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SF₆ Insulation: Possible Greenhouse Problems and Solutions

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Abstract

Sulfur hexafluoride (SF_6) is the most common insulating gas used in enclosed electrical systems to date. It has been identified, however, as a potent greenhouse gas and, thus, its use could impact environmental costs, regulations, and restrictions, in spite of its current low levels in the environment. This potential problem and current efforts in the search for short-term and long-term solutions are briefly outlined and discussed in this report. Limiting the release of SF_6 in the environment, recycling SF_6 , and limiting its use, are among the elements of an emerging consensus effort for the short run. A long-term solution may include the search for alternative high-voltage insulants, such as high-pressure gaseous dielectrics (e.g., N_2 and N_2/SF_6 mixtures), and would require accurate measurements and reference data to quantify their physical, chemical, and dielectric properties.

1 INTRODUCTION

This report aims at drawing attention to the possible emergence of an industrial problem, namely, the fact that the electrical industry's most commonly used high-voltage gaseous insulant, sulfur hexafluoride (SF_6), has been identified by the Intergovernmental Panel on Climate Change as a potent global warming (greenhouse) gas. The information provided in this report may help industry refine current practices in gas-insulated equipment, and may impact on future directions in the search for, and development of, an alternative gaseous insulation to replace the use of pure SF_6 .

Gas-insulated systems are widely used in the electric power industry for transmission and distribution of electrical energy. When SF_6 was first discovered, its potential application was considered solely to be for insulation, because of its good dielectric properties (breakdown strength typically about three times higher than air at atmospheric pressure.) However, a major expansion in the use of SF_6 came about when its excellent arc-quenching properties were appreciated. Circuit breakers with SF_6 were developed that are clearly superior in performance and cost to the competing oil and air-blast circuit breakers, and these took over the market for the high-voltage systems and in parts of the distribution systems. Compressed SF_6 is also extensively used for high-voltage insulation in the electric-power industry, such as in metal-clad high-voltage gas-insulated transmission lines, bushings, capacitors, and transformers. The SF_6 -insulated transmission lines provide a cost-effective alternative to overhead lines in situations where there are limitations and/or restrictions on transmission rights-of-way such as in congested or highly populated areas. A major use for SF_6 has been in gas-insulated substations (GIS), where the whole substation is insulated with SF_6 , i.e., the SF_6 -insulated circuit breakers, disconnects, grounding switches, busbars, potential transformers, power transformers, etc. are interconnected. Gas-insulated systems are now a major part of the transmission and distribution system all over the world. They offer significant savings in land use, are aesthetically acceptable, have relatively low radio and audible noise emissions, and enable substations to be installed in cities very close to the loads. Virtually every substation now being built uses SF_6 for circuit breakers, and every GIS and gas-insulated transmission line relies on SF_6 for insulation.

The electrical industry uses about 80% of the SF_6 produced world-wide [1, 2]. The other 20% of SF_6 production is used in aluminum and magnesium foundries, semiconductor manufacturing, and other technologies [2]. These and other (e.g., thermal insulation) applications of SF_6 resulted in rising demand for this gas. World-wide annual production of SF_6 has increased since the early 1970's to 7×10^6 kg (7,000 metric tons) per year in 1993 [1]. It is predicted that by the year 2010, SF_6 production levels could reach 10×10^6 kg (10,000 metric tons) per year [2].

Largely because of its many industrial uses, SF₆ is an extensively and comprehensively studied gas. It is a very stable electronegative (electron attaching) gas that readily reforms itself when dissociated under high-pressure conditions in an electrical discharge. In its normal state, SF₆ is chemically inert, non-toxic, and non-flammable. Due to the unique physical and chemical properties of this "man-made" molecule, the SF₆ gas has excellent dielectric and thermal properties which make it convenient to use in many industries. Because of its relative inertness and non-toxic characteristics, it has generally been assumed to be an environmentally safe and acceptable material in the sense that it does not interact unfavorably with the earth's biomass. A potential problem with SF₆ relevant to the environment is its indirect, long-term influence on global warming. Although its contribution to warming is considered, at present, to be insignificant due to its low concentration, SF₆ tends to accumulate in the earth's atmosphere (due in part to its inertness) and could, in the future, build up to the point where its effect on global warming is no longer negligible. Some of the perceived problems associated with the global warming potential of SF₆, the proposed solutions to these problems, and the implications of these solutions to the industries that use SF₆ are examined in this report.

2 SF₆ IS A POTENT GREENHOUSE GAS

It is broadly recognized that gaseous insulation must be environmentally acceptable, now and in the future. It is primarily for this reason that recent questions concerning possible environmental effects of SF₆ and other fully-fluorinated compounds (FFC) on global warming¹ have drawn the attention of the electrical and chemical industry, governmental and regulatory agencies, and users of SF₆-insulated equipment. The issue requires proper attention if the use of this excellent gaseous dielectric material is to serve the multitude of electrical-insulation needs of the electrical industry in a balanced way, now and in the future.

¹The earth's surface emits infrared radiation, a portion of which is reflected back by atmospheric gases with strong infrared absorption especially in the wavelength range from about (7 to 13) μm . Such gases are both naturally occurring (e.g., H₂O, CO₂, CH₄, N₂O) and man-made (e.g., FFCs). To the naturally-occurring gases, man adds large quantities of gases principally through the combustion of fossil fuels (e.g., CO₂). The "effective trapping" of infrared radiation results in an increase of the average temperature of the earth's atmosphere. The effect is known as "the greenhouse effect" and the gases responsible for it are known as "greenhouse gases". Naturally, the greenhouse effect has two components: the "natural greenhouse effect" due to the naturally-occurring greenhouse gases and the "enhanced greenhouse effect" due to the presence of greenhouse gases contributed by man. The man-produced contributions to greenhouse gases change the average net radiation at the top of the troposphere. They shift the balance between incoming and outgoing radiation toward the former causing "global warming" (see discussion in [3]; also see this reference for a definition of global warming potentials of greenhouse gases).

Sulfur hexafluoride does not naturally occur in the environment. It is a greenhouse gas, i.e., it can potentially have an effect on global warming. Actually, according to the Intergovernmental Panel on Climate Change [2, 3], SF₆ is "the most potent greenhouse gas ever evaluated" by this panel. Its global warming potential is estimated to be about 25,000 times larger than that of CO₂ [4]. This can be seen from Tables 1 and 2, respectively taken from references [3] and [2]. The extremely high potency² of SF₆ as a greenhouse gas is due to its very effective heat-trapping properties. Besides this, SF₆ is largely immune to chemical decomposition and, thus, it can contribute "permanently" to global warming. Its lifetime³ in the environment is estimated to be 3,200 years [3]. Its effects are, then, virtually cumulative and its contribution to global warming is virtually irreversible.

While the potency of SF₆ as a greenhouse gas is extremely high, its environmental impact is a strong function of its concentration in the environment. Recent measurements of SF₆ concentrations in the atmosphere [6, 7] have suggested that the amount of SF₆ in the atmosphere is increasing at a rate of about 8.7% per year; from barely measurable trace quantities a decade ago to current levels of 3.2 pptv (parts in 10¹² by volume)⁴, to doubling in a decade [1, 2, 3] (see Figs. 1 and 2). The long-term atmospheric concentration of SF₆ is estimated to be less than 10 pptv [1, 2]. The rate of increase of SF₆ in the atmosphere is higher than that for CO₂, and if its rate of growth continues in the future, it is feared that problems may arise.

There seems to be a controversy as to how much SF₆ is leaked to the atmosphere [8]. It has, for example, been pointed out [1, 8] that the release of SF₆ in the atmosphere is substantially lower than those which have been assumed in figuring the potential impact of SF₆ as a greenhouse gas⁵. It is also argued (e.g., [8, 10]) that the SF₆ production levels tend towards saturation and that the concentration of SF₆ in the atmosphere is small compared to the concentrations of other greenhouse industrial gases ([1, 2, 11]; Fig. 3). The current relative contribution of SF₆ to global warming is estimated to be about 0.01% [1]; in 100 years from now it is estimated to be less than 0.1% even if SF₆ is used at current levels [8]. If these estimates are correct, even though the long lifetime of SF₆ in the atmosphere and the large SF₆ global warming

²The potency of a greenhouse gas represents its relative contribution to the greenhouse effect. It depends on its relative abundance in the atmosphere, its infrared absorption in the critical wavelength range, and its lifetime in the atmosphere [3, 5, 6].

³This is the time for a quantity of given gas released in the atmosphere to be reduced (via natural processes) to about 37% of the original quantity.

