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Sulfur Hexafluoride

This is a look at Sulfur Hexafluoride (SF_6) gas, which is used in an ion accelerator at my job. SF_6 is the bad boy of greenhouse gases, with a 100-year global warming potential (GWP) of 22,800 (CO_2, by definition, has a GWP of 1). The radiative efficiency of SF_6, a measure warming of the earth's surface caused by the addition of 1 part per billion of the gas, is 0.52 Watts/sq meter/ppb (the value for CO_2 is 1.4E-5). The lifetime of SF_6 in the atmosphere is not well known. Estimates range from 800 to 3200 years.

Many accelerators – particularly the big ones - don't use much SF_6. Small accelerators commonly do. The accelerating columns and ion sources in small accelerators are hundreds of thousands to millions of volts above, or below, ground potential. These parts are enclosed in a tank filled with SF_6 at 3 to 5 atmospheres. The SF_6 is a gaseous insulator, which helps prevent electric arcs from jumping between parts at different voltages.

Before SF_6 came into widespread use, a mixture of CO_2 and N_2 at 10 to 20 atmospheres was the insulating gas. This made accelerators tempermental machines. Accelerators consist of hundreds of delicate seals between metal and ceramic, vacuum parts that must expand and contract with pressure, and electronic components like big capacitors. Pressurizing and depressurizing these parts risked breaking them. The advent of SF_6, with its lower required pressures, made all of this much better.

An accelerator contains several cylinders of SF_6, each cylinder being 50 kg and costing over $1200-. Accelerators usually come with an extra tank, plus a pump and a compressor, so SF_6 can be transferred to the holding tank when the accelerator is being serviced. There are leaks, however, and an accelerator requires an extra cylinder every year or so.

Despite its reputation as a stable, inert gas, SF_6 seems to be very fragile in an accelerator. Particularly if small amounts of water are present, arcs create corrosive breakdown products, which attack metal. For this reason, SF_6 is passed through a bed of activated alumina, which removes water and breakdown products, when the accelerator is serviced. In many accelerators the SF_6 is recirculated through the alumina bed continuously.

The business of recovering and reprocessing SF_6 from customers seems to be more a concept than a reality. This became apparent when interest arose in asking a vendor to purify gas, which had been in service for several decades. Customers in the Midwest must pay to rent a very expensive trailer with tanks and equipment, which is brought up from Florida. The trailer compresses the gas into tanks, which are trucked from the Midwest to a plant in Florida where it is refined. The gas is then trucked back to the customer, or the customer is issued a credit to buy new SF6. The cost is several times the cost of new SF6. It became apparent to us that the salesman had never actually done this before.

Uses of SF6

SF6 is a unique molecule – heavy (molecular weight 146), a gas at room temperature, and stable chemically and thermally. Over the years it has found many uses. Because of its opprobrium as a greenhouse gas, most of these uses are being phased out in favor of other technologies.

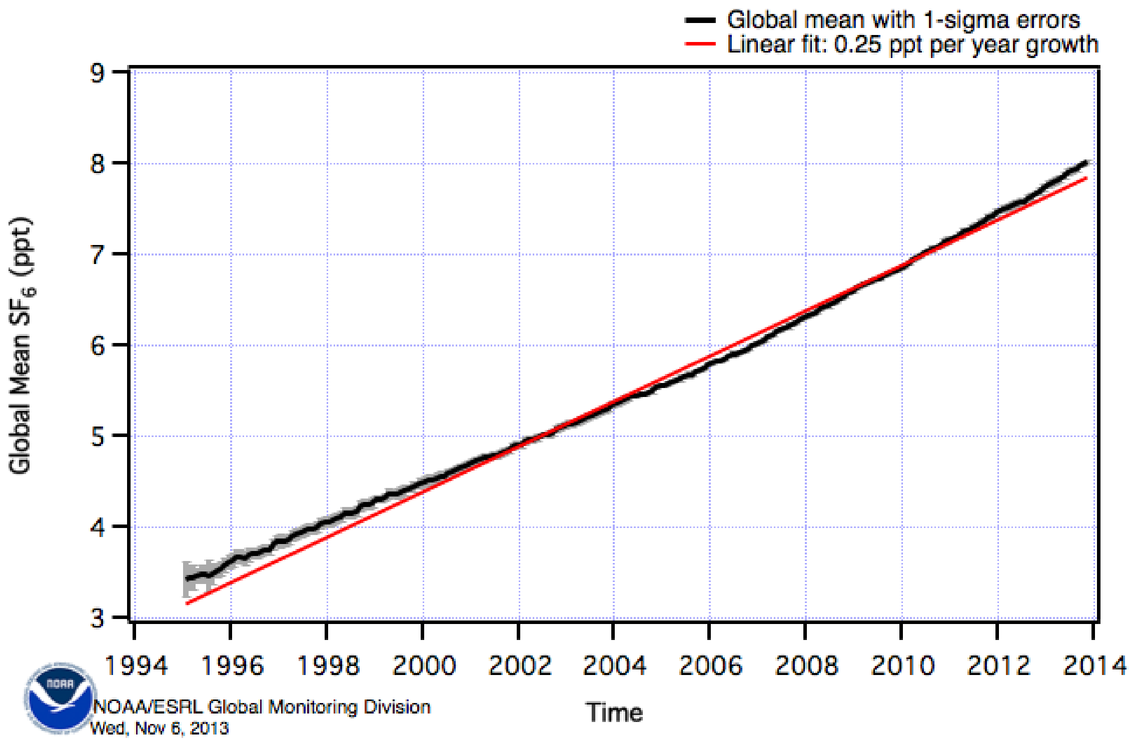
The principal remaining use is as an insulating gas in high-voltage electrical equipment – mainly switches and circuit breakers used by electric utilities. Equipment containing SF6 can be very compact. Additionally, the SF6 quenches the arcs that occur across a switch when the current is interrupted. As long as the SF6 has not become contaminated with water, it is not broken down by the arcs, and if broken down, quickly recovers.

