GTI Laboratories
1700 S. Mt. Prospect Road
Des Plaines, Illinois 60018

Static Discharge Failure of PE Pipe for Connecticut Natural Gas Corp.

May 5, 2003

Submitted to:

Mr. Ron Klezos
Connecticut Natural Gas Corporation
P.O. Box 1500
Hartford, CT 06144-1500

Phone: (860)-727-3427
Fax: (860)-727-3072
Email: rklezos@ctgcorp.com

GTI Technical Contacts

Daniel A. Ersoy
Gas Technology Institute
1700 South Mount Prospect Road
Des Plaines, Illinois 60018

Phone: (847) 768-0663
Fax: (847) 768-0569
Email: daniel.ersoy@gastechnology.org

Josie Riggio
Gas Technology Institute
1700 South Mount Prospect Road
Des Plaines, Illinois 60018

Phone: (847) 768-0537
Fax: (847) 768-0569
Email: josie.riggio@gastechnology.org

CONTENTS

The results of the analysis are presented in the following sections:

1. DETAILS OF FAILURE

CNG requested that GTI perform a failure analysis on segments of high-density polyethylene pipe that contained pinholes. These samples were from a field failure - the details are listed below.

Squeeze-Off Procedure and Static Discharge at Job Site

On Friday, October 26, 2001 an emergency call was received at the Connecticut Natural Gas Corporation Customer Dispatch Center at 2:25 pm. The Unionville Fire Department reported a ruptured plastic gas line caused by a third party excavator. A 4-inch HDPE 3408 gas main, with an operating pressure class of 3-100, operating at 96 psig was severed in half, see Figs. 1 and 2. The 4-inch main was a "dead-end" system (important fact later) that served eight customers. The severed gas main had been blowing for about 1 hour before the line was shutdown.

Partial Print Line: "Plexco ® Plexstripe II 4" IPS SDR 11.0 PE 3408"

Upon arrival, the repair crew performed the following steps:

1) Excavated a separate bell hole 25-30 feet upstream from the line break to begin the squeeze off procedure to repair the severed gas main.
2) No bypass lines were used during the squeeze off and repair.
3) The area leading up to the bell hole was wet down.
4) The crew maintained a wet bell hole during the repair procedure.
5) A Mustang, manual hydraulic squeeze tool (model DBS-40) was selected and set for the 4-inch diameter HDPE pipe (SDR of 11.0).
6) A burlap cloth was wrapped around the PE pipe and grounded by covering the end with soil. The burlap was then wet down with a soapy water solution.
7) The squeeze tool was grounded and stabilized.
8) Squeeze off began at 1.5 turns/min and was successfully completed.

9) The pipe was repaired with a 4-foot section of HDPE 3408 pipe with two 4-inch electro fusion couplings. The cooling time was met and a purge point was set up.

10) As the purging operation began, the squeeze tool was released at approximately 0.5 in/min.

11) The static discharge occurred when the squeeze tool was 90-95% released and the main was line packed. Witnesses described a loud, cracking sound and instantaneous flash of light.

12) After the discharge a soap test was performed for leakage. The crew found a small pinhole leak, Pinhole 1, on the top of the pipe, centered at the squeeze off point. It was repaired using the same squeeze off technique as previously employed. [It is interesting to note that the same procedure that resulted in the first pinhole did not result in a second pinhole. As will be shown later in this report, there are many factors that can contribute to the likelihood of a static discharge (velocity of the gas during squeeze off relaxation, cleanliness of the gas, electrical conductivity of the surrounding area, quality of tool grounding, etc.)].

13) A few days later on Thursday, November 1, 2002, another pinhole leak, Pinhole 2, was found in a different location 4 feet upstream from the original pinhole leak. A tracer wire (3M Scotch Lock Connector) was located approximately 1 inch below the PE pipe at this location (the wire was closest to the pipe at the location of the pinhole). Standard CNG Construction Standards dictate the tracing wire be installed 6 inches below the pipe and be separated by stone free sand.

14) Repairs were made to this pipe using the same squeeze off technique, but this time a bypass line was used.

GTI received four pipe samples for analysis in our laboratories. The samples were identified by CNG as listed in Table 1 below. Fig. 1 is a schematic of the samples relative to the installed pipe segment.

Table 1 - Sample Label and Description

Sample	Location And Description
A_1	Portion of pipe severed by third party.
A_2	Mating portion of pipe severed by third party.
C	Pipe segment containing first pinhole, pinhole 1 (at squeeze-off point).
D	Pipe segment containing second pinhole, pinhole 2 (at point near tracer wire).

