Journal of the Serbian Chemical Society
JSCS-info@shd.org.rs • www.shd.org.rs/JSCS

J. Serb. Chem. Soc. 89 (5) 693–704 (2024)
JSCS–5749

Original scientific paper
Published 9 May 2024

Sulphur hexafluoride in modern medium-voltage switchgear: Advantages, hazards and environmental impact

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(Received 3 December, revised 8 December 2023, accepted 2 February 2024)

Abstract: Sulphur hexafluoride is synthesised as a persistent and non-toxic gas with an exceptional dielectric strength. In contemporary medium-voltage switchgear within power distribution systems, SF_6 gas is used for the insulation and the extinction of electric arc. The application of SF_6 has advantages in terms of gas physicochemical characteristics and performance; the dimensions, the cost-effectiveness, the reliability of the switchgear equipment and the duration, as well as the cost of maintenance were significantly reduced. SF_6 is a known greenhouse gas, which tends to accumulate in the lungs, inducing oxygen depletion and respiratory complications. The by-products of SF_6 formed during the electric arc can be harmful and toxic. The equipment containing SF_6 is being replaced in the EU and worldwide. Using ALOHA® software the scenarios of leakage for SF_6 and by-products were modelled in urban areas, where the switchgear is frequently placed. In areas where the circulation of wind is lower (urban areas), in hazardous situations, it is not possible to depend on high dispersion levels or minimisation of concentration and threat. The models have shown that SF_6 poses an environmental problem and its by-products cause a serious health hazard in the case of leakage in urban areas, rendering red threat zones from 10 to 60 m in radius.

Keywords: greenhouse gas; switching device; persistence; toxicity; ALOHA® software.

INTRODUCTION

In the light of predominant effects of climate change that are becoming more evident every day, it is necessary to discuss and research the application of the greenhouse gases (GHG) produced, used, and abused in anthropogenic processes.

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https://doi.org/10.2298/JSC231203008B

GHGs have a significant role in the phenomenon recognized as a plethora of anthropogenically prompted climate change.

The substance proven to be a potent GHG chemical is sulphur hexafluoride. Sulphur hexafluoride (sulphur (VI) fluoride – SF_6), is a versatile and highly potent chemical compound with a broad range of applications. This inorganic compound has a unique and stable molecular structure, made up of one sulphur atom coupled to six fluorine atoms. SF_6 has found use in a variety of commercial and scientific practices due to its exceptional qualities.[1,2]

Because of the SF_6 electrical insulating characteristics, sulphur hexafluoride is a crucial component in high-voltage electrical equipment such as transformers, circuit breakers and switchgear.[3,4] SF_6 possesses the capacity of efficiently extinguishing the electrical arc, as well as non-reactivity to most common materials.

Sulphur hexafluoride also possesses prominent advantages and distinctive properties that render it highly useful in the vast variety of industrial practices, which make it an exceptionally versatile greenhouse gas (GHG). The key properties of SF_6 are its remarkable insulating properties, high thermal stability and non-flammability, effectively minimizing the risks of fires during use and applications. Additionally, SF_6 exhibits electronegativity nearly three times that of air, thus enhancing its performance significantly. One of the benefits is superior arc-extinguishing capabilities, which enable SF_6 switchgear to be designed in a more compact and robust manner. This, in turn, enables minimal maintenance, ultimately making SF_6 a highly cost-effective solution for various applications.[1,5,6]

Sulphur hexafluoride is also used in the manufacturing of semiconductors as a dielectric gas; as blanketing gas in the production of electronic devices, and it also finds applications in the medical field as a contrast agent for ultrasound imaging and ophthalmology, particularly during retinal detachment surgery (retinal ablation).[1,7,8]

Furthermore, SF_6 is widely used in environmental research and communal systems maintenance and diagnostics, as a tracer gas (flow patterns, leak detection), particularly in the research on air and atmosphere, due to its low reactivity and long atmospheric lifetime.[1]

However, the prominent disadvantage of SF_6 lies in its environmental impact, as it is a GHG with the highest global warming potential (GWP). The imminent and proven impact that SF_6 and its by-products have on the environment and health, prompted actions for its replacement, as it has been listed in the Kyoto Protocol, as a potent GHG. Corresponding to the European F-gas Regulation (EC 517/2014), which aims at cutting the EU's fluorine gas emissions to at least one-third by 2030, the replacement of switchgear using SF_6 as insulation gas has already begun.[1,9,10]

However, in Serbia, the electro-distribution industry regards switchgear equipment (SGE) that uses SF_6 as an insulating gas as the best available technology (BAT). In Vojvodina, approximately 5 % of all switchgear devices are the ones using SF_6. However, SF_6 SGE has been used in this region only since 2005, as it is characterised in this region as a BAT. Until then, devices insulation based on air, oil, low oil, and vacuum were used, so this percentage is expected to steadily increase over time, especially due to the automation and digitalisation of the power distribution network. This preference can be considered controversial and contradictory to EU practices, given the increasing trend of installing SGEs containing SF_6.