SF6 is uniquely suited to its use in electrical equipment. Substitutes with equivalent performance have not been developed, though bulkier, lower-voltage equipment insulated with vacuum, air, or other gas mixtures, is available. SF6-insulated equipment dominates the market in high-voltage transmission, as well as lower voltage distribution in urban areas where space is limited. SF6 proponents contend that the use of the gas reduces CO2 emissions by making the electrical distribution system more efficient.

The shift to DC electrical transmission systems promises to reduce the use of SF6, as DC systems require a single wire, while 3-phase AC systems require 3.

Amount Produced/Emitted Per Year

SF6 concentrations in air can be measured accurately with gas chromatography, and are shown below. The atmospheric concentration has been increasing roughly linearly since 1990, at 7000 metric tons per year, or 0.25 parts per trillion (ppt). The atmosphere currently contains about 7.5 ppt of the gas. Atmospheric measurements are so sensitive that emissions from regions of the world can be estimated by measuring concentrations downwind.



[Source]

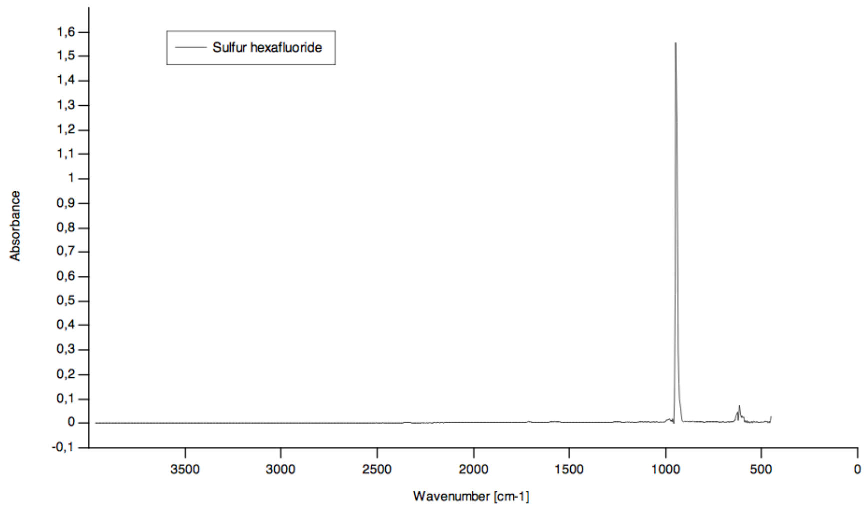
Worldwide production of SF6 is not known, as production outside of the US and Europe is not accurately reported. Estimates put production at [10,000 metric tons per year]. Since most SF6 is used in electrical equipment, and enters the atmosphere as slow leaks, or is dumped in the atmosphere years later when equipment is repaired or scrapped, there is a lag between production and emission. Worldwide production ends up being estimated based on figures for atmospheric concentration, or sales of electrical distribution equipment. This makes it impossible to measure the atmospheric lifetime for SF6 by comparing production figures with atmospheric concentration.

