SF_6 and the Environment

Guidelines for Electric Utility Substations

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Technical Update, November 2003

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1
INTRODUCTION

Worldwide, the electric utility industry is the dominant user of SF_6 – using 70%-80% of all SF_6 produced [1]. There is growing environmental interest in the use of SF_6 due to the fact that it is a powerful and long-lived greenhouse gas. (SF_6 is 22,200 times more effective a greenhouse gas than CO_2 on a per-kg basis [2] – and is extremely stable, with atmospheric lifetime estimates between 600 [3] and 3200 years [2]). Even though the present share of SF_6 from the electricity industry in man-made greenhouse gas emissions is low (it was estimated in 1999 as 0.1% [4]), there is concern over the long-term impact of SF_6 on global warming.

In understanding the role of greenhouse gasses to global warming, a brief description is as follows [5]: Energy from the sun heats the earth, which, in turn, radiates some of that energy back into space. Atmospheric greenhouse gases (water vapor, carbon dioxide, etc.) trap some of the outgoing energy and retain some of that heat. This is what is called the natural greenhouse effect and helps regulate the temperature of the earth. Problems may, however, arise when the atmospheric concentration of greenhouse gases (such as SF_6) increases. This increased trapped heat could have a destructive impact on future climate.

Restrictions on SF_6 usage could have a significant impact on substation owners. As electric utilities represent the largest user of SF_6, it is especially important that we are good stewards of this gas. Responsible use of SF_6 by the utility industry will go a long way to preventing or delaying restrictions on its future use. In light of this, substation owners need relevant information that can assist them in making both short-term and long-term decisions. Key questions for substation owners include:

- What is the total life-cycle environmental impact of SF_6 technology in my substation when compared against presently available alternatives ?
- Is there progress in finding a drop-in SF_6 replacement ?
- In the short-term, what technologies can assist in reducing SF_6 emissions ?
- In the long-term, are there emerging technologies that would eliminate or greatly reduce the need for SF_6 ?

These are the core issues this research program and this report will deal with – and are shown in Figure 1-1. In this research program, there are also a number of supporting, non-core, topics that this research needs to remain abreast of. These are also shown in Figure 1-1 outside the boundary of the core issues. For non-core issues, the technology will be tracked – and experts in that area used when and where necessary.

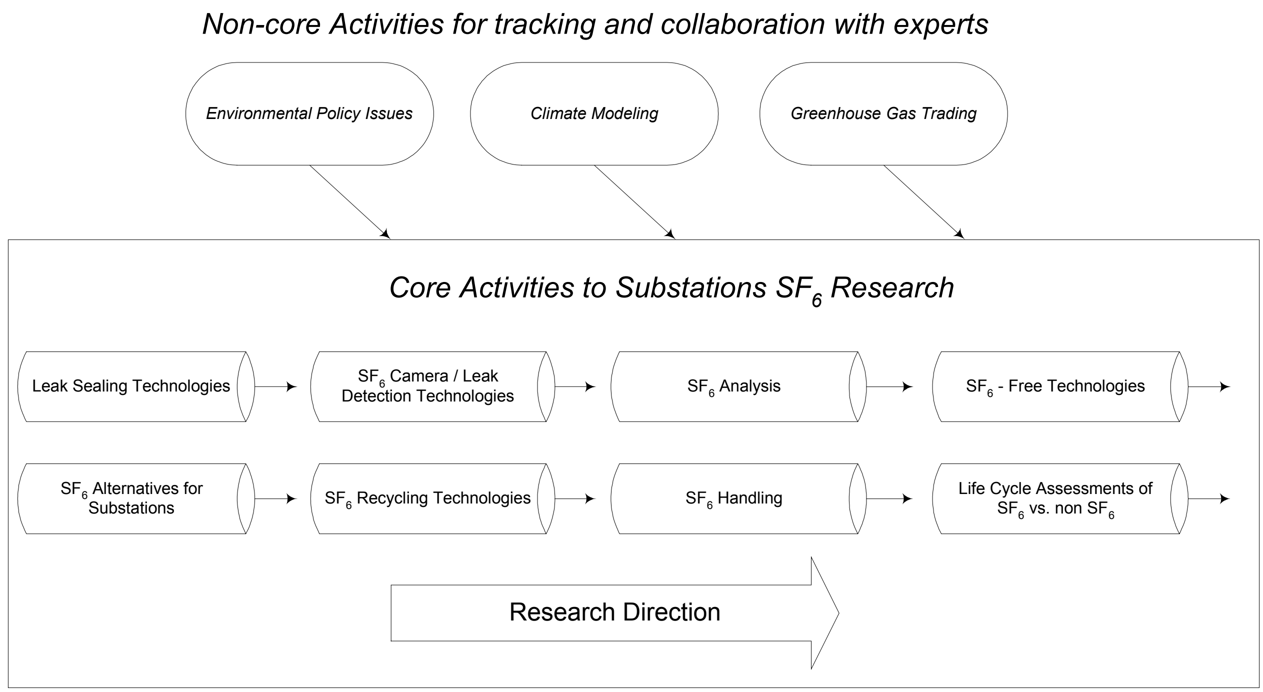

Figure 1-1. Core and non-core activities for the EPRI Substations SF_6 research program. The core issues will be dealt with directly. For non-core issues, the technology will be tracked – and experts in that area used when and where necessary.

The intended audience of this report is the owner or operator of electric utility substations that contain SF_6 Insulated equipment. This distinction is important since there are many other uses for SF_6 – and many of the research arguments or technologies would not be readily extended to other applications of SF_6.

2
ESTIMATING THE ENVIRONMENTAL IMPACT OF SF_6 TECHNOLOGY

The use of SF_6 in the Electricity Supply Industry provides certain benefits (reliability, economical power supply) – but does have an environmental impact due to the fact that it is a Greenhouse Gas. There are thus both environmental benefits and disadvantages to the application of SF_6 technology in a substation. For substation owners considering SF_6 and the environment, it is helpful to have an objective method of weighing up the benefits vs. the disadvantages. Such a tool exists in the form of the ISO 14040 standard [6] (Environmental Management – Life cycle Assessment) that defines a methodology for comparing the total life cycle environmental impact of two solutions to the same problem. Looking at the application of SF_6 in substations using this standardized approach provides a valuable all-inclusive perspective on the role SF_6 itself plays in the life-cycle environmental impact of a substation.

A revealing application of this Life Cycle Assessment tool is to compare the environmental impact of using SF_6 technology in substations vs. the environmental impact of using alternative, available technologies. To perform a Life Cycle Assessment of this scope, a sample portion of a utility grid would need to be considered as a case study – with and without SF_6 technology. Such a Life Cycle Assessment (LCA) study (using an actual urban power supply system in Germany) was conducted in 1999 [7] to quantify both the positive and negative environmental impact of SF_6 technology. Associates in the project were ABB, PreussenElektra, RWE Energie, Siemens and Solvay Fluor und Derivate.

The results from this study showed that the use of SF_6 technology actually lead to significant environmental advantages over the use of presently available SF_6-free alternatives.

