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SF_6 alternative circuit breaker for 145 kV gas insulated switchgear

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SUMMARY

A circuit breaker that uses a mixture of C4-fluoronitrile (C4-FN), carbon dioxide, and oxygen as an alternative to SF_6 was developed for application in sub-transmission gas insulated switchgear with a rated voltage of 145 kV and a short-circuit current rating of 40 kA. The circuit breaker was based on and took advantage of highly reliable SF_6 gas circuit breaker technology that has been refined and proven in the field for decades. Some design changes were made to the circuit breaker to take into account differences between the thermodynamic and transport properties of CO_2 and SF_6. CO_2 has a higher speed of sound and a higher adiabatic coefficient than SF_6. The changes to the circuit breaker included an increase in the filling pressure, modifications to some of the valves, and an increase in the opening speed. The circuit breaker successfully passed all required short circuit current test duties and other tests defined in the IEC 62271-100 standard, including the temperature rise and mechanical endurance tests.

C4-FN does not recombine after it decomposes in an arc. Therefore, extensive tests were performed under controlled laboratory conditions to determine the amount of C4-FN that decomposes under worst-case conditions. It was found that decomposition of C4-FN does not limit the lifetime of a circuit breaker. The lifetime is limited by nozzle ablation and contact erosion, as is the case for SF_6 circuit breakers. The concentration of decomposition products in the gas mixture was analyzed using GC-MS and FTIR, and the acute toxicity of the gas mixture was estimated. The decomposed gas mixture was not classified as toxic even when considering scenarios with extremely high arc energy input and volumes much smaller than those of the circuit breaker described in this work.

KEYWORDS

Circuit breaker, gas insulated switchgear, C4-fluoronitrile, SF_6-alternative, current interruption, sub-transmission

INTRODUCTION

For decades high voltage circuit breakers have used SF_6 as the current interruption and dielectric insulation medium. SF_6 has high dielectric strength, is very effective at interrupting electric arcs, is chemically stable, is non-toxic, and rapidly recombines and recovers its dielectric strength after being decomposed in or around an arc. Its low boiling point permits it to be used at the high pressures needed to provide sufficient dielectric strength in electrical equipment without it condensing at or above the minimum operating temperature. However, SF_6 also has a high greenhouse warming potential [1], which has led to the search for suitable alternatives. Already during the 1980s, studies that sought to determine if any other gas could exceed the dielectric and current interruption performance of SF_6 did not find a single-component gas with better performance [2][3]. A key obstacle was finding a single-component gas with both high dielectric strength and a low boiling point. More recently, research and development efforts have focused on mixtures of gases that combine a component with high dielectric strength, but high boiling point, with a background gas that has a lower dielectric strength, but also a low boiling point. High dielectric strength components including C5-perfluoroketone ($C_5F_{10}O$) [4], C4-perfluoronitrile (C_4F_7N) [5][6][7], and CF_3I [8] were investigated. C5-perfluoroketone- and C4-perfluoronitrile-based gas-insulated switchgear has been developed and successfully placed into service. CO_2, N_2, and O_2 have been investigated and used as the components of the background gas in electrical equipment.

In this contribution, we address the technical considerations important in the development of an SF_6-alternative gas circuit breaker. SF_6-alternative gas mixtures—when considering compositions relevant for practical applications—have thermodynamic and transport properties that differ significantly from those of SF_6 [9][10]. Such mixtures, for instance, have a higher speed of sound and a higher adiabatic coefficient [4]. A higher speed of sound can result in faster emptying of the puffer volume (where cold gas is compressed and stored to blow and cool the arc during opening of the circuit breaker) or the self-blast volume (where hot gas from the arc is collected during the high-current phase and then allowed to blow and cool the arc as the current approaches a zero-crossing). A design optimized for a specific arcing time window and SF_6 is not necessarily optimized for, for example, CO_2. The goal of developing an SF_6-alternative gas circuit breaker is to take into account differences in gas properties while taking advantage of and preserving key aspects of time-tested, highly reliable designs originally made for SF_6 gas insulation.