The recent decision of the United Nations Framework Convention on Climate Change (UNFCCC), from 2022, requires the use of 100-year monitoring values for GHGs to calculate the GWP of a chemical as a CO_2 equivalent.[11] According to the EPA and Intergovernmental Panel on Climate Change (IPCC), it is the most potent GHG known to date, with the astonishing 23,5 thousand times higher potential for global warming than an equivalent amount of CO_2 (Table I).

TABLE I. GHG properties in the atmosphere (lifetime in the atmosphere, global warming potential and approximate concentration in air)[12,13]

GHG compound	t / year	GWP / kg CO_2 m^{-2}	c / ppm; ppb; ppt
CO_2	–[a]	1	400 ppm
CH_4	12	28	1800 ppb
N_2O	109	265	320 ppb
PFCs	≤100	11,100	≤ 600 ppt
HFCs	≤15	12,400	≤ 80 ppt
NF_3	500	16,100	≤ 1 ppt
SF_6	3,200	23,500	8 ppt

[a] Is not provided, as it is a component of the atmosphere

The switchgear (SG) refers to the combination of electrical switches, fuses or circuit breakers used to control, protect and isolate electrical equipment. The switchgear controls the electrical system by switching on/off, regulating, and providing protection against abnormal conditions. SGs are used in substations, industrial setups, buildings and other places where electrical equipment is needed.[14] There are several points of classification of switchgear, medium voltage switchgear (MVSG) with SF_6 as the insulation gas was selected for the purpose of this research because of the physicochemical properties and environmental impacts of SF_6. In Serbia, about 5 % of all switchgear devices are the ones using SF_6 as insulation gas. In the examined area MVSG equipment is in urban and living areas, making the possibility of SF_6 and its by-products leakage plausible and an important issue to investigate.

The occurrence of an electric arc is advantageous in terms of managing overvoltage. However, when the arc is active, it generates a considerable amount of thermal energy, leading to substantial thermal and mechanical stresses. These stresses may include contact burning or combustion, insulation damage, and an elevation in internal pressure.[15]

During the arc, SF_6 will decompose and form SF_6 arc plasma, while forming many sulphur fluoride species. While arc temperature decreases, sulphur fluoride species will recombine into SF_6 molecules. However, if H_2O, O_2 and other vapours (nitrogen, helium, argon, hydrogen, *etc.*) are present in MVSG, the production of toxic by-products of SF_6 is inevitable.[1,9,16,17]

The inhalation of large quantities of SF_6 displaces oxygen in the lungs and can lead to asphyxiation. Furthermore, when arcs occur in switchgear, toxic by-products form, such as (hydrogen fluoride, sulfuryl fluoride, sulphur tetrafluoride, sulphur pentafluoride, sulphur(IV) oxide, among others), which may trigger a plethora of health problems, and in extreme cases can be life-threatening.[1,12,18]

Hydrogen fluoride is highly corrosive and toxic, causing severe chemical burns and respiratory damage upon exposure. It contributes to the formation of acid rain and has detrimental effects on aquatic life and vegetation when released into the environment.[1,19]

Sulfuryl fluoride is primarily a respiratory hazard and can cause severe lung damage and irritation to the eyes and skin. While sulfuryl fluoride is less persistent in the environment, its high global warming potential makes it a concern for climate change impacts.[1,20]

Sulphur tetrafluoride is extremely toxic, because the exposure to it leads to severe respiratory tract and skin irritation. SF_4 can decompose to form highly toxic and corrosive by-products, posing risks to wildlife and ecosystems.[1]

There is limited information on sulphur pentafluoride, but it is expected to be highly reactive and potentially toxic, similar to other sulphur fluorides. As with other fluorinated compounds, SF_5 could contribute to atmospheric and environmental degradation if released. SF_5 is particularly interesting as it can form highly toxic disulphur decafluoride (S_2F_{10}) in the appropriate conditions.[21]

Sulphur dioxide is a significant respiratory irritant, affecting lung function and exacerbating respiratory diseases. It is a major air pollutant, contributing to acid rain and causing harm to ecosystems and plant life.[1,22]

To address these problems, efforts are being made to reduce its emission into the atmosphere and create more ecologically friendly alternatives. Due to the previously mentioned environmental and safety issues and concerns, numerous countries and international bodies have implemented strict controls and regulations on the use, handling and disposal of SF_6.

