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Safety and Environmental Evaluation of Insulating Media in Medium-Voltage Distribution Equipment

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Abstract

The hazards associated with performing maintenance on energized electrical equipment have been the subject of massive amounts of literature as well as the driver for numerous product innovations aimed at mitigating the effects of this hazard. The intent of this paper is to highlight potential personal and environmental dangers associated with this same equipment when it is de-energized. This paper is specifically targeted at switchgear and circuit breakers rated above 1000V, and is more specifically targeted at personnel who perform maintenance, decommissioning, retrofitting, or clean up after catastrophic failures of this class of equipment.

Index Terms - asbestos, SF_6, Sulfur hexafluoride, oil, PCBs, Polychlorinated biphenyls, maintenance, GIS

Introduction

When one prepares to perform work on electrical equipment, it is recommended that a checklist of safety precautions and procedures be consulted, and in many cases filed with a site safety officer. These checklists instruct personnel to review the equipment product literature to familiarize themselves with the manufacturer's recommended practices, assure the proper lock-out and tag-out procedures are followed, remind the operator of safe grounding procedures, etc. What can be easily overlooked on these check lists is an item that addresses potentially hazardous materials that may have been utilized in the manufacture of this equipment. This paper is intended to bring awareness to this issue so appropriate equipment surveys and associated procedures may be developed to safely deal with them.

Throughout the electrical industry, manufacturers have designed their products around various types of insulation materials. Designers did not know the hazards of some of these materials at the time of their conception. Electrical equipment targeted for use in industrial environments is robustly designed to last many years. The very IEEE standards to which specifiers ask these products to be certified are targeted at assuring this attribute. The benefit of this philosophy is obvious at the time of purchase, but one of the negative aspects is the fact that they will last many years... As new knowledge is gained regarding the materials that pose health hazards to humans, the likelihood that older equipment contains these materials increases.

This paper will bring awareness to three switchgear and circuit breaker insulating materials. The first material was utilized in vintage switchgear and circuit breakers - asbestos; the second is in minimal use in new circuit breakers - oil; and the third is growing in use today - sulfur hexafluoride (SF_6).

Sulfur Hexafluoride (SF_6)

SF_6 is a colorless, non-flammable, non-toxic, non-ozone depleting gas. Its use in the electrical industry in the US has primarily been applied to circuit breakers for applications above 38kV and has displaced the use of OCBs [4] [6]. The superior dielectric and heat transfer properties of SF_6, and its ability to "self-heal or regenerate after arc interruption have driven designers to utilize it for both arc interruption and insulation of circuit breakers in this voltage class [9]. In recent years, however, this class of equipment has begun to find its way into the US in lower voltages in the form of gas insulated switchgear (GIS), which only utilizes SF_6 for its insulation system, and uses vacuum interrupters for arc interruption.

The properties of SF_6 described above would appear to pose no safety hazard to workers, which is generally true when SF_6 is in its pure state. The promotion of SF_6 as being non-toxic can mislead users into not understanding the hazard they may face if leakage occurs during system operation, or especially if clean-up is required after a failure resulting from a lighting strike or internal equipment failure.

When SF_6 is subjected to electrical arcing, toxic byproducts can be produced. Arcing in the presence of moisture is the worst condition. The catastrophic failure of electrical equipment presents the greatest opportunity for the production of toxic byproducts. Similar, but less toxic, exposure can result when dismantling and disposing of circuit breakers that utilize SF_6 as their arc interruption medium. SF_6 circuit breakers and insulated products utilize desiccants to absorb any moisture that may leak into the SF_6 chamber. If the level of moisture exceeds that absorption capability of the desiccant, toxic byproducts can be produced during the course of normal arc interruption. Excessive moisture entry into the SF_6 chamber during maintenance can produce similar results.

The byproducts of arced SF_6 manifest themselves as gases or a white powdery substance. Some of the byproducts demonstrated to be produced are shown in Table 1 [12].

