The Electro-Chemical Basis of Manhole Events

Key words: Manhole event, thermal decomposition, combustible gas, secondary cable, combustion, pyrolysis

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The article discusses the starting point for manhole events, defined as phenomena ranging from smoking manholes, fires, and cover blow-offs, as one that is mainly due to insulation failure of secondary cables, and for the most part, is the result of an aging infrastructure.

Introduction

The term "manhole event" refers to a range of phenomena which include smoking manholes, fires associated with manholes, and displacement of manhole covers as result of excessive pressure which can be caused by rapid evolution of gas within the duct/manhole or by rapid chemical reaction of gases within the manhole [1]. Manhole events can pose a danger to utility personnel or the public, although most are relatively benign [2]–[5]. More than 90% of manhole events involve nothing more than smoke, with a small minority comprising the most severe phenomena. Whereas some manhole events are caused by failure of primary distribution cable, the majority are caused by failure of unshielded cable in secondary network systems [6]–[8].

The advantage of secondary network systems is redundancy. Like the Internet, they provide so many "signal paths" that failure within the network generally does not cause loss of power to customers. The downside of this approach is that failures or load changes can occur which increase current flow through certain paths to the point that cables overheat. In time, this can cause the insulation to become brittle and crack. Exposure of such cracks to salt water, such as occurs in coastal environments or as a result of winter de-icing of roads, can cause electrical faults. In 2007, 71% of the manhole events on the Consolidated Edison system of 250,000 manholes occurred in structures containing mud, 11% in structures with water, and the incidence of manhole events was three times greater during the winter road de-icing season than at other times [9].

Because network systems are designed to deliver large amounts of power, fault currents in the range of 1000 A may not trip protection, with the result that substantial amounts of energy can be dissipated in the fault. Based on our analysis and knowledge of field conditions, we feel that manhole events can be divided into at least two classes, those in which electrical energy dominates and those in which exothermic chemical reactions dominate. The former tend to develop much more quickly than the latter, which are more likely to affect multiple manholes.

Based on this overview of manhole events, we concentrate discussion in this article on the thermal stability of secondary cable insulation, sources of energy during a manhole event, and mechanisms by which toxic and combustible gases can be generated.

Prior Work

Space does not permit an exhaustive literature survey; however, past work has focused on the mitigation of the hazard posed by rapid combustion of gases within a manhole. Some studies have focused on characterization of the secondary arcing faults [7], [10] and the development of arcing detection algorithms [6]; however, no effective arcing detection algorithms have been re-

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ported for secondary cable networks. Thermodynamic and mechanical analyses have been implemented to model the combustion process in manholes and compute the motion of manhole covers [11].

Reference [7] focuses on the evolution of manhole events caused by phase-to-phase or phase-to-ground electrical faults but does not provide a basis for explaining why some events result in "smokers" while others evolve to rapid combustion of gases within one or, as sometimes occurs, a series of connected manholes. To shed light on these issues, we will address various aspects of thermal-oxidative behavior of the materials which can be exposed to a secondary fault.

Material Properties

Manhole events develop as a result of thermal decomposition of organic materials present in the duct and manholes, including cable insulations, jackets, and duct wall material which can be wood, tar-impregnated cellulose, PVC, etc. At normal operating temperatures, these materials are quite stable; however, when overheated beyond their thermal stability, they can become brittle and decompose.

Thermal Aging and Tracking

The starting point for manhole events is thermal aging of the insulation which causes it to become brittle and crack. Modern secondary cables are typically insulated with a filled EPR (ethylene propylene rubber)-based insulation with roughly 30% inorganic content. The oxidation induction temperature (OITemp) for such cable is about 200°C (20 K/min, oxygen atmosphere). Older secondary cables are often insulated with filled SBR (styrene-butadiene rubber) which has an OITemp of about 150°C under the same conditions, which indicates that it is substantially less resistant to thermal degradation, i.e., it is likely to become brittle and crack more rapidly and at lower temperatures than the EPR-based insulation.

Once insulation becomes brittle and cracks as a result of thermal degradation, thermo-mechanical forces, etc., the cracked insulation must carbonize to provide a conducting path to initiate a fault, as the secondary voltage is much too low to sustain arcing. Tracking is promoted by salt water, as it provides a means by which dry-band discharge can occur across the surface of the cracked insulation. Salt water in combination with voltage is very effective at starting fires. For example, if two Cu strips are separated by a few cm on a piece of wood with 120 V ac between them, a fire can be started by spraying salt water on the wood. The fire which destroyed the Santa Barbara Pier is thought to have been started by failure of a distribution cable which applied distribution voltage to the salt water-soaked wood of the pier [12].