We present an example of a circuit breaker developed for gas-insulated switchgear (GIS) applications at a nominal voltage of 145 kV, a rated short-circuit current of 40 kA, a nominal current of 3150 A, and a power frequency of 50 Hz. We also summarize the circuit breaker's performance in key tests specified by the IEC 62271-100 standard, focusing on capacitive switching and terminal fault test duties, and illustrate how certain type-tests are more critical than others with regard to optimizing the design of the circuit breaker. Further, we demonstrate that high dielectric strength, high boiling point gas mixture components, which are typically added in low concentrations to avoid condensation at low temperatures, strongly influence the terminal fault performance at low current (e.g. T10 and T30 test duties), but play a smaller role in defining the performance for higher short circuit currents (T60 and T100 test duties). We also address decomposition of the C4-FN. Decomposition of C4-FN does not limit the lifetime of the circuit breaker, and it does not lead to an arc-exposed gas mixture that would be classified as toxic.

GAS MIXTURE

The GIS circuit breaker discussed in this work uses a mixture of C4-perfluoronitrile (C4-FN), CO_2, and O_2 (which we will abbreviate C4-FN / CO_2 / O_2 mixture) as the insulating and current-interrupting medium. This gas mixture combines the advantages of having a high dielectric strength, providing good current interruption performance, enabling low minimum operating temperatures (down to −30 °C), being practically non-toxic, being chemically stable in electrical equipment, and having a low global warming potential (GWP).

DESIGN CHANGES AND MODIFICATIONS

The GIS C4-FN / CO_2 / O_2 circuit breaker, which is illustrated in Figure 1, is closely based on reliable SF_6 gas circuit breaker technology that has been continually refined and used in sub-transmission and transmission power networks around the world for decades. A single tank is used to enclose all three interrupting chambers used for three-phase networks.

Figure 1. GIS bay using the C4-FN / CO_2 / O_2 145 kV / 40 kA / 50 Hz circuit breaker.

With the introduction of the C4-FN / CO_2 / O_2 gas mixture, the interrupting chamber had to be modified to take into account the difference in thermodynamic and transport properties between the C4-FN / CO_2 / O_2 gas mixture and SF_6. These modifications focused on the pressure build-up and dielectric coordination (electric field design) inside the interrupting chamber. The conditions during and after current interruption were also taken into account with regard to the electric field stress between the three interrupting chambers (one for each phase) and to the enclosure. One of the major topics addressed was the higher speed of sound of CO_2, which is the background gas and the main component of the gas mixture and which is especially important with regard to arc interruption.

When designing a self-blast circuit breaker, a balance must be found between pressure build-up by the energy of the arc in the heating volume and the gas compressed in the auxiliary puffer volume. A proper balance ensures that sufficient gas flow (blowing) is available to cool the arc for all switching cases and for a sufficient duration to address all arcing times.

This was achieved by different measures, including a higher filling pressure (8.8 bar_{abs} vs. 6.8 bar_{abs}) in the circuit breaker tank compared to the SF_6 version, which affects the pressure coordination in the interrupter, modification of effective flow cross sections, and a pressure-controlled valve system in the auxiliary puffer volume. Aside from modification of geometrical dimensions, the over-pressure valve setting in the auxiliary puffer was changed to increase the no-load pressure and the amount of cool gas available to interrupt smaller currents (when the self-blast effect is inactive) or to cool down the arcing zone when interrupting high short circuit currents.

Given the vertical arrangement of the interrupter and the fact that the moving contact is arranged on the upper side, the refilling valve of the auxiliary puffer remains in the open position until the pressure built up during an open operation is sufficiently high to close the valve against the force of gravity and its moment of inertia. To prevent gas leaking through the refilling valve from the very first moment of contact movement, this valve was equipped with a special closing mechanism. This closing mechanism keeps the auxiliary puffer closed in static condition and during open operations, while still enabling proper re-filling during closing operations [14].

With the goal of increasing the dielectric withstand capability during open operations and in order to maintain the arcing times in the same range that permits reliable and effective operation of SF_6 circuit breakers in the power grid, the opening speed was increased. The higher opening speed has advantages for specific switching operations, such as capacitive switching and additionally increases the pressure built-up in the auxiliary puffer. Nevertheless, a controlled gas flow with the increased no-load pressure must be kept in a certain range to avoid negative effects, such as current interruption prior to the natural current zero in special applications such as shunt reactor switching.

