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# Gases for Electrical Insulation and Arc Interruption: Possible Present and Future Alternatives to Pure $SF_6$

L. G. Christophorou, J. K. Olthoff, and D. S. Green

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**Abstract**

The electric power industry's preferred gaseous dielectric (besides air), sulfur hexafluoride ($SF_6$), has been shown to be a greenhouse gas. In this report we provide information that is useful in identifying possible replacement gases, in the event that replacement gases are deemed a reasonable approach to reducing the use of $SF_6$ in high voltage electrical equipment. The report focuses on the properties of $SF_6$ as a dielectric gas and on the data available for possible alternatives to pure $SF_6$ (i.e., $SF_6$ alone). On the basis of published studies and consultation with experts in the field, it was attempted to identify alternative dielectric gases to pure $SF_6$ for possible immediate or future use in existing or modified electrical equipment. The possible alternative gases are discussed as three separate groups: (i) mixtures of $SF_6$ and nitrogen for which a large amount of research results are available; (ii) gases and mixtures (e.g., pure $N_2$, low concentrations of $SF_6$ in $N_2$, and $SF_6$-He mixtures) for which a smaller yet significant amount of data are available; and (iii) potential gases for which little experimental data are available.

**Keywords**

gaseous dielectrics; gas mixtures; gas recycling; global warming; nitrogen; $SF_6$; $SF_6$-$N_2$ mixtures; sulfur hexafluoride

**Ordering**

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# Gases for Electrical Insulation and Arc Interruption: Possible Present and Future Alternatives to Pure $SF_6$

## Contents



## 1. Introduction

Sulfur hexafluoride ($SF_6$), the electric power industry's presently preferred gaseous dielectric (besides air), has been shown to be a greenhouse gas. Concerns over its possible impact on the environment have rekindled interest in finding replacement gases. In this report we provide information that is useful in identifying such gases, in the event that replacement gases are deemed a reasonable approach to controlling emissions of $SF_6$ from high voltage electrical equipment. The report focuses on the properties of $SF_6$ as a dielectric gas and on the data available for possible alternatives to pure $SF_6$ (i.e., $SF_6$ alone). On the basis of published studies and consultation with experts in the field, we attempt to identify alternative dielectric gases to pure $SF_6$ for possible immediate or future use in existing or modified electrical equipment.

This report first describes the properties that make a good gaseous dielectric, and the tests and measurements that are necessary to demonstrate and document the appropriateness of a gas as a high voltage insulating medium, or for use as an arc or current interrupting medium. An effort has been made to gather expert opinion regarding the possible adoption of likely $SF_6$ substitutes and the additional tests that are needed to effect their acceptability by electric equipment manufacturers and by the electric power industry. During the preparation of the report, we consulted with a broad spectrum of experts (see Acknowledgments) via a series of meetings on the subject matter and by correspondence. Representatives from electric equipment manufacturers, electric utilities, gas handling and manufacturing companies, and academic institutions were consulted.

An attempt was made during the preparation of this report to identify a gaseous mixture that could be adopted for "universal use" as an immediate replacement of pure $SF_6$. The large amount of available physical and laboratory data suggest that a 40%$SF_6$-60%$N_2$ mixture[1] may exhibit dielectric characteristics suitable for use as insulation in high voltage equipment. However, it is realized that there are difficulties in using this mixture for arc or current interruption, and as a replacement gas in

[1] All references in this report to mixtures and concentrations are by volume.

already existing equipment. The reasons for and against the use of this "universal-application" gas mixture are discussed.

The report also discusses other possible substitutes for which a significant but smaller amount of data exists. These include high-pressure pure $N_2$ and dilute $SF_6$-$N_2$ mixtures (concentrations of $SF_6$ in the mixture less than about 15%) as likely gaseous media for electrical insulation, and $SF_6$-He mixtures as a possible medium for arc interruption. Other gases and mixtures are also discussed for which the available data are too few to allow an assessment of their utility as a substitute, but which suggest some promise. The need for a future R&D program in these areas is indicated and suggestions are made as to possible elements of such a program. While the literature search utilized in this report was not intended to be complete, it is extensive and can serve as a guide to critical work on alternatives to pure $SF_6$.

This report concentrates on specific uses of $SF_6$ by the electric power industry. However, much of the discussion is appropriate for other uses of $SF_6$ as a high voltage insulating and current interrupting medium.

## 1.1 Sulfur Hexafluoride

Sulfur hexafluoride is a man-made gas which became commercially available in 1947 [1]. It is one of the most extensively and comprehensively studied polyatomic molecular gases because of its many commercial and research applications.[2] Its basic physical and chemical properties, behavior in various types of gas discharges, and uses by the electric power industry have been broadly investigated (see, for example, [2–7]).

In its normal state, $SF_6$ is chemically inert, non-toxic, non-flammable, non-explosive, and thermally stable (it does not decompose in the gas phase at temperatures less than 500 °C). Sulfur hexafluoride exhibits many properties that make it suitable for equipment utilized in the transmission and distribution of electric power. It is a strong electronegative (electron attaching) gas both at room temperature and at temperatures well above ambient, which principally accounts for its high dielectric strength and good arc-interruption properties. The breakdown voltage of $SF_6$ is nearly three times higher than air at atmospheric pressure [6]. Furthermore, it has good heat transfer properties and it readily reforms itself when dissociated under high gas-pressure conditions in an electrical discharge or an arc (i.e., it has a fast recovery and it is self-healing). Most of its stable decomposition byproducts do not significantly degrade its dielectric strength and are removable by filtering. It produces no polymerization, carbon, or other conductive deposits during arcing, and it is chemically compatible with most solid insulating and conducting materials used in electrical equipment at temperatures up to about 200 °C.

Besides its good insulating and heat transfer properties, $SF_6$ has a relatively high pressure when contained at room temperature. The pressure required to liquefy $SF_6$ at 21 °C is about 2100 kPa [5, 8]; its boiling point is reasonably low, –63.8 °C, which allows pressures of 400 kPa to 600 kPa (4 to 6 atmospheres) to be employed in $SF_6$-insulated equipment. It is easily liquefied under pressure at room temperature allowing for compact storage in gas cylinders. It presents no handling problems, is readily available, and up until recently has been reasonably inexpensive.[3] The electric power industry has become familiar and experienced with using $SF_6$ in electrical equipment.

However, $SF_6$ has some undesirable properties: it forms highly toxic and corrosive compounds when subjected to electrical discharges (e.g., $S_2F_{10}$, $SOF_2$); non-polar contaminants (e.g., air, $CF_4$) are not easily removed from it; its breakdown voltage is sensitive to water vapor, conducting particles, and conductor surface roughness; and it exhibits non-ideal gas behavior at the lowest temperatures that can be encountered in the environment, i.e., in cold climatic conditions (about –50 °C), $SF_6$ becomes partially liquefied at normal operating pressures (400 kPa to 500 kPa). Sulfur hexafluoride is also an efficient infrared (IR) absorber and due to its chemical inertness, is not rapidly removed from the earth's atmosphere. Both of these latter properties make $SF_6$ a potent greenhouse gas, although due to its chemical inertness (and the absence of chlorine or bromine atoms in the $SF_6$ molecule) it is benign with regard to stratospheric ozone depletion.

## 1.2 Principal Uses of $SF_6$ by the Electric Power Industry

Besides atmospheric air, sulfur hexafluoride is the electric power industry's preferred gas for electrical

[2]Besides the use of $SF_6$ by the electric power industry, other uses of $SF_6$ include: semiconductor processing, blanket gas for magnesium casting, reactive gas in aluminum recycling to reduce porosity, thermal and sound insulation, airplane tires, spare tires, "air sole" shoes, scuba diving voice communication, leak checking, atmospheric tracer gas studies, ball inflation, torpedo propeller quieting, wind supersonic channels, and high voltage insulation for many other purposes, such as AWACS radar domes and X-ray machines.

[3]From 1960 to 1994 the price of $SF_6$ in quantity purchases remained basically constant at about \$3.00 per pound (one pound = 0.4536 kg). The current price of $SF_6$ for quantity purchases in the United States varies from as low as \$12 per lb to over \$37 per pound (\$ 82 / kg) [Private communication, P. Bolin, 1997; P. Irwin, *Electrical World*, February 1997, pp. 27–30].

insulation and for arc quenching and current interruption equipment used in the transmission and distribution of electrical energy. Generally, there are four major types of electrical equipment which use $SF_6$ for insulation and/or interruption purposes: gas-insulated circuit breakers and current-interruption equipment, gas-insulated transmission lines, gas-insulated transformers, and gas-insulated substations. It is estimated [9–11] that for these applications the electric power industry uses about 80% of the $SF_6$ produced worldwide, with circuit breaker applications accounting for most of this amount. These estimates are consistent with a recent tabulation of $SF_6$ production worldwide [12] (See Appendix A). Gas-insulated equipment is now a major component of power transmission and distribution systems all over the world and employs $SF_6$ almost exclusively. It offers significant savings in land use, is aesthetically acceptable, has relatively low radio and audible noise emissions, and enables substations to be installed in populated areas close to the loads.

Depending on the particular function of the gas-insulated equipment, the gas properties which are the most significant vary. For *circuit breakers* the excellent thermal conductivity and high dielectric strength of $SF_6$, along with its fast thermal and dielectric recovery (short time constant for increase in resistivity), are the main reasons for its high interruption capability. These properties enable the gas to make a rapid transition between the conducting (arc plasma) and the dielectric state of the arc, and to withstand the rise of the recovery voltage. $SF_6$-based circuit breakers are presently superior in their performance to alternative systems such as high-pressure air blast or vacuum circuit breakers.

For *gas-insulated transformers* the cooling ability, compatibility with solid materials, and partial discharge characteristics of $SF_6$ – added to its beneficial dielectric characteristics – make it a desirable medium for use in this type of electrical equipment. The use of $SF_6$ insulation has distinct advantages over oil insulation, including none of the fire safety problems or environmental problems related to oil, high reliability, flexible layout, little maintenance, long service life, lower noise, better handling, and lighter equipment.

For *gas-insulated transmission lines* the dielectric strength of the gaseous medium under industrial conditions is of paramount importance, especially the behavior of the gaseous dielectric under metallic particle contamination, switching and lightning impulses, and fast transient electrical stresses. The gas must also have a high efficiency for transfer of heat from the conductor to the enclosure and be stable for long periods of time (say, 40 years). $SF_6$-insulated transmission lines offer distinct advantages: cost effectiveness, high-carrying capacity, low losses, availability at all voltage ratings, no fire risk,

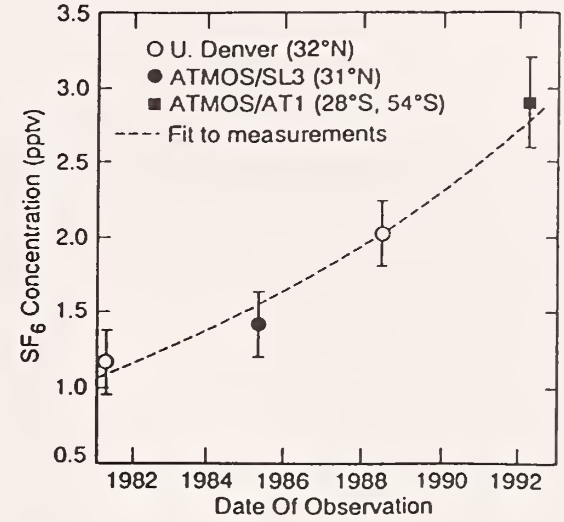


**FIG. 1.** Average $SF_6$ concentration (pptv = parts per trillion = parts in $10^{12}$ by volume) between 12 km and 18 km altitude as a function of time [16]. o University of Denver balloon-borne infrared measurements at 32° N latitude; ● Spacelab 3 ATMOS data at 31° N latitude; ■ Average of ATMOS ATLAS 1 data at 28°S and 54°S [16].

reliability, and a compact alternative to overhead high-voltage transmission lines in congested areas that avoids public concerns with overhead transmission lines.

Finally, in *gas-insulated substations (GIS)*, the entire substation (circuit breakers, disconnects, grounding switches, busbar, transformers, etc., are interconnected) is insulated with the gaseous dielectric medium and, thus, all of the abovementioned properties of the dielectric gas are significant.

## 1.3 Concentrations of $SF_6$ in the Environment

Because of the many and increasing commercial uses of $SF_6$, there has been an increased demand for it. The estimated world production of $SF_6$ has increased steadily since the 1970s to approximately 7000 metric tons per year in 1993 [9–11, 13, 14].[4] In turn, this has resulted in an increased concentration of $SF_6$ in the atmosphere [11, 13–18]. As seen in Fig. 1, measurements [16, 18] have shown that the amount of $SF_6$ in the atmosphere has been increasing at a rate of approximately 8.7% per year, from barely measurable quantities a decade ago to current levels near 3.2 pptv (3.2 parts in $10^{12}$ by volume). More recent measurements indicate atmospheric concentrations

[4]This figure is compatible with a compilation of worldwide $SF_6$ sales data by end-use markets from six companies from the USA, Europe, and Japan (see Appendix A). The total figures listed in Appendix A, however, must be higher than shown, since countries such as China and Russia were excluded from the survey [12].

of $SF_6$ ranging from 3.18 pptv (at 8 km) to 2.43 pptv (at 27 km) [17a], an atmospheric lifetime of 1937 years [17a], and a global growth rate for atmospheric $SF_6$ concentrations of 6.9% for 1996 [17b]. While the uncertainties in these numbers make extrapolations difficult, it is clear that the atmospheric concentration of $SF_6$ is increasing and could reach 10 pptv by the year 2010 [11, 15, 16, 18], depending upon the assumptions of release rates (see Fig. 2).

In some industrial applications $SF_6$ is not easily recoverable, e.g., in aluminum manufacturing. Releases of $SF_6$ into the environment by the electric power industry come from normal equipment leakage, maintenance, reclaiming, handling, testing, etc.[5] Without disposal methods that actually destroy $SF_6$, it can be expected that all of the $SF_6$ that has ever been or will ever be produced will eventually enter the atmosphere. This is so even if the present $SF_6$ leak rate from enclosed power-system equipment is only 1% per year or is improved to < 0.5% per year. It has been suggested [9] that impure, used $SF_6$ removed from "retired" electrical equipment can be destroyed by thermal decomposition in industrial waste treatment furnaces at elevated temperatures (T > 1100 °C), but no records are available indicating that this has ever been done at a significant level.

However, decreasing the rate of $SF_6$ leakage and increasing the level of recycling are high priorities since they both curtail use and production needs of $SF_6$ and thus reduce the quantities of $SF_6$ that are eventually released into the environment. Indeed, efforts have recently been undertaken by the electric power industry to reduce and monitor better the amount of $SF_6$ released into the environment from $SF_6$-insulated equipment [9–11]. These efforts include:

- *minimizing $SF_6$ releases* by improved methods to quantify and stop leakages, gradual replacement of older equipment which normally leaks at higher rates, implementation of a sound overall policy of using, handling, and tracing $SF_6$, better pumping and storage procedures, efficient recycling and setting of standards for recycling [19], and destruction of used $SF_6$,
- *reducing the amount of $SF_6$ used* by manufacturing tighter and more compact equipment, development of sealed-for-life electrical apparatus, and replacing $SF_6$ where possible by other gases or gas mixtures (see later in this report).

These efforts are partially motivated by the prospect

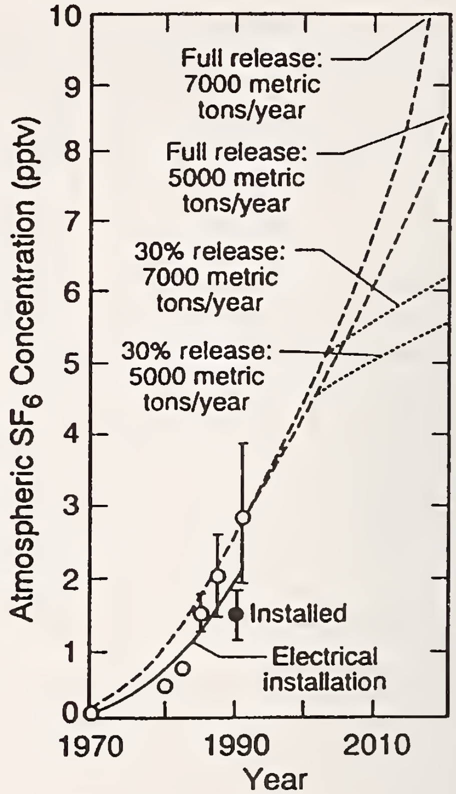


FIG. 2. Atmospheric $SF_6$ concentration (pptv = parts in $10^{12}$ by volume) as a function of time. The solid curve represents the estimated cumulative total $SF_6$ from gas-insulated equipment in the past, the open points are measured atmospheric trace concentrations, the solid point labeled "installed" is the estimated concentration assuming that all $SF_6$ enclosed in electrical equipment throughout the world in 1990 has been released into the atmosphere, and the broken lines are projected increases under various assumptions [11].

of regulation and the possibility of imposition of controls on the use and transport of $SF_6$ [11, 14, 20] (also see Appendix B for a summary of the current status of regulatory issues related to $SF_6$ use). The overall concern is motivated by virtually one reason only: *$SF_6$ is a potent greenhouse gas with an extremely long atmospheric lifetime.*

## 1.4 $SF_6$ is a Potent Greenhouse Gas

Greenhouse gases are atmospheric gases which absorb a portion of the infrared radiation emitted by the earth and return it to earth by emitting it back. Potent greenhouse gases have strong infrared absorption in the wavelength range from ~ 7 μm to 13 μm. They occur both naturally in the environment (e. g., $H_2O$, $CO_2$, $CH_4$, $N_2O$) and as man-made gases that may be released [e. g., $SF_6$; fully fluorinated compounds (FFC); combustion products such as $CO_2$, nitrogen, and sulfur oxides]. The effective trapping of long-wavelength infrared radiation

[5]We acknowledge private discussions on these issues with P. Bolin of Mitsubishi Electric Power Products Inc. (USA), J. Brunke of Bonneville Power (USA), H. Morrison of Ontario Hydro (Canada), M. F. Frechette of IREQ (Canada), L. Niemeyer of ABB Research Corporation (Switzerland), A. Diessner of Siemens AG (Germany), K. Nakanishi of Mitsubishi Electric Corporation (Japan), and F. Endo of Hitachi (Japan).

from the earth by the naturally occurring greenhouse gases, and its re-radiation back to earth, results in an increase of the average temperature of the earth's surface. Life on earth depends on a normal greenhouse effect to provide the appropriate temperature for its support. An imbalance in the earth's normal greenhouse effect occurs when the man-made, or anthropogenic, emissions of greenhouse gases contribute to an enhanced greenhouse effect which shifts the balance between incoming and outgoing radiation so that more radiation is retained, thus causing changes in the climate system.

Sulphur hexafluoride is an efficient absorber of infrared radiation, particularly at wavelengths near 10.5 $\mu$m [21]. Additionally, unlike most other naturally occurring greenhouse gases (e. g., $CO_2$, $CH_4$), $SF_6$ is largely immune to chemical and photolytic degradation; therefore its contribution to global warming is expected to be cumulative and virtually permanent. Although the determination of the atmospheric lifetime[6] of $SF_6$ in the environment is highly uncertain because of the lack of knowledge concerning the predominant mechanism(s) of its destruction, it is very long; estimates range from 800 years to 3200 years [11, 14, 17, 22–24], with the higher values being the most likely estimates. The strong infrared absorption of $SF_6$ and its long lifetime in the environment are the reasons for its extremely high global warming potential which for a 100-year time horizon is estimated to be ~24,000 times greater (per unit mass) than that of $CO_2$, the predominant contributor to the greenhouse effect [22]. The concern about the presence of $SF_6$ in the environment derives exclusively from this very high value of its potency as a greenhouse gas.

While the potency of $SF_6$ as a greenhouse gas is extremely high, the amount of $SF_6$ in the atmosphere compared to the concentrations of the naturally occurring and other man-made greenhouse gases are extremely low. Estimates of the relative contribution of $SF_6$ to non-natural global warming – using 1993 estimated $SF_6$-concentration levels – range from 0.01% [11] to 0.07% [9, 10]. In 100 years this value could become as high as 0.2% [9]. However, it is feared that $SF_6$ and other small-volume emissions may have a significant combined influence, and that environmental effects not yet anticipated may be exacerbated by their long lifetime in the atmosphere. Government and environmental protection agencies, electrical, chemical and other industries using or interested in the use of $SF_6$ [6, 11, 13, 14, 20] have expressed concerns over the possible long-term environmental impact of $SF_6$, and the electric power industry is responding in a multiplicity of ways to better control $SF_6$ usage than in the past and to reduce emissions into the environment [9–11]. Because $SF_6$ is already widely used, there are obvious economic implications about any attempts to regulate or control its production, use, and eventual disposal.

