SULPHUR HEXAFLUORIDE - ITS PROPERTIES AND USE AS A GASEOUS INSULATOR IN VAN DE GRAAFF ACCELERATORS

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SUMMARY

Investigations into the use of sulphur hexafluoride as an insulating gas for Van de Graaff accelerators have resulted in the decision to use it in the MP tandem accelerator presently being installed at Chalk River. Observations on a 3 megavolt vertical Van de Graaff and the EN 10 MeV tandem accelerator show that there are no problems due to the use of SF_6 which cannot be solved with normal engineering procedures. An outline will be given of the physical and electrical properties, and a method of detecting and removing the corrosive breakdown products will be described. The gas handling system for the MP accelerator and a system for air removal will be described. An economic and functional comparison with a system using a 4:1 mixture of N_2-CO_2 is given.

INTRODUCTION

The decision to use SF_6 gas instead of N_2-CO_2 as the insulating medium for our MP 20 MeV tandem accelerator was based primarily on three main factors.

First, experience with our three megavolt vertical accelerator and our model EN tandem accelerator, both of which have run with N_2-CO_2, showed that operation with SF_6 at 60 psig was as good as operation with N_2-CO_2 at 225 psig. The three megavolt machine has run intermittently since 1956 and the tandem machine has run an average of sixty hours a week since January, 1963 using pure SF_6 although some air contamination of the insulating gas has occurred during this time. There has been no fault encountered, either electrical or mechanical, which could be attributed to the SF_6 insulating gas or its breakdown products.

Secondly, a cost analysis made on comparable N_2-CO_2 and SF_6 gas storage and handling systems (including initial gas costs) showed that there is no appreciable difference in overall capital costs. The SF_6 yearly operating costs for replacement gas should be low and can be more than offset by the saving in accelerator pump out time.

The third and most significant factor was the possibility of increasing the limit on the operating voltage by increasing accelerator tank pressure to 100-125 psig. With the development of the inclined field accelerator tubes and improvements in solid dielectrics, this holds promise.

PROPERTIES OF SF_6

The usefulness of SF_6 as an insulating medium for Van de Graaff accelerators is due to its unique electrical, physical and chemical properties. The following characteristics are most important.

Dielectric Strength

The relative dielectric strength of SF_6 (N_2-CO_2 = 1) in the electric fields existing in the EN tandem accelerator is about 3.0. This is based on experiments by Philp[1], Camilli, Gordon and Plump[2], and on our own experience with the EN-1 tandem accelerator. Spark-over tests were performed on the EN-1 tandem accelerator with SF_6 at 60 psig in the tank and 15 psig in the accelerator tubes. Sparking did not occur below 7.5 megavolts and it is estimated that the most of the sparking occurred down the accelerator tube spark gaps at approximately 8.0 megavolts. These results are as good as any achieved in an EN tandem using N_2-CO_2 mixtures up to 250 psig.

Typical operating pressures for our EN tandem are 40 psig to five million volts and 60 psig to seven million volts.

Heat Transfer

Good heat transfer characteristics are essential, particularly in the MP tandem accelerator as most of the heat from the 100 HP charge-belt drivemotor must be transferred by the tank gas. Although the thermal conductivity of pure SF_6 is lower than air (3.36×10^{-5} vs 5.12×10^{-5} calories per sec/cm^2/°C/cm) its high density results in excellent cooling by natural and forced convection.

Density

The density of SF_6 at standard conditions is 0.37 lbs/ft^3 (about five times as heavy as air). The high density results in greater loads on the main drive motor. The drive motor load appears to vary directly as the density of the insulating gas. Figure 1 shows the results using our EN tandem accelerator. The tests were conducted without changing other operating conditions.

Chemical Properties

The insulating gas must be compatible with the materials of construction. It must also be stable at the elevated temperature of the motors and other electrical components used in Van de Graaff machines. SF_6 is stable up to 500°C which is higher than normally found in Van de Graaff accelerators except during an electrical spark.

Toxicity and Corrosion

SF_6 is non-toxic and non-corrosive. Rats exposed to 80% SF_6-20% O_2 mixtures for two hours were unaffected[2]. Tests by Allied Chemical Co.[3], Camilli, Gordon and Plump[2] and others, have shown pure SF_6 is physiologically safe. As SF_6 is stable under normal operating conditions, equipment and piping are carbon steel. However, thermal and electrical breakdown products are quite toxic and corrosive. Thermal decomposition probably occurs during accelerator sparking and electrical decomposition during sparking and corona discharge.

