

SAFETY BY DESIGN: SOLID INSULATED TECHNOLOGIES CHALLENGE THE USE OF SF6 IN MEDIUM-VOLTAGE SWITCHGEAR

Copyright Material IEEE
Paper No. ESW2015-03

David B. Durocher
Senior Member, IEEE
Global Industry Manager
Eaton Corporation
26850 SW Kinsman Road
Wilsonville, OR 97070 USA
davidbdurocher@eaton.com

Lawrence T. Connor
Member, IEEE
Global Application Specialist
Eaton Corporation
1000 Cherrington Parkway
Moon Township, PA 15108 USA
lawrencetconnor@eaton.com

Dr. Mario Haim
Member, IEEE
Director R&D/Portfolio Management
Eaton Corporation
Europalaan 202
Hengelo, Netherlands 7559 SC
mariohaim@eaton.com

Johan de Jong
Member, IEEE
Portfolio Manager, MV Systems
Eaton Corporation
Europalaan 202
Hengelo, Netherlands 7559 SC
johandejong@eaton.com

Abstract - Much information has been disseminated regarding the environmental impact and workplace safety of medium-voltage gas insulated switchgear (GIS) assemblies installed in industrial facilities. This paper will present some of the common myths and “technical documentation” available regarding circuit breakers utilizing Sulfur Hexafluoride (SF6) gas interrupters and switchgear using this gas for insulation. Focus will be on regulatory, operational and total life-cycle costs associated with this technology and safety from the perspective of not just the electrical workplace but the impact of SF6 designs on the business and the impact on the planet. Although SF6 designs have been commercially available and have functioned reliably for the past 30 years, new available technologies have emerged that offer comparable footprints and superior performance without adding the business risk of containment, required safety data sheet documentation and end of life disposal challenges presented by legacy SF6 based designs. A total ownership cost analysis will be presented including estimated purchase cost, operation and maintenance cost, regulatory compliance cost and dismantling-recycling cost of SF6 versus the next generation “safety by design” switchgear offering.

Index Terms — Environmental Impact, Gas Insulated Switchgear (GIS), Sulfur Hexafluoride (SF6), Global Warming, Greenhouse Gases, Air Insulated Switchgear (AIS), Medium Voltage Circuit Breaker, Vacuum Interrupter.

I. INTRODUCTION

Over the course of the past 100 years, medium-voltage switchgear has served as the primary switching and protection platform for virtually every global industry. Designs based on

application of oil design circuit breakers in the early 1900's gave way to air magnetic circuit breaker interrupters and air insulated bus compartments which were popular in the 1950's and 1960's. Later, “new” vacuum circuit breakers became available which, over the course of time, delivered higher interrupting ratings with the advantages of a smaller size and a contained interruption inside a vacuum sealed chamber. Around this same time, SF6 interrupters became commercially available with the advantage of both application at higher voltages and higher interrupting ratings. This natural progression took place as concerns escalated regarding environmental hazards associated with poly-chlorinated biphenyls (PCBs) that were found in insulating oil used in the previous generation of breakers. Many medium-voltage and high-voltage utility systems applied at 66 kilo-volts (kV) and above featured SF6 interruption. Power systems operating at these voltages today are almost exclusively based on SF6 as other switching technologies are generally not available at these ratings within the same dimensions. In addition to SF6 circuit breakers, designs based on SF6 as an insulating medium also became available and are today applied in many types of power systems. Designs of Gas Insulated Switchgear (GIS) offer assembly bus bars that are enclosed in a sealed chamber with the gas serving as an insulator between conductor phases, effectively replacing air.

Industry design and test standards for medium-voltage switchgear and circuit breakers whether they be air insulated, gas insulated, SF6 or vacuum interrupters, tend to conform to one of only two regional standards. In North America, the American National Standards Institute/Institute of Electrical & Electronics Engineers (ANSI/IEEE) Standard C37.20.2 *Standard for Metal-Clad Switchgear* with rated maximum voltage levels from 4.76 kV to 38 kV applies. A companion standard ANSI/IEEE Standard C37.20.7 *Guide for Testing Metal-Enclosed Switchgear Rated Up to 38 kV for Internal*

Arcing Faults defines a more robust design with specific tested ratings to withstand internal arcing faults. Outside of North America, the International Electrotechnical Commission Standard IEC 62271-200 *AC Metal-Enclosed Switchgear and Controlgear* for rated voltages above 1 kV and up to and including 52 kV applies. This standard includes testing of the switchgear assembly based on ratings to withstand internal arcing faults.

Today's industry standards for medium-voltage circuit breakers do not specifically delineate or define the method of arc interruption, so manufacturers are free to select from multiple technologies to suit the needs of their customers. Due to cost and rating requirement, switchgear systems applied at a voltage class of 15 kV and below have generally been based on vacuum interruption technology. System voltages above 15 kV, up to the voltage limitations as defined by the standards, have tended more toward SF6 designs. In recent years, there has been a distinct shift away from SF6 for a host of both technical and commercial reasons which will be described in this paper.

II. TRENDS IN POWER SYSTEMS DESIGN

Several of today's process industries require very high energy intensity. Processes such as aluminum smelters, steel rolling mills and oil refineries require power systems that are both large in scale and designed with a high degree of reliability. Increased source Mega-Volt Amperes (MVA) requirements for industrial power systems are driving systems toward higher distribution voltages to distribute power across a facility. As an example, Fig. 1 shows an abbreviated single line diagram for a planned grassroots nickel mine & smelter facility planned for construction in Central America. Note that a total of 22 MVA of connected loads are shown. This represents only a portion of the total connected 130 MVA electrical load required for this new manufacturing facility. Note also that there is application for only two voltages in the defined medium-voltage systems: one being 34.5 kV, and the other 4.16 kV. In this example, the grassroots facility planned for construction in Central America utilizes a 34.5 kV primary voltage. For ANSI/NEMA markets in North America, test and design standards for this voltage class are typically based on 38 kV. In IEC markets 36 kV voltage class applies and in China, 40.5 kV is the most typical in this nominal voltage.