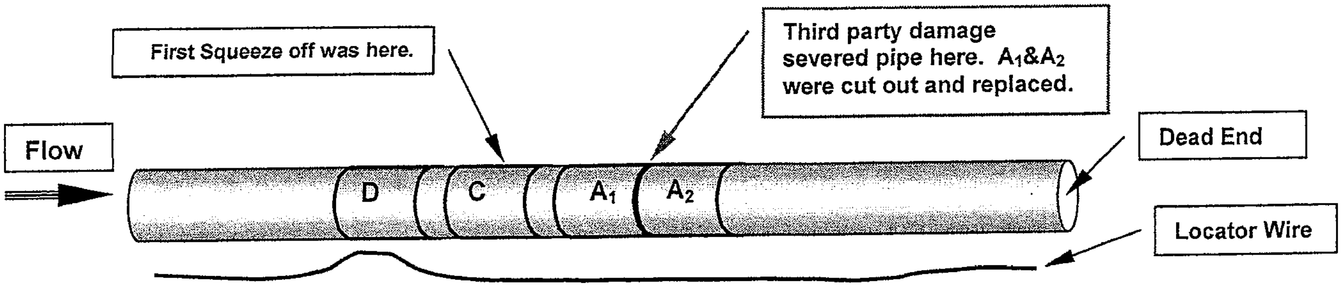


Fig. 1. Schematic of failure samples relative to pipe segment.

All pipe samples were digitally photographed as shown in Figs. 2-4 below. Samples C and D contained pinholes 1 and 2 respectively, see Table-2. These two samples were sectioned and the pinholes were examined with stereo-optical microscopy and scanning electron microscopy (SEM).

Table 2 – CNG Pinholes with their respective samples and locations.

Pinhole	Sample	Location
1	C	Found at squeeze-off point in wrinkles produced by squeeze off tool.
2	D	Found 4-ft upstream of pinhole 1, located near closest approach of the tracer wire.

Macroscopic Pictures

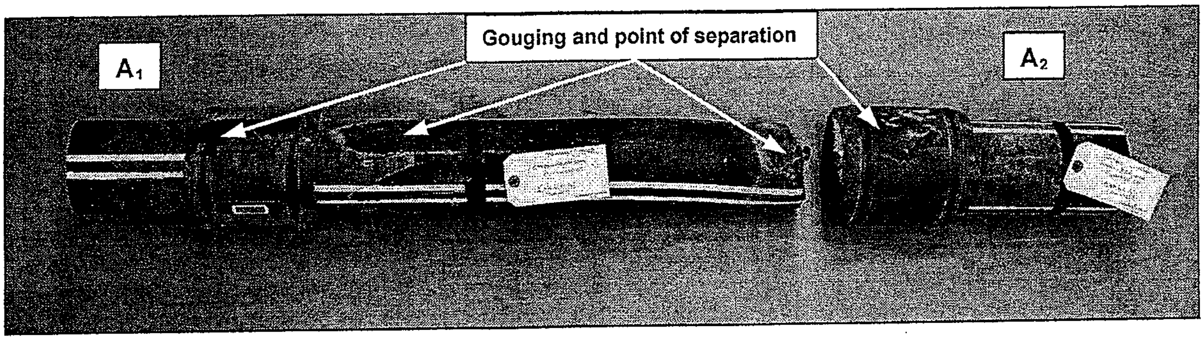
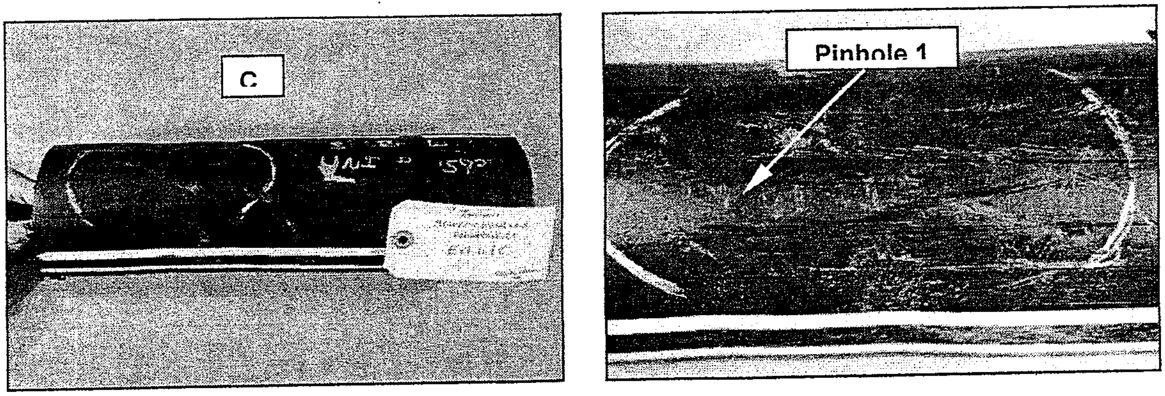
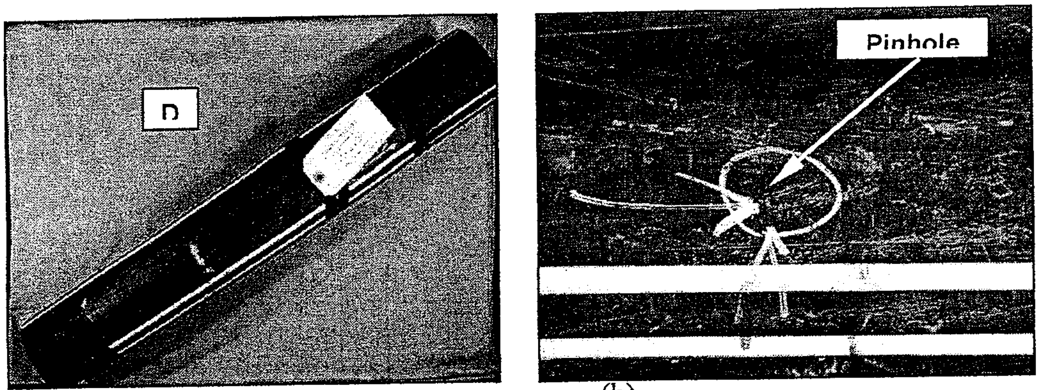


Fig. 2. Samples A_1 (left) and A_2 (right) as received. Severe mechanical damage/gouging from a 3rd party excavator can be seen along the length of the pipe (see arrows above).