*Sulfur hexafluoride is an superior dielectric gas for nearly all high voltage applications. It is easy to use, exhibits exceptional insulation and arc-interruption properties, and has proven its performance by many years of use and investigation. However, the extremely high global warming potential of $SF_6$ mandates that users actively pursue means to minimize releases into the environment, one of which is the use of other gases or gas mixtures in place of $SF_6$.*

### 1.5 $SF_6$ Substitutes

Gaseous insulation must be environmentally acceptable, now and in the future. Therefore, the best response to the concerns over the possible impact of $SF_6$ on global warming is to prevent the release of $SF_6$ into the environment. Clearly the most effective way to do this, is not to use $SF_6$ at all. While such a proposition might be environmentally attractive, it is difficult to envision the near term elimination of the use of $SF_6$ in view of the industrial reliance on the gas and demonstrated societal value of its use. This environmentally-friendly solution does highlight the need for a search for alternative gaseous insulation and perhaps also the need for alternative high-voltage insulation technologies.

$SF_6$-substitute gaseous dielectrics are more difficult to find than it seems on the surface, because of the many basic and practical requirements that a gas must satisfy and the many studies and tests that must be performed to allow confident use. For example, the gas must have a high dielectric strength which requires the gas to be electronegative; however, strongly electronegative gases are usually toxic, chemically reactive, and environmentally damaging, with low vapor pressure, and decomposition products from gas discharges that are extensive and unknown. Non-electronegative gases which are benign and environmentally ideal, such as $N_2$, normally have low dielectric strengths. For example, $N_2$ has a dielectric strength about 3 times lower than $SF_6$ and lacks the fundamental properties necessary for use by itself in circuit breakers. Nonetheless, such environmentally friendly gases might be used by themselves at higher pressures, or at comparatively lower

[6] The time taken for a given quantity of $SF_6$ released into the atmosphere to be reduced via natural processes to ~37% of the original quantity.

pressures as the main component in mixtures with electronegative gases, including $SF_6$, at partial concentrations of a few percent.

The search for $SF_6$ substitutes traces back many years. It was especially intense in the 1970s and 1980s when gases "superior" to $SF_6$ were being sought. A number of studies conducted mainly during this time period, produced a large body of valuable information (see, for example, Refs. 2 and 3) which needs to be revisited and be reassessed not from the perspective of finding "better" gaseous dielectrics than $SF_6$, but rather from the point of view of finding gases or gas mixtures which are environmentally acceptable and comparable in dielectric properties and performance to $SF_6$. A rekindled interest in "new" gaseous insulators may also direct itself toward finding gases or gas mixtures which are not necessarily universally optimum for every high-voltage insulation need, but which can be optimized for a particular application.

Any program on substitutes needs to address comprehensively the issues involved and evaluate possible substitutes within the framework of the total environment. Besides the obvious requirements of high gas pressure, non-toxicity, non-flammability, availability and cost, there should be basic, applied, and industrial testing to assess the thermal and electrical properties of other gaseous dielectrics. Performance under various voltages (DC, AC, impulse, transients), field configurations, and particle contamination must be tested. Gas decomposition under prolonged electrical stress, corona, breakdown, and arc must be investigated, along with gas aging and the influence of spacer and other materials. Gas mixtures in particular need to be looked at anew. Efforts must be made to address concerns regarding mixtures which include difficulties in handling, mixing, maintaining constant mixture composition, reclaiming of mixture's constituents, possible inferior performance with regard to thermal, insulation, and current interruption properties, and the associated equipment design changes that such use may entail. It must be emphasized, however, that gas mixtures should be tested under conditions (e.g., pressures, equipment design) where they are likely to perform well, not simply under conditions for which $SF_6$ is better. It must also be stressed that historically resources have not been as abundant for the study of gas mixtures as they had been for the study of pure $SF_6$.

### 1.6 Scope of this Report

It is the purpose of this report to provide information regarding the following:

1. The required or desirable properties of any dielectric gas for use in the various applications of the electric power industry.
2. The tests required to document the suitability and acceptability of a dielectric gas for the intended application(s).
3. The feasibility of a "universal" gas mixture that could substitute for pure $SF_6$ and help reduce the current levels of $SF_6$ utilized by the electric power industry.
4. Alternate gases or gas mixtures for which a significant amount of data are available supporting their possible use in newly-designed industrial equipment.
5. Possible gases or gas mixtures for which little physical data are presently available, but which are sufficiently promising to justify further research.
6. Recommendations on substitutes and future R&D aimed at the development of environmentally acceptable alternatives to pure $SF_6$.

Items 1 to 6 are respectively discussed in Sections 2 to 7 of this report.

## 2. Properties of Gaseous Dielectrics

The properties of a gas that are necessary for its use in high voltage equipment are many and vary depending on the particular application of the gas and the equipment. They are also interconnected and coupled. In their optimum combination one may achieve distinctly desirable synergisms with regard to dielectric strength, for instance, which clearly show that a gas mixture may be more than just the partial-pressure-weighted addition of the dielectric strength of the individual mixture components [2, 3, 25]. In the following sections, the gaseous dielectric properties which are of particular importance in high voltage applications are identified.

For the purpose of this report the properties of a gaseous dielectric are divided into four groups:

- intrinsic properties (physical and chemical);
- extrinsic properties (reactions, gas byproducts, discharge and breakdown);
- other requirements for commercial use; and
- specific properties required for arc interruption, transmission lines, and transformers.

### 2.1 Intrinsic Properties

Intrinsic properties are those properties of a gas which are inherent in the physical atomic or molecular structure of the gas. These properties are independent of the application or the environment in which a gas is placed.

### 2.1.1 Basic Physical Properties

One of the desirable properties of a gaseous dielectric is *high dielectric strength* (higher, for instance, than air). The gas properties that are principally responsible for high dielectric strength are those that reduce the number of electrons which are present in an electrically-stressed dielectric gas. To effect such a reduction in the electron number densities, a gas should:

• be electronegative (remove electrons by attachment over as wide an energy range as possible); it should preferably exhibit increased electron attachment with increasing electron energy and gas temperature since electrons have a broad range of energies and the gas temperature in many applications is higher than ambient;

• have good electron slowing-down properties (slow electrons down so that they can be captured efficiently at lower energies and be prevented from generating more electrons by electron impact ionization); and

• have low ionization cross section and high ionization onset (prevent ionization by electron impact).

The significance of these parameters, especially electron attachment, in determining the dielectric strength of the gaseous medium can be seen from the representative data for different gases in Table 1. It is evident in this table that some gases actually exceed the dielectric strength of $SF_6$. However, they all exhibit negative properties as to make them less desirable gaseous insulators in practical systems as presently designed. Figure 3 illustrates the basic physical properties of electron attachment, ionization, and scattering as they relate to the dielectric strength [25]. The most critical property of a gaseous dielectric for high dielectric strength is a large electron attachment cross section over a wide electron energy range. The second most significant property is a large electron scattering cross section at low electron energies to slow electrons down so that they can be captured more efficiently and be prevented from generating more electrons in collisions with the dielectric gas molecules.

**TABLE 1.** Relative DC uniform-field breakdown strengths $V_s^R$ of some dielectric gases.[a]

| Gas | $V_s^R$ [b, c] | Comments |
|---|---|---|
| $SF_6$ | 1 | Most common dielectric gas to date besides air |
| $C_3F_8$ | 0.90 | Strongly and very strongly electron attaching gases, especially at low electron energies |
| $n\text{-}C_4F_{10}$ | 1.31 | |
| $c\text{-}C_4F_8$ | ~1.35 | |
| $1,3\text{-}C_4F_6$ | ~1.50 | |
| $c\text{-}C_4F_6$ | ~1.70 | |
| $2\text{-}C_4F_8$ | ~1.75 | |
| $2\text{-}C_4F_6$ | ~2.3 | |
| $c\text{-}C_6F_{12}$ | ~2.4 | |
| $CHF_3$ | 0.27 | Weakly electron attaching; some (CO, $N_2O$) are effective in slowing down electrons |
| $CO_2$ | 0.30 | |
| $CF_4$ | 0.39 | |
| CO | 0.40 | |
| $N_2O$ | 0.44 | |
| Air | ~0.30 | |
| $H_2$ | 0.18 | Virtually non-electron attaching |
| $N_2$ | 0.36 | Non-electron attaching but efficient in slowing down electrons |
| Ne | 0.006 | Non-electron attaching and not efficient in slowing down electrons |
| Ar | 0.07 | |

[a] Based on Table 2 of Ref. 25.
[b] Some of the values given are for quasi-uniform fields and may thus be somewhat lower than their uniform-field values.
[c] The relative values listed in the table can be put on an absolute scale by multiplying by $3.61 \times 10^{-15}$ V cm$^2$, the uniform-field breakdown field, $(E/N)_{lim}$, of $SF_6$.

Furthermore, the gas properties must be such that electron detachment from negative ions is prevented since electron detachment is a major source of electrons that trigger gas breakdown. The negative ions that are formed (through the formation of negative ions by electron attachment) must be as stable as possible. Detachment of electrons from negative ions can occur via a number of processes, foremost by autodetachment, collisional detachment, and photodetachment. Especially the former process is a strong function of gas temperature [26].

The measurements needed to quantify the intrinsic physical properties of a gaseous dielectric for insulation include:

- electron attachment cross sections;
- electron scattering cross sections;
- electron impact ionization cross sections;
- electron detachment cross sections (photodetachment, collisional detachment, and the associated processes of clustering and ion-molecule reactions ); and
- coefficients for electron attachment, ionization, effective ionization, and transport.

Besides the above properties, there are a number of other basic properties which are necessary for the complete characterization of the dielectric gas behavior and its performance in practice. These include:

- secondary processes such as electron emission from surfaces by ion and photon impact;
- photoprocesses;
- absorption of photoionizing radiation (this is a controlling factor in discharge development in non-uniform fields);
- dissociation under electron impact decomposition;
- ion-molecule reactions;
- reactions with trace impurities; and
- reactions with surfaces.

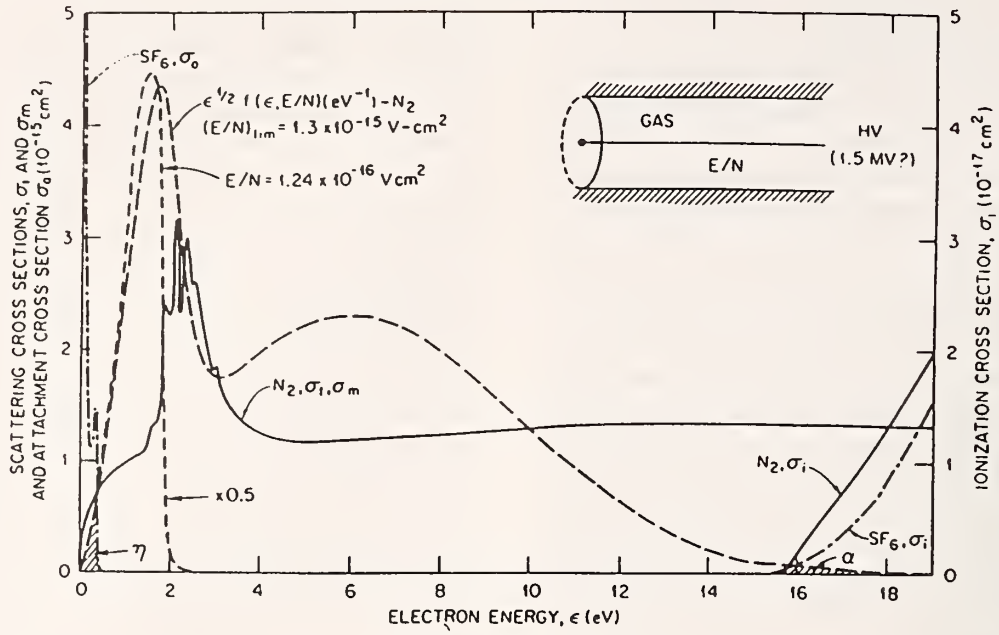


FIG. 3. Total ionization cross section $\sigma_i(\varepsilon)$ for $N_2$ (—) and $SF_6$ (-•-) close to the ionization onset. Total electron scattering cross section $\sigma_t(\varepsilon)$ as a function of electron energy, ε, for $N_2$ (—), and total electron attachment cross section $\sigma_a(\varepsilon)$ for $SF_6$ (-•-). Electron energy distribution functions in pure $N_2$ for two values of the density, N, reduced electric field *E/N*: at a value of 1.24 × $10^{-16}$ V $cm^2$, about ten times lower than the *E/N* value at which breakdown occurs under a uniform electric field, and at the limiting value of *E/N* (= 1.3 × $10^{-15}$ V $cm^2$) at which breakdown occurs under a uniform electric field. The shaded areas designated by η and α are, respectively, a measure of the electron attachment and electron impact ionization coefficients for $SF_6$ (from [25]).

### 2.1.2 Basic Chemical Properties

The dielectric gas must have the following "chemical" properties:

- high vapor pressure;
- high specific heat (high thermal conductivity) for gas cooling;
- thermal stability over long periods of time for temperatures greater than 400 K;
- chemical stability and inertness with regard to conducting and insulating materials;
- non-flammable;
- non-toxic; and
- non-explosive.

When used in mixtures, it must have appropriate thermodynamic properties for mixture uniformity, composition, and separation (see Appendix C).

## 2.2 Extrinsic Properties

Extrinsic properties are those which describe how a gas may interact with its surroundings, or in response to external influences, such as electrical breakdown and discharges.

### 2.2.1 Reactions and Byproducts

To be used in electrical applications, a dielectric gas should:

- undergo no extensive decomposition;
- lead to no polymerization;
- form no carbon or other deposits; and
- be non-corrosive and non-reactive to metals, insulators, spacers, and seals.

In addition it should have:

- no major toxic or adversely-reactive byproducts;
- removable byproducts; and
- a high recombination rate for reforming itself, especially for arc interuption.

Finally, the gas must be environmentally friendly, e.g., it must not contribute to global warming, must not deplete stratospheric ozone, and must not persist in the environment for long periods of time.

### 2.2.2 Electrical Discharge and Breakdown Properties

Specific properties of the gas under discharge and breakdown conditions include:

- a high breakdown voltage under uniform and

non-uniform electric fields;
- insensitivity to surface roughness or defects and freely moving conducting particles;[7]
- good insulation properties under practical conditions;
- good insulator flashover characteristics
- good heat transfer characteristics;
- good recovery (rate of voltage recovery) and self-healing;
- no adverse reactions with moisture and common impurities; and
- no adverse effects on equipment, especially on spacers and electrode surfaces.

Also some knowledge must be available concerning its discharge mechanisms (corona, breakdown, arc) and discharge characteristic behavior, and its decomposition under arc and various types of discharges.

## 2.3 Other Requirements for Commercialization

Commercial use of a dielectric gas requires certain non-physical characteristics, including widespread availability, reliable supply, and long-range stability of supply.

## 2.4 Properties of Gaseous Insulators for Specific Industrial Uses

### 2.4.1 Circuit Breakers – Arc Quenching and Current Interruption

An electric arc is the most crucial switching element in a circuit breaker. It has the unique ability to act as a rapidly changing resistor such that during the AC current, high conductance is maintained. As the current approaches zero, the conductance decreases rapidly, and finally, at zero current, the resistance rises to prevent re-ignition. Commercial circuit breakers utilize air, oil, $SF_6$, solid state, or vacuum as interrupting media. The arc properties for gas-based circuit breakers are a strong function of the arcing gaseous medium. The most significant required gas properties for arc interruption are:

• *High dielectric strength comparable to that of sulfur hexafluoride* - This is one of the most essential properties characterizing a good interrupting medium.

• *High thermal conductivity* - This is another important required property. The arc is initially hot (temperatures in excess of 10,000 K), and it must be quickly cooled down by removing energy from it by the gas. Additionally, the arc must have a short time constant for the increase in resistivity. For these requirements, the gas must have high thermal conductivity at high temperatures and also should capture quickly free electrons when the gas is hot and the electrons fast. These two properties – high thermal conductivity and high electron attachment – lead to a high interruption capability, i.e., enable a rapid transition between the conducting state (arc plasma) and a dielectric state able to withstand the rise of recovery voltage. $SF_6$ is known to have a time constant 100 times shorter than air and is used in circuit breakers for two main reasons: it has a high thermal conductivity at high temperatures which enables it to rapidly cool down; $SF_6$ and its decomposition products are electronegative and thus enhance the disappearance of electrons even when the gas is hot.

• *Fast gas recovery* - At the high temperatures involved, the gas molecules are dissociated into their constituent atoms (atomized). They must quickly reassemble, preferably to form their original molecular structure. (Besides $SF_6$, this is a property shared by a number of molecules with top symmetry such as σ-bonded perfluoroalkanes).

• *Self-healing / dielectric integrity* - This limits the preferred gases to those that are either atomic in nature or molecular with very compact and stable structure, such as $SF_6$, $CF_4$, and other compounds, which when "atomized" under the high temperature arc conditions reform themselves with high efficiency, that is, the original molecules are the main decomposition product.

### 2.4.2 High Voltage Insulation

There are two important types of basic gas-insulated apparatus used by the electric power industry: gas-insulated transmission lines and gas-insulated transformers. In this section are outlined some of the principal properties a gaseous dielectric needs to be used in such applications. Other applications with similar needs include buses and disconnects in gas-insulated substations.

**2.4.2.1 Gas-insulated Transmission Lines** - Here the dielectric strength of the gas and its long-range stability and inertness, along with its heat transfer properties at temperatures much lower than in circuit breakers ($\leq$110 °C), are important gas requirements. Specifically, the required properties include:

- high dielectric strength (in uniform fields, non-uniform fields, in the presence of electrode

[7] The optimum design of a gas-insulated system requires this knowledge. Perhaps one can determine this through the so-called figure of merit, i.e., from basic measurements of $(\alpha-\eta)/N$ versus $E/N$. It would certainly be desirable to have a gas for which these effects are less troublesome than for $SF_6$.

roughness and conducting particles, and for various geometries including co-axial configurations);
- high vapor pressure at operating and ambient temperature;
- chemical inertness;
- high thermal conductivity [but at temperatures far below those encountered in arcs (a few hundred degrees above ambient)];
- no thermal aging (long-term, 40 years or more);
- no deposits (no carbon deposits, no polymerization, and no decomposition);
- easily removable, non-harmful byproducts;
- no hazards (fire, explosion, toxicity, corrosion).

**2.4.2.2 Gas-insulated Transformers** - In very early transformers, air was the most commonly used insulating medium, but as the voltages were increased, oil was substituted for air. While oil is presently widely used and has many advantages, it burns when exposed to flame or heated to ignition point in the presence of air. Also, certain mixtures of oil vapor and air explode on ignition when confined. Additionally, breakdown due to charge accumulation on insulating parts by ions transported by the cooling pumps may occur, and flashovers due to particulate contaminants may be caused.

There are distinct advantages in using gas insulation in transformers. Firstly, the use of a gas instead of oil completely removes the undesirable characteristics of oil just mentioned. Secondly, gas-filled transformers are lighter, have better noise characteristics (since gas transmits less vibration than oil), and are easier to handle. Compared to oil, however, the gas is not as good for cooling (needs special techniques to remove the heat) and thus gas-insulated transformers presently are unable to meet the highest ratings achieved by oil transformers. The properties of the gas required for this application include:
- high dielectric strength at reasonable (e. g., 500 kPa) pressures;
- low boiling point (low condensation temperature, high vapor pressure);
- low toxicity;
- chemical inertness;
- good thermal stability (because transformers are operated in a wide temperature range);
- non-flammable;
- high cooling capability (heat transfer is important in transformers which frequently get quite hot);
- good compatibility with solid materials (because the gas must coexist with many different solid materials in the gas-insulated transformer);
- good partial discharge characteristics (because of the high possibility of partial discharges in the transformer);
- useable over a range of temperatures (basic properties as a function of temperature);
- safe, easy to handle, inexpensive, securely available.

## 3. Required Performance and Testing of Gases

At first consideration one may be tempted to adopt an extreme position for new gases*: ALL that has been done on* $SF_6$ *has to be repeated.* While there is a need for any new gas "to be proven," this approach is unrealistic, impractical, and perhaps unwise and unnecessary. Clearly, before any testing is done, the gas must:
- be environmentally acceptable, or confined for life,
- have no serious known health-related risks and serious safety-related problems (toxicity, flammability, etc.),
- have a high pressure (to be useful as a unitary gas or as an additive in mixtures), and
- be available, stable, and thermally and chemically inert.

These requirements must be satisfied whether one is looking for potential gas substitutes on which tests have already been made or for new gaseous systems for which tests will be made, independently of the intended use.