A significant consideration in this example is that the design voltages selected to deliver power across the entire site represent a fairly high medium-voltage at 34.5 kV. The higher voltage selection results in smaller conductors, less losses and lower costs. Then below 34.5 kV, the next system voltage is 4.16 kV used to service large motor loads. The only other 3-phase system voltage required for this site is a 3-phase low-voltage used for smaller motors and auxiliary loads such as lighting transformers. In the case of this project, the applied low-voltage was 480 Vac.

Traditional power systems for a site such as this might typically include a third medium voltage such as 27 kV, 15 kV or for IEC systems 11 kV. Although a third system voltage may be suitable for smaller electrical systems at perhaps 30 MVA and below, there is a trend toward power systems design based on higher voltages. The same holds true for switchgear interrupting ratings. Assuming the total 130 MVA source for this design was rated at a nominal impedance of

5.75%, the 34.5 kV switchgear interrupting rating would need to be $130 \text{ MVA} / (1.73 \times 34.5 \text{ kV}) / 0.0575 = 37.9 \text{ kA}$. Assuming application of 10 MVA distribution transformers as shown in Fig. 1, the 4.16 kV switchgear interrupting rating would need to be $10 \text{ MVA} / (1.73 \times 4.16 \text{ kV}) / 0.0575 = 24.1 \text{ kA}$. Both are significant interrupting ratings for this class of switchgear.

Historically, SF6 has been applied by utilities in high-voltage systems above 38 kV. Over the course of the past several years, there has been a trend toward application of SF6 based gas insulated switchgear applied in industry. Many designs are now available at 38 kV and down to 5/15 kV class. Because the practical system voltage at the point of service for most industrial facilities is 38 kV and below, the focus of discussion for this paper will be on industrial rather than utility applications of SF6 based switchgear assemblies.

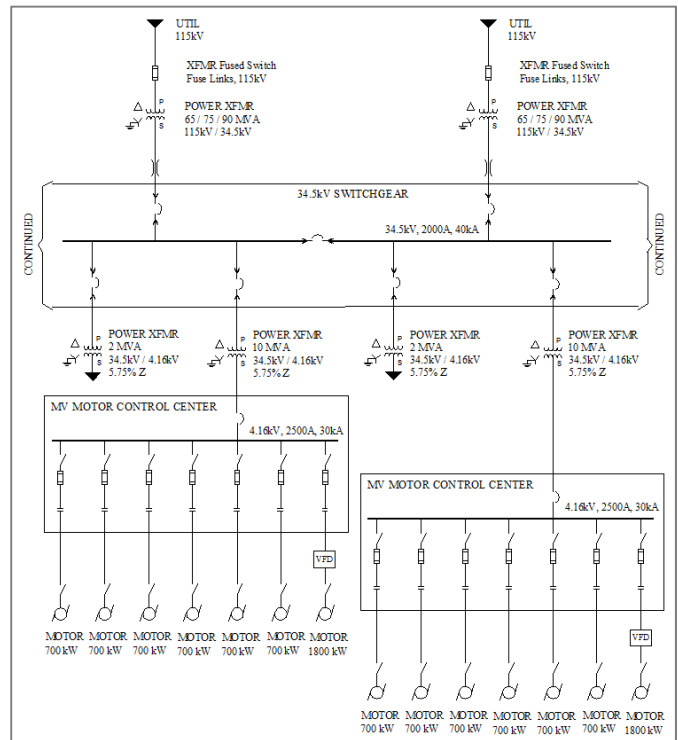


Fig. 1: Typical single-line diagram of grassroots nickel and smelter industrial facility.

III. SF6 – A BRIEF BACKGROUND

SF6 is a colorless, odorless, non-flammable, non-toxic, non-ozone depleting gas. This synthetic compound was originally developed for use as an electrical insulating medium for the power industry [1]. The gas offers excellent insulating and dielectric properties and, as such, the gas has historically been applied in medium voltage and high voltage electrical distribution equipment. SF6 switchgear falls under three categories: closed pressure systems, controlled pressure systems, and hermetically sealed systems. Among these, hermetically sealed systems do not allow maintenance, and manufacturers claim that SF6 leaks are very limited during the equipment's lifetime. However, with all three systems, SF6 is emitted into the atmosphere during various phases of the product's life cycle.

When subjected to electrical discharges, SF6 forms highly toxic and corrosive compounds. Some of the prominent byproducts and their toxicity levels include:

- Sulfur tetrafluoride (SF4) >>> Highly toxic
- Sulfur pentafluoride (SF5) >>> Toxic, but not hazardous
- Sulfur dioxide (SO2) >>> Highly Toxic
- Hydrofluoric acid (HF) >>> Hazardous and toxic

SF6 has been applied in various end uses such as arc furnaces, window insulations, car tires and sports shoes. Global regulators in select countries have banned use of the gas for application in several of these products, however today's medium and high-voltage switchgear systems continue to use the gas, effectively claiming there is no alternative suitable technology offering similar performance. On average, the electrical industry uses nearly 80% of the SF6 produced globally. Most of these applications are in utility systems at voltage ratings 38 kV and above.

