ENVIRONMENTAL AND SAFETY ASPECTS OF AIRPLUS INSULATED GIS

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ABSTRACT

New insulation gases as alternatives to SF_6 have been presented in the last years [2,3,4,5]. The main focus has been on technical performance and reduced global warming potential (GWP) compared to SF_6 GIS. Another very important aspect for customers is the environmental impact and safety in all operational situations, as well as during leaks or even internal arc failures. This paper introduces a solution using AirPlus™ as an insulation gas mixture, with results of comparison tests to SF_6 GIS and air-insulated switchgear (AIS).

INTRODUCTION

In the last few years, researchers have presented alternative insulation gases for medium-voltage (MV) gas-insulated switchgear (GIS). The insulation gas mixture AirPlus, a mixture of C5 fluoroketone and air, was recently introduced by ABB in pilot installations and initial products have been launched on the market. Actual switchgear design requires modifications and design changes to compensate for the lower dielectric and thermal performance of the gas mixture compared with SF_6. With these changes, switchgear using this gas mixture can serve as an alternative for a wide range of applications.

The main motivation for the development and introduction of the new insulation gas was a reduction in its GWP. This target was reached with a reduction from 23,500, the GWP of SF_6, to <1, that of AirPlus. For a complete picture, the overall lifecycle of GIS using this gas mixture is of interest with regard to environmental impact and safety during normal operation and in case of failures.
These aspects are of great importance to the operator of the switchgear when it comes to the techno-economic analysis and assessment of the compound environmental benefits brought about by choosing the new insulation gas mixture over SF_6. Currently, only limited information is available for the customer, which makes a decision in favor of the new technology difficult.

This paper addresses this issue and demonstrates that, in the context of environmental impact and safety, AirPlus GIS outperforms SF_6 GIS. Even in the unlikely event of an internal arc fault, the released gases and powders are less harmful than those generated in SF_6 GIS, and they are comparable in toxicity to those created in AIS equipment that uses pure air as insulation gas.

DETAILS OF AIRPLUS AS INSULATION GAS

AirPlus is a mixture of C5 fluoroketone ($C_5F_{10}O$) and air. Air itself is a mainly a mixture of oxygen (O_2) and nitrogen (N_2). For synthetic air the ratio is 20% O_2 and 80% N_2. Different mixtures of the components are required depending on the minimum required operating temperature for the equipment containing the gas mixture. To allow the gas mixture and the mixing ratio to be easily identified, we developed a brief nomenclature. The structure is:

AirPlus T/p

Where T is the condensation temperature in °C of the C5 fluoroketone (at the selected partial pressure) and p is the total absolute pressure in kPa of the gas mixture at 20°C.
AirPlus -15/130 describes a mixture at a total pressure of 130 kPa with a condensation temperature of C5 at -15°C. It´s composition is 13,6% C5 and 86,4% dry air. This is a gas mixture used in medium voltage primary GIS. For secondary GIS (ring main units) the rated operating temperature is lower and a mixture of AirPlus -25/140 is used, representing 7,5% C5 and 92,5% dry air. Other mixtures are possible and can be identified easily using this rule.
With the knowledge of the vapor curve of C5, the percentage of C5 in the gas mixture can be calculated easily.

ENVIRONMENTAL IMPACT

The environmental impact of a chemical substance covers a wide range of its interaction with its surroundings. Until now, the main focus for alternative insulation gases has been on global warming potential (GWP). Pure C5 fluoroketone has a GWP<1, and the GWP of AirPlus mixtures can be calculated according the formula given in F-gas regulation [1], reaching values down to <0.6. As with other compounds that contain no halogen other than fluorine, the ozone depletion potential (ODP) is zero. In addition, we determined that the atmospheric degradation of fluoroketones do not lead to the generation of long chain acids that are of environmental concern [6].
For liquid fluoroketone, care must be taken to prevent its discharge into water. However, this is not a relevant hazard when using the new gas mixture in switchgear, since the fluoroketone is gaseous under all normal working conditions.

