# ALTERNATIVE GAS INSULATION IN MEDIUM-VOLTAGE SWITCHGEAR

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## *ABSTRACT*

*$SF_6$ is used as insulation gas in gas-insulated switchgear (GIS) today since the technical performance of $SF_6$ perfectly matches to the technical requirements. The drawback of $SF_6$ is the high global warming potential (GWP) of about 23.500 (100 year time horizon, $CO_2$ equivalent) which is subject to discussion in the EU and in other countries. Several gases and gas mixtures have been analysed in the past, but no ecological alternative has been identified that provides a comparable technical alternative at acceptable cost.*
*A few years ago ABB intensified the search for an alternative insulation. The identified alternative to $SF_6$ is a mixture of a fluoroketone, developed by 3M Company, and a carrier gas. For medium-voltage switchgear, the most effective solution is a C5 fluoroketone, which has the best overall performance and a very low GWP of about 1. Intensive tests have been performed to verify that the new gas can be used in GIS whereof the majority was related to material compatibility and safety aspects. The results are promising and the new technology will be implemented in a technology pilot installation to gain field experience in this new technology. The pilot installation is an important new substation of the Swiss utility ewz in the city of Zurich, with the substation containing 50 panels of a 22 kV primary distribution switchgear with the new insulation gas. In order to meet all technical requirements, an existing medium-voltage switchgear design has been slightly modified.*

## INTRODUCTION

Since $SF_6$ was introduced into gas-insulated medium-voltage switchgear (GIS) in 1982 the market for this technology has grown continuously. $SF_6$ insulation offers the highest reliability and provides the most compact design. The high voltage part is decoupled from the environment so that maintenance is significantly reduced and related outages or failures can be prevented. Space saving is a premium in larger cities. A reduced footprint allows installations in very compact switchgear rooms as well as the replacement of older equipment with the possibility to extend the switchgear.
Nevertheless, from the start, switchgear manufacturers, the chemical industry, and universities have searched for alternative insulation gases. The focus was on gaseous substances in the complete operating range from between -5°C and 40°C. The second condition was high performance and the avoidance of e.g., toxicity and other negative factors. No alternative had been identified meeting the wide range of requirements. Possible substitutes were toxic and/or had lower insulation or arc interrupting performance compared to $SF_6$ so that $SF_6$ technology continued to be widely accepted as the standard technology in high- and medium-voltage gas-insulated switchgear.
For many years now, the greenhouse effect is under a more intensive supervision worldwide. Due to the very high global warming potential (about 23.500), $SF_6$ has been in the focus of attention. $SF_6$ has been replaced in those applications that release high quantities of material to the environment and where substitutes are readily available.
For gas-insulated switchgear, it had been shown that ecological substitutes were not available which met all of the technical requirements and at comparable costs. In order to limit the environmental drawback of $SF_6$ technology, leakage rates of $SF_6$ have been limited since the early days. The first designs have been made for high-voltage GIS with leakage rates of 0.5%/a. With new design principles this was decreased in the nineties to 0.25%/a and finally to 0.1%/a. Additionally, a very low overpressure of 0.2 to 0.5 bar and reduced volumes limit the required mass of $SF_6$. Considering the closed handling of $SF_6$ over its lifetime, $SF_6$ gas insulation technology has made substantial improvements since its introduction.

Today, the use of $SF_6$ in switchgear applications is monitored quite intensively and handling is only permitted by trained personnel. Nevertheless, in some areas taxes or even a ban of $SF_6$ is still under discussion. At the same time and based on similar discussions of refrigerant gases, chemical companies started to search for different technical solutions to create gaseous substances with low GWP.
Based on intensive research, the family of fluoroketones (FK) has been developed. A number of different compounds from this class have been investigated. The main differentiators are the number of carbon atoms in the molecule and the boiling point. The high vapour pressure of the fluids which results in a high content of gaseous substances even below the boiling point of the fluid, is beneficial for medium-voltage switchgear applications. This effect is common for all of the fluoroketones investigated. Due to this effect, a mixture with a carrier gas can contain a significant percentage of the fluoroketone in the operating temperature range of a medium-voltage GIS.

This was the starting point of intensive cooperation between 3M and ABB aiming at the identification and qualification of an alternative gas for GIS applications with a very low GWP.

