SF_6 Leak Rates from High Voltage Circuit Breakers - U.S. EPA Investigates Potential Greenhouse Gas Emissions Source

J. Blackman, *Program Manager, U.S. Environmental Protection Agency,*
M. Averyt, *ICF Consulting,* and Z. Taylor, *ICF Consulting*

***Abstract*—This paper highlights a recent collaborative study between the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems and the electric power industry to investigate SF_6 leak rates from high voltage circuit breakers manufactured and installed between 1998 and 2002. Information from over 2,300 circuit breakers were analyzed to quantify the frequency of leaks and to estimate the weighted average annual leak rate for this population of circuit breakers. The methodology, data, and results of this study are presented.**

***Index Terms*-- SF_6, annual leak rate, greenhouse gas emissions, circuit breaker.**

I. Introduction

SULFUR hexafluoride (SF_6) is a gaseous dielectric used in high voltage electrical equipment as an insulator and/or arc quenching medium. SF_6 is the most potent greenhouse gas with a global warming potential that is 23,900 times greater than that of carbon dioxide (CO_2); it is also very persistent in the atmosphere with a lifetime of 3,200 years [1]. Potential sources of SF_6 emissions occur from: 1) losses through poor gas handling practices during equipment installation, maintenance and decommissioning; and 2) leakage from SF_6-containing equipment. The operation and maintenance of SF_6 gas carts, which are used to remove, store, clean, and re-fill SF_6 gas to high-voltage equipment, are considered a major source of handling-related losses. Equipment leakage, on the other hand, is the result of the deterioration of SF_6-containing equipment fittings and materials with time and use through chemical, hardening, and corrosion effects.

Equipment leakage is one of the two potential sources of SF_6 emissions. Leak detection surveys have noted that approximately 10 percent of circuit breaker populations may leak [2, 3], and of these leaking populations, 15 percent of the breaker leaks were minor, with repairs that could be conducted immediately, while the remaining 85 percent were considered significant and had to be referred to operations for scheduled repairs [3]. In terms of where these leaks typically occur, studies have noted that the majority occurs at gas mechanisms (73 percent), 21 percent from worn or broken bushings, and 6 percent from gas tanks [4]. Typically, such losses can only be mitigated through equipment repair or replacement. As electrical equipment ages and reaches the end of its operational service life, replacement rather than equipment repair may provide the more attractive SF_6 mitigation strategy. Many equipment manufacturers now guarantee minimal to zero leak rates for new equipment. Additionally, industry standards recommend that new equipment be built to low leakage limits [5]. Since there is little published information on new equipment leak rates, in a study initiated in 2004, EPA sought to obtain an improved understanding of average leak rates associated with newly manufactured equipment (i.e., installed between 1998 and 2002).

This paper provides a brief review of the data and results of an equipment study funded by EPA [6]. The remainder of this paper is organized into four sections:

- Section II describes the methodology of the field study, including study scope and data parameters.
- Section III provides a summary of the data compiled from utilities participating in the study.
- Section IV presents the results of the equipment leak rate analyses.
- Section V summarizes the conclusions drawn from the study.

II. Field Study Methodology

Section II defines the scope of the study and describes the data collection and compilation process.

A. Study Scope and Data Parameters

The scope of the study was limited to data from three Partner utilities. Information was requested on high voltage circuit breakers manufactured and installed between 1998 and 2002. SF_6 equipment can take the form of sealed or closed pressure systems. Only closed pressure system breakers were included in the study; circuit breakers that are defined as "sealed-for-life" were not addressed by this study. The period in which equipment leakage was assessed was defined as from 1998 through 2005. For purposes of this study, a circuit breaker was classified as leaking if it had documented "top-ups" of SF_6, which occur after a density alarm is sounded, indicating that 10 percent of the circuit breaker gas volume

J. Blackman is with U.S. EPA, Washington, D.C., USA (e-mail: Blackman.Jerome@epa.gov). M. Averyt and Z. Taylor are with ICF Consulting, Washington, D.C. USA (e-mail: maveryt@icfconsulting.com; ztaylor@icfconsulting.com).

has been emitted.

