Dollar Loss
2002	Savannah River Operations/Savannah River Site	At 13:27, SRSFD personnel were dispatched to a call-in alarm for a possible fire at the 105-K substation. Fire fighters responded and upon arrival discovered that an electrical event in the 105-K containment substation blew the door open causing smoke and flame, which were momentarily visible. The fire self-extinguished when the breaker at 151-K tripped out. The entire event lasted 30 seconds or less. There were no SRSFD actions on scene. There were no injuries and the damage estimated is $50,000.	$50,000.00
2002	Savannah River Operations/Savannah River Site	At 14:00, Dispatch received a call-in request for assistance from 241-28H regarding an electrical problem. Upon arrival, SRSFD personnel discovered that a loss of incoming 13.8 kV phase resulting in an excessive load on the balance of the phases had caused minor heat damage to one or more of the cubicles. The affected MCC was de-energized and the fire self-extinguished. There were no injuries and the dollar loss cost estimate is $7500.	$7,500.00
2003	Idaho Operations/Idaho National Engineering & Environmental Laboratory	Generator, GEN-UTI-603, experienced an internal fault. The INELL Fire Department was notified.	$3,000.00
2005	Sandia Site Office/Sandia National Laboratory Albuquerque	SNL Event No. 12688 Bldg. 6640 Department 05133 was conducting a Marx generator characterization test in the south bay of building 6640. The Marx generator was contained in an aluminum oil tank with an open top. The Marx was being discharged into a ~50 ohm water/salt load. A Marx self break curve had been established and the experiment was proceeding through incremental steps in charge voltage to thoughtfully verify proper operation of the Marx up to the maximum 100 kV charge level. At ~1:30 pm the first shot at 100 kV charge was attempted. The Marx prefired at ~96 kV and erected fully. The expected peak output voltage of ~600 kV was achieved. At approximately 4 us into the discharge decay (~430 kV), it appears that an oil arc occurred from the trigger screw on the last Marx generator spark gap to the surface and then across the surface to ground on the tank. The result was oil vaporization and a fire ball which rose to the roof of the test bay and then flash charred some of the roof insulating material. The duration of the fire was approximately 5 seconds according to the personnel present. The personnel in the area secured the test site by draining the oil out of the MARX generator into 55 gallon barrel. The overhead door in the airlock was opened to ventilate the room to get the smoke out of the room. Cause: The fire was due to faulty component in the MARX generator that caused an oil arc to occur from the trigger screw on the last Marx generator spark gap to the surface and the across the surface to ground on the tank.	$14,000.00
2006	Savannah River Field Office/Savannah River Site	At 23:10, SRSFD personnel were dispatched to a call-in notification by a WSI LE unit of a 115 kV substation fire at 504-3G, which is off of Hwy. 125 @ Gate A13. Upon arrival, SCE&G personnel were already on-scene and had extinguished the fire with a 2.5 lb. fire extinguisher. There were no further actions on the part of the SRSFD except to stand-by until SCE&G personnel were clear of lines. There were no injuries.	$5,000.00

APPENDIX D: ANNOTATED BIBLIOGRAPHY

- *Attwood, S. S., W. G. Dow, and W. Krausnick, "Reignition of Metallic A-C Arcs in Air," Middle Eastern District Meeting for the A.I.E.E., pp. 854 – 870, March 11 – 13, 1931.*

Attwood developed experiments to investigate the effects of different electrode materials, geometries, and spacing on the reignition of metallic arcs in air. At the time, this work was commended for the oscillograms showing the current and voltage effects on a time axis during a current zero period. This work also addressed the glow-to-arc transition for the different experimental models. The development of these fundamental arcing characteristics provided insights into the phenomena itself. This paper provides insight into the initial research performed on HEAF phenomena.

- *Babrauskas, Vytenis, "Ignition Handbook," Society of Fire Protection Engineers, p. 766 – 773, 2003.*

Chapter 14 in the Ignition Handbook is really helpful in identifying a variety of resources to investigate the high energy arcing fault project further. He frames the problem by identifying typical reasons for arc fault occurrences. Some of his resources were from personal conversations with knowledgeable persons in industry so they may be decent contacts in the future. The author refers to some historical events that address the needs for further investigation into the problems. Different sources' main points are summarized and presented to the reader.

Many of the sources the author used in the Ignition Handbook have been requested for the initial research project. This book helped frame the initial problem and gather relevant sources on the high energy arcing fault project. One study that could not be obtained was: Peck, G. C., Fire and Explosion Hazards of Liquid-filled Electrical Equipment, Part 1: An Overview (ITB-R84/108), The Insurance Technical Bureau, London (1984). This cited document investigated low- and high-voltage equipment fire and explosion incidents in the UK.

- *Bjortuft, Tom Rune, Ole Granhaug, Svein Thore Hagen, Jan Henrik Kuhlefelt, Gerhard Salge, Pal Kristian Skryten, Silvio Stangherlin, "Internal Arc Fault Testing of Gas Insulated Metal Enclosed MV Switchgear," 18th International Conference on Electricity Distribution, CIRED, 2005.*

This paper was about full scale, gas insulated, metal enclosed MV switchgear tests carried out at NEFI High Power Laboratory in Skien, Norway. In particular, the aim was focused on the pressure differences when the gas inside the switchgear was air or SF_6 and the whether the electrodes were copper, aluminum, or iron. This is an issue because the IEC standards and utilities technical specifications allow testing with air replacing SF_6. The arc was ignited at the end of the 400 mm long bus bars using a thin piece of copper wire. The size of the metal enclosure is comparable to that of ABB's ring-main units.

Again, these tests only looked at the pressure build-up within the enclosure, the opening time of the pressure relief devices, and the characteristics of the gaseous outflow from the test vessel.

The pressure-rise was measured at different locations on the test object with stat./dyn. transducers from BD-sensors and Kistler. For the temperature rise, ordinary thermocouples were mounted in the gaseous flow at one meter distance from the bursting discs. This may, however, exceed the limitations of the thermocouples. It seems like the temperature rise is extremely sudden and may not be accurately captured by the instrumentation. Further investigation should be given in the area of instrumentation response.

The current in all of the tests were $16kA_{rms}$ and the area voltage varied from 250 V to 500 V depending on the electrode material and insulating gas. The maximum pressure rise was 100 ms using the SF_6 and either the copper or iron electrodes. When switching to air, the maximum pressure rise was found to be approximately 50 ms. This paper confirmed the IEC standard statement that there will be a different pressure rise if the arc fault tests are completed with air rather than SF_6. Their explanation is as follows: "when an arc fault occurs there will break out shock waves that will spread out from the arc core. The pressure waves spreads out in the volume with the speed of sound of the medium plus the velocity of flow within it. The velocity of the flow can be higher in air than in SF_6. The size of the pressure wave is dependent on the energy behind…the density of the SF_6 is almost 5 times greater than air. In practice this means that the velocity of flow must be almost 3 times greater in air versus SF_6 if the static pressure which the transducers measures shall be 50% higher."

The authors pointed out that approximately half of the electric energy is converted when the arc heats up the surrounding gas which leads to the pressure build up; while the rest goes to different modes of heat transfer, and the melting and evaporation of the electrode material and metal structure. This paper uniquely described the SF_6 gas dissociation. They explain that some of the fluorine reacts with aluminum to form aluminum fluoride (AlF_3) which is severely exothermal and thus increases the gas temperature. The authors conclude by stating that there is much debate on the proper testing procedure with testing of gas filled switchgears. Their work states that the different gases and electrode materials are only some of the issues that need addressing and, by the tests, obviously need special consideration.

- *Brown, Lloyd R., "Electrical Fire Opinions," Fire and Arson Investigator, p. 36 – 37, 1993.*

This article seemed like it had potential to help the HEAF project, but it really did not go into the issues of interest. The article was mostly opinion and experience based. The author did provide some consistency to other studies, e.g. the debris on the bus bars leading to HEAF events, but generally the article would not be helpful for the HEAF project. One source that this article identified that may be worthwhile to investigate would be Alexander S. Langsdorf's (of Washington University) experiments on arc voltages. This may provide insight into his experiments and results. No further references were mentioned in this paper.

- *Crnko, Tim, Dyrnes, Steve, "Arcing Fault Hazards and Safety Suggestions for Design and Maintenance," IEEE Industry Applications Magazine, p. 23 – 32, May/June 2001.*

This article provided great insight to the arc fault hazard from a perspective of personal protection. The authors referenced the IEEE article by Jones entitled "Staged Tests Increase Awareness of Arc-Flash Hazards in Electrical Equipment" quite extensively, in particular the experiments and results that were conducted. The authors' description of the arc fault phenomena and hazards are consistent with other sources. The temperatures were noted beyond 35,000ºF at the arc terminals. Pressure generation by expanding gases and metal vaporization was also addressed. It was noted that copper vapor expands to 67,000 times the volume of solid copper. The impact from this pressure increase is dangerous for personnel and surrounding equipment. The explosion of molten metal resulting from the event may lead to additional incidents and an ensuing fire may not be contained to the originating equipment.

The tests provided some insight into the experimental design and the data gathered. The tests studied in this particular article were numbers 4, 3, and 1. Test Number 4 simulated a 600-A feeder to a combination motor starter with the available fault current of 22,600 rms symmetrical A and a 640-A circuit breaker setting with a delay of 12 cycles. The lab interrupts the circuit at six cycles to simulate a short time delay. The fault is initiated on the line-side of the 30-A UL Class RK1 fuse protecting the motor branch circuit which simulates a worker causing a fault in the combination starter on the line-side of the branch-circuit device. This test resulted in pressure of over 2160lbf/ft^2. The temperatures recorded were greater than 225ºC at two feet away. Test Number 3 was similar to Test Number 4 except for the 601-A current-limiting overcurrent protective device. This cleared the arcing fault in ¼ of a cycle and limited the amount of current prevented as high of pressure rise and limited the maximum temperature rise to an isolated arc radius. Test Number 1 simulated a 600-A feeder to a combination motor starter branch circuit with a 30-A RK1 fuse. The arc was initiated in the load side of the starter and was cleared in less than a ¼ cycle which limited the energy released. Some interesting conclusions from the tests were that insulated buses in equipment are beneficial because the arcs observed traveled away from the source to the insulated bus area and was extinguished, that single-phase faults are harder to sustain than three-phase, the arc-fault damage and arc energy was greatly reduced by current-limiting overcurrent protective devices. The authors of this article indicate that the standards need to include tests with the doors open. Other articles and papers are discussed and tables of distances from phase-to-phase arcs at which the onset of a second-degree burn is predicted on exposed skin and three-phase fuse arc test results.

This article provides a review of previous work, offers suggestions for future research, and supplies references to other pertinent articles.

- *Deaton, Robert, Gostic, James M., "Installation and Operational Considerations of Arc Resistant Switchgear," Petroleum and Chemical Industry Conference, p. 307 – 313, 1996.*

This article is interesting because it refers to arc-resistant metal clad switchgear equipment as a means to prevent injury resulting from arcing. The author looks at one particular manufacture's arc resistant metal clad medium voltage switchgear in a large petrochemical facility. One of his sources states that arc flashes were the cause of 78% of electrical injuries in a 20 year span. Because of this, arc resistant switchgears have been making their way into industry. The main goal of this equipment is to contain the extreme pressure and temperature within the switchgear upon the initiation of an arcing fault until a pressure vent on the top of the switchgear releases. This allows the material to be vented away from personnel. However, since our concern is not for worker safety, this does not completely address the concern dealing with high energy arcing faults.

A couple of different companies may have vested interest in pursuing further research on this topic, in particular the American National Standards Institute/Institute of Electrical and Electronic Engineers (ANSI/IEEE), the National Electrical Manufacturers Association (NEMA), the International Electromechanical Commission (IEC), Underwriters Laboratory (UL), and Canada Standards Association/Electrical and Electronic Manufacturers Association of Canada (CSA/EEMAC). There is no standard currently available from IEC or CSA/EEMAC for arc resistant switchgear.

The background that this paper provided was insightful and consistent with other references. Arcs within the switchgear are caused by moisture contamination, insulation tracking or failure, ingress of rodents, loose connections, misplaced tools, voltage transients, wire cuttings, or mis-operation of mechanisms. Most arcing faults are line to ground faults. The author states that arcs occurring in switchgear will have a voltage drop due to the current flowing through the impedance, which is considered purely resistive, of the arc. The maximum power of the arc occurs when the magnitude of the resistance of the arc is equal to the magnitude of the system impedance.

The author notes a handful of calculations for the resistance, the maximum arc power, the amplitude of the pressure wave, and pressure increase in the switchgear. He provides a very good description of the different stages of the arc fault occurring in an arc resistant switchgear. They are the compression stage (which occurs at the initiation of the arc, when pressure begins to increase rapidly due to the pressure wave and increase in temperature, and continues to the time the vent opens), the expansion phase (which occurs when the vents open, the pressure decreases and the mass of air leaves at high pressure, and the temperature continues to rise; it is concluded when the pressure level inside the switchgear stabilizes to pre-arc conditions), the emission phase (which is the temperature increase due to the continuation of the arc and it is concluded when the air temperature within the switchgear reaches the arc temperature), and the thermal phase (which is the time when the materials within the switchgear begin to melt and vaporize and is concluded when the arc is interrupted).