⁴pptv = 10⁻¹² ppv; this concentration was measured [6] at an altitude of about 11.8 km. At this altitude the pressure is 20.26 kPa (200 mbar) and the temperature is 216.65 K. At 3.2 pptv concentration, there are about 20 million SF₆ molecules in one cubic centimeter of space.

⁵During a discussion of this issue at the 1990 International Symposium on Gaseous Dielectrics, it was suggested [9] that the concentration of SF₆ in the atmosphere corresponds roughly to its release rates and that it was roughly consistent with the SF₆ integral production since 1970 [9].

Table 1. Global warming potentials (GWP) of a number of gases referenced to the absolute GWP for CO₂. The typical uncertainty is $\pm 35\%$ relative to the CO₂ reference (from [3]).

| Species | Chemical Formula | Lifetime (yr) | Global Warming Potential (Time Horizon) | | |
|-----------------------------|---|------------------|---|--------------|--------------|
| | | | 20 years | 100 years | 500 years |
| Methane* | CH ₄ | 14.5 \pm 2.5** | 62 | 24.5 | 7.5 |
| Nitrous oxide | N ₂ O | 120 | 290 | 320 | 180 |
| CFCs | | | | | |
| CFC-11 | CFCl ₃ | 50 \pm 5 | 5000 | 4000 | 1400 |
| CFC-12 | CF ₂ Cl ₂ | 102 | 7900 | 8500 | 4200 |
| CFC-13 | CClF ₃ | 640 | 8100 | 11700 | 13600 |
| CFC-113 | C ₂ F ₃ Cl ₃ | 85 | 5000 | 5000 | 2300 |
| CFC-114 | C ₂ F ₄ Cl ₂ | 300 | 6900 | 9300 | 8300 |
| CFC-115 | C ₂ F ₅ Cl | 1700 | 6200 | 9300 | 13000 |
| HCFCs, etc. | | | | | |
| HCFC-22 | CF ₂ HCl | 13.3 | 4300 | 1700 | 520 |
| HCFC-123 | C ₂ F ₃ HCl ₂ | 1.4 | 300 | 93 | 29 |
| HCFC-124 | C ₂ F ₄ HCl | 5.9 | 1500 | 480 | 150 |
| HCFC-141b | C ₂ FH ₃ Cl ₂ | 9.4 | 1800 | 630 | 200 |
| HCFC-142b | C ₂ F ₂ H ₃ Cl | 19.5 | 4200 | 2000 | 630 |
| HCFC-225ca | C ₃ F ₅ HCl ₂ | 2.5 | 550 | 170 | 52 |
| HCFC-225cb | C ₃ F ₅ HCl ₂ | 6.6 | 1700 | 530 | 170 |
| Carbon tetrachloride | CCl ₄ | 42 | 2000 | 1400 | 500 |
| Methyl chloroform | CH ₃ CCl ₃ | 5.4 \pm 0.6 | 360 | 110 | 35 |
| Bromocarbons | | | | | |
| H-1301 | CF ₃ Br | 65 | 6200 | 5600 | 2200 |
| Other | | | | | |
| HFC-23 | CHF ₃ | 250 | 9200 | 12100 | 9900 |
| HFC-32 | CH ₂ F ₂ | 6 | 1800 | 580 | 180 |
| HFC-43-10mee | C ₄ H ₂ F ₁₀ | 20.8 | 3300 | 1600 | 520 |
| HFC-125 | C ₂ HF ₅ | 36.0 | 4800 | 3200 | 1100 |
| HFC-134 | CHF ₂ CHF ₂ | 11.9 | 3100 | 1200 | 370 |
| HFC-134a | CH ₂ FCF ₃ | 14 | 3300 | 1300 | 420 |
| HFC-152a | C ₂ H ₄ F ₂ | 1.5 | 460 | 140 | 44 |
| HFC-143 | CHF ₂ CH ₂ F | 3.5 | 950 | 290 | 90 |
| HFC-143a | CF ₃ CH ₃ | 55 | 5200 | 4400 | 1600 |
| HFC-227ea | C ₃ HF ₇ | 41 | 4500 | 3300 | 1100 |
| HFC-236fa | C ₃ H ₂ F ₆ | 250 | 6100 | 8000 | 6600 |
| HFC-245ca | C ₃ H ₃ F ₅ | 7 | 1900 | 610 | 190 |
| Chloroform | CHCl ₃ | 0.55 | 15 | 5 | 1 |
| Methylene chloride | CH ₂ Cl ₂ | 0.41 | 28 | 9 | 3 |
| Sulphur hexafluoride | SF₆ | 3200 | 16500 | 24900 | 36500 |
| Perfluoromethane | CF ₄ | 50000 | 4100 | 6300 | 9800 |
| Perfluoroethane | C ₂ F ₆ | 10000 | 8200 | 12500 | 19100 |
| Perfluorocyclo-butane | c-C ₄ F ₈ | 3200 | 6000 | 9100 | 13300 |
| Perfluorohexane | C ₆ F ₁₄ | 3200 | 4500 | 6800 | 9900 |

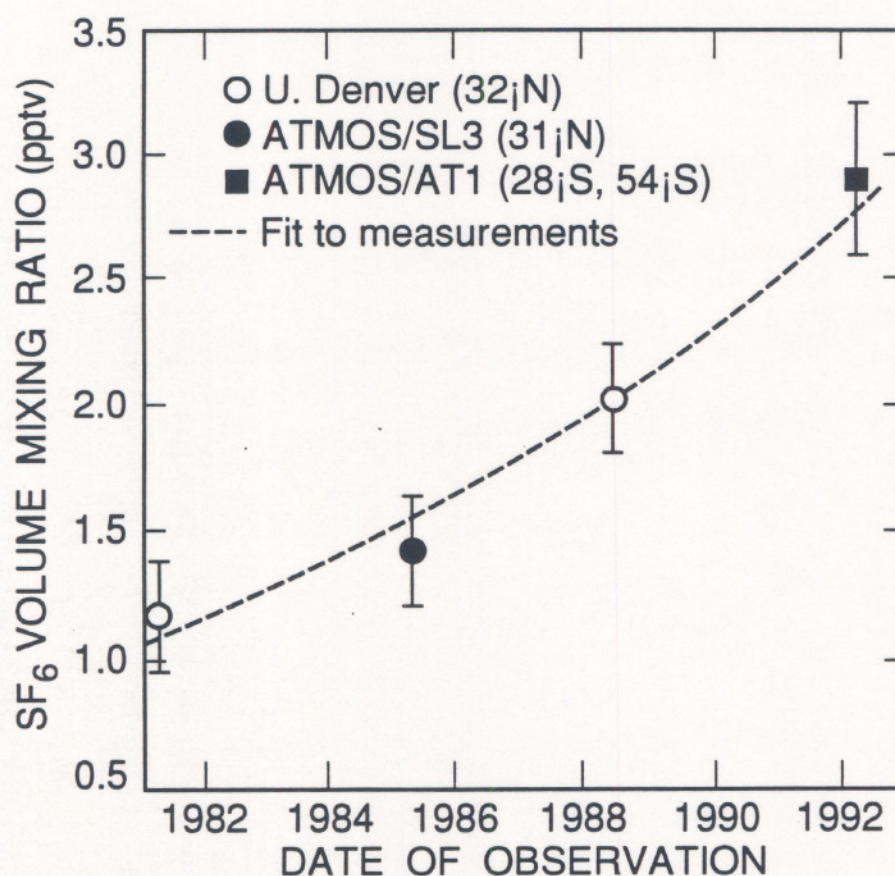
*The methane GWP includes the direct effect and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO₂ is not included.

**For methane the adjustment time is given, rather than the lifetime.

Table 2. The global warming potential of most common FFC's compared to CO₂ (from [2]).

| | Lifetime Years [3] | Global Warming Potential* | Main Sources and Applications |
|--------------------------------|--------------------|---------------------------|--|
| CO ₂ | 50-200 | 1 | Fossil Fuel Combustion |
| CF ₄ | 50000 | 6300 | Aluminum Smelters, Semiconductor Manufacturing |
| C ₂ F ₆ | 10000 | 12500 | Aluminum Smelters, Semiconductor Manufacturing |
| SF ₆ | 3200 | 24900 | Electrical Insulation, Aluminum and Magnesium Foundries, Semiconductor Manufacturing |
| C ₆ F ₁₄ | 3200 | 6800 | Electronic Testing, Heat Transfer Fluids, Substitutes for Ozone-Depleting Chemicals |

*Over a 100-year time horizon.

