Sulfur Hexafluoride and the Electric Power Industry

Key Words: Circuit breakers, gas-insulated transformers, gas-insulated transmission lines, greenhouse effect, high voltage insulation

by
L. G. Christophorou, J. K. Olthoff, and R. J. Van Brunt
National Institute of Standards and Technology

Because of the many and increasing commercial uses of SF_6, there has been an increased demand for it. In turn, this has resulted in increased concentration of SF_6 in the atmosphere.

Introduction

Sulfur hexafluoride (SF_6) is a man-made gas that became commercially available in 1947 [1]. It is one of the most extensively and comprehensively studied molecular gases to date largely because of its many commercial and research applications. (Besides the use of SF_6 by the electric power industry, other uses include: semiconductor processing, blanket gas for magnesium refining, 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 trace gas studies, ball inflation, torpedo propeller quieting, wind supersonic channels, and insulation for AWACS radar domes). 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, it is chemically inert, nontoxic, nonflammable, nonexplosive, and thermally stable (it does not decompose in the gas phase at temperatures $T<500^{\circ}C$). Because of its relative inertness and its nontoxic characteristics, it is generally assumed to be an environmentally safe and acceptable material in the sense that it does not interact unfavorably with the biomass.

Sulfur hexafluoride exhibits many properties that make it suitable for equipment utilized in the transmission and distribution of electric power. SF_6 is a strong electronegative (electron attaching) gas both at room temperature and at temperatures well above ambient, which principally accounts for its relatively 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 (that is, 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 200° C.

Besides its good insulating and heat transfer properties, SF_6 when contained has a relatively high pressure at room temperature. The pressure required to liquefy SF_6 at 21° C is about 2,100 kPa [5, 8]; its boiling point is reasonably low, - 63.8° C, and allows pressures of 400 kPa to 600 kPa to be employed in SF_6-insulated equipment). It is easily liquefied under pressure at room temperature, allowing for compact storage in metal cylinders. It presents no handling problems, is readily available, and up until recently has been reliably available and reasonably inexpensive. (From 1960 to 1994 the price of SF_6 in quantity purchases remained basically constant at about \$3 per pound [one pound = 0.4536 kilogram]. The current prices of SF_6 for quantity purchases is over \$30 per pound). The electrical 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; nonpolar 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 nonideal 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. 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 atoms in the SF_6 molecule) it is benign with regard to stratospheric ozone depletion.

Principal Uses of SF6 by the Electric Power Industry

Sulfur hexafluoride is the electric power industry's preferred gas for electrical insulation and, especially, for arc quenching/current interruption equipment used in the transmission and distribution of electrical energy. Generally, there are four major types of electrical equipment that use SF_6 for insulation and/or interruption purposes: gas-insulated circuit breakers, 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. Gas-insulated equipment is now a major component of power transmission and distribution systems all over the world, and it 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 cities very close to the loads.

Depending on the particular function of the gas-insulated equipment, the gas properties that 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 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 the avoidance of breakdown due to charge accumulation on insulators, no fire safety problems, high reliability, flexible layout, little maintenance, protected insulation, 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