## IDENTIFICATION OF NEW GASES

3M has had a long-standing initiative to develop alternative products to replace materials with high environmental impact. As a result, the replacement of compounds with high global warming potential (GWP) has been a focus of this effort. About 5 years ago the emphasis of the project expanded to the development of high dielectric fluids. A high number of existing and new substances have been investigated and tested. The combination of performance for the required application, the GWP, toxicity and other factors needed to be balanced. The results of the development effort have produced some interesting substances which can be used for electrical applications based on a good dielectric performance, chemical stability, a low toxicity level and a very low GWP.

One group of these substances are the fluoroketones. Depending on the number of carbon atoms in the molecule, they are referred to as C6 FK, C5 FK and C4 FK. C6 FK is already in use for several applications, e.g., for fire-extinguishing purposes and as an alternative to $SF_6$ in cover gases for molten magnesium. Due to the high boiling point of 49°C, the concentration in gas mixtures at lower temperatures is too low for switchgear applications, even considering the high vapour pressure. In this respect, C4 FK has an advantage, but the toxicity level is too high for applications such as GIS. Finally, C5 FK (1,1,1,3,4,4,4-heptafluoro-3-(trifluoromethyl)butan-2-one) has shown very good dielectric performance and the boiling point of 26.9°C combined with the high vapour pressure of 94 kPa (@25°C) allows gas mixtures which are suitable for dielectric applications down to temperature ranges of -15°C or even -25°C. In addition, the GWP of this substance is <1, meeting a demanding target. 3M has developed a product based on this substance named 3M™ Novec™ 5110 Dielectric Fluid (figure 1).

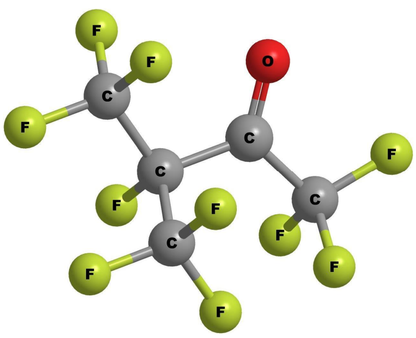


***Figure 1. C5 fluoroketone 3M Novec 5110 Fluid***

The second substance is the fluoronitrile (2,3,3,3-tetrafluoro-2-(trifluoromethyl)-propanenitrile). As with the fluoroketones, this substance has a boiling point in the operation temperature range of electric equipment. Compared to the fluoroketones, its boiling point is significantly lower at -4.7°C and the vapour pressure is quite high at 252 kPa (@25°C). This allows for a higher concentration of the fluoronitrile in a gaseous mixture and lower operation temperatures than for the fluoroketones. The dielectric performance of the pure gas is higher than for the fluoroketones. On the other hand, the GWP of 2210 is measurably higher than for the fluoroketones but is still significantly lower than that of $SF_6$. 3M has developed a product based on this substance as well named 3M™ Novec™ 4710 Dielectric Fluid (figure 2).

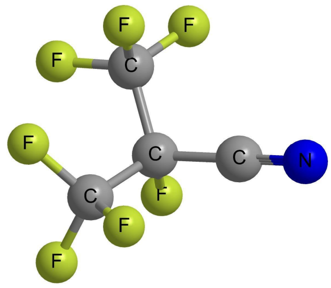


***Figure 2. fluoronitrile 3M Novec 4710 Fluid***

The results of the research at 3M have been presented to the electrical industry.

## DIELECTRIC PERFORMANCE

In order to evaluate the usage of the new substances in medium-voltage GIS, the first step was to test and compare the technical performance of the different fluoroketones (C6 FK, C5 FK, C4 FK) and the fluoronitrile looking at the requirements of medium-voltage GIS in the range of between 6 to 40.5 kV. Due to the significantly higher GWP of the fluoronitrile, ABB focussed on the fluoroketones.

A key element of using fluids with high vapour pressures is to define a mixture which covers the complete temperature range of the application providing the required dielectric performance. The concentration of FK has to be chosen so low that the corresponding partial pressure is below the vapour pressure of the substance at the lowest temperature. This avoids condensation even at the lowest specified operation temperature. For indoor MV primary GIS, the lowest temperature is normally -5°C. Some applications are also requiring -15°C. For compact secondary substations, including the ring main units, typically -25°C is a requirement.