(a) (b)

Fig. 3. Sample C as received (a) and close-up of area (b) with general location of pinhole 1 as determined by a soap bubble leak check.



(a) (b)

Fig. 4. Sample D as received (a) and close-up of area (b) with general location of pinhole 2 as determined by a soap bubble leak check.

2. Basic Electrical Properties of Polyethylene Pipe

The results from the analysis, conclusion and recommendations sections of this report will reference the information of this section.

Polyethylene is not an electrical conductor (i.e., it has no mobile electrons like metals do) and does not freely conduct electricity. It is therefore an excellent electrical insulator. Since polyethylene's carbon-carbon and carbon-hydrogen bonds have very low polar natures, they are essentially inert to electrical fields. The principal electrical characteristics of polyethylene can be defined in terms of resistivity, permittivity, dissipation factor, dielectric strength, and arc resistance. Those properties important to a static discharge event, of a polyethylene pipe undergoing squeeze-off, will be expanded below, followed by the modeling of the installed plastic gas pipe as a capacitor.

Resistivity (Bulk and Surface)

A material's electrical resistivity is usually defined in terms of (1) the bulk or (2) the surface conduction of current. Resistivity is really the resistance to electrical flow (electron movement) exerted by the material. The bulk resistivity is mostly a factor of the intrinsic nature of the polyethylene material and any additives. However, the surface resistivity is strongly influenced by superficial (surface) contamination. In particular, polyethylene is very sensitive to the presence of moisture, which reduces the surface resistivity considerably[1].

Dielectric Strength (Breakdown Voltage)

When electrical insulators (like PE) are subjected to an increasing potential difference, there is a point where the insulator will catastrophically "break down" and begin to conduct electricity. The "dielectric breakdown voltage" is the potential difference at which dielectric failure occurs, under specific conditions. The "dielectric strength" of a sample is the voltage gradient (i.e., volts/length) at which failure occurs. One could also say it is the maximum voltage a material can withstand without failing.

Charge can build up on one side of the material, but once the charge is enough to exceed the material's dielectric strength, the electrons will travel through the material to reach a lower voltage state. In the case of high-density polyethylene, the dielectric strength is found to be approximately 400-500 volts/mil.

In practice, dielectric strength or breakdown voltage is determined by applying an electric field across the insulator and ramping it at a fixed rate until failure (conduction of electricity and puncturing of the sample) occurs. Various metal electrodes are usually used with precise placement relative to a standard sample[2]. The manufacturer verified that the HDPE contained about 2.0-2.25% carbon black which would have no noticeable effect on the dielectric

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[1] Handbook of Polyethylene, Andrew J. Peacock, Dekker Press, New York 2000.

[2] ASTM D149 Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials (at Commercial Power Frequencies).

strength[3]. One would need about 20-25% carbon black additions before appreciable changes in dielectric strength or insulation resistance would be observed[4].

When failure of HDPE occurs from electrical breakdown, there is usually physical rupturing or generation of pinholes in the material that is frequently audible. A visible arc or flash will often be observed as well.

Dielectric strength varies with the thickness of the sample, temperature, and humidity. Thin pieces (a few mils thick) usually have higher dielectric strengths than thicker pieces (> 1/8 in.). As temperature and humidity increase the dielectric strength decreases. Dielectric strength is also time dependent, i.e. paths for current flow or discharge take a finite time to develop.

Static Charge Build Up In Natural Gas Lines

At its simplest, static electricity is an electrical charge that cannot move. It is created when two objects or materials that have been in contact with each other are separated. When in contact, the surface electrical charges of the objects try to balance each other. This happens by the free flow of electrons (negatively charged particles) from one object to the other. When the objects separate, they are left with either an excess or a shortage of electrons. This causes both objects to become electrically charged.

If these charges don't have a path to the ground, they are unable to move and become "static". If static electricity is not rapidly eliminated, the charge will build up. It will eventually develop enough energy to jump, as a spark, to some nearby grounded or less highly charged object in an attempt to balance the charge.

The outstanding properties of plastics, in general, and polyethylene, in particular, that favor their use for electrical insulation purposes create some distinct disadvantages related to static charge build up.

When polyethylene pipe conveying a compressed gas (e.g., methane) is being squeezed, the velocity of the gas flowing through the flattened area increases. The friction associated with the flow of a high velocity, dry gas, especially with particles present in the flow, can generate a static electric charge (by displacing electrons) on interior pipe surfaces that will attempt to discharge to ground[5]. It is not only moving particulates within the pipe that can cause static build up, but simply the flow of gas. Any obstacles to gas flow in the line can cause friction and in turn generate static. When a break occurs in the pipe wall, the charge on the inside pipe wall attempts to reach electrical neutrality by arcing to the surrounding ground. If there is no break in the pipe wall, then the static charge building up on the interior walls does not dissipate because it is residing on an electrical insulator[6].

