EXPLOSIVE FAILURE OF 230 kV AIR BLAST CIRCUIT BREAKERS AT CHERRYWOOD TS: THE CAUSE AND THE CURE

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SUMMARY

In September, 1987, two 230 kV CGE type AT air blast circuit breakers at the Cherrywood Transformer Station failed explosively within a one week period. The root cause of failure was attributed to excessive moisture contamination within the 7000 kPa compressed air system. Due to the nature of these two failures, extraordinary measures had to be expended to ensure adequate protection for personnel while rehabilitating the remaining circuit breakers and the associated air system.

This paper discusses the detrimental effects of moisture in a high pressure air system, the problems encountered in establishing reliable moisture monitoring systems in a switchyard of this size, and the need to initiate further research to develop a better understanding of the effects of moisture on insulating materials under high pressure conditions.

KEY WORDS: Air Blast Circuit Breakers; Tracking; Moisture; Compressed Air Systems; Hygrometers

Canadian Electrical Association
Engineering and Operating Division Meeting

Montreal, Quebec
March 21, 1988

INTRODUCTION

The Cherrywood Transformer Station, located East of Metropolitan Toronto, is the most important, and largest of all transformer stations within Ontario Hydro. The station contains twenty-seven 230 kV and 500 kV line terminals including the entire 4800 MW output of the Pickering Nuclear Generating Station. The station serves as a critical tie between the 230 kV and 500 kV systems and links all Eastern provincial hydraulic generation to the power system.

The 230 kV switchyard consists of 12 oil circuit breakers and 32 air blast circuit breakers arranged in 13 diameters. The air blast breakers are operated through a dual compressed air system extending radially from two compressor buildings. Although the air system was originally designed to be operated in a split fashion, the dual systems were tied together some time ago to provide greater flexibility in operation. Over the 17 years of service, this equipment has performed reliably, with minimal amounts of maintenance.

In late September, one of the air blast circuit breakers failed explosively. Initial examinations indicated a problem with the air column assembly. This porcelain air column supplies both low pressure insulating air at 515 kPa to the breaker entrance bushings and high pressure control air at 4200 kPa to the interrupting chamber. The high pressure control air is isolated from the insulating air via a fiberglass tube. As well as containing control air, this tube also houses the control rod which actually operates the interrupting mechanism. Under normal operating circumstances both the tube and control rod are required to withstand full line to ground voltage. A single pole of the breaker, showing the air column assembly has been illustrated in Figure 1.

Although failures of this type had been experienced by other utilities, the Florida Power Corporation being most notable, they were nonexistent within Ontario Hydro, and thus was treated as an isolated event [1],[2]. Priorities were placed on restoring surrounding equipment back to a reliable level of service since flying debris had extensively damaged nearby insulators, bushings, support column insulators and air columns.

Less than one week later, a second air blast circuit breaker exploded violently. Again the cause of failure appeared to be associated with the air column assembly. Due to the serious nature of these explosions, all planned work within the 230 kV switchyard was halted, access to the yard was restricted to emergency switching only and additional resources were brought in to assist in determining the mechanisms behind the two breaker failures.