IV. ARE THERE ADVANTAGES TO SF6?

Yes! Most certainly, SF6 designed switchgear, whether it is air insulated utilizing SF6 breakers or gas insulated switchgear (GIS) offers user advantages. Specifically focusing in GIS designs, a few of the most notable advantages include the following:

A. Sealed Enclosures

The fact that GIS switchgear assemblies offer a sealed enclosure design delivers several notable advantages. From the perspective of protecting the assembly from the external environment, issues such as contaminants, dust and moisture cannot penetrate the sealed gas enclosure so by definition, the design offers a high degree of operational reliability. Also because the assembly is sealed, exposure of operators to energized conductors and avoiding possible human error events such as a dropped tool causing a potential arc flash incident are eliminated. Sealed GIS enclosures function completely independently from their installed environment. This makes the design well suited for installations in many different climates.

B. Overall Size/Footprint

Because SF6 offers better insulating properties than air, GIS assemblies are typically designed with less phase conductor spacing than their AIS counterparts. The end result is the overall form factor for GIS assemblies that historically have been much smaller. Considering the overall cost of installation including design of smaller electrical rooms, GIS tends to offer an advantage. Consider the example of a Greenfield industrial manufacturing facility, for instance a new copper mine in South America. In the case of this type of project, often there is little or no local available skilled labor to construct brick and mortar buildings. So, a popular construction alternative is to install an integrated power assembly or electrical e-House. This building, containing both medium-voltage and low-voltage power distribution and control assemblies, is constructed at the e-House manufacturer's factory and then transported to the site. This approach allows the complete electrical system to be assembled, wired and tested at the factory prior to shipping it

to the jobsite. Because of the shortage of skilled labor at the site, overall cycle time prior to first production can often be reduced using the e-House approach. Fig. 2, image a. shows the plan view of a typical e-House that includes indoor 38 kV medium-voltage AIS switchgear, feeding an outdoor transformer which in turn distributes 4.16 kV power to indoor motor control centers. Careful study of the plan view reveals two structures of 38 kV metal-clad switchgear near the stairway at the right, with the motor control filling the balance of the e-House. Fig. 2 image b. is a photo of the actual installed e-House included in the plan view drawing above. Note the outdoor transformer in the foreground and also an external duct extending from side wall of the e-House. The external duct extends from the top of the 38 kV switchgear enclosure as this is an arc-resistant assembly.

Assume the project design engineer considered 38 kV arc resistant GIS switchgear for these two structures and was interested in comparing this approach to traditional AIS switchgear. Using typical per section width and depth dimensions of 600mm X 1500mm (24 inches X 60 inches) for GIS versus 1060mm X 3250mm (42 inches X 128 inches) for AIS yields a total GIS footprint for both structures of 3.6 m² (20 ft²) for GIS versus 13.78 m² (74.7 ft²) for AIS. Using an estimate cost of US \$350/ft² for the e-House, the additional required space for the AIS would cost (74.7 ft² X \$350/ft²) – (20 ft² X \$350/ft²) = (\$26,133 - \$7,000) = \$19,133; a significant cost difference. If the AIS assembly required rear access due to a typically designed rear cable compartment, the entire assembly would be mounted 900mm (36 inches) away from the wall, requiring an added 21 ft² or \$7,350 of added e-House cost. Many system designs requiring rear cable switchgear assess for e-House construction will include removable or hinged covers along the outside wall so the cable compartments of the switchgear can be accessed from outside the enclosure on a walkway while the assembly is mounted with its rear facing the exterior wall. This is as shown in Fig. 2, image c.

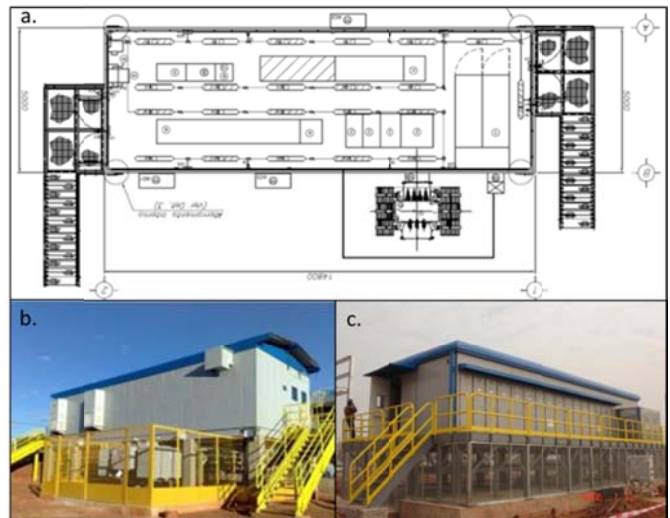


Fig. 2: Typical e-House construction favors 38 kV switchgear with smaller overall dimensions: a. Plan view of typical e-House. b. Actual installed e-House of layout shown in image a., and c. Using the outside wall of a typical e-House to serve as cable access allows the assembly to be mounted against the wall.