Based on these requirements, a mixture of the FK and a carrier gas needed to be prepared. The selection of the carrier gas is important. It must be inert, easily available and should not have any negative impact on the performance. Initially nitrogen was the most interesting gas, but the addition of oxygen generated dielectric and chemical advantages. Therefore, dry technical air has been selected being the best carrier gas.

Dielectric tests have been performed on all FKs in different mixtures [1]. Thanks to a 20°C lower boiling point, the C5 FK gas mixture's dielectric performance is superior compared to the C6 FK mixture. C4 FK mixtures have shown even better results, however those mixtures have been excluded due to their toxicity profile.

The dielectric performance of the C5 FK gas mixture is not as good as 100% $SF_6$. Only 12% of the gas mixture is C5 FK. However, all test voltages of the applicable test standard IEC 62271-200 have been passed without major modifications and keeping compact switchgear dimensions.

## GENERAL PERFORMANCE IN GIS

The current interruption in medium-voltage GIS intended for substation applications is based on vacuum technology. No switching (arc quenching) performance of the new gas is required. Nevertheless, the investigation cannot be limited to the dielectric performance. Additional important investigations and tests for the qualification of the new gas are listed in the following chapter.

### Thermal performance

$SF_6$ is a heavy gas normally used in 100% concentration. It is well known that it has a very good thermal performance. This is related to the high thermal conductivity and the good convection property. Air is significantly less effective in transporting the thermal losses to the outer surface in a GIS. FK is performing quite well, but the quantity in the gas mixture is too low to contribute significantly to the heat transfer. As a result, the thermal performance of GIS using FK instead of $SF_6$ is reduced. This has been confirmed in tests of several sample configurations. The achievable maximum current is 7 to 15% smaller in GIS using the alternative gas mixture. This gap needs to be covered by the design of the switchgear and improvements might be required. At extreme ratings (technical limits) even a de-rating cannot be excluded using FK gas mixtures.

### Behaviour during internal arc

Internal failures resulting in an internal arc are the worst-case event in any switchgear application. The arc burning between the three phases and/or between phase and ground has a very high energy. Short circuit currents up to 40 kA may flow through the equipment for up to 1 s. In order to get a qualification according to IEC 62271-200 the safety of the personnel in close distance to the switchgear must be verified by an adequate internal arc test.

In principle, the internal arc test can be divided into two phases.

1.) Pressure peak
2.) Continuous burning phase

The pressure peak in the first 10 to 20 ms is relevant for the mechanical stress on the enclosures. Any enclosure bursting, any damage of bolted connection or deformation of covers usually happens in this time.
When testing FK gas mixtures it has been observed that the pressure peak is up to 30% higher compared to $SF_6$ and that the rate of increase is higher. The peak for $SF_6$ is reached in 17 ms, while for the C5 FK/air mixture it is reached in 10-12 ms. This additional stress is not a significant impediment based upon the typical robust medium-voltage switchgear design. No bursting or deformation of switchgear compartments could be observed. Only a limited impact could be seen in a connected pressure relief duct. However this effect needs consideration.

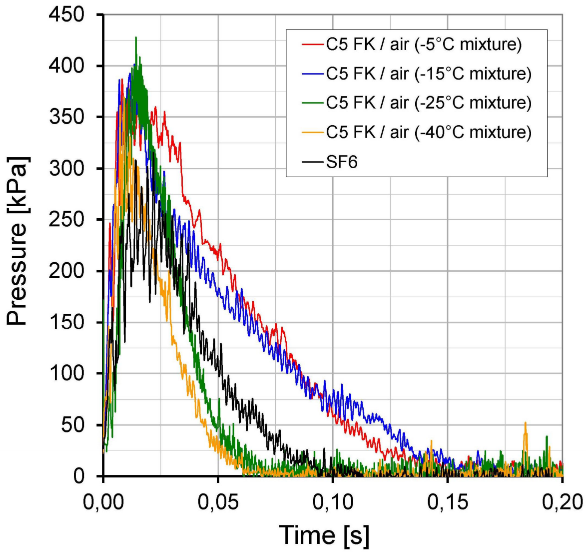


***Figure 3. Pressure inside gas compartment during internal arc tests using different gases and gas mixtures***

In the second phase of the internal arc fault, starting at 150 ms or later, no difference could be observed between $SF_6$ and C5 FK/air. This is reasonable because after the opening of the burst disc and the plasma flow out of the encapsulation, almost no insulation gas is left inside the compartment. The pressure is low and mainly burning copper, aluminum and steel produce plasma. This explains why no difference in the burn-trough behavior has been observed.