SF_6 Breakdown Products

An experiment was performed to determine whether breakdown products are formed during a corona discharge and if these can be removed by activated alumina.

A sample of gas, containing about 20% air, was taken from the accelerator and subjected to corona discharge in a 1 ft^3 tank at 15 psig for 6-1/2 hours. The operating voltage was 94 kilovolts and the power 230 watts. Gas samples taken before and after absorption by activated alumina were analyzed with a mass spectrograph. Pure SF_6 and tank gas without any corona discharge were also analyzed. Further analysis is intended using an infra-red absorption spectrograph and a gas chromatograph. These devices permit a non-destructive analysis which should clarify the results obtained with the mass spectrograph.

The corona discharge was maintained between strips of stainless steel screening and a flat copper plate. Other materials also in contact with the gas were Lucite, mild steel, polyethylene, aluminum and nylon. Since the breakdown products of SF_6 are very reactive, these materials can greatly affect products obtained, however, they are commonly used in accelerators.

A number of ion species are produced by any compound as it is ionized in the mass spectrograph. For SF_6 the species and their mass numbers are:

SF_5^+	127	SF_2^+	70	SF_3^{++}	44-1/2
SF_4^+	108	SF^+	51	SF_2^{++}	35
SF_3^+	89	SF_4^{++}	54	SF^{++}	25-1/2

Impurities found in the tank gas (and to a certain extent even in the "pure" SF_6) give the following ions.

N_2^+	28	O^+	16
N^+	14	A^+	40
O_2^+	32	CO_2	44

In the specimen of tank gas subjected to corona discharge, the following peaks appeared.

SOF_2^+	86	$SO_2F_2^+$	102	SOF_3^+	105
SOF^+	67	SO_2F^+	83		
SO^+	48	SO_2^+	64		

Ion species with mass numbers 86, 67 and 48 are breakdown products (in the mass spectrograph) of SOF_2. Peaks at 102, 83 and 64 are tentatively identified as being from SO_2F_2 but they could also be from S_2F_2. The peak at mass 105 is probably from SOF_4. Further analysis using gas chromatograph should clarify these identifications. Small peaks occurring one and two mass units higher than a major peak result from the same ion species as the major peak but with a heavier isotope of sulphur. The nitrogen, oxygen and argon peaks result from air contamination of the tank gas.

A comparison of the spectra of samples subjected to corona discharge shows that activated alumina effectively removes all breakdown products. Earlier experiments by Camilli et al[2] on toxic breakdown products, and by Schumb et al[4] on acidic and oxidizing breakdown products, showed that all these were removed by activated alumina.

Design of the Gas Transfer, Storage and Purification Systems for MP Tandem Accelerator

The general design requirements of the gas system are as follows:

(i) The storage tanks should hold sufficient gas to charge the accelerator to 90 psig with either SF_6 or an 80% SF_6-20% N_2 mixture (by volume).

(ii) The time required for pressurizing and evacuating the accelerator should be comparable to those for a system using N_2-CO_2.

(iii) The leakage of gas from the system should be a minimum.

(iv) A system for removing permanent gases (e.g. N_2 or air) from the insulating gas should be provided.

Storage and Handling System

Figure 3 shows the storage and handling system in simplified form. In practice, the accelerators at Chalk River have always contained varying amounts of air (up to 20%) mixed with the SF_6. Sufficient storage volume has therefore been provided to allow the MP accelerator to operate with up to 20% N_2. The gas will be stored in two interconnected tanks with a total volume of 1600 ft^3. Because of the large quantities of SF_6 required,it will be stored as a liquid in the 600 ft^3 tank. This tank is capable of holding 51,000 lb of liquid SF_6, a quantity sufficient to charge the accelerator to 140 psig. The pressure in the storage tanks will be the vapor pressure of SF_6 plus the pressure due to non-condensable gases up to a maximum working pressure of 600 psig.

Nitrogen and SF_6 may be added to the accelerator from the 1000 ft^3 tank and then SF_6 from the liquid storage tank until the desired accelerator pressure is obtained. The SF_6 is removed from the storage tank as a liquid, ensuring a pure, dry gas for the accelerator.