**Figure 1.** Average SF₆ volume mixing ratio (pptv) between 12 km and 18 km altitude as a function of date of observation [6].

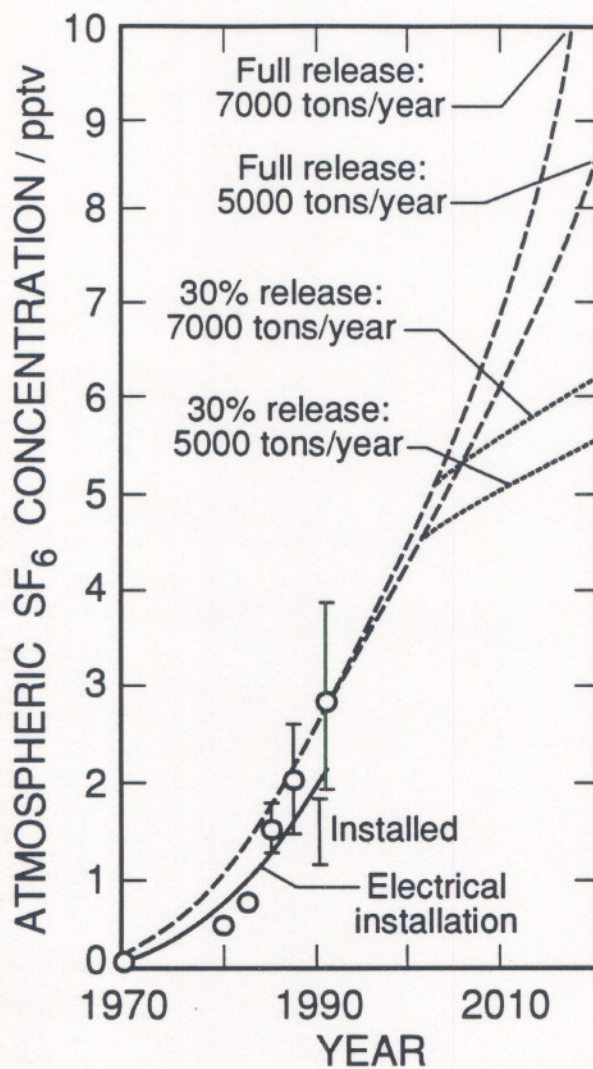


Figure 2. Atmospheric SF₆ concentration (pptv) as a function of year. The solid curve represents the share of SF₆ used in gas-insulated electrical equipment in the past, the open circles are measured atmospheric trace concentrations, and the bar labelled "installed" is the quantity of enclosed SF₆ installed in electrical equipment world wide in 1990 [1,11].

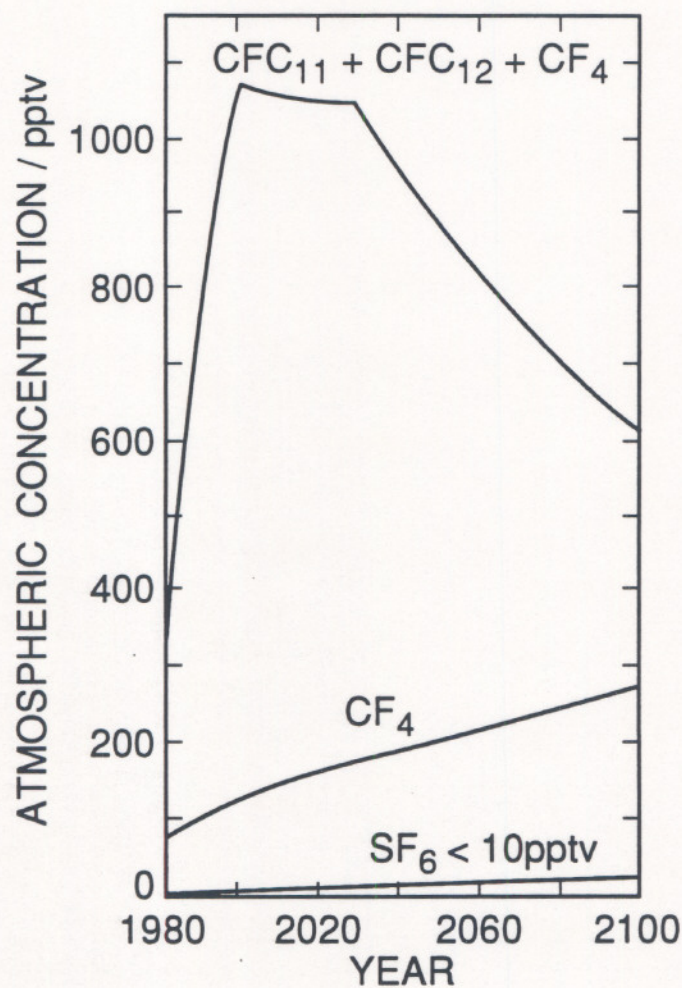


Figure 3. Long-term projected atmospheric concentration (pptv) of the FFC SF_6 , CF_4 , CFC11 (CFCl_3), and CFC12 (CF_2Cl_2) as a function of time [1,11]. See Table 1 for identification of chlorofluorocarbons.

potential are reasons for concern, the amount of SF_6 in the atmosphere may be too small to make its environmental impact significant.

It should be pointed out that while many of the decomposition products due to discharges associated with the uses of SF_6 in the electrical industries are toxic (e.g., S_2F_{10} , SO_2 , SOF_2 , $\text{S}_2\text{O}_2\text{F}_2$, SOF_4 [12]), these can be largely removed by filtration and by gas recycling. The more crucial issue concerning the environmental impact of SF_6 , is, therefore, the release of SF_6 itself in the environment with its possible impact on global warming. SF_6 is not a naturally occurring gas in the environment, and there seems to be no effective mechanism to easily dispose of it in the atmosphere. In this connection, it should be noted that about 20% of the annual consumption of SF_6 is in applications in which it is released in the atmosphere [1, 2]. These applications are mostly in semiconductor manufacturing and are not addressed in this report.

Unlike many other environmental pollutants (e.g., chlorofluorocarbons), there is no evidence that SF_6 contributes to stratospheric ozone destruction [1]. This is a welcomed consequence of the high resistance of the SF_6 molecule to decomposition, and the fact that the fluorine atom (which may result from the SF_6 decomposition) does not catalytically react with ozone [13].

3 WORLD-WIDE CONCERNS AND ACTIONS

Presently, there is no regulation regarding the use of SF_6 . There is, however, a real concern for possible regulation and restrictions in the use and transport of SF_6 in the future. This concern is based on actions being taken in a number of countries. For example:

1. Sweden is leading the way in terms of regulation and is near to putting SF_6 under regulatory control [2, 8]. Switzerland may also soon move in this direction [8]. Germany and Norway included SF_6 in their greenhouse inventories [2]. The SF_6 greenhouse issue has been raised in Germany and in France [8, 11]. In France, political pressure ruled out the use of pure SF_6 in a planned gas-insulated transmission line and forced the consideration of alternative, less efficient but environmentally acceptable, insulating gases such as N_2 and SF_6/N_2 mixtures (at pressures of about 1000 kPa, i.e., at pressures about 2.5 to 3 times higher than those normally employed for pure SF_6 (350 kPa to 400 kPa) [10, 11, 14, 15]. In Europe, some [8] fear restrictions on the transport of SF_6 . In Europe, also, there are pressures to recycle SF_6 . While the electrical industry in Canada and Japan is fully aware of the SF_6 environmental issue, there seems to have been no real position established by these countries on the subject [11, 16, 17, 18].

2. In the United States, the Environmental Protection Agency (EPA) is committed to action on this issue [19]. The agency plans to have a conference to address the problem and to formulate an action plan. EPA apparently wants to formulate with industry a "voluntary compliance program" which will recover SF_6 and which will reduce its release in the atmosphere. Such a program will, of course, come at a cost; it is in its infancy and is not yet designed. It will be one of the tasks of the workshop to help formulate such a plan.

In the United States and in other countries (e.g., Canada and Europe) the need to formulate a common approach to the SF_6 problem is emphasized. The centerpiece of this common approach is envisioned to be a policy of voluntary compliance. In this connection, a number of scientific committees and industry organizations [1, 8, 10, 11, 14, 15, 16] are looking into the issue.

A recent report on the subject by E. Cook of the World Resources Institute [2] recommends that (i) the international community not allow SF_6 and other FCC emissions or new sources for these industrial chemicals to grow uncontrolled, (ii) FCC's be phased-out over time because of their lasting impact on the environment, and (iii) the government include FCC's in the greenhouse gas inventories.