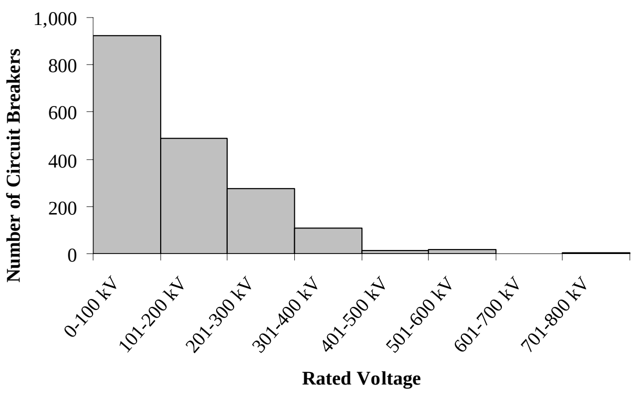
B. Data Collection and Compilation

The data collection was undertaken through a survey form via telephone and email correspondence. The form requested information on the utilities entire inventory of SF_6 breakers, defined by the study scope, including makes, models and installed quantities, number of breaker operations, and for leaking breakers, the quantity of SF_6 gas used during the "top-up" operation.

III. Data Summary

To ensure confidentiality, the names of the utilities involved in the study are not listed. The data provided covered equipment ranging from 33kV to 800kV. In total, information was provided on 2,329 circuit breakers. Figure I illustrates the proportion of circuit breakers size by standard rated voltage. As shown, the majority of the equipment included in the study fell into the range of less than 100 kV. Only 148 breakers were greater 300 kV.

FIGURE I
NUMBER OF CIRCUIT BREAKER BY RATED VOLTAGE



Of the 2,329 circuit breakers, 170 (7.3 percent) were reported as leaking.

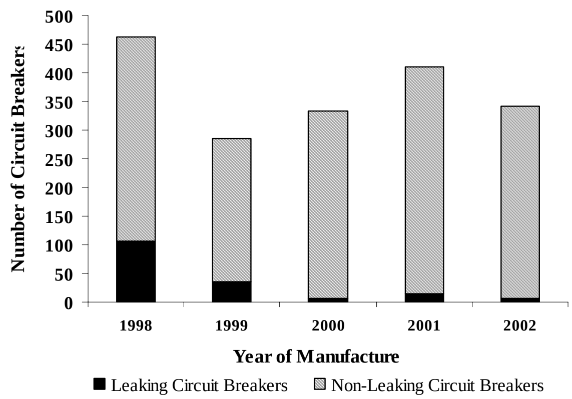
Table I and Figure II present a summary of the number of circuit breakers, leaking and non-leaking, included in the study.

TABLE I
SUMMARY OF LEAKING/NON-LEAKING CIRCUIT BREAKERS

Year of Manufacture	Leaking CB[a]	Non-Leaking CB[b]	Total CB	Leaking CB/Total CB	Leaking as % of Overall Total Leaking
1998	106	357	463	23%	62%
1999	35	250	285	12%	21%
2000	7	326	333	2%	4%
2001	15	396	411	4%	9%
2002	7	334	341	2%	4%
Total	**170**	**1,663**	**1,833[c]**		**100%**

[a]CB – Circuit Breakers
[b]No alarm triggered
[c]Number of circuit breakers does not total 2,329 because year of CB manufacture data are not available for all non-leaking circuit breakers.

FIGURE II
NUMBER OF CIRCUIT BREAKERS BY YEAR OF MANUFACTURE



For the circuit breakers in the data set that were manufactured in 1998, 23 percent were identified as leaking. These circuit breakers account for approximately 62 percent of the total number of leaking breakers. This result is intuitive considering the natural deterioration of seals and equipment over time.

Table II presents emissions data related to the leaking circuit breakers for each year of manufacture. Total emissions of SF_6 are indicated for the leaking circuit breakers manufactured in each year. Total emissions as a percent of total nameplate capacity associated with the leaking circuit breakers are also presented.