The list of other tests that are also useful and desirable is long (see Sec. 2 on required properties) and includes:
- breakdown tests as a function of pressure, field, types of voltage, and time;
- comprehensive dielectric strength tests using practical-size systems and voltages and waveforms (i.e., DC, AC, lighting and switching impulse, fast transients). Since the design of the high voltage insulation system is usually determined by the lighting impulse test level (BIL), the lighting impulse test is a crucial test;
- effects of surface roughness and conducting particles. Practical design levels for the dielectric strength are normally much lower than the "theoretical" dielectric strength of a gas insulator, because the dielectric strength of gases, especially those for strongly electronegative gases, are very sensitive to field perturbations such as those caused by conductor surface imperfections and by conducting particle contaminants;[8]
- dielectric strength measurements at high gas

[8]The design levels for $SF_6$ have been quoted [27] to be of the order of 37% of the theoretical strength of $SF_6$ for lighting impulse and 19% of the 60 Hz factory test for these stated reasons.

pressures (this is one type of measurement that has generally been lacking and is crucial);

- long-time tests;
- flashover voltages of insulators;
- thermal stability in the presence of other materials (long-time stability with metals and resins), and thermal aging;
- corona inception[9] and extinction
- thermal cooling.
- mass and light spectroscopy to identify the discharge products and their reactions for a number of purposes including diagnostics;
- measurement of dielectric strength as a function of gas pressure, especially for weakly electron attaching gases or mixtures;
- scaling data on small laboratory equipment to large practical systems, and extrapolating data taken over short time scales to the expected long life times of industrial systems (e.g., 40 years);
- byproducts and possible health effects.

The list of desirable tests for use of a gas under arc or current interruption applications must also include:

- tests of arc and current interruption properties;
- recovery tests; and
- nozzle design and behavior.

# 4. Possible "Universal-Application" Gas Mixtures

The most desirable $SF_6$ substitute would be a gas that could be put in all existing $SF_6$-equipment, requiring little or no change in hardware, procedures or ratings. Such a gas we refer to as a "universal-application" gas and we define it as a gaseous medium which can be used instead of pure $SF_6$ in existing equipment without significant changes in practice, operation, or ratings of the existing gas-insulated apparatus. It is a useful exercise to determine if such a substitute can be identified from the existing gaseous dielectric data.

Of the many unitary, binary, and tertiary gases or gas mixtures that have been tested over the last three decades or so, $SF_6$-$N_2$ mixtures seem to be the most thoroughly characterized [yet not completely tested, especially at high pressures (greater than 0.5 MPa)] gaseous dielectric media besides pure $SF_6$ [2–4, 6–8, 14, 25, 29–34]. There is broad acceptance of the view that these mixtures may be good replacements of pure $SF_6$. The main reasons are:

• they perform rather well for both electrical insulation applications and in arc or current interruption equipment,

• they have lower dew points and certain advantages especially under non-uniform fields[10] over pure $SF_6$,

• they are much cheaper than $SF_6$ especially after the recent large increases[2] in the price of $SF_6$, and

• industry has some experience with their use.

The relevant question, therefore, is: *does an optimum mixture composition and total pressure exist that allows the use of this mixture as a "universal-application" gas, and could the industry readily use such a mixture?* While the answer to this question is complex, it is desirable to attempt to identify, on the basis of existing knowledge, a particular mixture composition that may be best suited for consideration by the electric power industry for their needs. If such mixture can be identified, it can perhaps be standardized in composition. Although it would be desirable to have such a standard mixture prepared and sold by chemical companies for direct use in the field, this may not be feasible, and the two gases would probably have to be mixed to the standard composition at the point of use (see Appendix C).

Based upon research conducted world-wide over the last three decades or so, it appears that the optimum composition of an $SF_6$-$N_2$ mixture for use by the electric power industry in place of pure $SF_6$ for both high voltage insulation (for gas-insulated transmission lines and gas-insulated transformers) and arc or current interruption purposes may be in the range of 40% to 50%$SF_6$ in $N_2$. Thus, possible standard mixtures that can reasonably be considered are 40%$SF_6$-60%$N_2$ or 50%$SF_6$-50%$N_2$.

The savings[11] of replacing pure $SF_6$ by a 40%$SF_6$-60%$N_2$ gas mixture are potentially large. If it is assumed that 80% of the ~8,000 metric tons of $SF_6$ produced annually is used by the electric power industry (Sec.1.2; [12]), at a price[12] of $20 / lb (~$42 / kg) for $SF_6$, the total annual savings in the cost of $SF_6$ will be about $150 million.

[9]It has been pointed out by Wootton [28] that in tests on a full size GIS with a fixed particle, typically less than 10% of the breakdowns occur without corona stabilization. Based on this information, Dale et al. [27] suggested that in practical apparatus it would be the corona inception level and not the corona stabilized breakdown level which is important. However, the strong corona stabilization characteristics of electronegative gases can be advantageous.

[10]The more electronegative the gas is, the larger the reduction of its dielectric strength under non-uniform field conditions and in the presence of conducting particles.

[11]Perhaps even higher savings may be possible if the percentage of $SF_6$ is lowered further by increasing the total operating pressure of the mixture. Limited measurements on the arc interruption capability of pure $SF_6$ in the pressure range 0.41 MPa to 0.72 MPa ([3], p. 51) indicate that it increases almost as the square of the fill pressure.

[12]Based on the spectrum of prices, it seems logical to assume a price of about $20 per lb ($42 / kg).

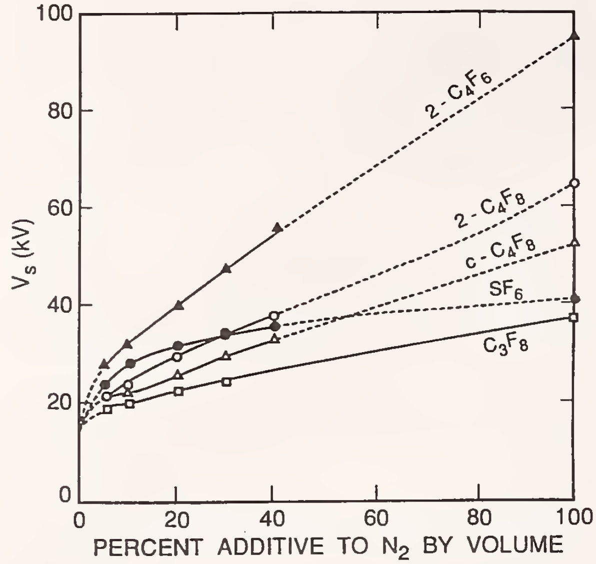


FIG. 4. DC breakdown voltage as function of electron attaching additive to nitrogen (uniform and quasi-uniform electric fields; the total gas pressure is 66.66 kPa and the electrode gap is 7 mm). The broken curves are extrapolations (from [35, 36]).

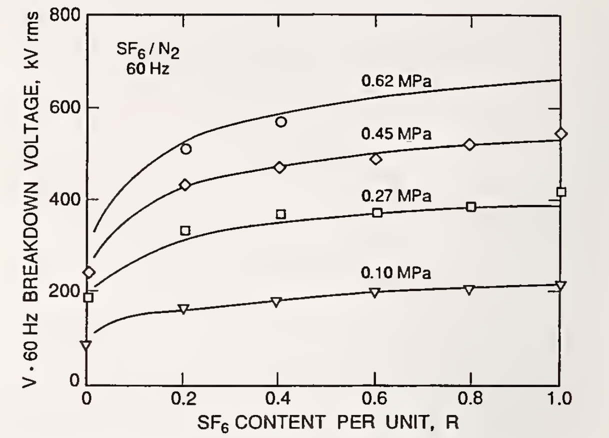


FIG. 5. Measured (symbols) and calculated (solid lines) 60-Hz breakdown voltage values for $SF_6$-$N_2$ in coaxial electrode geometry (from [37]).

The feasibility analysis of a universal application mixture for insulation applications, and arc and current interruption purposes is based on information obtained from a number of sources, the most significant of which are briefly discussed below. Additional pertinent information related to mixtures with even lower concentrations of $SF_6$ is presented in Sec. 5.2.

## 4.1 Insulation

### 4.1.1 Gas-insulated Transmission Lines

Existing information suggesting the use of $SF_6$-$N_2$ mixtures for insulation purposes has been summarized and discussed in a number of recent publications (see, for example, Refs. [3, 6, 14, 33, 34]). In this section we refer to and supplement the work summarized in those reports, which indicates the possibility of adopting the 50%$SF_6$-50%$N_2$ mixture as a standard gas option for gas-insulated transmission lines. Most of the information presented also supports the use of such mixtures for gas-insulated transformers (Sec. 4.1.2) and possibly also circuit breakers (Sec. 4.2). It has been known for a long time that the breakdown voltage of $SF_6$-$N_2$ mixtures saturates as the percentage of $SF_6$ in the binary mixture is increased above about 40%. This is seen from DC measurements ([35, 36], Fig. 4), AC measurements ([37], Fig. 5), and impulse measurements ([37], Fig. 6). Above this saturation level, addition of more $SF_6$ to $N_2$ yields limited returns for insulation applications. This has been shown by many studies. For instance, Bouldin et al. [30, 31] conducted an assessment of the potential of dielectric gas mixtures for industrial applications based mostly on DC uniform and quasi-uniform field data at pressures less than a few hundred kPa. They concluded that a 50%$SF_6$-50%$N_2$ mixture, operated at 15% higher pressures, exhibits the same dielectric strength as 100% $SF_6$, but at ~35% lower cost (calculated using a price of $SF_6$ more than ten times lower than it is today). A 50%$SF_6$-50%$N_2$ mixture was listed as having 0.88 the dielectric strength of pure $SF_6$ at the same pressure and a condensation point 20 °C lower.

Malik and Qureshi [38] reviewed the work on electrical breakdown in mixtures of $SF_6$ and other gases

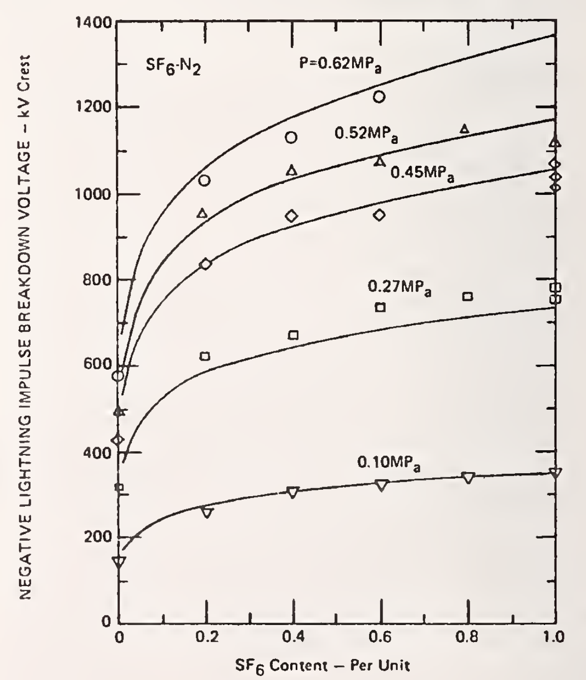


FIG. 6. Negative lightning impulse breakdown voltages for $SF_6$-$N_2$ mixtures. The solid curves are semiempirical fits to the measurements (from [37]).

including $N_2$. They state: "$SF_6$-$N_2$ mixtures containing 50% to 60% of $SF_6$ have dielectric strength of up to 85% to 90% that of pure $SF_6$. Such mixtures can have improved impulse and power-frequency breakdown strength in highly non-uniform field gaps and therefore are expected to be less sensitive (than pure $SF_6$) to the presence of free conducting particles and electrode surface roughness." Furthermore, the mixtures can be operated at pressures considerably higher than 600 kPa which is the upper limit for $SF_6$-insulated apparatus [39] and at considerable reduction in cost [38].

In view of the superior insulation properties of $N_2$ at higher pressures and in non-uniform fields compared to pure $SF_6$, the advantage of the 50-50 mixture over pure $SF_6$ may be even greater. For example, non-uniform (positive point-plane electrode geometry) DC breakdown measurements [36] as a function of the total pressure showed that the dielectric strength of a 30%$SF_6$-70%$N_2$ mixture at ~600 kPa is somewhat higher than that of pure $SF_6$ under the same conditions. Similarly, Nakanishi [40] concluded that "a gas mixture of $SF_6$-$N_2$ (and $SF_6$-air) is thought to be the most promising candidate for application to high power apparatus. $SF_6$-$N_2$ (and $SF_6$-air) mixtures have breakdown properties superior to pure $SF_6$ at non-uniform fields."

A recent example [41] of the voltage versus pressure characteristic of $SF_6$ and a 75%$SF_6$-25%$N_2$ mixture is shown in Fig. 7. Included in the figure are measurements of both the breakdown and the corona onset voltages for the two gases. The measurements were made using nonuniform fields and lightning impulse voltage. The corona onset for $SF_6$ and the $SF_6$-$N_2$ mixture scales with the respective uniform field breakdown voltages of the two gases, but the breakdown voltage exhibits the usual corona stabilization region which varies with mixture composition. Depending on the mixture composition there are total pressures for which the breakdown voltage of the mixture exceeds that of pure $SF_6$.

Similar conclusions have been reached by other impulse breakdown studies. Lightning and switching impulse breakdown measurements in the pressure range between 0.1 MPa and 0.7 MPa by Cookson and Pedersen [37] led them to conclude that "the $SF_6$ mixtures with $N_2$ (or air, or $CO_2$) look promising for compressed gas-insulated transmission (CGIT) applications with a 50-50 mixture at a typical pressure of 0.54 MPa being able to replace $SF_6$ at 0.45 MPa without loss of breakdown strength." Similarly, Cookson [42] concluded that mixtures of $SF_6$ with $N_2$ can be readily applied in practical CGIT lines at a cost savings over $SF_6$. Rein and Kulsetås [43] studied lightning and switching impulse breakdown of $SF_6$-$N_2$ mixtures using electrode configurations representative of open disconnectors and earthing switches and concentric cylinder systems, and pressures ranging from 0.5 MPa to 1.5 MPa. They concluded that "compared to pure $SF_6$ of 1.0 MPa, a 50%-50% mixture of $SF_6$ and $N_2$ with the same total pressure retains about 85% of the dielectric strength. An increase of $N_2$ content to a total pressure of 1.5 MPa gives a dielectric strength equal to that of 1.0 MPa $SF_6$. The condensation temperature is thereby lowered from −15 °C to −40 °C."

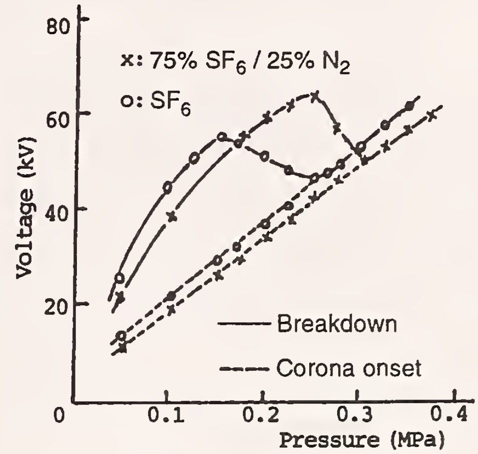


FIG. 7. Voltage versus pressure characteristic of $SF_6$ and a 75%$SF_6$-25%$N_2$ mixture for a point-plane gap and lighting impulse (+1.2 / 50 μs) (from Qiu and Feng [41]).

Furthermore, Fatheddin et al. [44] investigated the breakdown properties of $SF_6$-$N_2$ mixtures using lightning and switching impulses of both polarities, a point-plane geometry, and total pressures between 0.05 MPa and 0.5 MPa. From Figs. 1 to 5 of their paper it appears that a 40%$SF_6$-60%$N_2$ mixture is an excellent choice. For this mixture, the impulse polarity had negligible effect with lightning surges. However, the negative polarity $V_{50}$ ($V_{50}$ is the peak voltage with 50% breakdown probability) values were higher and the positive $V_{50}$ values were lower for the (slower) switching surge pulse. Interestingly, their positive DC point-plane geometry measurements (Figs. 6 and 7B of their paper) showed a 30%$SF_6$-70%$N_2$ mixture to be at least as good as pure $SF_6$ for total pressure greater than 500 kPa.

Very importantly, a number of studies [3, 29, 45–52] have shown that in the presence of particles a number of $SF_6$-$N_2$ mixtures perform well compared to pure $SF_6$. They have also indicated that the effect of particles on the breakdown strength of such mixtures depends on the total pressure and on the partial pressure of the component gases (Fig. 8; Table 2). The data in Table 2 are particularly interesting. They show that for certain conditions (DC, cylindrical electrodes, in the presence of conducting particles as contaminants) the highest breakdown voltage for a 50%$SF_6$-50%$N_2$ mixture corresponds to a total pressure of about 608 kPa (~ 6 atm) (see Table 2), which is a reasonable pressure for use in

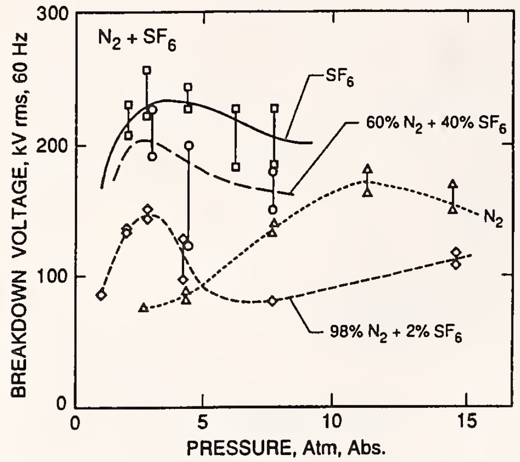


**FIG. 8.** AC breakdown voltage in $SF_6$-$N_2$ mixtures with 0.043 cm (0.017 in) diameter copper wires, 0.635 cm (0.25 in) long in a 7.62 cm (3 in) plane gap [3, 45, 46]. The 60%$SF_6$-40%$N_2$ data are shown by the broken line.

gas-insulated equipment. However, more work is needed on particle-contaminated $SF_6$-$N_2$ gas mixtures. Present data are not sufficient to fully characterize the behavior of such mixtures as a function of partial or total pressure.

The solid-gas interface has its own breakdown characteristics. Generally, the breakdown voltage is lowered by the presence of a spacer. A 50%$SF_6$-50% $N_2$ mixture has about 90% the flashover voltage of pure $SF_6$ in the presence of spacers [31] (see also [53]). Similar conclusions have been reached by other researchers. For instance, Nakanishi [40] cited work by M. Hara et al. on the flashover characteristics of a cylindrical spacer on which a conducting particle was affixed in an $SF_6$-$N_2$ gas mixture which "showed that the flashover properties can be improved by mixing 20%$SF_6$ into $N_2$."[13]

Furthermore, Eteiba et al. [54] measured the breakdown voltage of particle-contaminated spacers using 60-Hz and negative lighting impulse voltages. Figure 9 compares the dielectric strength of a clean spacer (curves A) to that obtained with a 2-mm long aluminum wire of 0.8 mm diameter particle attached on the spacer interface 2.6 mm from the center conductor (curves B) and from the outer envelope (curves D). The authors concluded that their results show no significant difference in the 60-Hz withstand voltage between pure $SF_6$ and the 50%$SF_6$-50%$N_2$ mixture for either the clean or the particle contaminated system and the 50%$SF_6$-50%$N_2$ mixture has only a slightly lower impulse ratio than pure $SF_6$. However, the breakdown characteristics of spacers for $SF_6$ and $SF_6$-$N_2$ mixtures as well as their cooling efficiencies need further investigation in order to quantify the performance of the mixtures under practical conditions, as has been pointed out by Endo [55].

[13]M. Hara et al. as quoted by Nakanishi [40].

**TABLE 2.** DC breakdown voltages of $SF_6$-$N_2$ mixtures with cylindrical electrodes and particle contamination [52]

| $SF_6$-$N_2$ | $V_{br}$ (kV) 303.9 kPa | $V_{br}$ (kV) 405.2 kPa | $V_{br}$ (kV) 607.8 kPa | $V_{br}$ (kV) 810.4 kPa | $V_{br}$ (kV) 1013 kPa |
|---|---|---|---|---|---|
| 100/0 | 59.6 | 62.1 | 70.0 | 67.5 | 60.0 |
| 80/20 | 45.7 | 49.0 | 59.6 | 58.6 | 50.1 |
| **60/40** | 50.7 | 54.1 | **66.0** | 62.4 | 61.2 |
| **40/60** | 24.3 | 39.5 | **55.7** | 50.9 | 43.5 |
| 20/80 | 26.3 | 38.5 | 37.2 | 41.9 | 33.4 |

Similarly Blankenburg [56] found that the flashover behavior of cylindrical insulators in $SF_6$-$N_2$ mixtures subjected to AC voltage was found [88] to be qualitatively similar to that in pure $SF_6$ independently of the amount of $SF_6$ in the mixture (even when the mixture contained as little as 1% $SF_6$).