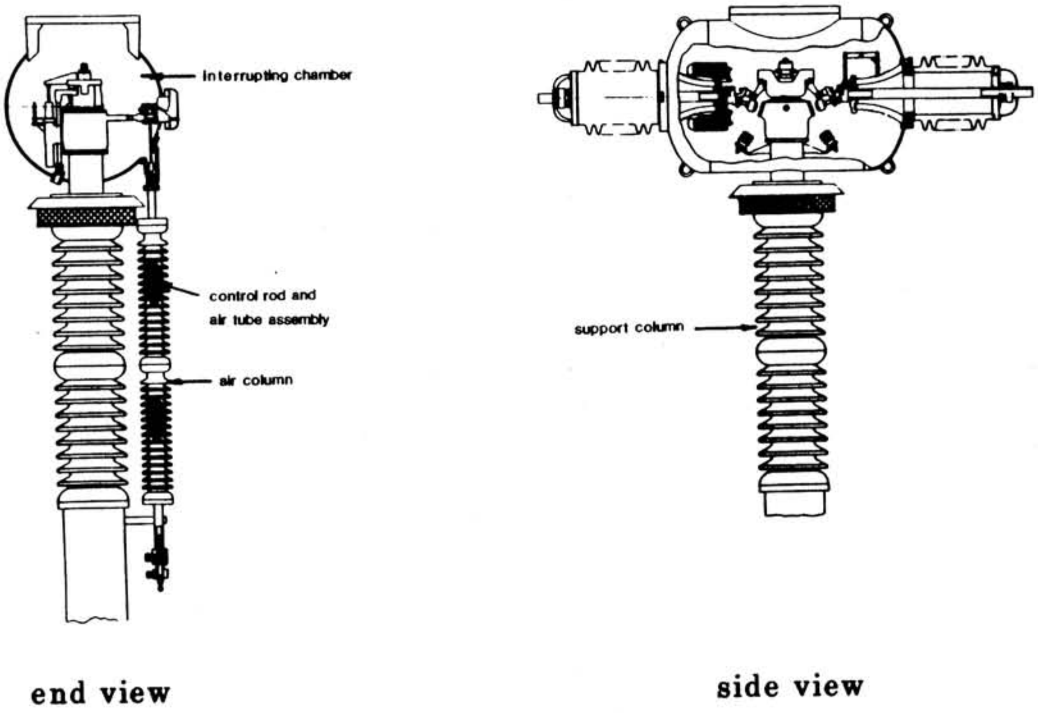

Fig. 1 CGE AT air blast breaker - single pole

THE CAUSE

Mechanism of Equipment Failure

In order to ensure reliable operation of the air blast circuit breakers it is essential that the compressed air is free from contaminants and that it contains very minimal amounts of moisture. Since the air which exits the compressors is 100% saturated with moisture vapour, a reduction of relative humidity is required to make the air suitable for operation.

In Ontario Hydro, chemical dryers are primarily used to remove the moisture vapour from the compressed air. The dryer units consist of dual chambers filled with activated alumina. While one chamber is in the process of drying the air, the other chamber is drying out or regenerating the desiccant bed. This operation is continuously cycled from one chamber to the other to provide a constant output of dry air.

Over a period of years, the desiccant in these dryers gradually begins to show signs of deterioration. In addition, any minor malfunction of the oil filters upstream in the air lines, or of the regeneration purge valves could drastically reduce the overall efficiency of the dryers by contaminating the desiccant with a fine oil film, or by causing the desiccant bed to fluidize or break up, respectively. This desiccant had never been replaced nor had it been inspected regularly and as a result allowed two dryers to deteriorate to the point where they became totally ineffective in eliminating moisture from the compressor output stages.

In addition to this equipment malfunction, it was discovered that a high dew point alarm relay had been inoperative for some time, and that dew point measurements taken over the last several months contained significant errors.

Consequently, moisture slowly progressed through the entire air system and contaminated all components. The most critical of these components were the fiberglass air tube and control rod assemblies. As the ambient temperature fluctuated through a normal daily cycle, the dew points were frequently exceeded and the moisture vapour would begin to condense onto all interior surfaces of the air system. The condensed vapour droplets on both the rods and tubes created distortions in the surface voltage stress and initiated discharges or scintillations. The heat from these discharges, over an extended period of time, gradually eroded the organic insulating material and released free carbon which formed dendritic paths or carbon tracks along the insulating surfaces. Some insulating components removed from service showed signs of severe tracking (see Figure 2). This degradation slowly extended along the surface of the rods and tubes until a point was reached where neither could withstand line to ground voltage.