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[3] Private communication with Mr. Mike Glasgow of Performance Pipe, October 11, 2002.

[4] Plastics: How Structure Determines Properties, G. Gruenwald, Hanser Publishers, New York, 1993.

[5] CP Chem Technical Note 801 - Polyethylene Pipe Squeeze-Off, 2002.

[6] GRI Report 92-0460.

Charges imparted to the interior PE pipe surfaces act as point sources and are immobile because of the inherent high resistivity of PE. Static inside PE pipe, once generated, remains and poses a spark discharge hazard at any time it is exposed to an electrical ground - either by tools, machines, workers or third party damage. In general, safety standards (e.g., wrapping the pipe with wet soapy burlap) for static discharge do not eliminate static electricity *inside* PE pipe. These procedures are effective for neutralizing *exterior* charge accumulation but do not affect the *interior* charge. Operators must still treat the wet burlap treated pipe as a potential spark discharge hazard. As noted earlier, squeeze-off operations, combined with particulate flowing in the gas, increase the charging problem. In such cases, the squeeze-off constriction in the pipe produces higher particulate velocities and results in higher charge levels. The charge conditions across the pipe wall can increase high enough to exceed material breakdown.

Because the discharge event that caused the pinholes in the polyethylene pipe can be modeled as a capacitive discharge this concept will be reviewed below.

PE Gas Pipe as a "Capacitor"

A capacitor is a device consisting of two conductors separated by an insulator (or vacuum) that stores energy in the form of an electric field. The charge on the capacitor is proportional to the potential difference between the conductors or plates. The capacitance of the system is:

$$C = Q/V$$

where "Q" is the charge on either plate of the capacitor and "V" is the potential difference between the plates. While a capacitor is being charged, the charge increases from an initial value of zero to a final value of Q. Similarly, the potential difference increases from zero to V. While the capacitor is charging there is resistance in the circuit due to the capacitor. However, once the capacitor is charged, it can discharge its electric energy into the circuit.

A parallel plate capacitor consists of two conductive plates separated by a dielectric material. The energy in the system is stored in an electric field between the plates. The capacitance of this system is:

$$C = K\varepsilon_0(A/d) \qquad \text{<plate capacitor>}$$

where "K" is the dielectric constant of the material between the plates (K=1 for a vacuum), "ε_0" is the permittivity of free space, a constant with a value of 8.85e-12 F/m, "A" is the area of the plates and "d" is the distance between them. Permittivity can then be defined as the ratio of the capacitance of a capacitor constructed using the insulator to an identical one in which the insulator is replaced with a vacuum. As can be seen from the equation, the area of the plates is directly proportional to the capacitance of the system, so as the area increases, so does the capacitance. The distance between the plates is indirectly proportional to capacitance and thus, as the distance decreases, the capacitance increases.

For a cylindrical capacitor, the capacitance is given by:

$$C = K \cdot 2 \cdot \pi \cdot \varepsilon_0 \cdot l/(\ln (b/a)) \qquad \text{<cylindrical capacitor>}$$

Here the length of the cylinder is "l" and the inner and outer radius of the surfaces are "a" and "b" respectively. As "l" increases so does capacitance.

Although the capacitance is an important idea to develop, it is the stored energy (and driving force to reduce it) that will drive discharge of the capacitor. What is important here is that it requires energy to bring like charges together on the interior surface of the PE pipe. This can be thought of as electrical potential energy. The general equation for the energy density (u) for a capacitor with a dielectric is:

$$u = \tfrac{1}{2} \cdot \varepsilon_0 \cdot K \cdot E^2 \qquad \text{<energy density>}$$

As the charge builds up on the inner wall of the PE pipe, the Electric Field "E" increases. The energy required to build up like charges in a localized spot came from the gas flow energy. This increased the stored energy. The discharge (through the pipe wall) to ground state "recovers" the flow energy.

When the external surface of the pipe is wrapped with burlap and wet down, one has set up and external conducting plate which interacts (through electric field theory) with the charge present on the interior of the pipe. Beyond the scope of this discussion, is the fact that the dielectric (PE pipe wall in this case) becomes polarized by the external electric field. This in turn results in an induced field (opposite direction) and surface charge *within* the dielectric which opposes the external field[7]. When the charge, and therefore electric field, are strong enough the dielectric breaks down and discharge of the capacitor takes place.

"[7] Fundamentals of Physics", Halliday and Resnick, John Wiley and Sons, New York, 1981.

3. Analysis of Failed Pipe

At GTI, the pipe segments C and D were photographed with a digital camera, and then sectioned with a band saw to reveal their inner surfaces, see Fig. 5.

The inner and outer surfaces of each section were then analyzed using stereo-optical microscopy and scanning electron microscopy (SEM). Pinholes and evidence of mechanical damage were located on both the inside and outside surfaces of the pipe sections. The inside of the PE pipe was covered with sand and dirt debris and there were particle impingements on the inside of both segments, see Figs. 6 and 7.