The aim of this paper is to perform the risk assessment *via* ALOHA® software of the possibility of SF_6 and its by-products leakage from MVSG. It has been observed that the current energy system layout in Serbia does not have any plans in place for the evacuation of people in the event of an accidental release of SF_6 and its byproducts. Additionally, there are no early warning systems that can detect any leakage, except for the pressure control in the chamber where SF_6 is stored. However, this can only be monitored through the network surveillance system and not on the site of the leakage itself. This type of modelling can improve the preparation and security by enabling the creation of evacuation and minimization plans and improving the system as a whole.

EXPERIMENTAL

Areal Locations of Hazardous Atmospheres, ALOHA®, open-source software was used to provide risk assessment for accidental leakage of SF_6 from MVSG in transformation substations. ALOHA® is the hazard modelling program, based on Gaussian plume, for the Computer-Aided Management of Emergency Operations, CAMEO®, software suite, which is used widely to plan for and respond to chemical emergencies, developed by USEPA. The Gaussian plume-based models have the lowest resource demand and, thus, are suitable for fast decision-making in emergencies.[23]

ALOHA is a computer program that helps develop plans and responses to chemical releases and prepare for emergencies. It deals with chemicals that become airborne and includes two air dispersion models – the Gaussian model for lighter gases and the heavy gas model for denser gases. ALOHA has a decision algorithm to choose between these models and includes a chemical library with important data required as input for modelling scenarios. ALOHA can help model various release scenarios, including toxic gas clouds, BLEVEs, jet fires, vapour cloud explosions, pool fires and flammable areas. The output results include threat zones, graphs of source strength, and specific location threats. It's important to note that ALOHA provides estimates, not precise results, and the accuracy of the results depends on the input data accuracy and interpretation of the results. ALOHA has limitations, such as the inability to estimate distances greater than 10 km, unreliability of results under very stable atmospheric conditions or during wind speeds of less than 1 m/s, *etc*. However, since ALOHA has been compared to similar models and verified against field data, it is considered reliable and is used for the simulations conducted within this research.[23]

Several different but similar programs can be used for the modelling of hazardous and accidental situations, process hazard analysis software tool (PHAST) were compared with the Korea off-site risk assessment supporting tool (KORA), but ALOHA is the most precise assessment open-source tool, according to the vast number of literature sources. This was the reason for selecting ALOHA as the most viable option for this research.[23–25]

The methodology used for this research is in detail available in the literature.[24,25] The parameters for ALOHA® were selected according to the real location and position of the substation located in the outdoor urban environment. The input data required for modelling, physical and chemical properties, can be found in the ALOHA® chemical library (CAMEO® Chemicals) which comprehends hundreds of substances and solutions.

While using ALOHA® software, it's necessary to select a chemical and source type, specify the location and time, and input weather-related parameters including atmospheric stability class, varying terrain, cloud coverage, air temperature, humidity, speed and direction of the wind. With the required inputs and integrated equations, ALOHA® can perform simulations of various release scenarios, including toxic gas clouds, boiling liquid expanding vapor explosions (BLEVEs), jet fires, vapour cloud explosions, pool fires and areas prone to flammability. The software generates output that comprises scenario-specific danger zones, threats at locations, and graphs showing source strength. These results are displayed both graphically and in a text summary.[25]

Methodology

To manage disaster risks in inhabited areas, the hazard and exposure parameters must be assessed. This helps decision-makers understand the problem and develop an effective risk management strategy. The hazard context is analysed based on the physical nature of the accident and its impact on people and the environment. Atmospheric temperature, wind speed, relative humidity, atmospheric stability, cloud coverage, terrain profile and urbanisation level, substance properties and release quantity for hazard are defined as necessary variables for hazard definition and modelling, as well as location and impacted population are defined as necessary variables for modelling scenarios in the context of exposure.