SAFETY HAZARD DURING NORMAL OPERATION

Under normal working conditions of GIS filled with AirPlus, the gas is encapsulated as “sealed for life”. These state-of-the-art encapsulations typically have leakage rates of <0.1%/a, as defined in IEC62271-200 [7]. Only very small amounts of the contained gas mixture is released due to leakages into the ambient air during normal operation.

Mechanisms of leakages

There are in principle three mechanisms for leakages:

1. Gas leakage between interface surfaces (e.g. between seal and sealing surface) of static connections.
2. Gas leakage between interface surfaces (e.g. between seal and sealing surface) of dynamic connections, where gas is leaking during operation of translating or rotating shafts.
3. Permeation of gas through elastomer or thermoplastic material.

For mechanisms 1. and 2. the leakage mainly depends on the pressure difference, i.e. the overpressure of the gas in the encapsulation. The gas component itself primarily has no influence on the leakage rate. Both mechanisms are sensitive to temperatures, especially mechanism 2., as the elastomer becomes less flexible at low temperatures and the leakage rate during operation of drives could rise.

This is different for mechanism 3., as the permeation rate depends on the material (seal or thermoplastic material) and significantly on the permeating gas. As this is a chemical process, not only the size of the molecule is relevant. The whole process depends on the temperature and on the partial pressure difference of the gas component, comparing inside to outside. Here the relationship between permeation factor and temperature varies exponentially with increasing temperatures.

The leakage value must be considered for each gas component of the gas mixture. Depending on the mixture and the ambient conditions, the leakage rate can be different for each mixture component. The carrier gases O_2 and N_2 are not of importance under hazard aspects. The focus is on the C5 fluoroketone and on decomposition products, which may be hazardous. Assuming the leakage rates are on a comparable level for all components, then only the partial pressure of the gases of interest are relevant (as the concentration outside the encapsulation is zero, this is equivalent to the partial pressure difference of this gas component). For the used gas mixtures this is valid for the lower temperatures; at higher temperatures the permeation of O_2 and N_2 are even higher than that of C5 or its decomposition products.

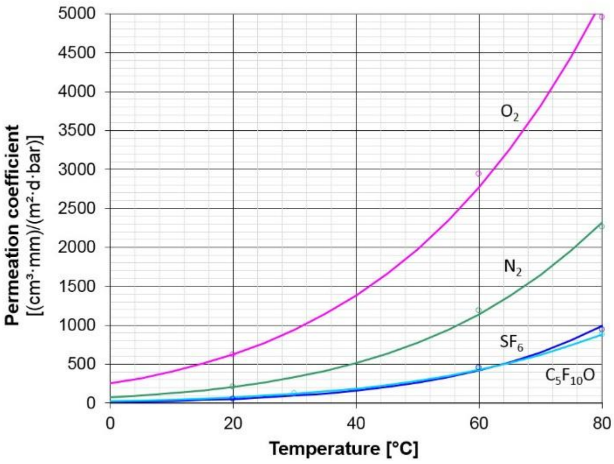

Figure 1: Permeation coefficients for different gases for a typical EPDM seal material

The permeation coefficient $P(J_S)$ depends on the temperature J_S of the seal and on the partial pressure difference Δp. The other influencing factors for the quantity of permeating gas depend only on the geometry, which is the same for all gases. For a comparison, the values must be divided by the percentage C of the gas in the mixture. The measure $P(J_S)$ ž Δp ž C may be used for the comparison. The unit [(cm^3 ž mm) / (m^2 žd ž bar) ž kPa] is left out in the table below. The calculations are done for a selected gas mixture at ambient pressure 101.3 kPa.

Table 1: Comparison of permeation effect of different gas components of AirPlus -15/130

	O_2	N_2	$C_5F_{10}O$
Δp	1.1 kPa	10.8 kPa	17.7 kPa
$P(20°C)$ ž Δp ž C	3974	3235	9579
$P(40°C)$ ž Δp ž C	8787	8034	30194
$P(60°C)$ ž Δp ž C	17657	17849	55443

As can be shown, the permeation of the C5 fluoroketone is higher than for the carrier gas components, even if their permeation coefficient is lower. This changes at higher altitudes, as the inside-to-outside pressure difference increases for these gases. The C5 permeation stays constant, but O_2 and N_2 permeation increases due to the increasing partial pressure difference.