In addition, further modifications were made to the shields and in the exhaust of the interrupting chamber to control the dielectric withstand capability under hot gas conditions. The higher sonic velocity and temperatures of the C4-FN / CO_2 / O_2 gas mixture require proper gas mixing and guiding of the gas flow.

IEC TEST DUTIES FOR CIRCUIT BREAKERS

The GIS circuit breaker successfully passed the IEC temperature-rise test for a nominal current rating of 3150 A_{rms} and frequencies of both 50 Hz and 60 Hz.

As noted above, the different thermodynamic and transport properties of the C4-FN / CO_2 / O_2 mixture compared to SF_6 can influence the convective performance. The C4-FN gas mixture has lower density at 8 bar absolute pressure compared to SF_6 at 6 bar absolute pressure. This is partially compensated by higher thermal conductivity and specific heat of the C4-FN gas mixture. Direct experimental and numerical comparison of the convective performance revealed that the C4-FN gas mixture resulted in, on average, a 12% higher temperature rise of the circuit breaker [15]. However, most current SF_6 circuit breakers were designed to fulfill the IEC 62271-1 2011-08 standard, which allowed only a 65 K temperature rise. According to the new version of that standard, IEC 62271-1 Ed. 2.0 2017-07, the permitted temperature rise has been increased to 75 K, which can compensate the slightly lower convective performance of the C4-FN gas mixture compared to SF_6. In addition, small design changes to the equipment would also be sufficient to compensate for the lower convective performance and to achieve the same temperature rise with the C4-FN gas mixture as with SF_6.

Due to the differences between the SF_6 and C4-FN gas mixtures mentioned earlier, some modifications to the mechanical design were made. The drive was adapted to accommodate the increase in opening speed and the increase in no-load pressure build-up mentioned above. The impact of the changes in the drive on the linkage were investigated using dynamic finite element (FE) simulations. The linkage was modified based on the outcome of the FE simulations to ensure a robust and reliable design. Extensive mechanical testing of the circuit breaker was performed, and the circuit breaker successfully passed the class M2 mechanical test specified by the IEC 62271-100 standard.

The 145 kV GIS circuit breaker successfully passed all the terminal fault and out-of-phase fault test duties specified in the IEC 62271-100 standard. As mentioned above, design changes were made to ensure that a gas flow cools the arc zone for a sufficiently long time to ensure that even for longer arcing times the arc is cooled effectively, despite the higher speed of sound and faster outflow of the C4-FN / CO_2 / O_2 gas mixture used. These modifications were particularly important for test duties with relatively low currents (such as T10), since the mechanically generated pressure is responsible for cooling the arc. For higher currents, the arc ablates nozzle material, resulting in a pressure build-up (and corresponding gas flow) that is largely independent of the mechanical compression.

Previous laboratory studies in prototype circuit breakers demonstrated that the presence of a high dielectric strength additive, such as C4-FN, in a CO_2 / O_2 gas mixture significantly improves the dielectric recovery for low to moderate currents (corresponding roughly to the currents used in T10, out-of-phase, and T30 test duties) [4][11]. Development and type tests in the 145 kV GIS circuit breaker confirmed this result under type-test conditions (for a transient recovery voltage meeting the requirements of the IEC 62271-100 standard), for the full arcing time window (rather than for a defined arcing time used in laboratory tests), and when performing two open operations in rapid succession (O-CO sequence as defined in the IEC 62271-100 standard).

Laboratory studies were also performed for higher currents in a prototype circuit breaker, and these tests indicated that in such cases the high dielectric strength additive (such as C4-FN) made a less pronounced contribution to the current interruption performance, specifically the dielectric recovery after the arc is successfully interrupted [4]. Development and type tests of the 145 kV circuit breaker clearly demonstrate that the requirements of the basic short-circuit test duties are fulfilled. Thus, the strong current-interruption performance of CO_2-based gas mixtures, which has been shown in the laboratory and in various prototype devices [4][11][12], has been confirmed in a real GIS circuit breaker.