Additionally, according to Waymel and Boisseau [57] recent dielectric tests on real-size gas insulated transmission line (GITL) compartments confirmed the good industrial performance of $SF_6$-$N_2$ mixtures. Partial conclusions could be reached by them in the particular case of buried 400 kV GITL. They concluded that "compared to pure $SF_6$, $SF_6$-$N_2$ mixtures offer good compromise with the diameter of busbar required by the thermal design of buried GITL."

Interestingly, the uniform field breakdown strength of $SF_6$ has been found [58] to increase by ~11% in the temperature range 300 K to 600 K. Because the presence of $N_2$ in $SF_6$-$N_2$ mixtures is not expected to change the dissociative electron attachment properties of $SF_6$ which are responsible for this increase, a similar increase in the dielectric strength of $SF_6$-$N_2$ mixtures with increasing temperature might be anticipated.

The behavior of a 50%$SF_6$-50%$N_2$ mixture under fast transient conditions has been investigated by Pfeiffer and co-workers. They found no significant difference in the behavior of the mixture compared to pure $SF_6$ (e. g, see Pfeiffer et al. [59] ; see also discussion in [6]).

Concerning the decomposition of $SF_6$-$N_2$ mixtures, there exist only limited data on the decomposition products of $SF_6$-$N_2$ mixtures (see discussion in [6]). These data are mainly of corona decomposition. They show that there is very little chemical interaction between $SF_6$ and $N_2$ in discharges and that the predominant oxidation byproducts are those seen in $SF_6$ ($SO_2$, $SOF_2$, $SO_2F_2$, and $SOF_4$). However, the presence of $N_2$ may reduce the ability of $SF_6$ to reform itself following an arc or a discharge and thus it may inhibit its recovery. This needs further investigation.

Finally, to our knowledge there is only one toxicological study [60] on $SF_6$-$N_2$ mixtures, which

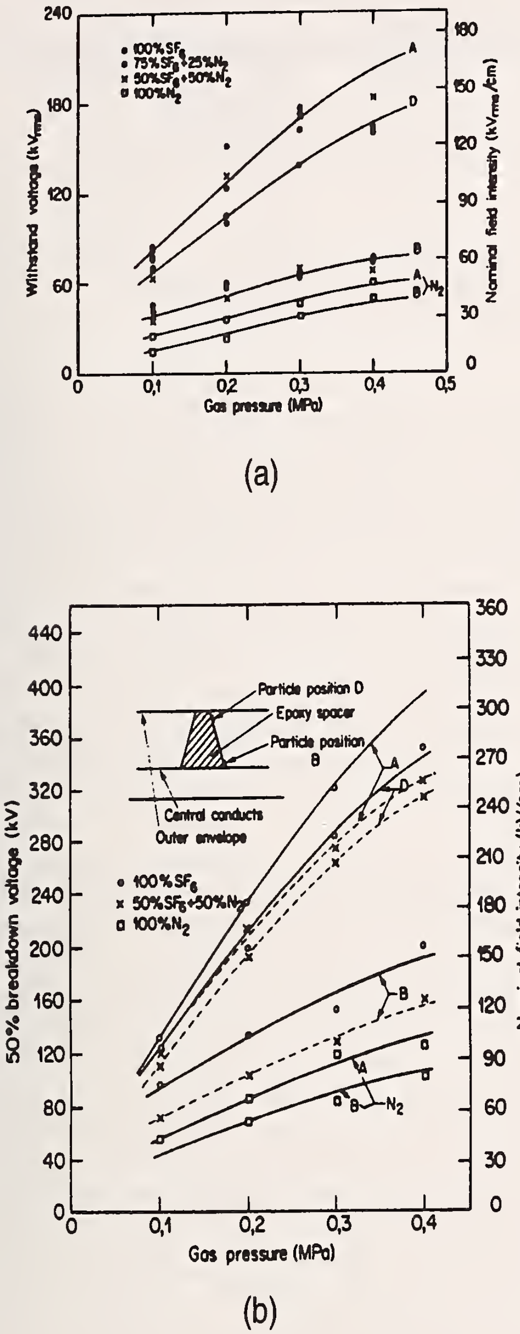


**FIG. 9.** (a) Variation of the AC voltage in $SF_6$, $N_2$, and the mixtures 50%$SF_6$-50%$N_2$and 75%$SF_6$-25%$N_2$ (from Eteiba et al. [54]). (b) Variation of the 50% negative impulse breakdown voltage for $SF_6$, $N_2$, and the mixture 50%$SF_6$-50%$N_2$ (from Eteiba et al. [54]).

concentrates on the toxicological action of arc-decomposed $SF_6$-$N_2$ mixtures (and pure $SF_6$). Its main conclusions are: (i) the lung, liver, and kidney can be attacked by arc-decomposed $SF_6$ gas and the alimentary system also can be influenced by the arced $SF_6$; and (ii) arced $SF_6$-$N_2$ mainly attacks the lungs of the animals exposed to the gas; livers, kidneys, and other organs are hardly affected, but the alimentary systems are generally influenced.

For gas-insulated transmission lines, $SF_6$-$N_2$ mixtures in general and the 40%$SF_6$-60%$N_2$ mixture in particular have great industrial potential. Depending upon the test, mixtures of $SF_6$-$N_2$ appear to perform at least at levels of 80% of pure $SF_6$, and in some cases $SF_6$-$N_2$ mixtures exceed pure $SF_6$ performance. Indeed, some members of the electric power industry are in the process of designing and/or building GITL using $SF_6$-$N_2$ mixtures for insulation purposes. The use of $SF_6$-$N_2$ mixtures in existing GITL designed for pure $SF_6$ is more problematic due to the need for possible equipment changes and derating or recertification of existing equipment.

#### 4.1.2 Gas-insulated Transformers

As was indicated in Sec. 2.4.2.2 of this report, heat dissipation is a significant requirement for gas-insulated transformers (GIT) in addition to the gas dielectric insulation characteristics. A number of recent studies [55, 61–65] considered $SF_6$-$N_2$ mixtures as the insulating and heat transfer medium for gas-insulated transformers in spite of the fact that their insulating and heat-transfer (cooling) capabilities are somewhat lower than for pure $SF_6$. A recent study on the temperature distribution in $SF_6$-$N_2$ mixtures-insulated existing transformers [63] has led to the conclusion that "$SF_6$-$N_2$ mixtures-GIT meets the standards completely and it can be applied in electric power systems." This same study found that a mixture ratio 55%$SF_6$-45%$N_2$ has "good characteristics." Similar studies [61, 62] concluded that: (i) the application of $SF_6$-$N_2$ mixtures as the insulating and heat-transfer medium is feasible, (ii) with the same construction as for pure $SF_6$, $SF_6$-$N_2$ mixtures can be selected with composition as high as 55%$SF_6$-45%$N_2$ with good insulation characteristics, and (iii) for 10 kV class $SF_6$-$N_2$ mixtures GIT, the heat-transfer characteristics of the gas mixtures are the controlling factor in the design of insulation construction.

Because the temperature rise [55, 64, 65], of a 50%$SF_6$-50%$N_2$ mixture over that of pure $SF_6$ is significant (approximately 15 °C to 20 °C) [63], it was suggested [64] that amorphous steel construction may help alleviate the heat transfer problem and allow use of a lower percentage of $SF_6$ in the $SF_6$-$N_2$ mixtures. The use of $SF_6$-$N_2$ mixtures may, thus, need to be coupled to the use of more heat resistant materials and modification of the transformer cooling design.

Overall, in spite of the difficulties mentioned in this section regarding the cooling capabilities of the $SF_6$-$N_2$ mixtures, a 50%$SF_6$-50%$N_2$ mixture can be a potentially useful gas-insulated transformer medium and further studies are indicated.

## 4.2 Interruption[14]

As discussed in Sec. 2, for arc and current interruption, the dielectric, switching, and thermal properties of the gas are important. Characterization of the cooling capacity of an interrupting gaseous medium involves consideration of the specific heat and specific thermal conductivity of the gas, as well as its ability to dissipate heat by convection. Nitrogen (and other light gases such as He) supplement $SF_6$ in this regard, $SF_6$ being efficient at the very high temperatures (say, 10,000 K to 3,000 K) and $N_2$ (or He) at the relatively lower temperatures (say, below 3,000 K). Table 3 lists the specific heats, specific thermal conductivities, and coefficients of viscosity of $SF_6$, $N_2$, and He.

There have been a number of studies on the arc and current-interruption capabilities of $SF_6$-$N_2$ mixtures and their performance in comparison to pure $SF_6$. Most such studies on circuit breakers used either of two types of gas circuit breakers (GCB). One is a double pressure type, and the other is a puffer type. Their structures and thus current-interruption capabilities are different. In the double pressure type GCB, high pressure gas is always stored in a high pressure vessel and the compressed gas in this vessel is blasted as soon as the contacts are separated. In the puffer type GCB, it is necessary to compress a gas in a puffer chamber during the opening stroke. The compressed gas is blasted to arc through an insulation nozzle. In this type of operation, the pressure increase and its duration are crucial variables for current-interruption capability. Most current GCBs are of the puffer type.

A comprehensive review and discussion of gases for arc interruption prior to 1982 was given in [3]. One of the significant results of this study is the observed strong dependence of the arc interruption performance of a gaseous medium on the total gas pressure, *P*. The rather limited data in this report [3] indicated that the arc interruption capability of $SF_6$ increased superlinearly with increasing pressure. This is significant because a small increase in the total pressure of an $SF_6$-$N_2$ mixture may compensate for the reduction in the arc interruption capability of the mixture relative to pure $SF_6$. This work [3] also concluded that: "For general purpose high voltage gas circuit breaker applications, $SF_6$ will be the interruption medium. However, there are applications for which other media can be viable alternatives. For example, a European manufacturer offers $SF_6$-$N_2$ as part of the puffer line with about 20% current derating in interrupting capability for applications in extreme low temperature environment ( < −40 °C). Our data confirms that our puffer interrupters can be applied without design alteration. Furthermore, with interrupters designed specifically for $SF_6$-$N_2$, no derating is necessary with benefits of less $SF_6$ gas required, elimination of special heaters, and because of overall lower gas mass for a given pressure level, lower mechanical energy to operate the breaker. The combination can offer a lower cost interrupter with wider operating temperature range. Additional data on interrupter development specifically for $SF_6$-$N_2$ will be required to be more quantitative in regard to the economic advantages of $SF_6$-$N_2$ interruption medium."

[14]See Ref. [3] for a list of patents up to 1980 on gases for electrical arc interruption. Also see Chervy et al. ([66, 67, 68]) for information on the arc interruption capabilities of $SF_6$-$CF_4$ and $SF_6$-$C_2F_6$ mixtures, Nakagawa et al. [69] for the interruption capability of $SF_6$-$CF_4$ mixtures in puffer type gas-blast circuit breakers, and Middleton et al. [70] for work on $SF_6$-$CF_4$ circuit breakers.

**TABLE 3.** Specific heat, specific thermal conductivity, and coefficient of viscosity for $SF_6$, $N_2$, and He.

| Gas | Specific heat[a] (cal g$^{-1}$ K$^{-1}$) | Thermal conductivity[a] (W m$^{-1}$ K$^{-1}$) | Coefficient of viscosity[b] (poise) |
|---|---|---|---|
| $SF_6$ | 0.157 | 0.0155 | 161 x 10$^{-6}$ (25 °C) |
| $N_2$ | 0.248 | 0.0238 | 163 x 10$^{-6}$ (0 °C) |
| He | 1.242 | 0.150 | 189 x 10$^{-6}$ (0 °C) |

[a]Data provided by Endo [55] (Toshiba Corporation).
[b]From Clark [71].

Another significant study is that of Grant et al. [72] who compared the performance of $SF_6$-$N_2$ mixtures as interruption media of gas-blasted arcs for various mixture compositions and total pressures of 500 kPa, 600 kPa, and 700 kPa. They measured the rate of rise of the recovery voltage (RRRV) capability, as a function of concentration of added $N_2$ (or He) to $SF_6$. Their results along with similar measurements by Garzon [73] are shown in Fig. 10. They show that the peak in the RRRV versus $SF_6$ percentage moves towards lower $SF_6$ concentrations at higher total pressures. These investigations also showed that the addition of appropriate amounts of $N_2$ (or He) to $SF_6$ can result in improved RRRV performance of up to 40% above that of pure $SF_6$ (Fig. 11). The measurements of Grant et al. [72] on $SF_6$-$N_2$ mixtures and Garzon [73] on $SF_6$-$N_2$ and $SF_6$-He mixtures are listed in Table 4. The measurements of Leeds et al. [74] on $SF_6$-air mixtures are also listed in Table 4 for comparison. As can be seen from Table 4, the measurements of Garzon [73] on the rate of rise of recovery of voltage (RRRV) for a synchronous interrupter show that the performance of $SF_6$-$N_2$ mixtures having 50%$SF_6$ by volume at pressures of 1300 kPa to 1900 kPa is approximately 1.39 times better than for pure $SF_6$. Garzon also found that the recovery capability of a non-synchronous circuit breaker using this gas mixture was at least as good as when pure $SF_6$ was used. The optimum interrupter performance, judged in terms of its voltage recovery capability, is observed to

**TABLE 4.** Recovery performance factors[a] normalized to pure $SF_6$ (as listed in [69]).

| $\%SF_6$ | $N_2$ 500 kPa [72] | $N_2$ 600 kPa [72] | $N_2$ 700 kPa [72] | $N_2$ 1700 kPa [73] | He 600 kPa [73] | Air 1000 kPa [74] |
|---|---|---|---|---|---|---|
| 100 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 90 | 1.32 | 1.07 | 1.13 | 1.02 | 0.98 | - |
| 75 | 1.03 | 1.24 | 1.46 | 1.08 | 1.12 | - |
| 65 | - | - | 1.52 | 1.17 | - | - |
| 60 | - | 0.93 | - | 1.22 | 1.13 | - |
| **50** | **1.0** | **0.82** | **0.86** | **1.33** | **1.14** | **0.52** |
| **40** | **-** | **-** | **-** | **1.39** | **-** | **-** |
| 25 | 0.56 | 0.38 | 0.52 | 0.90 | 1.08 | 0.28 |

[a]Ratio of the RRRV for a given mixture to the RRRV for pure $SF_6$.

occur when the mixture composition is roughly $50\%SF_6$-$50\%N_2$ (Fig. 10). Garzon pointed out that these results using a double pressure type cannot be generalized for the design of all circuit breakers, but in applications where conditions are similar to those of his experiments, "it will be safe to assume that the use of a 50%-50% mixture of $N_2$ and $SF_6$ will serve to improve the *dv/dt* recovery capability of the interrupter." While this conclusion is for higher pressures than are normally encountered in practice, Grant's data in Fig. 10 and the data in Table 4 clearly support this statement for lower total pressures as well.

The results of Garzon were obtained with a synchronously operated interrupter, and "therefore it is conceivable that non-synchronous operation may alter some of the findings." However, Garzon states that "it is our experience that the recovery capability of a non-synchronous breaker using a $50\%SF_6$-$50\%N_2$ mixture was at least as good as when $100\%SF_6$ had been used." Their results taken between 1.38 MPa and 1.93 MPa indicate improved capability with increasing total pressure and this finding is consistent with earlier results [3].

Studies on full-size puffer interrupters using pure $SF_6$ and $SF_6$-$N_2$ mixtures by Sölver [75] led him to conclude that "a mixture of 69% $SF_6$ and 31% $N_2$ had considerably higher recovery speed than pure $SF_6$ at the same $SF_6$ partial pressure."

As mentioned previously, Malik and Qureshi [38] reviewed the work on electrical breakdown in mixtures of $SF_6$ and other gases including $N_2$. They pointed out that previous work [72, 73, 76–78] shows that it is possible to further enhance the excellent arc interruption properties of $SF_6$ by using $SF_6$ mixed with lighter gases such as nitrogen or helium

Naganawa et al. [79] investigated the DC interruption by a spiral arc in $SF_6$-$N_2$ gas mixtures in the pressure range 0.1 MPa to 0.8 MPa . The mixtures they

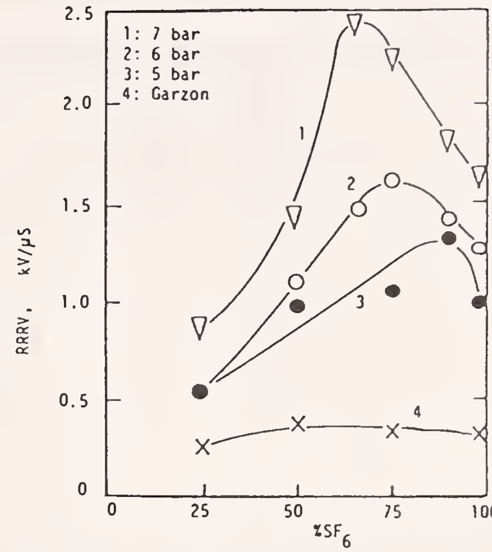


**FIG. 10.** RRRV as a function of $SF_6$-$N_2$ mixture ratio. Curves 1-3 are the data of Grant et al. [72] and Curve 4 are the data of Garzon [73] (adapted from Fig. 2 of [72]). The measurements of Garzon were made at a pressure of 1700 kPa.

studied contained a constant partial pressure of $SF_6$ equal to 0.1 MPa. The voltage-current characteristic curve of the spiral arc for the mixture $50\%SF_6$-$50\%N_2$ was slightly below the similar curve for pure $SF_6$ at the same total pressure (0.8 MPa). They recommended $SF_6$-$N_2$ as "an extinguishing medium of switch gear to avoid the liquefying phenomena of pure $SF_6$ gas of high pressure under extremely low temperature and to reduce gas costs."

However, other studies (see below) indicated that the $50\%SF_6$-$50\%N_2$ mixtures performed not as well as pure $SF_6$ as arc or current interrupting media.

A comprehensive evaluation of and measurements on gases for arc interruption (puffer-type interrupter, current range ~10–15 kA) was conducted by Lee and Frost [80]. They concluded that "the results of previous investigators reaffirmed the overall excellent arc interruption ability of $SF_6$, while other gases and gas mixtures can have comparable performance in some aspects of interruption." They themselves screened about 250 gases and out of these they selected 40 gases and gas mixtures for experimental evaluation. In Table 5 are given the arc interruption capabilities they measured for $SF_6$-$N_2$ mixtures, $SF_6$-He mixtures, and pure $SF_6$ for two values of the load line $Z_0$. These data show that the relative interruption capability of a $50\%SF_6$-$50\%N_2$ mixture is only about 70% that of pure $SF_6$. This seems to be at variance with the studies mentioned above and points to the need for further studies.

Nakagawa et al. [69] performed calculations aimed at examining $SF_6$-$N_2$ gas mixtures in a buffer-type GCB. Their theoretical study showed that (i) the current interruption capability of the mixture depends on the

**TABLE 5.** Measured arc interruption capabilities[a] of gases and gas mixtures at 0.6 MPa (Lee and Frost [80])

| Gas or mixture | $Z_0 = 450\ \Omega$ $I_c$ (kA) | $Z_0 = 450\ \Omega$ Relative interruption capability | $Z_0 = 225\ \Omega$ Relative interruption capability | $Z_0 = 225\ \Omega$ $I_c$ (kA) |
|---|---|---|---|---|
| 100% $SF_6$ | 21.0 | 100 | 100 | 26.3 |
| 75%$SF_6$ 25%$N_2$ | 17.8 | 85 | 78 | 20.4 |
| **50%$SF_6$ 50%$N_2$** | **14.9** | **71** | **65** | **17.2** |
| 75%$SF_6$ 25%He | 15.4 | 73 | 78 | 70.4 |
| 50%$SF_6$ 50%He | 14.7 | 70 | 75 | 19.7 |

[a]The critical current $I_c$ can be defined as that current where the critical RRRV line intersects the load line $Z_0$. Higher $I_c$ corresponds to higher interruption capability. For practical transmission and distribution power circuits, a $Z_0$ of 450 Ω is typical.

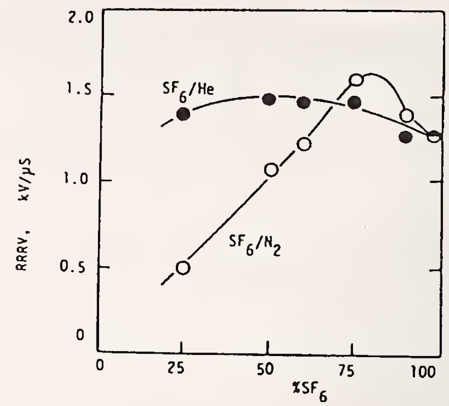


**FIG. 11.** RRRV as a function of $SF_6$-$N_2$ and $SF_6$-He mixture ratio for an upstream pressure of 600 kPa (from Grant et al. [72]).

partial pressure of $SF_6$ in the mixture, and (ii) that $SF_6$-$N_2$ gas mixtures are inferior to pure $SF_6$. The interrupting ability of the $SF_6$-$N_2$ gas mixtures containing a given amount of $SF_6$ was found to deteriorate when $N_2$ was added to the mixture. For instance, the interrupting capability of 300 kPa of pure $SF_6$ was higher than that of a mixture of 300 kPa $SF_6$ + 200 kPa $N_2$. The no-load characteristics of 300 kPa $SF_6$ + 200 kPa $N_2$ gas mixtures showed that the rate of pressure rise was higher than that of pure 300 kPa $SF_6$, and that in spite of the higher value of the total pressure of the $SF_6$-$N_2$ mixtures, the pressure fall occurred faster in the mixture than in pure $SF_6$.

