ELIMINATION OF PARTICLE EFFECTS IN SF₆
INSULATED TRANSMISSION SYSTEMS

CONS--3029-74

S. J. Dale

FIFTH QUARTERLY REPORT

Westinghouse R&D Center
Pittsburgh, Pennsylvania 15235

Sponsored By:

Department of Energy (DOE)

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Under Contract Number ET-78-C-01-3029

Period of Contract: October 1, 1978 to June 26, 1980

Westinghouse R&D Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

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QUARTERLY TECHNICAL PROGRESS REPORT

Number: 5

Period: 10/01/79 to 12/31/79

DOE Program Manager: Thomas F. Garrity

PROJECT:

Title: ELIMINATION OF PARTICLE EFFECTS IN SF₆ INSULATED TRANSMISSION
SYSTEMS

CONTRACT:

Number: ET-78-C-01-3029

Start Date: October 1, 1978

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Contractor: WESTINGHOUSE ELECTRIC CORPORATION
Research and Development Center
1310 Beulah Road, Churchill Boro
Pittsburgh, PA 15235

Program Manager: S. J. Dale

PROJECT OBJECTIVES

The purpose of this project is to eliminate the adverse effect of particles (contaminants) in SF₆-insulated transmission systems through development of improved equipment and methods so that the excellent dielectric properties of SF₆ are fully exploited.

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SUMMARY

The purpose of this program is to develop methods and equipment to eliminate the adverse effect of particle contamination in SF₆-insulated transmission systems, CGIT, so that the excellent dielectric properties of SF₆ can be fully exploited. Presently, CGIT systems are operated at about 10% of the dielectric strength capability of the SF₆ gas.

The program commenced in October 1978 and has a total duration of 21 months. The program consists of three major parts: theoretical and experimental evaluation of concepts; optimization and verification studies in CGIT systems; reliability analysis, documentation of designs and economic analysis.

Tests were made comparing a slotted particle trap elevated above the enclosure with a particle trap with slots flush with the enclosure surface. The advantages of the latter trap were: significantly reduced time to deactivate the particles and no discrimination of particle size. The elevated trap captures most of the particles through the opening between the trap and the enclosure. The time to trap larger particles were dependent on both the amplitude of the applied voltage and the particle size. However, the elevated trap was as good as the flush trap for smaller and more realistic contaminants.

Aging tests on adhesive materials for particle traps are continuing.

Mechanical vibration cleaning of the enclosure has been completed. A combination of air flow and mechanical vibration was found to be the most successful method and comparable to present methods of sheath cleaning.

A paper to the Second International Symposium on Gaseous Dielectrics in Knoxville, March 9-13, has been written. The major conclusions were:

Alternative conductor bundle and corrugated sheath designs for CGIT systems have been investigated in order to determine if these provide a system more tolerant to the presence of contamination. Although these designs showed some merit compared to the conventional CGIT designs, none of them resulted in sufficient improvement to allow systems to operate reliably at higher stresses than at the present. The position of discrete particle traps at the support insulators was shown to offer significant protection of the insulators against particle contamination and failure, thus increasing the reliability of the system. Significant improvements of the particle traps were achieved by the use of an adhesive material in the trap cavities both for ac and dc voltages. Tests showed that it is preferable to condition CGIT systems which incorporate particle traps through a number of voltage steps before applying the ac test voltage.

The application of the hybrid electrostatic-adhesive traps in combination with an effective voltage conditioning procedure offers the prospects of improved reliability for CGIT systems.

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SECTION 1

INTRODUCTION

1.1 Program Objectives

The purpose of this project is to eliminate the adverse effect of particles (contaminants) in SF₆-insulated transmission systems through development of improved equipment and methods so that the excellent dielectric properties of SF₆ are fully exploited.

1.2 Background

Gas-insulated equipment, such as compact substations and transmission lines, is rapidly becoming an important part of high voltage transmission systems, offering advantages of economy, savings in land space, ease of maintenance, improved safety, and freedom from pollution and radio interference problems. However, one of the most severe problems of gas-insulated systems is the presence of metal particle contaminants which can substantially reduce the breakdown voltage of the compressed sulfur hexafluoride (SF₆) gas used for the high voltage insulation between the conductor and the ground. These contaminants can be introduced during assembly procedures or can be produced by abrasion between components during operation. Under the influence of the electric field these particles are lifted and if allowed to migrate to the high voltage conductor, or support insulators, can

initiate a high voltage insulation failure -- either by breakdown in the gas or by flashover along the surface of the solid support insulators. As a result of the risk of contamination being left or generated in the CGIT system and the depressing effect that this has on the insulation characteristics, present day CGIT systems are being operated well below the dielectric capability of SF_6 .

Typical peak 60 Hz ac operating conductor fields of the present system ranges from about 26 to 56 kV/cm for 145 kV systems and 800 kV systems respectively, operating at 4.4 bar of pressure. For comparison, the theoretical insulation capability of SF_6 at 4.4 bar is 392 kV/cm. If the particle contamination could be eliminated from the CGIT systems, substantially higher operating stresses than presently feasible could be used thus making the CGIT systems economically more attractive than at present.