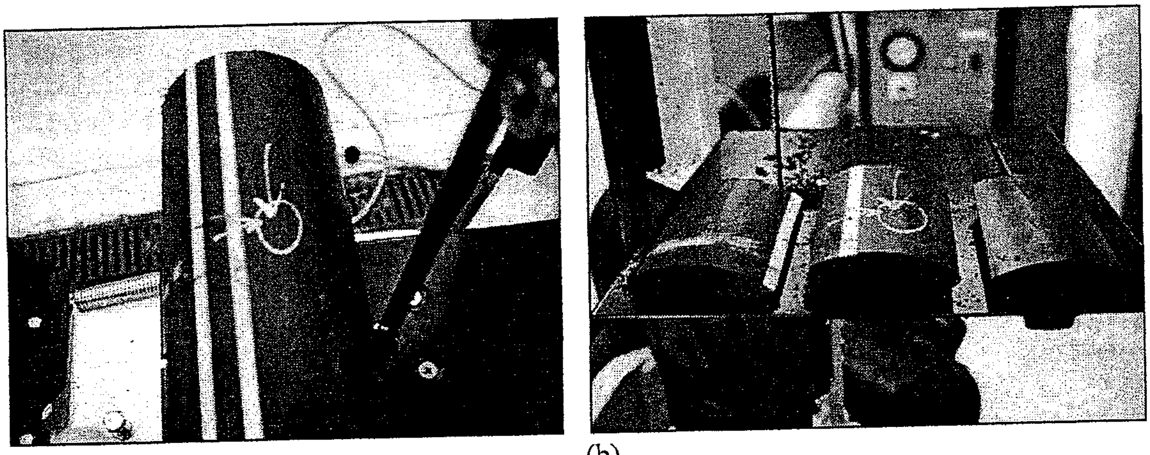
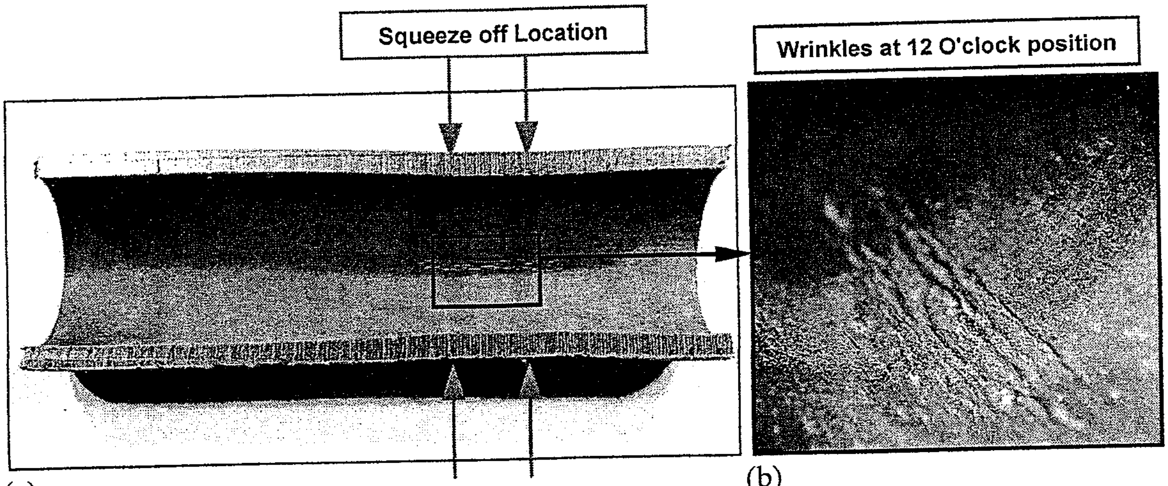
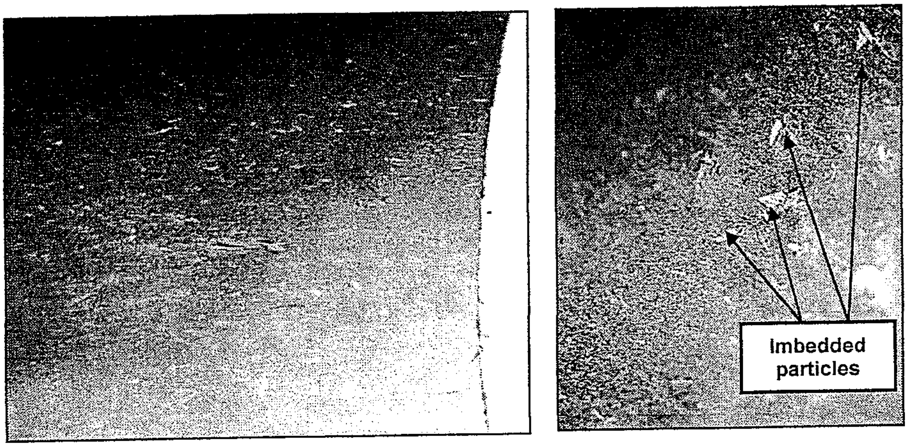

(a) (b)

Fig. 5. Example of sectioning of pipe to allow stereo-optical and scanning electron microscopy of all surfaces (a,b).