These findings are at variance with the work of Grant et al. [72] who reported that the interrupting abilities of $SF_6$-$N_2$ gas mixtures become higher at certain mixture ratio (see Figs. 10 and 11) but are consistent with the calculations of Tsukushi et al. [81] who examined the current interruption capability of $SF_6$ gas mixtures using puffer-type GCB. According to Tsukushi et al. for currents of ~15 kA, a 300 kPa $SF_6$ + 200 kPa $N_2$ showed 76% of *di/dt* of pure $SF_6$. Their calculation of the puffer pressure rise of gas mixtures in puffer-type gas blast circuit breakers for $SF_6$ and $SF_6$-$N_2$ mixtures indicated that the $SF_6$ partial pressure in a mixture was lower than the pure $SF_6$ pressure when the pure $SF_6$ filling pressure equaled that of the $SF_6$ partial pressure in the mixture. This was attributed to increases in the mass flow of $SF_6$ caused by the $N_2$ gas. Thus these calculations showed that the pressure characteristics in a puffer chamber are different for $SF_6$ and $SF_6$-$N_2$ mixtures. This seems to be born out by other calculations discussed below [82–87].

The interruption capability of $SF_6$-$N_2$ mixtures has been investigated by Gleizes et al. [82–87] in a series of papers. Specifically, Gleizes et al. [82–84] reported measurements of the axial temperature in a steady state arc plasma burning in $SF_6$-$N_2$ as a function of current intensity. They found that the axial temperature value is a complex function of radiation, thermal, and electrical conductivities and it may not be intermediate to those of pure $SF_6$ and pure $N_2$. At high currents the energy losses were found to be dominated by radiation. In another paper Gleizes et al. [81] calculated thermodynamic properties and transport coefficients for $SF_6$-$N_2$ mixtures in the temperature range 1000 K to 3000 K under the assumption that the number densities involved in the computation are those of a plasma under local thermodynamic equilibrium. Figure 12 shows some of their results on the dependence of the thermodynamic properties of $N_2$, $SF_6$, and $SF_6$-$N_2$ mixtures. It seems that the thermodynamic properties of the 40%$SF_6$-60%$N_2$ are not significantly different than those of pure $SF_6$.

Gleizes et al. [84] also performed calculations on the variations of temperature and conductance during the extinction of nonblown, atmospheric pressure, wall-stabilized arcs and concluded that "the use of $SF_6$-$N_2$ mixtures as a gas fill for circuit breakers will be efficient (i.e., will largely preserve the interruption properties of $SF_6$) when the proportion of $SF_6$ is higher than 50%." See Refs. [85–87] for further calculations on the various parameters of significance in the performance of gas circuit breakers depending on type and gas medium and on the role of plasma convection.

Sasao et al. [88] simulated the arc dynamic behavior of gas-blasted arcs using $SF_6$-$N_2$ mixtures. Their simulations indicate that the use of $SF_6$-$N_2$ mixtures may require design changes of the arc chamber in order to optimize the arc quenching capability, and that these changes would depend on gas composition. They did not, however, indicate the "optimum" mixture composition. They found that the arc quenching ability of the $SF_6$-$N_2$

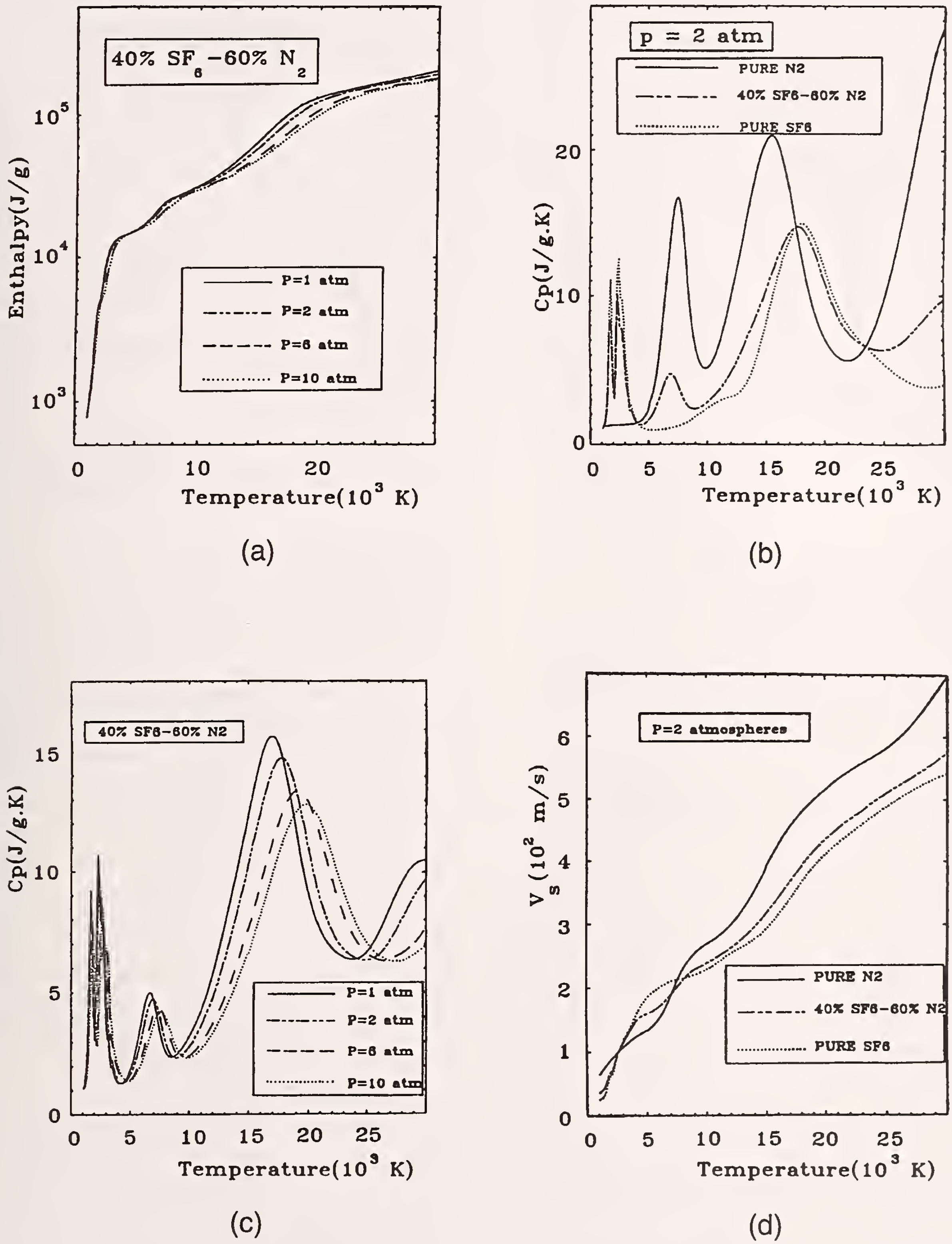


FIG. 12 A, B, C, D. Calculations by Gleizes et al. [83] of the variation of enthalpy with temperature and pressure of a 40%$SF_6$-60%$N_2$ mixture (Fig. 12a); variation of the constant-pressure specific heat, $C_p$, with temperature for pure $N_2$, pure $SF_6$, and 40%$SF_6$-60%$N_2$ mixture (Fig. 12b); evolution of the peaks of the constant-pressure specific heat with pressure of a 40%$SF_6$-60%$N_2$ mixture (Fig. 12c) ; and variations of the speed of sound, v, as a function of temperature for pure $N_2$, pure $SF_6$, and 40%$SF_6$-60%$N_2$ mixture (Fig. 12d). Note that these parameters for pure $SF_6$ and the 40%$SF_6$-60%$N_2$ mixture are rather close.

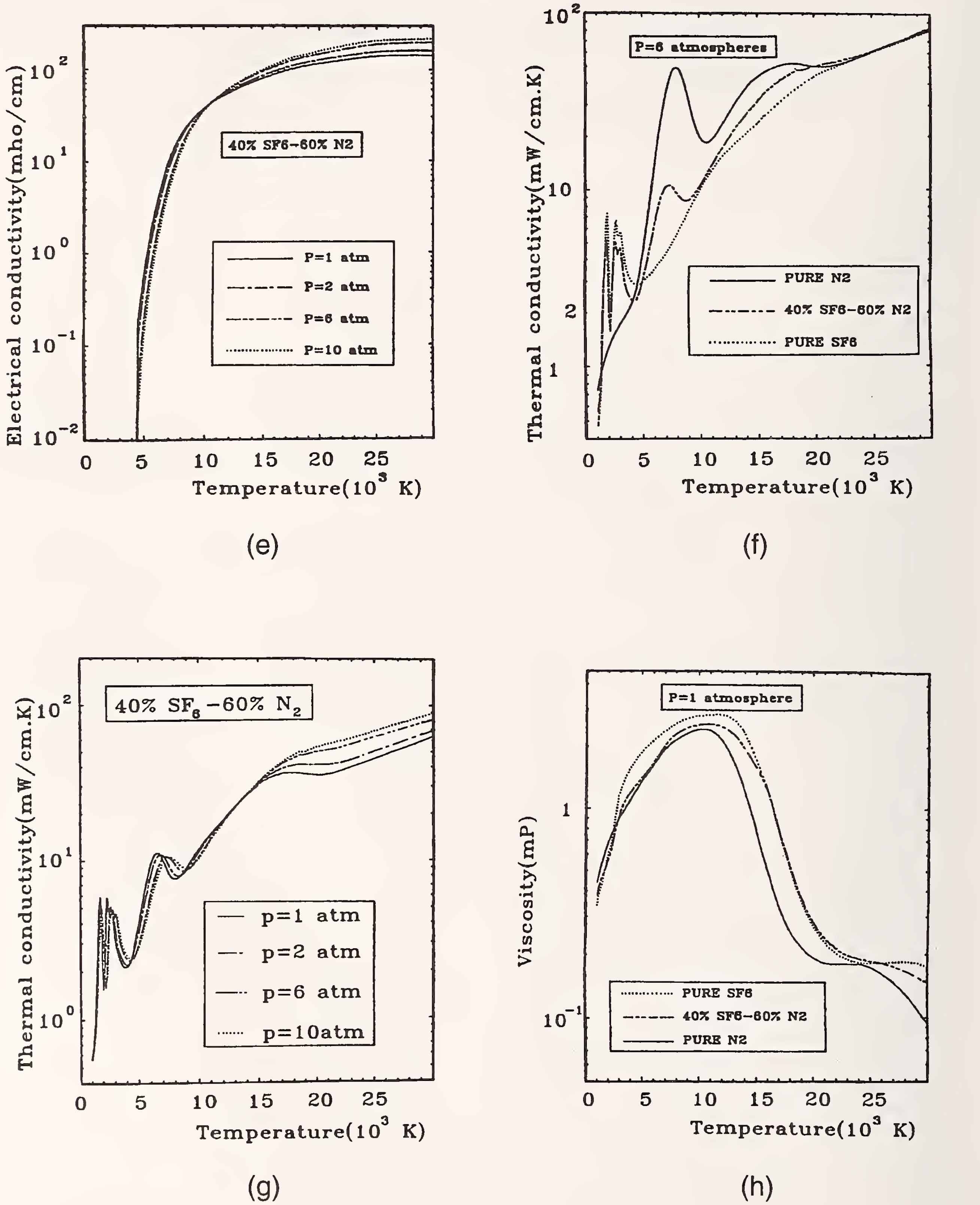


FIG. 12 E, F, G, H. Calculations by Gleizes et al. [83] for the electrical conductivity of a 40%$SF_6$-60%$N_2$ mixture as a function of temperature and pressure (Fig. 12e); variation of the total thermal conductivity with temperature for pure $N_2$, pure $SF_6$, and 40%$SF_6$-60%$N_2$ mixture at a total pressure of 6 atm (Fig. 12f); variation of the total thermal conductivity with temperature and pressure for 40%$SF_6$-60%$N_2$ mixture (Fig. 12g); and variation of viscosity with temperature forpure $N_2$, pure $SF_6$, and 40%$SF_6$-60%$N_2$ mixture at a total pressure of 1 atm (Fig. 12h).

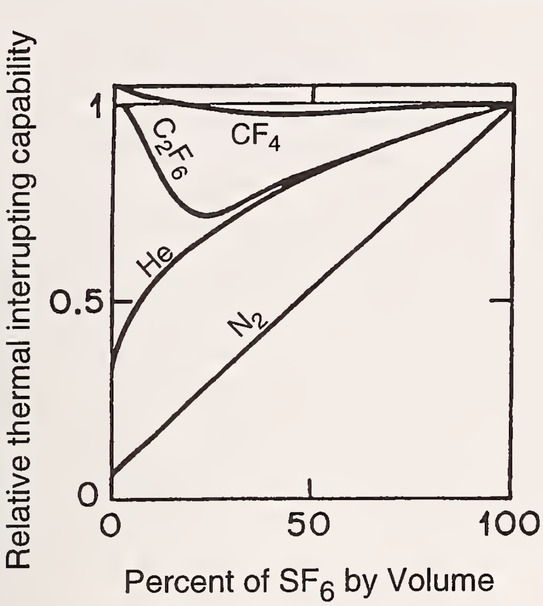


**Fig. 13.** Relative thermal interrupting capability of mixtures of He, $N_2$, $CF_4$, and $C_2F_6$ with $SF_6$ [70].

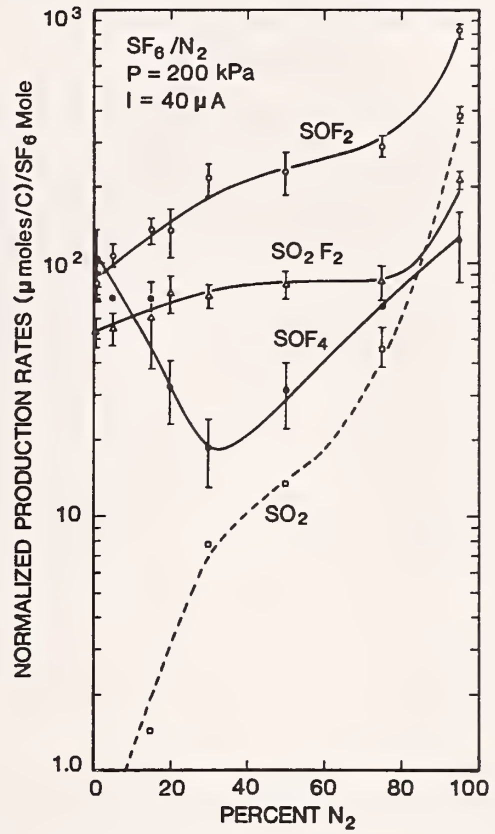


**Fig. 14.** Production rates normalized to the $SF_6$ content vs $N_2$ percent volume in $SF_6$-$N_2$ mixtures for negative point-plane corona in gas at a total absolute pressure of 200 kPa and a constant discharge current of 40 μA [6, 89].

mixtures (including pressure rise and decrease) depends significantly on the configuration of the arc chamber and interruption current in addition to the arc quenching properties of the mixture itself.

Hence, these studies indicate that the actual performance is a function of many design variables. Thus a "drop-in" gas mixture (i.e., a gas mixture for use in existing equipment) does not appear to be feasible for GCBs designed specifically for use with pure $SF_6$. However, the concept of new circuit breakers designed for use with a mixture, rather than for pure $SF_6$, must be explored and tested before the possibility of a replacement mixture for circuit breakers is ruled out.

According to Waymel and Boisseau [57], gas-insulated substation circuit breakers require high arc-breaking properties that are not compatible with $N_2$ or low percentage $SF_6$-$N_2$ mixtures and for this reason $SF_6$-$N_2$ mixtures are not considered for switchgear and other gas-insulated equipment existing or re-designed.

Similarly, Middleton et al. [70] concluded that the use of $SF_6$-$N_2$ mixtures for circuit breakers involves significant derating of the circuit breakers under short line fault because of their reduced thermal capability compared to pure $SF_6$. These authors reported the relative thermal switching capabilities of various gas mixtures shown in Fig. 13 which indicate a poor performance for $N_2$ and a good performance for $CF_4$. As other studies have shown, the build up pressure is higher for the $SF_6$-$N_2$ mixture than for the $SF_6$-$CF_4$ and both are higher than for pure $SF_6$. It may thus be inferred from the studies mentioned above that the performance deficiencies of $SF_6$-$N_2$ mixtures in circuit breakers are principally due to thermal effects.

Finally, Christophorou and Van Brunt [6] reviewed the limited data on the decomposition of $SF_6$-$N_2$ mixtures. Their conclusion, based on corona decomposition measurements, was that "there is little chemical interaction between $SF_6$ and $N_2$ in discharges, and the predominant oxidation byproducts are those seen in pure $SF_6$ such as $SO_2$, $SOF_2$, $SO_2F_2$, and $SOF_4$." These byproducts are principally formed via interactions of $SF_6$ decomposition fragments with oxygen and water impurities [6]. The relative abundances of these byproducts may, however, be different, especially that of $SO_2$ which is much larger for the 40%$SF_6$-60%$N_2$ mixture compared to pure $SF_6$ (see Fig. 14). The very much larger concentrations of $SO_2$ in a 40%$SF_6$-60%$N_2$ mixture compared to pure $SF_6$ may be useful for diagnostic purposes. It might be noted also that the presence of $N_2$ may affect the ability of $SF_6$ to reform itself in arc or discharge decomposition.

Overall, the data for use of $SF_6$-$N_2$ mixtures in circuit breakers are contradictory, thus suggesting the need for additional research. It seems clear that $SF_6$-$N_2$ mixtures may not be used in existing breakers designed specifically for pure $SF_6$, but new designs may make effective use of $SF_6$-$N_2$ mixtures.

### 4.3 Gas Handling, Storing, Recycling, and Recovering

Clearly, if an $SF_6$-$N_2$ mixture is to be used in existing electrical equipment, a number of other issues need to be addressed and one of them pertains to information on handling, storing, recycling, and recovering $SF_6$ from the $SF_6$-$N_2$ mixtures. In this connection, Mitchel et al. [8] investigated the practical thermodynamics of $SF_6$ recovery from $SF_6$-$N_2$ (and $SF_6$-air) mixtures. They discussed recovery of $SF_6$ from mixtures with various non-condensible gases using a compressor/refrigerator system, and presented simulation results showing $SF_6$ recovery efficiency and capacity in terms of cooling temperature, total pressure, and gas composition. This study indicated that $SF_6$ extraction from a 50%$SF_6$-50%$N_2$ mixture presents no real problems. However, Probst [90] argues that $SF_6$-$N_2$ mixtures have problems in terms of recyclability and reusability and that economic factors may be significant (see Appendix C for additional discussion of this issue). The $SF_6$ gas can be reclaimed from the mixture but at a cost. Thus it seems reasonable to conclude that recycling of mixtures can be done, but the technologies used need to be improved. CIGRE 23.10 Task Force just published a document [19] dealing with $SF_6$ recycling, reuse of $SF_6$ gas in electrical equipment and final disposal. Unfortunately, no such work has been done on mixtures.

The data presented in earlier sections of this report suggest that there can be considerable tolerance for variation of the percentage of $SF_6$ in $N_2$ for a proposed 50%$SF_6$-50%$N_2$ mixture without significant effect on the dielectric performance of the mixture. This is because the properties of the mixture are not generally a strong function of the $SF_6$ concentration at this mixture composition. Certainly a tolerance in the percentage of $SF_6$ content of ±5% seems reasonable. It should also be noted that the removal of byproducts from the mixture is not expected to be much different than in pure $SF_6$. Furthermore, there seem to be no serious problems in making a standard gas mixture or in recovering the $SF_6$ from the mixture (see Appendix C).

### 4.4 Discussion

The electric power industry seems willing to consider $SF_6$-$N_2$ mixtures for insulation, for instance, in new gas-insulated transmission lines. Indeed, much work is being conducted world-wide in this area. Most such studies focus on low concentration mixtures (10% to 15%) for insulation, although work is also being done on higher concentration $SF_6$-$N_2$ mixtures for circuit breaker use. A 40%$SF_6$-60%$N_2$ mixture performs well as an insulating medium. This "universal-application" mixture has no apparent physical or chemical problems, but the fact that its dielectric performance is only 85% to 90% of that of pure $SF_6$ would require equipment recertification along with hardware changes or derating. This is nearly impossible for equipment already in service, and would be costly for new equipment presently certified only for pure $SF_6$ use. Thus it would appear that the development of a replacement gas for use in existing equipment (a "drop-in" gas) is not presently a viable alternative. However, the application of standard gas mixtures to newly designed equipment is certainly worthy of further consideration.