There was also a very good description of the switchgear construction from the ANSI/IEEE and NEMA evolution. It would be interesting to learn how much the pressure was lowered with the increase in the main bus compartment volume by adding 4" to the depth. There is good discussion on the installation methods for arc resistant switchgear in substations.

- *Desborough, M., "Pressure Rise and Burn Through Predictions and the Principles of Pressure Relief Device Design," IEE Colloquium on Risk Reduction: Internal Faults in T&D Switchgear, 1997.*

The article discusses the factors associated with arc faults in equipment. The enclosure itself must contain the pressure increase, erosion effects of the internal arc, and the thermal effects due to the event. The equipment must be robust enough to withstand the thermal and mechanical loads experienced during an arc fault. For this discussion, the author illustrates a high voltage enclosure and proceeds to talk about a short circuit fault. It is stated that the unbalanced magnetic forces can act on the arc if the electric currents flowing during the fault are not symmetric and that, if the current is large enough, the arc is driven by these magnetic forces in the axial and azimuth directions. This implied that for a period of time, the arc is in motion along the conductor and inner surface of the equipment until it reaches the insulation partition. Minimal damage occurs while the arc is moving, but substantial damage occurs when it stabilizes.

The basis for the pressure model comes from Bernard but it is re-evaluated to account for more accurate prediction of pressure and temperature rises. The ideal gas simplifying assumption was discounted due to a compressibility factor. Tests were conducted at the British Short Testing Station at Hebburn and the model's results were justified.

To look at the erosion effects of the internal arc, a simple one-dimensional thermal conduction model was used. They consider a slice through the shell thickness which is initially at ambient and then heated at the inner surface by heat flow from the arc. The outer surface is in a convective environment of still air. When the temperature in the inner surface reaches the melting point of the material, erosion of the shell was initiated. The results from the model have shown good agreement with formulations from a referenced source.

The thermal effects of the arc were investigated to account for an arc that traveled throughout the enclosure thus increasing the temperature. The description of this section was not as detailed as it probably should have been; it was very unclear.

The three separate sections of analysis (pressure, erosion, and thermal) then led to a discussion on relief flaps and bursting discs. The thermal effects of an arc lead to a pressure increase which is relieved by ventilation. The hot gases leave the enclosure through pressure relief devices and the mass flow velocity is assumed to be constant for the opening.

This article provided some decent ideas, but nothing that was particularly interesting. The results from his model could have been more significant if there were additional studies performed; however, the author admits that the current state of knowledge is not sufficient for total reliance on such models. An interesting idea to consider is that the Rolls Royce Transmission and Distribution Company has been a strong focus for the past many years. This may be a decent opportunity to investigate their efforts and tests on high voltage switchgear.

- *Dunki-Jacobs, J. R., "The Effects of Arcing Ground Faults on Low-Voltage System Design," IEEE Transactions on Industry and General Application, Vol. 1A-8, No. 3, pp. 223 – 230, May/June 1972.*

  This article looks at the issues of arcing faults from a protection perspective for the power distribution industry. It details the history and progression of arc faults in different systems and some of the mitigation techniques used by early system designers. This article was helpful in defining HEAF events and analyzing methods (e.g. compartmentalization) to prevent them in the future.

- *Falkingham, Leslie T., Cheng, Kam, "Further Experiments in High Current Switching Using Small Contact Gaps," IEEE 18th Symposium on Discharges and Electrical Insulation in Vacuum, p. 455 – 458, 1998.*

  This paper details an effort to determine the effect of the contact gap on high current interruption ability. It is an extension off of previous work that aims to decrease the contact gap to 0.25 mm. It was originally intended to take the gap distance down to 1 mm; however, the authors were unable to do so due to mechanical limitations. In recent years, vacuum interrupters have been more widely used in the power distribution setting. These tests have been aimed at minimizing the probability of short circuiting. Two different types of interrupters were analyzed. Type A was rated at 12kV, 31.5kA and Type B was rated at 27kV, 13.1 kA. Some of the results of the tests were really interesting. Previous experiments, not detailed in this paper, showed the effects of different contact geometries. When the gaps were reduced with varying contact geometry, severe damage and failure of the normal arc control occurred. One interesting hypothesis to this problem may be that the small gaps collects the metal vapor and acts as a conductor in addition to the arc column.

  Their results on these particular experiments were interesting and possibly useful for future investigations into protecting switchgears. Unfortunately, their tests were not greatly detailed and could use further investigation.

- *Finke, S., Koenig, D., Kaltenborn, U., "Effects of Fault Arcs on Insulating Walls in Electrical Switchgear," IEEE International Symposium on Electrical Insulation, p. 386 - 389, 2000.*

This paper analyzes test methods to evaluate the effects of high energy arc faults on switchgear insulation walls of different materials. Experimental studies were performed and discussion followed. According to this source, there is no regulation that focuses on the amount of damage of tested equipment even though there are internal arc tests performed by the manufacturer. Some sources that should be looked at from this study are the IEC 517, 298, and 61641 standards for testing the high voltage, medium voltage and gas insulated, and low voltage switchgear, respectively. From a reference, the authors and Deaton (1996) describe the four phases of pressure rise in an arc fault.

Plastic materials are used for different functions in switchgear panels, such as isolating the bus bars or separating compartments and sections. This is an issue in low voltage switchgears which are typically smaller and thus subject to greater pressure increase. The partitions within the equipment need to handle this extreme in pressure and the associated temperatures. After 15 ms, the pressure decreases quickly; however, the equipment may have experienced mechanical stresses causing breaks or rupture. The authors identify these cracks and breaks as a potential starting zone for a fire. The resulting fire may indeed cause additional thermal and smoke damage in this particular piece or others in the vicinity. From other sources, it was found that some experiments had damages with equipment linked to the piece of arc origin. Extensive repair and cleansing costs may be expensive. The plastic material has been used to make switchgears more compact, but most of these plastics are combustible.

To reduce the fire hazard, the authors suggest that fillers added to the material could increase its heat conductivity and ultimately a reduction in material temperature within the vicinity of the flames. This could help prevent flame propagation. Agents, like aluminum hydroxide, split of water in an endothermic reaction. The water evaporation consumes thermal energy and thus reduces the temperature in the zone of the flames. The primary objective is to cool the material to under the ignition temperature. Halogen chemicals could also be used in switchgears; however, they pose a threat to humans and the environment. The chemical industry has released incomplete information in regards to switchgear operation and the equipment manufactures may have additional information that is not public. This article provides some of the first clues to the arcing fault on different materials under mechanical and thermal stress.

Experiments were conducted in two facilities at the High Voltage Laboratory of Darmstadt University. The authors had a fairly decent description of their tests. One was able to generate a current up to 6 kA DC with a maximum power output of 1.5 MW. It is possible to overload the installation every 8 minutes for a period of 15 s. There was a 20 kV supply connection. The output of the installation is a 12-pulse direct current. The contact blades may be varied which allows for variation in the current and voltage. The maximum current is 6 kA at a voltage of 500 V. At a maximum voltage of 6 kV a test current of 500 A is applied. Both of these maximum values are valid for 15 s with a pause for cool down. The second facility is a 50 Hz-capacitor bank which consists of 3 separate capacitor banks and 3 tuned inductances. The system has a total capacitance of 2.99 mF, a maximum charging voltage of 25 kV, and a maximum energy of 2.939 MW.

The test room is 15 m away from the capacitor bank. Both are connected with 4 insulated medium voltage cables. The connection between the 1.5 MW installation and the test room is done with two test bars. The arc and current are measured at every test. The power and energy are calculated with software. The test objects are plates of varying material and wall thickness. Future analysis could include thermoplastics and thermosetting plastics. For the first test arrangement, the researchers looked for the time which is necessary to ignite the material. To be considered as burning. The plate must sustain burning for 30 s after the fault is cut. The fire either extinguishes itself or, if it spreads, by fire protection foam. For the second test, the arc "attacks" the surface of the test plate. The time to burn a hole into the plate is measured. Fires starting at the edges of the hole were noted for particular tests. The third test arrangement is used to test the mechanical strength of the material. The pressure developed in the arc chamber design was measured by a pressure sensor. The forth test arrangement was designed to simulate a very fast pressure rise without presence of an arc.

There was some discussion on the authors' test results. The time that the arc burns against a test plate is decisive for a fire event. Arcs from the 50 Hz capacitor bank were unable to generate fire events of the insulating test plates even in currents ranging from 2 to 21 kA. The arc duration of 15 ms was too short to ignite the plates. Arc faults from the 1.5 MW DC source were able to ignite some of the test objects. A fairly long arcing time (up to 6 s) seemed to be necessary to heat up the plastic over its ignition temperature. Thermosetting plastics as well as thermoplastics behaved differently under the same conditions. Thermosetting plastics maintained their shape and flowing and dropping of burning material cannot be seen. They were highly resistant to inflammation, but those that did ignition were not necessarily self-extinguishing. The non-reinforced thermoplastics melt and flow easily. Fire can thus be spread to different areas in the equipment. The reinforcement of these materials with glass-fiber allowed the specific plates to maintain their shape. Increasing the thickness of the test specimen caused an increase in ignition time. A relationship of the thickness and the ignition time varies for each material. In the second test arrangement, most of the thermoplastics could withstand the fault longer than thermoplastics with the same thickness. After the development of a hole caused by an arc, some of the plastics caught fire at the edges of the hole. For this, there was no particular difference between the two types of materials.

This paper was an extremely interesting preliminary study of fires within switchgear equipment. The testing of the plates was a great initial step and provided some real insight into the problem. These tests have the ability to be reproduced and expanded upon.

- <u>*Finke, S., Koenig, D., "Recent Investigations on High Current Internal Arcs in Low Voltage Switchgear," IEEE International Symposium on Electrical Insulation, p. 336 – 340, 2002.*</u>

The results of tests which evaluated the effects of high current fault arcs in electrical switchgear were detailed in this paper. In particular, the authors focused on the mechanical and thermal stressing on the insulating walls made of different materials.

This is due to the ability to quickly repair and restart operations after a high energy arcing fault event. One point the authors made was that there are standards to protect personnel but none to protect the switchgear itself, in particular a break in the compartments or an ensuing fire.

A couple of interesting standards that would be worth investigating include IEC61641 and IEC 298 for the low and medium voltages, respectively.

General descriptions of the low and medium voltage switchgears are described throughout the paper. From the authors' literature search, they detail the steps to a high energy arcing fault event: the first 20 ms is a great pressure increase inside the switchgear, over the next 100 ms the pressure decreases to normal levels but the radiation from the arc impacts the insulation in the switchgear. Because plastic has been used more in sectioning and compartmentalizing within the switchgear, this is a major concern for manufacturers. If the walls of the compartment were to break, either mechanically or thermally, the arc, pressure, or other issues associated with the event may not be confined to the initial equipment and secondary events may result. It is reemphasized that manufacturers are attempting to produce different materials for plane plates; however, there is no standardized test method so each new design must be tested in high power test laboratories. It would be interesting to collaborate with these different facilities.

The two test facilities (High Voltage Laboratory of Darmstadt University of Technology (HVL) and "Institut Pruffeld fur elektrische Hockleistungstechnik" (IPH) in Germany) is as described. The HVL is able to generate 6 kA DC with a maximum power output of 3 MW for 15 s. The test facility is supplied with energy from the 20 kV grid of the local utility. The output is a 12-pulse direct current. The maximum current is 6 kA at a voltage of 500 V. At the maximum voltage of 6 kV, a test current of 500 A is supplied. The IPH is able to use a 50 Hz capacitor bank. This facility consists of 3 separate capacitor banks and 3 tuned inductances. The total capacitance of the system is 2.99 mF. The maximum charging voltage is 25 kV, the maximum energy is 2.939 MWs. However, at this facility there is no possibility to carry out tests with three-phase high current arcs. In these laboratories, tests with a nominal short-circuit current of 50 kA can be supplied. The voltage was set to 720 V. The tests conducted mainly focused on the plate materials of varying thickness. The dimensions of the switchgear were 1.6 m wide by 0.6 m deep by 1.8 m high. The right section is separated from the left by a metal partition carrying the bus bar-bushing. The distance between the bus bars is 40 mm each. On the left side of the switchgear, the power supply is connected. The bus bars end 40 mm in front of the cutout (360 x 260 mm) later on covered by the insulating plates in the right side panel. The fault is initiated in the right compartment by the bushings with a 0.3 mm thick igniter wire. Because of the magnetic forces of the arc current, the arc moves away from the power supply and attacks the surface of the face plate. After ignition, the temperature and pressure increase causes mechanical stress on the plates. Tests with a nominal circuit current of 20kA, 30 kA, 40 kA, and 50 kA are carried out. The arc duration varied from 100 ms, 300 ms, and 1 s. The pressure rise inside the compartment was measured by two pressure sensors; one was mounted in the middle of the top, the other in the rear panel. The pressure sensors were piezoelectric type with a response time of less than 2 ms. A high speed camera was set up to capture the images at 2000 pictures per second and a fourfold or eightfold filter was used to reduce the brightness.