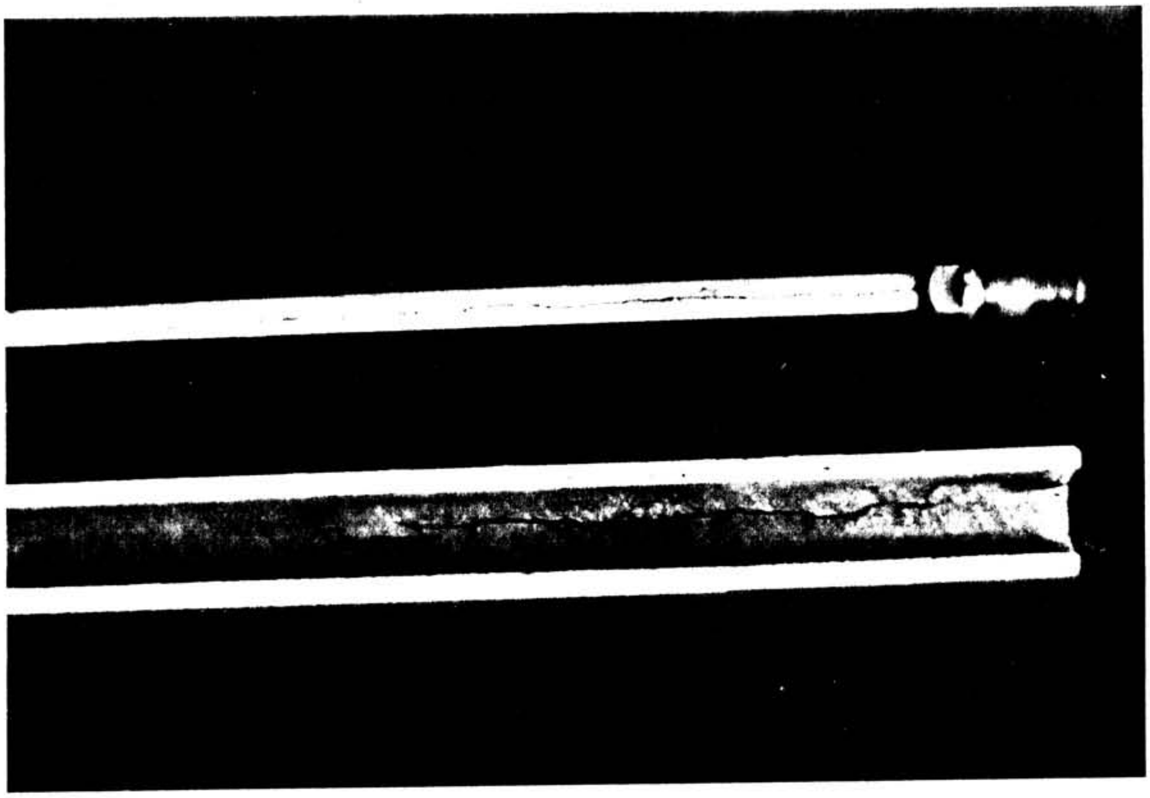

Fig. 2 Electrical Tracking Along Control Rod and Air Tube

When this tracking phenomena finally led to the flashovers at Cherrywood TS it ruptured the 4200 kPa air tube which in turn shattered the porcelain air column insulators, as illustrated in Figure 3. Initial calculations indicated that the explosive force of the failures propelled the shattered porcelain projectiles through the switchyard at a velocity exceeding 71 m/s. Consequently, special measures had to be put in place to ensure the safety of personnel required to rehabilitate the air system within the switchyard.

