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Product Safety Engineering Section
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Report for
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U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, ***Secretary***
James A. Baker, III, ***Under Secretary***
Dr. Betsy Ancker-Johnson, ***Assistant Secretary for Science and Technology***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Acting Director***

Analysis of Failure of a Polyethylene (PE) Gas Service Pipe (Lenoir County, North Carolina)

A section of polyethylene (PE) gas service pipe was submitted to this laboratory for an evaluation of the possible cause of in-service failure. The pipe was personally delivered to this laboratory on November 21, 1975 by Mr. Thomas L. Dixon, Pipeline Safety Engineer for the North Carolina Utilities Commission (NCUC), who had conducted a field investigation of the incident on September 30, 1975.

Prior to receipt of the PE pipe the NCUC had requested the NBS to conduct an analysis on the pipe. This request was contained in a document entitled: "Notice of Analysis of Pipe, Docket No. G-21, Sub 143," dated October 29, 1975, and subsequently amended by an Errata Order dated November 10, 1975. This document stated that an explosion had occurred on September 29, 1975, on the Tull Hill Farm on North Carolina State Road 1004 in Lenoir County, North Carolina. It also stated that the explosion, which killed three people, appeared to have occurred in conjunction with an escape of gas from a section of pipeline of the North Carolina Natural Gas Corporation.

Mr. Dixon provided the following verbal information:

1. The pipe had been purchased and installed by the North Carolina Natural Gas Corporation.

2. The only known purchase specification required the use of a specific, modified high density PE pipe compound to produce a nominal 3/4 inch diameter Standard Thermoplastic Pipe Dimension Ratio (SDR) pipe capable of withstanding pressures to 150 pounds-force per square inch (psi).

3. The specified pipe compound and its manufacturer were identified.

4. The purported pipe fabricator was identified.

5. The SDR ratio was not known.

6. The gas service pipe was installed in 1964, at a depth of approximately 32 inches and was connected to a gas main equipped with 52 psi relief valves.

7. The gas service line provided fuel to a furnace located in a building component attached to a tobacco barn.

8. In 1965, a 16-inch-diameter concrete sewer pipe leading to a floor grating in the same attached structure was installed above the PE gas service line. The sewer pipe was described as being constructed of sections of corrugated bell and spigot pipe, the joints of which were sealed by means of a "tar paper" wrap.

9. After the explosion a trench was dug to expose the gas service pipe. The sewer pipe was reportedly found to be in direct contact with a portion of the gas pipe. Photographs taken at this point, and provided to the author, indicated that the visible part of the sewer pipe crossed over the gas pipe at an estimated angle of 10°, but did not show whether the two pipes were in actual contact.

10. A bell and spigot joint was located approximately one foot from the area of the apparent leaks in the gas service pipe. The pipe wrap seal on the bottom of this joint was said to exhibit considerable damage.

11. When the partially exhumed gas pipe was cut upstream from the apparent leak (i.e., in a section away from the building) and was pressure tested with air, air was noted to be escaping through the sewer grating in the building. Therefore, it was surmised that gas had leaked from the service pipe, entered the sewer line through the nearby partially unprotected pipe joint, and collected in the building structure housing the gas furnace.

12. When a section of the gas service pipe was exhumed and further tested by air pressure at about 40 psi, two leaks were noted and subsequently marked. This section of pipe was the one received at this laboratory, and still remains in the author's custody.

13. An on-site investigation had also been conducted by Mr. H.M. Shepherd of the Pipeline Safety Division, National Transportation Safety Board.

In addition to the above information, it was reported that the pipe may have been fabricated to meet the requirements of the Department of Commerce, National Bureau of Standards, Commercial Standard CS255-63 for Polyethylene (PE) Plastic Pipe (SDR-PR), issued July 1, 1963. The requirements of this Standard were essentially the same as a current American Society for Testing and Materials (ASTM) D2239-73a, Standard Specification for Polyethylene (PE) Plastic Pipe (SDR-PR).

Description of Pipe

The submitted sample of black, plastic pipe was approximately 1.9 meters (m) in length, and had a nominal inside diameter of 0.8 inch (in). The two points at which leaks had been noted during field tests of the exhumed pipe had been marked. These points were located approximately 15 centimeters (cm) apart and about 65 and 80 cm from one end of the sample. The section of pipe was permanently bowed. The areas marking the two leaks were located on the side of the pipe with respect to the bow (see figure 1), and were in essentially a straight line parallel to the longitudinal direction of the pipe. At least a portion of one crack was visible on the outer wall of the pipe, but the other crack was not discernible.