Table 1. Gaseous SF_6 Decomposition Byproducts and Typical Concentrations During Repeated Sparking

CHEMICAL FORMULA	CHEMICAL NAME	CHEMICAL ABSTRACTS SERVICE REGISTRY NUMBER	EXPERIMENTAL CONCENTRATION (PERCENT BY VOLUME)*
HF	Hydrogen fluoride	7664-39-3	1.0
SOF_2 (SF_4)[b]	Thionyl sulfide (sulfur tetrafluoride)	7783-42-8	0.5
SOF_4	Sulfur tetrafluoride oxide	13709-54-1	0.085
SiF_4	Silicon tetraflouride	7783-61-1	0.085
S_2F_{10}(SF_5)[c]	Disulfur decafluoride	5714-22-7	0.025
SO_2F_2	Sulfuryl fluoride	2699-79-8	0.006
S02	Sulfur dioxide	7446-09-5	0.002

Conditions resulting from exposure to some of the above compounds consist of eye, skin, nose, and throat irritation, pulmonary edema, bronchitis and other lung damage. Concentrated Hydrogen fluoride (HF) solutions can cause severe, deep, and disfiguring burns. Absorption of HF into the body can cause the heart to beat irregularly, leading to death [11].

In the U.S., six workers were exposed during repair work on electrical equipment (Kraut and Lilis 1990). The workers experienced symptoms including burning/watering eyes, nasal irritation/epistaxis, throat irritation, chest tightness/wheezing/ shortness of breath, coughing (in one case producing blood), nausea/vomiting, fatigue, and headaches. Most symptoms occurred immediately following or up to one week after the exposure event. Some workers' symptoms did not resolve until a month later or (in one case) a year later. No long-term physical effects were observed. Chemical evaluation at the site qualitatively identified the presence of SF_4 [12].

In the U.K, two workers collapsed after entering an SF_6 storage tower (James et al. 1993). One of the workers suffered pulmonary edema for the three days following exposure. No long term effects were reported for either worker. Following the incident, both SF_6 and SO_2F_2 were detected at levels that exceeded occupational exposure limits [12].

In the Netherlands in 1989, an accident was reported involving two people who were exposed to unidentified substances resulting from a switchgear equipment failure (Mauthe and Pettersson 1991). The equipment contained SF_6; upon failure, a small amount of powder was observed (likely solid metal fluorides). Both people recovered within two weeks [12].

A case of serious injury was reported to CIGRE in which an electrician repairing a circuit breaker was exposed to SF_6 decomposition products released by the equipment (Mauthe and Pettersson 1991). The worker lost consciousness and then awakened with a burning sensation in his chest. The worker's lung capacity was reduced by 45 percent. (CIGRE reports that had oxygen been administered more quickly, the damage would have been greatly reduced) [12].

Based upon the above, it is obvious that clean up after a fault requires appropriate personal protective equipment (PPE). It would be prudent if this class of equipment is utilized, that a proactive plan be established that protects workers from hazardous exposure. Several contracting firms are available to deal with such situations and might be considered vs. developing internal expertise in dealing with such conditions.

SF_6 products provide alarm and lockout features when reduced levels of SF_6 pressure are detected. Operators should be prohibited from disabling these safety features.

Since SF_6 is heavier than air, leakage can collect in lower areas and sub-floors of equipment rooms, displacing breathable air. Caution is required to avoid personnel exposure of SF_6 to heat sources, like cigarettes, running engines, heaters, etc, which can result in the decomposition of SF_6 into toxic compounds such as HF gas.

In addition to the personnel safety hazard that arced SF_6 poses, non-arced SF_6 does pose an environmental concern... Although SF_6 is non-toxic and non-ozone depleting, it is the most potent greenhouse gas (GHG) the EPA has ever evaluated [13]. GHGs do not deplete the earth's ozone layer, but they do trap the Earth's heat, contributing to global climate change. With a global warming potential 23,900 times greater than CO_2 and an atmospheric life of 3,200 years, one pound of SF_6 has the same global warming impact as 11 tons of CO_2. For reasons of being environmentally responsible, discharges of SF_6 must be minimized through sound operating practices and specialized equipment. For this reason, the continued "topping off" of SF_6 is not a responsible practice. Leak sources should be identified and repaired quickly. Again, unless this type of equipment is frequently utilized at a facility, contracting a specialized service provider is prudent.

SF_6 circuit breakers and gas insulated equipment have historically been utilized by electric utilities in high-voltage outdoor applications. Due to the quantity of equipment on their systems, utilities have had the opportunity to develop sound operating procedures to deal with the unique aspects of SF_6 equipment. Utilities have embarked upon leak detection of their SF_6 circuit breakers on a routine basis. The outdoor environment also allowed for dissipation of toxic gaseous byproducts after catastrophic failures. Recently, however, indoor versions of this equipment in lower voltage classes have worked their way into non-utility North American markets. Because it is so different from traditional equipment purchased for these industry segments, users need to be aware of the above unique aspects and plan accordingly. Most manufacturers do not proactively provide procedures for dealing with the above issues.