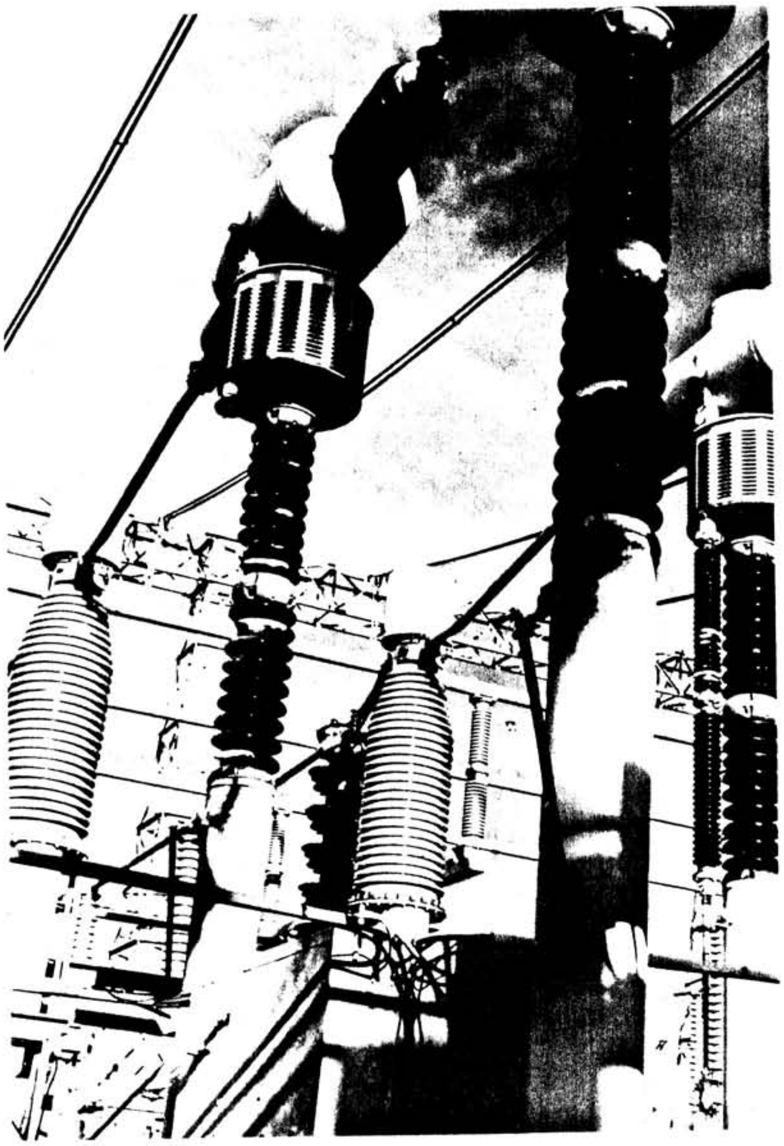

Fig. 3 Cherrywood TS Air Blast Breaker Failure

Moisture Monitoring Problems

Determination of the air system moisture levels in both the compressor buildings and in the switchyard was hampered by problems with the moisture measurement instrumentation (dew point hygrometers). Inconsistent and unreliable moisture readings were obtained with both portable and permanently installed hygrometers. These factors led to an investigation of the moisture measurement equipment and the complete moisture measurement process.

The moisture monitoring system at Cherrywood TS was designed to continuously monitor moisture levels at a stage in the air system where the output of all individual dryers has been combined. Deterioration of any one of the dryer efficiencies must therefore be recognized quickly such that the suspect dryer can be isolated and repaired. The hygrometer installed at the continuously monitored point has alarm contacts which trigger an annunciation in the control room when the dew point exceeds a preset limit (Ontario Hydro's current requirement is for moisture levels less than 10 parts per million by volume (ppm(v)) of water vapour at the continuously monitored point in the compressor building).

All of the hygrometers installed at Cherrywood TS prior to the explosive failures used a thin film, aluminum oxide, capacitance sensor to detect water vapour concentrations in the sample air. The impedance of the aluminum oxide "capacitor" (the plates are gold and aluminum) varies with concentrations of water vapour in the gas being sampled. A measure of the sensor's impedance is processed to yield a dew point reading which can be converted to ppm(v) of water vapour [3].