From the linear, or slightly exponential, increase in SF6 concentration, it is obvious that most SF6 ends its useful life by being dumped into the atmosphere. If recovery and reprocessing were practiced on anywhere near a universal scale, the rate of growth would be declining.

Radiative Efficiency

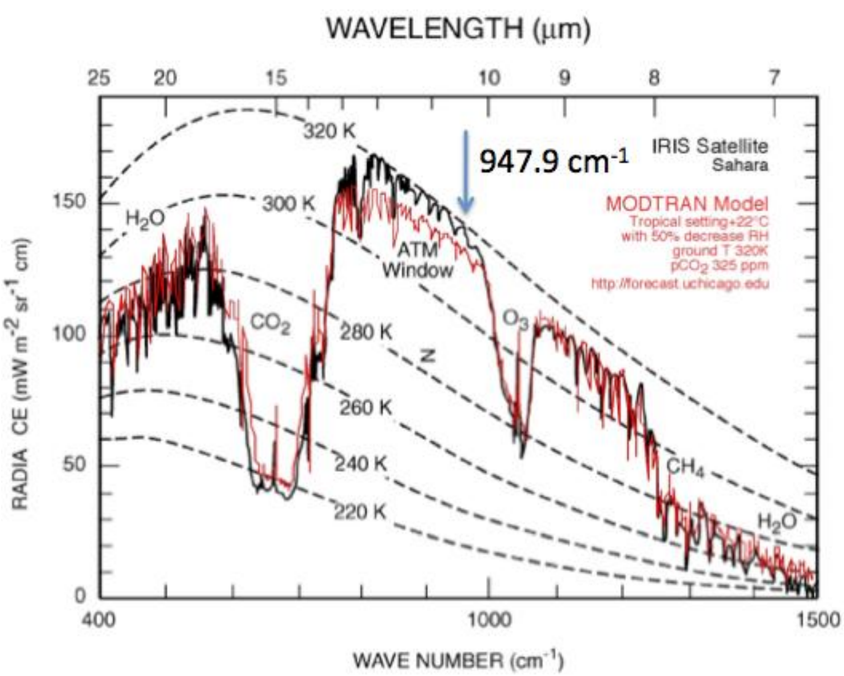
The high 100-year global warming potential of SF6 is primarily due to its high radiative efficiency. The high radiative efficiency is in turn due to the low amount of SF6 in the atmosphere, and its strong interaction with infrared radiation in a portion of the spectrum where there is little interaction from other gases.

The SF6 molecule strongly absorbs infrared radiation of wavelength 10.7 microns (wavenumber 947.9 cm-1). This wavelength falls in the 'atmospheric window', where most infrared radiation escapes the Earth's surface into space without being absorbed. The absorption spectrum of SF6 is shown below:



Source

An arrow marks the approximate position of 947.9 cm-1 on the Modtran graph we have been using in class:



SF6 has a Radiative Efficiency of 0.52 Watts/sq meter/ppb. The approximately 7.5 ppt in the atmosphere contribute 3.9 milliwatts/sq meter. Each year another 0.25 ppt of SF6 is added to the atmosphere, adding 0.13 milliwatts/sq meter of warming.

Using a ballpark value for climate sensitivity (0.75 C warming per 1 Watt/sq m increase), current total warming from SF6 is 3E-3 C, a number which increases by 1E-4 C each year.

The Radiative Efficiency of SF6 is roughly twice that of other common airborne chlorine and fluorine compounds. Since far more of these other chemicals are present in the atmosphere than SF6, the radiative forcing from SF6 is a small part of forcing from this category of chemicals (3 milliwatts v. 300 milliwatts per square meter). The forcing by anthropogenic CO2 is, by comparison, 2 Watts per square meter.