1.3 Program Philosophy and Approach

The program consists of three major parts.

- Theoretical and experimental evaluation of concepts.
- Optimization and verification studies in CGIT systems.
- Reliability analysis, documentation of designs and economic analysis.

The first part is a study of the feasibility of concepts by the evaluation of alternative solutions and designs for reliable particle elimination and control methods.

Manufacturing and field installation techniques will be examined for methods of improved cleanliness. Procedures for field conditioning of compressed gas insulated transmission systems will be suggested which are compatible with the improved particle control techniques.

The second part of the program deals with optimization, verification and reliability tests of selected concepts in full scale CGIT systems.

Finally, a reliability analysis of the system will be performed based on the experimental results. All manufacturing and field assembly procedures will be documented and economic benefit of being able to operate CGIT systems at higher stresses will be analyzed.

1.4 Summary of Program Tasks

Task 1. Theoretical analysis and experimental investigation. Perform theoretical investigation and analysis needed to prove the effectiveness of designs and methods proposed.

Task 2. Major experimental system and verification studies. Perform experimental investigation involving prototypes built according to proposed designs and methods.

Task 3. Reliability analysis. Perform statistical analysis of experimental data to insure that the proposed methods and designs will provide reliable operation on long transmission systems particularly with respect to contaminants.

Task 4. Documentation. Provide documentation of manufacturing and field installation procedures of those designs and methods which will help reduce the adverse effects of free conducting particle contamination.

Task 5. Economic benefit analysis. Provide an analysis and documentation of the savings that could be realized by fully exploiting the dielectric properties of the gas or gas mixture and to the extent possible, provide an outline of follow-on work.

Task 6. Final report. Prepare a final report documenting in detail all the work performed under the project.

1.5 Milestone Schedule and Status Report

The Milestone Schedule and Status Report is shown in Figure 1.1. A milestone log is given in Table 1.1.

U.S. DEPARTMENT OF ENERGY
MILESTONE SCHEDULE AND STATUS REPORT

PAGE 1 OF 1

FORM APPROVED
MAY 1978

1. Contract Identification Elimination of Particle Effects in SF ₆ Insulated Transmission System		2. Reporting Period through		3. Contract Number ET-78-C-01-3029																							
4. Contractor (Name, address) Westinghouse Electric Corporation Research and Development Center 1310 Beulah Road, Pittsburgh, PA 15235		5. Contract Start Date 9/28/78		6. Contract Completion Date 6/26/80																							
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		FY 78						FY 79						FY 80													
		O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J			a) Planned	b) Actual	
1	Theoretical and Experimental Investigation																										
.1	Electrostatic Traps				▽ A							▽ B															
.2	Adhesive Trap Materials				▽ A	△							▽ B														
.3	Solid Dielectric Insulation								▽ A					△													
.4	Manufacture and Field Control Methods											▽ A															
2	Major Experimental System and Verification Studies												▽ A														
3	Reliability Analysis																										
4	Documentation																										
5	Economic Benefit Analysis																										
6	Final Report																										
7	Program Management and Technical Report Schedule				▽			▽				▽						▽									
11. Remarks																											
12. Signature of Contractor's Project Manager and Date Steinar J. Dale														13. Signature of Government Technical Representative and Date													

SECTION 2

TASK 1. THEORETICAL ANALYSIS AND EXPERIMENTAL INVESTIGATION

2.1 Task 1.1 Electrostatic Particle Elimination Concepts

2.1.1 Particle Traps

Elevated Trap. The mode at which the elevated particle traps operate has been investigated for different voltage levels. The tests were made with a 292 mm/102 mm coaxial electrode system, the same size system as for the 242 kV system voltage. The elevated particle trap, consisting of a cylinder mounted coaxially between the enclosure and the conductor, 6 mm above the enclosure is shown in Figure 2.1.

Three voltage levels were used: 95 kV rms, corresponding to just above the lift-off voltage for most particles, 140 kV rms and 200 kV rms. The latter voltage level was just below the breakdown voltage for 6.4 mm long particles. Five tests were made at each voltage level with twenty (20) 6.4 mm or 1.6 mm long particles used in each test. The time taken for particles to be trapped were recorded and the position of the particles in the trap after each voltage level was determined. The results showing the positions of the particles in the trap after the tests are given in Table 1.

(a) Trap slot designs

(b) Applied to Westinghouse Tripost trap

Figure 2.1 -- Elevated electrostatic particle trap.