3. The electrical industry apparently is engaged in a "voluntary" program aiming at (i) reducing SF_6 releases in the environment (the release of SF_6 to the atmosphere is largely avoidable), (ii) pressing for recycling (restoration of SF_6 to its initial state), and (iii) curtailing the quantity of SF_6 used. This program is still in its infancy. In this connection, however, chemical companies are now interested in recycling used SF_6 and are raising the price. (One chemical company, for example, has recently raised the price of SF_6 by 20% [10], after having kept the price constant for a number of years).
4. While SF_6 is the electrical industry's favorite gaseous insulant, industry is looking at alternative gases and gas mixtures for specific high-voltage insulation needs (e.g., SF_6/N_2 mixtures for long gas-insulated transmission lines).
5. One must not lose sight of the fact that the future global warming effect of SF_6 cannot be accurately predicted. Although there is scientific evidence which shows a continuing increase in the earth's mean atmospheric temperature that can be correlated with increases in carbon dioxide and other infrared absorbing gases, the atmosphere is a complex system that is not yet completely understood. The influence that human modifications of the earth's atmosphere have on global warming is an ongoing topic of major internationally supported research efforts. While the technical uncertainty remains, political decisions will be made based on the best information available.

4 CONVERGING VIEWS

There seem to be certain elements in the current discussion of the SF₆ issue on which the various views of experts in this area converge. There is, for instance, broad agreement that SF₆ must be recoverable, must not escape the system in which it is used, must be cleaned of its by-products after use, and must be recycled (preferably on site). The "intrinsic" contaminants such as H₂O, N₂, O₂ and CF₄ can affect decomposition and electrical breakdown of SF₆ under some conditions [21, 22]. However, O₂, N₂, and CF₄, in particular, are non-polar gases that are nearly impossible to remove by conventional gas filtering procedures. Moreover, the extent to which they adversely affect the performance of SF₆ as a practical and reliable insulating medium is not known with certainty. The standards and requirements for intrinsic impurities in SF₆ are currently under review by the IEEE Technical Committee on Gaseous Dielectrics S-32-11 and the IEC Working Group 23.03 on Metalclad Substations. Current recommended practices for handling of SF₆ and its decomposition products [23] may need to be modified.

Finally, it seems that the idea of voluntarily reducing the amount of SF₆ used and the quantity of SF₆ which escapes to the environment, along with recycling, is gaining acceptance at least as an interim solution until alternatives to SF₆ can be found.

5 RECYCLING

Recycling of used SF₆ is currently being done on a small scale, but may increase in the future. Recycling is envisioned to be done in two general ways: by portable equipment to recycle the SF₆ at the location where it is used, and by centralized facilities to which used SF₆ is sent for cleaning. The latter approach is better suited for recycling "very dirty" SF₆ and large quantities of SF₆. In both cases, standards have to be established and maintained.

Chemical companies are now interested in recycling and this may change the recycling situation because presently there are only a few companies that can recycle SF₆ in the field. The majority of small electrical industries cannot recycle and thus release the gas in the atmosphere. The ABB, Switzerland, sells its used SF₆ to a German company for recycling [8].

Producers and users of SF₆ are both becoming increasingly aware of the environmental issue and this awareness will probably result in more recycling, and more support for the development of cheaper, compact, and efficient recycling equipment and the development of recycling procedures and usability standards which are presently lack-

ing. These efforts will also remove the economic incentive to release the used gas to the environment (since it is often cheaper to release the used gas and to replace it with new SF₆.)

Finally, as we noted earlier in this report, about 20% of the SF₆ is used for applications in which the process releases the gas to the atmosphere and recycling may be difficult and expensive.

6 SF₆ SUBSTITUTE GASES

A possible solution to the SF₆ greenhouse problem is the development of suitable alternatives. Efforts to find "better" gas dielectrics than SF₆ trace back a few decades. Extensive research, especially in the seventies [24, 25, 26, 27, 28], has shown some attractive alternatives to using pure SF₆, particularly among the perfluorocarbons and their mixtures (see Table 3 and Fig. 4). Some of the perfluorocarbons are as much as 2.5 times better in dielectric strength than pure SF₆. Unfortunately these too are greenhouse gases. Moreover, little is known about their chemical stability in electrical discharges and about their compatibility with other insulating materials used in electrical power systems.

Among the gas mixtures which exhibit desirable dielectric, chemical, and heat transport properties are clearly those of the electronegative SF₆ and the non-electronegative N₂. Nitrogen is the ideal gas: it is abundant, cheap, inert, non-toxic, non-flammable, and unquestionably environmentally acceptable. Existing measurements [24-41] on N₂, SF₆ and SF₆/N₂ mixtures indicate that:

- Under uniform field conditions and low pressures (less than 300 kPa) pure SF₆ is superior to N₂ by about a factor of three (see Table 3 and [25, 26]).
- The breakdown voltage (DC or AC) of N₂ increases with pressure as does that of SF₆ (see Fig. 5 and [26, 33, 34, 35, 36, 37, 38]), but it tends toward saturation at high pressures.
- The dielectric strength of N₂ is less sensitive than SF₆ (and any other electronegative gas) to non-uniform field conditions (at least at low pressures). This advantage is understood on the basis of the energy dependence of the electron attachment and ionization cross sections [25, 26], and by the so-called figure of merit M values [42] (see Table 4). Similarly, N₂ is less sensitive than SF₆ to conductor roughness; surface roughness effects are a strong function of the cable system size. Little is known about the behavior of insulating gases at high pressures and under these conditions.

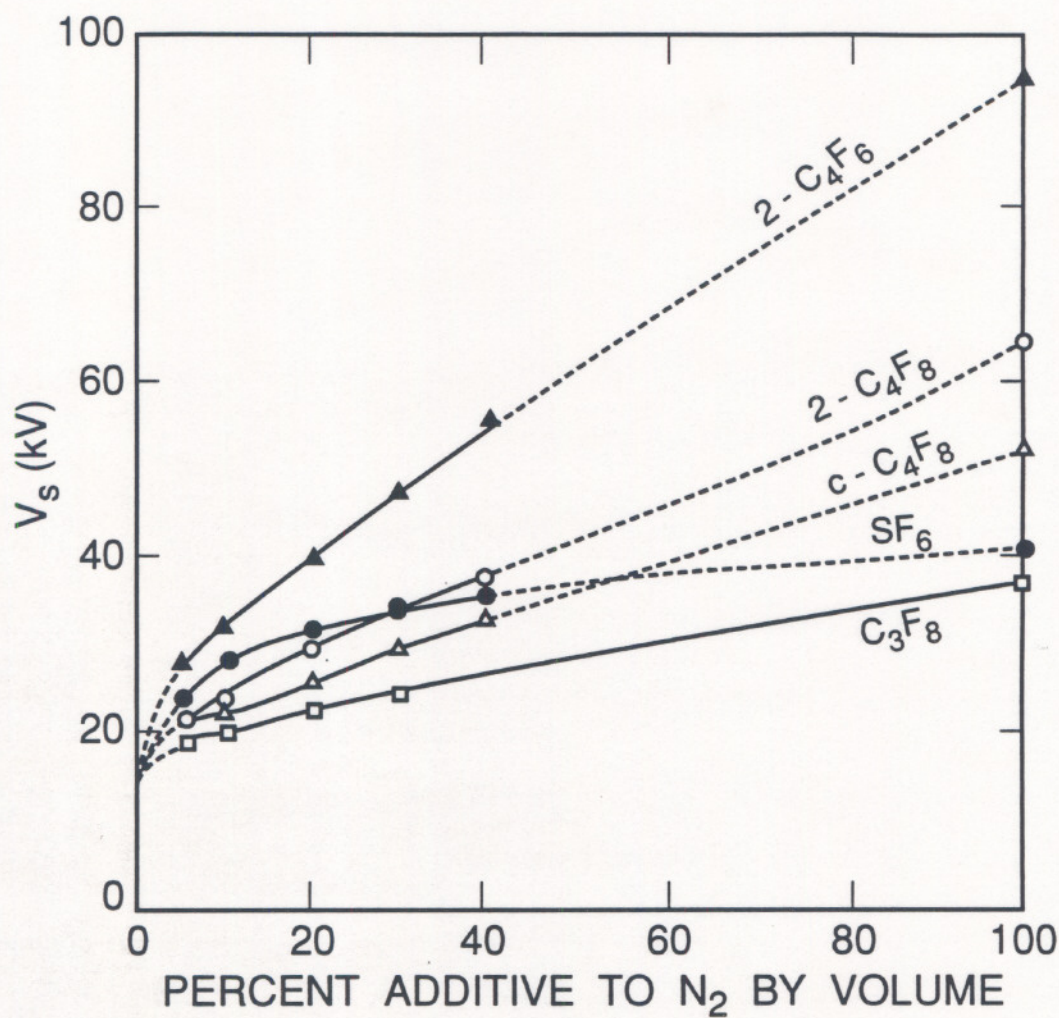


Figure 4. D.C. breakdown voltage as a function of electron-attaching additive to N_2 (uniform and quasi-uniform fields; total pressure: 66.66 kPa (500 Torr); electrode gap: 7 mm) [26]. (The broken lines are extrapolations).