The atmospheric parameters were fixed throughout all the modelled scenarios. The average and/or predominant conditions for selected locations were observed for environmental parameters that apply to selected locations – air temperature (11.6 °C), wind velocity (7 m s^{-1}) and direction (north-west), terrain (urban/forest), cloud coverage (40 %), atmospheric stability class (D), temperature inversion (no) and relative humidity (50 %).[26,27]

While varying the source parameters and chemicals (SF_6, HF, SO_2, SF_4, SF_5 and SO_2F_2) the analysis was performed for parameters incorporated into the ALOHA® concerning acute exposure guideline level (*AEGL*) or protective action criteria (*PAC*) values for outdoor stationed MVSGs (Table II).

TABLE II. The concentration of AEGL and/or PAC 1, 2 and 3 values and density in the gaseous state for SF_6 and its by-products[28-30]; c_1 – concentration of substance for AEGL1 or PAC1, c_2 – concentration of substance for AEGL2 or PAC2, c_3 – concentration of substance for AEGL3 or PAC3

Parameter	HF	SO_2	SF_4	SF_5	SO_2F_2	SF_6
c_1 / ppm	1	0.2	0.01	0.001	1	3,000
c_2 / ppm	24	0.75	0.1	0.1	21	33,000
c_3 / ppm	44	30	0.82	1	64	-
ρ / kg m^{-3}	0.69	2.62	3.78	5.38	3.72	6.5

When establishing a model, ALOHA® uses values from Table II to render a visualization of the data for inserted parameter values as 3 threat zones (TZ) as levels of concern (LOCs) – red, orange and yellow. The red LOC represents the worst hazard level; the orange and yellow LOC represent the areas of decreasing hazards.

RESULTS AND DISCUSSION

After conducting an analysis involving 60 distinct scenarios using the ALOHA® software, a crucial deduction has emerged. For 1 g of SF_6, there are no threat zones generated, the first mass of SF_6 that gets only yellow threat zones (TZ) generated for the average conditions is 114 kg with a 17 m radius. The first mass of SF_6 released that generates orange and yellow threat zones for the average conditions is 5 t with a 37 and 129 m radius, respectively. The release of 10 t of SF_6 generates red, orange, and yellow threat zones of 19, 54 and 184 m in radius, respectively. It has come to light that to pose a genuine threat to human health and overall well-being, an approximate release of 5 to 10 metric tons of SF_6 gas into the atmosphere is required, which is neither a realistic nor possible scenario. Interestingly, when we shift our focus to ambient air conditions, this threshold drops significantly to a mere 5 kg of SF_6. To put this into perspective, 5 kg is roughly half the volume of SF_6 typically found within a single medium voltage switchgear (MVSG).

Upon the evaluation of this data, it is determined that SF_6, when used as an insulation medium, emerges not as a direct health and safety concern, but rather as a prominent environmental issue. This concern, however, comes with a caution, that it primarily relates to situations where MVSGs are not enclosed within confined spaces.

According to the results of 60 different scenarios in ALOHA® software, it has been determined that to pose a danger to human health and well-being it is necessary to release approximately 5 to 10 t of SF_6 gas in the air, for the ambient air it is 5 kg of SF_6 which is approximately half the volume of SF_6 in one MVSG. Therefore, evaluating the obtained data, SF_6 as an insulation medium is clearly an environmental problem, not a health and safety concern when the MVSGs are not in closed spaces.

In a typical MVSG, there is approximately 10 L of sulphur hexafluoride, and a typical urban location usually houses about 3 to 5 devices. Considering SF_6 has a density in the range from 6 to 6.5 kg m^{-3}, this means that each litre of the gas has a mass from 6 to 6.5 g. The insulating gas is under a pressure of 20 kPa, with an estimated leak rate of 0.011 atm* cm^3 h^{-1}. In Table II the densities of all observed SF_6 by-products are shown.[28–30]

The results of the most relevant scenarios that were modelled are shown in Table III.