Gas loss in real equipment

The total volume of all gas-filled encapsulations may be calculated for real equipment and the mixture as defined above can be used to calculate the amount of contained C5 fluoroketone. The amount of all relevant substances inside the encapsulation can be calculated using the decomposition rate of C5 and the resulting levels for each decomposition product. Taking the maximum permitted leakage rate from this allows the amount of substance released to the ambient air to be calculated. As the amount of the leakage is very small, this is a very slow process. The gases will be mixed with the ambient air and distributed homogenously through the complete switchgear room. The concentrations can be calculated and compared, e.g. with the permitted occupational exposure limit (OEL).

The OEL is the maximum 8-hour, time-weighted-average concentration of the specified chemical that is allowed in the workplace air. It is set to protect human health based on a worker's exposure to the material for eight hours a day, five days a week, 52 weeks a year, for an occupational lifetime typically assumed to be 30 years or more.

For example, it can be shown that developed concentrations are very low level and not at all dangerous to personnel.

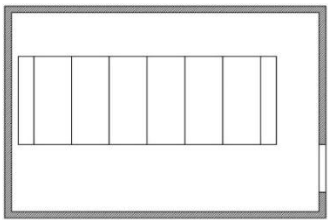

Figure 2: Typical switchgear installation (6 panels)

A (comparably small) switchgear installation of 6 panels is shown above. Each panel is 600 mm wide and 1860 mm deep. According to the minimum space around the panels and the lateral pressure relief ducts of 250 mm width, the room dimensions are 5.0 m width, 3.6 m depth and 3.0 m height. The room volume is 54 m³. Estimating that the complete panel volume is 1.5 times the gas encapsulation volume, this is reduced by 7 m³. The resultant available space is 47 m³.

Assuming all panels are double busbar panels, each one has a total gas volume of about 0.8 m³, for a total of 4.8 m³. Filled with AirPlus -15/130 it contains 0.85 m³ of C5 fluoroketone (recalculated to 100 kPa pressure).

Taking the maximum permitted leakage rate of 0.1%/a this results in 0.85 liters accumulating within one year. In the total room (space around the panels) these 0.85 liters are diluted in 47,000 liters of air, for a C5 concentration of 18.1 ppm_v. The TWA value of C5 fluoroketone is 225 ppm_v, so the figure is one order of magnitude lower, even under the unrealistic assumption that the air inside the switchgear room is not replaced within one year. Under realistic conditions, the concentration will be 10 or even 100 times lower, depending on the room ventilation (e.g. 10m³ per day) and the real leakage rates.

Decomposition by-products under normal operating conditions

Tests were performed to identify decomposition by-products over the lifetime and under normal operating conditions of the GIS, and mathematical models were developed for quantification.

There are different factors that can lead to decomposition:

1. Chemical reaction with materials in contact with the gas (material incompatibilities).

2. Decomposition of the gas by electrical arcs upon switching operations or at partial discharge.

The values were quantified under the boundary to limit the total decomposition by selecting highly compatible material and using vacuum interrupters for current interruption or load break switches (optimized for use in new gas mixtures). The total decomposition of C5 over the lifetime of the GIS can be kept at a low level of <2%.

The decomposition by-products identified during the gas analysis are mainly heptafluoropropane (C_3HF_7) and hexafluoropropene (C_3F_6). Other decomposition by-products were found at a level below 10 ppm_v.

Under worst-case conditions, the concentrations of decomposition by-products (see table 2) accumulate inside the gas encapsulations. The figures are a result of test duties and of consumption calculations based on material compatibility tests. Assuming the by-products are not adsorbed by the molecular sieve, they will leak into the switchgear room. Assuming that the total leakage rate for any decomposition by-products is at the same level as for C5 fluoroketone, the concentration of these gases in the switchgear room can be calculated by comparing the ratio in the encapsulated gas.

Table 2: OEL values of decomposition by-products and maximum concentration in the aged insulation gas mixture

	OEL value	Maximum concentration in AirPlus (inside GIS)
C5 fluoroketone	225 ppm_v	13.6 %vol
heptafuoropropane	non toxic	2600 ppm_v
hexafluoropropene	0.1 ppm_v	50 ppm_v

If a 13.6% vol of the C5 fluoroketone inside the GIS leads to a concentration of 18,1 ppm_v outside the GIS, inside the GIS concentrations of 2600 ppm_v lead to 346 ppb_v for heptafuoropropane and to 6.5 ppb_v for hexafluoropropene. Both values are significantly below the permitted OEL values.