While there are assumptions unique to the specific study, the results do, however point clearly to the fact that the application of modern SF_6 technology provides significant environmental advantages – and these need to be carefully weighed against the greenhouse effect of SF_6 before drawing hasty conclusions on the incompatibility of SF_6 and the environment.

Future Work

The Life Cycle Assessment above considered a typical German urban supply system. It would be a valuable exercise to repeat the study for typical applications of SF_6 technology in the USA.

The findings would be valuable technical input for utilities and would place the issue of SF_6 and the Environment in the context of available alternatives.

The Life Cycle Assessment study in the US context is proposed for 2004 research in EPRI. While the study will have to consider a specific supply system, the variables will be made as easy to adjust as possible - to allow different assumptions in other member utilities to be readily incorporated. There are commercial software tools to assist in this research (e.g. [8]) and these will be evaluated as a possible aid to the analysis – allowing the analysis to be easily adapted for different member scenarios.

3
PROGRESS IN FINDING AN SF_6 REPLACEMENT

In this section we review the results of a number of significant research efforts searching for a drop-in replacement for SF_6. To-date, no such replacement has been found. This is a continually evolving subject and EPRI's research in the area of SF_6 plans to remain abreast with developments - and relay key developments to the members.

Past efforts by EPRI

In 1982 EPRI concluded a two and a half year study on potential SF_6 Replacements [9]. Interestingly, the reasons for looking for a replacement at that time were not the concern of Global Warming – but the high cost of SF_6, its relatively high boiling point and its sensitivity to surface imperfections and particles.

The study examined the insulation and arc interruption characteristics of gases and gas mixtures considered as possible replacements. Both experimental and theoretical studies were conducted – using the following approach:

- A literature survey was conducted to choose gases of interest,
- Available gases were screened as direct substitutes for SF_6 or and as blends dopants,
- New gases were suggested based on theoretical developments
- New gases and mixtures were synthesized and tested
- An economic analysis of each gas or mixture was conducted.

No gas or mixture was found to be superior to pure SF_6 in all respects for either insulation or arc interruption. If a specific gas was superior in one aspect, it was often found to be inferior in another. A number of promising gas mixtures were identified for further investigation – but no gas or mixture was identified as a drop-in replacement for SF_6 for existing equipment designs.

European search for an SF_6 Replacement

Several industrial and academic partners (CESI, EDF, Schneider Electric, Solvay Fluor, Accelrys, Université Aix-Marseille III) are contributing to a project on the "Development of SF_6 alternative for electrical equipment". The goal is to use molecular modeling tools to investigate potential alternatives to SF_6. The project is scheduled to run from October 2000 to September 2003 [10]. The present funding mechanisms for the project limit what results can be shared publicly. EPRI will track further developments and report on what findings are made available.

Past efforts by NIST

In 1997 NIST (National Institute of Standards and Technology) concluded a large study on possible present and future alternatives to pure SF_6 [11]. An important contribution this work made was to list the required performance of an SF_6 substitute – plus the required testing for a potential new gas. This information serves as a valuable guide for future groups that identify possible new gasses – showing what that new gas needs to do – and how to go about proving it.

The NIST results – plus their review of the past 20 years of research – revealed no drop-in replacement to SF_6 for electric utility applications.

The report did identify a number of promising SF_6 gas mixtures. The maximum benefits from the use of these mixtures would, however, require new equipment designs or manufacturers would need to recertify existing equipment.

If an SF_6 mixture was found suitable, an additional issue to address will be the handling of SF_6 mixtures – which require special handling compared to pure SF_6. For further reading, CIGRE has recently published a guide for SF_6 Mixtures that deals with the issues in detail [12].

ABB Research on SF_6 Alternatives

A 1998 study by the ABB Research Center conducted a systematic search for potential SF_6 replacement gases [13]. The selection criteria for a replacement gas were comprehensive and took into account:

- **Functional Requirements –** Such as insulation strength and switching criteria

- **Environmental Effects –** Such as Ozone Depletion Potential and GWP (Global Warming Potential)
- **Safety Effects –** Such as toxicity and chemical stability
- **The Environmental Lifecycle Assessment –** which included the re-design of equipment to meet the same performance levels of SF_6.

The conclusion was that only air or nitrogen could be considered as SF_6 substitutes – but with only one third of the SF_6 performance. An Environmental Lifecycle Analysis [6] comparing a 300kV SF_6 insulated GIS with a hypothetic air insulated equivalent showed that the total environmental impact of the new equipment would be higher than that for SF_6.

Silicon Oil as a possible replacement for SF_6

A recent 2001 proposal from Japan [14] suggested the combination of Silicon Oil and vacuum breakers as a replacement technology for SF_6. They report that the breakdown strength of Silicon oil is similar to SF_6 at 5 bar. Silicon oil is synthesized from natural silica and is used widely in cosmetics and household goods. It thus offers advantages from a health and environment perspective. Decomposed gas is also harmless – being composed of CO_2, Water, CO and silica as an ash.

A new design of breaker would be required to use this concept (i.e. the Silicon Oil is not being suggested as a drop-in replacement for SF_6).

SF_6 Alternatives for Non-Switching Applications

For GIL (Gas Insulated Transmission Lines) mixtures of SF_6 and N_2 are commonly used – since arc interruption is not a factor and the dielectric strength of even a 10%-20% SF_6/N_2 mixture is close to that of pure SF_6. Conceivably the use of SF_6 mixture is possible for long GIS bus-runs – with pure SF_6 being retained in the switching compartments.

4

WHAT IS THE PROGRESS IN TECHNOLOGIES THAT COULD REDUCE THE NEED FOR SF_6 ?

Introduction

In the long-term (10-15 years), there may be technologies that reduce or eliminate the need for SF_6 in the transmission and distribution of electricity. In this section, we review a number of possibilities - and speculate on the potential impact on the need for SF_6.

Vacuum Circuit Breakers

For certain new medium voltage applications, vacuum circuit breakers can offer an alternative to SF_6 Circuit Breakers. For existing installations, replacing SF_6 circuit breakers with vacuum circuit breakers would require some re-engineering - since the vacuum technology usually has larger external dimensions [15]. The use of vacuum equipment to replace SF_6 circuit breakers is currently limited to 36kV [16] although manufacturers are working to extend that limit. The EPA lists the use of vacuum circuit breakers (where feasible) as one of the possible actions to reduce SF_6 emissions [17].

Solid State Circuit Breaker

EPRI is presently engaged in research on a Solid State Fault Current Limiter/Circuit Breaker [18]. The primary driver for the Solid State Fault Current Limiter/Circuit Breaker is to reduce the fault currents in substations where rising fault current levels would otherwise demand the replacement of existing substation equipment (e.g. Circuit Breakers, bus-work and grounding systems). If, however, in the long-term this technology did see widespread application, a secondary benefit would be a reduction in the use of SF_6 – since solid-state circuit breakers use power electronics and not SF_6 to insulate the breaker and interrupt the current.

Any benefits in the reduction in SF_6 from this technology would however be on the 5-10 yr horizon since the Solid State Fault Current Limiter/Circuit Breaker is only starting field trials at the Distribution voltage level in 2004. If successful, the technology is planned to be scaled up for Transmission voltage levels.