TABLE III. Results of threat zone radiuses, *r* / m, for modelled scenarios for each compound

Compound	Treat zone		
	Red	Orange	Yellow
HF	19	26	112
SO_2	13	79	133
SF_4	60	141	335
SF_5	36	240	562
SO_2F_2	<10	13	18

On the other hand, the by-products of the SF_6 that are formed if SF_6 is in contact with a spark or direct flame render a completely different outcome with only 1 g of substance. Grams are used in ALOHA® software as a unit of measure to perform the risk assessment. For HF, a quantity of 1 gram (1449 cm^3) of the gas produces a red TZ (RTZ) spanning 19 m in radius, while for SO_2, the same mase (381.7 cm^3) of gas results in an RTZ of 13 m in radius. In the case of SF_4, 264.5 cm^3 amounts to an RTZ of 60 m in radius, while the SF_5, with volume of

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* 1 atm = 101325 Pa

only 185.9 cm^3, creates an RTZ of 36 m in radius. Lastly, for SO_2F_2, 1 g (268.8 cm^3) creates a red threat zone of less than 10 m in radius.

The stations and substations housing MVSG filled with SF_6 are strategically located in urban areas, often in close proximity to densely populated areas, a compelling concern emerges. This concern revolves around the potential and, in many cases, well-justified risk of exposure in the unfortunate event of SF_6 and its by-products leakage. The urban setting amplifies the seriousness of the situation, as any release of this insulating gas and by-products can directly impact the nearby populace. In such circumstances, the paramount security measure in place remains the continuous monitoring of the pressure levels within the insulating system.

Fig. 1 shows a preview of the red threat zone radiuses for every SF_6 by-product discussed in this research for a specific realistic layout of an urban area. The possible source of SF_6 and its by-products is on the ground level, surrounded by 8 to 10-storey buildings (approximately 25 to 36 m). In this figure, a real location has been observed and the obtained RTZ have been shown on the selected real location. The spacing of the buildings and the location of streets, as well as the playground portray the real location in one city in Serbia.

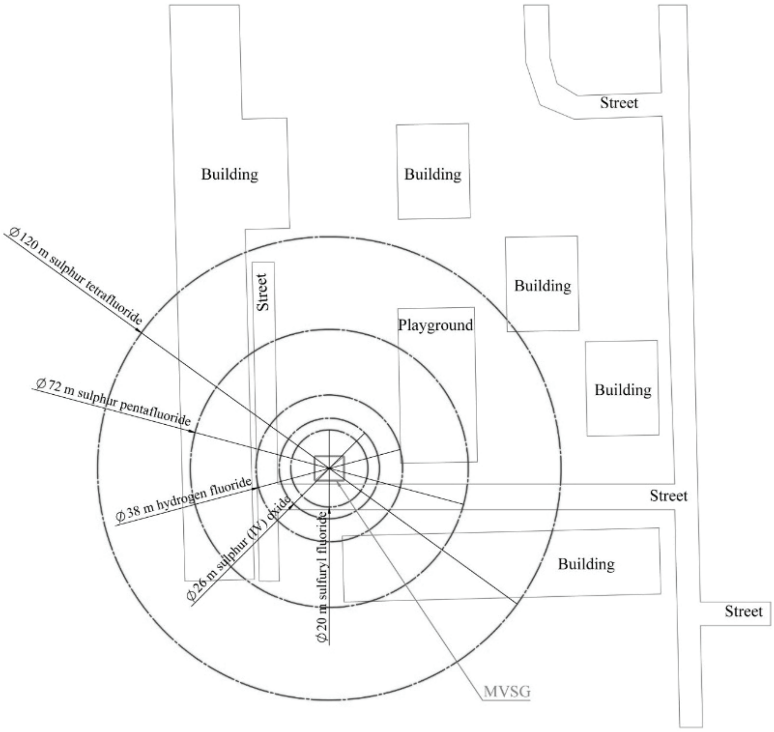

Fig. 1. A preview of the generated red threat zones (RTZ) for all SF_6 by-products in the urban area without impact of wind parameters (velocity and direction).

This type of research is the first in the area of MVSG using SF_6 as insulation gas and the potential risks to health and the environment in the Republic of Serbia. It opens the question and inquiry into the characteristics and the implications of SF_6 in this specific domain.