The velocity of the arc is approximately 80 m/s. For this particular test arrangement, it was interesting to read that there were multiple arcs going on at one time. Tests with a duration of 100 ms were conducted to investigate the effects of mechanical stress on the plates rather than looking at the fire event. They point out that this arc duration is short enough to prevent a fire. All of the plates tested were able to withstand the 100 ms arc, but when stressed again some of the plates suffered failure. There were tests with an arc duration of 1 s to focus on the generation of fire to the test objects. The tests were not sealed anymore to see if the plates would fail thermally rather than mechanically. During the tests, it was observed that achieving or exceeding a test current of 30 kA the test plates break into pieces an projectile themselves up to 5 meters away. This happened after approximately 120 ms. When evaluating the high speed images, the plates oscillated until breaking. This may have been cause by the extreme temperature differences relative to the arc. Some of the plates did catch fire.

This is one of the best articles for the formation of the HEAF project. This nicely lays out their experiment and results. Additional information from these authors on this project would be extremely interesting. Also, this shows another group who may be interested in a collaborative research effort.

- *Fisher, Lawrence E., "Resistance of Low-Voltage AC Arcs," IEEE Transactions on Industry and General Applications, Vol. 1GA-6, No. 6, p. 607 – 616, 1970.*

  The author's main goal was to estimate a better and more probable value of the resistance of low-voltage arcs and primarily to develop an acceptable technique for measuring the arc resistance. The experiments involved single phase AC tests. Stable arcing was initiated from the end of the bus bar to the box of panelboard using a bent paperclip. The author pointed to similar methods employed by scientists in the early 1930s. The tests were conducted at 263-volt single phase 60-Hz AC between the two bus bars and from one bar to the box. He did provide an interesting diagram to illustrate the physics of an arc event. Looking at his discussion, the arc resistance continued to decrease with increasing current.

  This article provides decent insight into some of the experimental work aimed at addressing the issue of resistance. However, recently there have been further studies that deal more precisely with this matter. Though it does not completely help with the HEAF project, it is useful to see what other projects have been designed and completed.

- *Floyd, H. Landis, Daniel R. Doan, C. T. Wu, Susan L. Lovasic, "Arc Flash Hazards and Electrical Safety Program Implementation," Industry Applications Conference, Fourtieth IAS Annual Meeting, Vol. 3, p. 1919 – 1923, 2005.*

This paper provides an introduction of the arc flash hazard, a comprehensive arc flash management program that includes analysis, electrical system design, and work practices and protective clothing plans. Since the 1980s, there have been IEEE groups set up to study arc flash burns, develop standards, and find cost effective techniques to eliminate or mitigate arc flash hazards. This includes flash hazards analysis tools and techniques, safer equipment and system design, improved work processes, and developed proper personal protective equipment and clothing to minimize injury. The authors detail arc fault injuries and the estimated costs of hospitalization and rehabilitation to exceed $1 billion annually.

- *Friberg, G., Pietsch, G. J., "Calculation of Pressure Rise Due to Arcing Faults," IEEE Transactions on Power Delivery, Vol. 14, No. 2, p. 365 – 370, April 1999.*

  This article was unique from the others found in relation to the high energy arcing fault project from the use of Computational Fluid Dynamic (CFD) based methods for pressure increases in small sized geometries. This model was compared to the standard calculation methods and a Ray-tracing method with regards to computational efforts. The results were compared to experimental studies and were particularly focused on three different geometrical sizes.

  The different calculation methods were detailed. The standard method is based on the conservation of energy and the ideal gas law. This ultimately provides decent results if the geometrical size of the electrical arrangement is small. The improved standard calculation takes air disassociation into account by introducing temperature and pressure dependent gas properties. The results are more reliable and have a negligible increase in computation time. The Ray-tracing calculation method is based on pressure particle energy and velocity. The pressure at a given time and location is calculated from the actual density of pressure particles at that point. Static pressure rise with superimposed pressure waves can be determined. Unlike the geometrical limitations of the standard calculation methods, this method yields time and spatially resolved results that may be applied to free burning arcs in a large room. The computational efforts are moderate. The new CFD method is based on the continuity, energy conservation, and Navier-Stokes equations. Additionally, the gas law and the constitutive equation for the enthalpy of gas are used in conjunction with the driving equations. The CFD calculation allows for time and spatially resolved results for the determination of pressure rise. This method also considers gas flow, heat transfer, turbulence, and pressure waves. There is, however, a considerable amount of computational time involved in the three dimensional analysis. When the model is reduced to two dimensions, the computation time is reduced and the results are not greatly impacted.

  The experiments were set up as a medium voltage switchgear room. When the model was measured against experimental data, the results seemed to be in good agreement. This CFD model development will be a valuable tool for the calculation of pressure rise. This may be an interesting avenue to investigate further, especially when considering experimental design and goals.

- *Fujinami, H., T. Takuma, T. Kawamoto, "Development of Detection Method with a Magnetic Field Sensor for Incomplete Contact in Gas Insulated Switches and Bus Connecting Parts," IEEE Transactions on Power Delivery, Vol. 10, No. 1, p. 229 – 236, 1995.*

  This paper describes a detecting method for incomplete contact in gas insulated switches and bus connecting parts. The authors did this by measuring the change in the magnetic field caused by the current distribution. They ended up testing this theory with a full scale experiment with more incomplete contact conditions.

  The Japanese have been using the gas insulated switchgear for some time now due to reliability and environmental and site area limitations. It was pointed out that the rate of major faults of Japanese GIS is on the order of 0.01 substations per year, although the term major was never quantified during the paper. Of these major faults, the main cause was due to incomplete connection. Two contact structures are used in GIS, a slide contact and butt contact. Mechanical vibrations, inappropriate assembly of components, and an increase of contact resistance may all cause incomplete contact. Methods like thermal monitoring and X-ray photography, according to the authors, provide an unsatisfactory response time. The magnetic sensing technique they use is similar to the one that EPRI and General Electric developed, but their method investigates the application of an opto-magnetic sensor on the detection of biased load current distributions.

  Initial tests were completed on a small scale in order to test the magnetic sensor's capabilities in detecting the incomplete connection. Once satisfactory results were obtained, full tests were conducted to see if the worked in the practical setting. The model has rated values of 300 kV, 2000 A, and 0.5 MPa of SF_6 gas pressure.

  The researchers were looking at three specific things: conduction through a bolt (or four) and no contact of the conductor current-carrying surfaces, partial contact of the conductor surfaces together with a bolt (or four), and partial contact of the conductor surfaces with no contact through an insulated bolt. The final conclusions from these tests show that the magnetic sensor outside the enclosure is feasible.

  One consideration for this paper is that the Japanese seem to have an interest in switchgear research and may be a valuable resource in the future.

- *Gammon, Tammy, Matthews, John, "Arcing-Fault Models for Low-Voltage Power Systems," Industrial and Commercial Power Systems Technical Conference, p. 119 – 126, 2000.*

  Gammon and Matthews presents a very good framework for the issue of faults in low-voltage power systems. From their paper, "An arcing fault is a dangerous form of short circuit that may have a low current magnitude. In the case of such faults, the magnitude of the current is limited by the resistance of the arc and may also be limited by the impedance of a ground path. This lower level fault current is often insufficient to immediately trip over current devices, resulting in the escalation of arcing fault, increased system damage, tremendous release of energy, and threat to human life."

This paper details preliminary literature research extending back to the 1930s and further development of current-dependant arc voltage models. For their particular work, a medium-sized industrial building with a 480Y/277V service was used to illustrate the phenomena of arcing in low-voltage power systems. Some of the topics were not fully detailed in their study, i.e. the re-strike voltage, conduction angle, and magnetic energy. These areas could use some further investigation. A greater understanding of these topics would allow others to fully grasp some of the referenced experiments, results, and additional concerns. Concluding their work, the authors state that their model performs better than existing ones. Some of their sources have been sought out to gain a greater understanding of the problem.

- *Gammon, Tammy, Matthews, John, "Conventional and Recommended Arc Power and Energy Calculations and Arc Damage Assessment," IEEE Transactions on Industry Application, Vol. 39, No. 3, p. 594 - 599, 2003.*

    The authors of this paper identify important issues in arc fault research and have done some very current work. It is obvious that they have a strong interest in this topic and they may be a valuable contact in the future. They discuss the increasing arc fault incidents has led IEEE to establish a forensics team, but indicate that the majority of research is 25 to 50 years old and that there is only a limited amount of applicable technology for their use in the field.

    The current method of damage assessment is the kW-cycles method and also Stanback's damage indicator which relates arc energy and arc current. From the first method, the energy released by the arc is proportional to the rms arc current. From the second method, system damage was assumed to be tolerable within specific limits. Other engineers in the field have developed a theoretical maximum power delivered to the arc which is when the arc resistance equals a purely inductive system impedance. Original equations to calculate this energy are not accurate because they do not account for harmonics in the current and voltage. There are other equations, however, that looks at this issue. From previous research and experiments, an arc voltage limiting current flow may not activate in overcurrent devices causing an increase in damage. Damage assessment has been measured in kW-cycles. Minimal damage occurs anywhere from 1800 to 2400 kW-cycles, limited damage occurs below 6000 kW-cycles, and extended damage which can destroy equipment occurs at 10000 kW-cycles. Stanback's method for assessing damage avoids error associated with assuming an arc voltage. A 277-V single-phase to ground quantifies the damage occurring to the bus bars and steel housing. The amount of material burned was related to the arc current, the time span for arc duration, and material type.

Stokes and Oppenlander defined the instantaneous power which was assumed to be more constant than instantaneous arc current or voltage. It is assumed to be quasi-static which is valid near the peak of an ac current and only applies to currents above a transition level. This is based on free-air arcs with copper or aluminum electrodes varying in separation distances from 0.005 to 0.5 m. Arc currents ranged from 0.1 to 20 kA, and a 6-kV power supply was used. The instantaneous power equation they developed was used to develop a current-dependent arc voltage model.

Arcing faults release the most energy within a building system at the main distribution panel, which has a high available fault current and the least energy at the branch. The presence of current-limiting fuses and a ground-fault-protective system with the capability to activate the system impacts the arc fault risk. The kW-cycle and Stanback methods for calculating damage threshold lack uniformity and require further investigation. It was found, however, that the 10000 kW-cycle limit is substantially more conservative than Stanback's method which does not predict the energy released by an arc.

The authors point out that the relationship between the energy released by the arc and the amount of damage occurring is not necessarily linear and currently depends on the geometry and arc fault location. The arc energy is a function of the arc current by a power greater than 1.0 but less than 1.5. Based on many different studies, this value is rather inconsistent. Stokes and Oppenlander's extensive tests and validation studies have led the authors to consider 1.12 to be the most accurate relationship presently known.

In closing, this paper looks at the nonlinear relationship between arc current and arc power and energy. This relationship is complex and needs further considerations. Assessing the damage also should be looked at in the future. This paper analyzes and addresses the historical and background research on the arc fault problem. From preliminary considerations, the issue of arc fault damage needs to be broken down from the arc event, to the resulting fire, and then to secondary damages.

- *Goda, Yutaka, Mikimasa Iwata, Koichi Ikeda, Shin-ichi Tanaka, "Arc Voltage Characteristics of High Current Fault Arcs in Long Gaps, IEEE Transactions on Power Delivery, Vol. 15, No. 2, p. 791 – 795, 2000.*

  This paper describes experiments simulating arc faults on 500kV class transmission lines; up to this point data has been extremely limited. A 3.4 m gap was used and the voltage near the arc gap was measured. There was a good description of the test that the scientists performed. Even though they did tests that simulated over head power lines, the experiments may be useful to gain an overall appreciation for high voltage tests which were conducted in an indoor test cell measuring 40 m by 25 m wide by 29 m high. Two high speed cameras were used to capture images of the resulting arc. Some issues that were not investigated by the authors include the arc jet pressure, blowing speed, and arc diameter. These would all impact the durability of the switchgear equipment. As the temperature of the arc increases due to the accumulated energy, the conductivity of the air increases and the arc resistance becomes smaller. The authors have limited discussion on mathematical models used to calculate arc voltage.

This paper describes tests conducted for high current faults and some of the results. It would have been more useful if the researchers commented more on the designed experiments. However, the fact that they completed tests of this magnitude lends itself to further discussion and research to figure out exactly how the tests were conducted. It is also interesting to learn that the Japanese seem to have an interest in high current fault arcs and may lend themselves to support in the future.

- *Harrower, J. A., S. J. MacGregor, F. A. Tuema, S. M. Turnbull, "A Long Lifetime, High PRF Plasma Closing Switch," IEE Colloquium on Pulsed Power, Paper No. 45, p. 4.5/1 - 4.5/4, 1998.*

  This paper looked at high pulse repetition frequency of spark gap switches. The plasma closing switch has been recognized as a limiting factor in repetitive operating systems. The spark gap switch provides durability, excellent voltage and current handling capabilities, high di/dt, low cost, and simplicity. This paper may be out of our scope since the focus is on pulsed power facilities. The experiments seemed pretty interesting though; however, the detail was pretty limited. The power supply was 20 kW, 70 kV using a 1 μF smoothing capacitor. The high voltage was supply was connected to the switch via a solid state charging resistor (variable between 20 kΩ and 200 kΩ). This, for the most part, was the detail described by the authors.