We were able to demonstrate that under normal service conditions the AirPlus gas mixture or decomposition by-products are not harmful to the operator and the values are far below the permitted OEL values.

SAFETY HAZARDS DUE TO DEFECTS

Defects are exceptional, but cannot be entirely excluded. The main type of defect in this context is leakages due to defects in components that are normally gastight. This may be due to a damaged seal or a cracked bushing. These defects lead to increased leakage rates that can range up to major leaks, in which the overpressure of the gas encapsulation decreases to zero within weeks, days or even minutes. In this case, the amount of gas mixture escapes into the ambient air in relation to the overpressure. As modern MV GIS are separated into several gastight compartments without gas connection, the amount of gas per compartment is limited. In most cases, this type of defect only affects one or two gas compartments. Calculating this analogously to the previous calculation, complete leakage would lead to the figures below.

The worst case would be the simultaneous leaking of one circuit breaker and one busbar compartment (due to a crack in the bushing between both compartments). This would affect about 0.6 m^2 in gas volume. The pressure would be reduced to ambient pressure, i.e. drop by 30 kPa. 180 liter of AirPlus would enter the switchgear room, containing about 25 liters of C5 gas at 20°C and 100 kPa. This is about 30 times the value of the maximum permissible leakage accumulated over a year. Also using this factor for decomposition by-products leads to the figures below.

Table 3: OEL values of decomposition by-products and maximum concentration inside the substation room.

		Concentration at	
	OEL value	leak	leak + defect
C5 fluoroketone	225 ppm_v	18.1 ppm_v	561 ppm_v
heptafluoropropane	non toxic	346 ppb_v	10.7 ppm_v
hexafluoropropene	0,1 ppm_v	6.5 ppb_v	0.2 ppm_v

All figures are based on the assumption of a closed room without any ventilation, which is quite unrealistic. But even in this case the OEL value is exceeded by a factor less then 3, so working in this environment would be allowed for 30 minutes. Any ventilation (even opening the doors) would directly lead to a decrease in the concentrations. An ventilation system in the room would drastically reduce all the values to negligible amounts.

A defect causing a leak also results in values that are at a level where it is not harmful for people to enter the substation.

SAFETY HAZARDS DUE TO FAULT CONDITIONS

The worst case for GIS is an internal arc failure, which is caused by a defect or operator failure, resulting in an arc between the phases and/or between phase and ground that burns until the arc energy is interrupted by the feeding circuit breaker. The energy is (depending on the network) very high-level, which leads to a massive pressure increase inside the encapsulation. To avoid the uncontrolled cracking of the encapsulation, burst discs open after a few milliseconds and the produced plasma is guided to the outside in a controlled way. In many cases pressure relief ducts are used to guide the plasma to areas where no direct contact with the operator or even to the outside of the building can occur. This event is limited to one gas encapsulation. Consequently, the entire volume of gas encapsulated in the compartment is released. Due to the high temperature of the electric arc (10,000 to 20,000 K), the gas molecules are decomposed, forming a plasma. As it cools down, the plasma created from the gas, evaporated metals, burned insulation material, ambient air and humidity recombine to new molecules. Internal arc tests were performed and gas samples near the switchgear were collected at different times during and after the internal arc tests. The samples were chemically analyzed using GC-MS (gas chromatography – mass spectrometry).

With AirPlus, the detected gases during different tests at different conditions are listed below (the highest measured concentrations normally occur within the first few seconds).

Table 4: Detected gases during internal arc tests and test setup with gas sampling bottles

Detected gas	max. concentration [ppm_v]	OEL [ppm_v]	
CO	6200	25	
CO_2	61000	5000	
$C_5F_{10}O$	39	225	
CF_4	100	-	
C_2F_6	<10	-	
HF	690	0.5	
C_3F_8	19	-	
C_4F_{10}	2	-	
C_3F_7H	<15	-	
C_3F_6	14	0.1	
C_4F_8O	5	0.1	

For gaseous components the toxicity is dominated by CO_2 and CO. Tests performed with air as insulation gas have shown similar results with comparable values.