TABLE II
SF_6 EMISSIONS FROM LEAKING CIRCUIT BREAKERS

Year Manu-factured	Total Emissions (lbs. SF_6)	No. Leaking CBs	Total Emissions as % of Nameplate Capacity[a]
1998	2,859	106	6%
1999	302	35	0.96%
2000	24	7	0.07%
2001	140	15	0.29%
2002	81	7	0.12%
Total	**3,407**	**170**	

[a]Nameplate capacity of leaking circuit breakers only.

Consistent with the observations in Table I, circuit breakers manufactured in 1998 were also the largest contributors to SF_6 emissions reported in the study. Their emissions as a function of total SF_6-contained in the equipment (nameplate capacity), is approximately 6 percent, significantly larger than the values reported for leaking breakers manufactured in 1999 through 2002.

IV. Leak Rate Results and Analysis

Section IV presents the results of an analysis to define circuit breaker leak rates (as a percent of nameplate capacity) that are representative of the entire reported dataset. These estimates are referred to as the lower and upper bound leak rates, respectively, and are intended to illustrate potential industry trends. The key variables used to perform this analysis are 1) circuit breaker nameplate capacity, 2) total circuit breaker SF_6 leakage (lbs), and 3) the number of years that circuit breaker has been in operation.

Specifically, three leak rates (as a percent of nameplate capacity) were estimated. The first analysis generated a lower bound, or best case scenario, of an average circuit breaker leak rate estimate. The second two analyses both generated upper bound, or worst case scenario circuit breaker leak rate estimates, that are based on different methodologies and assumptions.

A. Lower Bound Weighted-Average Leak Rate

For the lower bound estimate, the weighted-average circuit breaker leak rate is approximately 0.2 percent per year. The lower bound leak rate was calculated by applying the raw reported data to Equation (1) and assuming that 1) through 2005, no additional "top-ups" have occurred after the last reported "top-up" (e.g., if the last reported "top-up was in 2003, it was assumed that no additional leakage occurred through 2005), and 2) for circuit breakers that have not reported any "top-ups" (i.e., they have not reached the 10 percent leakage threshold, and thus have not triggered a notification alarm), their emissions are zero.

This estimate is defined as the weighted average of circuit breaker annual leak rates as a percentage of SF_6 nameplate capacity, across all circuit breakers both leaking and non-leaking. The calculation for the weighted average annual leak rate per nameplate capacity is provided in Equation (1):

$$LC = \frac{\sum \frac{Q_{SF6i}}{Y_i}}{\sum C_i} \qquad (1)$$

Where:

LC = Weighted average annual leak rate per nameplate capacity (percent/year)

Q_{SF6i} = Total mass (i.e., lbs) of SF_6 for all top-up operations since installation for circuit breaker, i

Y_i = Number of years the circuit breaker, i, has been in use

C_i = Individual nameplate capacity for circuit breaker i (lbs SF_6)

B. Upper Bound Weighted-Average Leak Rate – Method 1

For the lower bound estimate, it was assumed that equipment that had not reported "top-ups" were not leaking; however, since "top-ups" are defined by density alarm triggers, it is possible that many more breakers had leaked, but had not reached the 10 percent density alarm leak threshold. To account for potential leakage under the density alarm threshold, an upper bound leak rate estimate was developed based on the following assumptions:

(1) All circuit breakers that have not indicated an alarm trigger leaked slightly less than 10 percent of their capacity between their installation date and 2005. Thus, the 2,159 circuit breakers (93 percent) in the dataset which have no documented "top-ups" (and are assumed for the lower bound to have a leak rate of zero percent) are scaled to assume a leakage rate of 10 percent (this is an asymptotic upper bound).

(2) The second adjustment assumed that for previously identified leaking breakers (those that have reported "top-ups"), an additional 10 percent of capacity (i.e., another "top-up") occurred between the last documented service call and 2005. For example, a circuit breaker with an annual leak rate of 5 percent whose last reported service call occurred one year before the company data submittal is assumed to have 10 percent additional leakage during that last year.

Based on these assumptions and the application of equation (1) the weighted-average upper bound estimate for circuit breaker leak rate is estimated to be 2.5 percent. This result represents a *worst case* upper bound leak rate.