C. Application at High Altitudes

One unique advantage to GIS switchgear is the dielectric properties of the assembly. As discussed previously, SF6 has excellent insulating properties far superior to air. So, using SF6 as the insulating medium versus air requires these assemblies to be sealed from the atmosphere, thus able to function at high altitudes without any de-rating factor. Some applications require switchgear to be installed at very high elevations. In this instance, GIS designs with main bus systems sealed in a gas filled chamber offer an advantage over air insulated switchgear designs with a similar rating. Since air insulated switchgear is dependent on air as an insulator between energized phases and ground, higher elevations where air insulating properties are lower will require the switchgear be de-rated. So for instance, a project that specified 15 kV, 3000 A switchgear rated at 95 kV basic impulse level (BIL) withstand testing, planned for installation at a mine site in Chile at 3500 meters above sea level, would require that a de-rating factor be applied. Most switchgear manufacturers will publish a de-rating table similar to the one shown in Fig. 3. In this example, the 95kV BIL voltage rating would be the most significant factor to consider. At 3500 meters above sea level, the effective BIL of the 95 kV tested assembly would be $95 \text{ kV} \times 0.76 = 72.2 \text{ kV BIL}$. In order to achieve the 95 kV rating, most manufacturers of air insulated switchgear would offer the next higher voltage class switchgear, in this case a 27 kV assembly rated at 125 kV BIL, which would result in an effective rating of $125 \text{ kV} \times 0.76 = 95 \text{ kV BIL}$. Of course the 27 kV air insulated assembly will be much larger and at a higher cost than the comparable 15 kV class 95 kV BIL GIS switchgear assembly which effectively requires no correction factor for altitude.

		Altitude		De-rating	
		Meters	Feet	V	I
MV SWGR	1000	3,281	1.00	1.00	
	1250	4,101	0.98	1.00	
	1500	4,921	0.95	0.99	
	2250	7,382	0.88	0.98	
	3000	9,843	0.80	0.96	
	3500	11,483	0.76	0.95	
	4000	13,123	0.72	0.94	
	5000	16,404	0.65	0.92	

Fig. 3: Altitude correction factor for air insulated switchgear applied at high elevations. Table 8, IEEE/ANSI C37.20.2.

V. ARE THERE RISKS IN THE USE OF SF6?

Yes, there are additional costs and inherent risks to users who own, operate and maintain switchgear utilizing SF6 gas. Some published papers presented at recent conferences focused on electrical workplace safety [2] have included risks associated with SF6 in the same discussion with previously banned insulating media including asbestos and polychlorinated biphenyls (PCBs). Several of the largest global manufacturers of switchgear containing SF6 have publically stated their desire to make SF6-free product available wherever feasible. A few have refused to market or

sell switchgear containing SF6 as a matter of company policy. A few of the most notable disadvantages to use of the gas applied in switchgear include the following:

A. Environmental Impact

Perhaps the most significant drawback of SF6 is the Greenhouse Gas impact. The gas is non-toxic and non-ozone depleting, but GHGs do trap the Earth's heat, contributing to global climate change. With a global warming potential 23,900 times greater than CO2 and an atmospheric life of 3,200 years, one kg of SF6 has the same global warming impact as 24.2 tons of CO2. Environmental discharges of SF6 must be minimized and "topping off" of SF6 is not considered a responsible practice. Leak sources must be identified and quickly remedied.

B. Consequences of Gas Leaks

Most medium-voltage GIS designs use SF6 for this bus insulation system with energized phase conductors encased in sealed and pressurized gas-filled compartments. As described in previous sections, although the gas is non-toxic in its pure state, a system failure during an electrical discharge causes the potential release of arced SF6 and a multitude of toxic chemicals. Specially trained workers and hazardous material suits are required in these conditions. SF6 can also be released when GIS is being dismantled and removed from service. Another consequence of gas leaks is compromise of the insulation system. In the absence of the proper amount of SF6, air leaking in to the sealed compartments can result in dielectric strength dropping to close to that of air. Since the shorter clearance and creeping distances are designed for an SF6 gas environment, risk of flashover and failure become a concern. Moisture is also a concern in a potential toxic discharge. GIS designs use desiccates to absorb moisture but these have a limited capacity. Because of these risks, GIS assemblies typically include gas and moisture monitoring devices and associated alarms to warn operators of possible breach in sealed compartments.

C. Application in Underground or Low Ventilation Areas

One often overlooked fact regarding SF6 is that the gas is colorless, odorless and heavier than air. Because the gas excludes oxygen, use of the gas in underground or areas of low ventilation can cause a significant danger. Adding the fact that the gas is toxic in decomposition increases the risk in these applications. Surprisingly, SF6 breakers and GIS are frequently installed in these environments including underground mines, poorly ventilated basements and equipment rooms, cellars and traffic tunnels where there is no means for the gas to escape. For mine sites in the USA regulated by the Federal Government's Mining Safety & Health Administration (MSHA), there are regulations requiring properly trained persons when operators are called upon to interact with SF6 gas, but there are no regulations banning its use in underground mine sites. For many designs of GIS switchgear, cable vaults below the enclosure are required.

D. Recording Requirements

There are strict regulations that require reporting detailed information to local authorities as to the amount, location,

maintenance activities, etc. associated with all SF6 site sources. Because of the growing concern regarding emissions and controls, many global regulators have stepped in to address environmental concerns.

1) *European Union:* The European Union (EU) has initiated measures to minimize the emission of fluorinated greenhouse gases (F-gases) within the framework of the climate protection policy. These measures are stipulated in EC Regulation No. 842/2006 and in other detailed supplementary regulations. In the regulation, certain fluorinated greenhouse gas (SF6) applications in electrical equipment at voltages above 1000 V are defined based on Recovery of SF6 in the course of decommissioning and in major maintenance activities. Training and certification of personnel along with reporting and labeling requirements are also clearly defined. The updated EU F-gas regulation published in 2014 does not ban the use of SF6, but it does contain two key elements a) Much tighter controls on the use, recording of installation and disposal of SF6 and b) The inclusion of a clause which asks member states to put in place plans for MV secondary switchgear systems without SF6.