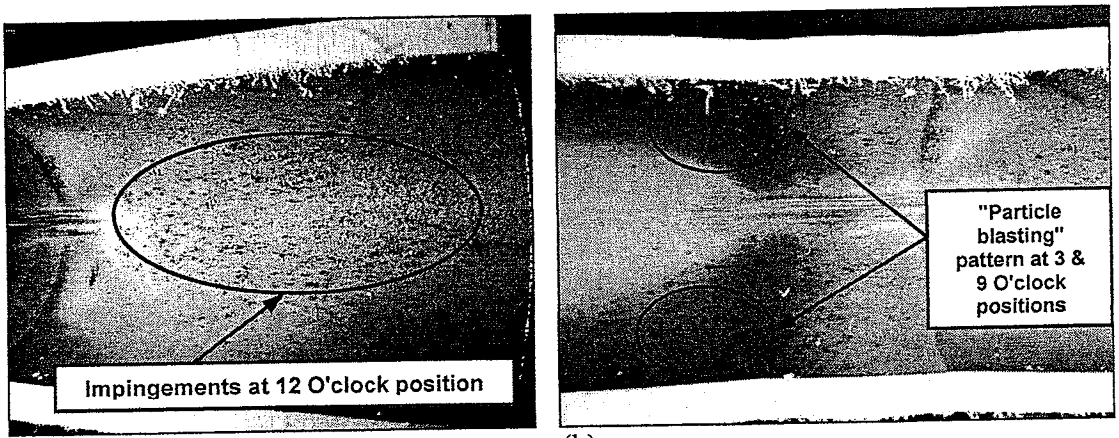
(a) (b)

Fig. 6. Picture of squeeze off area (a) showing the squeeze direction with red arrows. The blue box highlights the wrinkles at the 12 O'clock position on the pipe (b).



(a) (b)

Fig. 7. Downstream impingements of debris into the pipe wall (a). Higher magnification (b) shows actual particles partially imbedded into the pipe wall.



(a) (b)

Fig. 8. Squeeze off morphology and impingement in a yellow PE pipe provided courtesy of Performance Pipe Company[8] (i.e., <u>not</u> the CNG pipe). (a). Wrinkle and impingement pattern shows high rates of particle deposition at the 12 O'clock position downstream of the squeeze off (b). "Particle Blasting" of the pipe is also evident upstream of the squeeze off, maximized at the 3 and 9 O'clock positions (areas of maximum squeeze off. This pattern is typical of a line which is squeezed off and then reopened without being equalized first by a bypass and valve arrangement.

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[8] Private communication with Mr. Mike Glasgow of Performance Pipe, October 11, 2002.

Pinhole 1, in sample C, was found at the location of the squeeze-off. The pinhole was in the wrinkles made in the plastic by the squeeze-off tool. Images of the pinhole are shown in Figs. 9 and 10 below.

(a) (b)

Fig. 9. SEM micrographs of pinhole 1 in sample C on the (a) inside surface and (b) outside surface.

Pinhole 1 has a clean, single entry point on the inner surface of the pipe wall. The size is between 400-500 microns. The exit point is much less well defined but resolvable. As will be shown with the other pinhole, there was branching of the arc path through the pipe wall. This is typical for a discharge resulting from a high voltage event producing an electric field greater than the dielectric strength of the material.

If one assumes that the dielectric strength of the polyethylene is 450 V/mil, and a pipe thickness of 0.409 inches (409 mil) then the required voltage to reach the dielectric strength is:

450 V/mil x 409 mil = <u>184,050 volts</u>

This value is reasonable based on (1) the intensity of the discharge event (audible sound and large area, brilliant flash) observed by the personnel in the direct area; (2) published data for dielectric strength and instantaneous high voltage breakdown of polyethylene[9].

Pinhole 1 is also shown in Fig. 10. These stereo-optical micrographs clearly show the interior pinhole and signs of localized melting at the entry point of the pinhole to the pipe wall. This smooth, melted surface is typical of high voltage discharge events on the inside of through pipe wall events.

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[9] "Pinhole Leaks in Polyethylene Tubing Used for Gas Services", Pimputkar, et. al., International Plastic Pipe Symposium, 1997.