The EPA has published an excellent document, Catalog of Guidelines and Standards for the Handling and Management of Sulfur Hexafluoride (SF_6), surrounding this subject. This catalog lists more than 65 references that address topics related to cautions, guidelines, and standards for the handling and management of SF_6. These provide a wealth of information from which users of this equipment may draw upon to develop their own safety plans.

Oil

Mineral oil is the most widely used dielectric fluid in transformers, load tap changers, oil filled circuit breakers (OCBs), bushings, and cables [5]. Minimum oil circuit breakers utilize high-pressure oil as their arc interruption medium whereas bulk oil circuit breakers additionally utilize oil as their insulating medium. Oil content of bulk OCBs is measured in 1000's of gallons of oil vs. minimum oil circuit breakers, which are measured in gallons [3] [4]. Bulk OCBs are obvious due to their large oil reservoir(s). Depending upon the voltage class, manufacturer, and vintage of the product, OCBs may consist of a single oil tank that houses all three phases, or a separate tank for each phase. OCBs can range from 11kV through 750kV [6].

Leakage of oil during system operation presents potentially hazardous conditions if the insulating liquid is exposed to external arcing conditions or flames. Leak sealing of valves, bushings, flanges, gaskets, drain plugs, etc can be complex repair operations. In addition, many States treat the leakage of oil into the environment as a serious release requiring a complete clean-up process. One incident in the State of New Jersey resulted in hundreds of thousands of dollars of environmental clean up due to the spillage of insulating oil. Another difficulty with this event was that the clean-up process also required the clean up of past oil spillage residue. Spill prevention and counter-spill measures must be in place prior to the handling of any oil.

When decommissioning OCBs, the obvious precaution is elimination of potential for exposure of the oil to open flames. Due to their design, bulk OCBs are visibly obvious, but minimum oil breakers are more discrete in appearance, so review of nameplate information and manufacturer's information should be consulted to verify the class of equipment being decommissioned.

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Another concern beyond its flammability stems from oil that contains polychlorinated biphenyls (PCBs), which are mixtures of synthetic organic chemicals. PCBs' high flash point made it desirable as a dielectric and interrupting material for OCBs, but PCBs may also be found in the hydraulic fluid of other types of vintage circuit breakers that utilized hydraulic operating mechanisms [7].

Effective May 2, 2001 [8], the EPA defines PCB Contaminated Electrical Equipment as: "any electrical equipment including, but not limited to, transformers (including those used in railway locomotives and self-propelled cars), capacitors, circuit breakers, reclosers, voltage regulators, switches (including sectionalizers and motor starters), electromagnets, and cable, that contains PCBs at concentrations of > 50 ppm and < 500 ppm in the contaminating fluid. In the absence of liquids, electrical equipment is PCB-Contaminated if it has PCBs at > 10 μg/100 cm^2 and < 100 μg/100 cm^2 as measured by a standard wipe test of a non-porous surface" [7].

One concern is past maintenance practices of replacing the oil. Original instruction books recommend internal inspections after each fault. If pumps were used for both oil and non-flammable insulating fluids (containing PCBs), then the MV OCB may be internally contaminated with PCBs.

Numerous studies have been conducted that demonstrate a link between PCBs and cancer in humans. Due to this evidence, and the fact that PCBs persist in the environment, US manufacture of commercial mixtures was stopped in 1977 [2]. Equipment containing PCBs should be clearly labeled to warn personnel of its potential hazard. When in doubt, oil from vintage electrical equipment should be assumed to contain PCBs and handled in accordance with the provisions of the Code of Federal Regulations Section 40, Part 761 (40CFR761) [8]. As discussed for asbestos, removal of PCB laden oil requires the services of a certified contractor. Again, it is prudent to verify contractor insurance coverage and certifications before work is performed.

Asbestos

On July 12, 1989, the United States Environmental Protection Agency (EPA) established a ban on new uses of asbestos. Prior to this date, however, asbestos was utilized as an insulating and high temperature sealing material in some switchgear and circuit breakers. The EPA and The International Agency for Research on Cancer (IARC) have determined that asbestos is carcinogenic to humans. The level of asbestos in the air that leads to lung disease depends upon several factors. The most important of these are how long one is exposed, and whether the individual smokes. Smoking and asbestos exposure increase one's chances of getting lung cancer. It is accepted that it is not usually of concern to people exposed to low levels of asbestos [1].