Preliminary investigation showed that the following factors significantly affected the moisture measurement results.

i. Errors in moisture measurement due to temperature changes were found to be significant. Since the sensor is calibrated at room temperature (approx. 21°C), any deviation in ambient temperature will result in significant measurement errors. A 20°C shift in sample temperature can cause a shift in the sensor admittance curve equivalent to 3°C or 4°C dew point at high moisture concentrations. At the dry end, however, the shift can amount to 15°C or 20°C in dew point. This error indicated the need for temperature control or compensation for moisture measurement of a dry gas unless the sample temperature was maintained very close to room temperature [4].

ii. With age, especially if there are contaminants in the sampled air, the aluminum oxide sensor calibration drifts dry. The hygrometers at Cherrywood TS were reading dry when their calibration was checked after the failures. These optimistically dry readings created a false sense of security and allowed the deterioration of the air system and insulating components to continue insidiously. Other aging effects include instability and lack of repeatability. These effects can reoccur soon after calibration under certain conditions [5].

Another factor which becomes more significant as the sensor ages and slowly becomes more contaminated is an increase in response time. If the aluminum oxide sensor is exposed to atmospheric moisture and then a dew point reading in a dry gas is desired, the sensor can typically take hours to "dry down" before a stable dry reading can be obtained. This delay combined with the time required for the sample handling system to dry out, made spot check readings very time consuming.

Thus, the sensor requires frequent calibration and cross checking with an air sample of known moisture content to ensure that reasonable moisture readings are obtained.

iii. The moisture measurement sample handling systems originally installed at Cherrywood TS were found to be inadequate. A continuous flow of air is maintained across the sensor by varying the position of a valve at the outlet of the sensor block. If too much flow is allowed across the sensor, the cooling effect of the flow causes temperature errors similar to those described earlier. Although the dew point is a function of the pressure that the reading is taken at, there were no gauges in place to record the actual pressure across the sensor. Furthermore, there were no means to prevent moisture from contaminating the sensor block as a result of moisture diffusion from the outlet tube, and there were no filters installed in the sample handling system. Particulate filters are required to protect the sensor from contamination and hence allow longer time periods between sensor calibration.

iv. Ontario Hydro has set a moisture concentration limit of 10 ppm(v) as a standard for the high pressure compressed air systems. Since most of the existing hygrometers give readings only in dew point, conversions are necessary to compare these readings to our standard. Dew point readings at Cherrywood TS were taken at the full line pressure (approx. 7000 kPa) and then converted to either equivalent readings at lower pressures or to moisture concentration in parts per million by volume.

These conversions can be performed through the use of tables, slide rules and nomographs, provided mostly by hygrometer manufacturers, and are based on relationships which assume that the application of ideal gas laws are independent of pressure. Some of these aids claim that they can be used for converting dew points to ppm(v) at pressures of up to 69 MPa. Unfortunately, numerous graphs based on experimental data indicate that at elevated pressures, the relationships assuming ideal gas behaviour can no longer be used [3],[6]. Indications are that above about 1700 kPa the difference between nonideal and ideal conversions becomes significant and at 7000 kPa the difference in moisture concentrations can be as much as 40% at the 10 ppm(v) level. Figure 4 shows comparisons between the two types of conversions at different pressures.