A second impact is related to the chemical reaction of the insulation gas in the plasma. Even stable chemical substances are decomposed at very high temperatures. This effect can be seen with $SF_6$ as well as with solid material in the roots of the arc. Some molecules are destroyed and the fragments react with other molecules in the plasma. Some of the molecules have only a short lifetime or will react e.g., with water, which is contained in the atmosphere. Similar to $SF_6$, the decomposed FK can also produce HF during an arc fault. Most of the HF reacts with the metal surfaces of the switchgear housings or the pressure relief ducts, leaving powder on the surface, before being released to the ambient atmosphere.

Safety of personnel is most important in the unlikely event of an internal arc. Personnel should not enter the switchgear room without intensive ventilation of the room following the internal arcing event. This procedure is well known for $SF_6$ insulated switchgear, but also for air-insulated switchgear. The same procedure is applicable to switchgears with C5 FK/air gas mixtures.

## Long-term behaviour

It has been proven that a GIS filled with the new insulation gas could pass the relevant type tests and that the operation of the switchgear was not affected by the new gas. But what will happen during 30 or even 40 years lifetime of the equipment?

For $SF_6$, long-term experience and intensive investigations are available.

C5 FK is not as inert as $SF_6$ but can chemically react with some substances. Some theoretical information and tests in the liquid phase of C5 were available, but this was not sufficient to evaluate the usage in medium-voltage switchgear applications.

Intensive investigations about the material compatibility between C5 FK and the materials used in GIS are required to decide about a long term behaviour. This is another important milestone for the approval of an alternative insulation medium.

Two factors are of importance in compatibility investigations:

1.) The impact of materials on the gas:
Quantity of C5 FK which is decomposed and nature of decomposition products

2.) The impact of C5 FK and its decomposition products on the material:
Reduction of electrical or mechanical properties

Therefore, a two-step approach has been followed:

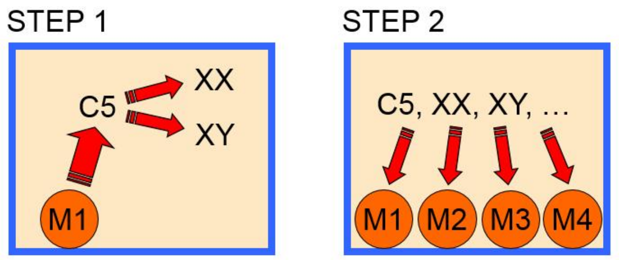


***Figure 4. Two step approach for investigating material compatibility***

In the first step, the materials used in GIS were subject to an accelerated aging test at 100°C being in contact with the selected C5 FK/air mixture over a defined time. The decomposition rate of C5 FK reflects the compatibility. The materials with zero or with limited decomposition passed the Step 1 test. In the second step, these materials were combined in a larger gas compartment and have been aged again at 100°C for up to 12 weeks. Real switchgear components have been used rather than material probes. The materials were inspected in detail after the test. Additionally, the aged components were included in tests according to type test conditions. Only materials that passed both tests are qualified.
Based on the results, some standard materials, primarily polymers, have been replaced by new materials.

## Conclusion for eco-efficient GIS

The investigations and tests have shown that it is feasible to modify existing $SF_6$ GIS designs allowing the usage of an alternative insulation gas based on a mixture of C5 FK and technical air. The required modifications of the switchgear intended for circuit-breaker applications are limited and the cost impact are in balance with the ecological improvement.
Based on the results of the study, ABB decided to perform type tests for selected variants of a slightly modified ZX2 targeting a technology pilot installation to gain field experience in this new technology.