- *Iwao, T., Y. Inoue, T. Inaba, "Temperature and Radient Power Emitted from DC Horizontal Short Free Arc Discharge Mixture with Tungsten Vapor," Pulsed Power Plasma Science, IEEE Conference Record, 2001.*

  This paper provided very little help for our potential project, even though it only seems to be the abstract. The one thing that could be taken out of the paper was that perhaps the University of Minnesota would be a point of contact since one of the author's of this brief article is a research fellow there. The authors talked limitedly about free arcs not having radial restrictions and therefore continuing to expand in this direction. They stated that the radius increases in proportion to the square root of the current in case of constant current density. This may be a factor when considering thermal damage from the arc; however, it has been shown in other papers that radiant heat is very limited in switchgear applications. It was interesting to note that the authors used tungsten rather than the more traditional copper, aluminum, or iron as the electrode materials.

- *Jamil. S., Jones, R. A., McClung, L. B., "Arc and Flash Burn Hazards at Various Levels of an Electrical System," Petroleum and Chemical Industry Applications, p. 317 – 325, 1995.*

This paper looks at the arcing and flashing effects from high energy equipment on humans. The author points out that arcing may occur when a worker is several feet from the energized equipment. Though the author mentions a concern dealing with radiation effects from the arc, he does not go into a great amount of detail. It was pointed out that arcs may come from short circuits from poor electrical contact, insulation failure, or human error. He noted that the temperatures of the hot gases at 1000ºC or more, but he did not mention a temperature radius in relationship to the arc. There were some interesting tables that indicated the power in electrical arc and curable burn distances for electrical equipment at industrial installations which may be useful in determining the potential size of the arc.

- *Jones, Ray A., Danny P Liggett, Mary Capelli-Schellpfeffer, Terry Macalady, Lynn F. Saunders, Robert E. Downey, L. Bruce McClung, Arthur Smith, Shahid Jamil, Vincent J. Saporita, "Staged Tests Increase Awareness of Arc-Flash Hazards in Electrical Equipment," IEEE Transactions on Industry Applications, Vol. 36, No. 2, p. 659 – 667, 2000.*

This article provides a great level of detail. The main goal of the paper is to improve worker safety, but the authors go into very specific tests that would be a potential starting point for our work. The authors look at explosions and fires that occur from switchgear equipment and perform many full scale experiments. Copies of their testing reports would provide more guidance towards conducting additional tests on switchgear.

Human error and equipment malfunctions have both contributed to explosive arcs in industry. There have been many technical committees who have been developing safety standards for workers. Research on these types of explosions extends back to the early 1960s. The information was developed to assist in recommendations in ground-fault protection devices with phase overcurrent protection equipment. Topics like burning damage were roughly estimated from equations based on experiments; however, these ballpark estimates do not provide the best results and should therefore be revisited. When a large substation building collapsed due to the effects of an arcing fault, Drouet and Nadeau measured the amplitude of the pressure wave generated by an ac arc with currents ranging from 10 A to 80 kA with an arc length from 8 mm to 15 m. Arcs at low power suggested a correspondence between the pressure amplitude and the rate of change of power that might be expressed as an empirical formula, although this was not consistent at higher power levels. Later on, Lee developed curves relating the distance from the arc center to effective pressure for arc currents ranging from 500 A to 100 kA rms. Dunki-Jacobs provided a detailed description of the arcing ground-fault phenomenon using failure analysis based on on-site observations. He described the "triggering" of arc initiation, the effect of bus bar insulation on arc escalation, the timing of the interaction between the effectiveness of insulated buses and ground-fault relays, and suggested a schematic explanation for the arc-travel phenomena. There have been additional tests on enclosed arcs and interest in creating reproducibility of experimental observations has led to further development of theoretical and experimental observations.

The authors performed 11 preliminary tests and an additional 27 at the Paul Gubany High Power Laboratory in Ellisville, MO. Two mannequin workers were dressed in ordinary cotton clothing and outfitted with safety glasses, hard hats, and leather gloves. One was positioned two feet away at the chest and the other was further back. The equipment doors were left open for several tests to simulate work being performed. This is not uncommon in the field for personnel without an understanding that the equipment should be de-energized before work is performed or for those who believe the equipment is de-energized. Open doors are perceived to be required to enable troubleshooting and diagnostics required to identify equipment or system problems. Both new and used equipment was used for the tests. Current flow for the tests was initiated to the laboratory control panel and these conditions were recorded throughout the tests. Fault initiation was intended to simulate a misplaced screwdriver or a lost wrench. A small piece of #18 AWG wire was used to simulate a strand or two touching ground. Type-T thermocouples were connected to an Astromed GE Dash-10 recorder were placed on the lead mannequin's extended hand, neck, and under the shirt on the chest. Thermal measurements were taken using infrared photography. Pressure probes were placed on the mannequin's chest and condenser microphones were placed 20 and 25 ft away. A high speed camera taking 10000 frames/s for 1.5 s was used to capture images of the arc. It was started by electronic control synchronized with the initiation of the current flow to the setup. The author did not describe the limitations of the equipment used. This would have helped in planning for future tests.

The tests supported Dunki-Jacobs' prediction that the arc would travel away from the source. Even tests that attempted to force the arc toward the source resulted in the same outcome. Theoretically, the arc always travels away from the source because of the electromagnetic forces created by the currents. This is important for workers who may be positioned by the equipment during an event. Field investigations indicated that damage at the site of the arc initiation was minimal compared to the damage at the end of the arc path. If the bus is enclosed in metal and the bus bars are bare, the arc energy is concentrated at the end of the travel path until it is interrupted by the upstream branch circuit, short circuit, or ground-fault protective device. After an arc fault event, investigators may conclude that the short circuit started at the end of the travel path rather than its true initiation site. The arc escalation in some of these tests created upstream secondary faults. In one of the tests, the magnetic forces created by the flowing currents moved the wires upstream of the initial fault with enough force to damage insulation or tear conductors from their terminations creating additional short circuits. The arc self-extinguished in less than one cycle during tests with insulated bus bars which contrasted with tests observed by Tslaf. His tests, however, were orders of magnitude higher than the ones present in this article. The arcs in Tslaf's report were created by insulation flashover where the arc was from the surface of the insulation to another conductor. The insulation surfaces partially melted, which maintained sufficient temperatures to help sustain the ionized gas and thereby sustain the arc more than that of bare bus. The authors conclude that more research and testing is required to determine the voltage level, insulation type, and construction where bus insulation may help extinguish or sustain arc once established. The results confirm that single-phase faults are much more difficult to sustain than three-phase faults. Single-phase arcing faults pass through a current zero twice a cycle during which they produce no ionized arc plasma. The arc plasma is required to maintain the arc current. Three-phase arcing faults produce a constant source of arc plasma that can easily maintain the arcing fault. Historically, the protection to selectively coordinate a 480-V high resistance grounded system on ground faults has been prohibitively expensive. However, solid-state protective overload relays may make this type of system more practical. The results supported the observation that current-limiting devices reduce damage and arc-fault energy. Several identical tests were performed with and without current-limiting devices. A wrench was laid on the incoming lugs and the MCC was energized with 601-A class-L current-limiting fuses in circuit. The doors did not open and all three fuses cleared the fault. There was minimum pitting on the bus bars that were in contact with the wrench and there was some carbon on the left wall of the incoming section. The MCC could have been placed in service without cleanup or repair required. This was repeated with the current-limiting fuses removed from the circuit. This resulted in a very violent arc that destroyed the MCC. The comparable tests show that current-limiting fuses play a significant role in arc suppression. The authors noted studies conducted by Neal, Bingham, and Doughty that established the high degree of variability in arc phenomena. Using copper calorimeters at a uniform distance of 1 ft from the arc gap of 4 in (open-circuit voltage was 2440 V, arc duration was 6 cycles, available prospective fault current was 45.05 kA) with nine sensors uniformly circling the arc source demonstrating radial variation of the observed temperature rise around the arc. Temperature rises ranged between 100 – 200° C in a three phase fault scenario. For the authors' test measurements, the temperature rise ranged from 20 to over 200° C at the mannequin's clothing surface and 90% of the temperature rise was at the worker's extended hand. Lee presented the thermal energy exposure from an arc as a radiant source varied with the inverse of the distance squared from the arc and has served as the basis for safe work distances. The authors concluded that their tests produced arcs that were highly unpredictable and variable in occurrence, path, energy, and duration. This is contrary to the bolted fault tests for short circuiting which is more predictable and presently used by manufacturers.

This paper provided solid background for future projects. This is relatively recent in comparison to the preliminary work that is currently out there and there is a lot of valuable information about test methods. It gives a very detailed insight into the facility and instrumentation.

- *Kapustin, V., Podolsky, D., Mestcherjakov, V., "Arc Penetration to the Arc Chute and Arc Chute Plates Erosion," Electrical Contacts Proceedings of the Forty-Second IEEE Holm Conference, p. 50 – 59, 1996.*

This paper discusses the issues of arc penetration into the chute and the erosion of different plates. The authors placed an emphasis on the importance of electrode and plate life. The authors look to study the interaction of the arc and electrodes. In particular, the repulsive force on both of the plates interests them the most because the magnetic forces can be calculated "easily." The authors have a really good description of the heat displacement in an arc event. "Speaking about movement of arc we keep in mind a shift of conducting state in gas. Such displacement of heating state with reference to environment is commonly called sliding. The ununiformity of electric field is one of the reasons initiated sliding. At this the notions of generalizing forces and flows in introduced by analogy with nonequilibrium thermodynamics." Though some of the paper was easy to follow, most of the terms and their context were confusing.

From experiments, the authors found that the arc moves perpendicularly to the plates will experience repel from the edges that results in a delay of discharge quenching. This seems consistent with other studies found throughout this literature search. Some of the figures are hard to distinguish, but would be useful if they were clearer. The reported plasma jets were pretty intense, from 60 – 130 m/s and the current density reached 100 – 200 A/mm^2.

Erosion depends on the velocity of metal vaporization, oxidation and other kinds of chemical interaction of material with the environment, mechanical strength loss, and many other conditions. Arc glowing can greatly impact the initial structure of the electrode by surface vaporization and diffusion of easily boiling admixtures, recrystallization, and diffusion of environmental gases. This boiling and gas emission assists in the formation of pits, cavities, and spots within the plates.

This paper lends itself to some decent analysis and discussion on the erosion of arc plates. There were some interesting experiments and this may be useful when explaining the causes of prior incidents and future work.

- *Kaufmann, R. H., Page, J. C., "Arcing Fault Protection for Low-Voltage Power Distribution Systems - Nature of the Problem," Transactions of the American Institute of Electrical Engineers, Vol. 79, p. 160 – 167, 1960.*

  Kaufmann's work help spark new research on the HEAF topic. He addressed the concern of these incidents by discussing different occurrences and outcomes after an arc event. HEAFs are discussed in some detail and different mitigation techniques were suggested. The intention of the paper was to provide background for worker safety and offer possible designs and instrumentation that would prevent an arc occurrence. This work seemed to frame the preliminary problem of HEAF events in low-voltage power distribution systems.

- *Keski-Rahkonen, O., Mangs, J., "Electrical Ignition Sources in Nuclear Power Plants: Statistical, Modelling, and Experimental Studies," Nuclear Engineering and Design 213, p. 209 – 221, 2002.*

  This paper had a lot of potential in addressing many of the areas of concern with the high energy arcing fault problem. Some interesting statistics were reported from the Advanced Incident Reporting System (AIRS) reported that 18% of failure mechanisms leading to fire were due to arcing and an additional 28% were due to ground faults and shorts. When identifying the failed components in fires originating from electrical faults from the same report, 26% were in the switch/breaker and another 26% were in transformers. Though there has been a decent amount of research completed on transformer fires, the switchgear issue has been less studied. This directly points to the need for further research.

The paper then strongly talks about cable research as a root event and then looked at arcing along cables. Their experiments seemed unsuccessful in producing the desired results. A major flaw in the design experiment was the production of the arc by using a current supplied from batteries. When this did not provide a sustained arc, a welding machine was used. It seems unclear whether the authors looked at cables that were energized, which may or may not have contributed to a fire. Some of the observed results were the arcs created were so strong that the flames blew out before they could propagate. Besides providing some interesting statistics, the paper did not help out greatly.

- <u>*Lee, Ralph H., "The Other Electrical Hazard: Electric Arc Blast Burns," IEEE Transactions on Industry Applications, Vol. 1A-18, No. 3, May/June, 1982.*</u>

Lee investigated the issue of arcing faults from the perspective of worker safety. This research looked at the temperature and pressure effects on humans in the vicinity of the arc incident. He discusses the nature, temperature effects, and presents the development of the arc size. Many of the diagrams represented in paper help determine the temperature effects on skin and clothing. This is the initial work that truly analyzes worker safety. Much of the work was later used to formulate the IEEE standards.