The most severe short-circuit test duty with regard to energy input of a high voltage circuit breaker according to the IEC 62271-100 standard is the T100a test. The T100a test not only tests the ability of a circuit breaker to interrupt the very high current (with maximum DC component) between the arcing contacts, but it also tests whether breakdown can occur between the interrupting chambers and the surrounding tank due to the presence of hot gas. Due to differences in the temperature-dependent adiabatic coefficient between the C4-FN / CO_2 / O_2 mixture and SF_6, a higher temperature results in the exhaust region of the circuit breaker, where hot gas from the arc zone is cooled before it is released to the surrounding tank. As noted above, the 145 kV GIS circuit breaker was modified to accommodate these higher temperatures, and it successfully passed the three-phase T100a type test.

Fault current interruption often plays a defining role in the design of a circuit breaker, but the operations a circuit breaker performs routinely during its service life, such as switching resistive loads, overhead transmission lines, or cables are also important. Switching lines or cables places demands on the cold dielectric strength of the insulating and interrupting medium—the circuit breaker must open sufficiently quickly to sustain the capacitive power frequency voltage that rises across the circuit breaker. The low currents typically switched under these conditions lead to interruption at very short arcing times (and correspondingly small contact gaps). The 145 kV GIS circuit breaker successfully passed the three-phase line and cable charging and the single capacitor bank switching type tests defined in the IEC 62271-100 standard. An example of a test operation is given in Figure 2.