CONCLUSION

While SF_6 has several benefits that have helped it become a fixture in medium-voltage switchgear, its proven environmental effects, and risks, as well as the risk considering population, should not be neither underestimated nor ignored. Based on 60 scenarios in ALOHA® software, it's found that releasing 5–10 t of SF_6 gas poses a threat to human health. In open air, just 5 kg of SF_6 (half of a typical MVSG's volume) is enough to cause concern. This highlights SF_6 as an environmental issue, but not a health and safety hazard when MVSGs are outdoors. A typical MVSG has about 10 L of SF_6 in urban areas with 3–5 devices. SF_6 density ranges from 6–6.5 kg m^{-3}. It's pressurized at 20 kPa, with a leak rate of 0.011 cm^3 h^{-1}. In case of a spark or flame, SF_6 produces different by-products of only 1 gram in quantity. The ALOHA® software uses grams for the risk assessment. For example, 1 g of HF spans a 19 m radius RTZ, SO_2 a 13 m radius, SF_4 a 60 m radius, SF_5 a 36 m radius, and SO_2F_2 a <10 m radius.

The purpose of this paper is to conduct a risk assessment using the ALOHA® software to determine the likelihood and the possible effects of SF_6 and its by-products leaking from the medium-voltage switchgear. It has been observed that the current energy system layout in Serbia does not have any evacuation plans in place in case of an accidental release of SF6 and its by-products. Furthermore, there are no early warning systems to detect any leakage, except for the pressure control in the chamber where SF_6 is stored. However, this can only be monitored through the network surveillance system and not on the site of the leakage itself.

This type of modelling can enhance the preparation and security by allowing the development of the evacuation and the minimization plans, as well as the improvement of the entire system.

The urban medium-voltage switchgear installations introduce a prominent element of concern due to the potential leakage. In response to this concern, a central security measure takes precedence: the continuous monitoring of pressure levels within the insulating system. This responsible surveillance acts as the first line of defence, mitigating risks associated with SF_6 in these urban settings, as well as serious and compulsory responses and guidelines for conduct, protection, and actions in the case of leaks. Consequently, a growing resolve has emerged within the industry to explore viable alternatives to SF_6. There is an increasing determination to investigate SF_6 alternatives that might deliver the benefits of SF_6, while avoiding the related hazards and risks. Meanwhile, stringent regulations and routine maintenance can reduce many of the dangers connected with its usage. The only eco-efficient SF_6 alternative that shows promise to this date, other than air, which is already in use, is the HFO1234zeE (trans-1,3,3,3-tetrafluoropropene), as it has low, but more importantly, known toxicity and is not carcinogenic, mutagenic or reprotoxic.[31] As the environmental issues of SF_6 properties are more prominent (GWP = 23,500), it seems promising that the new generation of environment-friendly gas insulation, like HFO1234zeE has extremely low GWP (6) and ozone depletion potential (ODP = 0).

Acknowledgement. The work was partially supported by the Ministry of Education, Science and Technological Development through project no. 451-03-68/2020-14/200156: "Innovative scientific and artistic research from the FTS (activity) domain".

ИЗВОД

СУМПОР-ХЕКСАФЛУОРИД У МОДЕРНИМ СРЕДЊЕНАПОНСКИМ ПРЕКИДАЧИМА: ПРЕДНОСТИ, ОПАСНОСТИ И УТИЦАЈ НА ЖИВОТНУ СРЕДИНУ

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Сумпор-хексафлуорид синтетише се као постојан и нетоксичан гас са изузетном диелектричном чврстином. У савременим средњенапонским прекидачима система за дистрибуцију електричне енергије, SF_6 се користи за изолацију и гашење електричног лука. Примена SF_6 има предности у погледу физичко–хемијских карактеристика и перформанси гаса; димензијама, економичности и поузданости опреме прекидача, те у трајању и трошковима одржавања који су значајно умањени. SF_6 је познат као гас стаклене баште који има тенденцију да се акумулира у плућима, изазивајући смањење концентрације кисеоника и узрокује респираторне компликације. Нуспроизводи SF_6 могу настати током електричног лука и могу бити штетни и токсични. У ЕУ и широм света опрема која садржи SF_6 као изолациони гас је у процесу замене. Користећи софтвер ALOHA® моделирани су сценарији за неконтролисано испуштање за SF_6 и нуспродукте у урбаним подручјима, где се најчешће постављају прекидачи. У подручјима где је циркулација ветра слаба (урбана подручја) у опасним ситуацијама није могуће ослонити се на висок ниво дисперзије или минимизацију концентрације и претње. Модели су показали да SF_6 представља опасност по животну средину, а његови нуспродукти и озбиљан хазард по здравље ако се неконтролисано испусте у урбаним срединама, стварајући црвену зону опасности од 10 до 60 m у полупречнику.

(Примљено 3. децембра, ревидирано 8. децембра 2023, прихваћено 2. фебруара 2024)

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