- <u>*Lippert, Kevin J., Donald M. Colaberardino, Clive W. Kimblin, "Understanding IEEE 1584 Arc Flash Calculations," IEEE Industry Applications Magazine, p. 69 – 75, May/June 2005.*</u>

This is a helpful article for using the arc flash calculations in IEEE 1584. The equations are presented and quickly described. The authors then seek to answer some of the common questions for using them. The "point" in the system where the arc-flash hazard calculations should be performed were either at: the incoming point to the enclosure <u>or</u> if the cables terminate immediately into the main device and are not readily accessible at the load terminals of an incoming overcurrent protective device (OCPD), <u>and</u> at the load side of the OCPDs that are separated from the line side. The spreadsheets available detail the Basic Information (instructions, range of models, cautions, disclaimers, and general user information), Data-Normal (specific user input is needed along with a summary), Calcs-Normal (input data and results from calculations), Summary (easy access to outputs calculated), Reference Tables and CB Reference (for further explanation). A description on how to being using the arc flash calculator is discussed. This details the cells and what should be input into them. An OCPD fuse is an overcurrent protective device and different ratings are listed in IEEE 1584: Class RK 1 fuse – 100 A, 200 A, 400 A, 600 A; and Class L fuse – 800 A, 1,200 A, 1,600 A, and 2,000 A. If the fuse is not one of these specified, the time/current curve is required. For OCPD breakers, the use of specific manufacturer's time/current information is the most accurate method of calculation. However, this data has not been a focus of circuit breaker manufacturers and thus are very conservative. When entering specific OCPD times, two calculations are performed. The second one is 85% of the originally calculated arc current as a "reducing" arc current. There are secondary methods if primary courses are not available for certain low-voltage circuit breakers within specific ranges of bolted-fault currents. The authors point out that none of calculations account for the current limiting characteristics of circuit breakers.

The OCPD current limiting devices are discussed a little further. There are two active systems occurring simultaneously. During an arc event occurring downstream, there is a current magnitude reduction due to the added impedance of the arc at the bus bars. The upstream OCPD begins to open which creates another arc inside the OCPD and is in series with the bus bar arc. There are two arc systems acting simultaneously. There are two components to consider when accounting for current limiting affects of circuit breakers. One is arc current duration which is controlled by the actual time of interruption. The other is the reduction of the arc current magnitude due to the breaker's impedance. The authors developed a current limiting model that is in progress and need further validation. They have also listed other existing technologies for reducing the arc flash: Zone Selective Interlocking (ZSI), Ground Fault Detection, the use of finger-safe electrical components, use of insulated buses, sizing the current-limiting branch circuit as low as possible, and limiting the ampere rating size main and feeders where possible.

This paper provided some quick insights into IEEE 1584 and clarifies some issues that people have experienced in the past. This would be a better starting point than the actual standard because of its simplicity; however, the standard should still be read and the excel sheets should be practiced.

- *MacGregor, S. J., F. A. Tuema, S. M. Turnbull, "Repetitively Operated Spark Gap Switches," IEE Colloquium on Pulsed Power, Paper No. 1, p. 1 – 5, 1994.*

This paper looks at high power spark gap switches found in pulsed power systems. The article makes no reference to alternative applications for this technology, but it may be interesting to find out if these devices could be used in nuclear power plants. More background information on these particular devices would be useful, but as of now this document does not seem too helpful for this project.

- *Mawhinney, J. R., "Findings of Experiments Using Water Mist for Fire Suppression in an Electronic Equipment Room," Proceedings: Halon Options Technical Working Conference, 1996.*

This paper highlighted a three year study conducted at the National Research Council Canada (NRCC). The research focused highly on the effectiveness of water mist systems on extinguishing three specific scenarios: fires in electrical switchgears, in under floor cable plenum, and in overhead cable tray arrangements. Different droplet diameter sizes were used for the 90 plus tests, though it is not clear as to how many tests were done on each scenario. Another goal of the study was to determine the feasibility of designing a fire detection system capable of "pin-pointing" fire location. This would prevent excessive water damage.

There is an obvious issue with water damage in electrical equipment rooms. Short circuits, corrosion, and equipment damage are all associated with excessive water exposure. Finding an alternative to traditional suppression systems is highly desirable. For a while, Halon systems were installed in these rooms, but almost complete discontinued after it was found to have adverse environmental effects. This study aimed at testing one of the alternatives.

From fire statistics found in their literature search, the majority of cabinet fires were self-extinguishing or could be suppressed with handheld devices. The statistics seem misleading to the actual effects and intensity of the arcing fault. This does lead to an interesting thought, however, in terms of effects that a water mist system would have on a HEAF event. The author does not mention anything along these lines and would thus lend itself to further investigation.

The author provided the procedures and dimension for the experiments. Because of the noxious fumes produced by the PC boards, masonite boards were substitute. There was no further justification for the use of this material. The ignition source was an electric stove element or piloted after 8 minutes if flaming did not commence. There were two different cabinet sizes used: 0.86 by 0.50 wide by 1.69 m (2.8 x 1.6 x 5.6 ft) high and 0.95 by 0.78 wide by 1.70 m (3.12 x 2.6 x 5.6 ft) high. Different ventilation rates ranging from 0, 0.25 to 1.0 m/s were used. Thermocouples and gas sensing probes were other instruments used in the tests.

The summary of findings concluded that fires in cabinets would not extinguish unless the water mist system was allowed to penetrate the inter-board systems, that control over the direction of the spray was the most important factor to extinguishing the fire, very fine sprays with low momentum and low mass flow rate were ineffective, there was no measurable advantage to fine sprays being carried with ventilation air into board spaces, mist from superheated water did not increase the rate of oxygen displacement, and that linear spray distribution provided greater extinguishment than conical sprays.

Interesting results from the study showed that water mist systems that flooded equipment rooms did not perform well in suppressing the fire. This was due to unpredictable spray velocities leading to unpredictable extinguishment. However, the direction of water mist application was shown to be a great factor in fire suppression and thus more time should be spent designing the system. Additionally, the author points out that there needs to be a method to assess sensitivity to water damage in specific equipment and that water mist may not be appropriate for all scenarios and should be taken on a case by case basis.

One of the goals of the tests was to used zoned suppression based on early detection; however, air sampling devices were not mentioned. These tests were mostly aimed at telecommuting facilities and did make mention of power producing plants, but the information may be useful when looking at possible suppression methods. To reemphasize the point, these tests did not look at the effect of HEAF events or the ensuing fire.

- *Okabe, S., M. Kosakada, H. Toda, K. Suzuki, M. Ishikawa, "Investigations of Multiple Reignition Phenomena and Protection Scheme of Shunt Reactor Current Interruptions in GIS Substations," IEEE Transactions on Power Delivery, Vol. 8, No. 1, p. 197 – 202, January 1993.*

  The article presents the problem of reignition in gas-insulated switchgear (GIS) equipped with a gas circuit breaker (GCB). From the authors' research, there have been a decreasing number of breaking point and increased voltage per breaking point which increases the possibility of multiple reignitions due to reactor current interruptions. These reignitions may cause rapid discharges in energy which has the potential to damage the equipment. The authors used an electromagnetic transient program to measure the oscillations due to reignition at substations. This paper lacks the background to fully understand the intension of the authors. It needs to be reinvestigated and the authors would be able to provide a greater insight.

- *Schau, H., Stade, D., "Requirements to be Met by Protection and Switching Devices from the Arcing Protection Point of View," ICEFA Proceedings of the Fifth International Conference, p. 15 – 22, 1995.*

  This paper looks at the specifics of arcing faults in relation to personnel and equipment protection. Protection devices such as fuses or circuit breakers greatly determine the duration of short circuits. The authors note that fuses provide faster response time in operation and that breakers may take longer to actuate. Fuses may operate efficiently if the real fault currents are used to select the fuse rated currents and confirmed with the switching behavior, and when there is a high ration between fault currents and fuse rated currents to reach short interruption times.

  When discussing the arc fault phenomena, the authors address the issues of pressure and temperature rise. Even in low voltage operations, they point out that the currents are still high. The stochastic behavior of the arc is dependent on arc roots, arc length, extinguishment, and re-ignition. Catastrophic destruction of equipment may occur if there is an extended arc duration, a non-selective fault interruption, or a protection level underflow.

  The article's content is pretty decent; however, the translation makes it hard to follow at times.

- *Shields, Francis J., "The Problem of Arcing Faults in Low-Voltage Power Distribution Systems," IEEE Transactions on Industry and General Applications, Vol. 1GA-3, No. 1, p. 15 – 25, Jan/Feb 1967.*

  This article is one of the earlier studies focusing on the problem of arcing faults in low voltage power distribution systems. The paper defines burndown as the severe damage to electrical equipment by arcing. The author points out that these arcs are so intense that they vaporize conductors and the surrounding structures releasing noxious gases from the insulation material. Though this particular article does not address the issue of fire, it is noted that they may occur after an arcing fault. The specific systems looked at in this article operate at 600 V or less. One interesting point that the author illustrates is that the arc tends to spread to areas outside of the fault zone.

  From the author's study, arc faults at 480 and 600 V are usually self-sustaining. If a single phase arc is initiated among a bare bus, a three phase arc will develop. If these arcs are not quenched, further ionizing and a temperature increase of the surrounding gas will take place.

  Arcing faults may be initiated many different ways such as the presence of rodents, an intrusion of metallic objects like tools, loose connections from poor insulation, the mechanical effect of high current surges, insulation aging, deterioration, and excessive moisture or dust. Minimizing the arcing events is a primary means to prevent these burndowns, but there was importance stressed to isolating and compartmentalizing events should they occur. Additionally, alternative methods to supplementary relaying are necessary for adequate protection.

  This article provided some valuable insight into the problem. It is a very good way to understand the issues of high energy arc faults and describes the phenomena and burndown associated with it. Methods to prevent and minimize the problems are discussed.

- *Slade, Paul G., Hammer, Cutler, "Growth of Vacuum Interrupter Application in Distribution Switchgear," Fifth International Conference on Trends in Distribution Switchgear: 400V-145kV for Utilities and Private Networks, p. 155 – 160, 1998.*

  This article is a review of the development of vacuum interrupter technology and presents reasons for its expanded applications. The development of this technology has led to better interruption capabilities, reliability, operation life, and a decrease in cost. The vacuum interrupter has seen expanding growth in India, China, and throughout Southeast Asia and is becoming widely accepted in distribution systems.

  The interrupter development has been focused on control of the vacuum arc, high vacuum technology, and materials development. Two technologies have been developed to control the high current vacuum arc and then ensure a diffuse arc which can be easily interrupted. Transverse magnetic field (TMF) forces the rotation of the arc around the periphery of a spiral or contrite cup contact. Axial magnetic field (AMF) forces the arc to remain diffuse at high currents. Testing by finite element analysis has been increasing in this field due to software and computational processing development. Material improvement has led the industry to use alumina ceramic material which has great strength.

The future application of vacuum interrupters will continue to grow as concerns on SF_6 as a greenhouse gas becomes more widespread. The developing research on vacuum arc erosion will result in better algorithms for interrupter life as a function of interrupter current. Maintenance will become less of an issue with further development and reliability will continue to improve.

In general, this paper presents an overview of the vacuum interrupter technology which includes its development, application, and future use. Preventing an arcing fault is the best way to ensure that a fire would not be an issue and therefore learning more about this particular technology would be beneficial.

- *Stanback Jr., Harris I., "Predicting Damage from 277-V Single Phase to Ground Arcing Faults," IEEE Transactions on Industry Applications, Vol. 1A-13, No. 4, pp. 307 – 314, 1978.*

In the late 1970s, Stanback Jr. performed laboratory experiments on 277 V single phase systems. The research was detailed and provided rather interesting results. One of the observations from the experiments was that a stable arc was difficult to establish with increased spacing between the bus bar and enclosure, an increase in available current, and with an increase in the number of bus bars. The experiments also illustrated the random nature of arcing faults. Other researchers calculated that arcs having less than 38 percent of the available bolted fault current will self-extinguish. Stanback Jr.'s experiments showed that many arcs did indeed extinguish with less than the 38 percent but also that arcs may not necessarily be self-sustaining with greater available bolted fault currents. The author hypothesized "a formula for the approximate prediction of maximum probable burning damage," given in units of cubic inches, relating it to the arc duration and current.

$$Y = AI_{arc}^{1.5}t$$

Equation 1: Practical approximation for the burn damage of copper and aluminum bus bars and steel housing

For Equation 1, the burning damage was represented by Y, a material constant was given as A, and the arc current and arc duration were given as I_{arc} and t, respectively. This equation could be used to evaluate the cost differences between possible equipment options and with damages and the interruption of operation. The author stressed that this equation was only verified for 277/480 V systems and should not be applied to other voltages. This research provided comprehensive experiments that identified some interesting aspects of arcing faults.