Electromagnetic Arc Spinning Research

The University of Liverpool, with support from EPSRC (Engineering and Physical Sciences Research Council - the UK Government's funding agency for research and training in engineering and the physical sciences), NGC (National Grid Company) and VAtech are investigating novel electric are quenching concepts [19]. The technique is presently under development – so not much information is publicly available – but the research is focused on electromagnetically spun arcs – with the goal of reducing the amount of SF_6 required for interruption. EPRI will continue to track any breaking news from that research effort.

Superconducting Substation Research

EPRI has long-term research plans to investigate the concept of a Superconducting Substation [20]. The primary benefits would be greater throughput per substation, a footprint about 1/3 of existing substations, on a KVA basis – and incorporation of additional features such as current limiting and energy storage. An additional feature of a superconducting substation would be the likely elimination of the need for SF_6 in that design of substation. The two reasons SF_6 is likely to not be needed are as follows:

1. The voltage levels in a Superconducting Substation are likely to be far lower that existing substations (since losses at high currents are negligible). The insulating properties of SF_6 are thus less likely to be required.
2. Fault and load interruption is envisioned to be performed by Superconducting Switchgear, eliminating the need for the arc interrupting properties of SF_6.

The research in this area is of a long-term nature – so any reductions in SF_6 usage due to this technology are only likely in 10-15 years.

The EPRI concept of an Energy Supergrid

The concept being proposed for the Energy Supergrid is to integrate the transmission of electricity and hydrogen in one 'energy pipeline' [21]. This energy pipeline is envisioned to be a Superconductivity DC cable (suggested to be MgB_2) with hydrogen acting as the coolant – and acting as an energy carrier.   In this way the same pipeline can deliver both low-loss electrical energy and hydrogen. The primary use for the hydrogen could be in powering fuel-cell vehicles.

Besides the numerous significant engineering benefits this Supergrid would offer, a spin-off of the adoption of this concept could be a reduction in the reliance on long-distance high voltage transmission (due to the fact that low loss transmission could be obtained at far lower voltages using superconductors). This, in turn, would potentially reduce the need for SF_6 for insulation and arc interruption purposes of the presently population of high voltage devices.

5
PRESENTLY AVAILABLE OPTIONS FOR REDUCING SF_6 EMISSIONS

There are numerous technologies and good practices that can assist utility staff in reducing SF_6 emissions in substations – and this chapter outlines the majority of the key options. As electric utilities represent the largest user of SF_6, it is especially important that we are good stewards of this dielectric. Responsible use of SF_6 by the utility industry will go a long way to preventing or delaying restrictions on its future use.

Since the audience for this report is utility staff, this chapter focuses on presently available options for reducing SF_6 emissions in the substation. (SF_6 manufacturers and equipment manufacturers also have a role to play in reducing SF_6 emissions – but their role is beyond the scope of this report – and is reported on in [4]).

Leak Location - SF_6 Camera Leak Detection

The SF_6 Camera technology allows the visualization of SF_6 leak sites using a unique video detection system. The main benefits over traditional SF_6 leak detection (halogen detectors and soapy water) are twofold: Firstly the ability to perform leak detection without having to take equipment out of service and secondly the dramatic reduction in time necessary to detect and locate a leak site. The technology exploits the strong IR (Infra-red) absorption of SF_6 gas to make it visible to the camera operator. A laser illuminates the leak area in a raster fashion at a wavelength that coincides with strong spectral absorption of SF_6. An internal IR sensor focused on this same laser-illuminated area enables the re-construction of a real-time video image. Areas of the image where SF_6 is present strongly absorb the reflected IR – and this allows SF_6 leaks to be visualized in real-time as a plume of black gas. Because of the strength of the optical absorption by SF_6, the laser camera is sensitive to SF_6 leaks as small as 2lbs/yr, viewed at distances as far as 100ft [22]. The principle of operation of the camera technology (BAGI – Backscatter Absorption Gas Imaging) is shown in Figure 5-1. The SF_6 Camera Technology was developed by LIS (Laser Imaging Systems) in is marketed under the trade name of GasVue. EPRI conducted numerous field trials on the device [23] during its development – and helped guide the refinement of future versions. To-date, over two-dozen different utilities and contractors own GasVue cameras.

Recently there has been some interest in a new SF_6 leak detection camera technology that could possibly produce a lighter and perhaps cheaper offering. The details are still not public, but

EPRI is in contact with the developers and in 2004 plans to evaluate the best role to play as this technology emerges.

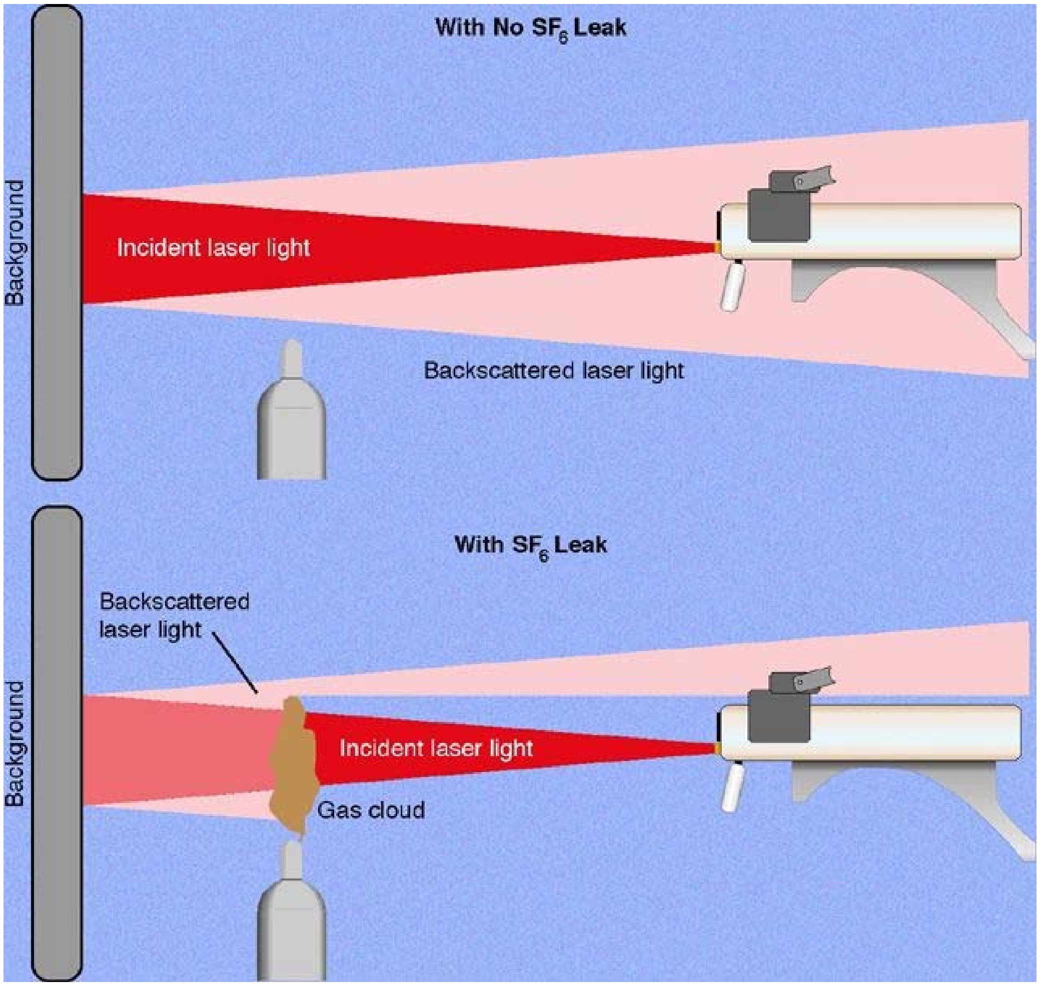

Figure 5-1. Principle of operation of the SF_6 Camera. Shown with and without the presence of leaking SF_6 [24].