Table 1

Applied Voltage	Position of Particles in p.u. Values		
	Under Trap Edge	Through Slots In Trap Surface	Behind Trap
95 kV rms	0.85-1.00	0.00-0.30	0-0.10
140 kV rms	0.41-0.87	0.00-0.56	0-0.20
200 kV rms	0.41-0.67	0.13-0.45	0-0.18

This showed that the opening between the trap and the enclosure, the top edge, captured the majority of the particles. However, as the applied voltage was increased this mode of trapping became less effective and the trap relied more on trapping the particles through slots on the trap surface. The number of such slots, 5 mm wide running circumferentially in the trap surface did not affect the trapping probability significantly when altered from one slot to four slots, probably because the number of particles entering onto the trap surface was not sufficient to determine this probability with reasonable consistency. The test results also showed that there was an increase in the proportion of particles which failed to be trapped as the voltage level was increased.

The time taken to trap particles, 6.4 mm long, is shown in Figure 2.2 as a function of the applied voltage level. The particles were placed about 0.15 m from the edge of the trap and the enclosure was on a 0.5° slope. The modal value of the trapping time decreased from 29 minutes at 95 kV rms to about two minutes at 200 kV rms. Smaller length of particles 3.2 and 1.6 mm, did not show the same time-voltage characteristic for trapping but were trapped within about one minute at 95 kV rms by the trap edge. A particle trap with the slots running axially in the trap surface showed a similar time-voltage characteristic as the circumferentially slotted trap.

Trap with Slots Flush with Enclosure Surface. The effectiveness of particle traps utilizing circumferential slots should be dependent on the

Curve 720623-A

Figure 2.2 -- Time at conditioning voltage for particle trapping in 292/102 mm coaxial electrodes with elevated electrostatic particle trap.

number of slots provided each slot is sufficiently wide to not interfere with the trapping. It should also be dependent on the level of the conditioning voltage since this determines the particle motion. Tests were made to determine the efficiency of the slots to capture particles in a coaxial electrode system with 102 mm diameter conductor and a 279 mm inner diameter enclosure when the circumferential slots were in the enclosure, flush with the enclosure surface. The width of each slot was 5 mm and adjacent slots were spaced 10 mm apart. The result of the tests for 1.6 mm and 6.4 mm long aluminum particles at various voltage levels are shown in Table 2 for one, two and four slots. The trapping efficiency is defined as the ratio of the number of particles found in the slots to the total number of particles, i.e., the sum of the particles in the slots and the number of particles which went over the slots. The trapping efficiency decreased as the conditioning voltage was increased and also with increasing particle length, but increased with the number of slots. The efficiency of such traps can be calculated from the relationship

$$P_t = 1 - (1 - P_i)^n$$

where P_t is the overall efficiency for n slots and P_i is the efficiency for a single slot. For example, at 200 kV rms, at least nine slots are required to trap 99% of the 6.4 mm long particles. A trap with 15 circumferential slots captured 99-100 percent of the 6.4 mm long particles.

Table 2

TRAPPING EFFICIENCY FOR PARTICLE TRAP WITH SLOTS FLUSH WITH SURFACE
OF ENCLOSURE

Particle Size	Applied Voltage kV rms	No. Of Slots In Trap		
		1	2	4
6.4 mm	95 kV	0.82	0.93	1.00
	140 kV	0.44	0.60	0.90
	200 kV	0.43	0.62	0.88
1.6 mm	95 kV	0.97		1.00
	140 kV	0.97		1.00
	200 kV	0.93		1.00

The time to trap particles with this trap configuration was independent on particle size and was of the order of one minute. The particles were placed about 0.15 m away from the first slot.

Influence of Front Edge of Elevated Particle Trap. Above it was shown that the elevated particle trap required considerably longer time to trap particles than the trap in the enclosure surface. The main reason for this was the elevation of the trap above the enclosure. Particles which were smaller than this elevation and had bounce heights lower than this elevation had usually no problems in entering the opening between the trap and the enclosure but the longer particles required the conditioning voltage to be applied for much longer time in particular at the lower voltage levels. As the voltage level was increased, the particle bounce height and vigor of motion increased and could then enter the trap surface and trapped through the surface slots. As shown in Table 1, up to nearly fifty percent of the particles were trapped in this mode when a voltage close to the particle crossing voltage (to the conductor) was applied. Although the particles had sufficient bounce height at lower voltage levels (~ 120 kV) to jump onto the trap surface they showed a certain reluctance to do so.

Thus, the geometry of the trap edge were thought to influence the particle motion close to the trap, acting as a barrier to the particles. The particle trap was modified by bending the front edge down towards the enclosure as indicated in Figure 2.3, leaving a gap approximately 3 mm

Figure 2.3 -- Particle trap with bent down front edge.

between the edge and the enclosure. This reduced the field at the trap edge and therefore should make the trap less "visible" to the particles. However, the time to trap particles with this trap was not significantly different from that shown in Figure 2.1 when the trap edge was straight and square cut. The reduction in the trap opening also reduced the capturability of 6.4 mm long particles through the front edge. Particles 1.6 mm long were not affected. This modification of the edges of the elevated particle trap did not improve the ability of the trap to capture particles nor did it reduce the time required to trap the particles at the lower voltage levels.