Tracking resistance can be assessed using ASTM D-495, *Standard Test Method for High-Voltage, Low-Current, Dry Arc Resistance of Solid Electrical Insulation* [13]. Under this test, the EPR-based insulation has a tracking resistance time of 64 s and its EPR-based jacket has a tracking resistance time of 136 s. The SBR insulation has a tracking resistance time of 33 s and its neoprene jacket has a tracking resistance time of 3 s. In this test, the severity increases more or less exponentially with the duty cycle, which changes every minute. As a result, tracking tends to occur soon after an increase in duty cycle. However, the difference in tracking resistance of the present generation of cable relative to the much older cable is dramatic, especially in the case of the jackets, as the older cable jacket has almost no tracking resistance, which makes it very susceptible to salt water-induced tracking.

Thermal Decomposition

Thermal stability of material is often evaluated by thermal gravimetric analysis (TGA) which measures the change in sample weight (for milligram-scale samples) as a function of sample temperature in a controlled atmosphere. Under anaerobic conditions, the decomposition onset temperature (the temperature at which the sample undergoes 1% weight loss) is about 300°C for the filled EPR-based cable (Figure 1) and 240°C for the SBR-based cable (Figure 2), while intensive thermal decomposition starts at 440 and 400°C, respectively.

Thermal decomposition can take place as a result of combustion or pyrolysis. Pyrolysis is defined as the chemical decomposition of a condensed substance by heating which does not involve an oxidative reaction, while combustion involves oxidation. Smoldering is a form of flameless combustion which can occur on the surface of solid fuel and is characterized by degradation of the polymer material, smoke, and a visible glow [14]. Smoldering combustion in a porous combustible material is generally oxygen limited [15].

Most polymers will burn in air, meaning that their combustion is highly exothermic, as is necessary for self-sustained combustion. The situation for polymers compounded with inorganic fillers is somewhat more complex, as the polymer tends to char or combust, leaving a layer of filler which impedes combustion. The conditions required for self-sustained combustion of polymeric materials in a cable conduit can be evaluated using a cone calorimetery test (such as ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release for Materials and Products Using an Oxygen Consumption Calorimeter* [16]). In this test, the specimen is subjected to an elevated heat flux in air. If the material starts burning within 10 minutes at a given heat flux

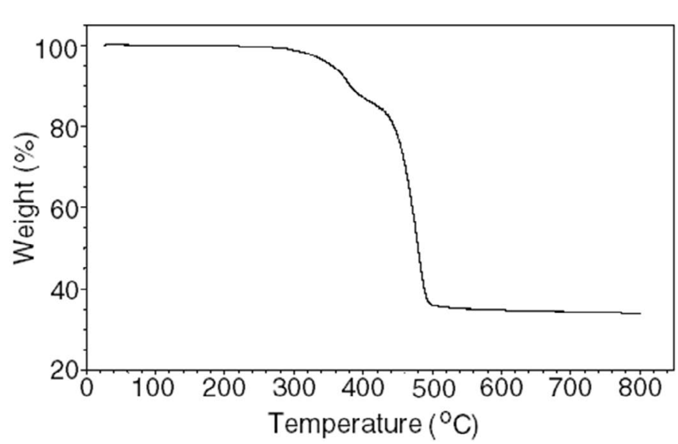

Figure 1. TGA thermogram for EPR cable dielectric. The heating rate is 20°C/min. and the purge gas is N_2.

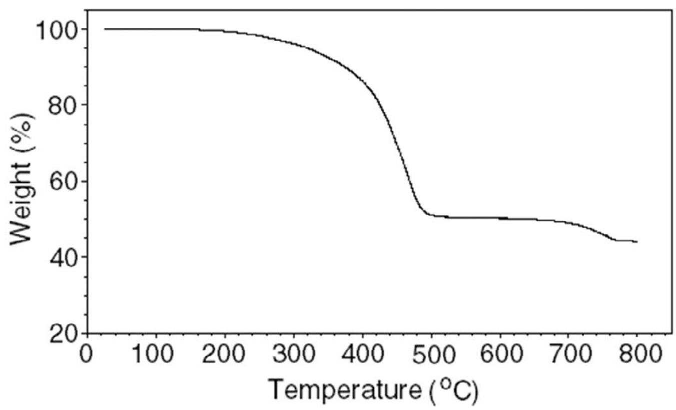

Figure 2. TGA thermogram for SBR cable dielectric. The heating rate is 20°C/min. and the purge gas is N_2.

level, the material is considered flammable at that heat flux, and the minimum incident heat flux which induces combustion within 10 minutes is defined as the threshold heat flux for initiating self-sustained combustion. Both EPR- and SBR-based secondary cables characterized using this test have a minimum incident heat flux of 15 kW/m^2, meaning that they are very similar in the context of fuel for a fire.