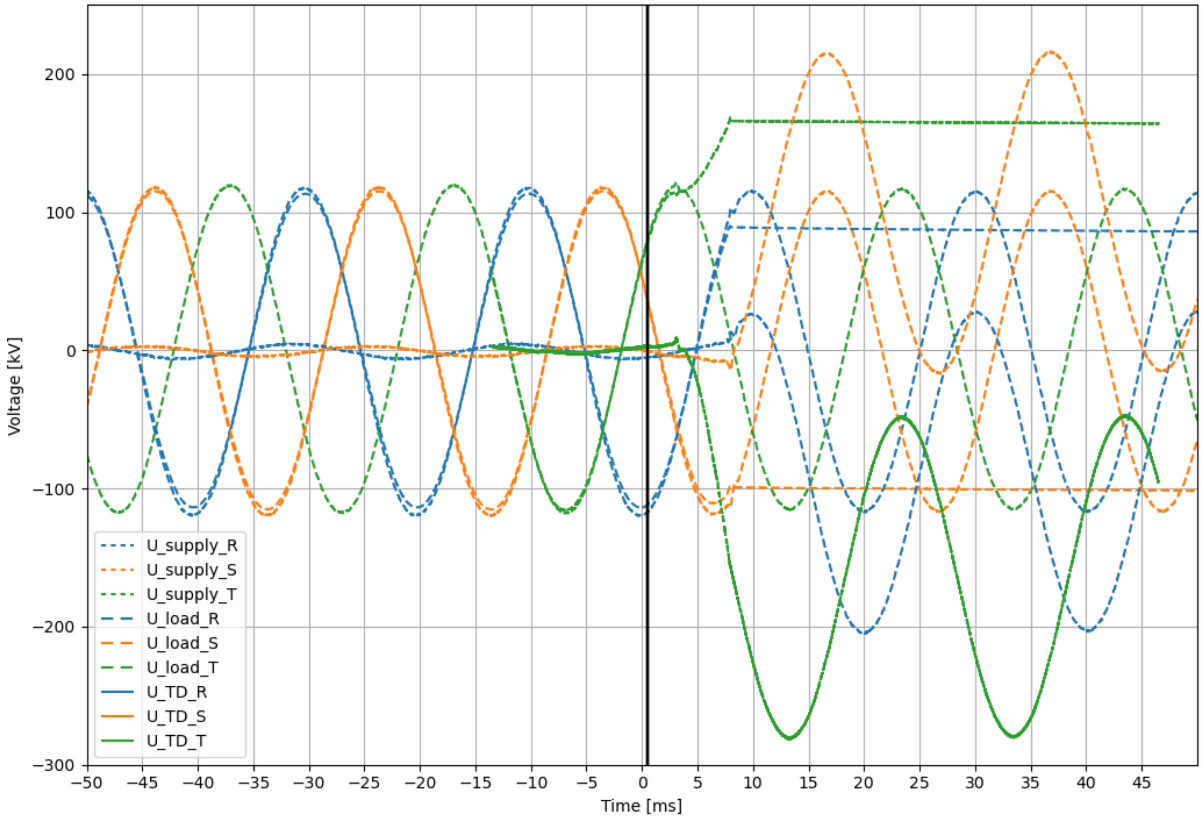

Figure 2. Plot of an example test shot from a line and cable-charging switching test. The voltage across the circuit breaker is labeled "U_TD".

DECOMPOSITION OF C4-FN DUE TO ARCING

Unlike SF_6, C4-FN does not recombine after it decomposes in an electric arc. Therefore, its decomposition must be taken into account when designing a circuit breaker. Here, we show that decomposition plays a negligible role in determining the lifetime of the 145 kV GIS circuit breaker. To determine the decomposition of C4-FN as a function of arc energy input, short-circuit current tests were performed in a circuit-breaker-based test device with a volume of approximately 60 L, analogous to tests described in [13]. After several operations, a gas sample was collected using an automated gas-sampling system (also described in [13]) and then analyzed using gas chromatography – mass spectrometry (GC-MS) and Fourier transform infrared spectroscopy (FTIR). In Figure 3 the measured concentration of C4-FN in the gas samples is plotted as a function of arc energy normalized to the volume of the test device. Note that these tests represent an extreme case—an energy equivalent to approximately fifteen short-circuit current interruptions with an average energy of 110 kJ each was input into the test device (1.65 MJ total). The GIS circuit breaker has a much larger volume, approximately 1.5 m^3. Even if we assume an extremely high arc energy input over the entire lifetime—for example, 6 MJ, the energy corresponding to twenty single-phase fault operations with a short-circuit current of 40 kA, an arc voltage of 500 V, and an arcing time of 15 ms—the energy density is approximately 4 kJ/L. A glance at Figure 3 illustrates that the C4-FN concentration only drops by a very small amount for this input energy density (by roughly 0.3 mol% absolute, or roughly 6 % of the total concentration). The drop in the amount of C4-FN when going from the nominal filling pressure (880 kPa) to lock-out pressure (800 kPa) is roughly 10 %. For the case considered above—twenty single-phase short-circuit current operations—the lifetime of the circuit breaker will be defined by contact erosion and nozzle wear, rather than by decomposition of C4-FN.