There was evidence that the pipe had been marked with a legend in at least three places. However, the surface of the pipe in the marked area had been abraded to the extent that the legend could not be deciphered, either visually, by low power stereo microscopy, or by long wavelength ultraviolet radiation. When plastic pipe is claimed by the manufacturer to meet the requirements of a specific standard, it must be marked to identify the nominal pipe size, type of plastic pipe material, the SDR or pressure rating for water at 23°C (73.4°F), the designation of the appropriate standard, and the manufacturer's name (or trade mark) and code. However, there is no known requirement that this information remain legible after final installation.

In the absence of any identifying markings on the pipe, it was not possible to conduct this analysis with respect to compliance or non-compliance to a specification or standard. However, on the basis of information received at the time the pipe was submitted for analysis, appropriate testing procedures set forth in CS-255 and ASTM D2239 were used as guidelines in characterizing the pipe.

Evaluation of Pipe

Visual

The two marked areas of leakage were designated as A and B. These two areas were, respectively, 80 and 65 cm from the nearest end of the overall sample, figure 1. A portion of crack A was visible on the outer wall of the pipe. A crack somewhat transverse to the longitudinal direction of the pipe was visible. This crack was approximately 2 cm in length but curved into a longitudinal groove, apparently the result of abrasion, which extended for about 11.5 cm along the outer pipe wall, consequently, the actual length of the crack could not be determined initially. Microscopic examination of area B did not reveal the presence of a crack, although numerous pits, scratches and embedded particles were observed. The pipe was then pressurized to 4 psi gauge (psig) air pressure. The leak at A was obvious, but no leak was detected at B. Subsequently, a liquid leak detector was applied over area B and the approximate location of two small leaks was determined. The pipe was then placed under the microscope, again pressurized and the leak detector applied to this area. The two leaks were located and found to be about 3 millimeters (mm) apart in the longitudinal direction and 5 mm apart in the transverse direction of the pipe. No holes were actually observed under magnification, but one leak appeared to be at or adjacent to a small piece of embedded debris. The latter leak was located in a shallow furrow in the pipe wall that appeared to have resulted from external abrasive damage.

A section of pipe, containing the two cracks, was cut from the sample. This section was about 45 cm in length with the two cuts being made approximately 15 cm to the left of crack A and to the right of crack B (see figure 1). Examination of the inside of this section showed the presence of two cracks on the inner wall at the approximate location

of the leaks. The inner wall was found to contain corrugations in the transverse direction, extending over approximately one-fourth of the circumference. There were at least six of these corrugations which appeared to be located about 6 cm apart. Both cracks were oriented perpendicularly at the approximate center of these corrugations.

This section of pipe was subsequently separated into five pieces by transverse cuts. Cuts were made at about 3 cm from the midpoints of each of the two areas containing the leaks. Examination of the interior of each section resulted in the discovery of a third crack located about 3.5 cm from the end of crack A on the side away from crack B, i.e., to the left of A as viewed in figure 1. This crack appeared to be about 2.5 cm in length. Subsequently, a section of pipe about 7.5 cm in length containing this crack, which was designated as C, was removed.

Each of the three sections of pipe containing the cracks were then split longitudinally at points approximately 90°, circumferentially, on each side of the crack. The cracks on the inner wall were then subjected to microscopic examination in an effort to locate the probable point of crack initiation and the reasons for failure. A unique feature of the cracks was that all three exhibited the same general configuration. The major portion of each crack, although exhibiting varying degrees of curvature, was generally in the longitudinal direction of the pipe. One end of each crack exhibited a rather abrupt change in direction, partially transverse to the major crack. When the three cracks were observed in the positions in which they were located in the pipe, this change was in the same, somewhat transverse, direction and at the same end of the crack, e.g., the left end. In the case of crack B, this portion of the crack was on the end nearest crack A.