A discussion of particle elimination and CGIT conditioning is given in the Appendix.

2.2 Task 1.2 Adhesive Materials and Concepts

Current results of the aging tests are as shown in Table 3.

Due to inconsistent aging results obtained at 160°C and 150°C using SF₆ gas, a number of bombs have been recharged and are being retested. Gas and material combinations are being analyzed to determine if the SF₆ gas is degraded by the presence of organic materials. These findings will determine the test program for the aging tests at 160°C and 150°C using SF₆ gas.

Table 3

Material	Gas	Temperature	Adhesion Retention Time (Hours)
Royston Tape	Argon	250°C	38
Royston Tape	Argon	200°C	408
Royston Tape	SF ₆	160°C	Incomplete
Royston Tape	SF ₆	150°C	2200
Pliobond 8004	Argon	250°C	32
Pliobond 8004	Argon	200°C	432
Pliobond 8004	SF ₆	160°C	1992
Pliobond 8004	SF ₆	150°C	2400
Pliobond 5001	Argon	250°C	20
Pliobond 5001	Argon	200°C	552
Pliobond 5001	SF ₆	160°C	Incomplete
Pliobond 5001	SF ₆	150°C	Incomplete

Tests of release papers indicate that silicone treated paper has the best release properties of any of the treated papers or plastics evaluated (Table 4).

2.3 Task 1.4 Manufacture and Field Control Methods

2.3.1 Mechanical Vibration Cleaning of the Sheath

The test program to evaluate the effectiveness of mechanical vibration as a means of eliminating particles from inside surface of the CGIT sheath has been completed.

The program was divided into two test series. The first series covered testing of a smooth aluminum sheath and the second series a corrugated sheath. In both cases the sheath was supported at the ends and mechanically vibrated at the mid-length point. The value of the frequency was varied from 5 Hz to 10 kHz to determine the most effective level for the removal of particles from the sheath. The added effect of air flow was also determined. The test records that were taken were: accelerometer readings, frequency level, tilt angle, weight of particles removed, video tape showing action of particles, value of air flow rate and sheath deflection. The length of time for each test was five minutes. Five grams of mixed aluminum particle sizes were used ranging in length from 0.4 mm to 10 mm.

Table 4

RELEASE VALUE FOR VARIOUS RELEASE MATERIALS

(GM./SQ.IN.)

	Royston Tape	Pliobond 8004	Pliobond 5001
Silicone treated paper	12	12	75
Vegetable oil treated paper	Not run	105	50
Teflon FEP	200	50	200
Teflon TFE	50	60	210
Polyethylene	275	225	No release (2000+)
Aclar 33C	200	200	No release (2000+)

The test set-up for the smooth sheath is shown on Figure 2.4. The sheath was 38.1 cm (15 inches) outside diameter, 36.2 cm (14.25 inches) inside diameter, 12.2 m (40 ft.) long. The material was 6063-T6 aluminum. A photograph of the test set-up is shown on Figure 2.5. The electromagnetic mechanical vibration source was connected to the sheath at the mid-length point of the sheath. The tilt angle was 30° from the horizontal.

The test set-up for the corrugated sheath is shown on Figure 2.6. The sheath was 76.2 cm (30 inches) inside diameter, 6.1 m (20 ft.) long, 3.4 mm (0.13 inch) wall thickness. The corrugation section was 6.78 (2.67 inches) x 1.27 cm (0.15 inch). The material was 3004 H34 aluminum. A photograph of the test set-up is shown on Figure 2.7. The mechanical vibration source was connected to the mid-length point of the sheath. A larger tilt angle was used for the corrugated sheath than for the smooth sheath. This was done to insure that both sides of the corrugation section had a downward slope. The corrugated sheath was included 35° from the horizontal.

As a result of the test program the following conclusions can be drawn:

1. The cleaning action, when mechanical vibration is used, is a function of both sheath deflection and g level.

Figure 2.4 -- Smooth Sheath Test Set-Up Mechanical Vibration Cleaning

Figure 2.5 -- Arrangement of vibration cleaning tests of the sheath, 12.2 mm long, 362 mm i.d.
Vibration source in center.

Figure 2.6 --Corrugated Sheath Test Set-Up Mechanical Vibration Cleaning

Figure 2.7 -- Arrangement of vibration cleaning tests of corrugated sheath section, 6.1 m long, 0.726 m i.d.