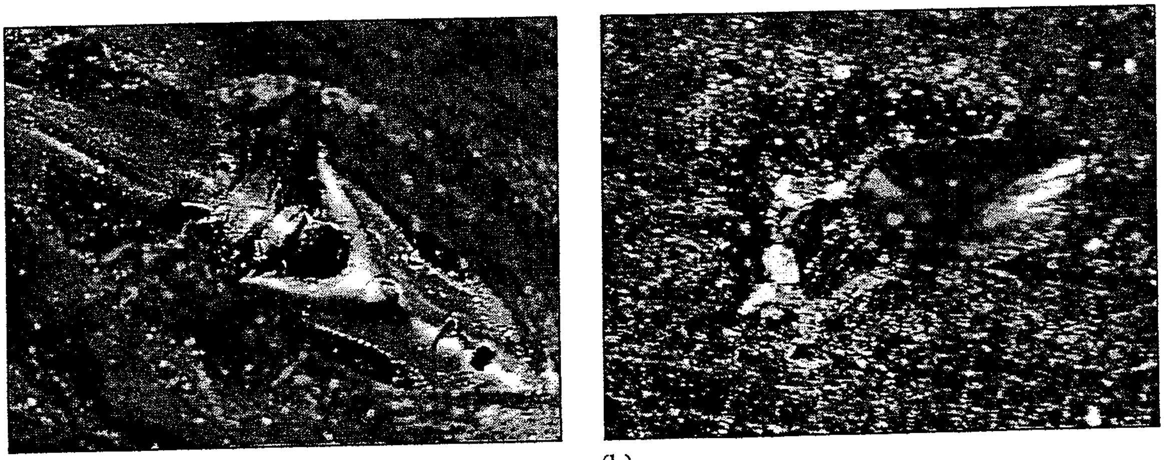
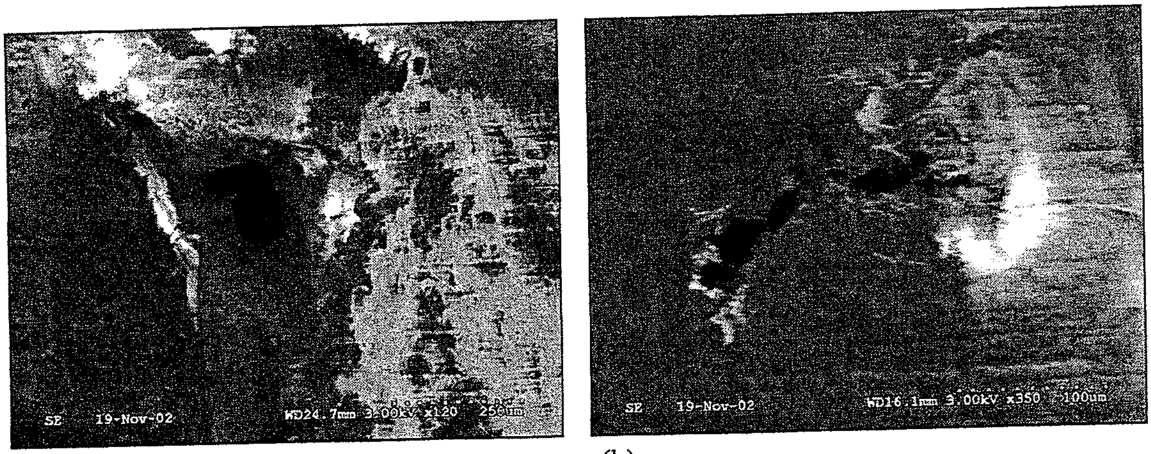

(a) (b)

Fig. 10. Stereo-optical micrographs of pinhole 1 (see Fig. 9) in sample C. (a) Entry point of pinhole on the inside surface, note the evidence of localized melting around the hole. (b) The outside surface is not nearly as well defined and shows evidence of branching.

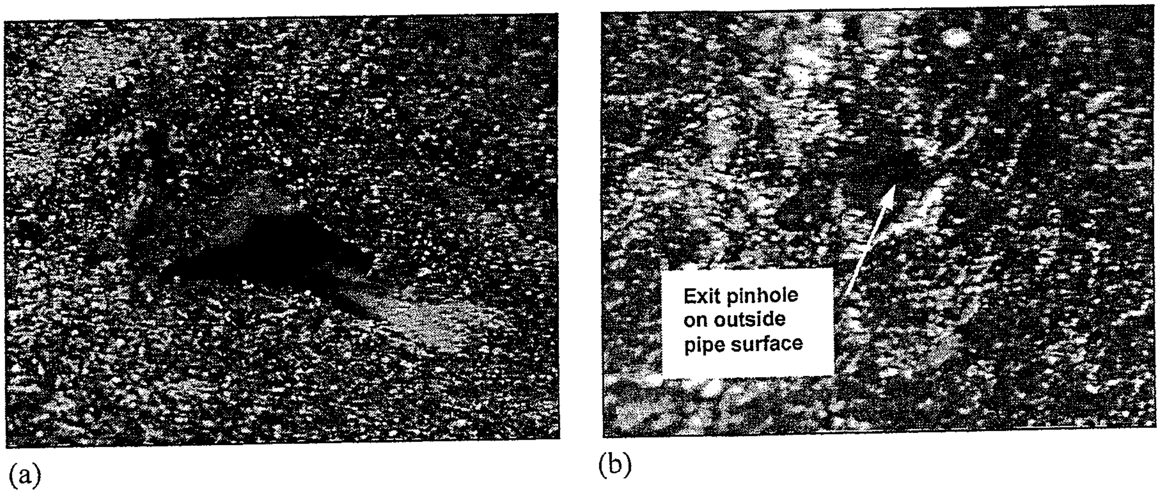
Pinhole 2, in sample D, was found in a portion of the pipe that was *upstream* from the squeeze-off point and pinhole 1. It is suspected that a pipe locator wire, approximately 1 inch below the pipe, played a role in the static discharge and subsequent formation of pinhole 2.

CNG Construction Standards state that tracer wire should be 6 inches below plastic pipe separated by 6 inches of stone-free sand. The pinhole can be seen in Figs. 11 and 12 below.



(a) (b)

Fig. 11. SEM micrograph of pinhole 2 in sample D: (a) Single entry point on the inside surface and (b) branched exit site on the outside surface.



(a) (b)

Fig. 12. Stereo-optical micrographs of pinhole 2 in sample D: (a) Non-symmetric entry point on inside surface and (b) exit site on the pipe wall outside surface. A tracer wire (metal conductor) was located approximately 1 inch from the exit site and represented a potential ground path.