2) *United States of America:* SF6 Emissions from the US Utility industry in 2007 was equivalent to 12.6 million metric tons of CO2, the equivalent of 2.4 million cars. Beginning in 2002, the U.S. Environmental Protection Agency (EPA) established a voluntary program in which partner companies agreed to reduce SF6 emissions through technically and economically feasible actions [3]. The EPA program report states: "SF6 is a potent and persistent greenhouse gas, with a global warming potential approximately 24,000 times greater than carbon dioxide over a 100-year time horizon and a residency in the atmosphere of more than 3,000 years." Because of these known concerns, electric utilities across the globe that use equipment containing SF6 gas have been forced to adhere to strict environmental procedures controlling its use. Some of these include:

- Tracking and recording maintenance activities of all equipment that uses SF6 gas
- Minimizing on-site storage of SF6 used to support maintenance of existing equipment
- Assuring that a robust program is in place to remove and destroy all SF6 prior to decommissioning at the end of equipment life
- Identify and repair leaks from operating equipment immediately upon detection
- Have a written and approved hazardous material handling/cleanup process in the event of an SF6 leak
- Minimize the release of SF6 gas into the atmosphere

Although the EPA has to date not issued Federal legislation curtailing the use of SF6, implied in the voluntary program is that if this approach is not successful, legislation may be required to restrict the use of SF6.

The US State of California, often considered a bell weather leader in driving environmental and sustainability regulations, initiated a June 2007 regulation "Sulfur Hexafluoride (SF6) Emission Reductions from Gas Insulated Switchgear" as part

of the California Global Warming Solutions Act of 2006. This regulation, designed to reduce SF6 Emissions in the State by 70% by the year 2020. This regulation defines Maximum Annual SF6 Emission Rates, Measurement, Recordkeeping, Annual Reporting and Enforcement/Assessed Penalties for violators. 80% of California's SF6 emissions result from leakage and handling losses from GIS [4].

3) *Australia:* Under the current Carbon Tax legislation in Australia, utility users typically are obliged to pay UPFRONT for 100% SF6 contained in their gas insulated switchgear installed and operational at their facilities. Additional carbon tax costs can add up quickly, typically around US \$500/kg for SF6 (as opposed to US \$25/ton for CO2). By consensus, major utility companies such as Energex and Ausgrid in Australia are paying carbon tax penalties that can add about 40%-80% to the price of GIS in Australia. And since electricity utilities employ significant GIS (zone substations and transmission assets at 36 kV and above), this carbon tax has resulted in the unintended consequence of almost doubling electricity costs. Although SF6 emissions are not specifically regulated in Australia, this issue has been blamed as the likely cause for closure of a number of energy-intense industrial facilities in the country such as aluminum smelters and steel rolling mills.

E. Product Stewardship and Contracts

To further complicate the matter, global manufacturers of medium-voltage switchgear are now seeing increased exposure to product stewardship requirements as a part of new equipment purchase contracts. Product stewardship is loosely defined as an element of Environmental, Health and Safety (EHS) which includes a product centered approach to environmental protection focusing on reducing the environmental impacts of products from cradle to grave. Regional environmental standards such as The European Union's Registration, Evaluation, Authorization and Restriction of Chemical Substances (REACH) and the Waste Electrical and Electronic Equipment (WEEE) Directive, serve as platforms to dictate that all product manufacturers maintain a culture of environmental responsibility. Consider the sample of product stewardship focused contract language below:

"Seller shall comply with European Union REACH (Chemical Content) restrictions and Buyers EHS corporate policy with respect to **the products, including all components and subcomponents thereof**. Seller must provide Buyer with a list of all substances and their concentrations within 15 days of contract award. If Seller fails to comply, such failure warrants **Termination for Default** and Buyer may recover **all damages**, including losses from any **business interruption** of Buyer's operation."

With draconian remedies such as those stated above, every global switchgear manufacturer will surely want to limit the scope of their obligation to environmental regulations. One sure way to accomplish this is to refrain from designing products that use toxic or greenhouse gasses such as SF6. Most industry standards today exclude restrictions in use of SF6 gas for high-voltage switchgear, but these standards are constantly changing.

VI. MYTHS VERSUS FACTS REGARDING SF6

Over the course of the past 30 years, designers have been constantly challenged to defend technologies such as air insulated switchgear and vacuum interrupters versus SF6. Without debating over which supplier offers the superior technology, it seems important at this point to address and correct some common misconceptions regarding SF6 interrupters and switchgear applied in power distribution systems:

A. SF6 insulated switchgear assemblies are factory sealed and there is no leakage.

Most certainly SF6 offers superior dielectric and heat transfer properties compared to air and vacuum. It also has a demonstrated ability to “self-heal” or regenerate after an arc interruption. The integrity of the insulation system is completely reliant on no gas entering or exiting the sealed system. Over the course of time, it is an irrefutable fact that all sealed systems will deteriorate. In the case of SF6 during system interruption, leaks can be particularly problematic as the arced gas escaping into the open air is toxic and also outside air/moisture entering the chamber can compromise the insulation system and potentially cause catastrophic failure. In the end, all GIS manufacturers will include pressure and moisture indicators with any version of their commercial SF6 based products – there is most assuredly a reason for this.