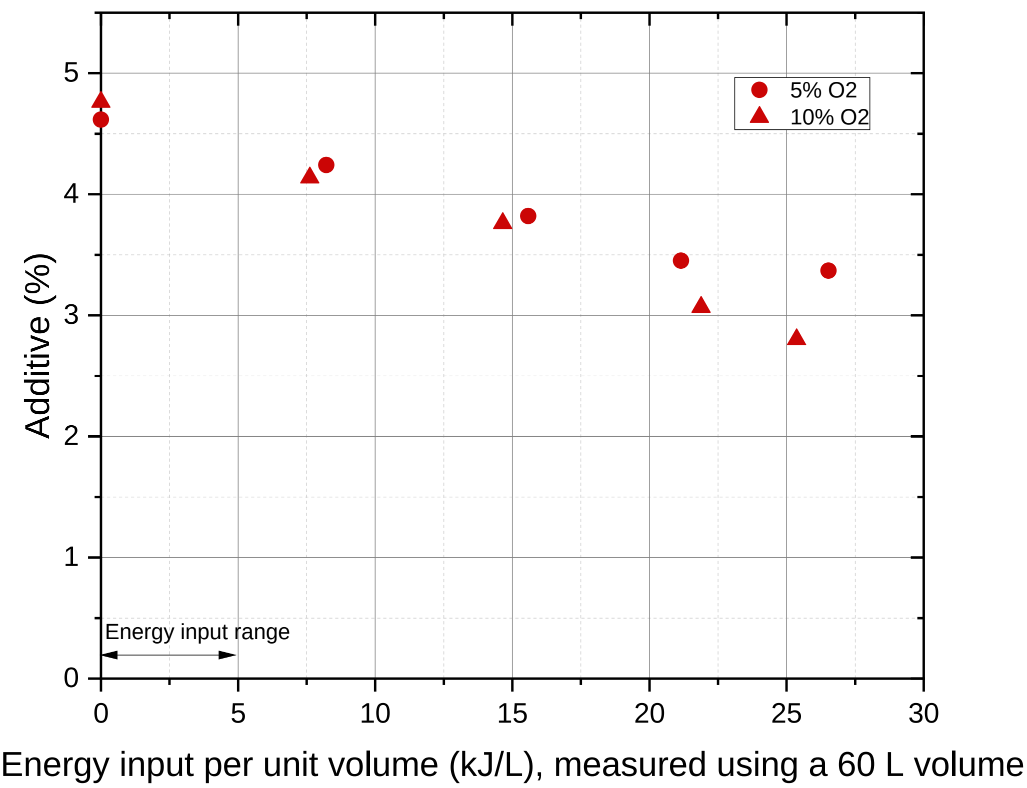

Figure 3. C4-FN concentration as a function of arc energy input (normalized to the total volume of the test device) obtained during a series of short-circuit current tests with an rms current of approximately 31.5 kA, an arcing time of roughly 12 ms, and an arc energy input per operation of approximately 110 kJ. Note that the typical energy input per unit volume for GIS circuit breakers extends up to roughly 5 kJ/L, illustrating that extremely high energy input per volume was used in these tests.

The GC-MS and FTIR analyses of the gas samples mentioned above also permitted detection (and, in some cases, quantification) of the decomposition products of C4-FN generated during arcing in a circuit breaker. These decomposition products include CF_4, C_2F_6, C_2F_4, CF_3CN, C_3F_6, C_2F_6CN, C_2N_2, COF_2, and CO. The concentrations of these decomposition products were found to increase with increasing arc energy input into the test device. It should be noted that CF_3CN, C_2F_5CN, and C_2N_2, while present, were found only in very low concentrations and did not significantly impact the overall toxicity of the gas mixture. The total toxicity of the gas mixture was calculated using the approach described in more detail in [13]. Briefly, the toxicity (expressed as the 4-hour LC_{50}, or the lethal concentration at which 50 % of the subjects in an animal test would die after four hours of exposure) was determined using the following formula:

$$LC_{50}^{mix} = \frac{1}{\sum_i \frac{c_i}{LC_{50}^i}},$$

Where c_i represents the concentration of each individual species and LC_{50}^i its 4-hour LC_{50}. The results of the calculation are presented in Figure 4. The toxicity classification according to the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) is also indicated in the plot. It can be seen that for the energy input per volume relevant for the GIS circuit breaker (4 kJ/L), the gas mixture after 20 single-phase short-circuit current operations is well inside the “not classified” region according to GHS. The figure also shows the 4-hour LC_{50} used in the safety data sheet (SDS) for heavily arced C4-FN / CO_2 / O_2 mixtures. It can readily be seen that the LC_{50} value in the safety data sheet corresponds to higher toxicity than can be expected from any real application. To determine an LC_{50} value for the safety data sheet, the worst-case measured concentrations taken from a number of different gas samples from different tests are rounded up to the nearest order of magnitude. In addition, the highest concentration of all the decomposition products measured in any sample is assumed, even if in samples from real tests this is not the case. Thus, it is not surprising that the LC_{50} value used in the SDS is lower (corresponding to higher toxicity) than that observed in gas samples from tests that represent realistic conditions for electrical equipment, even when considering an extreme number of short-circuit current interruptions. The low LC_{50} value (corresponding to higher toxicity) used in the SDS ensures that all cases are covered and that the protective equipment and other recommended precautions for handling the gas mixture after it is exposed to arcing are more than adequate. It should be noted that decomposition products can also be found in SF_6-filled electrical equipment after the gas is exposed to electric arcing. Proper procedures for handling and disposing of arc exposed SF_6 have been used routinely, safely, and reliably for decades.