- *Sundin, D., "Increasing the Fire Safety Distribution Switchgear with Fire-Resistant Hydrocarbon Fluids," Distribution Switchgear, Third International Conference on Future Trends, p. 51 – 55, 1990.*

  This paper talks about the use of hydrocarbon fluids being used in transformers and switchgear. The author states that these hydrocarbon fluids have a fire point of at least 300ºC, are excellent arc-suppressants, and compatible with manufacturer's equipment. They are also biodegradable. This paper goes into the tests performed on switchgear equipment willed with hydrocarbon fluids.

  Test Series One was conducted at McGraw-Edison Corporation's Thomas Edison Laboratories in Franksville, Wisconsin. The equipment was manufactured by G&W Corporation. It was a standard 15 kV oil switch with contacts operated with 1400 in-lb springs. The closing and opening timing tests were found to be 12.4 ft/sec and 11.8, respectively. Eleven capacitive and ten magnetizing current interruption tests were successfully conducted. There were four 600 A interruptions performed and results showed that the arcing time was no longer than conventional oil filled transformer switches. The dielectric strength was slightly increased. G&W concluded that the use of hydrocarbon fluid was acceptable in switchgears.

  For Test Series Two, the test location was not specified in the text. This series of testing was focused on the physical, electrical, and chemical characteristics of the fire-resistant hydrocarbon fluid was compared to the conventional transformer oil after both were subjected to 500 switching operations at 400 A, 13.8 kV. The fire-resistant hydrocarbon fluid was extinguished the 400 A arc in 1.0 to 1.5 cycles and the conventional transformer oil interrupted the arc in 0.5 to 1.5 cycles.

  Several tests were performed at low temperatures, but these are of no particular interest to this project. An interesting series of tests looked at catastrophic failure. The city of Seattle, Washington contracted with British Columbia Hydro and Power Authority's High Power Laboratory to conduct tests on three-phase oil switches filled with the fire-resistant hydrocarbon fluid. The VCR switches were manufactured by McGraw-Edison and were designed for use with conventional transformer oil. The switches were tested to violent failure in order to establish their ability for use on 30 kA rms systems. The investigation tested their ability to close and to pass a current of these systems. Fire-resistant hydrocarbon fluid was also tested to catastrophic failure. Five tests were performed: two with the switch in the open position and three with the switch closed onto a faulted circuit. The supply energy was 230 kV via a 500 MVA stepdown transformer in series with reactors to limit the test current to 30 kA. One switch successfully withstood a symmetrical short-circuit through-current of 30 kA rms applied for 0.43 seconds. The same switch failed violently after a few cycles when the instant of fault initiation was selected to result in an asymmetrical current flow corresponding to fully offset current of 30 kA rms on a system with 75.7 kA peak. The failure resulted in a large fireball which quickly self-extinguished. Severe contact erosion and burning was evidenced. Another switch successfully operated and remained closed for approximately 16.7 ms. The same switch violently failed when it closed on asymmetrical current flow. There was massive arc damage, a fireball, and a release of fluid that did not ignite. Transformer oil may have ignited under the same conditions. None of the spilled hydrocarbon fluid ignited and any fireball that developed was self-extinguishing.

Fire-resistant hydrocarbon fluids have been shown to be an excellent arc-extinguishing media that are resistive to fire and explosion. The properties it possesses, like lubrication and biodegrading, make it a good choice when the probability of fire needs to be minimized. These hydrocarbon fluids are being manufactured and refined better to improve their heat transfer and electrical characteristics.

This test provides an interesting look at different dielectric materials used in switchgear operations. It would be useful to find additional tests and implementation of this hydrocarbon fluid.

- *Terzija, V. V., Koglin, H. -J., "Long Arc In Still Air: Testing, Modeling, Simulation And Model Parameter Estimation," Harmonics and Quality of Power, IEEE, Vol. 1, p. 36 – 44, 2000.*

This paper may be broken down into four specific sections: 1) long arc in still air is reproduced under laboratory conditions to obtain arc voltage and arc current data records to derive the main features of arc, 2) a new arc model is developed and evaluated, 3) the computer model is used to investigate arcing faults on overhead lines, and 4) the estimation of the unknown arc voltage model parameters the Least Error Squares estimation method is used. Long arcs are the typical phenomena occurring on overhead power lines. The elongation of the arc is determined by the magnetic forces produced by the supply current, the convection of plasma and the surrounding air, and the atmospheric effects (wind, humidity, and pressure).

The laboratory tests appeared to be a simple circuit. A switch was closed and the arc was initiated by a fuse wire. The distance between the electrodes was increased. On arc initiation (which is the time immediately after melting and evaporating of the fuse wire) the arc voltage was determined by distance between the horns. The arc column was assumed to be 1.3 kV/m. The data was digitized with a sampling frequency of 0.16 MHz to provide a possibility for investigating high frequency components existing in current and voltage signals. The arc is nonlinear, non-stationary, random, and time variant. The various electro-dynamics is a main reason for the non-stationary properties.

Long arc in free air is a source of harmonics causing distortions in other network currents and voltages. It is expected that the voltages and currents at the line terminals are containing harmonics. Arc voltage can be represented as a nonlinear differential equation. The unknown parameters must be estimated from test data. New model present by the authors is current dependent voltage source with the characteristic shape of its waveform. It is developed by observing the arc voltage waveform and its relation to the arc current. Electromagnetic Transient Program (EMTP) was developed for the purpose of investigating arcing faults phenomena. Least Error Squares method used to estimate unknown parameters.

- *Terzija, V. V., Koglin, H. -J., "Testing, Modeling, and Simulation of Long Arc In Still Air," Power Engineering Society Winter Meeting, IEEE, Vol. 3, p. 1140 – 1145, 2001.*

  This paper is an extension off of further research by the authors. They have continued to refine their efforts to account for arc length. They state that existing models have particular limitations and are just not practical for some fields of power engineering. This effort has been to add accuracy to modeling an arc by accounting for arc elongation. The elongation of the arc was determined by the magnetic forces produced by the supply current, the convection of the plasma and surrounding air, the atmospheric conditions, the arc medium, and etc.

  There was a series of experiments that were conducted, but they were looking at overhead power line scenarios rather than electrical switchgear equipment. One interesting result from the experiments was that the arc current slightly decreases its amplitude as it elongates. Based on the authors' laboratory results, the long arc in free air randomly changes its length but it generally increases. The arc elongation increases the amplitude and the resistance.

  In general, this paper presents an opportunity to pursue the research at the High Power Laboratory in Germany. It also identifies others who may have an interest in collaborating in such experiments.

- *Terzija, V. V., Koglin, H. -J., "New Approach to Arc Resistance Calculation," IEEE, Electrical Engineering, Archiv fur Elektrontechnik, Vol. 83, Issue 4, p. 193 – 201, 2001.*

  This paper investigates validity of the Warrington formula method used to calculate arc resistance. Because of the limitations that the original formula was derived from, the authors felt that there were better ways to calculate this important feature of arc faults. One of the ways that arc length is derived is by factoring in the arc resistance.

  This paper goes into the short comings and downfalls of the Warrington formula by analyzing the experiments used in their derivation. Some of the "bad" results from the experiments were removed without explanation. The equipment used was fairly crude and inaccurate. The variation and elongation of the arc length was not considered. The authors found a need to reinvestigate the widely used Warrington formula.

  The tests were performed in the same high voltage facility as in the other articles. A very simple experiment design was created and the data gathered was used to assist in new arc resistance equations. As of this article, the authors are waiting for comments from the electrical engineering community.

- *Terzija, V. V., Koglin, H. -J., "On the Modeling of Long Arc in Still Air and Arc Resistance Calculation," IEEE Transactions on Power Delivery, Vol. 19, No. 3, p. 1012 - 1017, 2004.*

  This paper is a comprehensive overview of the research that was conducted at the high-power test laboratory in Germany. It is the comprehensive integration of the other articles which were mentioned in this specific bibliography. One would get a great overview of their data analysis work and equation derivation; however, the experimental studies were less detailed.

- *Weichert, Ing. H., "Shock Waves in Arc Chambers of Miniature Circuit Breakers," Electrical Contacts, Proceedings of the Thirty-Sixth IEEE Holm Conference, p. 580 – 585, 1990.*

  This paper was really interesting. The issues with pressure build up leading to shockwaves in miniature circuit breakers (MCBs) seem similar to those that are experienced in gas insulated switchgear. The arcing time steps that are used by the author to describe the fault event in MCBs may be applied to switchgears. "At contact opening time t_o the contacts are separated and the arc forms between them. An important interval of time is the immobility time t_i during which the arc remains nearly immovable at the contacts. t_i depends for example on the electromagnetic forces acting upon the arc, the contact material, the contact opening speed and the pressure conditions in the arc chamber. At the end of t_i the arc is rapidly driven off the contacts by self-generated Lorentz-force."

  The author later describes the arc lengthening between the narrowly spaced walls in the arc chamber causes a voltage increase. The rapid motion of the arc generates a shockwave which is able to stop the arc. Reignitions are caused by the electrical stress due to the high arc voltage.

  The information and descriptions in this article may provide different insights into the arc fault event in switchgear equipment.

- *Wilson, W. R., "High-Current Arc Erosion of Electric Contact Materials," AIEE Transactions, Vol. 74, No. III, pp. 657 – 663, August 1955.*

  According to Wilson[3], very few of the 1,500 references were published for high-currents of 5,000 amperes and over. He also emphasized that the conclusions established "from experience at low current could not be applied at high current without specific verification." The report primarily focused on the erosion rates of different materials and alloys at high currents in addition to subsequent comparison between the electrodes. It was assumed that all of the electric power went into the melting and vaporizing the contact material. The information from Wilson's work was used to directly improve the electrode reliability in circuit breaking devices.

- *Zalosh, Robert G., "Industrial Fire Protection Engineering," JW Wiley, p. 322 – 336, 2003.*

This particular Chapter in the Industrial Fire Protection Engineering book provided a similar insight into the high energy arc fault problem as Babrauskas' Ignition Handbook. There were some valuable statistics reported from various sources and the issue itself was broken down into components such as cables, cabinets, transformers, and limitedly switchgears. Many of the resources in this book have been actively pursued for this current project. In general, this particular chapter provides great insight into the problem from a broad perspective and is an initial point for further research.

- *Zhang, Jin Ling, Jiu Dun Yan, Michael T. C. Fang, "Electrode Evaporation and Its Effects on Thermal Arc Behavior," IEEE Transactions on Plasma Science, Vol. 32, No. 3, p. 1352 – 1351, 2004.*

This paper seemed like it had potential; however, much of it ended up leading outside of the scope of this project. This is because the research was more focused on supersonic nozzles typically used in arc heaters or welding apparatus. Some of the topics they investigated were interesting and will be further elaborated upon.

The authors point out that the phase changes of metals being vaporized is an issue that cannot be avoided. One reason is due to the contribution of mass, momentum, and energy. The other is due to the alteration of thermodynamic and transport properties, especially the electrical conductivity and radiation characteristics of the arc. Between the electrode surface and the arc plasma is sheath region which is not apart of the local thermal equilibrium (LTE). The mixture between SF_6 and metal vapor is extremely complex to calculate in this region and is therefore excluded in this study. The authors use the experimental and theoretical based to calculate the energy flux into electrodes. This energy flux determines the vaporization and melting. The metal vapor from the electrode mixes with the SF_6 through diffusion and convection; local chemical equilibrium (LCE) simplifies the calculation the mixture composition and the diffusion coefficient. With this assumption, the thermodynamic and transport properties can be described as functions of temperature, total pressure, and the mass or volume concentration. In particular, copper was chosen as the electrode material due to its vaporization. The CFD software, PHOENICS, is used in this study to obtain the simulation results. This study assumes that the metal vapor and the SF_6 are completely mixed. The nozzle wall is assumed to be adiabatic for the purposes of this investigation. The arc is considered a gas mixture and the enthalpy is a function of temperature and depends on the vapor concentration. Outside of the arc, the gas is mostly SF_6 and inside the arc it is considered mostly or pure copper vapor.

It was pointed out that the electrode would start to vaporize when the temperatures reached its melting point. For copper in particular, the latent heat of fusion is much smaller than that of evaporation and the molten material is quickly heated into vapor. Many of the sources the researchers listed were essential in obtaining the thermodynamic and transport properties of the gas mixture. These sources may be useful if a potential project details the phenomena in material vaporization.

The CFD code PHOENICS was used to solve the governing equations. The design of the study, however, was out of our potential scope for the high energy arc fault project. An interesting result was that the arc temperature was significantly affected by upstream electrode vaporization. The radial temperature profile tends to become flatter and the axis temperature becomes slightly lower than the arc edge. The arc temperature from the program was found to be 22000 K in pure SF_6 and decreased to 16000 K in the presence of copper vapor.

This paper had some interesting background work that was more detailed than necessary for the scope of this potential project. The research presented is important to note, but may not be important for this project on fire events.