Liquid SF_6 is vaporized in a steam heated vaporizer and then superheated. Superheating compensates for the temperature drop on expansion from storage pressure (up to 600 psig) to accelerator pressure (initially 1 torr) through a throttling valve. The temperature of the gas entering the accelerator is controlled to within $\pm$ 10°F of the accelerator temperature to eliminate thermal shock. The vaporizer and superheater will deliver 160 lb of SF_6 per minute.

The gas is removed from the accelerator with a 300 std ft^3/min compressor and condensed for liquid storage. The condenser will liquify 100 lb of SF_6 per minute from a gas mixture containing up to 20% N_2. When the accelerator pressure drops below atmospheric, a 500 ft^3/min vacuum pump is used in series with the compressor to remove the remaining gas from the accelerator. Mixtures of SF_6 and non-condensable gas will be vented to the gas storage tank to keep the liquid storage tank pressure below 600 psig. The accelerator pressure can be reduced from 90 psig to 5 torr in 6 hours.

A comparison of the operating conditions for the N_2-CO_2 and SF_6 system is given below.

	SF_6	N_2-CO_2 (5)
Normal Accelerator Operating Pressure (psig)	70	225
Max. Storage Pressure (psig)	600	2400
Gas Requirements (standard ft^3)	67,800	180,000
lbs	26,300	13,000
Compressor H.P.	100	150

Pumping times for different phases of the operating cycle are given in the following table for N_2-CO_2 and SF_6 systems.

Operation	SF_6	N_2-CO_2
1. Lowering accelerator pressure to atmospheric	4 hrs (from 90 psig)	10 hrs (from 225 psig)
2. Evacuate gas from accelerator tank	2*	1**
3. Fill accelerator with air	1/2	1/2
4. Exhaust air from accelerator	4	4
5. Recharge with dielectric	3-1/2 (to 90 psig)	2 - 4 (to 225 psig)

* SF_6 evacuated to 5 torr and exhausted to storage system.

** N_2-CO_2 evacuated to 50 torr and exhausted to atmosphere.

Purification System

The buildup of non-condensable gases over a period of time makes the condensing of SF_6 difficult. With a non-condensable gas content of 40%, SF_6 will not condense below 600 psig with the cooling water temperature available. A system for separating SF_6 from any non-condensable gas, such as air, has been provided and is shown in figure 4. Gas may be drawn from either storage tank, compressed to 3000 psig using a 25 std ft^3/min diaphragm compressor, and condensed. The condenser is cooled by a refrigeration system. When the pressure in the condenser increases to 3000 psig, due to the buildup of non-condensable gas the temperature is reduced to $-50^\circ F$. At these conditions the percentage of SF_6 in the gas phase is less than 1.5%. The gas mixture is then vented to atmosphere and liquid SF_6 returned to the storage tank.

The purification system will be used only when necessary and may be operated independently of the gas transfer system so that the accelerator is not affected by the purification system.

Leak Testing

As SF_6 is expensive, methods of sensing and locating leaks are important. Halide leak detectors are commercially available which are suitable for locating leaks in welds, valve stems and gaskets etc. For detecting SF_6 in equipment areas, a device is being developed at Chalk River which will respond to an increase as small as .01%. This device detects a change in the velocity of sound in the air being sampled. Detectors will be located at low points under the accelerator and storage tanks.

Economics

The capital cost of the SF_6 system, including the purification system and initial gas charge is within ten percent of an N_2-CO_2 system. Estimates of the operating costs vary depending on the vacuum pulled on the accelerator tank when exhausting insulating gas and the value assigned to shutdown time of the accelerator. Assuming $150.00/hr for accelerator shutdown time, a N_2-CO_2 system exhausted to atmospheric pressure, and an SF_6 system exhausted to 5 torr, then SF_6 operating costs will be approximately $350.00/cycle less than the N_2-CO_2 system. This assumes 16-1/2 hour and 14 hour cycle times respectively for the N_2-CO_2 and SF_6 systems.