2. For the support method and type of vibration used, the best cleaning action, using mechanical vibration, occurred at the second mode natural frequency. The combination of maximum deflection and g level took place at this frequency.
3. Using mechanical vibration only, the maximum particle removal rate in the 5 minute test period was 30% for the smooth sheath at a frequency of 32.5 Hz. For the corrugated sheath, the maximum rate was 2% at a frequency of 90.5 Hz. Very little particle motion was observed at frequencies greater than 500 Hz due to low sheath deflection.
4. The mechanical vibration cleaning rate was lower for the corrugated sheath compared to the smooth sheath due to: (a) the corrugated shape and spiral joint acted as a barrier to the motion of the particles, (b) the sheath deflection was lower.
5. Using air flow only, at a rate of $26.9 \text{ m}^3/\text{min.}$ ($950 \text{ ft.}^3/\text{min.}$), the particle removal rate in 5 minutes was 90% for the smooth sheath and 87% for the corrugated.
6. The best cleaning action occurred with a combination of mechanical vibration acting concurrently with air flow. At a mechanical vibration frequency of 32.5 Hz and $26.9 \text{ m}^3/\text{min.}$ ($950 \text{ ft.}^3/\text{min.}$) air flow, the cleaning action was 99% for the smooth sheath. At a frequency

of 90.5 Hz and air flow of 26.9 m³/min. (950 ft.³/min.), 98% of the particles were removed from the corrugated sheath.

7. The remaining 1 to 2% of the particles remaining after air flow and vibration cleaning seem to cling to the surface of the sheath. Added cleaning time did not remove these particles. They will need to be removed by a method such as a close wiping action.
8. The use of moderate to high air flow rates would eliminate the need to have the sheath positioned on an angle.
9. The cleaning method of mechanical vibration in combination with air flow is comparable to present methods of sheath cleaning. An economic analysis would need to be run to determine which scheme would be most desirable from a production standpoint.

Spin Blast Sheath Cleaning. A test was run recently to determine if the Spin Blast Method could be applied to cleaning the inside surface of CGIT smooth and corrugated aluminum sheath. Basically, the Spin Blast method employs a very fine glass bead 0.051 to 0.102 mm (0.002 to 0.004 inch) in combination with compressed air 0.65 MPa (80 psi) impinging on the surface of the aluminum at high velocity to give the cleaning action. A diagram of the test set-up is shown on Figure 2.8. The glass bead is mixed with the compressed air in the pressure pot. From there the combination of glass bead and air flows through a connecting line to the

Figure 2.8 - Test of Spin Blast Cleaning of Sheath

Spin Blast head. The mixture leaves the head through twin nozzles at high velocity and strikes the inside surface of the aluminum sheath. The Spin Blast head rotates clockwise and travels longitudinally through the sheath. The sheath samples were 30.5 cm (12 inches) diameter x 60.9 cm (24 inches) long.

Good cleaning action was obtained for both the smooth and corrugated sheath. All burrs, particles, oil, etc., were removed from the inside surface of the sheath samples. A very thin coating of fine powder remained on the surface. It was the consistency of talcum powder. This could be removed by a method such as a water flush operation.

A production set-up would incorporate a reclaimer unit so that the glass bead could be used over again. Figure 2.9 shows a possible production scheme. The possibility of running a cleaning test on a full scale 12.1 to 18.2 m (40 or 60 ft.) long sheath using the production set up on Figure 2.9 will be investigated.

Figure 2.9 -- Production Set Up Of Spin Blast Cleaning Of Sheath

SECTION 3

PROGRAM FOR NEXT QUARTER

Aging tests on adhesive materials will continue and application methodology commenced.

Tests of particle control concepts in vertical CGIT sections will commence.

Factory tests of full scale 242 kV CGIT sections with improved particle control methods will commence.

AC CGIT conditioning studies in 145 kV CGIT test section will commence.

SECTION 4

LIST OF CONTRIBUTORS

Electrostatic Particle Elimination Concepts

S. J. Dale

Adhesive Trap Materials and Concepts

G. D. Dixon

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Manufacture and Field Control Methods

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SECTION 5

APPENDIX

Paper submitted to the Second International Symposium on Gaseous Dielectrics; Knoxville; March 9-13, 1980.

EFFECTS OF PARTICLE CONTAMINATION IN SF₆ CGIT SYSTEMS AND METHODS OF PARTICLE CONTROL AND ELIMINATION

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ABSTRACT

Improvement in reliability and operation at higher fields could be achieved in compressed gas insulated transmission systems if the effects of particle contamination could be eliminated. Results from a development program to achieve this goal are presented. These include the effects of conductor and enclosure geometry and the design of improved particle traps. This work is supported by the U. S. Department of Energy.

INTRODUCTION

Compressed gas insulated transmission lines (CGIT) consist basically of a conductor supported on insulators inside an enclosure which is filled with sulfur hexafluoride gas (SF₆). Typical operating pressures for the CGIT systems are from 240 kPa to 440 kPa. The critical dielectric design factor for the present systems is usually the lightning impulse test where the conductor design field is of the order of 160 kV cm⁻¹ at 440 kPa. The present design levels are of the order of 37 percent of the theoretical strength of SF₆ for lightning impulse and 19 percent for the 60 Hz factory test. The operating fields vary from about 6 percent to 14 percent depending on the system voltage.