Table 3. Energy-integrated electron attachment cross section, IA , thermal electron attachment rate constant, k_{th} , and relative DC uniform-field breakdown strength, V_S^R , of some gaseous dielectrics [26].

| Gas | $\int_{0.04}^{2.5\text{eV}} \sigma_a(\epsilon) d\epsilon = IA$ ($10^{-16} \text{ cm}^2 \text{ eV}$) | k_{th} ($10^{-8} \text{ cm}^3 \text{ s}^{-1}$) | V_S^R | Comments |
|---|--|---|-----------|--|
| SF ₆ | 11.1 | 24.9 | 1.0 | Group A: anions mostly parent at low energies and long lived ($\tau_a \geq 10^{-5} \text{ s}$); $\langle IA \rangle = 6.6 \times 10^{-16} \text{ cm}^2 \text{ eV}$. |
| 1-C ₇ F ₁₄ | 4.4 | 0.38 | 1.2 | |
| c-C ₄ F ₆ | 5.1 | 14.3 | 1.7 | |
| 2-C ₄ F ₆ | 7.2 | 4.7 | 1.7 | |
| c-C ₄ F ₈ | 9.7 | 1.3 | 1.2-1.3 | |
| 1,3-C ₄ F ₆ | 10.5 | 12.6 | ~ 1.5 | |
| 2-C ₄ F ₆ | 12.9 | 5.4 | 2.2-2.4 | Group B: anions mostly parent at low energies and long lived ($\tau_a \geq 10^{-5} \text{ s}$); $\langle IA \rangle = 19 \times 10^{-16} \text{ cm}^2 \text{ eV}$. |
| c-C ₈ F ₁₆ | 17.4 | 7.4 | ~ 2.4 | |
| c-C ₅ F ₈ | 18.1 | 38.9 | ~ 2.1-2.2 | |
| c-C ₆ F ₁₂ | 18.1 | 15.0 | 2.3-2.4 | |
| c-C ₆ F ₁₀ | 19.1 | 39.2 | 1.9-2.2 | |
| C ₇ F ₈ | 20.3 | 27.4 | ~ 2.4 | |
| c-C ₇ F ₁₄ | 26.6 | 5.2 | 2.1 | |
| 1,1,1-C ₂ Cl ₃ F ₃ | 13.5 | 28.0 | 2.47 | Group C: anions are dissociative attachment fragments, mostly Cl ⁻ ; the electron affinity of Cl is 3.61 eV. |
| 1,1,2-C ₂ Cl ₃ F ₃ | 5.94 | 1.1 | 2.41 | |
| 1,1-C ₂ Cl ₂ F ₄ | 3.23 | 0.5 | 1.68 | |
| 1,2-C ₂ Cl ₂ F ₄ | 1.85 | 0.07 | 1.63 | |
| 1,1,1-C ₂ Cl ₃ H ₃ | 1.74 | 1.5 | 1.62 | |
| 1,1,2-C ₂ Cl ₃ H ₃ | 1.02 | 0.02 | 1.50 | |
| 1,1-C ₂ Cl ₂ H ₄ | 0.23 | 0.002 | 1.01 | |
| 1,2-C ₂ Cl ₂ H ₄ | 0.07 | 0.003 | 0.88 | |
| CCl ₄ | 24.9 | 23.7 | 2.36 | |
| CCl ₃ F | 6.4 | 1.2 | 1.84 | |
| CCl ₃ H | 4.4 | 0.38 | 1.77 | Group D: weak dissociative attachment. |
| CCl ₂ F ₂ | 0.66 | 0.012 | 1.08 | |
| CF ₄ | | | 0.39 | |
| C ₂ F ₆ | | | 0.80 | |
| C ₃ F ₈ | | | 0.90 | |
| n-C ₄ F ₁₀ | | | 1.31 | |
| CO | | | 0.40 | |
| CO ₂ | | | 0.30 | |
| N ₂ O | | | 0.44 | Group E: non-electron-attaching. |
| Ne | | | 0.006 | |
| Ar | | | 0.07 | |
| H ₂ | | | 0.18 | |
| N ₂ | | | 0.36 | |

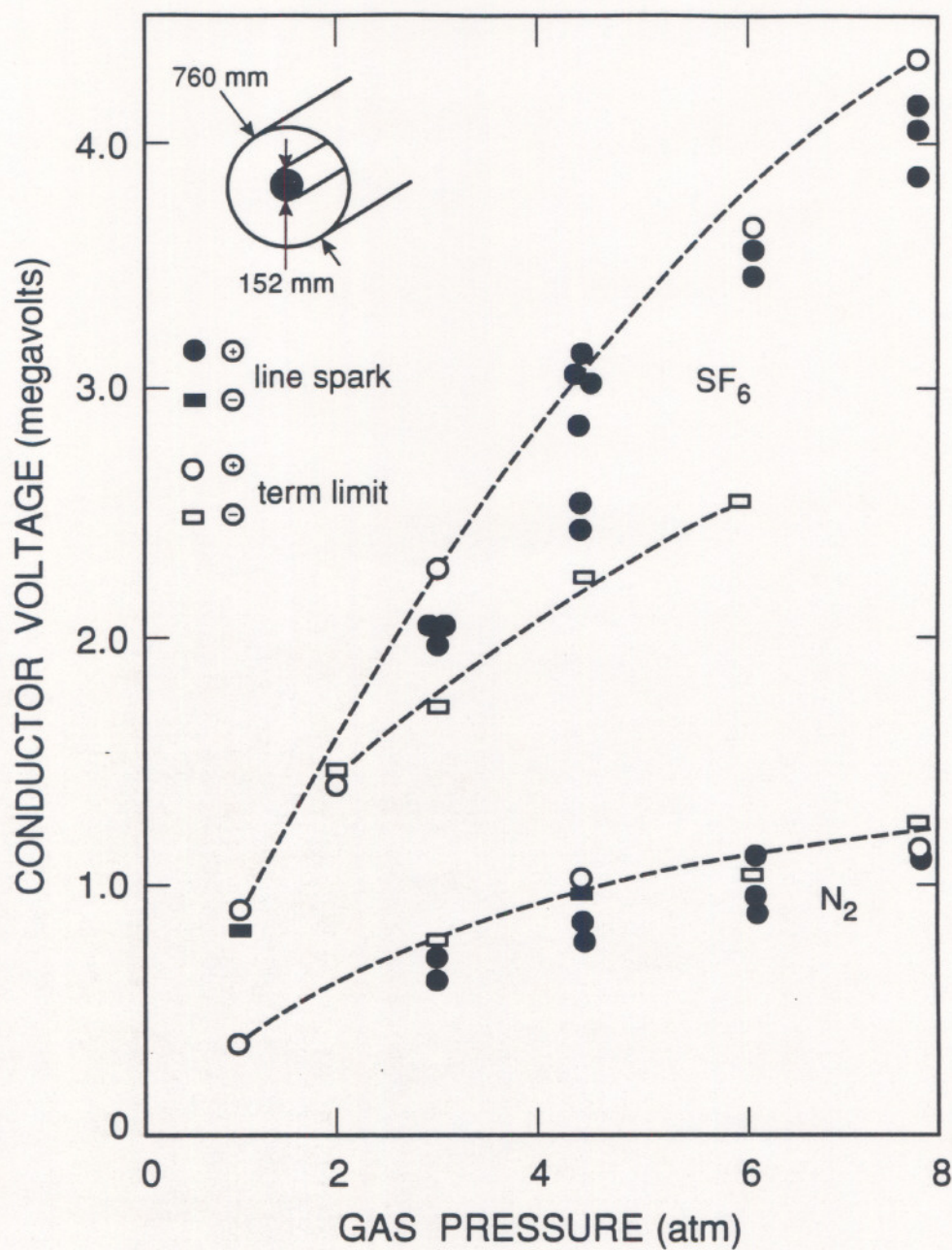


Figure 5. Conductor voltage as a function of gas pressure for SF₆ and N₂ using coaxial geometry (152 mm system) [35]. The data represented by the solid and open symbols are for breakdowns at two locations as indicated in the figure [35].

