THE GENERATOR CONDITION MONITOR AND ITS APPLICATION TO THE HYDROGEN-COOLED GENERATOR

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INTRODUCTION

The Generator Condition Monitor (GCM) is a sensitive real-time detector of submicron particles created by the thermal decomposition of coatings and insulation. Also referred to as a “Core Monitor” because it was originally designed to warn of core overheating caused by circulating currents between laminations, the monitor’s applications have been extended to include all forms of overheating sufficient to produce thermal degradation.

The onset of particle production, as an organic material is heated, occurs at a temperature characteristic of the material and its surrounding atmosphere. Below this temperature, no particles can be detected; yet once the critical temperature is reached, millions of submicron particles will be generated each second for every square centimeter of surface. C.B. Murphy and co-workers[1] reported the results of tests in which the particle threshold temperatures of polymers were determined and compared with data obtained from differential thermal analysis (DTA) and thermogravimetric analysis (TGA). The resulting thermoparticulate analysis (TPA) curves of particle concentrations versus temperature showed decomposition temperatures comparable to the other techniques, with better reproducibility in many cases. This indicates that, by detecting particle generation from materials, the initiation of thermal degradation can be determined.

DETECTION OF SUBMICRON PARTICLES

Two basic methods are in use for the detection and measurement of submicron particles. One method takes advantage of the phenomenon by which water can be made to condense on the particles (for which reason they are also called condensation nuclei). The sample stream is humidified and then expanded adiabatically. The resulting supersaturation causes the excess water to condense on the particles, each of which becomes the center of a growing water droplet. In a few milliseconds, the droplets grow large enough to be detected optically by their light-scattering or attenuation properties. This virtually noise-free amplification from an invisible particle to a relatively large droplet permits the design of instruments having a wide dynamic range, from a hundred or fewer particles/milliliter to several million. By cycling the expansion at a rate from once to several times a second, a continuous reading of particle concentration can be obtained. This type of instrument was used in early feasibility rests on generators and helped confirm the important fact that the submicron-particle background of a normal machine is negligibly low, if not zero.

Submicron particles can also be detected by their influence on the output current of an ion chamber, arranged to collect the small ions produced by a radiation source in the gas stream containing the particles.

In the absence of particles, almost all the ions are collected, resulting in maximum output current of a magnitude determined by the strength of the radiation source, the ionization properties of the gas stream, and the flow rate. With the particles present, some of the ions combine with them. Because the particles are much larger than the ions, the mobility of the resultant charged particle is less, and only a few are collected in the ion chamber. The result is a decrease in the output current of the ion chamber, this decrease being a function of the particle concentration and particle size.

This method can be used in a closed-loop which permits returning the sample gas stream to the generator and is the method used in the GCM. Because of the low pressure drop in the ion-chamber detector, adequate gas flow can be obtained from the pressure differential within the generator so that no pumps or blowers are required. Because it alarms on a drop in output current, the system is inherently failsafe in that the current will also drop if the gas flow through the detector is accidentally shut off.

ION-CHAMBER DETECTOR THOERY

A detailed analysis of the ion-chamber design employed in the Generator Condition Monitor, and covered by a United States Patent issued to the author2, appears in Reference 3. A simplified expression for the change in ion-chamber current due to the presence of particles is:

EQUATION 1

–?I = Qe (1 – Fc) r Z/2?
?? ? change in ion-chamber current due to presence of particles, Amperes
Q = flow rate, ml/s
e = electronic charge = 1.6 x 10-19 coulombs
r = particle radius, cm
Fc = fraction of particles which become charged; f(r)
Z = particle concentration/ml
? ? self-recombination rate of ions, 1/6 x 10-6 ion pairs/ml/s

The normal ion-chamber current, Io, with no particles is:

EQUATION 2

Io = Qe
q = birth rate of ions, ion pairs/ml/s

Equations 1 and 2 can be combined to give an expression in terms of the ratio ?I to Io:

EQUATION 3

$$\frac{?I}{Io} = (1 – Fc)\ rZ/2$$

These relationships are based on the assumption that the particles and ions are together long enough for the interactions between them to come to equilibrium. This time is in the order of six seconds and must be considered in the design volume of the ion chamber and the flow rate.

From equation 2 it can be seen that the normal ion-chamber current is determined largely by the volumetric gas-flow rate Q. The ion birth rate is determined by the strength of the radioactive source; and, although this remains constant, there is some evidence that, for low hydrogen pressures (below 25 psig), the value of q is reduced because some of the alpha particles traverse the chamber without creating ions. There is also evidence that, for increasing pressures, the value of ? is increased because of the reduced mean free path, which results in more ion recombination.