In addition to cable dielectrics and jackets, organic duct wall material can also participate in manhole events through combustion, if oxygen is present, or by pyrolysis in the absence of oxygen. Heat of pyrolysis is the net heat evolved or absorbed during the transition from the original reactant to the final decomposition products. Pyrolysis of most organic materials is endothermic; however, some older ducts are made from tar-impregnated cellulose which can be highly exothermic in pyrolysis. Mok and Antal [17] measured exotherms of 142 kJ/kg under charring conditions of cellulose, while Rubtsov *et al.* [18] measured an exothermal heat of decomposition under anaerobic charring conditions of 580 kJ/kg for microcrystalline cellulose.

Evolved Gases

As discussed previously, intensive thermal decomposition of polymeric material during the development of a manhole event can take the form of either combustion or pyrolysis. The most severe consequences of manhole events are caused by generation of combustible gas during thermal decomposition of polymers. Manhole covers can be displaced by rapid combustion of gases within a manhole leading to a rapid increase in pressure and temperature within the manhole structure. Manhole fires also involve ignition of combustible gas, but without a large pressure rise. Smoking manholes are caused by the incomplete combustion of gases, which can generate toxic gases such as carbon monoxide. By combining a thermogravimetric analyzer (TGA) with a residual gas analyzer (RGA), we have been able to identify gases produced during combustion and pyrolysis of polymeric materials found in secondary cable systems.

A schematic of our evolved gas analysis system is shown in Figure 3. The TGA provides a confined environment with controlled temperature, and measures the sample mass as a function of time, so that the weight loss as a function of time and temperature is known. The bypass of the exhaust outlet of TGA is connected to the capillary inlet of the dilution system of the RGA, which reduces the sample pressure to 10^{-6} torr before it is introduced into the mass spectrometer of the RGA. A stable positive pressure is applied to the inlet of the TGA sample chamber so that the RGA can sample the gas composition continuously. The sample chamber in the furnace is sealed to allow full control of the atmosphere to which the sample is exposed.

Material samples are taken from the secondary cable in the form of a cross-section in the radial direction through both the insulation and jacket. To simulate the anaerobic environment, N_2 or Ar is used to purge the sample chamber at a constant and controlled flow rate. The TGA can be programmed to heat the sample rapidly to the desired test temperature; however, the mass loss curve from the TGA suggests that for target temperatures beyond about 600°C, the milligram-scale sample is decomposed

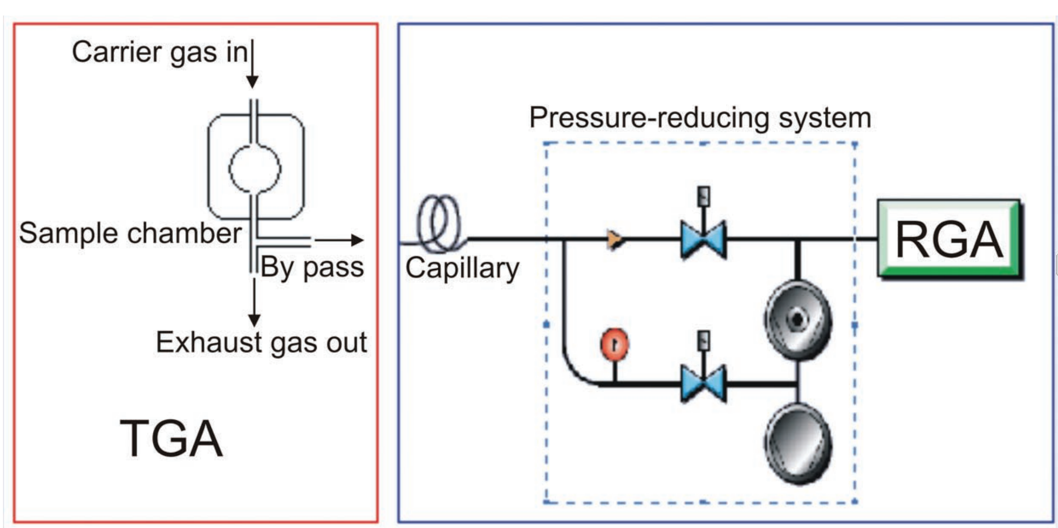

Figure 3. Schematic of evolved gas analysis system.