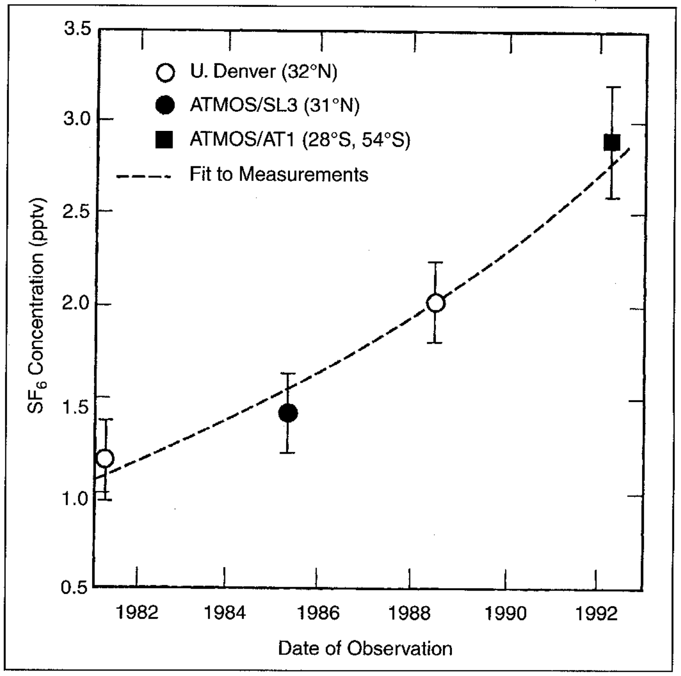


Fig. 1: Average SF_6 concentration (pptv = parts in 10^{12} by volume) between 12 km and 18 km altitude as a function of time [15]. ○ University of Denver balloon-borne infrared measurements at 32° N latitude; ● Spacelab 3 ATMOS data at 31° N latitude; ■ Average of ATMOS ATLAS 1 data at 28° S and 54° S [15].

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

Concentrations of SF6 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 steadily increased since the 1970s to ~ 7,000 metric tons per year in 1993 [9-13]. In turn, this has resulted in increased concentration of SF_6 in the atmosphere [11-17]. As seen in Fig. 1, recent measurements [15, 17] have shown that the amount of SF_6 in the atmosphere has been increasing at a rate of ~ 8.7%/yr, from barely measurable quantities a decade ago to current levels of ~ 3.2 pptv (~ 3.2 parts in 10^{12} by volume). The atmospheric concentration of SF_6 could reach 10 pptv by the year 2010 depending upon the assumptions of release rates (see [11, 14, 15, 17] and Fig. 2). In many industrial applications SF_6 is not recoverable, and the releases of SF_6 into the environment by the electric power industry come from normal equipment leakage, maintenance, reclaiming, handling, testing, etc. 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 (within the next few centuries). 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. This release of SF_6 into the environment cannot be reduced significantly since there are no currently accepted economically feasible methods for controlling or destroying SF_6 as it leaks from enclosures. It has been suggested that impure used SF_6 in storage containers can be destroyed by thermal decomposition in industrial waste treatment furnaces at elevated temperatures (T>1,100° C) [9].

However, decreasing the rate of SF_6 leakage and increasing the level of recycling are high priorities since they will both curtail production needs of SF_6 and thus will 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 better monitor the gas pressure in SF_6-insulated equipment and the amount of SF_6 released into the environment [9-11]. These efforts include improved methods to quantify and stop leakages, better pumping and storage procedures, setting of standards for recycling, manufacturing tighter and more compact equipment, development of sealed-for-life electrical apparatus, gradual replacement of older equipment which normally leaks at higher rates, and implementation of a sound overall policy of using, handling, and tracing SF_6. (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 Corp. [Switzerland], and A. Diessner of Siemens AG [Germany]). These efforts are partially motivated by the prospect of regulation and the possibility of imposition of controls on the use and transport of SF_6 [11, 13, 20]. The overall concern is motivated by virtually one and one reason only: *SF_6 is a potent greenhouse gas.*

SF6 is a Potent Greenhouse Gas

Greenhouse gases are atmospheric gases that 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 and occur naturally in the environment (e.g., H_2O, CO_2, CH_4, N_2O) or are man-made gases that are released into the environment, e.g., fully fluorinated compounds (FFC); combustion products such as CO_2, nitrogen, and sulfur oxides; SF_6. The effective trapping of infrared radiation by the greenhouse gases and its re-radiation back to earth results in an increase in the average temperature of the earth's atmosphere. The effect is known as the "greenhouse effect." The man-produced contribution to the greenhouse effect shifts the balance between incoming and outgoing radiation at the top of the earth's troposphere toward the former, causing "global warming."