Improved SF_6 Handling

A significant amount of SF_6 can be released to the atmosphere during SF_6 handling. Estimates for 1999 by CIGRE [13] estimate handling losses at approximately twice that of equipment leakage. Improved SF_6 Handling thus provides a short-term opportunity for significantly reducing SF_6 emissions. EPRI responded to that need and, in 1999, produced the first version of the EPRI Practical Guide to SF_6 Handling Practices [25]. This guide has been revised to keep pace with changes in technology. The latest revision is dated 2002 [26] and a further revision is planned for 2004. The EPRI Practical Guide to SF_6 Handling Practices covers the key issues facing field staff dealing with SF_6 – including:

- Classifications for switching and non-switching equipment types along with indoor and outdoor applications
- Risks, warning signs, and written instructions for various low-, intermediate-, and high-risk situations as well as abnormal operating conditions
- Handling procedures for equipment commissioning, maintenance, and failure situations, with information on the use of gas carts for temporary SF_6 storage during maintenance tasks
- Personal protective equipment, with emphasis on clothing and respiratory devices
- Disposal and environmental protection practices for clean and contaminated SF_6 gas as well as solid decomposition products under normal and abnormal conditions
- Cylinder transportation, handling, and storage, focusing on U.S. Department of Transportation Regulations
- Latest and emerging techniques dealing with utility related SF_6 handling issues

A further valuable EPRI research effort that assists in SF_6 Handling is the EPRI Guidelines for Life Extension of Substations. The latest version of these extensive Guidelines [27] has been updated to include an Appendix on SF_6 Management.

SF_6 Handling guidelines have also been produced by bodies besides EPRI. A catalog of these guidelines is compiled by the EPA (Environmental Protection Agency) [28].

Recycle and Re-use SF_6

Today the technology is commercially available from numerous gas cart manufacturers to readily remove moisture, solids, oil and acidic by-products from SF_6 on-site. The following sub-sections discuss research on the removal of air and nitrogen – and on SF_6 Analysis to confirm that recycled gas is fit for re-use:

Removal of air or Nitrogen from SF_6 as an aid to SF_6 Recycling and Re-use

Users of SF_6 are occasionally faced with the problem of handling SF_6 that has been mixed with air or Nitrogen or CF_4. In the case of Nitrogen or CF_4, the mixture was likely intentionally performed to prevent liquefaction of the SF_6 in colder climates. In the case of air, the mixture was likely unintentional and due to handling errors or gas handling equipment leaks. The handling of these mixtures needs to be performed in isolation from the handling of the pure SF_6. Utilities are often not equipped to deal with two different categories of gas (Pure SF_6 and mixtures) – and the inclination may be to vent of the mixture rather than deal with the complications and risks.

There are large commercial units capable of separating air from SF_6 [29] [30]. The current option many utilities take is to ship the contaminated SF_6 to a central recycling depot. The associated handling and shipping costs are a major deterrent to this option. EPRI Is presently researching techniques to allow for low-cost recovery of SF_6 from air and N_2 on site – preferable as a retrofit to an existing gas cart - and thus help in minimizing environmental impact due to SF_6 losses [31].

Traditionally, SF_6 purification was carried out using cryogenic means. Some purification is possible in the field using gas carts if the SF_6 is always drawn from the liquid phase. However, the vast majority of the air will remain in the vapor phase and as the air content increases as the cart is used, higher pressures will be required to liquefy the SF_6. If the air content is high enough, the compressor will be unable to liquefy the SF_6 and the contents will require disposal. Retrofitting a purification unit to the gas cart will remove this air contamination in situ and allow not only withdrawal of clean gas from the vapor phase, but could eliminate having to remove contaminated gas for further processing.

The two types of technologies investigated were membrane separation and adsorption processes. The first technology researched was membrane separation - involving separation modules containing bundles of hollow fibers. Flowing contaminated gas through the hollow fibers allow the air to pass through the walls of the fiber but not the SF_6. Depending on the hollow fiber, the process works by either passing the gas through the fibers or flowing around the outside of the fibers and letting the air to permeate inside. The mechanism is one of size exclusion, the SF_6 molecule being much larger than the oxygen or nitrogen (air) molecules, will be retained. A schematic of the process appears in Figure 5-2. This schematic shows the air contamination with SF_6 flowing into the hollow fiber.

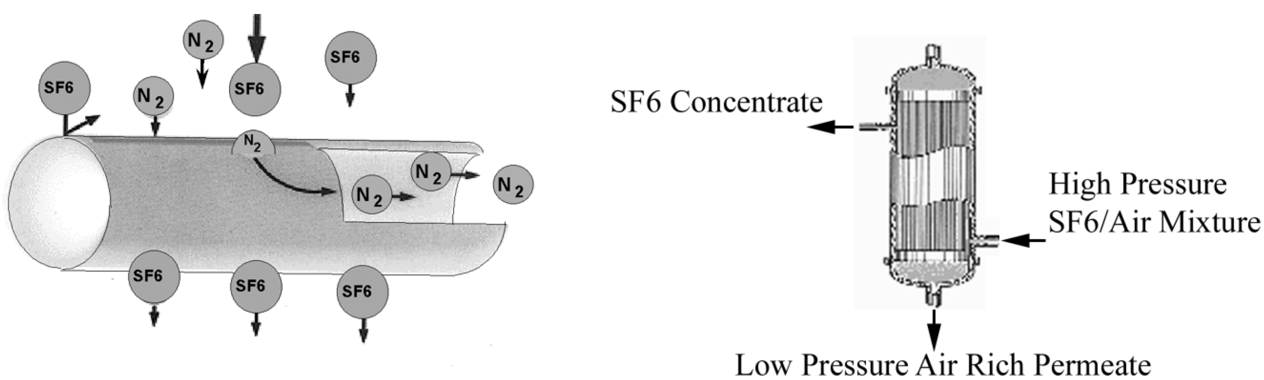

Figure 5-2 Semi-permeable membrane separation [31]

The second technology researched was Pressure Swing Adsorption (PSA). Separation of air from SF_6 using adsorption processes such as PSA requires the use of modules packed with a specific adsorbent. The process is similar to the desiccant towers used traditionally for drying and removal of decomposition products from SF_6. The main difference is that the impurities in the desiccant towers (moisture, decomposition products) are permanently retained and the SF_6 just passes through. In a purification process utilizing PSA, the contaminants (oxygen, nitrogen) are retained more strongly, but not permanently, than the SF_6. This is due to differing molecular interactions between the adsorbent and the gases. The process begins by flowing of a fixed volume of a contaminated mixture (air and SF_6) through a module packed with the appropriate adsorbent. The SF_6 passes quickly through separating from the air and before the air has the time to come through the adsorbent, the flow is reversed and the air is collected in another vessel. Thus pressure swing. Other types of adsorbents allow the air to pass through quickly and the SF_6 to be retained. Ideally, the component in highest concentration is not retained, and the impurities are. Therefore, depending on the degree of air contamination (less than 20% compared to greater than 80%), the choice of absorbent is critical. A schematic of simple PSA apparatus appears in Figure 5-4. The actual apparatus appears in Figure 5-5. The timing of the solenoid valves is critical to the process. Retrofitting this to a gas cart will be made easier by utilizing vacuum pumps and compressors on the cart. Future EPRI research in 2004 will focus on implementation of the optimal technology in a gas cart – for field trials.