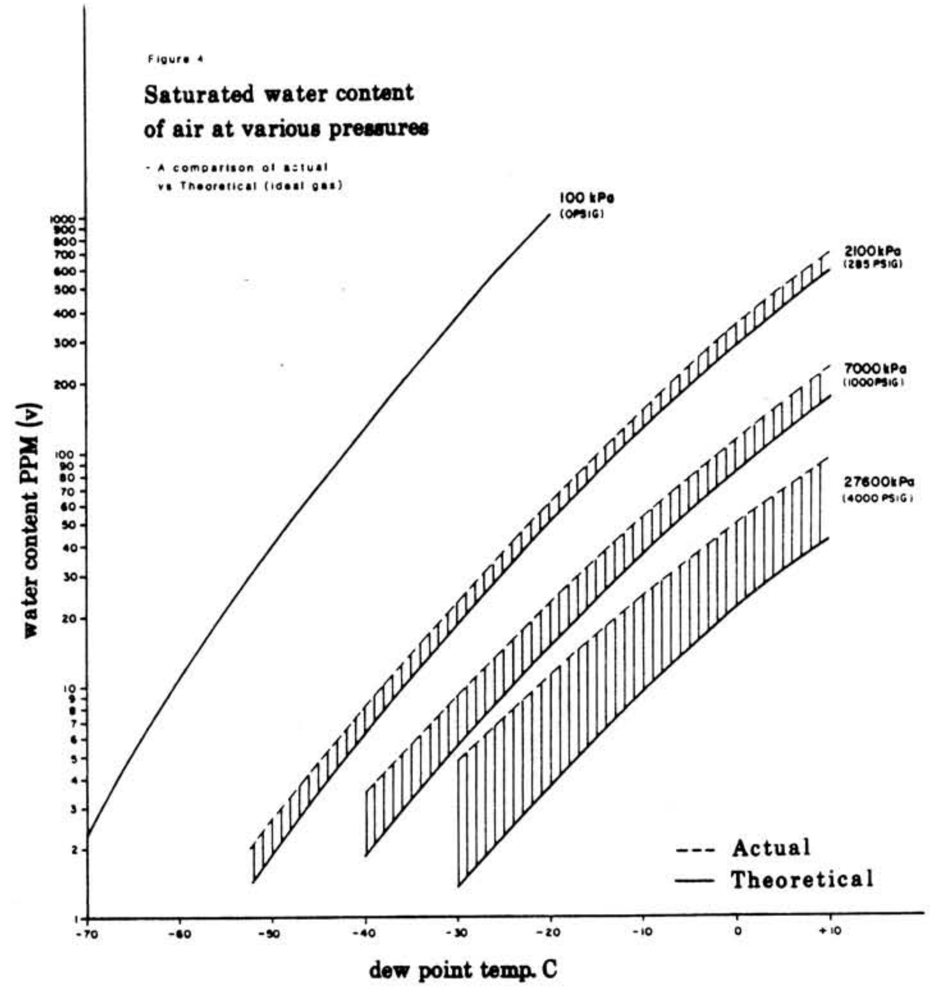

Fig. 4 Saturated Water Content of Air at Various Pressures

THE CURE

Moisture Elimination

With the entire switchyard in an unknown state of deterioration, it was imperative that moisture already present in the system had to be eliminated as quickly as possible. Using the few compressor plants still capable of producing dry air as a starting point, a plan was devised to purge the entire 120,000 cubic metre compressed air system over a period of 4 days. The air system was split into separate wet and dry supplies, and while the wet air system continued to supply the switchyard and all circuit breakers, the dry system was slowly built up and expanded through the systematic purging of all air lines and equipment.

The purging procedure utilized for eliminating moisture from the air lines consisted of exchanging the air in a particular section of pipe repeatedly until acceptable moisture levels were obtained. This process was slow and arduous since many sections of air line were buried under roadways and as such acted as natural water traps. In some cases this necessitated 15 or 20 purges before the moisture levels began to drop.

When purging the actual circuit breaker, a different approach was used. The purging was performed at pressures ranging from 800 to 1500 kPa since this increased the capacity of air to hold moisture. Furthermore, the introduced low pressure air was allowed to remain in the breaker for 30 minutes before repeating the procedure to allow moisture to be extracted from the body of the organic insulation.

Around the clock rotating shifts were employed to ensure the work would be finished on schedule, with minimal power system impact. The moisture concentration of the entire compressed air system was reduced to a level below 20 ppm(v).

Equipment Inspection and Repair

Although the elimination of moisture arrested any further tracking along the control rod and air tube assemblies, the extent of damage to the insulating material was undetermined until a visual inspection of all critical parts could be completed.