C. Upper Bound Weighted-Average Leak Rate –Method 2

Since the second assumption listed in the prior section, may overestimate emissions from documented leaking circuit breakers, an additional upper bound estimate was calculated by redefining how additional "top-ups" for these circuit breakers are treated. That is, it was assumed that circuit breakers which are currently leaking will continue to leak at their current rate. That is, if a circuit breaker is calculated to have an existing leak rate of 2 percent per year per nameplate capacity between its installation and last reported top-up date, then it was assumed that this rate continues through the end of the study period. This alternative approach maintains the original assumptions for non-leaking circuit breakers by assuming a leakage of just under 10 percent has occurred since circuit breaker installation.

Based on these assumptions and the application of equation (1), the alternate weighted-average upper bound leak rate estimate is 2.4 percent.

V. CONCLUSION

For the study dataset, the lower and upper bound weighted-average leak rate estimates of 0.2 and 2.5 percent, respectively, represent the best and worst case scenarios for circuit breaker leakage. To put this into some context, NEMA's SF_6 management guidelines state, "…Over a 50 year service life the emission of SF_6 gas due to its use in electrical equipment will not exceed... 5% equipment leakage…" (i.e., 0.1 percent/year) [7]. Also, the IEC standard for new equipment leakage is 0.5 percent per year [5]. While the upper bound is significantly larger than both the NEMA and IEC guidelines, the lower bound leak rate estimate is comparable, and sits between the NEMA and IEC recommendations.

VI. ACKNOWLEDGMENT

The authors would like to acknowledge representatives from Eastern Research Group, Inc (ERG), the Electric Power Research Institute (EPRI), and the electric utilities, and original equipment manufacturers that assisted EPA in undertaking this study.

VII. REFERENCES

[1] IPCC, *Climate Change 1995: The Science of Climate Change.* Intergovernmental Panel on Climate Change; J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds; Cambridge University Press. Cambridge, U.K.

[2] McCreary, J.D., "AEP: A Case Study," presented at the International Conference on SF_6 and the Environment: Emission Reduction Technologies, November 2-3, 2000, San Diego, CA. [Online]. Available: http://www.epa.gov/electricpower-sf6/pdf/mccrearyppt.pdf

[3] D. Keith, J. Fisher, and T. McRae, "Experience with Infrared Leak Detection on FPL Switchgear," presented at the International Conference on SF_6 and the Environment: Emission Reduction Technologies, November 2-3, 2000, San Diego, CA. [Online]. Available: http://www.epa.gov/electricpower-sf6/pdf/fischerp.pdf

[4] Salinas, A. and Flores, M., "Southern California Edison: SF_6 Gas Management Program Update," presented at the International Conference on SF_6 and the Environment: Emission Reduction Technologies, December 1-3, 2004, Scottsdale, AZ. [Online]. Available: http://www.epa.gov/electricpower-sf6/pdf/dec04/Salinas_ok2use.pdf

[5] IEC, International Electrotechnical Commission Standard 62271-1, 2004.

[6] EPA, "High Voltage Circuit Breakers Field Study," prepared by EPRI and the Eastern Research Group, July, 2005.

[7] NEMA, "Management of SF_6 Gas for Use in Electrical Power Equipment," Ad-Hoc Task Group on SF_6, Switchgear Section (8-SG), February, 1998.

VIII. BIOGRAPHY

Jerome Blackman is Program Manager for EPA's SF_6 Emission Reduction Partnership for Electric Power Systems. Mr. Blackman joined EPA in 1995 and has work in several commercial/industrial non-regulatory voluntary pollution prevention programs within the Office of Atmospheric Programs.

Mollie Averyt is an Associate at ICF Consulting. Ms. Averyt specializes in environmental policy analyses related to climate change and ozone depletion issues; and provides support for EPA's SF_6 Emission Reduction Partnership.

Zephyr Taylor is a Research Assistant at ICF Consulting. Mr. Taylor specializes in quantitative modeling and analysis specifically related to climate change issues. Mr. Taylor provides technical support for EPA's SF_6 Emission Reduction Partnership.