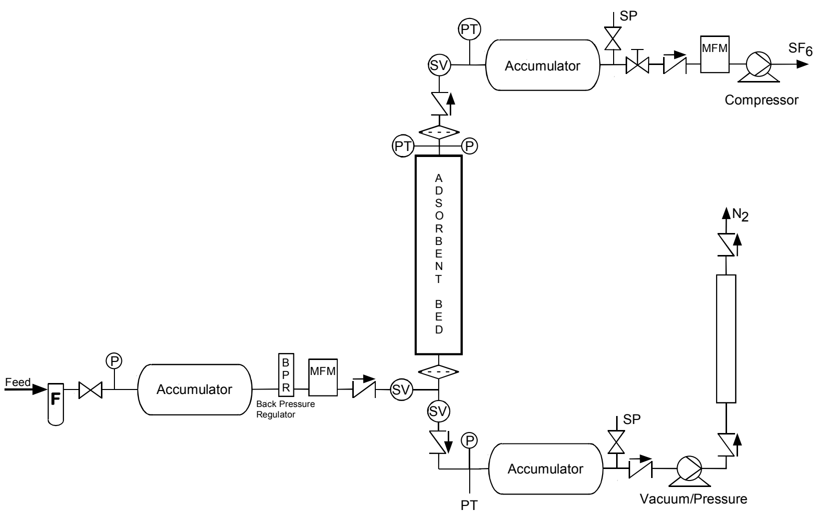

Figure 5-3. Schematic of a Simple Pressure Swing Adsorption (PSA) Apparatus.
Key: sv – solenoid valve, PT – pressure transducer, P – pressure gauge, MFM – mass flow meter, BPR – back pressure regulator

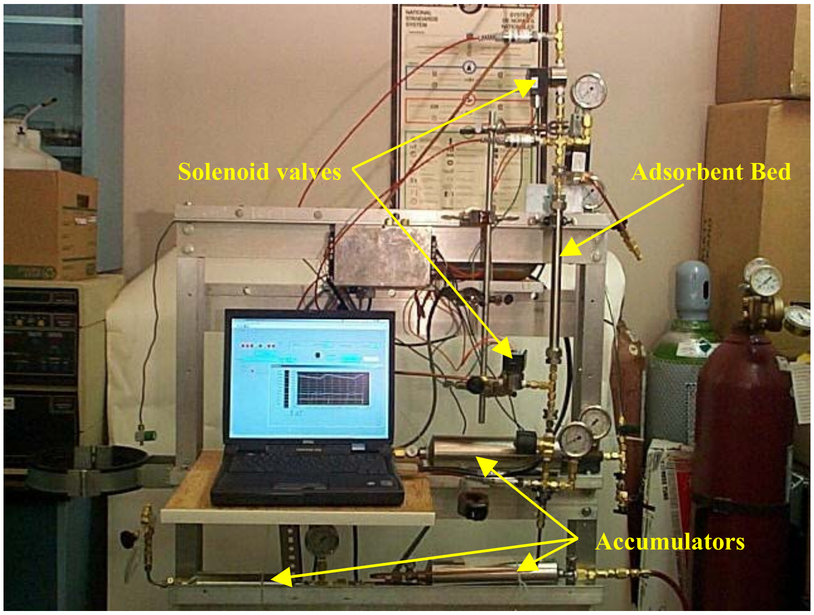

Figure 5-4. Pressure Swing Adsorption Laboratory Setup (Powertech Laboratories under an EPRI research contract).

Only a few new technologies/concepts regarding SF_6 separation from air or nitrogen have emerged in the past five years. Just six patents were found and a few publications. Basically, all the works dealt with applying membrane separation, or adsorption processes, or in some cases a combination of both. Even though SF_6 purification or separation was the main objective of these works, some methods were applicable for very low (less than 1%) or low (10-20%) SF_6 concentrations (for removing SF_6 from vented emissions) while only a few were applicable for concentration of SF_6 in the feed stream higher than 60%. With the exception of one work, which is at the prototype stage, all adsorption processes were energy intensive (the purified SF_6 gas was at low pressure). That is, the gas was treated at a lower pressure than the source and required recompressing. This requires more energy than if the purification were possible at the feed pressure. The same was true for membrane separation. These separation processes wasted the pressure of the SF_6 feed gas mixture during the separation process. The exceptions were a membrane process involving a molecular sieve separation principle and an adsorption process involving an adsorbent that had smaller pore openings than the kinetic diameter of SF_6 gas. Therefore, the product SF_6 gas stayed at approximately the same pressure as the feed gas, hence conserving the initial feed energy. These two approaches were the focus of the EPRI research, since they are the most energy productive. Furthermore, they were the most promising from the SF_6 recovery and separation process efficacy point of view. The adsorption process was very similar to one that will best be suited for electrical utility applications. However, based on the prototype size, the process proposed will be smaller and lighter and more efficient.

Based on this literature search and evaluation, ten different adsorbents were examined and tested for the suitability of SF_6/air (nitrogen) separation. The results can be seen in Table 5-1. The separation factors are the ratio of the retention times of each impurity (N_2, O_2, CF_4) to that of SF_6 when a mixture of these gases is introduced into a packed column of the particular absorbent that has an inert gas flowing through it. These experiments are basically gas chromatography and are useful in determining suitable absorbents to be further tested in the PSA apparatus. Therefore, the higher the factor, the greater the difference in retention time and the better the two can be separated using a given adsorbent with PSA. Only one adsorbent (number 4) turned out to be suitable for the separation of SF_6 from air or nitrogen in a gas mix containing higher amounts of SF_6. Five other adsorbents appeared very promising for recovering SF_6 from the air/nitrogen gas mixtures containing a low concentration of SF_6 (numbers 1,2,5,9 and 10). For adsorbent 3, the numbers in parentheses are the ratios of N_2/SF_6 and O_2/SF_6 (the inverses) indicating this adsorbent retained the SF_6 more strongly than the air. Absorbents 6, 7 and 8 retained the SF_6 far too strongly for the PSA process but show promise for release abatement. Using these adsorbents allows for the collection of SF_6 usually vented during sampling and venting of lines onto a cartridge for subsequent removal later.