Through a series of extensive equipment outages, lasting a total of 12 weeks, every air blast circuit breaker was inspected internally, and had all air column assemblies removed, dismantled, inspected for corona activity, electrical tracking damage, or the presence of moisture. Both the tubes and rods were cleaned and hipot tested at 425 kV ac prior to being reassembled. Upon inspection, if any sign of deterioration was detected on either the control rod or the air tube, both components were replaced. Table 1 summarizes the extent of rod and tube damage.

Type of Damage	No. of Rods/Tubes Affected
Mechanical damage	6
Corona activity	10
Hipot failure	7
Electrical tracking	9
Initial failures	4
TOTAL:	36

TABLE 1: ROD AND TUBE DAMAGE

In addition to the above inspections, all dryers had the desiccant replaced, failed or damaged equipment was repaired, and the moisture analyzing equipment was replaced.

Revisions in Moisture Monitoring

Considering the moisture measurement equipment inadequacies discussed earlier, the age of the existing equipment, and the high cost of having another failure, it was necessary to investigate the replacement of our existing dew point hygrometers at Cherrywood TS and at other stations with similar air systems.

Correspondence with utilities, other companies and hygrometer manufacturers, identified competing technologies which are presently on the market. Earlier investigative work performed at Ontario Hydro Research Division as well as other published sources all indicated that hygrometers incorporating silicon technology were superior in accuracy, stability and response time over competing technologies [5],[7]. Silicon hygrometers equipped with temperature controlled sensors were therefore chosen as field replacement units.

The silicon hygrometer incorporates features and characteristics which best suit our application. Figure 5 shows typical wet-to-dry response times for the various sensor technologies. The fast response speed of the silicon sensor offers definite advantages when numerous moisture readings are required.

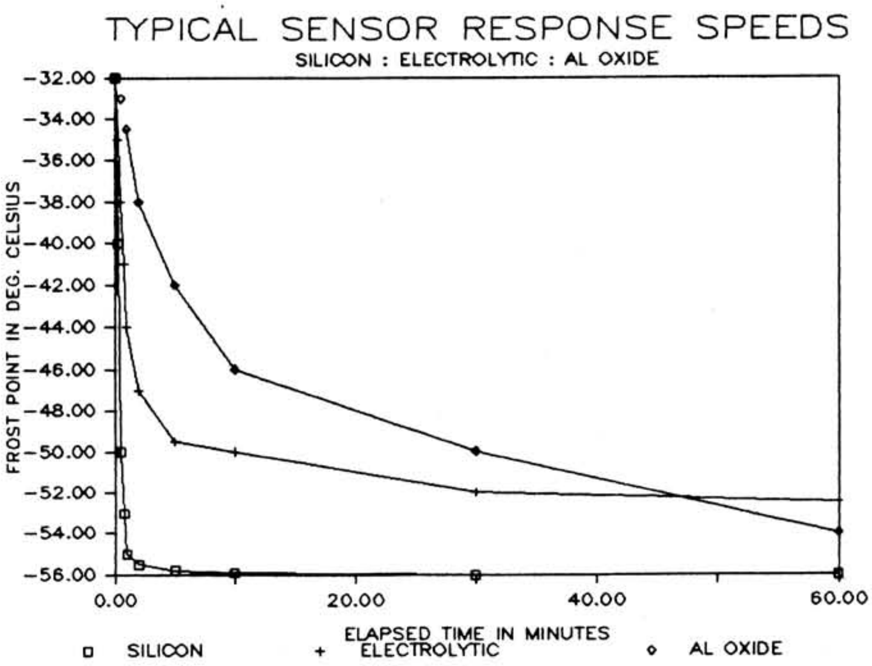

Fig. 5 Typical Sensor Response Speeds

Until confidence could be reestablished with the overall integrity of the compressed air system, a number of interim measures were introduced. The operation of similar compressed air plants have been verified at all other stations, weekly dew point measurements are being taken at random locations throughout the Cherrywood TS switchyard, and all moisture readings are being recorded for each sampling point. The logging of this moisture data will not only identify seasonal fluctuations that can be expected in an air system of this design but will also serve as a tool capable of predicting long term maintenance requirements.