The Occupational Safety and Health Administration has defined workers' permissible exposure to asbestos: "Exposure to airborne asbestos fibers may not exceed 0.1 fibers per cubic centimeter of air (0.1 f/cc) averaged over the 8-hour workday, and 1 fiber per cubic centimeter of air (1.0 f/cc) averaged over a 30 minute work period" [14].

During normal equipment operation, asbestos based insulating materials are not disturbed, thus posing little danger to personnel. Some air-break circuit breakers utilized asbestos in their arc chutes to seal-in the high temperature arc byproducts. Even during normal arc interruption, insignificant amounts of asbestos are potentially dislodged. The periods in which workers would have the opportunity to be exposed to higher than normal levels of asbestos are during cleaning of arc chutes during periodic maintenance or repair, decommissioning of vintage equipment, or after an equipment failure. These situations have the potential for dislodging and spreading much higher levels of asbestos into the air.

The EPA regulates the disposal of waste asbestos materials or products, requiring these to be placed only in approved locations. The EPA's web site contains numerous references to incarcerations and penalties levied against individuals and organizations improperly disposing of asbestos. The most prudent course of action when dealing with asbestos laden insulation materials is to contact a certified asbestos removal contractor. In addition to legally and safely disposing of this material, a certified contractor can also confirm that the atmosphere in the electrical equipment room or maintenance area from which the material was removed is within safe limits.

In a recent upgrade of medium-voltage (MV) switchgear, which involved new MV vacuum replacement circuit breakers and new cubicle wiring, it was found that the control wire insulation contained asbestos. The older circuit breakers were removed intact, wrapped, and shipped for proper disposal. Removal of the asbestos laden wiring required additional tasks. First, the room was monitored for base line or existing asbestos in the air. Second, a sealed enclosure was formed around the existing switchgear with monitors both within the sealed area and external to the switchgear. Trained personnel, properly suited for handling asbestos, then removed the wiring and placed it in sealed containers, all while within the sealed area. The external area was continuously monitored to ensure no leakage of asbestos beyond the sealed area. Following removal of all wiring, trained asbestos personnel cleaned any residual area and follow-up wipe and air samples were obtained to ensure an asbestos-free substation. During this equipment upgrade, contingency plans were in place should electrical circuit breaker switching been required within the sealed enclosure area, since the majority of the equipment line-up remained energized during this modernization.

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The first step in mitigating the potential hazard of asbestos is to survey the electrical equipment on site and record this content for future reference. The original equipment manufacturer can be contacted to verify if any equipment on site manufactured prior to 1989 contains asbestos. If asbestos is found to exist on site, a Material Safety Data Sheet (MSDS) for asbestos should be filed where readily available for future reference. Awareness is the first step towards avoidance of this potential hazard. A reminder on the safety checklist regarding the need to verify if the equipment upon which maintenance will be performed contains asbestos is a recommended practice. It is prudent to verify contractor insurance coverage and certifications before work is performed.

Conclusion

The potential dangers associated with working on energized electrical equipment are well known. Maintenance workers need to be aware of other potential dangers that exist even when equipment is de-energized. Maintenance safety check lists should be followed when performing maintenance on electrical equipment and reviewed to be sure they include checks for toxic materials. Equipment built prior to 1989 should be investigated for the presence of asbestos. Where possible, equipment utilizing oil for dielectric or arc interrupting medium built prior to 1977 should be tested for the presence of PCBs. Where oil sampling is not possible, such products should be assumed to contain PCBs and handled accordingly. Spill containment measures should be in place prior to handling of any oil.

Sites containing circuit breakers and switchgear utilizing SF_6 for insulation or arc interruption should have proactive procedures established to address the safe handling of SF_6 gas and for the handling of toxic materials involved in faulted gas insulated switchgear. Procedures to eliminate the discharge into the atmosphere of SF_6, which is the most highly potent greenhouse gas, should be established to prevent contributions to global climate change.

Finally, there are contractors that specialize in the safe removal and disposal of these hazardous substances. Rather than dealing with these conditions themselves, owners can hire these resources to perform these functions.

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