Questions must also be raised with regard to the recovery, reusability, recycling, separation, and transportation of gas mixtures using existing technologies. These points are discussed in Appendix C of this report.

The electric power industry clearly prefers to use pure $SF_6$ for arc interruption. While still more work is necessary to resolve open questions and differences in published work, the standard mixture seems to have the potential to perform well even in circuit breakers, especially if used in new equipment designed specifically for use with a particular mixture. Nonetheless, it appears that industry is hesitant to consider $SF_6$-$N_2$ mixtures for arc interruption. Some of the reasons given [55, 91, 92], in addition to those mentioned above for insulation applications, are:

- Thermal derating would be required for many applications.
- The pressure rise during an internal failure arc in equipment will be much faster and higher with the mixture. This may be limited by rupture disk properties, which presents a possible safety issue.
- Some studies indicate significant reduction in the performance of mixtures, as compared to pure $SF_6$, in current circuit breaker designs, thus indicating the possible need for substantial breaker redesign.
- Recycling of mixtures will be more expensive and would require new equipment.
- Benefits of $SF_6$ substitutes can only be adequately judged by complete life cycle analysis of the equipment which is used, including the effects of different materials.

*In general, the physical and chemical properties of a 40% or 50% mixture of $SF_6$ in $N_2$ suggest that it may be appropriate as a "universal application" gas mixture in new equipment, particularly if designed specifically for use with $SF_6$-$N_2$ mixtures. However, the practical difficulties of using $SF_6$-$N_2$ mixtures in existing equipment seem to be particularly large at present.*

# 5. Other *Promising* Gases or Mixtures

In the previous section we have attempted to identify a gas mixture that would be acceptable as a "universal-application" replacement of $SF_6$ for both high voltage insulation and arc interruption. In this section we focus on gases or mixtures which are likely substitutes for specific high voltage insulation or arc interruption applications,[15] and are thus worthy of immediate exploration (i.e., sufficient data are presently available to demonstrate their potential, but not to sufficiently prove their performance). Their possible use may require changes in equipment designs. We focus on three such gaseous dielectric media for which a significant amount of data are available:

- high-pressure pure $N_2$ for high voltage insulation;
- low concentration $SF_6$-$N_2$ mixtures for insulation and arc interruption; and
- $SF_6$-He mixtures for arc interruption.

Besides the gaseous media mentioned above, there are many other unitary gases, and binary and tertiary gas mixtures which are superior in dielectric strength to pure $SF_6$ and can potentially be used in high voltage needs (e.g., see [2, 3, 27, 31–33] and Table 1). However, the overwhelming preponderance of these gaseous dielectrics are not acceptable for various reasons such as their environmental impact, toxicity, or flammability, or because they cannot satisfy one or more of the required overall properties discussed in Sec. 2. From the long list of these we have identified a number of the most promising. These are discussed in Sec. 6.

## 5.1 High-Pressure $N_2$ for Insulation

As mentioned earlier [6, 14], nitrogen is an ideal gas to use: it is abundant, cheap, inert, non-toxic, non-flammable, and unquestionably environmentally acceptable.

However, nitrogen is a non-electronegative gas (it does not attach electrons) and for this reason its dielectric strength is rather low. Nitrogen, however, is a strong electron-slowing down gas and this property accounts for its relatively good dielectric properties in non-uniform fields and in the presence of conducting particles, and for its excellent performance in mixtures with electronegative gases [6, 25, 29]. Its thermal conductivity (Table 2) makes it a good cooling gas, especially at temperatures less than a few thousand degrees. In this regard, it nicely complements $SF_6$.

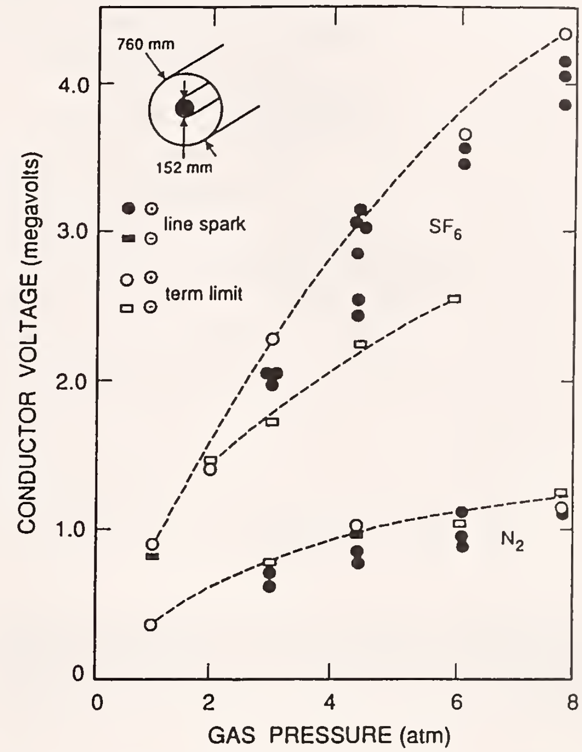


**Fig. 15.** DC breakdown voltage applied to the conductor as a function of gas pressure for $SF_6$ and $N_2$ using coaxial geometry (152 mm / 776 mm system; positive or negative polarity). The data represented by the solid and open symbols are for breakdowns at two locations as indicated in the figure. The solid symbols correspond to breakdown in the line and the open symbols are those cases where line sparks were not the limiting factor (see [95]).

Existing measurements [3, 6, 14, 34, 37, 51] show that:

- Under uniform field conditions and low pressures (less than about 300 kPa) $N_2$ has about one third [25, 93] the dielectric strength of pure $SF_6$.
- The breakdown voltage (DC or AC) of $N_2$ increases with pressure as does that of $SF_6$ (see Figs. 4 and 15) [37, 48, 50, 94, 95], but it turns toward saturation at high pressures. The falling of the breakdown voltages for both $N_2$ and $SF_6$ below the linearly projected dielectric strength as the pressure increases, is due to the "magnification" at high pressures of the field non-uniformity due to surface roughness and imperfections. Such effects are more pronounced for $SF_6$ (and other electronegative gases) for which the effective ionization coefficient increases with the field much faster than does the ionization coefficient of the non-electronegative gas $N_2$ [6, 25, 93]. In Fig. 16 are shown the results of a recent comparison of AC and DC measurements using

[15]Depending on a particular application, the mixture, composition, or pressure of the replacement gas will be varied to maximize the performance of the equipment.

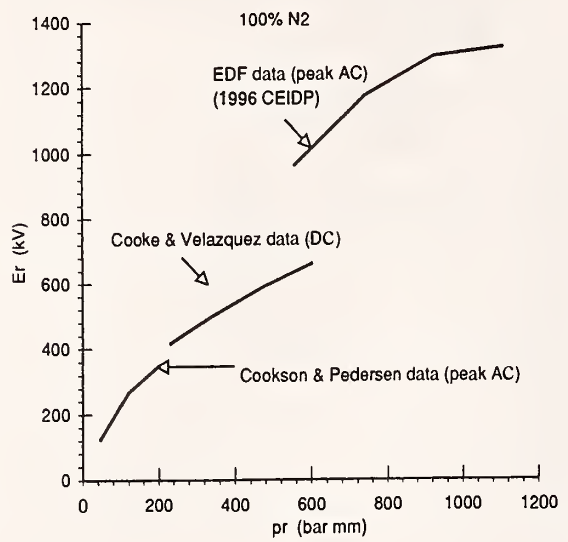


FIG. 16. Breakdown voltage Er vs Pr (r is the radius of the inner conductor) for cylindrical electrode geometries (similarity plot) for pure nitrogen [34]. Data of Pace et al. [34], Cooke and Velazquez [95], and Cookson and Pedersen [37].

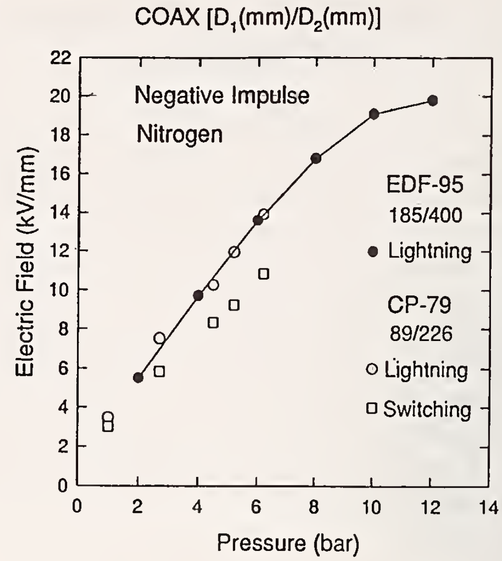


FIG. 17. Lightning impulse breakdown stress in nitrogen using cylindrical electrodes as a function of gas pressure [34, 96]. ●, Lightning data of Elecricité de France [34, 96]; ○, Lightning data of Ref. 36; □, Switching data of Ref. 37. The ratio of the diameters of the two coaxial electrodes is given in the figure.

cylindrical electrodes.[16,17,18] Pace et al. [34] argued that when the area effect is taken into consideration, the recent Electricité de France measurements [96] are compatible with the DC measurements of Ref. [37]. The limited lightning impulse measurements of Medeiros et al. [97] are consistent with the rest of the data in Fig.16. Breakdown voltages of 1 MV are possible for values of the product $P \times r$ ( pressure times radius of inner conductor) of 8 MPa cm. The level of voltage is a function of the system dimensions and the total pressure. According to Pace et al., a rough estimate of the level of voltage may be determined by employing similarity rules.[16]

- Impulse breakdown studies [37, 96] with co-axial electrodes of various inner and outer conductor radii have been made and they vary with the ratio of the inner to outer conductor radius (see Fig. 17). The measurements of Cookson and Pedersen [37] with lightning impulse, are in excellent agreement with the recent measurements of Electricité de France as reported by Pace et al. [34, 96]. For a coaxial electrode arrangement with 185 mm inner and 400 mm outer conductor radius, electric fields as high as 19 kV/mm can be sustained for nitrogen pressures of about 1MPa.

- The dielectric strength of $N_2$ is less sensitive to non-uniform fields than that of $SF_6$. This is understood from basic physical measurements such as the variation of the effective ionization coefficient with $E/N$ close to $(E/N)_{lim}$ [14, 25, 93, 99, 100]. Similarly, $N_2$ is less sensitive than electronegative gases to conductor roughness. In practice, surface roughness effects are a strong function of the cable system size.

- Under conditions of conductive particle contamination and high pressures (about 1.0 MPa), $N_2$ performs very well compared to pure $SF_6$ (Fig. 8).

- The arc interruption capability of pure $N_2$ is significantly inferior to that of pure $SF_6$, although at high pressures (> 1 MPa) there may well be some use of pure $N_2$.

The physical data presented here suggest that high pressure ($\gtrsim$ 1MPa) $N_2$ may be a good alternative to pure $SF_6$ for certain electrical insulation purposes. However, more work on practical systems at high pressures (high $P \times r$) is desirable to check its performance stability in industrial equipment. Also the question of environmental and economic impact of designing and constructing the required high pressure vessels must be investigated.

[16] We are thankful to M. O. Pace for Figs. 15, 16, and 19, and to X. Waymel and C. Boisseau for their permission to reproduce the EDF measurements.

[17] The similarity rule helps consolidate data from various experimental set ups. Two experiments are "similar" if one can be converted to the other by a change in scale. For example, two coaxial cylinder experiments are similar if the corresponding radii and lengths are all in the same ratio from one system to another [34, 98].

[18] The measurements of Refs. [36, 50, 94, 95] were made on coaxial geometries with various inner and outer conductor diameters.

## 5.2 Low-Concentration $SF_6$-$N_2$ Mixtures for Insulation[19]

There have been many studies aimed at the development of nitrogen-based gaseous dielectrics. In Sec. 4 of this report we attempted to identify an "optimum" mixture of $SF_6$ and $N_2$ and in so doing we referenced many literature sources dealing with $SF_6$-$N_2$ mixtures as a function of $SF_6$ concentration. In this section we focus on the possibility of developing *low-concentration* $SF_6$-$N_2$ mixtures for possible use in electrical insulation. By low concentration is meant a percentage of $SF_6$ in $N_2$ of less than 15%. The available information on such mixtures is outlined below (see also, Sect. 4).

- Small amounts of electron attaching gases such as $SF_6$ in $N_2$ substantially increase the dielectric strength of the mixture (Fig. 4). Depending on the electron attaching properties of the electronegative gas which is added to $N_2$, the increase in the dielectric strength of the mixture may or may not saturate as the electronegative gas concentration is increased [25, 42].
- Pace et al. [34, 96] compared the AC measurements of Cookson and Pedersen [37] with the measurements of EDF for co-axial cables. Their results are shown in Fig. 18 for 5% and 10% mixtures. A similar comparison was made by them for the negative lighting impulse breakdown voltage as a function of pressure for a number of gas mixture compositions. An example of these measurements and comparisons are given in Fig. 19 for a 10% mixture. The data [34, 96] are in reasonable agreement when the similarity law for cylinders is applied (Fig. 19). It should be noted, however, that the increase in the breakdown voltage with pressure is not linear and any simple extrapolation to higher pressures of these results may be in error.
- Malik et al. [101] measured the breakdown properties of low concentrations (< 1.5%) of $SF_6$ in $N_2$ in a highly non-uniform field arrangement (rod-plane geometry). Their results for negative polarity clearly show a large increase in dielectric strength even at very low concentrations ( < 0.3%). Such mixtures may be useful for filling substations. In such situations there are parts that have special requirements in terms of higher levels of insulation. These can be separately insulated with gases or mixtures containing higher percentages of $SF_6$ or even with pure $SF_6$ if indeed this is necessary. They certainly can be used for transmission of lower level voltages.
- A lightning impulse (1.2 / 50 μs) study [102] of $SF_6$-$N_2$ mixtures with 0.15% to 0.2% $SF_6$ content for rod/plane gaps with both positive and negative voltages showed that for both polarities the effect of the addition of $SF_6$ to $N_2$ is dependent on both the gas pressure and gap spacing. Maxima in voltage versus $SF_6$ percentage curves were observed which were a function of the total pressure.

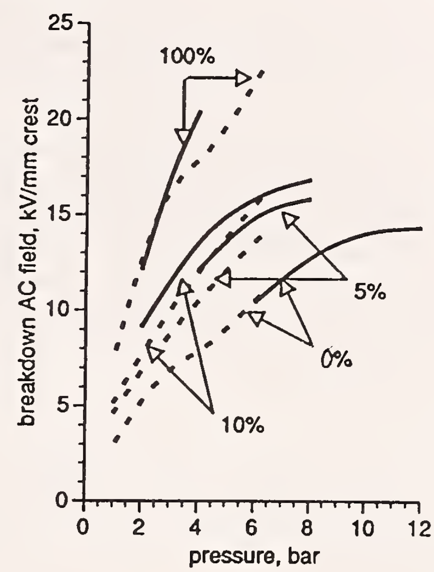


**Fig. 18.** Measured breakdown fields in coaxial cables of diameters 185 mm/400 mm (EDF-95 [96], solid curves), and 89 mm / 226 mm ([37], dashed curves). The percentage of $SF_6$ in mixtures with nitrogen is indicated in the figure [34, 96].

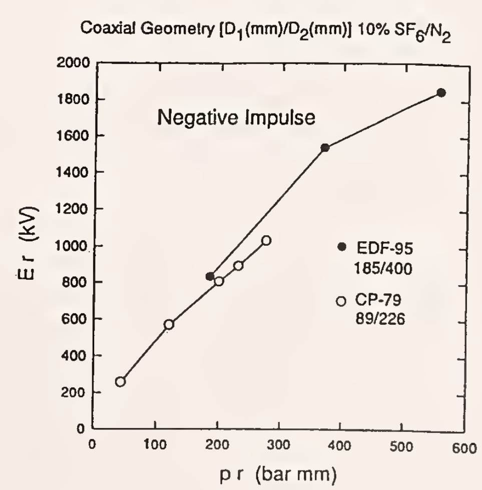


**Fig. 19.** The product Er as a function of the product Pr for a 10%$SF_6$-90%$N_2$ mixture for lightning impulse breakdown (E is the electric field, r is the radius of the inner cylinder of the coaxial cylinder electrode geometry, and P is the total pressure) [34, 96].

[19]See, also, Volume 2 of the Proceedings of the 10th International Symposium on High Voltage Engineering, August 25–29, 1997, Montréal, Québec, Canada. For instance, H. I. Marsden, S. J. Dale, M. D. Hopkins, and C. R. Eck III, "High Voltage Performance of a Gas Insulated Cable with $N_2$ and $N_2$-$SF_6$ Mixtures," pp. 9–12; T. B. Diarra, A. Béroual, F. Buret, E. Thuries, M. Guillen, and Ph. Roussel, "$N_2$-$SF_6$ Mixtures for High Voltage Gas Insulated Lines," pp. 105–108; and X. Waymel, V. Delmon, T. Reess, A. Gibert, and P. Domens, "Impulse Breakdown in Point-Plane Gaps in $SF_6$-$N_2$ Mixtures," pp. 289–292.

For positive polarity voltages the maximum in breakdown strength occurs when the $SF_6$ content in the mixture is about 0.5% at 100 kPa, 5% at 300 kPa, and 10% at 500 kPa.

- Qiu and Kuffel [103] investigated the increase in dielectric strength of nitrogen (and helium) mixtures due to 1% $SF_6$ additive. Table 6 shows their data on the $V_{mixture} / V_{gas}$ of the breakdown voltage for the mixture to the breakdown voltage of the buffer gas ($N_2$, or He). It is seen that even 1% $SF_6$ in $N_2$ significantly improves the dielectric strength, and that this improvement varies with the type of applied voltage.

- Yializis et al. [104] studied impulse breakdown and corona characteristics of $SF_6$-$N_2$ mixtures with less than 1% of $SF_6$ content using rod-plane gaps. Measurements of 50% impulse breakdown voltage were made mainly in $SF_6$-$N_2$ mixtures containing 0.1% $SF_6$ content by pressure over the range of 100 kPa to 500 kPa and gap lengths of 10 mm to 50 mm using positive and negative polarity 1.8 / 50 µs and 310 / 3500 µs pulses. Their results show that the positive impulse breakdown of $N_2$ in the pressure region of 100 kPa to 250 kPa increases considerably with the addition of small traces of $SF_6$.

- Naganawa et al. [73] made measurements on DC interruption by spiral arc in $SF_6$-$N_2$ mixtures (0.1 MPa to 0.8 MPa). They recommended $SF_6$-$N_2$ mixtures as an extinguishing medium of switchgear to avoid liquefication of pure $SF_6$ at high pressure under extremely low temperatures and to save on gas cost. They concluded that compared to the case of pure $SF_6$ "even a small content of $SF_6$ in the mixture is effective to decrease the magnitude of interrupting overvoltages with the arcing time unchanged." On the other hand, Wootton and Cookson [51] found that "addition of trace amounts of $SF_6$ (e.g., 2%) to nitrogen at high pressures (e.g., 1.2 MPa) can reduce the breakdown strength (by ~40%), while increasing the strength at low pressures.

- Finally, according to Bolin [105], recent reports from ABB and Siemens show that GITL are being designed for use with low percentage $SF_6$ mixtures (containing less than 20% $SF_6$).

TABLE 6. $V_{Mixture} / V_{Gas}$ for a mixture of 1% $SF_6$ in either $N_2$ or He for various types of applied voltage [103].

| Applied Voltage | $V_{Mixture} / V_{Gas}$ (400 kPa) | $V_{Mixture} / V_{Gas}$ (200 kPa) |
|---|---|---|
| | He | $N_2$ |
| −1.5 /40 µs | 1.35 | 1.55 |
| + 1.5 /40 µs | 1.92 | 1.70 |
| AC | 2.59 | 2.79 |

TABLE 7. Breakdown strength of mixtures of $SF_6$ and He [106].

| Gas mixture | Strength relative to $SF_6$ (quasi-uniform field ; sphere-plane electrodes at 150 kPa) | Maximum strength relative to $SF_6$ (non-uniform field ; pin protrusion; 100 kPa < P <500 kPa) | Minimum strength relative to $SF_6$ (non-uniform field ; pin protrusion; 100 kPa < P <500 kPa) |
|---|---|---|---|
| 100% $SF_6$ | 100 | 100 | 100 |
| 100% He | ~3 | - | - |
| 75% $SF_6$ 25% He | 78 | 130 | 71 |
| 50% $SF_6$ 50% He | 56 | 126 | 58 |
| 25% $SF_6$ 75% He | 33 | 101 | 41 |

## 5.3 $SF_6$-He Mixtures for Arc Interruption

$SF_6$-He mixtures are considered for use in circuit breakers. Helium has a very low dielectric strength (~ 3% that of $SF_6$ in uniform fields, Table 7) and contributes virtually nothing to the dielectric strength of the mixture. Unlike the $SF_6$-$N_2$ mixtures which exhibit substantial synergism in terms of their dielectric strength, the $SF_6$-He mixtures show no such synergism.