Sulphur hexafluoride is an efficient absorber of infrared radiation, particularly at wavelengths near 10.5 μm [18]. Additionally, unlike most other naturally occurring greenhouse gases (e.g., CO_2, CH_4), SF_6 is largely immune to chemical and photolytic degradation and therefore its contribution to global warming is expected to be cumulative and virtually permanent. Although the determination of the lifetime of SF_6 in the environment (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) 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 3,200 years [11, 13, 19-22]. 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 horizon is estimated to be ~ 25,000 times greater than that of CO_2,

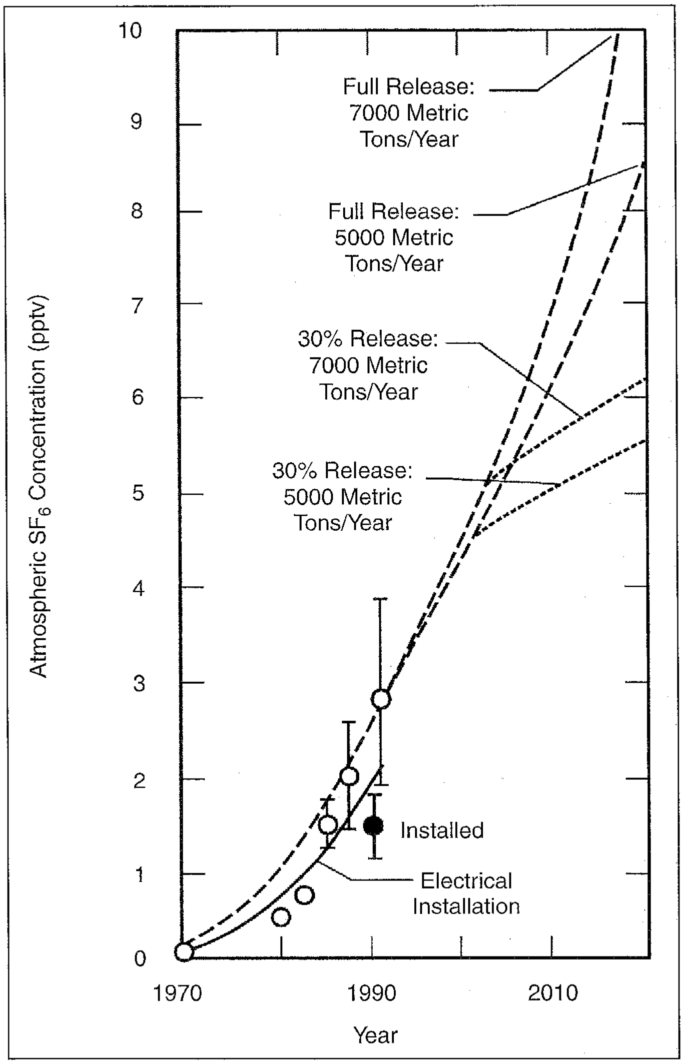


Fig. 2: Atmospheric SF_6 concentration (pptv = parts in 10^{12} by volume) as a function of time. The solid curve represents the estimated cumulative total SF_6 from gas-insulated equipment in the past, the open points are measured atmospheric trace concentrations, the solid point labeled "installed" 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 increase under various assumptions [12, 14].

the predominant contributor to the greenhouse effect [19]. 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 should, in the near term, be too small to have significant environmental consequences. 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]. Government and environmental protection agencies, electrical, chemical, and other industries using or interested in the use of SF_6 [6, 11-13, 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 than in the past and to reduce its releases 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.

SF6 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 presently difficult to envision the near term elimination of the use of SF_6 in view of the demonstrated industrial and societal value. However, it stresses 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. 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, environmentally damaging, have low vapor pressure, and their decomposition in the various types of gas discharges is extensive and unknown. Nonelectronegative gases that are benign and environmentally ideal, such as N_2, normally have low dielectric strengths. For example, N_2 has a dielectric strength about three times lower than SF_6 and lacks the fundamental requirements for use by itself in circuit breakers. Nonetheless, such environmentally friendly gases might be used by themselves at higher pressures, or at comparatively lower pressures, as the main component in mixtures with electronegative gases, including SF_6, at partial concentrations of a few per cent. Suggestions have been made repeatedly over the last two decades to use high-pressure N_2 and mixtures of N_2 with SF_6 for insulation, arc quenching, and current interruption [2-4, 6], and more recently, high-pressure nitrogen is seriously being considered for gas-insulated transmission [6, 23]. Mixtures of N_2 / SF_6 have been and are being used in circuit breakers under severe weather conditions ($T<-40^\circ$ C) where SF_6 used under pressure in circuit breakers may liquefy and thus lose part of its current interruption properties. It was found that for such uses the SF_6/N_2 mixtures with 50% SF_6 are efficient arc interrupting media [24, 25]. Besides SF_6/N_2, other mixtures in use include SF_6/CF_4 and SF_6/He [3, 25, 26].