These low design levels are used because SF₆ is very sensitive to field perturbations such as those caused by conductor surface imperfections and by conducting particle contaminants. These contaminants can be introduced during assembly or be produced by abrasion between components during operation. These particles can be lifted by the electric field and migrate to the conductor or insulators where they can initiate breakdown at voltages significantly below the insulation characteristics of the SF₆ gas.

The presence of contamination can therefore be a problem with CGIT systems operating at high fields. If the effects of these particles could be eliminated then this would improve the reliability of CGIT systems. It would also offer the possibility of operating at higher fields to effect a potential reduction in the CGIT size with subsequent savings in the cost of manufacture and installation (Ref. 1).

Particle traps (Refs. 1,2) are finding increasing use in CGIT systems. The principle is to create a region of very low or zero field, usually at the enclosure, into which particles can be moved by the field and trapped. This migration usually is achieved by a conditioning voltage. Present CGIT trap designs include a slotted metallic shield surrounding the insulators, as well as cavity traps and hollow, perforated longitudinal cylindrical traps at the enclosure bottom.

This paper studies the effects of particle contamination on present and new designs of CGIT systems and reports the preliminary results on the development of new particle trapping systems. Tests were made in a 0.7 m long 242 kV size CGIT model. The particle contamination was simulated by aluminum wires, 0.45 mm in diameter, ranging in length from 1.6 mm to 12.8 mm. For reference, the factory and field test voltages for the 242 kV system are 425 kV rms and 320 kV rms respectively.

DESIGNS TO MINIMIZE PARTICLE EFFECTS

One philosophy of contamination control in CGIT systems is to incorporate designs of the major system components, the conductor and enclosure, such that a certain degree of immunity can be achieved against the presence of particles.

Conductor Design

A bundle conductor design has been proposed for CGIT systems (Ref. 3); a beneficial effect of such a conductor design has been shown recently for contaminated insulators (Ref. 4). A bundle conductor design was tested for a 242 kV size CGIT model and compared to the performance obtained with the conventional single conductor with the same over-all outer diameter of 102 mm mounted in a 292 mm diameter enclosure. The bundle conductor consisted of four 25 mm diameter aluminum subconductors mounted 90° apart with an overall diameter of 102 mm.

The results in Fig. 1 show that the lift-off voltage with the bundle conductor was, on average ten to twenty percent above that for the single conductor. The orientation of the bundle conductor influenced the lift-off and crossing voltages. The particle crossing voltage was highest for the conductor bundle in configuration (a) of Fig. 1; being 35 percent higher than for the single conductor with the 6.4 mm long particles. However, as a result of the higher conductor surface stresses the particle initiated breakdown voltage was not improved with the conductor bundle; for the 6.4 mm long particles the average value of the breakdown voltage for the bundle conductor was some twenty percent *below* that for the single conductor. The orientation of the conductor bundle did not affect the breakdown voltage.

Corrugated Enclosure Design

A corrugated enclosure was tested to see if this would give a system more tolerant to the presence of particle contamination than the present smooth enclosure. The corrugations, which had a depth of 12.5 mm and a width of 70 mm, have some of the characteristics of electrostatic particle traps by providing regions of lower fields on the sheath. For the 305 mm inner diameter corrugated enclosure used in these tests the field at the bottom of the corrugations was one third of that inside the smooth enclosure. Thus, the lift-off voltage for the particles in the bottom of the corrugations was about three times that for a smooth enclosure with the same inner diameter. While the voltage required for 6.4 mm long aluminum particles to cross from the enclosure surface to the conductor in a smooth 292/102 mm coaxial electrode system was of the order

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Fig. 1. Lift-off, crossing and breakdown voltages for single and bundle conductors in 102/292 mm coaxial electrode geometry.

Fig. 2. Breakdown voltage in 305/102 mm coaxial electrode system with corrugated enclosure and free aluminum particles.

of 50 percent higher than the lift-off voltage, it was found that once the same size particles lifted from the corrugated surface, the field was then sufficiently high for them to cross to the conductor. Figure 2 shows the modal value of lift-off with respect to the breakdown voltage for 12.8 mm and 6.4 mm long particles. The 222 kV rms average breakdown voltage for the 12.8 mm long particles was only 20 percent above the modal lift-off voltage. With the 6.4 mm long particles the breakdown voltage was 291 kV rms, 45 percent above the modal lift-off voltage. The ratio of breakdown to lift-off voltage in an equivalent smooth electrode system was of the order of 3.7 and 2.7 for the 6.4 mm and 12.8 mm long particles respectively. Aluminum particles 1.6 mm long were not observed to lift out of the corrugations for voltages up to 350 kV rms. The breakdown voltage for these size particles in a smooth electrode system of similar dimensions was of the order of 350 kV rms as shown in Fig. 1.

These tests showed that the corrugated sheath was only partially effective as a particle trap. The particles were trapped for a given voltage level which depended on the size of the particles. The close proximity of the breakdown voltage to the lift-off voltage also indicated that the application of a conditioning voltage to migrate particles into designated trap areas might cause a high risk of breakdown. However, the use of an adhesive coating, as discussed in a later section, proved very effective for trapping particles in this sheath system both for 60 Hz and dc voltages.