for pressure at two locations as indicated in the figure [32].
 Geometry (125 mm diameter) [32]. The data represented by the solid and open symbols are
 Figure 2. Conductor voltage as a function of gas pressure for $2F^+$ and H^+ using conductors

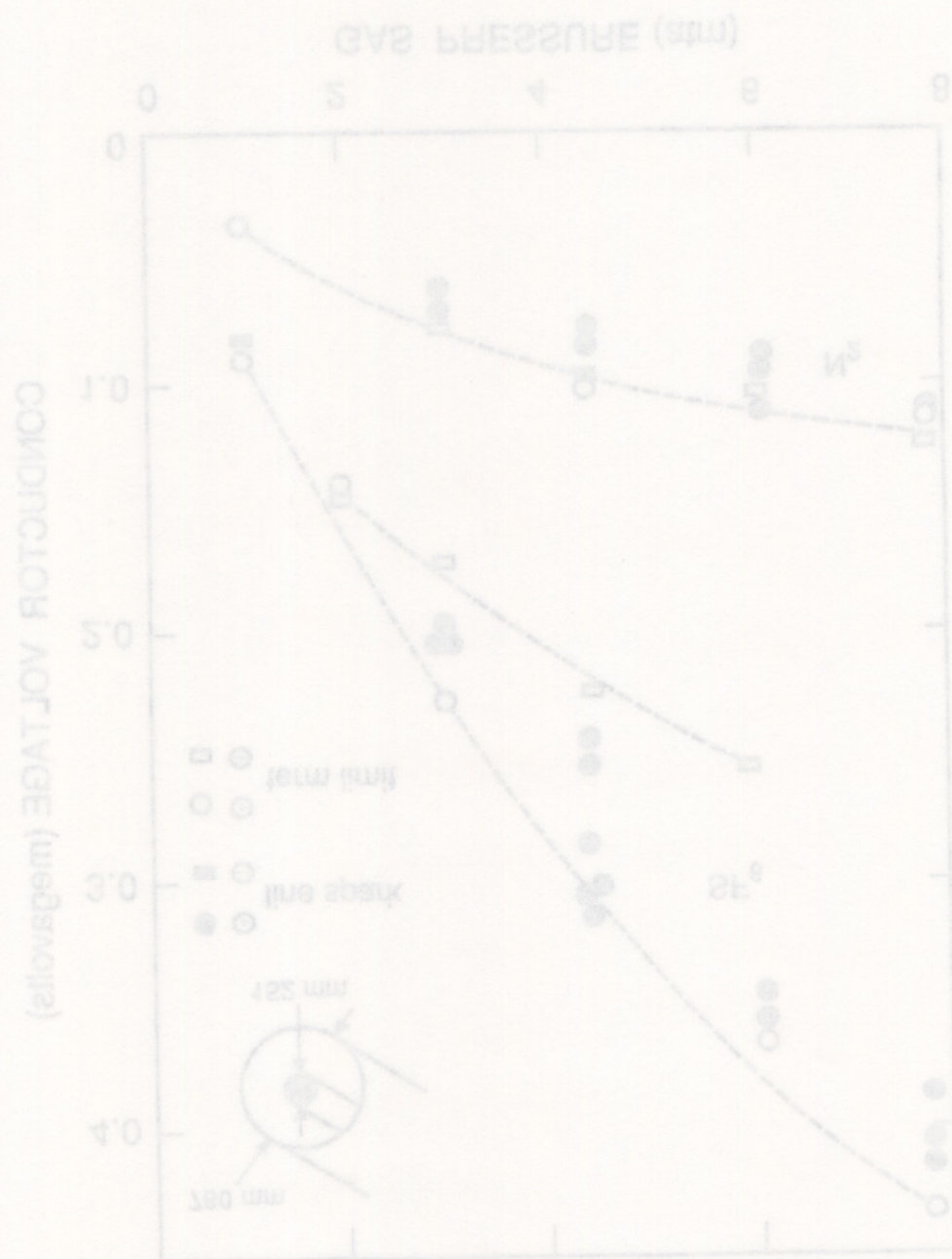


Table 4. Figure of merit, M , for SF₆ and SF₆/N₂ mixtures [42]. (The higher the value of M , or the relative value M_r , the better the non-uniform field dielectric properties of the gas; i.e., the larger M is, the less sensitive is the gas to the effects of electrode and surface roughness).

| SF ₆ (%) | M (bar mm) | M_r |
|---------------------|--------------|-------|
| 100 | 0.040 | 1 |
| 50 | 0.053 | 1.33 |
| 25 | 0.091 | 2.28 |
| 10 | 0.147 | 3.68 |
| 5 | 0.182 | 4.55 |

- Under particle contamination conditions, pure SF₆ substantially loses its dielectric strength [27, 38]. Under particle contamination conditions, pure SF₆ may not be much better than pure N₂ at pressures of about 10 atm (Fig. 6).
- Small amounts of SF₆ in N₂ substantially increase the dielectric strength of the mixture (Figs. 4 and 7); this increase tends toward saturation as the amount of SF₆ is increased above about 50%. This behavior is well understood and is supported by basic measurements (Fig. 8).
- It is also known that SF₆/N₂ mixtures are less sensitive to electric-field non-uniformities, surface roughness (Fig. 9), and particles (Fig. 6) than SF₆ alone. For electrode protrusion radii $R > 190 \mu\text{m}$, SF₆/N₂ mixtures, down to small percentages, are almost as good as pure SF₆ (Fig. 9). This is, also, illustrated in Fig. 10 where it is seen that, for a given degree of surface roughness, the higher the total pressure the lower the percentage of SF₆ in N₂ for which the maximum improvement (over pure nitrogen) is effected. The superiority of the SF₆/N₂ mixtures over pure SF₆ in nonuniform fields may improve the reliability of gas-insulated systems.

While more work is needed on these and other (for example, on CO₂-containing) dielectric gas mixtures, it seems that SF₆/N₂ mixtures (and even pure N₂ at 2 to 3 times the pressure of pure SF₆) can be as good insulating gases as pure SF₆, if used at higher pressures (say, around 1000 kP (10 atm)) [25, 26, 27, 44, 45].

It should be noted that mixtures of SF₆ and N₂ are actually being used by industry in some applications, as, for example, in cold climates where the pure SF₆ gas deviates from an ideal-gas behavior [16, 27, 46]. These mixtures have also been recommended for transmission lines. However, as a rule, there has been no wide use of gas mixtures by industry.

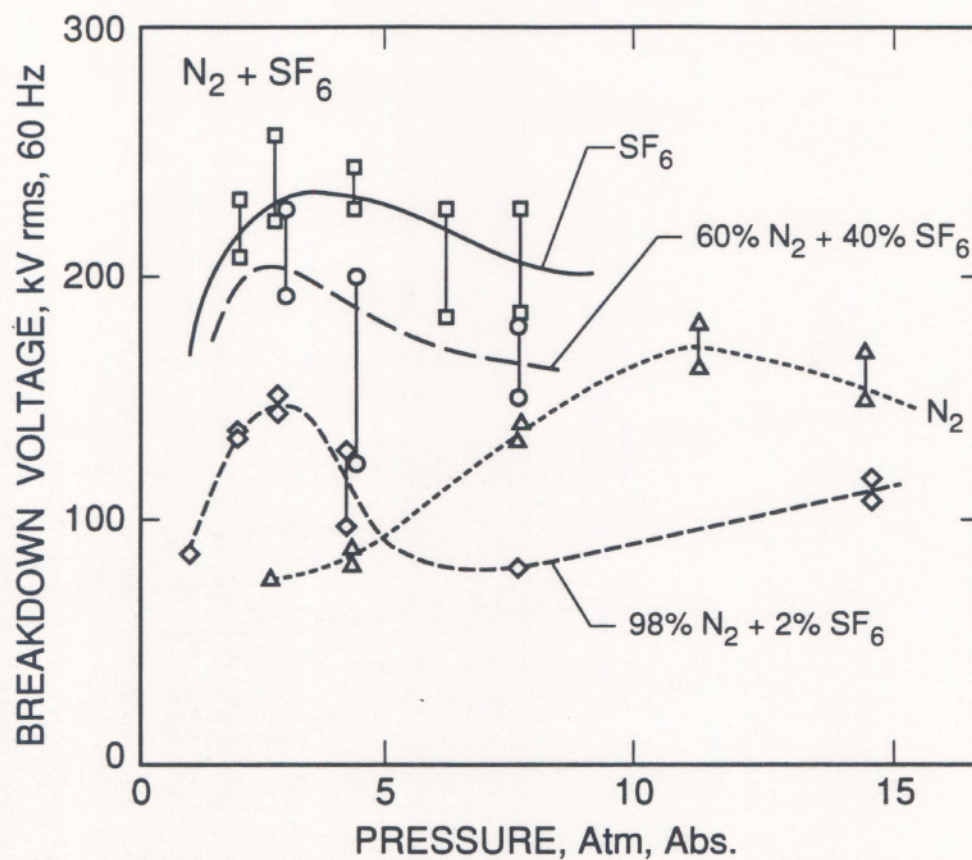


Figure 6. Breakdown voltage as a function of pressure in SF₆/N₂ mixtures contaminated with copper wires having a diameter of 0.43 mm and a length of 0.66 cm. The plane electrode gap was 7.62 cm [27,40,41].