Personnel Protection

Due to the explosive nature of the failures and status of the air system, work crews would not enter the switchyard unless two diameters adjacent to either side of the work zone were removed from potential. Outages of this nature required significant reduction in the output from Pickering Nuclear GS and was considered extremely undesirable from both an economical and system reliability point of view. In an effort to reduce the amount of equipment required out of service at any given time, several strategies were developed simultaneously.

Portable barriers consisting of a series of 3.5 m x 6 m blankets constructed from 3 layers of Kevlar were manufactured for use in the switchyard. The blankets were designed such that they could be fastened together and erected between equipment to provide a continuous barrier, extending along an entire three breaker diameter. These portable barriers, capable of withstanding impacts exceeding 150 m/s, could be installed in less than one hour once some minor fastening devices were attached to nearby structural steel components.

To afford similar protection to staff working in aerial devices, 6.5 mm thick Lexan enclosures were designed and installed on all work platforms. A series of sliding panels allowed staff to still work on the electrical equipment while minimizing their exposure to potentially explosive hazards.

For those instances where staff were required to enter the switchyard for short durations or for performing minor work, bomb disposal suits were borrowed from the provincial police force. These suits were made from 18 layers of Kevlar, capable of stopping projectiles travelling in excess of 700 m/s.

The final strategy developed in an effort to minimize equipment outages consisted of paralleling 230 kV transmission lines and buswork to allow some critical circuits to be rerouted to different locations within the switchyard. Although numerous outages were required to place such bypass facilities in place, the overall benefits exceeded those of the aforementioned plans, and thus were relied on most frequently during the refurbishment work.

CONCLUSIONS

The ingress of moisture in a compressed air system can easily cause deterioration of organic insulating materials to the point of electrical flashover. This paper has presented findings on the detrimental effects of high moisture levels in such a system, the problems encountered in eliminating this contamination and the procedures utilized in reestablishing a dry, reliable air system.

Although limited equipment outages were possible to rehabilitate the overall air system, several rather unique measures had to be developed to ensure the safety of all personnel required to work in the switchyard. A number of equipment and procedural modifications described in this paper can effectively minimize the risk of such a future occurrence. In addition, training in moisture testing techniques as well as essential maintenance requirements for all personnel involved in working on compressed air plants will ensure that the integrity of the air systems shall be adequately maintained.

It has been recommended that further work should be initiated to develop a more thorough understanding of moisture behaviour in high pressure air systems. The long term effects of both moisture vapour and free water on organic insulating materials must be known in order to set accurate maximum allowable moisture concentrations in any air system. The factors which increase the capacity of air to hold water vapour at high pressures, and account for the nonideal behaviour of gases have been determined through experimentation, and need to be defined formally. Finally, the process by which moisture contamination is introduced into a pressurized system through small leaks, and the significance it has on the overall dew point requires further investigation.

REFERENCES

[1] N. Barbeito, and F.L. Reynolds, "ATB Column Failure Investigation", Paper presented at Doble Engineering Conference, 1983.

[2] N. Barbeito, "ATB Column Failure Investigation Follow-up Report", Paper presented at Doble Engineering Conference, 1984.

[3] R.P. Holloway, "Practical Humidity Measurement and Control in Gases at High Pressures", Moisture and Humidity 1985: Measurement and Control in Science and Industry, Proceedings of the International Symposium, pp. 1021-1025, April 1985.

[4] J.C. Harding, "Overcoming Limitations to Aluminum Oxide Humidity Sensors", Moisture and Humidity 1985: Measurement and Control in Science and Industry, Proceedings of the International Symposium, pp. 367-378, April 1985.

[5] A. Stephens, "Trace Moisture Analysis in Gases: Fact or Fiction", Engineering Digest, vol. 33, No. 1, pp. 43-45, January 1987.