All the characteristics of these pinholes match those routinely generated by a high-voltage instantaneous discharge, which generally produces holes that[10]:

1. Branch along the discharge path.
2. A size greater than 100µm.
3. May produce carbon traces (from degradation of the polyethylene).
4. Do not have clogging fibrils in the discharge path.
5. Melting on the inside pipe wall surface (entry site), but not the outside (exit site) surface.

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[10] GRI Report 96/0014, "Analysis of Microscopic Leaks in Polyethylene Gas Distribution Piping", Gas Research Institute 1996.

4. Conclusions and Recommendations

Conclusions

The polyethylene pipe can be thought of in terms of a capacitor, with the inside of the pipe acting as one plate and the wet ground on the outside being the other plate. The pipe wall could be considered the dielectric. Charge builds up in the system until the electrons can travel to a lower energy state when the dielectric strength of the polyethylene is exceeded.

The gas traveling through the PE pipe (with dirt/debris particles) transferred charge onto the nonconductive internal pipe wall. Once the charge built up so much that it exceeded the dielectric strength of the PE, it discharged through the pipe wall creating a pinhole.

Many steps involved in the squeeze-off procedure, while working to prevent an *external* spark on the pipe, actually increased the probability of an *internal* static discharge occurring. The grounding of the squeeze-off tool and burlap cloth provided a ground state to which the electrons could travel. The wetting down of the bell hole increased the size of the plate outside the pipe giving the electrons on the inside of the pipe wall more pathways through which to travel. Additionally, the wetting down of the pipe lowered the surface resistivity of the outer pipe wall and the dielectric strength of the exposed polyethylene.

Because no by-pass lines were used in the repair of the first pinhole, the velocity of the gas upon relaxation of the squeeze off tool would be greatly increased compared to a line that was equalized before squeeze off release. The affect of the excavation details is listed in Table 3 below.

Table 3 - Excavation Details and Affect on Potential for Discharge

CNG Excavation Detail	**Affect On Potential For External Static Discharge**	**Affect On Potential For Internal Static Discharge**
Area *leading up to* bell hole was wet down.	Reduced chances of external discharge in work area by increasing surface conductivity.	Increased potential for internal discharge by increasing the size of the external grounding "plate" and ensured good electrical contact with the soil of any grounding rods (from tools and burlap connections) driven into this area.
Crew wrapped pipe with wet burlap and grounded it to the soil.	Reduced the chance of external discharge on pipe outer wall by increasing surface conductivity (i.e., discourages static charge build up).	Increased potential for internal discharge by increasing the size of the external grounding plate and provided a lower resistance path from the outer wall of the pipe to ground state. Increases in humidity and moisture can also lower the dielectric strength of polyethylene on the surface (where water is adsorbed)[11].

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[11] Handbook of Polyethylene, Andrew J. Peacock, Dekker Press, New York 2000.

CNG Excavation Detail	Affect On Potential For External Static Discharge	Affect On Potential For Internal Static Discharge
Squeeze off tool was grounded.	Reduces the likelihood of an external spark at the tool since it is connected to ground (does not allow charge to build up on tool).	As the tool is used to compress the pipe, it is grounded and provides a fully conductive path to ground for the interior electrons if they can pass through the pipe wall.
A bypass line was not used to equalize pressure before relaxation of the squeeze off tool.	Minimal impact on external spark generation.	Greatly increased the chance of static discharge from the inside of the pipe due to high gas velocities when the squeeze off is relaxed.
Evidence of debris/dirt/sand in gas stream.	Minimal impact on external spark generation.	Greatly increases the chance of charge transfer onto the interior surface of the pipe and subsequent internal spark generation.

In the case of the second discharge, the pipe locator wire may have provided a lower resistance ground state for the electrons. Because of the close proximity of the tracer wire to the pipe, there was a higher driving force (shorter distance) for the electrons to reach this lower energy state.

Recommendations

1. All the proper safety precautions were followed to prevent an *external* spark source during squeeze off, and the repair operation. These procedures should be followed to prevent the likelihood of an external spark that could ignite any flammable mixtures of methane and air present at the dig site.

2. However, the use of a bypass line, with a controlled packing (re-pressurizing) of the repaired line would have allowed both sides of the squeeze off to be equalized prior to release of the tool. This would have greatly reduced the velocity upon relaxation of the squeeze off tool. The lower velocity would generate less static charge on the *interior* surfaces of the pipe wall (less gas flow and friction), therefore reducing the chance of a discharge event from the inside of the pipe to the outside.

3. The second pinhole was most likely caused by the close proximity of the tracer wire (a ground source for the built up static charge). The tracer wire was located approximately 1 inch from the pipe where the pinhole was found. This wire represents a grounded electrical conductor in close proximity to the pipe wall. Its interaction with the local electric fields increases the chance of discharge through the pipe wall to the grounded wire. Standard procedures dictated that the wire should be 6 inches from the pipe. The use of "tracer wire spacers" should be considered for installations where tracer wire placement is hard to control.

4. If this particular system has a large amount of debris (e.g., fine corrosion products from metal components) in the gas stream, then the use of filtering or anti-static devices might be considered.

Sincerely,

Daniel A. Ersoy
Materials Scientist

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