Helium, however, complements $SF_6$ in terms of its cooling capability because it is very light. Its specific heat and thermal conductivity are very large (see Table 3). Helium is an inert gas and does not react chemically with either $SF_6$, or the gas impurities present in commercial $SF_6$, or the system components.

Grant et al. [73] investigated the recovery performance of $SF_6$-He mixtures as a function of the $SF_6$ content in the mixture. Their results were presented earlier in Table 4 and show the performance of $SF_6$-He mixtures which for a total pressure of 0.6 MPa seem to be ~10% higher than pure $SF_6$ for virtually all mixture compositions from 75% to 25% $SF_6$ (see Fig. 11).

Basile et al. [107] found that $SF_6$-He mixtures show a synergistic maximum in the 50% breakdown voltage at a percentage of He around 30%. At the maximum content of He used in these tests (50%), the breakdown voltage of a rod-plane electrode system was still higher than in pure $SF_6$. This suggests that $SF_6$-He mixtures could be considered as an alternative to pure $SF_6$ in operating conditions of low temperature.

Wootton and Cookson [51] measured the 60-Hz dielectric strength of $SF_6$-He mixtures in a plane-parallel electrode system with particle contamination (free 6.4 mm long x 0.45 mm diameter copper and aluminum particles).

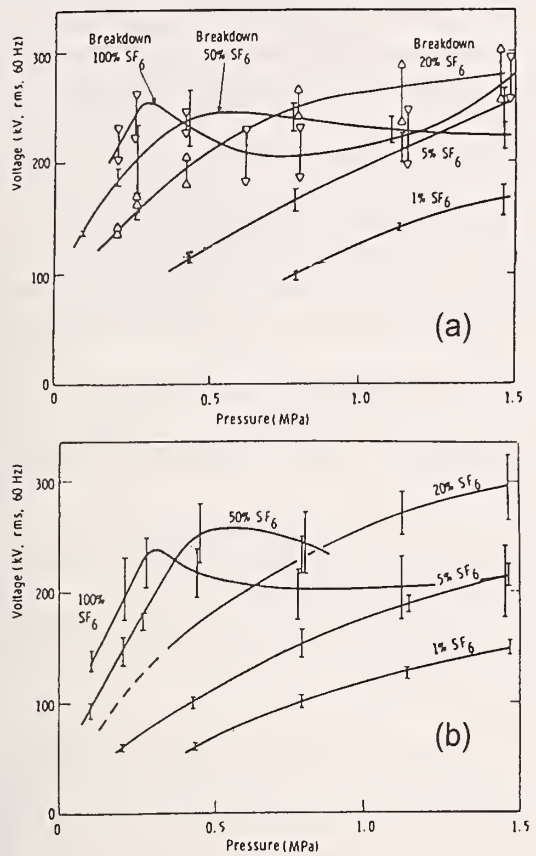


**FIG. 20.** Dielectric strength for $SF_6$-He mixtures with 1%, 5%, 20% and 50% $SF_6$ for copper (Fig. 20 a) and aluminum (Fig. 20 b) particles [51].

Figure 20 shows the dielectric strength for mixtures with 1%, 5%, 20% and 50% $SF_6$ for copper (Fig. 20a) and aluminum (Fig. 20b) particles. While the breakdown strength of helium in uniform fields is only a small fraction of that of $SF_6$ and mixtures of the two gases in uniform fields have dielectric strengths which are intermediate to those of the two gases, the data in Fig. 20 show that the dielectric strength of the He-$SF_6$ mixtures under particle contamination is equal to or greater than that of $SF_6$ at its optimum pressure of about 0.29 MPa. Further analysis of these data by Wootton and Cookson showed that the maxima in the curves for total pressures of 1.43 MPa, 1.1 MPa, 0.77 MPa, and 0.43 MPa occurred at a partial pressure of $SF_6$ of about 0.3 MPa. It was also found that for mixtures with the optimum partial pressure of $SF_6$ (0.29 MPa), addition of He increases the breakdown strength linearly, in contrast to addition of $SF_6$ which decreases the breakdown strength. The data in Fig. 20b show that a 20%$SF_6$-80%He mixture at total pressures greater than 0.7 MPa is superior in performance to pure $SF_6$. Even a 5%$SF_6$-95%He mixture at a total pressure greater than 1.3 MPa performs better than pure $SF_6$.

This work on particles – and the work discussed in this and earlier sections (e. g., Table 4, Figs. 10 and 11) on arc interruption – would suggest that $SF_6$-He mixtures containing 0.29 MPa of $SF_6$ at total pressures in excess of about 1MPa may be suitable for arc/current interruption applications. However, Niemeyer [108] points out that the published data on $SF_6$-He synergisms in switchgear only refer to the initial thermal recovery under short line fault switching where the dielectric stress is still low and not to terminal fault interruption where the dielectric stress is high. Clearly, there are still a number of issues regarding the $SF_6$-He mixtures which include gas compression, separation and leakage which need to be addressed.

*The data presented here strongly suggest that pure $N_2$ and mixtures of low concentration of $SF_6$ in $N_2$ may be appropriate for many insulating applications. The data also suggest that $SF_6$-He mixtures may be viable for use in gas-insulated circuit breakers. Further research on their use in practical systems must still be performed.*

## 6. Other *Possible* Substitutes: Future Long-term R&D

As mentioned previously, other gases exist for which there are data that indicate some potential for use as a gaseous dielectric or interruption medium. Some of those with the most potential are listed in Table 8, and an investigation of these gases could form the core of a future long-term research and development effort to develop acceptable substitute gaseous media for the various needs of the electric power industry. This program could include efforts in the following specific areas:

- A search for single gases at high pressure (besides $N_2$) for insulation purposes , including $CO_2$, $N_2O$, and $SO_2$ [2, 3, 6, 14, 30, 31, 109–111]. These are weakly electronegative gases and their electron attaching properties and dielectric strength may increase with gas density [110, 111].
- A search for binary mixtures (other than $SF_6$-$N_2$ and $SF_6$-He) suitable for particular applications [3, 2, 25, 30, 31, 42, 51, 53, 80, 112–123], including: $SF_6$ + Ar, $SF_6$ + $CF_4$, $SF_6$ + $C_2F_6$, and He + an electronegative component gas (for arc and current interruption); $N_2$ + $SO_2$, $N_2$ + c-$C_4F_8$, $SO_2$ + $SF_6$, $SF_6$ +$CO_2$ , and $N_2O$ +$SF_6$ (for insulation).

TABLE 8. Gases and gas mixtures, for possible use in insulation and arc and current interruption applications, which may be appropriate for further research based upon presently known information.

| | Insulation | Interruption |
|---|---|---|
| Possible Universal Mixtures | • 40% $SF_6$ + 60% $N_2$<br>• 50% $SF_6$ + 50% $N_2$ | • 40% $SF_6$ + 60% $N_2$<br>• 50% $SF_6$ + 50% $N_2$ |
| Near Term Research | • High pressure $N_2$<br>• Low concentration $SF_6$ in $N_2$ | • $SF_6$ + He |
| Long Range Research | • $CO_2$<br>• $SO_2$<br>• $N_2O$<br>• $N_2 + SO_2$<br>• $N_2$ + c-$C_4F_8$[a]<br>• $SO_2 + SF_6$<br>• $SO_2$ + c-$C_4F_8$<br>• $SF_6 + CO_2$ | • $SF_6$ + Ar<br>• $SF_6 + CF_4$[a]<br>• $SF_6 + C_2F_6$[a]<br>• $SF_6 + N_2$ + He<br>• $SF_6 + N_2$ + Ar<br>• He + electronegative gases |

[a]These are also greenhouse gases, but their global warming potentials are about one third that of $SF_6$. Over a 100-year time horizon the global warming potentials of c-$C_4F_8$, $CF_4$, $C_2F_6$, and $SF_6$ are respectively 8,700, 6,500, 9,200, and 23,900 [22].

• A search for ternary mixtures, including the following systems: $SF_6 + N_2$ + He and $SF_6 + N_2$ + Ar [3, 2, 30, 31, 124, 125].

While a large amount of effort was expended in the 1970s and 1980s to search for gases exhibiting better dielectric performance than $SF_6$, the emphasis of any new research program would be to identify gases with acceptable dielectric properties, and minimal environmental impact. This could include a search for new synthetic gases, better additives than $SF_6$, better buffers than $N_2$, and gases with an IR window near 10 µm to avoid any contribution to global warming. It could even be suggested that an investigation of gaseous media that are detrimental to the environment is justified, if the gas has superior performance properties for a particular application where its release into the environment could be absolutely prevented.

Other areas of productive investigation that are suggested by the research presented in this report include the following:

- the role of humidity and impurities on dielectric gas properties;
- electron attachment and detachment in low concentration $SF_6$-$N_2$ mixtures;
- decomposition of $SF_6$-$N_2$ mixtures as a function of concentration, impurity content, and type of discharge;
- dielectric behavior of gas mixtures at high gas pressures;
- thermal and electrical conductivities of $SF_6$-$N_2$ mixtures; thermodynamic properties, thermal conductivities, and viscosities of gas mixtures under the conditions they are used in electrical equipment;
- the role of particles and improved particle control methods;
- interface phenomena and partial discharge behavior;
- assessment of available data;
- life cycle analysis of the overall environmental gain by using mixtures instead of pure $SF_6$ ;
- handling, storage, recovery, and disposal of gas mixtures;
- ways to reduce the cost of recovery of $SF_6$ from gas mixtures;
- new equipment designed specifically to eliminate emissions;
- improved recycling procedures;
- relaxation of equipment constraints that would make other gases acceptable;
- alternative technologies not requiring gaseous dielectrics, such as high temperature superconductors and solid state switching.

*A significant amount of research must be performed for any new gas or gas mixture to be used in electrical equipment. Such a program necessarily would require the systematic study of potential replacements, including their physical, chemical, and performance properties. A concerted national or international effort in this area by equipment manufacturers, utilities, government labs, universities and gas manufacturing companies would be beneficial.*

## 7. Conclusions and Recommendations

Sulfur hexafluoride is an superior dielectric gas for nearly all high voltage applications. It is easy to use, exhibits exceptional insulation and arc-interupption properties, and has proven its performance by many years of use and investigation. It is clearly superior in performance to the air and oil insulated equipment which was used prior to the development of $SF_6$-insulated equipment. However, the extremely high global warming potential of $SF_6$ mandates that users actively pursue means to minimize releases into the environment, one of which is the use of other gases or gas mixtures in place of $SF_6$.

An evaluation of the results of the last two decades, and a detailed analysis of the data presented in this report, indicate that no replacement gas is immediately available for use as an $SF_6$-substitute ("drop-in gas") in existing electric utility equipment. For gas insulated transmission lines and gas insulated transformers, the limitation is primarily due to the need for re-certification and possible re-rating of equipment that is already in use. For gas insulated circuit breakers there are still significant questions concerning the performance of gases other than pure $SF_6$.

However, various gas mixtures show considerable promise for use in new equipment, particularly if the equipment is designed specifically for use with a gas mixture:

- Mixtures of nearly equal amounts of $SF_6$ and $N_2$ exhibit dielectric properties that suggest that they could be used as a "universal application" gas for both electrical insulation and arc/current interruption purposes. In this connection, standard procedures for mixture handling, use, and recovery would need to be further developed.
- Mixtures of low concentrations (<15%) of $SF_6$ in $N_2$ show excellent potential for use in gas insulated transmission lines, although further work on their performance in practical systems is necessary.
- Pure high pressure nitrogen may be suitable for some electrical insulation applications. Consideration of the use of such environmentally friendly gases where $SF_6$ is not absolutely required should be investigated and promoted.
- A mixture of $SF_6$ and helium has shown promise when used in gas insulated circuit breakers, and should be investigated further.

Finally, it is clear that a significant amount of research must be performed for any new gas or gas mixture to be used in electrical equipment. Such a program necessarily would require the systematic study of potential replacements, including their physical, chemical, and performance properties (see for example Sections 3 and 6). A concerted effort in this area by equipment manufacturers, utilities, government labs, universities, and gas manufacturing companies would be beneficial.

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# Appendix A

Sales of $SF_6$ by end-use application [12] (This survey excludes contributions from China and Russia).

| YEAR | Utilities and Accelerators | Original Equip. Manufacturers | Magnesium Industry | Electronics Industry | Utilizing $SF_6$ Adiabatic Prop. | All Other Uses | TOTAL |
|---|---|---|---|---|---|---|---|
| (units in metric tons) | | | | | | | |
| 1961 | 0 | 91 | 0 | 0 | 0 | 0 | 91 |
| 1962 | 14 | 145 | 9 | 0 | 0 | 0 | 159 |
| 1963 | 14 | 181 | 0 | 0 | 0 | 0 | 204 |
| 1964 | 18 | 204 | 14 | 0 | 0 | 14 | 250 |
| 1965 | 32 | 231 | 23 | 0 | 0 | 18 | 304 |
| 1966 | 61 | 233 | 27 | 2 | 5 | 23 | 374* |
| 1967 | 63 | 239 | 32 | 5 | 9 | 27 | 392* |
| 1968 | 63 | 256 | 36 | 5 | 13 | 32 | 428* |
| 1969 | 84 | 269 | 11 | 7 | 14 | 36 | 496* |
| 1970 | 140 | 277 | 13 | 9 | 13 | 44 | 606* |
| 1971 | 468 | 289 | 71 | 10 | 13 | 72 | 1,018* |
| 1972 | 515 | 263 | 63 | 11 | 13 | 64 | 1,017* |
| 1973 | 700 | 355 | 83 | 11 | 14 | 84 | 1,385* |
| 1974 | 732 | 334 | 46 | 12 | 13 | 72 | 1,378* |
| 1975 | 937 | 559 | 120 | 11 | 14 | 111 | 1,754 |
| 1976 | 1,236 | 760 | 195 | 13 | 14 | 126 | 2,344 |
| 1977 | 1,299 | 924 | 214 | 11 | 14 | 151 | 2,615 |
| 1978 | 1,473 | 1,019 | 256 | 13 | 20 | 134 | 2,915 |
| 1,979 | 1,962 | 1,267 | 312 | 16 | 32 | 134 | 3,776 |
| 1980 | 1,861 | 1,542 | 320 | 16 | 35 | 216 | 3,991 |
| 1981 | 2,055 | 1,397 | 320 | 17 | 59 | 210 | 4,053 |
| 1982 | 2,096 | 1,550 | 360 | 18 | 59 | 246 | 4,329 |
| 1983 | 1,966 | 1,421 | 374 | 17 | 80 | 233 | 4,091 |
| 1984 | 2,348 | 1,859 | 397 | 16 | 146 | 232 | 4,960 |
| 1985 | 2,440 | 1,734 | 397 | 20 | 111 | 254 | 4,996 |
| 1986 | 2,717 | 1,666 | 431 | 38 | 110 | 300 | 5,262 |
| 1987 | 2,784 | 1,641 | 415 | 13 | 146 | 265 | 5,324 |
| 1988 | 2,654 | 1,649 | 398 | 100 | 162 | 307 | 5,270 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1989 | 2,832 | 1,753 | 363 | 117 | 270 | 323 | 5,658 |
| 1990 | 3,323 | 1,722 | 385 | 140 | 220 | 435 | 6,225 |
| 1991 | 3,414 | 2,022 | 357 | 151 | 260 | 682 | 6,886 |
| 1992 | 3,312 | 2,173 | 266 | 201 | 290 | 645 | 6,887 |
| 1993 | 3,523 | 1,847 | 274 | 229 | 290 | 658 | 6,821 |
| 1994 | 3,295 | 2,402 | 354 | 262 | 325 | 587 | 7,225 |
| 1995 | 3,126 | 2,659 | 399 | 300 | 356 | 617 | 7,457 |
| 1996 | 3,139 | 2,795 | 544 | 307 | 344 | 442 | 7,571 |
| Subtotal | 56,696 | 39,728 | 7,972 | 2,161 | 3,426 | 7,857 | 118,512 |
| 1997 | 3,669 | 2,155 | 426 | 342 | 472 | 257 | 7,321 E |
| 1,998 | 3,870 | 2,118 | 388 | 378 | 502 | 235 | 7,491 E |
| 1,999 | 3,711 | 2,270 | 362 | 417 | 559 | 212 | 7,531 E |
| 2,000 | 3,709 | 2,281 | 347 | 461 | 584 | 189 | 7,571 E |
| | | | | | | | |
| TOTAL | 71,655 | 48,552 | 9,495 | 3,759 | 5,543 | 8,750 | 148,426 |

* For the years 1966-1974, some companies could not provide a breakdown by end use. TOTAL SALES includes an additional 672 metric tons sold in these years. The sum of sales by end use does not equal total sales.

[E] Manufacturers provided projections for sales in 1997-2000.

# APPENDIX B

## Status of Environmental, Economic, and Policy Issues Driving $SF_6$ Reduction

This appendix is a brief summary primarily of the policy (or regulatory) issues that may drive the need for reduction of $SF_6$ use and emissions by industry.

Environmental concern is a significant motivation toward improved $SF_6$ management or use of alternatives. Pure $SF_6$ has a greater ability to absorb infrared radiation than most other gases and it has a very long atmospheric lifetime. These properties make $SF_6$ a potent global warming gas. To put this in perspective, the long-term radiative effect of 1 kg of $SF_6$ emitted exceeds that of 1 kg of $CO_2$ by a factor of 23,900. This number refers to the direct Global Warming Potential $(GWP)_{100}$, that is, the extra amount of long wavelength radiation absorbed over a 100-year period.

In recent years, the price of $SF_6$ has increased, thus promoting the possibility of using alternate gases or gas mixtures. An evaluation of the total cost for switching from one gas to another, requires performing a technology impact assessment including a full life-cycle analysis. Among the economic factors to be considered are (*i*) the price of the compounds and material resources consumed, (*ii*) the costs of new and modified equipment, (*iii*) the costs during equipment operation, including energy dissipated, emissions control, repair and servicing, (*iv*) the cost and effectiveness of recycling, and (*v*) the cost of additional personnel and training. Other factors to consider include (*i*) availability and life of the alternative gas, (*ii*) electrical reliability, certification and testing of equipment, (*iii*) health hazards and safety, and (*iv*) equipment size and land use.

Global emission control measures for perfluorocompounds (PFCs) and $SF_6$ are at present following the general course set for the "major" greenhouse gases in the Framework Convention on Climate Change (FCCC) and the ongoing Conference of the Parties (COP) meetings. In the United Nations' efforts to develop an international protocol (under the FCCC) for stronger controls of greenhouse gas emissions, the European Union (EU) proposed to the Ad Hoc Group on the Berlin Mandate (AGBM) that fluorocarbon control be incorporated into the final treaty. The EU proposal suggested policies and measures that include:

- product standards with respect to leakages of emissions
- use of selected low GWP (global warming potential) instead of high GWP chemical
- reducing emissions through improved equipment and practices in the electrical equipment industry.

The concern over emissions of $SF_6$ was further addressed in 1996 as the Second Conference of the Parties formally directed countries to inventory $SF_6$ emissions and report them to the internal governing body. The Intergovernmental Panel on Climate Change has proposed methods for countries to consider for use in inventorying emissions of $SF_6$ from electric power equipment.

Individual countries are developing proposals to shape stronger climate protocols under development for COP-3 (scheduled for late 1997). The European Union proposal specifically highlights HFCs (hydrofluorocompounds), PFCs (perfluorocompounds), and sulfur hexafluoride in the list of greenhouse gases that countries would be able to control under the protocol. The current intent of the COP-3 meeting is to produce a protocol for greater control of greenhouse gas emissions worldwide.

While several important issues remain unresolved, it appears likely that "the U.S. will propose that negotiations for post-2000 year emissions reductions focus on realistic, binding commitments that will produce real environmental benefits. . . . the United States will continue to seek market-based solutions that are flexible and cost effective. . . . international cooperation of this challenge remains critical to any effective response."[1] It is important to recognize that alternatives taking the form of $SF_6$-containing mixtures or any other PFC gas or mixture will be subject to these evolving regulations.