# PILOT PROJECT FOR ECO-EFFICIENT GIS

At this time ewz, a large Swiss utility, started the planning of a new substation in Zurich. This substation is located in the city and intended to replace an existing AIS installation on only $1/5^{th}$ of the space. This advanced substation shall include technologies which are modern, compact, reliable and environmentally friendly. Even new technologies, not yet available on the market, were taken into account.
The cooperation between ABB and ewz has been very open about exchanging the development status of the new technology, including limitations. Based on this, a common decision has been taken to use the new eco-efficient technology using a mixture of C5 FK and air as insulation gas in a GIS.
The size of the substation is large, consisting of 50 medium-voltage panels. The operation voltage is 22 kV and the nominal current is 1600 A for the incoming feeder and 2000 A for the busbar. In order to reduce the switchgear size further, very compact solution double feeder panels have been selected. Each 630A outgoing feeder is only 400 mm wide (see figure 5), which is challenging regarding dielectric insulation.
Compared to the standard $SF_6$ panel design some modifications have been done, in addition to the use of the new insulation gas (see figure 5). As the former desiccant was absorbing C5, a new desiccant had to be introduced (1). Some thermoplastic materials have been replaced by others (2) and the seal material has been changed (4). As the switchgear is no longer $SF_6$ insulated and oxygen is part of the insulation gas, according to IEC 62271-200 all contacts of the primary current path needed to be silver plated (3).

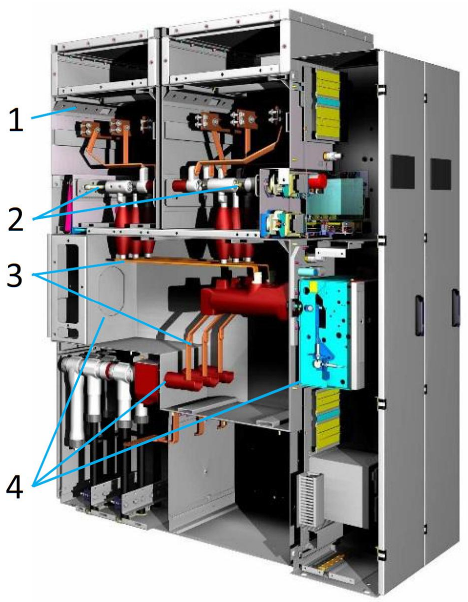


***Figure 5. Eco-efficient ZX2 double feeder panel***

All selected panel variants have been type tested according to the applicable test standard IEC 62271-200. Special focus has been set to those tests that are impacted by the change of the insulation gas or by material change.
Based on the passed type tests, the eco-efficient switchgear version has been produced and prepared for delivery.
The first panels arrived at the substation in November 2014. Energization of the switchgear is scheduled for summer 2015 after the completion of the substation.
Gas samples will be taken within the upcoming years to verify the long-term stability of the new insulation fluid and to reconfirm the results of aging tests and mathematical models in a real application.

## CONCLUSIONS

$SF_6$ technology is well accepted in gas-insulated switchgears due to its outstanding technical performance. $SF_6$ technology has improved significantly considering its closed handling over the equipment lifetime and the low leakage rate in current designs.
Nevertheless, $SF_6$ gas insulation in switchgear applications is still under discussion in many markets due to the very high global warming potential. After many years of intensive research, an alternative to $SF_6$ insulation has been identified. From a technical point of view, the alternative C5 FK/air gas mixture fulfils the main requirements. Based on limited modifications, the new alternative gas mixture is also a viable option from an economical perspective. The impact on the switchgear design is limited with the advantage that no complete new design is required. The same platform can be used for $SF_6$ and non-$SF_6$ insulation gas, avoiding unattractive coexistence of two independent designs for the same function.
No significant impediment has been identified for the new environmentally sustainable technology. Future challenges will be ultra-low temperature applications and designs for highest nominal currents.
The collection of further experience in the pilot installation and the continuation of product development projects might leave the decision to the end user soon if proven traditional $SF_6$ insulation is selected or a new eco-efficient alternative with a very low GWP of below 1.

## REFERENCES

[1] J.D. Mantilla, N. Gariboldi, S. Grob, M. Claessens, 2014, "Investigation of the Insulation Performance of a New Gas Mixture with Extremely Low GWP", *IEEE Electrical Insulation Conference*, 469-473