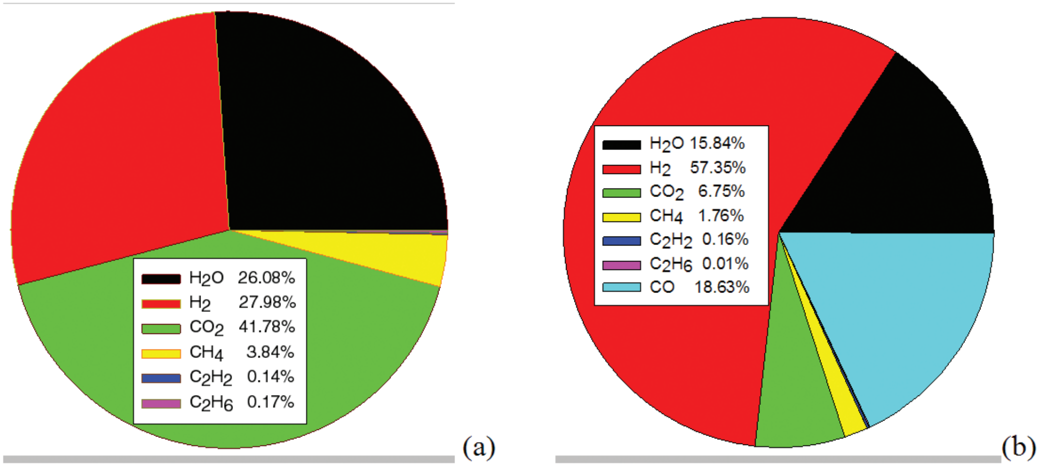

Figure 4. Composition of detectable gaseous products at 500°C (a) in air, and (b) in argon with 1% O_2. In air, CO cannot be identified using an RGA because of interference from N_2.

fully before the chamber temperature reaches the target high temperature. Experiments run at 300 to 600°C on samples from the SBR- and EPR-insulated cables reveal that H_2 is the only combustible gas detected during anaerobic decomposition.

Under aerobic conditions, the situation is more complicated because the oxygen concentration could range from that of air to near zero. Figure 4(a) shows the composition of gaseous products when the cable sample is decomposed in air at 500°C, which is below flame temperature of most combustible gases. Four combustible gases are identified, H_2, CH_4, C_2H_2, and C_2H_6, although the majority of the combustible gas evolved (90% by volume) is still hydrogen. The evolution of methane is an order of magnitude less than hydrogen, and the other two gasses are less than 1% of the total. When the oxygen concentration is reduced to 1% [Figure 4(b)], CO constitutes 25% of the combustible gases evolved, with the remainder dominated by H_2.

Classes of Manhole Events

We believe that manhole events can be separated into those driven by electrical fault energy and those driven by air flow through the duct that results in sustained combustion of the polymeric materials therein.

An Electrically Driven Manhole Event

A manhole event in New York initiated from a high-impedance line-to-line fault in a secondary duct. As a result of the electrical energy, the temperature near the fault location increased rapidly, causing rapid melting and vaporization of the copper conductor near the fault. The violent expansion of the copper and organic materials during vaporization and decomposition swept the air from the conduit, creating an anaerobic environment for subsequent decomposition of polymeric materials, so that pyrolysis dominated the decomposition processes. As a result, combustible gas accumulated rapidly in the manhole closer to the fault, resulting in a fire at the mouth of the manhole where the combustible gases met oxygen in the air. Shiny copper droplets dispersed along the conduit which were observed during field inspection tend to confirm an anaerobic environment. The event was made more severe by the exothermic pyrolysis of the tar-impregnated cellulose duct as a result of the arcing energy and molten copper lying on its surface, which contributed substantial additional energy and combustible gases to the event.

Combustion-Driven Manhole Events

The fire process in a horizontal, ventilated passage which contains an axial distribution of fuel is discussed in [19]. In this one-dimensional duct fire model, the propagating fire is broken into three zones, combustion, excess fuel, and preheating, as interpreted schematically in Figure 5.