The value of 1.6 x 10-6 for ??is the generally accepted constant for air. However, the currents Io for air and for hydrogen pressures from 30 to 100 psig are within about +/- 20%, providing flowmeter readings are corrected for density and the actual volumetric flow rate is used. This leads to the conclusion that using the same ??for air and hydrogen would not cause serious errors.

GENERATOR CONDITION MONITOR DESCRIPTION

A schematic diagram of the GCM is shown on Figure 1. The gas from the generator first passes by a test particle source. This source, consisting of a coated heater wire, can be energized to create particles to test the operation of the system. The flow is monitored by a variable area flowmeter which also incorporates a valve to control the flow. The gas then goes through a solenoid valve, which, in its normal position, causes the gas to bypass a particle filter and go to the ion-chamber detector.

The ion-chamber detector consists of an ionizing section and a separate collecting chamber. The ionizing section contains an alpha source of Thorium 232, which produces 3.00 MeV alphas and has a half life of over 10^{10} years. Total activity is less than one microcurie. The collecting chamber contains an electrode maintained at –10 Volts (actually obtained from the electrometer power supply) which causes negative ions to be driven to the collector.

These ions produce the current Io, typically in the range of 4 to 8 x 10^{-12} Amperes. This current is amplified by a sensitive current amplifier (electrometer). The output of the electrometer goes to a recorder and to an alarm circuit which initiates an alarm when the output current drops below a specified level.

In the event of an alarm, the solenoid valve can be actuated so that the gas will pass through the filter. If the alarm is real and particles are present in the gas, they will be removed by the filter, and the electrometer output current will return to its normal Io level. In this manner, positive confirmation of an alarm condition can be obtained.

A photograph of the GCM is shown on Figure 2. This model has a meter instead of a recorder on its front panel because it is intended for use with a remote recorder which can be located in the station control room. The test particle source, a particle-filter solenoid, and alarm reset can also be controlled remotely.

Figure 3 is an interior view with the cover removed, showing the locations of the electrometer/alarm circuit controls and other components.

THE GCM IN USE

Connections between the GCM and the generator are usually half-inch pipe. Because gravity and inertial forces have negligible effects on submicron particles, piping bends and lengths up to 100 feet will have little influence on signal levels. The transport time in 100 feet of half-inch pip is about 20 seconds so that this length should not be exceeded because of possible coagulation losses of the extremely small particles (.001 micron and under). Minimum pressure differential required at the monitor is six inches of water. Of course, no devices such as driers or filters which would remove particles should be installed in series with the inlet line. If a drier is connected in parallel with the monitor, its effect on the pressure drops in the piping should be checked out so that flow changes through the drier (as when it is being reactivated) will not affect the flow through the GCM enough to trigger the alarm.

For convenience, the variable area flowmeter used is a standard air-calibrated instrument with a 0-to-20 scale so that with hydrogen at varying pressures the scale is only an arbitrary reference. Usual practice is to adjust the flow to about 15 on the scale with the generator pressure at its normal operating level. At 70 psig, this corresponds to a hydrogen flow rate (at standard conditions) of 60 liters/minute ($2ft^3$/min), and a true volumetric flow of 12 liters/minute (.4 ft^3/min). The electrometer gain is then adjusted to produce an output current, Io, of 80% of full scale on the recorder or panel meter The alarm level is usually set at 50%.

Once these adjustments have been made and, if the hydrogen pressure in the generator remains fixed, the recorded output current will stay constant as long as no particles are present. (A change in generator speed will also affect flow, but this is usually not a variable except in machines undergoing tests.) However, at some installations, the hydrogen pressure is allowed to vary. Figure 4 is a plot of Io versus hydrogen pressure, if the flowmeter is kept at a constant setting by adjusting the flow control each time the pressure is changed. This variation of Io is due to several factors.

The increase between 0 and 25 psig is thought to be due to an increase of q (Equation 2) because of a lack of complete ionization at low pressures. The reduction beyond 25 psig is partially due to reduced volumetric flow rate and partially to an increased ion-recombination loss (?, Equation 2) with increasing pressure. However, if the flow control valve is not adjusted so that the indicated flow is allowed to change with hydrogen pressure, the variation of Io will be less, as shown by the broken line of Figure 4. If the initial adjustments are made at a hydrogen pressure midway between the expected extremes, the normal output current should stay in the “safe” zone, above the 50% alarm point, if no further adjustments are made. This of course will vary the margin between the normal and alarm levels. However, because the initiation of particle production is essentially a go-no-go proposition, the only effect will be a small change in heated area before the alarm level is reached. If it is desired to keep the alarm margin fixed, flow adjustments can be made to maintain a constant Io as the pressure varies. Whichever approach is followed–fixed flow setting with variable Io, or variable flow with fixed Io–it is recommended that the Io and flowmeter indications be recorded at several hydrogen pressures. A curve can then be plotted (Io versus psig or flow versus psig) so that the reference conditions can be established at any operating pressure, and in this way a gradual trend from normal can be detected.