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 sought. A number of studies conducted mainly during this time period produced a large body of valuable information (see, for example, [2, 3]) that needs to be revisited and reassessed not so much for finding "better" gaseous dielectrics than SF_6 but rather from the point of view of finding gases/mixtures that are environmentally acceptable and comparable in dielectric properties and performance to SF_6. A rekindled interest in "new" gaseous insulators may also direct itself to finding gases/mixtures that are not necessarily universally optimum for each and every high-voltage insulation need but that can be optimized for a particular application.

A 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, nontoxicity, nonflammabilty, availability, and cost, there should be basic, applied, and industrial testing to assess the thermal and electrical properties of the gaseous dielectric. Its performance under various test voltages (dc, ac, impulse, transients), field configurations, and particle contamination must be assessed, as well as studies conducted of gas decomposition under prolonged electrical stress, corona, breakdown, and arc, ageing, and influence of spacer and other materials. Gas mixtures in particular need to be looked at anew, and efforts need to be made to address industry's concerns with regard to difficulties in handling, mixing, maintaining constant composition, and reclamation of the mixture's constituents.

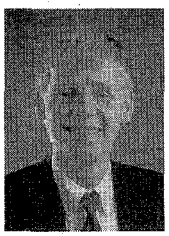
Conclusions

The use of gas-insulated electrical equipment has a demonstrated value for society. The problems relating to SF_6 are not without solution and can lead to new opportunities. To this end, besides the current efforts to curtail the releases of SF_6 into the environment, a comprehensive and focused program is needed to develop alternative gaseous insulators and alternative high-voltage technologies.

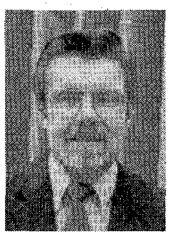
Acknowlegments

We wish to thank Dr. Alan H. Cookson and Dr. David S. Green of The National Institute of Standards and Technology for valuable comments.

LOUCAS G. CHRISTOPHOROU received his B.Sc. degree in physics from the University of Athens, Greece, and his Ph.D. and D.Sc. degrees from the University of Manchester, England. From 1963 to 1994 he was at Oak Ridge National Laboratory and at the University of Tennessee. At Oak Ridge, he served as head of the Atomic, Molecular, and High Voltage Physics Group, and he was appointed corporate fellow in 1981 and senior corporate fellow in 1991. At the University of Tennessee he has been a Ford Foundation professor of physics since 1969. He is currently at the National Institute of Standards and Technology and The University of Tennessee. He conducted extensive and broad research in atomic and molecular physics, radiation physics and chemistry, chemical physics and photophysics, electron and ion physics, and materials for radiation detector, pulsed power, gaseous dielectrics, and plasma processing. He can be reached at the U.S. Dept. of Commerce, NIST, Bldg. 220, Room B344, Gaithersburg, MD 20899-0001, or at the Department of Physics, The University of Tennessee, Knoxville, TN 37996-1200.



JAMES K. OLTHOFF received his B.A. from Calvin College in physics and mathematics, and his Ph.D. in physics from the University of Maryland in 1985. He then became a post-doctoral fellow at The Johns Hopkins School of Medicine. Since 1987 he has been a researcher at the National Institute of Standards and Technology, and he is presently the leader of the Electrical Systems Group of the Electricity Division. He has performed research in the areas of atomic and molecular physics, with an emphasis on electron molecule interactions, plasma processing, and gaseous dielectrics.



RICHARD VAN BRUNT received his B.Sc. in physics from the University of Florida in 1961 and his Ph.D. in physics from the University of Colorado-Joint Institute for Laboratory Astrophysics in 1969. He has been a researcher at the National Institute of Standards and Technology since 1978 and is presently a NIST fellow in the Electrical Systems Group of the Electricity Division. He is an IEEE fellow and was the IEEE Whitehead Memorial Lecturer in 1994. He has conducted extensive research in atomic and molecular physics, with recent emphasis on gaseous dielectrics, plasma processing, and partial discharge detection.

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