B. Maintenance costs for GIS assemblies with SF6 are lower than their AIS counterparts.

The sealed gas system has historically been smaller, lighter and has less accessible parts. So, typical activities for AIS such as thermal scanning, bus and insulator inspection will likely be more extensive. However, the breaker mechanisms for GIS are routinely more complex than vacuum with up to 30% more parts, resulting in this being a more frequent maintenance item that requires attention. Also, be sure to account for all additional costs to maintain SF6 itself – they add up. Most utilities with extensive SF6 based assets have a



Fig. 4: Image of a standard gas cart used for inspection and repair of SF6 utility assets.

specialized gas cart, as shown in Fig. 4, which is used to open units for inspection and repair without venting SF6 to the atmosphere along with recharging and cleaning gas in older units. A hygrometer (moisture detection) is standard equipment along with a halogen leak detector and gas sampling equipment. SF6 is inventoried at an added cost and location/use of all SF6 is required to be reported to local authorities on a frequent basis in most countries. Finally, there are end of life disposal costs. Preferred disposal is by burning the gas in a kiln at temperatures about 1000°C. This causes thermal dissociation of the SF6 to form sulphur oxides (SOX) and fluoric acid, which then react with lime to form naturally occurring raw materials gypsum and fluorspar. Recycling and reuse of SF6 is also an economically viable option.

C. GIS offers an Environmental Impact Superior to AIS.

It is disappointing in the global technical community that “facts” such as this are considered the truth. One fairly recent technical article [5] claims that GIS is clearly superior to AIS in several important environmental performance areas including Primary Energy Demand, Global Warming Potential, Acidification Potential and Nutrifaction Potential. Some of these assertions included in this technical journal can also be found at <http://electrical-engineering-portal.com/gis-vs-ais-life-cycle-assessment>. Although this sounds wonderful and the results are supported by research, a little further digging traces the source of this research back to a similar study by one of the world’s leading manufacturers of SF6. In reading through the description of the research approach used to support these claims, we see an example of a 40 square kilometer city of 130,000 inhabitants was assumed, requiring a 120 MW peak load with annual energy consumption of 400 Giga-watt hours. Designing this make-believe system using SF6 with GIS resulted in a 37% energy consumption reduction, 86% required area reduction, 21% greenhouse gas reduction and even greater reductions in acidification and nutrifaction potential. The major reasons for the reduced environmental impact was because the GIS switchgear required less material and energy to produce, plus the compact designs allowed for 110 kV transformer substations to be built directly at the downtown city loadcenters. Conversely, the AIS power distribution system design required additional substations and transmission voltages, resulting in added cable costs, losses, distribution systems, etc.: overall, a testimony to ingenuity in creating a scenario where the desired outcome is predetermined, then research to support the outcome can be irrefutably proved.

VII. ALTERNATIVES TO SF6 AND GAS INSULATED SWITCHGEAR

Although some switchgear manufacturers have elected to downplay the environmental and other hazards in applying SF6 in medium-voltage switchgear, in truth, all manufactures realize the need to move away from this substance for both medium and high-voltage switchgear applications as soon as practical. In this section, we will review two alternatives including other emerging options in synthetic gas and a new design in development that offers similar advantages of SF6 in terms of dielectric strength, but based on application of an air insulated platform.

A. Next Generation of Synthetic Gases

Alternative solutions to SF6 have been researched for many years. Scientists have worked to identify alternative synthetic gasses with similar quenching properties and dielectric insulating strength, but without the negative environmental and toxicity impacts should the SF6 gas leak into the atmosphere. Some of the most promising alternatives researched have been fluorinated compounds such as Fluoroketones with the generic formula of $C_nF_{2n}O$. A variation of this fluorinated compound has been used in fire extinguishers for the past several years. These compounds show promise with a dielectric strength 1.7 times higher than SF6 and a very low environmental impact in terms of GWP. One discovered drawback is the compound high boiling point temperature, making the gas liquid under natural conditions. To offset this, the compound cannot be used in its pure form but instead must be diluted into another buffer gas which is used as an additive under low pressure. Testing using the buffer CO2 in a gas mixture has shown good dielectric performance, low toxicity and reduced GWP. Although there is no product currently commercialized, research as outlined in [6] shows these alternate synthetic gas mixtures could one day be a viable SF6 alternative.

Recently, one switchgear manufacturer announced a significant breakthrough in developing an “eco-efficient insulation gas” that will replace SF6. The announcement referred to the “new gas mixture” as one that has the potential to lower carbon dioxide equivalent emissions by up to 50% as compared to similarly rated equipment using SF6 gas through the product life cycle. This new mixture is reportedly being tested at a utility site in Europe. Long term behavior of alternative gases remains a question. The reason why some gases have a lower CO2 equivalent than SF6 is because they decompose under UV radiation and don’t remain in the environment for thousands of years. The main question now is “how does this impact the environmental life of these new gases and how are they impacted by potential partial discharges”, which by definition creates UV radiation.

B. New Technology Offering A Path Forward

It has been well understood for many years that solid insulation, the method of covering live parts that present steep electrical gradients in epoxy resin, reduces the field and improves dielectric strength. Historically the problem with this approach has been it requires a significant increase in the volume of the switchgear, rendering the assembly non space or cost competitive versus SF6 GIS designs. One emerging new solid insulation approach looks to offer perhaps the most promising alternative to gas insulated switchgear without the historic size and cost compromises of legacy air insulated designs.

Fig. 5 shows a side elevation view of a commercially available assembly based on the solid insulation design concept. The switchgear panel shown is internal arc classified and tested to the IEC62271-200 Standard with ratings to 24 kV and 25 kA. The panel is remarkably compact, only measuring 2100mm high X 500mm wide X 1440mm deep for 630/800/1250 ampere circuit breakers and 2100mm high X 1000mm wide X 1440mm deep for 1600/2000 ampere circuit breakers. The solid insulation design uses epoxy insulation to encapsulate the live parts including the main bus bars and

circuit breaker vacuum interrupter. Fig. 6 shows a design concept for a similar solid insulation design rated at 38 kV with bus capacity of 1250/2500A and initial interrupting capacity of 25 kA with future design capacity to 40 kA.