If air flow through the duct is sufficient to create a sustained, propagating combustion zone, oxygen is consumed in the combustion zone, which heats the remaining gas to a high temperature. This gas then enters the excess fuel zone where the hot, oxygen-depleted gas causes at least partial pyrolysis of polymers, resulting in generation of combustible gases and leaving behind decomposed polymer and/or carbon which becomes fuel for the propagating fire zone. Carbonization of the polymeric material during pyrolysis leaves behind a porous surface which

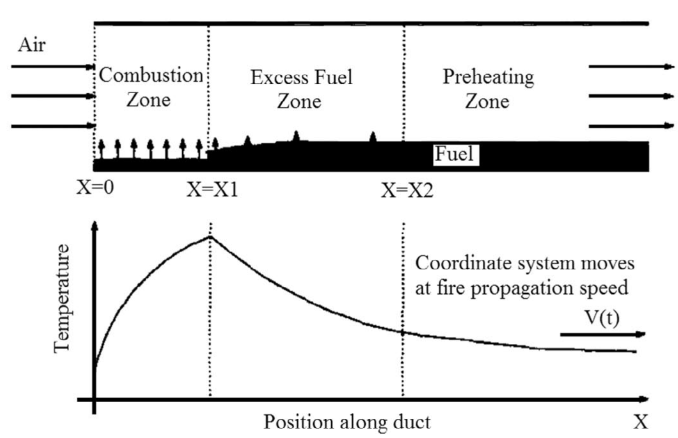

Figure 5. Model for one-dimensional duct fire propagation [19].

favors smoldering. Although fire propagation in an underground cable conduit may start with flaming combustion, it has a tendency to convert into smoldering while propagating. Stationary smoldering combustion occurs if sufficient heat is generated by oxidation of the char layer [20].

In contrast to the electrically driven manhole event described previously, two other 2008 manhole events in Manhattan, New York City [21], [22] progressed more slowly, with events in multiple manholes near the secondary fault. In these two cases, almost all the manholes affected by the event were aligned in one direction, along which some of the manholes had fires, some heavy smoke, some displaced covers, and a few had covers ajar. Gases and smoke moved through the ducts over relatively large distances, and both aerobic and anaerobic decomposition of organic materials was almost certainly involved in the development of these manhole events.

Comparison of Event Types

In the electrically driven event, the arcing energy is so great that it causes rapid vaporization of the copper conductor and nearby polymers, which sweeps the oxygen from the duct so the event evolves on the basis of electrical fault energy and pyrolysis. In the combustion-driven events, the electric fault energy ignited the cable insulation near the fault, resulting in self-sustained combustion as a result of air flowing down the duct. This establishes a fire front, which generates hot gases, causing anaerobic decomposition of polymeric materials downstream of the combustion zone resulting in generation of combustible gases. In this case, air flow through the duct plays an important role in evolution of the manhole event. If the air flow is sufficient to support a sustained combustion zone, as described above, sustained anaerobic decomposition of polymers beyond the combustion zone will generate large amounts of combustible gases over a relatively long period of time, which allows the gases to distribute more widely through nearby ducts to numerous manholes.

Minimizing air or gas flow rate in underground conduits should reduce the scale of the combustion zone and the fire propagation speed. We plan to study the relationship between gas flow rate and generation rate of combustible gas using both numerical and experimental approaches in future research to provide better insight into control of manhole event evolution.

Conclusion

The starting point for manhole events is dominated by failure of secondary cable insulation in network systems, which is, in part, the result of aging infrastructure with older cable dielectrics and jackets which have poor thermal stability and tracking resistance. The nature of network systems, which are so interconnected that current flow cannot be predicted accurately and changes over time with opening of protective devices, changes in load, etc., exacerbates cable degradation. Cracking of secondary cable insulation, especially in the presence of salt water, can lead to tracking of the insulation and a phase-to-phase or phase-to-ground fault. When the fault current is high, electrical energy can drive the manhole event, which can become severe within a few minutes. When the fault current is lower but air flow through the duct is sufficient, the electrical energy is likely to create a self-sustained combustion zone, heating the gas which passes through it to the fuel zone where the oxygen-depleted hot gas decomposes polymeric materials and generates large amounts of combustible gases, particularly hydrogen. Carbonization of the polymeric material during pyrolysis leaves behind a porous surface which favors smoldering, and smoldering can generate large amounts of smoke and toxic gases.

A general solution to manhole events is not obvious. We believe that the most catastrophic consequences of fire-driven manhole events might be lessened by controlling air flow through the ducts, although this has not been confirmed through experiment or numerical analysis.

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