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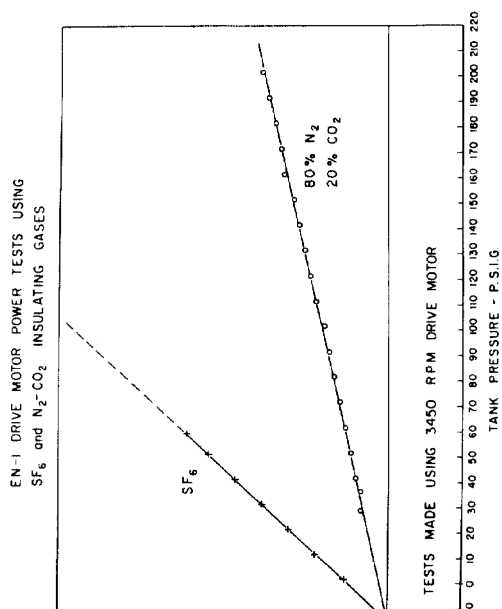

Fig. 1. Drivemotor load vs tank pressure for SF_6 and N_2-CO_2.

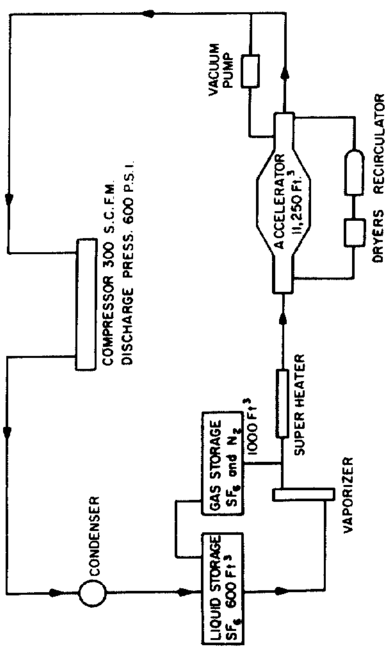

Fig. 3. MP accelerator dielectric gas handling system.

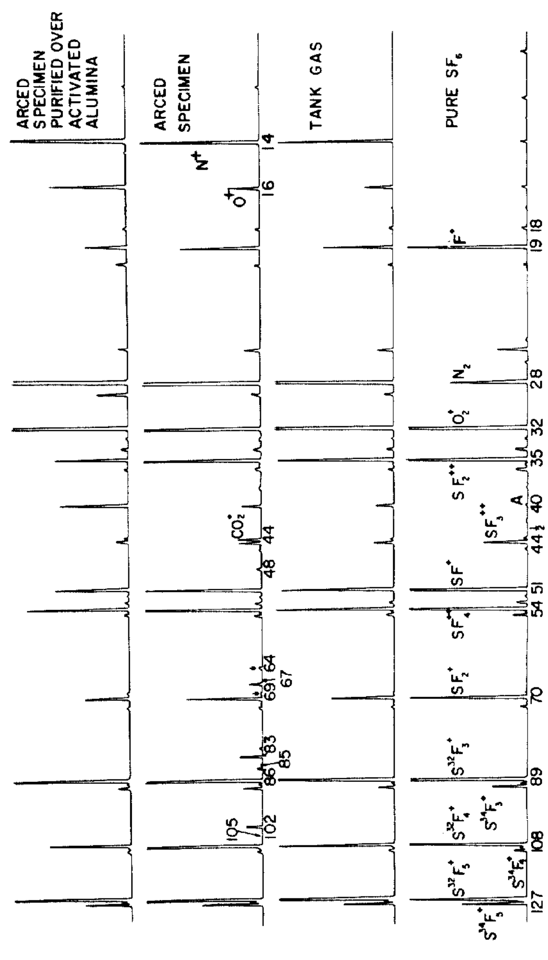

Fig. 2. Mass spectra of SF_6 and its breakdown products.

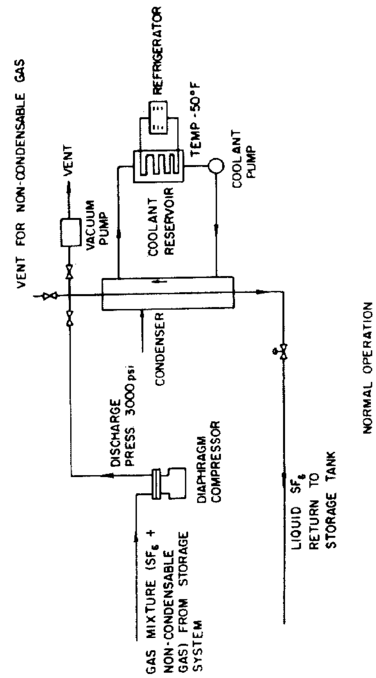

Fig. 4. MP accelerator dielectric gas purification system.