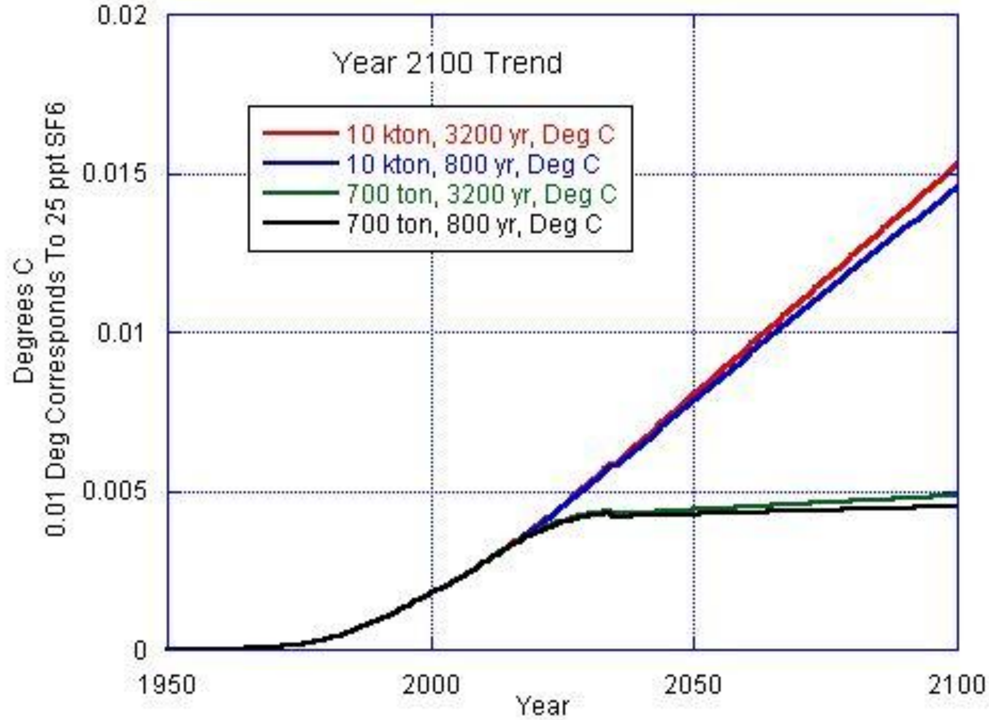
SF6 is not now an important greenhouse gas. The concern is that with continuing emissions, its global warming contribution will grow, and by then, the long atmospheric lifetime will have locked in that contribution, possibly for millennia. An even more alarming prospect is that SF6 might become more widely used, as more and more applications exploit its unique properties.

Atmospheric Lifetime

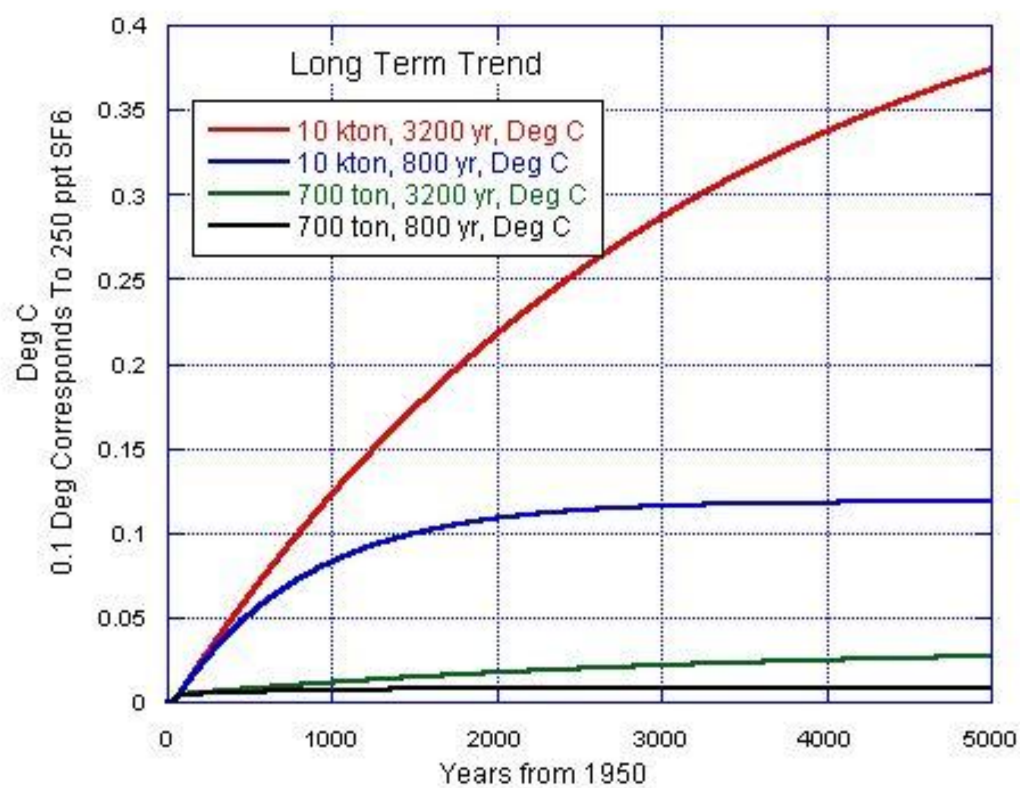
A second worrisome property of SF6 is its exceptional stability in the atmosphere, and hence its long atmospheric lifetime – estimated to be from 800 to 3200 years. Measurements of SF6 in the atmosphere indicate that the concentration of SF6 drops rapidly above 45 kilometers, in a region of the atmosphere called the mesosphere. Air enters the mesosphere by rising near the equator, and leaves by falling near the poles. As air passes from equator to poles, it is bombarded by high-energy ultraviolet radiation. It is believed that the drop in concentration in this region is due to breakdown of SF6 by the ultraviolet bombardment. I had thought this might be due to heavy SF6 molecules falling to the bottom like marbles in a bucket of popcorn, but this is fortunately not the case. Breakdown in this region is believed to be the only sink for SF6 at its current, low atmospheric concentration. Very little of Earth's atmosphere is in the mesosphere, so this is a very weak sink. At low concentrations, SF6 does not dissolve in rainfall or seawater in appreciable amounts; similarly lightning does not affect enough of the atmosphere to destroy significant SF6.