The overall length of the cracks in the longitudinal direction, disregarding curvatures and directional changes, were: 3.6 cm for crack A, 2.6 cm for crack B, and 2.8 cm for crack C. The major, essentially longitudinal portion of each crack was: 2.7 cm for crack A, 1.9 cm for crack B, and 2.0 cm for crack C. In the cases of cracks A and B, these were the regions in which leakage occurred.

Examination of crack A revealed the presence of two particles, which looked like sand, embedded in the crack near the mid wall (the cylindrical surface parallel with and halfway between the inner and outer walls of the pipe) of the pipe. These particles were located about 4 mm from the end of the crack on the inner wall and were near the right end of the visible crack on the outer wall as illustrated in figure 1. The crack in the 2.7 cm section appeared to be a stress crack.

In examining crack B, special attention was given to those points on the inner wall in the area of the two leaks. These occurred near one end of the 1.9 cm segment of the crack or the end most distant from crack A. There was no evidence of any occluded particles, voids, or other irregularities at these points on the inner wall edges of the crack. The edges of the crack in the 1.9 cm section did exhibit a

reddish discoloration. The edges of the remainder of the crack, however, did not exhibit this discoloration but were rather translucent and reminiscent of a tensile failure.

Examination of crack C did not reveal anything of significance with regard to its cause. However, the edges of the crack at the inner wall appeared to have been subjected to a tensile failure. There was no visual evidence that any portion of this crack completely penetrated the pipe wall.

After the preliminary microscopic examinations were completed the sections containing the three cracks were cut to expose the crack surfaces in the pipe wall.

That portion of crack A which completely penetrated the outer wall was found to be about 2.3 cm in length. When the pipe was cut at each end of this crack, the two sections readily separated as illustrated in figure 2. The red mark on the inner pipe wall near the left end of the crack marks the location of the apparent origin of the stress crack. There was a small, raised irregularity in the crack surface of the smaller piece located about 0.25 mm from the inner wall. It was somewhat less than 0.25 mm in length in the longitudinal direction of the pipe, and was estimated to be on the order of 0.04 to 0.05 mm in width. A corresponding matching cavity was observed on the opposite crack surface on the larger piece of pipe. The yellow mark on the inner pipe wall near the right end of the crack in figure 2 indicates the locations of the two particles previously noted. These two particles fell out when the crack was separated. Examination of the crack surfaces in this area showed the presence of three very small voids and a small pit near the mid wall. It could not be determined whether the pit had been caused by the presence of one of the particles. Two small reddish spots were also observed in this area, but it could not be determined whether they were due to occlusions or to debris.

Crack B is illustrated in figure 3. The two portions of this crack did not separate when the pipe was cut. Examination of the surfaces of the crack in the area of the two leaks observed on the outer wall did not indicate any obvious defects in the pipe. The two sections were then bent and broken apart. There was some visual evidence that the crack had penetrated the outer wall for a distance of about 6 mm at the right end of the crack in the area of the two leaks. The red mark on the inner wall is the location of the probable point of initiation of the stress crack. The larger piece of pipe had a very small irregularly shaped pit, located about 0.25 mm from the inner wall, and approximately 0.25 mm in diameter, at the apparent initiation point. A similar, but much shallower pit was observed on the opposite crack surface. It could not be determined whether this pit was a void or had been caused by the presence of an occluded particle. Two small voids were found near the mid wall of the pipe, in the crack surface, but neither appeared to have been a crack initiation point.

Attempts to separate crack C indicated that this crack did not extend much beyond the mid wall of the pipe. The crack was forced open, resulting in some tensile failure, in order to examine the crack surfaces. Although the point of origin of the crack seemed quite obvious, there were no indications of any artifacts, voids, or occlusions to enhance crack formation. The apparent origin of the crack was near the point of directional change in the crack, as illustrated in figure 4.

In the section of pipe between the two sections containing cracks A and B, a severely abraded area was noted on the same side of the pipe as crack A. This area is located on the outer pipe wall just to the right of the two arrows showing the location of crack A (figure 1). This area was approximately 2.5 by 2.5 cm and its center was located about 4 cm from the nearest end of the visible part of crack A. The outer wall of the pipe at this point was concave. It was also noted that three similar abraded areas exhibiting less severe damage occurred a distance of 15, 30 and 45 cm to the left of the above area as viewed in figure 1. The outer wall of the pipe was visibly deformed and concave in these areas. This concavity is typical of compressive deformation.