Table 5-1 SF_6 Separation Factors of Different Adsorbents

Adsorbent	Separation Factors at Room Temperature		
	SF_6/N_2	SF_6/O_2	SF_6/CF_4
1	1.86	4.14	9.05
2	1.47	3.68	8.13
3	0.114 (8.77)	0.314 (3.19)	_
4	21.74	21.74	7.06
5	2.38	2.38	2.24
6	>>25	>>25	-
7	>>25	>>25	-
8	>>25	>>25	-
9	4.55	4.55	3.00
10	2.68	5.73	10.17

A simple PSA process was designed for the preliminary testing of potential adsorbents and for the determination of their suitability for PSA separation and for gathering enough information for the design of an efficient PSA cycle for SF_6 separation. Initial findings indicated a high degree of purification (>99%) from mixtures of gas containing up to 25%v air. More work is planned for 2004 to determine the losses and the final design may be a combination of PSA and semi-permeable membranes.

SF_6 Analysis as an aid to SF_6 recycling and re-use

Accurate on-site SF_6 analysis is important in knowing whether used SF_6 (stored in cylinders or handled and filtered by gas carts) is fit for re-use. The criteria used for this decision are based on the manufacturers requirements and/or CIGRE Guidelines [32] or standards. At this point in time, the CIGRE guidelines on the quality of recycled gas are being included into the latest revision of IEC60480 [33].

Previously a comprehensive such analysis of SF_6 against the CIGRE guidelines required samples to be sent to a laboratory for analysis. The advantages to analyzing the gas directly from in-service equipment includes the elimination of sampling errors, reducing the depletion of reactive decomposition products during storage and shipping, rapid analysis and immediate results which results in a quicker response to detected problems. Another advantage is the amount of gas required.

EPRI research developed two devices for on-site SF_6 analysis – a tailored portable Gas Chromatograph (GC) and, together with Powertech Labs, a Decomposition By-products Detector (DPD). Both require only a few grams of gas. In contrast, if sampling with 150 cc cylinders for laboratory analysis, one requires approximately 20 grams of gas for purging and sampling. Furthermore, conventional hygrometers can require 150 grams of gas and often approximately half an hour for an accurate reading.

Each of the two EPRI developments is described below:

Customized Portable Gas Chromatograph

Traditionally, gas chromatography suitable for complete SF_6 analysis was only possible in the laboratory. Recently, strides in the development of gas chromatography have produced devices that can be easily transported to the field. The gas chromatograph shown in Figure 5-5 has been demonstrated by previous EPRI research [34] to measure contaminants, decomposition products and moisture in SF_6 in the field at the levels recommended by CIGRE [32] for in-service equipment.

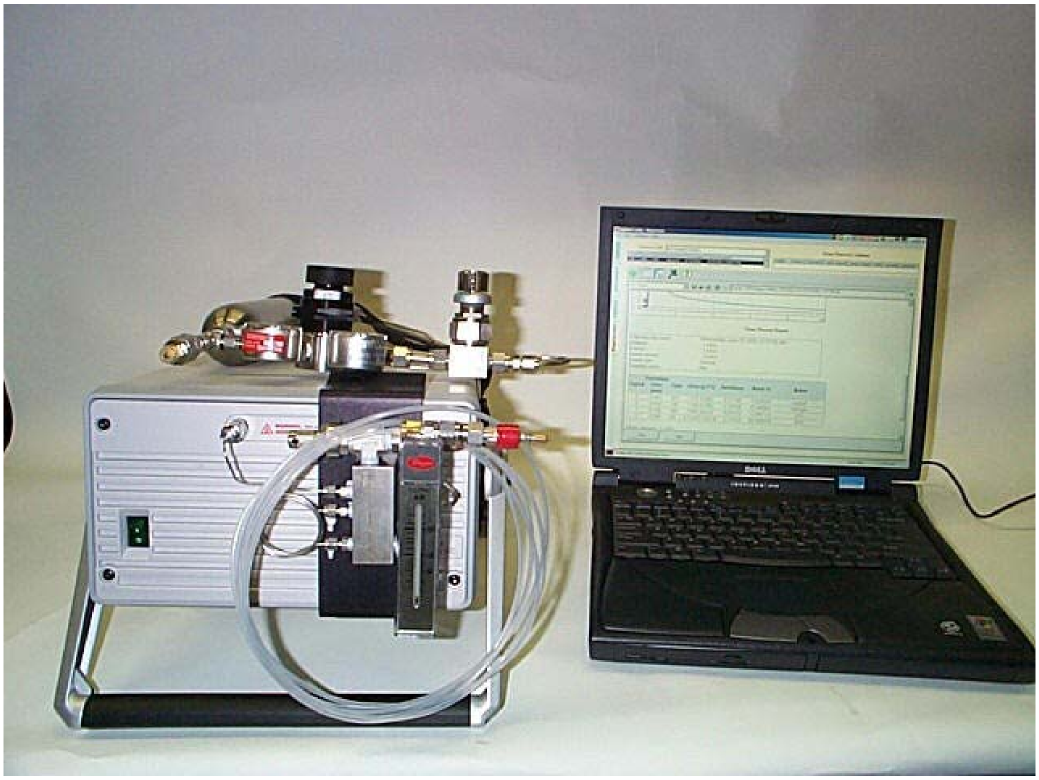

Figure 5-5
Customized Portable Gas Chromatograph [36]

In a previously EPRI sponsored research ([34] and [35]) existing and emerging technologies suited for comprehensive field assessment were evaluated. The results indicated that a customized portable gas chromatograph was capable of analyzing in-service SF_6 to CIGRE criteria with a single analysis (rather than using a collection of individual devices on site). Briefly, the portable unit consists of a customized portable gas chromatograph [36], equipped with a built in sampling pump, and an in line frit. Based on Powertech Labs Inc. established procedure for SF_6 analysis (Powertech was an EPRI contractor for this portion of research), similar chromatographic columns were chosen, a method and procedure was then developed. Extensive lab testing was conducted with all contaminants to ensure sensitivity and linearity of response over a large concentration range. Collaboration with the manufacturer is continuing to improve the performance even further - and to insure availability of components, particularly the specific chromatographic columns.

This customized portable gas chromatograph can easily measure the impurities oxygen, (O_2), nitrogen (N_2) and carbon tetrafluoride (CF_4) with detection limits of less than fifty parts per million by volume (ppmv). It can also determine the concentrations of the common gaseous decomposition products thionyl fluoride (SOF_2), sulphur dioxide (SO_2), carbonyl sulfide (COS) and sulfuryl fluoride (SO_2F_2) to a level of 10 ppmv each and 50 ppmv for SO_2 (the relatively high 50ppmv detection limit of SO_2 is due to its greater adsorption on sampling lines). It is also capable of detecting moisture to 20 ppmv (at 100 kPa) which is well within the CIGRE criteria of 4000 ppmv (at 100 kPa) for in-service equipment. The entire analysis can be done in about five minutes. The GC software prints or displays a simple report giving the results in ppmv or %v of each component detected.

The detection and control of moisture is a major component of effective maintenance practices for SF_6 gas insulated electrical equipment. The moisture level needs to be maintained sufficiently low that no condensation occurs over the entire operating range of temperatures. Also, the presence of moisture enables the formation of decomposition products when SF_6 breaks down due to arcing, partial discharge or over heating. Traditional moisture measurements are carried out with hygrometers, which require large volumes of gas, and careful sampling procedures using well-conditioned sampling lines in order to get accurate results. The GC is able to detect moisture as part of its analysis – so no extra gas sampling is required. The lower detection limit is estimated from field trials to be about 20 ppmv.