Projections of Warming in Various Scenarios

I have calculated timelines for global warming from SF6 for various levels of emissions, and for various estimates of atmospheric lifetimes.



Year 2100 Trend
10 kton, 3200 yr, Deg C
10 kton, 800 yr, Deg C
700 ton, 3200 yr, Deg C
700 ton, 800 yr, Deg C
Degrees C
0.01 Deg Corresponds To 25 ppt SF6
0.02
0.015
0.01
0.005
0
1950
2000
2050
2100
Year



Long Term Trend
10 kton, 3200 yr, Deg C
10 kton, 800 yr, Deg C
700 ton, 3200 yr, Deg C
700 ton, 800 yr, Deg C
Deg C
0.1 Deg Corresponds To 250 ppt SF6
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
1000
2000
3000
4000
5000
Years from 1950

The ‘business as usual’ calculation assumes that the current production of 10,000 metric tons continues indefinitely, and eventually leaks into the atmosphere. For the ‘business as usual’ scenario, the contribution of SF6 to warming by 2100 is 0.015 C. Assuming ‘business as usual’ for 5000 years, the scale of warming depends on the atmospheric lifetime of SF6 – 0.12 C for an 800 year lifetime, 0.37 C for a 3200 year lifetime. Business as usual over the longer term is intolerable.

Short term, the outlook looks less bleak. However, SF6 is but one of many greenhouse gases, these gases together pose a big problem, and emitters of one particular gas cannot be given a ‘bye’.

My second timeline is for an emissions rate of 700 tons/year, one tenth of current levels. This assumes that SF6 is recovered and reprocessed worldwide; it also accommodates real-world rates of leaks and accidents.

The 700-ton/year scenario includes the legacy of our current emissions of 7000 tons/year and a 20-year ramp down to 700 tons/year. Warming by 2100 would be 0.005 C; by 5000 years, warming would be 0.008 C for an 800-year lifetime, and 0.027 C for a 3200-year lifetime.

Under this scenario, SF6 suppliers would also be in the business of recovery and reprocessing. A truck would pull up to a defective high voltage switch, the gas would be tested for its chemical content, pumped out of the system, and the system owner credited for the amount of SF6. Upon repair of the equipment, a truck would return with fresh SF6. The system would be leak-tested, then refilled. For most users, this system would work fairly well. An alternative to recycling SF6 may be destroying it when equipment is about to be scrapped or opened up for repair.

For its problems, SF6 has a huge advantage. Its users are not billions of individuals scattered all over the world with old, leaky air conditioners and refrigerators in their houses. The users of SF6 are big utilities, big corporations, and big universities and national labs. They are few in number, and have the resources to do a job right if necessary. These large organizations can contract with a supplier to maintain a certain number of cubic feet of SF6 in equipment, or provide a gas service contract for all SF6-containing equipment. Government could require that such a contract be in place as a condition for using SF6.

Manufacturers are developing switches and circuit breakers which are suitable for wind farms and other medium-voltage applications. These use vacuum, or gases other than SF6, for insulation. In the future, SF6 use may be required only in high-voltage transmission systems.

The task of maintaining an inventory of SF6 in electrical equipment without losing it to the environment seems like a big problem. But on the scale of mankind’s challenges, it is trifling. Many of the substances upon which we base our civilization are not part of any natural cycle, and many of those are incompatible with the natural world. These substances must be collected and reprocessed on a universal scale, if technology is to be sustainable. Handling SF6 correctly can be an easy first step toward a stainable world. Cleanly recapturing and reprocessing widely used things like petrochemicals, consumer electronics, automobiles, building materials … these will be much harder.