DISCRETE PARTICLE TRAPS

Another philosophy in the design of CGIT systems, as already mentioned, is to provide designated low field areas in the system where the particles can be safely trapped and contained (Refs. 1,2,5).

There are several important factors that must be considered for particle control with such traps:

- Particle contaminants must be migrated through the CGIT system to the location of the traps. This must be achieved without risking damage to the system from breakdown or contamination of solid insulators which can cause flashover at later times.
- Once the particles have arrived at the trap location the trap must provide rapid and positive capture of the particles.
- The trap must have positive retention characteristics under 60 Hz, dc and transient voltages as well as under mechanical vibration and when installed on sites with a slope.

Slotted Particle Trap

Detailed observations with elevated slotted particle traps, similar to that in Fig. 3, showed that there were two modes in which particles were captured. The major and most effective mode was capture through the opening edge between the elevated trap and the enclosure. The other mode was to trap particles through the slots in the trap surface. This latter mode required the particles first to move onto the surface of the trap.

In the first trapping mode, particles bounced or rolled under the trap. This required a conditioning voltage only equal to or slightly above the particle lift-off voltage, thus minimizing the risks of breakdown and of particles scattering on to the insulators.

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Particles which were smaller than the separation of the trap above the enclosure were trapped in this manner for voltages of up to some 50 percent above the lift-off voltage. Although longer particles were also captured through the trap-enclosure opening, the majority were trapped by moving onto the trap surface and falling through the slots. The relationship between the time to trap groups of aluminum particles ranging in length from 1.6 mm to 6.4 mm, and the value of the applied conditioning voltage is shown in Fig. 4. The particles were placed approximately 0.15 m from the trap. The time for the particles to reach the trap was less than one minute. At all the voltage levels the 1.6 mm and 3.2 mm particles were trapped within the first minute through the open end of the trap. The trapping times shown in Fig. 4 therefore are for the 6.4 mm long particles. The modal value of the trapping time decreased with increasing voltage from 29 minutes at 95 kV rms to about 2 minutes at 200 kV rms. Since the 6.4 mm long particles were longer than the elevated distance of the trap, most of these particles were required to enter the trap surface in order to be trapped. This condition was met at the higher conditioning voltage levels since the particle bounce height increased with the electric field and the length of the particles (Ref. 6).

Fig. 3. Elevated electrostatic particle trap.

Fig. 4. Time at conditioning voltage for particle trapping in 292/102 mm coaxial electrodes with elevated electrostatic particle trap.

Fig. 5. Voltage conditioning tests in 292/102 mm coaxial electrodes with free conducting particles with SF_6 pressure of 440 kPa.

Although the elevated particle trap was shown to work very effectively by trapping the particles through the opening between the trap and the enclosure at low and safe conditioning voltages it was found that these particles were not positively trapped but could escape when the voltage level was increased. An example of this is shown in Fig. 5 where forty particles, ranging in length from 1.6 mm to 12.8 mm were initially trapped through a conditioning procedure which consisted of increasing the voltage in 20 kV rms steps from 100 kV rms, with each voltage level held for one minute. At 160 kV rms all the particles were trapped. The voltage was then attempted to be ramped to 350 kV rms. As shown in Fig. 5 several breakdowns occurred before 350 kV rms could be maintained for 3 minutes. These breakdowns were caused by particles which came out from the opening between the trap and the enclosure. The above results showed the need to improve the particle retention characteristics of the trap and the procedure for voltage conditioning. These are discussed in the next sections.

CGIT AC CONDITIONING

CGIT systems have to pass a field voltage test prior to service. This is usually an ac test at 75 percent of the ac factory test level. A study was made to determine the most effective way of applying this test voltage in order to condition the system by migrating particles into the designated areas, i.e., traps, under controlled conditions. Three alternative techniques were evaluated:

- ramping the voltage to the test level.
- increasing the voltage in discrete steps until the particles were trapped and then ramping the voltage to the test level.
- increasing the voltage in discrete steps up to the test level.

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Tests were made in a 242 kV size CGIT model mounted on a 0.5° slope. The section contained a tri-post cast epoxy insulator which was mounted either with a particle trap, as shown in Fig. 3, or without the trap. The system was contaminated with thirty particles of each length of 1.6 mm, 3.2 mm, 6.4 mm and 12.8 mm. This contamination level of 120 particles was an extremely severe test to evaluate the traps.

In the first test series the voltage was ramped at 2 kV sec⁻¹ up to breakdown or to a maximum of 350 kV rms and held for 3 minutes. Figure 6 shows the results of the breakdown voltage as function of the number of voltage applications. The results obtained without the trap around the insulator for the ramp voltage had low breakdown levels. These were caused by the longer particles in the group. Although the short particles migrated past the insulator, the longer particles remained under the insulator and initiated breakdown. In an attempt to remove these particles the voltage was held constant at 100 kV rms, approximately ten percent above the lift-off voltage. During this period five breakdowns occurred and the particles were not removed. Similar results were obtained at 120 kV rms and 140 kV rms. The latter voltage level is the same as the line-to-ground voltage for the 242 kV system. The longer particles could not be removed by the voltage and the system had to be opened in order to remove them.