Table 5: CO and CO_2 concentration at internal arc test in AirPlus and air.

Detected gas	AirPlus (container) [ppm_v]	Air (container) [ppm_v]	AirPlus (substation) [ppm_v]
CO	6200	2780	700
CO_2	61000	25000	7100

The additional gases produced by an internal arc in the new insulation gas mixture are at a significantly lower level (see table 4). The most important is hydrogen fluoride (HF). In this case, the very low OEL value is exceeded during and directly after the internal arc event. After 30 minutes (even without active ventilation), the concentration decreases due to the fast reaction of the acid to the surfaces of the switchgear or other material, mainly metals. Most of the levels are below the OEL after 15

minutes. Another important factor is room size. The most challenging test condition involved a small container. In a larger test room (reflecting a real substation more completely) the concentrations are much lower, as the gases are diluted in a higher ambient air volume.
For internal arc tests with SF_6 insulation gas (values taken from [8]), the gaseous components have a much higher impact compared to AirPlus (gas analyzed after tests).

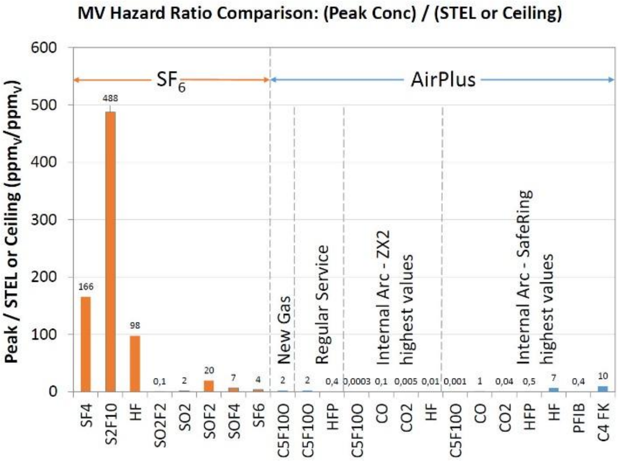

Figure 3: Hazard ratio of SF_6 compared to AirPlus

The gas toxicity after an internal arc with the new insulation gas mixture is close to air and significantly lower when compared with SF_6. This is clearly visible in figure 3, where the hazard ratio (peak concentration/STEL (short-term exposure limit) or ceiling) is shown for SF_6 and AirPlus -15/130, as used in primary GIS.

Another aspect involves solid particles in the air or on surfaces. In this case as well, samples were taken after the internal arc tests with the new insulation gas mixture and air were completed. The main toxic substances we identified are metals and metal oxides such as CuO and CuO_2. They appear in air tests as well. In addition, the new insulation gas mixture produced substances containing fluorine (for example FeF_2 and AlF_3), but at a decade lower toxicity level. As opposed to SF_6, which includes additional substances containing sulfur, AirPlus does not. Therefore, the toxicity of the new insulation gas mixture is close to air insulated switchgear and significantly lower than that of SF_6 GIS. In any case, with any insulation medium, after an internal arc event the air in the related switchgear room must be exchanged several times before anyone enters without protective equipment. This implies removing the toxic gas and the particles in the air. Particle masks and gloves are required when working on the switchgear (cleaning, removing defect parts). The same safety practices and protective equipment utilized today with SF_6 or AIS would be used to work with equipment containing AirPlus.

CONCLUSIONS

Operating AirPlus-insulated GIS does not generate high-level environmental or human safety risks for operating personnel. Even in the case of defects leading to gas leakages, the risks are negligible and no threshold values are exceeded. An internal arc failure can produce toxic gases, no matter whether the equipment is insulated with air, SF_6 or the new insulation gas mixture. The concentrations of harmful decomposition by-products for the new insulation gas mixture are moderately higher than for air, but significantly lower than for SF_6. Therefore, AirPlus offers a technology that is not only a step forward in terms of GWP, but also safe during operation and events to due defects. The environmental and safety impact in the event of failures is clearly lower than for SF_6.

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