The concept offering is only 600mm/800mm wide (1250A/2500 ampere circuit breakers) X 2150mm high X 1700mm deep. Again because of the solid insulation design, the assembly is 40 to 60% smaller than traditional air insulated switchgear. The installed footprint is essentially

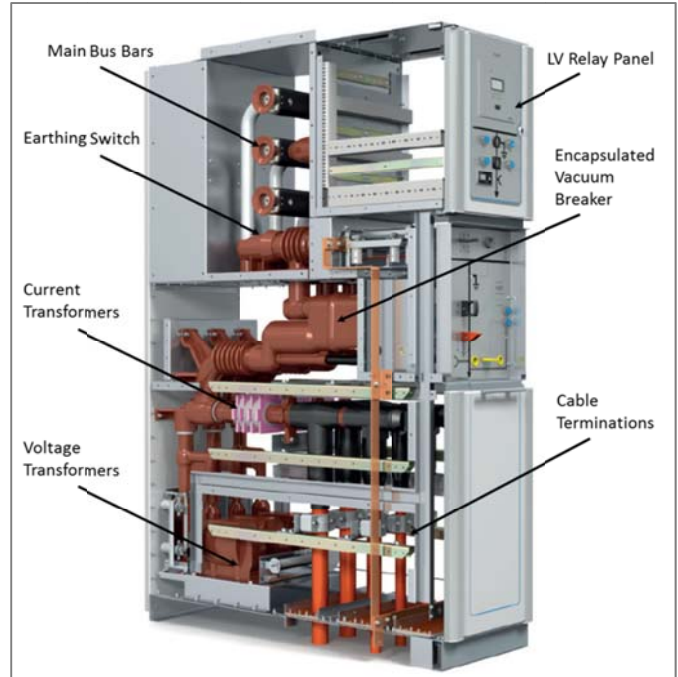


Fig. 5: Side view of single panel (structure) of solid insulated switchgear. Vacuum breaker is a fixed design.



Fig. 6: Front view of four panels (structures) of the new solid insulated switchgear design.

equal to existing commercially available GIS designs employing SF6 gas insulation and circuit interruption. Circuit interruption for all designs would utilize a solid epoxy insulated vacuum interrupter. The vacuum breaker element would be withdrawable from the front and, similar to existing air insulated switchgear designs, would offer three position operation (connected-test-disconnected).

VIII. LIFE-CYCLE COST COMPARISON

A total cost of ownership model comparing a 5-section line-up of the solid insulated switchgear concept offering versus a similarly equipped SF6 gas insulated switchgear line-up for a typical 38 kV installation is shown in Table 1. To avoid the commercial implications of a financial comparison, life-cycle cost of the two alternatives is shown using a first purchase price of each design at an equal amount of 100 units. Then from this first cost, an estimated range for the additional total owning cost elements including installation, maintenance & repair, decommissioning and ultimate removal/recycling is also shown in units, effectively a percent of the first cost. Installation costs of the two alternatives would be similar. The cost range shown for installation includes only setting the switchgear on prepared pad, making all line, load and control terminations and performing appropriate tests prior to commissioning. Switchgear maintenance consisting of breaker and relay testing, checking for mechanical wear, lubrication, etc. is assumed to be performed every 2 years over a 30-year product life. Maintenance costs for the SF6 design is shown to be marginally higher, the difference attributable to additional equipment required for inspection and repair as outlined in a previous section of this paper. Costs for leak detection services every 5-years and also annual recording and reporting of SF6 on-site as required by the in-country government officials are also itemized. These added ownership costs are applicable only to the SF6 switchgear design as these costs would be zero for the solid insulated switchgear.

TABLE 1
TOTAL OWNERSHIP COST: SOLID INSULATED SWITCHGEAR VS SF6 GIS SWITCHGEAR

	5-sections, 2000 A, 38 kV Solid Insulated Switchgear	5-sections, 2000 A, 38 kV SF6 Gas Insulated Switchgear
Initial purchase price	100.0	100.0
Switchgear installation	13.0-17.0	13.0-17.0
Biennial electrical maintenance (30 year life)	37.0-43.0 (X 15)	42.0-48.0 (X 15)
SF6 leak detection services (every 5 years)	0.0 (X 6)	27.0-33.0 (X 6)
SF6 Annual reporting (30 year life)	0.0	10.0-14.0 (X 30)
End of service site removal	7.0-9.0	8.0-10.0
End of life dismantling/ recycling (including positive scrap value)	4.0-5.0	6.0-9.0
TOTALS	161.0-174.0	206.0-231.0

Finally, the cost to remove the switchgear from active service at the end of useful life along with the cost to dismantle and recycle the switchgear is shown. These

components of total cost are often overlooked by switchgear owners in industry. The estimated costs are shown to be marginally higher for the SF6 design, accounting only for handling of the gas during removal. However, disposal of SF6 which has been subjected to arcing during service such as an arc within an SF6 interrupter or an arcing ground fault, would have a significant impact on end of life recycling costs. To adequately protect the environment, proper decontamination processes would need to be performed prior to disposal. Conversely, the epoxy based solid insulation system does not deteriorate over time and the material can be separated and ground for use as fill or future insulation molding.