Data from Reference 4 indicates that, with the recommended adjustments, the alarm level will be reached with a typical generator when an area in the order of two to three square inches is overheated. Some idea of the mass of material involved can be obtained by solving Equation 3 for the Z required to produce a $\mathfrak{I}$/Io of .375 (alarm at 50%, normal current 80%). This data is shown on Table 1, which gives the particle concentration and mass/100ft3 for several assumed particle sizes.

TABLE 1

Particle Concentration and Mass at Alarm Level

Particle Radius Microns	(1 – Fc)	Particle Concentration Number/Milliliter	Mass/$100ft^3$ Milligrams
0.005	.993	363,000	$.54 \times 10^{-3}$
0.01	.892	201,000	2.4×10^{-3}
0.1	.299	60,200	.71
1	.094	19,000	220
10	.09	2,000	24,000

A particle density of 1 g/ml was assumed, and a value of q of 36,000 ion pairs/ml/s was used. The term (1 – Fc) is also tabulated and was obtained from Reference 5. The mass/$100ft^3$ is based on the actual volume of compressed gas so that the mass concentration would be reduced under standard conditions. From Table 1 is can be seen that the mass concentration would be reduced under standard conditions. From Table 1 it can be seen that, although the ion-chamber detector sensitivity on a number-concentration basis is higher for the larger particles, on a mass basis the reverse is true. For submicron particles, a fraction of a milligram of a milligram of particulate material/100ft^3 of gas volume will produce an alarm, while for the larger particles, as much as 24 g/100ft^3 would be required. This indicates that any large particles which may be present in the machine due to mechanical abrasion, scale, etc., will have little effect on the GCM.

When an alarm condition is reached, the first step is to confirm it by energizing the solenoid valve which introduces the particle filter. If this causes the output current to increase to its original normal level, it can be reasonably expected that the alarm was triggered by particles. In this case, procedures which may have been established by the generator manufacturer should be followed. These will usually call for reducing load and possibly increasing hydrogen pressure to determine whether the alarm condition is marginal. Depending on the operating conditions, it may be possible to localize the fault to the armature or field by the load change or by varying excitation and power factor. As a further confirmation and localization of the fault, one of the sampling techniques now being developed by others[4,6,7] can be applied. These involve extracting a sample of the products of overheating from the gas stream and performing a chemical analysis to locate their origin. Such a sampling system can be combined with the GCM and the sample automatically extracted when an alarm condition is reached.

Generator Condition Monitors (or Core Monitors) have been in service for several years and have proven reliable and maintenance free, with little or no change in normal operating levels. There have, however, been reported instances where, due to an abnormal generator condition, excessive amounts of oil or moisture have entered the ion-chamber detector. These conditions can lead to deposits on the flowmeter float which will result in erroneous flow settings, or, if severe enough, to trapping of liquid in the ionization section of the detector. Because of the low energy of the alpha particles, excess liquid deposits on the source would reduce the ionization, causing a reduction of output. Because of the low current levels involved, the insulators in the ion chambers must have very low leakage, and moisture or oil deposits on them can increase leakage and reduce output current.

Many of these problems can be eliminated can be eliminated by problems can be eliminated by proper maintenance and installation. On those machines subject to excess oil or moisture in the hydrogen, the piping should be laid out using the practices for compressed-air lines; that is, horizontal runs should slope in the direction of flow, with a drain leg installed at all low points. At each drain leg, the succeeding length of pipe should start with a vertical tap at the top of the preceding section. In this way, condensed liquid will not remain in the pipes to form pools through which the gas will bubble and entrain fine droplets. To reduce these problems further, several types of liquid traps are being evaluated for installation at the inlet of the GCM.

CONCLUSIONS

The Generator Condition Monitor/Core Monitor is a sensitive and a reliable detector of overheating in a hydrogen-cooled generator. The use of integral test- and alarm-confirmation modes, as well as the application of a few simple installation and maintenance procedures, can make the operation virtually foolproof.

Its usefulness can be extended by sampling, or “fingerprinting,” techniques now being developed to localize overheated areas.

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