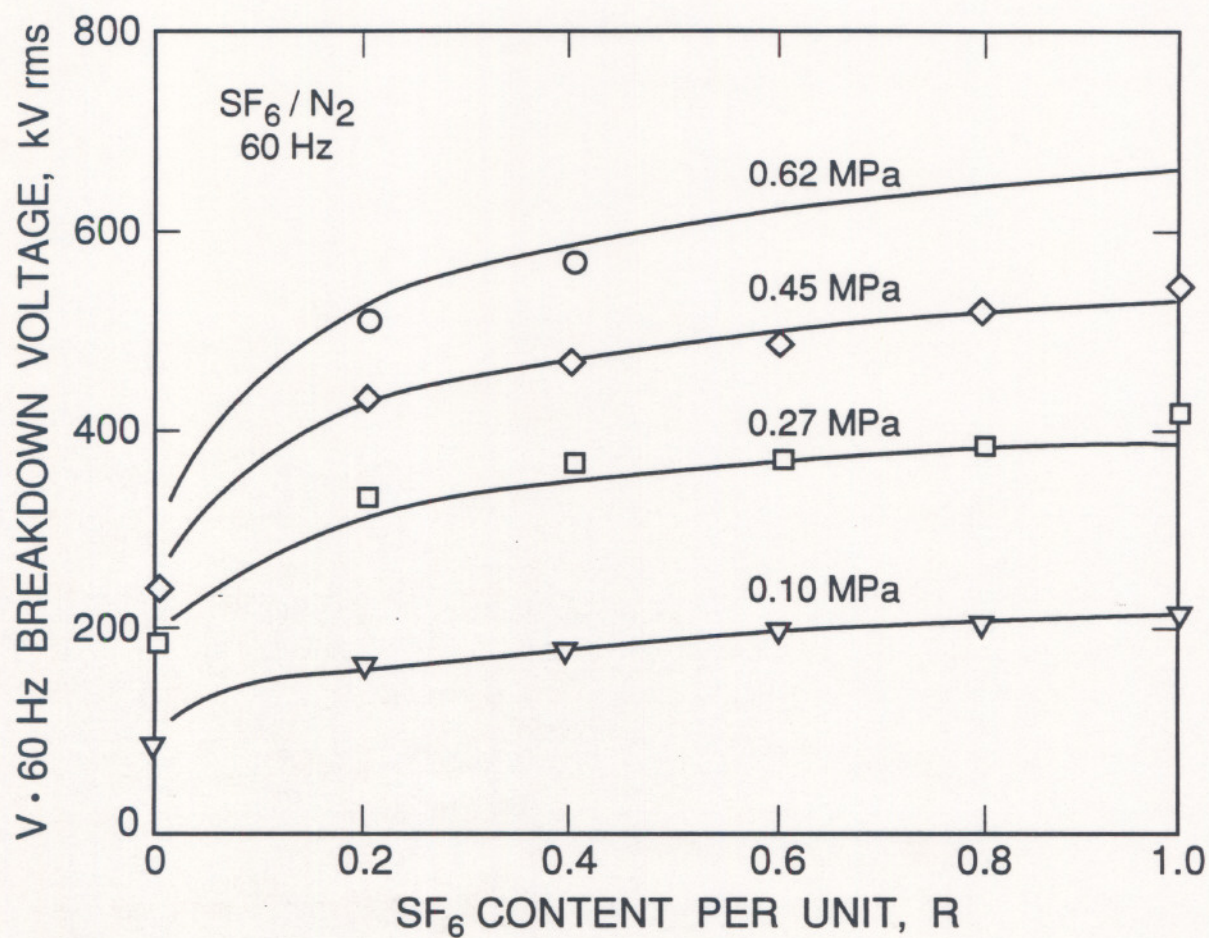


Figure 7. Measured (data points) and calculated (solid lines) 60-Hz breakdown voltage values for SF₆/N₂ mixtures [33]. Similar behavior is exhibited under lighting and switching impulse voltages [33].

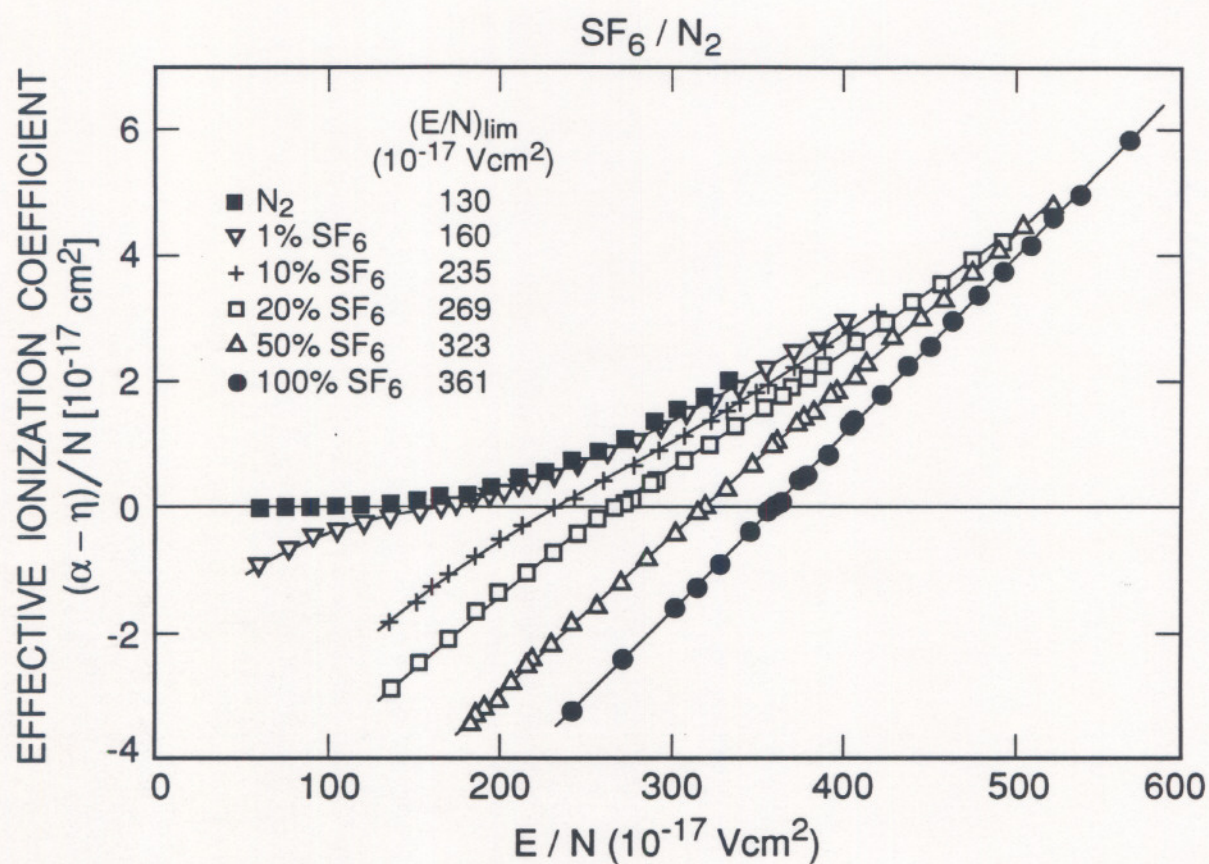


Figure 8. Effective ionization coefficients for SF₆, N₂, and SF₆/N₂ mixtures as a function of the density-reduced electric field E/N [34]. The limiting values of the density-reduced electric field for nitrogen, sulfur hexafluoride, and their mixtures are shown in the figure inset.