Using the assumption that the first cost and installation cost of the two alternatives are the same, the total ownership cost over a 30 year life is shown at a range between 161.0 to 174.0 units for solid insulated switchgear versus 206.0 to 231.0 units for a comparable SF6 GIS design – a lifetime incremental cost for GIS ranging from 18% to 43% higher. Most certainly, the incremental cost components shown in Table 1 are subject to many variables and there are some scenarios where cost components could be higher for the solid insulated system than the SF6 gas insulated counterpart assembly. Regardless of discussions around particular discrepancies, it seems clear that given a common switchgear assembly footprint and installation cost, dealing with the added costs and risks associated with switchgear designed and assembled based on SF6 would burden the owner with higher overall ownership costs in several measurable areas.

IX. CONCLUSIONS

Over the course of the past 50 years, many manufacturers of medium-voltage switchgear rated up to 38 kV have elected to design and market their products based on SF6. The advantages of a smaller foot print and lower cost have been the most significant driver for this choice. Although there are some economic advantages, the overwhelming science has proved there is also significant potential risk and cost in operating and eventually dismantling SF6 designs at the end of useful life. New awareness and regulations focused on greenhouse gasses have squarely focused on reducing or eliminating use of SF6, putting significant pressure on manufacturers that offer these designs. SF6 producers have responded with marketing campaigns that describe the gas as “earth friendly”, irrefutably it is not. Over the long term, the authors see SF6 going the way of another insulating media historically used in power transformers, polychlorinated biphenyls (PCBs). Use of this substance has been banned since 1977 and the cost of removal by certified contractors has been a significant burden on industry. In addition to the total cost of ownership for the users of SF6 switchgear, product stewardship contract language is potentially transferring new risks to the manufacturers. In the end, historic selection of SF6 based product technology based on the lower installed cost will likely become too costly to produce or support.

It is clear that alternatives for this insulating media should be considered. Some recent progress in discovery of a replacement gas for SF6 appears to be moving in the right direction. Early results indicate that replacement gasses for SF6 could serve as a possible alternative, however increased business risks including impact on the environment must be

considered. Thus far, none have been proven to be completely safe and without risk. New developments in solid insulation systems look like another path forward. Some manufacturers have both commercially available and concept designs with a much smaller footprint. Availability at a similar first cost delivers a functional equivalent coupled with the peace of mind that there are no gasses with which to contend. These “gas-free” designs may indeed be the best choice when considering total cost of ownership for the industrial user.

X. REFERENCES

- [1] SF6 Gas Condition Assessment and Decontamination – Technical Report, Electric Power Research Institute, Palo Alto, California, June 2000.
- [2] R. Yanniello, G. Paoletti “Safety and Environmental Evaluation Of Insulating Media In Medium-Voltage Distribution Equipment”, IEEE IAS ESW, 2008.
- [3] Management and Safe Handling Procedures for Sulfur Hexafluoride (SF6) Gas, Facilities Instructions, Standards & Techniques, United States Department of the Interior Bureau of Reclamation, March 2004
- [4] Sulfur Hexafluoride (SF6) Emission Reductions from Gas Insulated Switchgear, California Environmental Protection Agency Air Resources Board Website. Final Regulation Order: <http://www.arb.ca.gov/cc/sf6elec/sf6elec.htm>
- [5] R. Nagarsheth, S. Singh “Study of Gas Insulated Substation and its Comparison with Air Insulated Substation”, Electrical Power and Energy Systems, 55 (2014) 481-485
- [6] Y. Kieffel, A Girodet, F. Biquez, Ph. Ponchon, J. Owens, M. Costello, M. Bulinski, R. Van San, K. Werner “SF6 Alternative Development for High Voltage Switchgears”, D1-305, CIGRE 2014
- [7] IEC62271-4 “Certification of SF6 Gas Handling on all Electrical Power Equipment, 2014
- [8] IEC60480 “Guidelines for the checking and treatment of sulfur hexafluoride (SF6) taken from electrical equipment and specification for its re-use”, 2004

XI. VITA

David B. Durocher is Global Mining & Minerals Processing Industry Director for Eaton’s Electrical Business. He has over 35 years of experience with Westinghouse and Eaton serving in a variety of product engineering, sales and global marketing roles, authoring numerous technical papers that have been presented at conferences around the world and published in IEEE Industry Applications, Plant Engineering and EC&M Magazine. Dave is a Senior Member IEEE and presently serves as a member of the IEEE IAS Mining Industry Committee, Cement Industry Committee, Pulp & Paper Industry Committee and as President-Elect of the IEEE Industry Applications Society.

Lawrence T. Connor is a Senior Application Engineer at Eaton for Utility and Nuclear applications. He has over 36 years of experience with Eaton Corporation and Westinghouse Electric Corporation in various Engineering and Management assignments with a primary focus on medium voltage switchgear, circuit breakers, and vacuum Interrupters. Larry graduated from Penn State University in 1977 with a BS in Electrical Engineering and is an active member of the IEEE and the Power & Energy Society.

Dr. Mario Haim is Director R&D and Portfolio Management at Eaton for Electrical solutions and services. He has several years of experience with Eaton Corporation and other Energy and Power Management companies in various Engineering Management assignments with a primary focus on medium and low voltage switchgear, circuit breakers, and switching technologies. Mario graduated from University of Bundeswehr Munich in 2003 with a M.Sc. in Electrical Engineering and a Ph.D. in High Voltage in 2013.

Johan de Jong is Portfolio Manager, MV Systems at Eaton for Electrical solutions and services. He has over 27 years of experience with Eaton Corporation and Holec in various Engineering and Management assignments with a primary focus on medium voltage switchgear, circuit breakers, vacuum interrupters and testing. Johan graduated from Leeuwarden University in 1987 with a BS in Electrical Engineering and is an IEC member of MT29 maintaining IEC 62271-202 High-voltage/low-voltage prefabricated substations.