- *Zhang, Xiang, Gerhard Pietsch, Ernst Gockenbach, "Investigation of the Thermal Transfer Coefficient by the Energy Balance of Fault Arcs in Electrical Installations," IEEE Transactions on Power Delivery. Vol. 21, No. 1, p. 425 – 431, January 2006.*

This article discussed an alternative method to obtaining the thermal transfer coefficient, k_p, which has been traditionally obtained from experimental results and thus limited the application to specific boundary conditions. The new method was accomplished by solving the conservation equations taking melting and evaporation and chemical reactions with the surrounding gas into account. The thermal transfer coefficient was assumed to be the ratio of internal energy of the surrounding gas to the electrical energy of the arc fault. A free body diagram was illustrated to show the energy balance of the arc fault event. This step has been discussed by references in the paper. The authors have chosen to the neglect the radiative thermal transfer coefficient because many different experiments have found this to be negligible.

The term "relative purity" was introduced to explain an arc that is not contaminated with impurities from the equipment electrodes or walls. They state that the gas density is high enough to neglect these impurities. These types of arcs have been experimentally proven to have constant thermal transfer coefficients for SF_6 insulating gas. The energy occurring from evaporation and chemical interaction must be accounted for in arcs that are not pure by an energy balance and chemical combination analysis. The conservation equations are then applied for this particular mathematical model.

The volume of the simplified models were small (0.07 to $0.14m^3$) in comparison to the tests that should be conducted for full sized experiments. The comparison of gas density between air and SF_6 was interesting, which points to the importance of analyzing the O_2 and the Al particle interaction in these types of tests.

The most fascinating aspect of this article was the medium voltage switchgear experiments; however, they were not detailed nearly enough to be extremely useful. The paper noted that the pressure release openings did not function properly. The vaporization of the interior metals, such as the copper electrodes, seemed similar to historical accounts that eventually led to fire events. Since the researchers were focused on the pressure development by finding the thermal transfer coefficient, further elaboration on issues like fire or explosion were not investigated.

APPENDIX E: ADDITIONAL REFERENCES

Author (1)		Author (2)		Authors	Title	Journal	Edition	Year
Alverson	T. E.	Barken	P.	Et al.	A Report on Research on Fire Safety Test Methods and Performance Criteria for Transformers Containing PCB Replacement Fluids	Fluid-Filled Transformers Flammability Study Committee - NEMA	Contract No. NB795BCA0024	1980
Arita	H.	Natsui	K.	Et al.	Interruption Ability of a Self Extinguishing Type Gas Circuit Breaker	IEEE Transactions on Power Delivery	Vol. 5, No. 3, p. 1362 - 1369	1990
Attwood	S. S.	Dow	W. G.	Et al.	Reignition of Metallic A-C. Arcs in Air	Middle Eastern District Meetin for the A. I. E. E.	p. 854 - 870	1931
Babrauskas	Vytenis				Ignition Handbook			2003
Baldwin	Thomas L.	Hittel	Michael J.	Et al.	Using a Microprocessor-Based Instrument to Predict the Incident Energy From Arc-Fault Hazards	IEEE Transactions on Industry Applications	Vol. 40, No. 3, p. 877 - 886	2004
Bjortuft	Tom Rune	Granhaug	Ole	Et al.	Internal Arc Fault Testing of Gas Insulated Metal Enclosed MV Switchgear	18th International Conference on Electricity Distribution	CIRED2005	2005
Borkowski	Piotr	Haswgawa	Makoto		A Computer Program for the Calculation of Electrode Mass Loss under Electric Arc Conditions	IEICE Trans. Electron.	Vol. E90-C, No. 7, p. 1369 - 1376	2007
Brown	Lloyd R.				Electrical Fire Opinions	Fire and Arson Investigator	p. 36 - 37	1993
Chapin	J. Thomas	Gandhi	Pravin	Et al.	Comparison of Communications LAN Cable Smoke Corrosivity by US and IEC Test Methods	Fire Risk & Hazard Research Assessment Research Application Symposium San Francisco	June	1997
Chavez	J. M.				An Experimental Investigation of Internally Ignited Fire in Nuclear Power Plant Control Cabinets: Part 1: Cabinet Effects Tests		SAND86-0336	1987
Cheeca	Elio	Helfrich	William		Vacuum-Fused Circuit Breakers for Low and Medium Voltage AC Trailing Cable Protection	IEEE Transactions on Industry Applications	Vol. 30, No. 2, p. 245 - 252	1994

Author (1)		Author (2)		Authors	Title	Journal	Edition	Year
Chen	Degui	Dai	Ruicheng	Et al.	Experimental Investigation on the Arc Motion with Different Configuarations of Quenching Chamber in AC Contactor	IEICE Trans. Electron.	Vol. E89-C, No. 8., p. 1201 - 1205	2006
Crnko	Tim	Dyrnes	Steve		Arcing Fault Hazards and Safety Suggestions for Design and Maintenance	IEEE Industry Applications Magazine	May/June	2001
Deaton	R.	Gostic	J. M.		Installation and Operational Considerations of Arc Resistant Switchgear	Petroleum and Chemical Industry Conference	p. 307 - 313	1996
Desborough	M.				Pressure Rise and Burn Through Predictions and the Principles of Pressure Relief Device Design	IEE Colloquium on Risk Reduction: Internal Faults in T&D Switchgear		1997
Doughty	Richard L.	Neal	Thomas E.	Et al.	Predicting Incident Energy to Better Manage the Electric Arc Hazard on 600-V Power Distribution Systems	IEEE Transactions on Industry Applications	Vol. 36, No. 1, p. 257 - 269	2000
Doughty	Richard L.	Neal	Thomas E.	Et al.	Testing Update on Protective Clothing and Equipment for Electric Arc Exposure	IEEE Industry Applications Magazine	p. 37 - 49	1999
Doughty	Richard L.	Neal	Thomas E.	Et al.	The Use of Low Voltage Current Limiting Fuses to Reduce Arc Flash Energy	IEEE Transactions on Industry Applications	Vol. 36, No. 6, p. 1741 - 1749	2000
Dunki-Jacobs	J. R.				The Effects of Arcing Ground Faults on Low-Voltage System Design	IEEE Transactions on Industry Applications	Vol. 1A-8, No. 3, p. 223 - 230	1972
Dunki-Jacobs	J. R.				The Escalating Arcing Ground-Fault Phenomenon	IEEE Transactions on Industry Applications	Vol. 1A-22. No. 6, p. 1156 - 1161	1986
Falkingham	Leslie T.	Cheng	Kam		Further Experiments in High Current Switching Using Small Contact Gaps	IEEE 18th Symposium on Discharges and Electrical Insulation in Vacuum	p. 455 - 458	1998
Finke	S.	Koenig	D.	Et al.	Effects of Fault Arcs on Insulating Walls in Electrical Switchgear	IEEE International Symposium on Electrical Insulation	p. 386 - 389	2000
Finke	S.	Koenig	D.		Recent Investigations on High Current Internal Arcs in Low Voltage Switchgear	IEEE International Symposium on Electrical Insulation	p. 336 - 340	2002

Author (1)		Author (2)		Authors	Title	Journal	Edition	Year
Fisher	Lawrence E.				Resistance of Low-Voltage AC Arcs	IEEE Transactions on Industry and General Applications	Vol. 1GA-6, No. 6, p. 607 - 616	1970
Floyd	H. Landis	Doan	Daniel R.	Et al.	Arc Flash Hazards and Electrical Safety Program Implementation	Industry Applications Conference, Fourtieth IAS Annual Meeting	Vol. 3, p. 1919 - 1923	2005
Fox	Francis K.	McClung	L. Bruce		Ground Fault Tests on High Resistance Grounded 13.8 kV Electrical Distribution System of Modern Large Chemical Plant - I	IEEE Transactions on Industry Applications	Vol. 1A-10, No. 5, p. 581 - 600	1974
Friberg	G.	Pietsch	G. J.		Calculation of Pressure Rise Due to Arcing Faults	IEEE Transactions on Power Delivery	Vol. 14, No. 2, p. 365 - 370	1999
Fujinami	H.	Takuma	T.	Et al.	Development of Detection Method with a Magnetic Field Sensor for Incomplete Contact in Gas Insulated Switched and Bus Connecting Parts	IEEE Transactions on Power Delivery	Vol. 10, No. 1, p. 229 - 236	1995
Gammon	Tammy	Matthews	John		Arcing-Fault Models for Low-Voltage Power Systems	Industrial and Commercial Power Systems Technical Conference	p. 119 - 126	2000
Gammon	Tammy	Matthews	John		Conventional and Current-Dependent Methods for Predicting RMS Arc Currents in Building Systems	Industrial and Commercial Power Systems Technical Conference	p. 75 - 82	2001
Gammon	Tammy	Matthews	John		Conventional and Recommended Arc Power and Energy Calculations and Arc Damage Assessment	IEEE Transactions on Industry Application	Vol. 39, No. 3, p. 594 - 599	2003
Gammon	Tammy	Matthews	John		Instantaneous Arcing-Fault Models Developed for Building Systems Analysis	IEEE Transactions on Industry Application	Vol. 37, No. 1, p. 197 - 203	2001
Goda	Yutaka	Iwata	Mikimasa	Et al.	Arc Voltage Characteristics of High Current Fault Arcs in Long Gaps	IEEE Transactions on Power Delivery	Vol. 15, No. 2, p. 791 - 795	2000
Gregory	G. D.	Lyttle	I.	Et al.	Arc Flash Energy Limitations Using Low-Voltage Circuit Breakers	Petroleum and Chemical Industry Conference	p. 291 - 299	2002
Gregory	George D.				Arc Flash Calculations in Systems Protected by Low-Voltage Circuit Breakers	IEEE Transactions on Industry Applications	Vol. 39, No. 4, p. 1193 - 1199	2003

Author (1)		Author (2)		Authors	Title	Journal	Edition	Year
Harrower	J. A.	MacGregor	S. J.	Et al.	A Long Lifetime, High PRF Plasma Closing Switch	IEE Colloquium on Pulsed Power	Paper No. 45, p. 4.5/1 - 4.5/4	1998
Hasegawa	Makoto	Kamada	Yusuke		An Experimental Study on Re-interpretation of Minimum Arc Current of Electrical Contact Materials	IEICE Trans. Electron.	Vol. E88-C, No. 8, p. 1616 - 1619	2005
Health and Safety Executive					Electrical Switchgear and Safety: A Concise Guide for Users		ISBN 0717621871	2004
Heberlein, Jr.	G. Erich	Higgins	Jack A.	Et al.	Report on Enclosure Internal Arcing Tests	Petroleum and Chemical Industry Conference	p. 271 - 284	1994
Holmberg	Magnus E.	Gubanski	Stanislaw M.		Discharges from Moving Particles in GIS	IEEE Transactions on Power Delivery	Vol. 13, No. 1, p. 17 - 22	1998
Honba	Ryoichi	Murakami	Youichi	Et al.	Characteristics of Arc-Reducing Effect by Capacitor in Commutation Circuit	IEICE Trans. Electron.	Vol. E89-C, No. 8, p. 1153 - 1159	2006
IEC 1639					Direct Connection Between Power Transformers and Gas-Insulated Metal-Enclosed Switchgear for Rated Voltages of 72.5 kV and Above	International Electrotechnical Commission		1996
IEC 1641					Enclosed Low-Voltage Switchgear and Controlgear Assemblies - Guide for Testing Under Conditions of Arcing Due to Internal Fault	International Electrotechnical Commission		1996
IEC 61634					High-Voltage Switchgear and Controlgear - Use and Handling of SF6 in High Voltage Switchgear and Controlgear	International Electrotechnical Commission		1995
IEC 61958					High-Voltage Prefabricated Switchgear and Controlgear Assemblies - Voltage Presence Indicating Systems	International Electrotechnical Commission		2000
IEC 62271-200					AC Metal-Enclosed Swtichgear and Controlgear for Rated Voltages Above 1 kV	International Electrotechnical Commission		2003
IEC 62271-203					Gas-Insulated Metal-Enclosed Switchgear for Rated Voltages Above 52 kV	International Electrotechnical Commission		2003

Author (1)		Author (2)		Authors	Title	Journal	Edition	Year
IEEE Standard 1584					IEEE Guide for Performing Arc-Flash Hazard Calculations			2002
IEEE Standard 1584a					IEEE Guide for Performing Arc-Flash Hazard Calculations Amendment 1			2004
IEEE Standard 242					IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems			2001
IEEE Standard C37.20.1					IEEE Standard for Metal-Enclosed Low-Voltage Power Circuit Breaker Switchgear			2002
International Atomic Energy Agency					Experience Gained From Fires in Nuclear Power Plants: Lessons Learned		IAEA-TECDOC-1421	2004
Iwao	T.	Inoue	Y.	Et al.	Temperature and Radient Power Emitted from DC Horizontal Short Free Arc Discharge Mixture with Tungsten Vapor	Pulsed Power Plasma Science, IEEE Conference Record		2001
Jamil	S.	Jones	R. A.	Et al.	Arc and Flash Burn Hazards at Various Levels of an Electrical System	Petroleum and Chemical Industry Conference	p. 317 - 325	1995
Jones	Ray A.	Liggett	Danny P.	Et al.	Staged Tests Increase Awareness of Arc-Flash Hazards in Electrical Equipment	IEEE Transactions on Industry Applications	Vol. 36, No. 2, p. 659 - 667	2000
Kapustin	V.	Podolsky	D.	Et al.	Arc Penetration to the Arc Chute and Arc Chute Plates Erosion	Electrical Contacts, Proceedings of the Forty-Second IEEE Holm Conference	p. 50 - 59	1996
Kaufmann	R. H.	Page	J. C.		Arcing Fault Protection for Low-Voltage Power Distribution Systems - Nature of the Problem	Transactions of the American Institute of Electrical Engineers	Vol. 79, p. 160 - 167	1960
Keski-Rahkonen	Olavi	Mangs	Johan		Electrical Ignition Sources in Nuclear Power Plants: Statistical, Modelling and Experimental Studies	Nuclear Engineering and Design	213, p. 209 - 221	2001