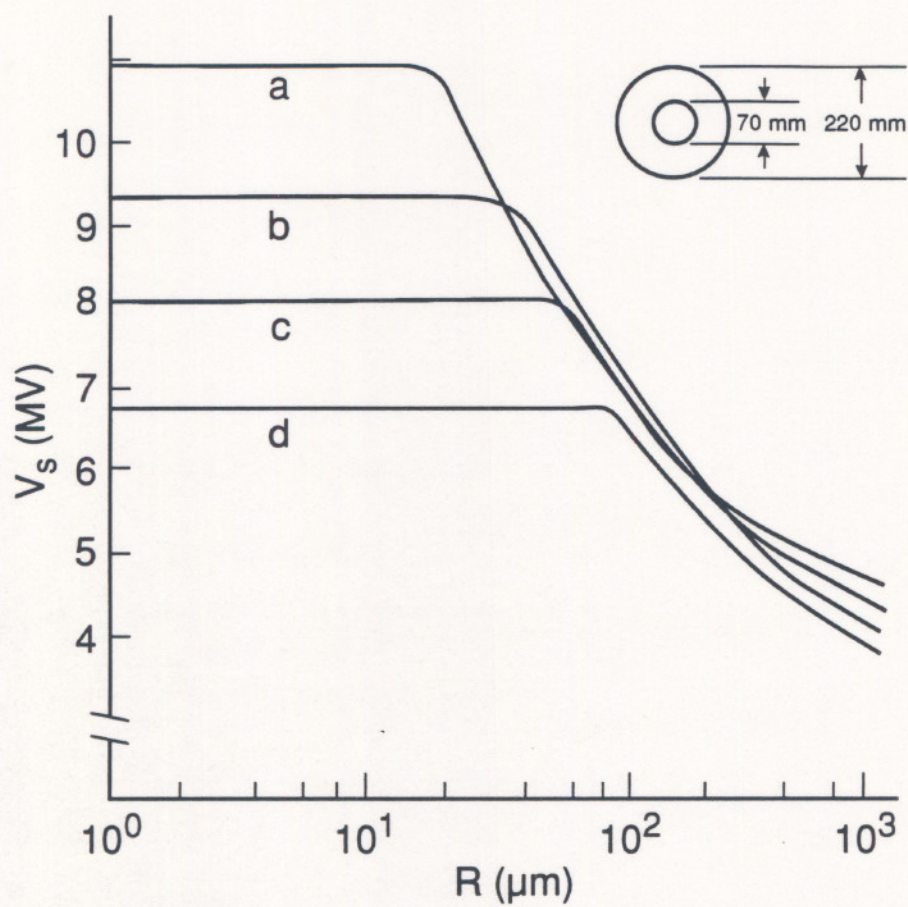


Figure 9. Calculated breakdown voltage/roughness characteristics for coaxial electrodes in SF₆/N₂ mixtures at pressures of 3 bar. Curves a, b, c, and d correspond to SF₆ concentrations of 100%, 50%, 25%, and 10%, respectively [39].

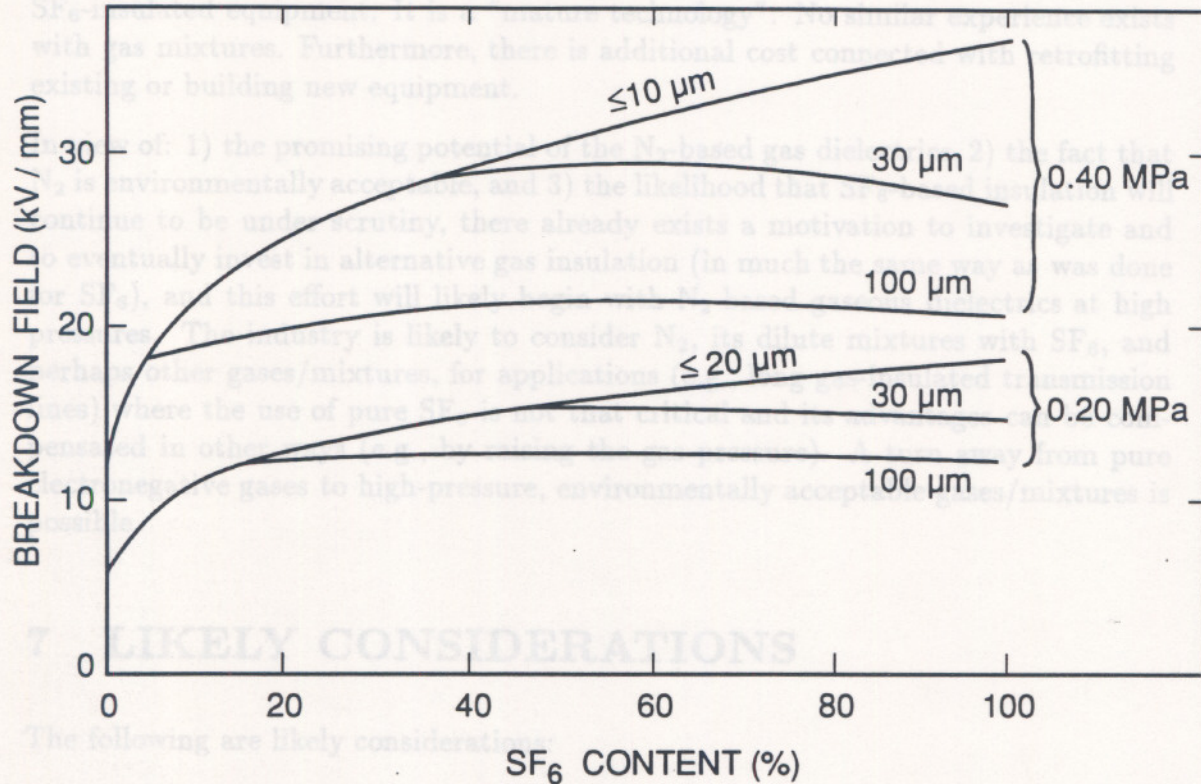


Figure 10. Effect of electrode-surface roughness on the calculated breakdown field/gas characteristics in SF₆/N₂ mixtures [43]. Note the dependence of the breakdown-field saturation level on both the degree of surface finish (surface roughness) and the total pressure (at 0.4 MPa, a 30% SF₆ mixture would be the best choice for a 30 μm roughness, while a 10% SF₆ mixture would be adequate with 100 μm surface roughness). In other words, for a given degree of surface roughness (a given electrode surface finish), the higher the pressure the lower the concentration of SF₆ in the mixture beyond which no improvement in the dielectric strength occurs.

3. Collectively, electrical industry/utilities, chemical companies, regulatory agencies, and researchers from universities and national laboratories are developing a program that would eventually reduce the use of SF₆, prevent its uncontrolled release into the environment, and encourage recycling where possible.

*Presently, perhaps more than 50% of the SF₆ used by the electrical industry is used in circuit breakers [15].

4. The development of recycling equipment will be encouraged.
5. An "educational initiative" to familiarize the users of SF₆ with the SF₆-greenhouse issue will occur.
6. Industry will take measures to reduce or prevent leakage of SF₆ from SF₆-insulated equipment.

8 MEASUREMENTS, STANDARDS, AND DATA ISSUES

Current and future efforts in search for solutions to the SF₆ insulation problem need data and key input from measurements on possible replacement gases, especially in the following areas:

- Basic physical and chemical properties of high-pressure gas dielectrics such as CO₂, N₂ and their dilute mixtures with SF₆ at pressures ranging from (500 to 1500) kPa, including electron-impact ionization and electron attachment at high applied electric fields.
- Identification of the decomposition products of such high-pressure gas dielectrics and measurement of their production rates for corona, breakdown and arc conditions.
- Evaluation of the influence of contaminants such as air and water vapor on the chemical stability and electrical properties of the gas.
- Compatibility of high-pressure gas mixtures with metals and solid insulation under high-temperature and partial-discharge conditions.
- Behavior of high-pressure gaseous dielectrics under conditions simulating their industrial uses (e.g., under non-uniform fields and transient electrical stress).

A database for alternatives to SF₆ gases/mixtures is also desirable, especially for SF₆/N₂ mixtures and high-pressure N₂. Also desirable are measurements of SF₆ in the atmosphere and measurements and standards to support recycling.

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