It was noted that the abraded area located 15 cm from the one between cracks A and B, was in the area of crack C at the point of the directional change in the crack configuration. This was also the location of the suspected point of initiation of this stress crack.

Examination of the pipe revealed a series of abrasion marks associated with shallower deformations of the outer pipe wall at intervals of approximately 7.5 cm, including those previously observed. That is, starting at the abrasion mark indicated in figure 1 there was evidence of a similar mark 7.5 cm to the right, located at the suspected origin of stress crack B, while to the left there was a mark 7.5 cm away located at the suspected origin of crack A. The next mark to the left was the one observed at crack C, while further to the left there were five additional marks located at 7.5 cm intervals, including the two previously noted marks at the 30 cm and 45 cm intervals from the one in figure 1. There was also some evidence, though not conclusive, of three or four additional abrasion marks to the right of crack B in figure 1. These marks appeared to be associated with the rib-like projections previously noted on the inner wall of the pipe. As a point of verification, wall thickness measurements made adjacent to the cracks and parallel to the longitudinal direction of the pipe across these areas indicated that thickness did not vary by more than about 0.0004 - 0.0005 in (0.010 - 0.013 mm), over a distance of 1 to 1.5 cm. This compares to wall thickness variations of .007 - .010 in (0.18 - 0.25 mm) when a cross section of pipe was measured circumferentially.

In the normal process of examining the inner wall of the split sections of pipe, the three areas opposite the crack positions were found to have a pair or irregularly shaped white lines parallel to the longitudinal direction of the pipe. Similar small white spots and other

particulate matter were observed between these lines. Microscopic examination of these lines revealed that they were composed predominately of opaque white particles. These particles appeared to have collected along the top of ridges extending away from the inner wall for a distance estimated to be of the order of 0.5 mm or less. Other darker particles, which may have been sand, were observed in the area between the two lines and particularly in the white spots. Microscopic examination indicated that none of these particles were embedded in the plastic. They seemed to be loosely adhered to the pipe wall, and could best be described as debris. It was felt that the white particles, in particular, might be deposits of salts remaining from evaporated ground water which had seeped into the piping system. The presence of such salt residues, particularly if they contained cations such as calcium and magnesium would provide unequivocal verification that the cracks located opposite to them were located on the top of the pipe in its installed configuration. Subsequently, the two pipe sections opposite cracks A and B were submitted to the NBS Analytical Chemistry Division for possible identification of these residual materials. A qualitative electron microprobe analysis indicated a preponderance of silicon cations and considerable amounts of aluminum. Traces of calcium, iron, potassium, sulfur and titanium were also found. Pure clay consists of a compound composed of hydrogen, aluminum, silicon and oxygen with the following empirical formula: $HAlSiO_4$. Ordinary clay is a complex mixture of aluminum silicates frequently containing combined iron and other metals, and often admixed with iron compounds, calcium carbonate (limestone), and silicon dioxide (sand). Clay particles, although essentially insoluble in water, are capable of forming colloidal suspensions in water. Ground water containing such suspensions could have seeped into the pipe, for example through crack A, flowed to the bottom and on subsequent evaporation resulted in deposition of the particles on the pipe wall.

Dimensional Measurements

The inside diameter (I.D.) was measured at four cross sections of the pipe where cuts had been made to remove the cracked sections. The average I.D. was of the order of 0.805 in (2.045 cm) or slightly below the allowable minimum of 0.809 in (2.055 cm) for 3/4 inch I.D., SDR PE pipe (CS255). (In Voluntary U.S. Standards for plastic pipe, U.S. customary units are regarded as standard.) The inside diameter of SDR PE pipe is controlled to allow use of standard size insert fittings. For any given nominal pipe size the I.D. is the same for all PE standard dimension ratio pipe. The SDR is determined by the wall thickness.

Wall thickness measurements were made on cross sections of the pipe at each end of each of the three cracks. Using standard procedures, the wall thickness was determined by averaging the maximum and minimum values obtained on each cross section. The wall thickness at each of the six measured areas exceeded the minimum requirements, 0.118 in (0.30 cm), for SDR7 PE pipe (CS255). In every case the minimum wall thickness was located at least 90°, in the circumferential direction, from the areas containing the cracks.

The pipe was also found to meet the requirements of CS 255 for the wall thickness range, or eccentricity.