Author (1)		Author (2)		Authors	Title	Journal	Edition	Year
Kharin	S. N.				Mathematical Model of the Short Arc Phenomena at the Initial Stage	Electrical Contacts, Proceedings of the Forty-Third IEEE Holm Conference	p. 289 - 305	1997
Kumar	Ambadi S.	Okazaki	Ken		Electrobe Surface Control of the Transition from Micro-Arcs to High-Current Arcs in Atmospheric-Pressure Plasmas	IEEE Transactions on Plasma Science	Vol. 23, No. 4, p 735 - 741	1995
Kyrki-Rajamaki	Riitta	Puska	Eija Karita		The Finnish Research Programme on Nuclear Power Plant Safety 1999-2002	Technical Research Centre of Finland	VTT Reseach Notes 2164	2002
Laycock	W. J.				On Site Testing of Protection and Automatic Switching Equipment in 275 and 400kV Substations	Fourth International Conference on Developments in Power Protection	p. 27 - 29	1989
Lee	Ralph H.				Pressures Developed by Arcs	IEEE Transactions on Industry Applications	Vol. 1A-23, No. 4, p. 760 - 764	1987
Lee	Ralph H.				The Other Electrical Hazard: Electric Arc Blast Burns	IEEE Transactions on Industry Applications	Vol. 1A-18, No. 3, p. 246 - 251	1982
Li	Jincheng	Kohler	Jeffery L.		New Insight into the Detection of High-Impedance Arcing Faults on DC Trolley Systems	IEEE Transactions on Industry Applications	Vol. 35, No. 5, p. 1169 - 1173	1999
Li	Xingwen	Chen	Degui	Et al.	Investigations on the Interruption Process of Molded Case Circuit Breakers Including the Influence of Blow Open Force	IEICE Trans. Electron.	Vol. E89-C, No. 8, p. 1187 - 1193	2006
Li	Xingwen	Chen	Degui		Study of the Effect of Gassing Material on Arc Behavior in Low Voltage Circuit Breaker	IEICE Trans. Electron.	Vol. E90-C, No. 7, p. 1460 - 1465	2007
Lippert	Kevin J.	Colaberardino	Donald M.	Et al.	Understanding IEEE 1584 Arc Flash Calculations	IEEE Industry Applications Magazine	May/June	2005
Love	Daniel J.				Discussion of "Predicting Damage from 277-V Single Phase to Ground Arcing Faults"	IEEE Transactions on Industry Applications	Vol. 1A-14, No. 1, p. 93 - 95	1978
MacGregor	S. J.	Tuema	F. A.	Et al.	Repetitively Operated Spark Gap Switches	IEE Colloquium on Pulsed Power	Paper No. 1, p. 1- 5	1994
Mangs	Johan	Keski-Rahkonen	Olavi		Full Scale Fire Experiments on Electronic Cabinets	Technical Research Centre of Finland	VTT Publications 186	1994

Author (1)		Author (2)		Authors	Title	Journal	Edition	Year
Mangs	Johan	Keski-Rahkonen	Olavi		Full Scale Fire Experiments on Electronic Cabinets II	Technical Research Centre of Finland	VTT Publications 269	1996
Manufacturer	Ganz Transelektro Electric Co. Ltd.				Gas Insulated Switchgear			
Manufacturer	Siemens				Gas-Insulated Metal-Enclosed Surge Arresters (GIS-Arresters)			1997
Marschall	Charles S.				San Onofre Nuclear Generating Station NRC Special Team Inspection Report	Nuclear Regulatory Commission	50-362/01-05	2001
Mawhinney	J. R.				Findings of Experiments Using Water Mist for Fire Suppression in an Electronic Equipment Room	Proceedings: Halon Options Technical Working Conference		1996
McBride	J. W.	Weaver	P. M.		Review of Arcing Phenomena in Low Voltage Current Limiting Circuit Breakers	Science, Measurement and Technology, IEE Proceedings	Vol. 148, Issue 1, p. 1 - 7	2001
McClung	L. Bruce	Whittington	Bernard W.		Ground Fault Tests on High Resistance Grounded 13.8 kV Electrical Distribution System of Modern Large Chemical Plant - II	IEEE Transactions on Industry Applications	Vol. 1A-10, No. 5, p. 601 - 617	1974
Meinecke	Herbert				High Voltage Gas Insulated Switchgear	IEE Colloquium on Gas-Insulated Switchgear (GIS) at Transmission and Ditribution Levels	p. 3/1 - 3/8, Nov	1995
Millar	J. Donald				Polychlorinated Biphenyls (PCB's): Potential Health Hazards from Electrical Equipment Fires or Failures	Current Intelligence Bulletin 45	DHHS (NIOSH) Pub No. 86-111	1986
Miller	R. B.				An Introduction to the Physics of Intense Charged Particle Beams	Plenum Press	p. 12 - 17	1982
Neal	Thomas E.	Parry	Roger F.		Shrapnel, Pressure, and Noise	IEEE Industry Applications Magazine	May/June	2005
NFPA 70E					Standard for Electrical Safety Requirements for Employee Workplaces	NFPA 70E		2000
None Listed					Arc Flash Users Guide Reference Manual			

Author (1)		Author (2)		Authors	Title	Journal	Edition	Year
Okabe	S.	Kosakada	M.	Et al.	Investigations of Multiple Reignition Phenomena and Protection Scheme of Shunt Reactor Current Interruption in GIS Substations	IEEE Transactions on Power Delivery	Vol. 8, No. 1, p. 197 - 202	1993
Pons	A.	Leconte	C.	Et al.	Breaking Capacity at Low Temperatures	IEEE Transactions on Power Delivery	Vol. 8, No. 3, p. 1165 - 1172	1993
Quintana	John				Arc Flash Exposure Thresholds, Analysis, and Controls	Western Area Power Administration, Power Systems Maintenance Manual	Chapter 14	2000
Ramming	L.	Aristizabal	M.		Cold Characteristics Development Test of a New SF6 High Voltage Circuit Breaker	IEEE Transmission & Distribution Conference and Exposition	p. 1 - 4	2006
Rochette	D.	Clain	S.	Et al.	Two-Dimensional Modelling of Internal Arc Effects in an Enclosed MV Cell Provided with a Protection Porous Filter	Journal of Physics D: Applied Physics	Vol. 40, Issue 10, p. 3137 - 3144	2007
Roop	D. W.	Vidonic	N. G.		Arcing Fault Protection on VEPCo's 480Y/277 Volt Secondary Spot Networks	IEEE Transactions on Power Apparatus and Systems	Vol. PAS-102, No. 2, p.364 - 372	1983
Rummer	Dale				Case of Chronic Boiler Burndown	EC&M Magazine		2001
Schau	H.	Stade	D.	Et al.	A New Concept of Arcing Fault Protection in Low Voltage Switchgear	Short-Circuit Currents in Power Systems	Vol. 6, p. 4.11.1 - 4.11.8	1994
Schau	H.	Stade	D.		Requirements to be met by Protection and Switching Devices from the Arcing Protection Point of View	ICEFA Proceedings of the Fifth International Conference	p. 15 - 22	1995
Sekikawa	Junya	Kubono	Takayoshi		An Experimental Equation for Dependence of Duration of Breaking Arcs on Supply Voltage with Constant Circuit Resistance	IEICE Trans. Electron.	Vol. E88-C, No. 8, p. 1584 - 1589	2005
Shields	Francis J.				The Problem of Arcing Faults in Low-Voltage Power Distribution Systems	IEEE Transactions on Industry and General Applications	Vol. 1GA-3, No. 1, p. 15 -25	1967

Author (1)		Author (2)		Authors	Title	Journal	Edition	Year
Slade	Paul G.	Hammer	Cutler		Growth of Vacuum Interrupter Application in Distribution Switchgear	Fifth International Conference on Trends in Distribution Switchgear: 400V-145kV for Utilities and Private Networks	p. 155 - 160	1998
Smeets	Rene Peter Paul	van der Linden	Wim A.		Verification of the Short-Circuit Current Making Capability of High-Voltage Switching Devices	IEEE Transactions on Power Delivery	Vol. 16, No. 4, p. 611 - 618	2001
Spaulding	Dylan Kenneth				Computational Modeling and Adaptation of High Voltage Spark-Gap Switches for Pulsed Power Applications	Sandia Summer Student Symposium		2002
Stanback Jr.	Harris I.				Predicting Damage from 277-V Single Phase to Ground Arcing Faults	IEEE Transactions on Industry Applications	Vol. 1A-13, No. 4, p. 307 - 314	1977
Sundin	D.				Increasing the Fire Safety Distribution Switchgear with Fire-Resistant Hydrocarbon Fluids	Distribution Switchgear, Third International Conference on Future Trends…	p. 51-55	1990
Terzija	V. V.	Koglin	H. J.		Long Arc in Free Air: Testing, Modeling, and Parameter Estimation: Part 1		p. 404 - 409	2000
Terzija	V. V.	Koglin	H. J.		Long Arc in Still Air: Testing, Modeling, Simulation and Model Parameter Estimation	Harmonics and Quality of Power	Vol. 1, p. 36 - 44	2000
Terzija	V. V.	Koglin	H. J.		Long Arc in Still Air: Laboratory Testing, Modeling, Simulation and Model Parameter Estimation	IEEE Proc.-Gener. Transm. Distrib.	Vol. 149, No. 3, p. 319 - 325	2002
Terzija	V. V.	Koglin	H. J.		New Approach to Arc Resistance Calculation	Electrical Engineering, Archiv fur Elektrontechnik	Vol. 83, Issue 4, p. 193 - 201	2001
Terzija	V. V.	Koglin	H. J.		Testing, Modeling and Simulation of Long Arc in Still Air	Power Engineering Society Winter Meeting, IEEE	Vol. 3, p. 1140 - 1145	2001
Terzija	Vladimir V.	Koglin	Hans-Jurgen		On the Modeling of Long Arc in Still Air and Arc Resistance Calculation	IEEE Transactions on Power Delivery	Vol. 19, No. 3, p. 1012 - 1017	2004
Toman	Gary	Gazdzinski	Robert	Et al.	Aging Management Guideline for Commerical Nuclear Power Plants - Electrical Switchgear		SAND93-7027	1993

Author (1)		Author (2)		Authors	Title	Journal	Edition	Year
Wactor	Michael	Miller	Gregory H.	Et al.	Modeling of the Pressure Wave Associated with Arc Fault	Petroleum and Chemical Industry Conference	p. 333 - 341	2000
Wakatsuki	Noboru	Akiba	Yuuich	Et al.	Time-Coordinated Switching Relay for Arc Discharge Suppression	IEICE Trans. Electron.	Vol. E88-C, No. 8, p. 1635 - 1640	2005
Weichert	Ing. H.				Shock Waves in Arc Chambers of Miniature Circuit Breakers	Electrical Contacts, Proceedings of the Thirty-Sixth IEEE Holm Conference	p. 580 - 585	1990
Wilson	W. R.				High -Current Arc Erosion of Electric Contact Materials	AIEE Transactions	Vol. 74, No. III, p. 657 - 663	1955
Yokokura	K.	Matsuda	M.	Et al.	Capacitor Switching Capability of Vacuum Interrupter with CuW Contact Material	IEEE Transactions on Power Delivery	Vol. 10, No. 2, p. 804 - 810	1995
Zalosh	R.	Lin	W. H.		Effects of Gravel Bed on the Burning Rate and Extinghuishment of High Flash Point Hydrocarbon Pool Fires	LPS 1995	p. 371 - 380	1995
Zalosh	Robert G.				Industrial Fire Protection Engineering			2003
Zhang	Jin Ling	Yan	Jiu Dun	Et al.	Electrode Evaporation and Its Effects on Thermal Arc Behavior	IEEE Transactions on Plasma Science	Vol. 32, No. 3, p. 1352 - 1351	2004
Zhang	Xiang	Pietsch	Gerhard	Et al.	Investigation of the Thermal Transfer Coefficient by the Energy Balance of Fault Arcs in Electrical Installations	IEEE Transactions on Power Delivery	Vol. 21, No. 1, p. 425 - 431	2006

DISTRIBUTION

1	MS0748	Jason W. Brown, 6761
1	MS0748	Steven P. Nowlen, 6761
1	MS0748	Francis J. Wyant, 6761
1	MS0899	Technical Library, 9536 (electronic copy)

Sandia National Laboratories