SF_6 Decomposition Products Detector

The second SF_6 Analysis device developed under EPRI research is the EPRI/Powertech Labs Inc. Decomposition Products Detector (DPD). The major application of the DPD is to provide a quick and accurate measurement of SF_6 decomposition products in field situations. It is far cheaper (a tenth) than a portable GC – but since it only measures the total level of dominant by-products, it's role is primarily a screening tool – to determine where the problem sites are for further GC analysis.

It is advantageous to test the gas at the source due to the unstable nature of low levels of decomposition products and to detect faults quickly without having to wait for lab analysis. Therefore, the instrument was designed to be portable, rugged and easy to operate. The detector is able to handle sampling from energized equipment at system pressure. Personnel safety can also be rapidly assessed before maintenance begins so that appropriate procedures and precautions can be implemented. The DPD can detect the most predominant SF_6 decomposition product, thionyl fluoride (SOF_2) and SO_2 to a concentration of one ppmv. It has a limited response to carbonyl sulfide (COS) and does not respond to sulfuryl fluoride (SO_2F_2). A photograph of a DPD can be seen in Figure 5-6.

Figure 5-6
SF_6 Decomposition Products Detector (DPD)

The DPD consists of a flow controller, flow meter, a catalytic reaction tube, and LCD readout of concentration. The sample gas is metered into the DPD at a controlled flow rate and the response time is less than one minute.

(The DPD is now commercially available and comes with a one year limited warranty. The purchase also consists of a three year performance verification program calibration, which includes two annual calibrations. Any improvements to the detector will also be incorporated during this three year period.)

The detection limits of both the GC and the DPD for various contaminants are compared against the purity limits for new gas and recycled gas in Table 5-2.

Table 5-2
Purity Criteria and Detection Limits

Contaminant	Purity Criteria			Detection Limits	
	IEC 376*[2] new gas	CIGRE[3] recycled gas	CIGRE[3] in-service gas	GC	DPD
Air	2517 ppmv	2%v	3%v	< 50 ppmv	not detected
CF_4	830 ppmv	incl. with air	incl. with air	< 50 ppmv	not detected
H_2O	120 ppmv	1600 ppmv at 100 kPa	4000 ppmv at 100 kPa	20 ppmv	not detected
SOF_2, SO_2, SOF_4, SF_4, WF_6	7.3 ppmv as HF	50 ppmv total or 12 ppmv SOF_2 + SO_2	100 ppmv	10 ppmv for SOF_2, COS; 50 ppmv for SO_2	1 ppmv for SOF_2 and SO_2
SO_2F_2			2000 ppmv	not determined	100 ppmv

* converted from parts per million by mass

From Table 5-2 it can be seen that, together, both SF_6 Analyzers can prove the quality of both new and recycled gas. Application of these analyzers on site will allow for confident re-use of SF_6 and quality checks on new gas.

Capturing SF_6 previously lost during on-site analysis

When SF_6 analysis is performed, the SF_6 that has been analyzed is usually vented to atmosphere. If there are long filling lines between the equipment under test and the analyzer, a significant amount of gas may need to be bled from those sampling lines before a representative sample can be obtained. EPRI thus conducted research [31] on techniques to capture this vented SF_6 gas. Various procedures were considered. These included Tedlar bags, plumbing the exhausted gas back into gas carts or other recovery systems and adsorbents. All these procedures will inevitably result in some air contamination of the recovered gas. The use of adsorbents was the least intrusive to existing handling equipment. Clean cartridges of adsorbents supplied to field personnel could be returned to a central facility for desorption and processing with contaminated gas. (The desorption process involves heating the modules slightly and collecting the gas by vacuum). The adsorbent ultimate uptake capacity for SF_6 gas at room temperature was determined for 5 commercially available adsorbents. Four of them have an adsorption capacity for SF_6 gas higher than 22.5% w/w. The highest SF_6 uptake was of 40% w/w. All of the tested adsorbents were able to completely and quickly desorbs SF_6 gas at temperatures lower than 200°C. This indicates that one of these adsorbents with appropriate cartridge design will be an adequate solution to the abatement of SF_6 during the sampling process. An example of a potential cartridge design is shown in Figure 5-7. Before making the final decision on the design, additional tests regarding the heat of adsorption are planned for EPRI research in 2004.

Figure 5-7 An example of a possible adsorbents cartridge design for capturing lost SF_6 during the sampling process

Dispose of SF_6 in an Environmentally sound manner

Situations can arise where it is not possible for a utility to recycle the gas in-house – either due to very high levels of by-products or air contamination. In these instances it is recommended that this unrecoverable SF_6 is not released to atmosphere – but sent to an appropriate company for recycling or disposal. There are a number of companies that offer such a service and the best approach is to contact the supplier of the SF_6 to locate the facilities closest to you.

In-situ temporary SF_6 Leak Sealing

In it often not possible to take leaking SF_6 equipment out of service and dismantle it to affect a permanent leak repair. In these situations, a temporary SF_6 seal could help reduce the emissions of SF_6 to atmosphere until a permanent repair can be scheduled.

In 2001, EPRI conducted research on the Management of SF_6 leakage by Electric Utility Companies – and published a guideline on the reduction of emissions [37]. The report covers the following key topics that will assist members in SF_6 leak sealing efforts:

- Extent of SF_6 usage and leakage rates
- Methods for the identification of leaking compartments
- Methods for the quantification of individual leaks
- Methods for the accurate location of leaks
- The common locations and causes of leaks
- Methods for elimination of leaks

Presently (2003-2004) EPRI is conducting further research on the topic of SF_6 leak sealing under a Tailored Collaboration Opportunity. The research is directed at leak sealing in the field that meets the following requirements:

- The temporary seal should last for 5 years – allowing for a more permanent repair during an overhaul or maintenance event
- The sealing material should be easy to remove without damage to the equipment
- There should be minimal surface preparation required – to minimize the time the equipment needs to be de-energized.
- The seal should be able to be applied with a slight over-pressure of SF_6 (to avoid the ingress of air and moisture).

These requirements above could also serve as helpful guidelines for utilities contracting leak sealing services. The Tailored Collaboration research continues through 2004 and interested utilities are welcome to join the research opportunity. (If interested, the best approach would be to contact the author directly. Contact details are in the report front-matter).

New designs of SF_6 Insulated Equipment

Improvements from OEM efforts to reduce SF_6 emissions in new equipment designs include:

- Fewer Seals due to simplified designs with fewer components.
- Better seal designs for both static and dynamic seals.
- Improved gasket seal materials [38].

- Options for real-time monitoring and analysis of SF_6 gas density in equipment – to provide as early a warning as possible of the start of a leak.

- More compact designs that therefore use less SF_6. A example is a study performed in Japan [29] on the SF_6 required for a typical 66/77kV class of GIS. Over the years the of design improvements, the latest design used only 40% of the SF_6 of the original design.