Since the wall thickness and wall thickness range met the requirements for SDR 7 PE pipe, there was no reason to suspect that the substandard I.D. would have any detrimental effect on either the pressure rating or the useful service life of the pipe.

Density of Pipe Compound

Density measurements were conducted in accordance with the procedures set forth in ASTM D1505-68, Standard Method of Test for Density of Plastics by the Density-Gradient Technique.

Two sets of three specimens were measured. One set consisted of specimens cut from the end of a pipe section cut about 3 cm to the left of crack B, in figure 1, at points approximately 120° from each other in the circumferential direction of the pipe. The other set consisted of specimens cut from the pipe at points about 1.5 to 2.0 mm from each of the three cracks at locations adjacent to the suspected points of crack initiation. Both sets of specimens had an average density of 0.957 grams per cubic centimeter (g/cm^3), indicating that it was a Type III, high density PE resin as defined in CS-255. The specified pipe compound reported used to manufacture this pipe has a nominal density of 0.960 g/cm^3.

Infrared Spectrographic Analysis

A hot pressed film specimen prepared from a sample of the pipe was analyzed by infrared spectrographic techniques. The resulting spectrum indicated that the polymeric component of the pipe was a high density polyethylene resin copolymerized with 1-butene. This was the type of compound reportedly specified for this pipe.

Results

The surfaces of all three cracks found in the pipe exhibited characteristic conchoidal fractures normally associated with brittle failure. Among the causes of brittle failure, in the type of plastic used in the submitted sample, are the intermittent or continuous application of stress which over a period of time may result in a stress crack due to fatigue.

Due to the linearity of the polyethylene molecules and the orientation effects induced in the extrusion molding process, stress cracks in the type of pipe that was evaluated are generally parallel to the length of the pipe. The partially transverse portions found at the end of each crack were atypical of stress crack failure in high density polyethylene pipe. However, this directional change occurred at points where both the inner and outer pipe wall exhibited permanent deformation. These deformed areas were typical of creep deformation due to compressive stresses on the outer wall and tensile stresses on the inner wall.

Creep deformation occurring over a long period of time may result in a change in the morphology of a plastic material, for example by inducing molecular disorientation and perhaps resulting in a change in the crystallinity of the material.

The regularly spaced abrasion marks found over at least a 60-cm length of the gas pipe can reasonably be assumed to have been caused by contact with the concrete sewer pipe installed above it. Abrasion, at these contact points, could have occurred as a result of movement of either or both pipes against one another due to such factors as differences in the thermal expansion characteristics of the two pipe materials, or to expansion, contraction or compacting of the surrounding soil. The varying degree of severity of damage noted at the different, apparent, contact points could be attributed in part to the fact that the concrete pipe was rigid and unyielding, whereas the more resilient plastic pipe could yield to some extent from compressive forces applied to one side. However, the degree to which the pipe was capable of yielding could well be expected to be either limited or enhanced by the localized condition of the surrounding soil.

Since small artifacts were observed at the apparent origin of both cracks A and B, the possibility of stress cracks developing at these points without pressure being exerted by the sewer pipe cannot be eliminated. However, the permanent deformation, or corrugations, previously noted on the inner pipe wall, would indicate that the plastic material at the inner wall in the vicinity of these artifacts would have been subjected to abnormal tensile stresses. Since the same conditions were found to exist at crack C, but no apparent artifacts were observed, it would appear that external forces were the primary cause of failure, while the artifacts in cracks A and B may have been contributory causes to the extent of the failure.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A fatal explosion in Lenoir County, North Carolina was apparently caused by the accumulation of natural gas from leaks, due to in-service failure, in a 3/4-inch, inside diameter polyethylene (PE) gas service pipe. Three stress cracks were found on the inner wall of the pipe, two of which had penetrated the outer pipe wall. The apparent primary cause of the stress cracks was due to creep deformation of the pipe wall at the site of each crack, resulting from pressure exerted on the plastic pipe by a 16-inch diameter concrete sewer pipe which had been installed across the plastic pipe. These deformations appeared to have resulted from compressive stresses on the outer wall of the pipe. Small artifacts near the apparent origins of the two cracks, which penetrated the pipe wall, may have been contributory causes to the extent of the failure.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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Figure 1

Figure 2

Figure 3

Figure 4