In the meantime, the U.S. Environmental Protection Agency (EPA) is continuing with the development of a voluntary program for users of $SF_6$ in electric power equipment. EPA's goal for the program is to reduce U.S. emissions of the gas from equipment through voluntary means. The program is expected to incorporate best work practices, capture and recycling of used gas, and design of business plans for replacement of obsolete equipment with uncontrollable $SF_6$ leaks. In the long term, EPA desires to work with industry to eliminate emissions. Elimination of emissions will require cooperation from the users of

[1]Statement to Industry/NGOs on U.S. Intervention at Climate Change Negotiations by T. E. Worth, U.S. Department of State

equipment as well as the manufacturers of such devices.[2] For further information on the voluntary program, contact Elizabeth Dutrow of EPA at (202) 233-9061 or at <*dutrow.elizabeth@epamail.epa.gov*>.

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[2]Private communication from Elizabeth Dutrow, Environmental Protection Agency, September 29, 1997.

# APPENDIX C

# Potential Barriers to Using Gas Mixtures as a Gaseous Dielectric

## 1. Perceived Disadvantages

There are several potential barriers to using even simple mixtures in electrical equipment. These are:

- more difficult gas supply, recovery and recycling procedures,
- monitoring and maintaining proper concentrations,
- challenge of handling leaks and emergencies,
- unknown long-term stability and performance,
- difficult disposal, and
- cost-of-ownership.

The applicability or significance of the perceived disadvantages listed above will depend on the application. It is simple to fill up equipment with a mixture, but for some applications routine maintenance requires the gas to be removed, recycled, refilled, or disposed. This maintenance routine may entail pumping, purging, filtering and separation of the mixture components, replacement of the gases in the desired ratio, and volume percentage analysis. Such a routine must be reliable and rapid, minimizing down time. To accomplish this task will require different chemical management practices and associated technologies from those used for pure $SF_6$. In particular, this may require more training, equipment development, process automation, and other higher-function gas handling equipment. *However, there seem to be no fundamental limitations to the use of gas mixtures.*

## 2. Mixed Gas Availability and Costs

It is not viable economically or physically for gas suppliers to provide large quantities of certified mixtures. This is due to the fact that a mixture cannot be significantly compressed and still maintain the appropriate concentrations in the gas phase. Therefore transportation of mixtures would require large tanks of gas mixtures in the gas phase. Similarly, there are limitations associated with certification, storage, and transport of mixtures. Instead, suppliers recommend that gas be delivered certified pure, then stored and mixed on-site as needed [C1].

Major $SF_6$ producers are in the USA, Italy, Japan, and Germany, see Table C1 [C1, C2]. $SF_6$ is prepared for commercial and industrial use in various grades (minimum 99.8 mole percent pure) and delivered in a wide range of volumes and pressures. The most commonly found impurities, include air, nitrogen, water vapor, carbon dioxide, $CF_4$, $SO_2$, HF, $H_2S$, $SO_2F_2$, $SOF_2$, COS, and trace metal oxides and metal fluorides. Pure $SF_6$ is readily available in a wide range of volumes and pressures.

At present, only small quantities of calibrated mixtures of $SF_6$ with other gases can be purchased from a limited number of gas-suppliers. Dilute mixtures such as 1% to 5% $SF_6$ in air, helium or nitrogen, and in various grades, are routinely available from most gas-suppliers. Other mixtures are typically treated as specialty orders and prepared in small quantities (single cylinders or lecture bottles of desired partial pressure) to specified tolerance and certification accuracy.

$SF_6$ is shipped, under the appropriate regulations, in cylinders or in tube trailers in liquid form. The maximum filling density permitted for $SF_6$ in cylinders is 120 % (i.e. percent water capacity by weight). Nitrogen gas is shipped in cylinders, tube tank cars, and tube trailers according to regulations. Liquid nitrogen is shipped as a cryogenic fluid in vacuum-insulated cylinders, and in insulated portable tanks, tank trucks, and tank cars. Storage standards would be recommended if gas mixtures were to be routinely handled, recovered, recycled or transported.

While there is no limitation to the availability of the gases, cost and policy considerations cannot be overlooked. Costs of servicing are relatively high for compounds that are restricted under national or international regulations. Consequently, the choice of replacements must consider the dynamics of environmental policy (as discussed in Appendix B). An evaluation of the total cost for recover/recycle and switching from one gas to another, requires performing a

**TABLE C1.** Major producers of sulfur hexafluoride [C1, C2].

| Company | Country |
|---|---|
| Air Products and Chemicals Inc. | USA |
| AlliedSignal Chemicals | USA |
| AGA Gas AB | Sweden |
| Kanto Denka Kogyo Co. | Japan |
| Asahi Glass Co. | Japan |
| Ausimont (Montecatini Edison) | Italy |
| Solvay (Kali-Chemie) | Germany |

Source: C. M. A. Nayar, GEC Alsthom, France

technology impact assessment including a full life-cycle analysis. Among the costs to be considered are (1) the compounds and material resources consumed, (2) the new and modified equipment required, (3) equipment operation, including energy dissipated, emissions control, repair and servicing, and (4) additional personnel and training. The cost of using gas mixtures will depend on the relative quality and quantity of the alternative gas required to meet the necessary certification tests and operating specifications. In addition, new equipment would need to be purchased for storage, gas cooling, pumping, leakage testing, mixing, refilling and other servicing practices.

## 3. Preparing Gas Mixtures and Material Compatibility

Refilling of equipment with mixtures can be time consuming and take considerable time to verify or certify to the accuracy desired. Similarly, to "top-off" equipment that has suffered a loss of pressure, i.e., to restore the original pressure and gas composition, is a greater challenge than for systems containing a single gas. The filling and maintenance of any electrical equipment with gas mixtures will require development of concentration range standards, preparation tolerances, and analytical accuracy specifications. For example, when preparing a mixture of 40%$SF_6$-60%$N_2$ an acceptable concentration range of 10% might require a preparation tolerance of 5% of component and a 2% analytical accuracy of component.

Studies examining the chemical and physical properties of $SF_6$-$N_2$ mixtures have been partially motivated by an interest in the ability to reduce condensation (effective dew point) of $SF_6$ in equipment located in cold climates [C3, C4]. The temperature at which $SF_6$ liquefies depends on the gas pressure. Miners et al. [C3] demonstrated that $SF_6$-$N_2$ gas mixtures are non-ideal. From a practical standpoint a manufacturer who uses ideal gas assumptions to predict the mixture dew point temperatures at system-fill pressures of 100 kPa to 500 KPa would under-predict the temperature by as much as 10 °C. These results suggested that similar considerations be given to all $SF_6$-containing mixtures. In some cases electrical equipment may require designs incorporating heaters to ensure $SF_6$ fractions remain above the liquefaction temperature (this is, of course, undesirable). But liquefaction is only one among many parameters to be considered when refilling with a selected mixture and re-rating the pressure of the electrical equipment and application.

While $SF_6$-$N_2$ mixtures are relatively inert, other mixtures of gases with known stability problems may require special techniques such as passivation or surface preparation to eliminate the degradation of the unstable component, generation of undesirable byproducts, chemical attack of surfaces or general corrosion. In the case of pure $SF_6$, considerable progress has been made in improving the reliability of seal and gasket design and protection against environmental conditions, resulting in proven long-term performance. When determining what materials can be used with a gas mixture, it is important that design and manufacture value compatibility with each of the components of the mixture separately as well as all of the components when they are combined. This implies careful choice of material composition, surface finish and contact methods for walls, spacers, inserts, shields, electrodes, O-ring seals, or use of epoxy formulations, glues and resins. Modes of equipment operation and location for use must be considered to design for temperature, pressure, and humidity variations or gradients. For example, equipment with $SF_6$-$N_2$ mixtures should be designed for or maintained at temperatures that will prevent water and $SF_6$ from condensing, thereby losing performance and homogeneity. If a mixture with a condensable component has been subjected to temperatures at or below its saturation temperature, it will need to be re-homogenized prior to the withdrawal of any of the gas. Various techniques have been developed for the latter purpose.

Since $SF_6$ is packaged as liquefied gas, special precautions need to be observed when filling equipment. This applies to both to a new mixture and the processed gas after recovery and recycling. One concern is particulate matter generated in storage or transfer leading to the recommendation to filter use to protect contamination of the electrical equipment. Another issue is the enhancement of chemical transfer rate by the common practice of warming the gas cylinder or storage vessel. Warming the storage container during transfer minimizes the refrigeration effect caused by the evaporation of $SF_6$ while allowing its transfer in the gaseous state. If liquid phase transfer of $SF_6$ is employed, care is required to ensure the gas is completely vaporized before it enters the equipment to avoid over-pressurization or undesirable refrigeration.

## 4. Mixed Gas Recovery and Recycling

Recovery, recycling, and destruction of $SF_6$ is possible, such that there is no need for deliberate release into the atmosphere. However, it appears that current practices are such that economical separation of $SF_6$ from nitrogen is not possible without some venting of $SF_6$ into the atmosphere. In the event that end-of-life disposal is required, all regulations governing air emissions and waste management should be followed. $SF_6$ can be

destroyed by thermal decomposition at elevated temperatures (>1100 °C). Such thermal waste treatment furnaces process the sulfur and fluorine constituents to produce naturally occurring materials, e.g. gypsum and fluorspar.

Choice of alternatives should consider the availability of internal treatments to the electrical equipment, including gas absorbent filters, desiccants, and particle filters used in an effort to stabilize the gases and aid recovery and recycling. Gases, whether initially pure or mixed, can be expected to degrade with time due to a variety of factors including contamination caused by moisture and decomposition products. The composition and concentration of potentially toxic by-products is unknown for most mixtures and will be quite variable between applications and equipment.

Lower fluorides of sulfur formed by the decomposition of $SF_6$ may be removed by gas scrubber/filter systems. Gaseous decomposition products may be absorbed on molecular sieves or on soda lime (50/50 mixture of NaOH and CaO), or on activated alumina (specially dried $Al_2O_3$). The quantity of decomposition products and the amount of absorbent required to capture all of the products will need to be determined. It has been suggested that a practical rule-of-thumb is to use a weight of absorbent corresponding to 10% of the weight of gas [C5]. The absorbent should be located in the equipment to maximize gas contact, unless both liquid and gas phases are present. In the latter it may be necessary to locate the absorbent in contact with both phases or only the liquid phase. The effectiveness and saturation of absorbents, desiccants and filters will depend on the equipment design, maintenance schedules, temperature, as well as consequence of equipment faults and contamination.

The gas from a faulted breaker, leaking transmission line or transformers, or gas-insulated substation, once treated to remove decomposition products and moisture, may be reused if the material meets device specifications. The key to continued reusability of the gas is to establish purity standards, certification requirements, and recovery / recycling protocols to performance specifications. It takes a combination of factors to achieve this goal:

- Contamination minimization must be built in to electrical equipment design and operation;
- Contamination minimization must be built in to delivery, mixing, recover, and recycle equipment design, operation and chemical management practices; and
- Monitoring of gas condition including electrical properties and chemical properties (e.g., purity, decomposition products, moisture content) must be available; and
- Quality of chemical equipment manufacture, equipment maintenance, and chemical management practices must be continuously improved.

The desired purpose of gas recycling is to recover the original gas, remove any undesirable byproducts (such as moisture, oil, and particles), verify and possibly correct the mixture composition, and return the gas back to the electrical equipment in a satisfactory certifiable state. A moisture specification of around 30 ppmv (parts-per-million-volume) is typical while the IEC Standard 376 for new $SF_6$ gas specifies an oil content not to exceed 5 ppmw (parts-per-million-weight). Two international committees (CIGRÉ WG 23-10 TF 01 and IEEE-EI S32; [C6]) are attempting to define purity standards for on-site recycled $SF_6$. The standards and protocols for recovery and recycling of alternatives could be developed in a similar manner. Draft standard IEEE P1403, which compares air-insulated substations and gas-insulated substations (GIS), mentions that recent advances in GIS construction include sophisticated equipment to reprocess $SF_6$. Similar integrated technology could be developed for dealing with the potential alternatives.

In Japan, the Task Committee on the Standardization of the Use of $SF_6$ Gas for Electrical Power Equipment is currently examining the practices for recycling and handling of $SF_6$ gas. Among the targeted voluntary actions is the reduction of releases of $SF_6$ at all stages of equipment development, installation, and testing. Targets for recovery are 97% of the purchased gas by the year 2005. This is to be accomplished by the development of economical and large capacity recycling systems which evacuate vessels to higher vacuum. Similar recovery and recycle practices could be implemented for mixtures but have not been explicitly discussed by this task force.

Control of the temperature and pressure is critical to successful reclamation in gas mixtures. In the case of recovering $SF_6$ from $SF_6$-$N_2$ mixtures, the $N_2$ typically represents a compressible but non-liquefiable component that reduces the overall extraction efficiency, unless higher operating pressures or lower temperatures can be attained. It should be noted that very little thermodynamic data on $SF_6$-containing mixtures are available in the scientific literature. Computational tools are currently available to help predict some of these missing data [C7]. Efforts to employ these tools may enhance efforts to implement the chemical management of $SF_6$-containing mixtures as alternative gases. Studies by Mitchel *et al.* [C8] calculated the $SF_6$ liquid / $SF_6$ gas / $N_2$ gas phase equilibrium assuming a constant volume for an initial fill of various blends at several initial pressures at 20 °C, subsequently cooled to –50 °C. They concluded that reclamation of $SF_6$ from $SF_6$-$N_2$ and $SF_6$-air mixtures is best accomplished by a combination of compression and refrigeration to liquefy the $SF_6$. Volumetric efficient handling of mixtures is considered to require cooling assisted high-pressure (rather than low-pressure) devices.

Generally, more dilute $SF_6$ mixtures require lower temperatures and/or higher pressures.

To date, commercially available gas reclamation technology for the electrical industry has been designed primarily for separation, processing, analysis, and compression of nearly pure $SF_6$ gas. Much of this work has been done by companies specializing in $SF_6$ processing, working in cooperation with one or more manufacturers of $SF_6$ insulated equipment. In most cases, gas carts use pressurized liquefaction of $SF_6$ (via compressors) to minimize the necessary volumetric storage required [C8–C10]. When the stored gas is nearly 100% pure $SF_6$ this method of reclamation is highly satisfactory and recovery rates greater than 99% yield are possible [C5, C10]. Losses of $SF_6$ to the environment depend strongly on the $SF_6$ percentage in the mixture, the operating pressure, the extent of cooling, and the residual pressure remaining in the evacuated volume. Table 2C shows the losses predicted by Probst [C10], using *currently available* technology based on a two-cycle distillation process operating at high pressure (5000 KPa) and low temperature (−40 °C), where liquid $SF_6$ is withdrawn and the remaining gas cushion is vented, when the purity of liquid gas is to be better than 99%.

Conventional $SF_6$ gas reclamation carts have limited capability for processing $SF_6$ containing $N_2$, air or decomposition byproducts at levels exceeding a few percent [C5, C9]. If gases are heavier than $N_2$ (for example $CF_4$) then the $SF_6$ losses can be substantial. On conventional carts, $SF_6$ is cycled and liquefied but the nitrogen gas cannot be liquefied. Liquefaction lowers the total pressure in the process tank. Each cycle consists of adding mixed gas until the total pressure equals the initial pressure, followed by additional cooling. If the on-board volumetric storage tank is not sufficiently large, the potential exists for $N_2$ gas to shut down the compressor at some limiting high pressure. The ultimate capacity of the cart storage is reached when the residual gas is compressed to the maximum safe pressure. At this point the volume being evacuated inside the electrical equipment may still contain some unknown ratio of mixed gas and the storage tank will hold liquefied $SF_6$ and gaseous $N_2$. The protocol used to minimize evaporative loss of $SF_6$ recommends always reaching full capacity before emptying the tank, and when emptying to first transfer the $SF_6$ liquid and then purge the residual gas [C5, C8].

Practical applications of $SF_6$-$N_2$ mixtures where $N_2$ gas is the predominant gas requires refrigeration to separate and recover the $SF_6$ efficiently. B. Smith [C5] recommends that in some instances it may be more appropriate to use low pressure-assisted cooling operation instead of high pressure devices [C10]. In this case, pumps are configured to maximize the quantity of gas withdrawn from the electrical equipment (reaching base pressures on the order of 100 Pa) [C5]. Commercial refrigeration systems are available that use an initial liquefaction of the reclaimed gas (e.g., $SF_6$ and contaminants), followed by a further liquefaction of the gas phase by sub-cooling of the gas/liquid mixture in a separate column. Nitrogen gas and contaminants can be slowly vented while the entrained $SF_6$ can be re-liquefied and stored. Continuous sub-cooling of the liquid $SF_6$ further separates the gases. Once isolated the $SF_6$ can be continuously recycled to dry and purify the gas.

**TABLE 2C.** Estimated losses for recover/recycling procedures

| $SF_6$ Percentage in Mixture | Expected Losses |
|---|---|
| > 98% | 10 |
| >90% | 12 |
| >80% | 15 |
| >70% | 20 |
| >60% | 30 |
| >50% | 50 |

Source: R. Probst, DILO company, Inc. [C10]

To assure efficient $SF_6$-$N_2$ mixing, the recommended protocol for returning recycled gas to the electrical equipment should be to start with nitrogen gas transfer [C5]. As pressure is equalized between the equipment and $SF_6$ storage tank, heated $SF_6$ gas can be transferred from storage tank to electrical equipment until the desired mixing ratio (partial pressure) is obtained. The uniformity of mixing among gas components is important when refilling with recycled gas. This can be accomplished by allowing sufficient time for diffusion, designing equipment with several carefully selected points of gas injection, and by creating turbulence during the mixing period. The rate of recovery varies with process used, for example the recovery can be quite slow (on the order of 10–400 lbs/hr) using conventional gas carts. Such limitations may not exist with refrigeration systems. More complex, low pressure gas carts are typically faster, and recover more gas, then comparable high pressure systems [C5]. Refill and storage does not appear to be a problem. Refilling of any container with or without refrigeration devices or heat exchangers is commercially viable.

If a replacement gas mixture cannot be recovered and recycled in a safe, cost effective, and environmentally protective manner, then no real improvement has been achieved [C11]. Additional study of the chemical and physical properties associated with recovery and recycle of possible replacement gas mixtures needs to be pursued to accelerate the recommendation, testing, and implementation of any alternatives to pure $SF_6$.

## 5. Retrofit

A number of manufacturers of electrical equipment and specialty companies have developed methods to retrofit circuit breakers and other devices with vacuum and $SF_6$ interrupters. Depending on the type of application and equipment it may be reasonable to retrofit equipment with modified gas manifolds, heaters, storage compartments, material coatings, filters and traps, etc. This concept of retrofitting technology has been proven reliable and cost effective in certain specific applications. Past experience in this area can be used to help retrofit devices for use of alternatives.

In some applications, the use of replacement gas mixtures would require considerably higher operating pressures than pure $SF_6$ requires. Specific equipment designs, construction, and manufacture will have to be evaluated for the ability to accommodate such pressure changes. Otherwise, to maintain similar electrical properties at the same operating pressure, larger and more robust equipment might be required. Larger insulating clearances, improved rupture disks, or whatever the retrofit for pressure requires may only be readily introduced in the design of new equipment. In other cases, the changes in operation may be associated with thermal changes, transport properties, or other mechanisms not readily addressed via retrofitting. The feasibility of electrical and/or thermal derating of existing equipment while purchasing additional equipment will have to be carefully examined. Further research and development into material properties along with gas thermodynamics and kinetics is needed to recommend and implement the retrofit of the installed base of electrical devices.

Any change from the original equipment design, such as substituting a new insulating gas or gas mixture, in existing equipment would require complete resetting and certification of the equipment. Again, there are no fundamental limitations to such testing but there are economic concerns. The testing procedures are described in a number of international and national standards. For example with circuit breakers, the required tests are defined in IEEE Standard C37.09-1979 (Reaff 1988) "Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis." Current practices are such that complete type testing on high voltage electrical equipment can be prohibitively expensive with estimated costs reaching from $500,000 to $1,000,000 for each type of breaker tested [C11]. The move to alternate gases would require research, development, and policy changes. These would be intended to provide more cost-effective, rapid and accurate testing and certification procedures.

## 6. Monitoring and Analysis

Monitoring and analysis are primarily used to determine when maintenance is required and to evaluate the equipment condition and gas quality. This includes monitoring of gas adsorbent column, desiccants, particle filters, and gas scrubbers. Monitoring equipment designed specifically for pure $SF_6$ applications is currently available and may be useful to monitor $SF_6$-or alternative gas mixtures. Research and development may be warranted to certify the performance of such equipment with mixtures and advance microprocessor technologies for multiple gas sensing. In all cases, multi-gas testing would measure moisture content and trace contaminants. Because moisture is the most detrimental contaminant in pure $SF_6$ applications, careful monitoring of humidity will remain an issue with fluorocompound-containing mixtures.

Monitoring equipment for $SF_6$-containing mixtures or other alternatives must be sensitive to key byproducts and be reliable over long periods of time. In the case of large equipment, such as substations, automated and multipoint sampling would be valuable. To safeguard the environment against leaks from installed and newly manufactured equipment, use of alternatives may require that monitoring systems be developed for installation at transformer and switch-gear stations.

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