Fig. 6. 60 Hz breakdown voltage of 292/102 mm coaxial electrode system with and without particle trap and with free conducting particles. SF₆ pressure 440 kPa.

The test was then repeated with the trap surrounding the insulator, still with the voltage ramp. The breakdown voltage levels (Fig. 6(a)) were the same as those for the contaminated electrode system without the insulator and trap. The breakdowns occurred from particles that had moved to the conductor outside the trap region. The particles were being trapped during the voltage ramps but seven breakdowns occurred before 350 kV rms could be held for 3 minutes.

In another series of tests, using the same insulator and particle trap system, the voltage was increased in steps of 20 kV rms from 100 kV rms. The voltage at each step was held for one minute. When all the particles were observed to be trapped, the voltage was ramped at 2 kV sec⁻¹ to 350 kV rms. If breakdown occurred before

this, the voltage ramp was reapplied from zero. The results of a typical test series are given in Fig. 5. The cause of these breakdowns, as discussed previously, were particles which came out between the trap and the enclosure. These particles were initially trapped at the edge of the trap.

Conditioning tests were then made where the voltage was increased in 20 kV rms steps from 100 kV rms up to 300 kV rms, then ramped to 350 kV rms. With this test procedure it was possible to reach 350 kV rms without breakdown. This was never achieved with the other above-mentioned procedures. If the particles were pulled out from the trap edge they could result in breakdown if this happened in the upper voltage range of the conditioning procedure. However, because the voltage was kept constant, the particles were also easily trapped again within a few seconds.

It should be noted that these tests were made under unrealistically contaminated conditions with 120 particles in order to elucidate the mechanism by which particle traps operated and their mode of failure. The results showed that particle traps are an important factor in achieving reliability in CGIT systems and in preventing particles from contaminating the insulators when mounted around them. The beneficial effect of particle traps around the insulators has also been confirmed by Boggs (Ref. 8).

These tests demonstrated that it is preferable to condition the CGIT system through a number of voltage levels, starting just above the particle lift-off level and increasing the voltage in steps of 10% to 20%. The results in Fig. 4 also show that the lower voltage levels should be held for longer times than the higher voltage levels: e.g., thirty minutes, decreasing to one minute at the field test level. A different conditioning procedure may be necessary for systems which do not incorporate particle traps.

TRAP RETENTION

It was observed that particles could escape from the trap region after having initially been trapped, not only in the elevated trap discussed above but in traps designed into the sheath (Ref. 5) and also in the corrugated sheath. Tests with the elevated traps under dc and ac conditions showed that particles in the low field region under the trap often were in motion when other particles were bouncing on the trap. This motion of the particles was found to be particularly serious with dc voltages even when no particles were free in the system. Under dc conditions the trap could be completely emptied for particles which sometimes resulted in breakdown. This occurred at 300 kV dc, but might also occur at lower voltage levels given sufficient time.

The apparent reason for these phenomena is gas flow into the trap region as a result of ions being moved by the field in the gas. These ions are produced by discharges in the system.

One method of solving the particle retention problem was by sealing the ends of the trap using a barrier between the trap and the enclosure. An alternative method involved the use of an adhesive material applied to the surface of the enclosure underneath the particle trap. This method was extremely effective in retaining the particles both inside the trap and at the trap ends for ac voltages as well as for dc voltages. It proved to be a significant contribution to the reliability of the particle traps. The adhesive coating was also tested in a corrugated sheath with excellent results for both ac and dc voltages. Thus, the use of adhesive materials in any low field regions designed for particle trapping in CGIT systems is of major importance for the enhanced reliability of such traps. Adhesive systems are under development for compatibility with the SF₆ gas and the enclosure material and which maintain their adhesive properties in excess of forty years.

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CONCLUSIONS

Alternative conductor bundle and corrugated sheath designs for CGIT systems have been investigated in order to determine if these provide a system more tolerant to the presence of contamination. Although these designs showed some merit compared to the conventional CGIT designs, none of them resulted in sufficient improvement to allow systems to operate reliably at higher stresses than at the present. The position of discrete particle traps at the support insulators was shown to offer significant protection of the insulators against particle contamination and failure, thus increasing the reliability of the system. Significant improvements of the particle traps were achieved by the use of an adhesive material in the trap cavities both for ac and dc voltages. Tests showed that it is preferable to condition CGIT systems which incorporate particle traps through a number of voltage steps before applying the ac test voltage.

The application of the hybrid electrostatic-adhesive traps in combination with an effective voltage conditioning procedure offers the prospects of improved reliability for CGIT systems.

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