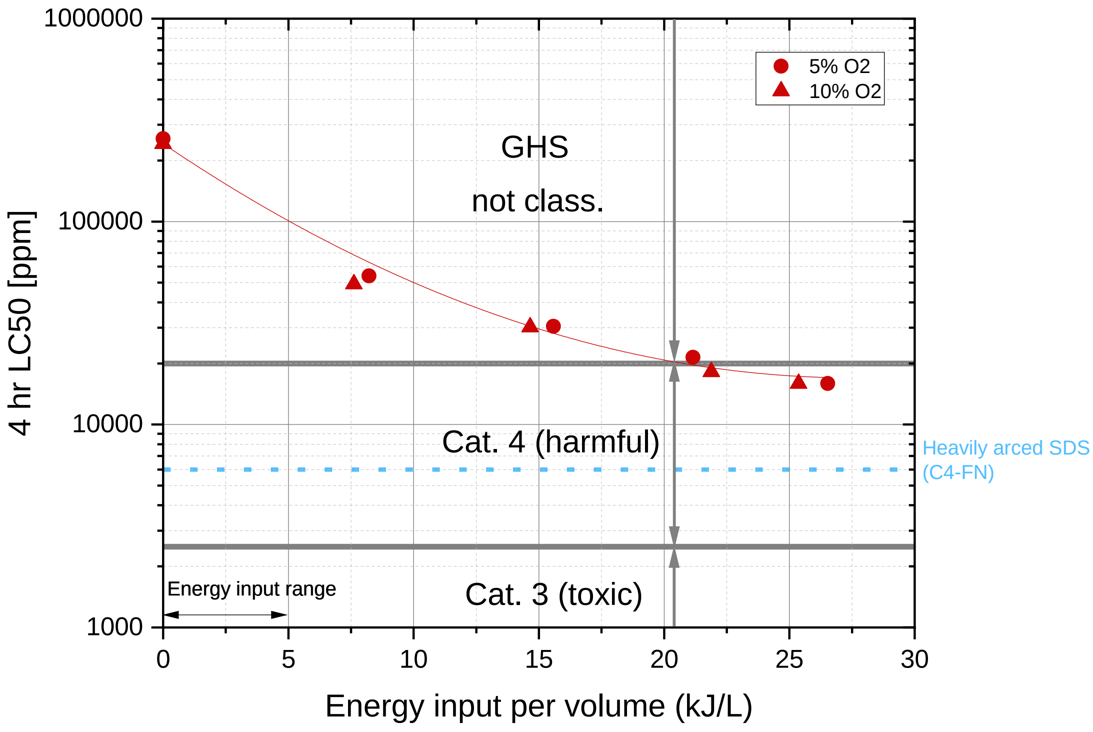

Figure 4. 4-hour LC_{50} calculated for two different gas mixtures containing C4-FN and exposed to different total amounts of arc energy per volume. The plot also indicates the thresholds for the different GHS toxicity classifications. Note that the typical energy input per unit volume for GIS circuit breakers extends up to roughly 5 kJ/L, illustrating that extremely high energy input per volume was used in these tests.

CONCLUSION

C4-FN / CO_2 / O_2 gas mixtures represent an alternative to SF_6 as the switching and insulating medium in gas circuit breakers. By making adjustments to the mechanical design and the arc zone of a circuit breaker, strong current interruption performance can be achieved with such mixtures, as confirmed by extensive development and type testing. Decomposition of C4-FN was shown through careful testing not to limit the lifetime of the circuit breaker, which, as in the case of SF_6 circuit breakers, is defined by nozzle ablation and contact erosion instead. Analysis of gas samples from short-circuit current tests further demonstrate that even gas exposed to heavy arcing is not classified as toxic according to the GHS toxicity classification. Thus, C4-FN / CO_2 / O_2 gas mixtures permit the design and construction of circuit breakers that provide the robust, reliable performance of time-tested SF_6 technology with a much smaller ecological footprint.

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