- Combined functions that completely eliminate entire SF_6 compartments (e.g. new 3-way switch designs that combines the function of isolation and grounding in one unit).

Table 5-3
Summary of Actions to Reduce SF_6 Emissions

Actions available to utilities	Technologies to assist the actions
Improved SF_6 leak location	The GasVue SF_6 Camera Technology [23] can reduce the time necessary to accurately locate SF_6 leaks – particularly for leaks on live components that would have required an outage to inspect.
Improved handling of SF_6	EPRI SF_6 Handling Guide [26] provides a good foundation from which to build in-house utility procedures.
Increased recycling of SF_6	• EPRI and commercial research into on-site separation of SF_6 from air and nitrogen [29, 31]. • Increased recycling of SF_6 on site requires accurate SF_6 Analysis to ensure the gas meets the quality requirements for re-used gas. EPRI has developed two devices to perform this analysis – and the latest results on this work can be found in the 2003 EPRI Report "Improving the Diagnostic Capability of SF_6 Gas Analysis" [39]
Correct disposal of SF_6	Numerous companies offer to take back and process SF_6 that cannot be recycled in-house by a utility.
On-site SF_6 leak sealing	• EPRI research "Management of SF_6 leakage by Electric Utility Companies" [37] • Under a Tailored Collaboration, EPRI is presently conducting research on in-service SF_6 leak sealing. • A range of service companies offer to conduct such leak repairs.
Replacement of old, leaking equipment with new equipment	The decision to update SF_6 equipment is often not made based on SF_6 leak rates – but a secondary benefit is that new equipment designs have very low leak rates.

6
THE EPA EMISSIONS REDUCTION PARTNERSHIP FOR ELECTRIC POWER SYSTEMS

The EPA's SF_6 Emissions Reduction Partnership for Electric Power Systems [40] is part of a set of EPA voluntary programs working in various industries (aluminum, semiconductors and magnesium castings) to reduce potent greenhouse gases.

The Partnership was launched in 1999. The goal is to pursue technically and economically feasible actions to minimize SF_6 emissions.

Partners sign a Memorandum of Understanding (MOU) and agree, where possible, to estimate a baseline between 1190 and 1998, track annual emissions, establish a strategy for replacing leaky equipment, improve SF_6 recycling, restrict SF_6 handling to knowledgeable staff and submit annual progress reports.

To assist utilities in estimating emissions, the EPA provides an Excel SF_6 report form to capture the changes in inventory, purchases, sales and changes in nameplate capacity. From this input data, the report calculates the annual emission rate [40].

Under the Partnership, the EPA shares technical information and successful strategies, recognizes partners achievements and provides a credible repository of emissions reductions. Presently the partners represent 45% of the US generating capacity [17], with over 60 utilities having joined. The partnership estimates an emissions reduction of 206,000 lbs of SF_6.

Under the partnership, the EPA highlights a number of actions that help reduce SF_6 emissions [17], including Leak detection & Repair, proper use of recycling equipment, training, equipment replacement and the use of vacuum circuit breakers where feasible.

7
CASE STUDIES

A number of utilities have published and presented techniques that have worked in their organizations for reducing SF_6 emissions. In this section we present a number of these as case studies:

In 2001, Entergy became the first US Electric Power Company to establish a stabilization target for its CO2 emissions [41]. One of Entergy's Internal Projects to reduce Greenhouse Gases is the replacement of older leaking SF_6 Insulated Equipment.

Con Edison has established and practices best management practices for SF_6 – including [42]:

- Establishment of SF_6 reclamation centers and use of "gas cart" recycling units that enable the company to recover, purify, and reuse SF_6
- Periodic internal inspection of SF_6 with an SF_6 Camera.
- A policy that SF_6 is added to equipment only when a low gas alarm is received
- Monitoring and tracking of low gas alarms to prioritize work requests (i.e., sealing leaks or replacing equipment)
- Implementing SF_6 weighing procedures to determine the quantity of gas used and that which is returned to the supplier.

Since the use of the SF_6 camera - and subsequent repairs, SF_6 usage is estimated to be reduced by approximately 500 cylinders or 57,500 pounds per year [43].

PG&E (Pacific Gas and Electric) recently awarded their SF_6 Management team with an award (the Clarke Award) for their leadership role in managing PG&E's use of SF_6 [44]. Over a four year period, PG&E reduced their leak rate from 12% per year down to 4% per year. From a 1998 baseline, they achieved a 56% reduction in SF_6 emissions – which bettered their target reduction of 50%. Part of PG&E's strategy is the use of the SF_6 camera for accurate leak location.

BPA (Bonneville Power Administration) reported significant reductions in 2001 SF_6 gas loss [43]. The techniques used by BPA were to replace older SF_6 equipment with newer technology, improve maintenance practices for SF_6 handling, locate leaks with the SF_6 camera and increase awareness of environmental concerns.

Oncor Transmission reported on their successful SF_6 emission reduction efforts [43]. Their main activities were overhauls or replacements of high leak-rate breakers (old two-pressure breakers and some single-pressure puffer breakers), employee education, leak location using the SF_6 camera (especially before an overhaul) and strict inventory standards.

BC Hydro's efforts to reduce SF_6 emissions [43] included staff training and the implementation of an SF_6 tracking system. The tracking system identified the small group of equipment that was responsible for over 80% of the 2001 losses – allowing for focused repair efforts on this equipment.

8
CONCLUSIONS AND FUTURE RESEARCH

In EPRI's original long-term planning, this report was planned to begin in 2004. In response to comments from the EPRI advisors on the urgency of the topic, the research was initiated in 2003 using some reserves in the project. The accelerated research plan allowed this present report to be written in 2003 – in which we could cover many of the main points of the research. The accelerated schedule and reduced budget didn't, however, allow for a full investigation of all the necessary topics. The research focus on SF_6 and the Environment is planned for continuation into 2004 – and it is proposed that this future research increases the breadth and depth of this present work.

Specifically, it is proposed that the 2004 research focused on the following topics relating to SF_6 and the Environment:

- ***Influencing the development of new SF_6 camera technologies:*** There are some promising developments that could lead towards a smaller and cheaper leak detection camera. The timeline given by the developers for the prototype development of a new generation of SF_6 camera is mid 2004. Tracking of this technology and influencing its development to accurately meet the needs of the utility industry is important - since SF_6 leaks have repeatedly been cited by members as the top issue related to the use of the gas.

- ***Providing tools for the evaluation of the environmental impact of SF_6 vs. non-SF_6 technologies for local (US) conditions:*** The ISO 14040 standard on Environmental Management – Life Cycle Assessment provides a valuable tool for objectively comparing the overall environmental impact of one technology over another. A small number of studies have been conducted in Europe that show the overall environmental benefit of SF_6 technology (despite its effectiveness as a Greenhouse gas and its long life). The results of these studies are not immediately translatable into the US context. Due to the great value these studies can provide, it is proposed that a number of US-specific studies be conducted in 2004. The scenarios selected will focus on the specific issues facing the 2004 project funders.

- ***Advising members on SF_6 replacements and replacement technologies.*** This report presents numerous research activities that could lead to significant developments in reducing the need for SF_6. In 2004 these efforts will be closely tracked and previously undiscovered efforts sought out.

9
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