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Failure Analysis of a Poly (Vinyl Chloride) (PVC) Plastic Natural Gas Transmission Pipe From Las Vegas, Nevada (NBS Failure Analysis No. 106)

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

A section of cracked poly(vinyl chloride) (PVC) plastic natural gas transmission line was submitted to this laboratory for the purpose of conducting a failure analysis. The analysis was requested by the Office of Pipeline Safety, National Transportation Board, and the sample was received through the NBS Metallurgy Division. The pipe, according to information supplied in an accompanying letter from the Public Service Commission of Nevada, had been located beneath the intersection of Commerce Street and Oakey Blvd., Las Vegas, Nevada. Gas leaking from the crack was determined to be the cause of an explosion and fire in a nearby section of the Monte Carlo Motel on June 24, 1973.

Description of the Pipe

In addition to the manufacturer's tradename, the pipe was marked with the following legend: 2" IPS SCH A PVC2110 88 PSI WP @ 73.4°F -nSf- CS 237-61. This translates as follows: nominal 2-inch O.D.; Iron Pipe Size; lightweight pipe; produced from rigid poly(vinyl chloride), Type 2, Grade 1, (high impact, normal chemical resistance); with a hydrostatic design stress of 1000 psi; pressure rated for continuous use to 88 psi water pressure at 73.4°F; conforming to the requirements of the National Sanitary Foundation for use with potable water; and conforming to Commercial Standard No. 237, issued in 1961 by the National Bureau of Standards, for Dimensions and Tolerances of Schedule A, Type 1 and Type 11 PVC pipe.

The sample was a composite consisting of two sections of pipe, one about 32 cm (12.5 in) long in which the crack was located, and one about 132 cm (52 in) long, both of which had been joined by means of a 7.6-cm (3-in) long, in-line socket fitting. The short section also had attached to it a metal nut, a metal seal retainer, and a rubber seal located about 18 cm (7 in) from the socket. These components were part of a typical compression coupling, reportedly used to make an in-line attachment of the PVC pipe to a 5-cm (2-in) metal pipe. Figure 1 shows the pipe in the "as received" condition, although it does not include all of the attached long section of the pipe. A 20-cm (8-in) long section of steel pipe had been inserted into the coupled end of the plastic pipe as a reinforcement. Several turns of a black pipe wrap had been applied over the nut and tapered along the adjacent four inches of the plastic pipe. In the process of disconnecting the coupling, the pipe wrap covering the nut had been completely severed from that on the plastic pipe. The visible section of the crack, which was reported to have been on the top of the pipe in its installed position, extended for about 3.8 cm (1.5 in) from the wrap towards the socket fitting.

Figure 2 is a close-up illustration of the crack, in the "as received" condition. There was also a crack in the pipe wrap, which is shown in this figure. However, it was later found, on removal of the tape wrap, that the crack in the pipe wrap was superficial and had no apparent bearing on the failure of the pipe.

The long section of the pipe had been permanently deformed in the downward direction with respect to the location of the crack. The total deflection at the outer end, away from the socket, was on the order of 8 cm (3.15 in). This downward bending of the pipe appeared to be a typical example of creep deformation and would be expected to result in an increase in tensile stress on the upper surface of the pipe, near the coupling, where the plastic pipe presumably was rigidly constrained against bending by the metal insert. At several places on this section of the pipe there were chunks of very hard, clay-like soil firmly adhered to the outer pipe wall. Consequently, it was surmised that deformation may have been caused by forces exerted on the pipe, over a long period of time, probably due to the expansion of the soil whenever it became wet. Although the installed depth of the pipe was not definitely stated, from the information supplied, it apparently was approximately 1 m (3 ft) below the pavement. Consequently, any expansion of the soil in the upward direction would have been limited by the presence of the pavement, thereby increasing the amount of downward (compressive) forces on the pipe, and resulting in the deformation. Lateral expansion forces could reasonably be expected to have little, or no, significant effect on the pipe. There was a possibility that the amount of deformation in the sample as received in this laboratory was less than that in the actual installation. The end of the long section of the pipe was badly damaged. Visual examination indicated that it had been manually, or mechanically broken off by an upward force applied to the pipe, when it was removed from the ground. This rather poor technique of removing the sample could have resulted in some straightening of the deformed section of the pipe.

Following the initial visual examination, the cracked section of pipe was cut off at the socket. Starting at the point of emergence of the crack, a half-inch wide longitudinal strip of the pipe wrap was removed, revealing that the crack extended to within a fraction of an inch of the compression fitting and was approximately 14.5 cm (5.7 in) in total length. The crack was essentially straight in the longitudinal direction, with two exceptions noted below. Following the examination of the crack and surrounding pipe surface, the remainder of the pipe wrap was removed, essentially in one piece.

Figure 3 is an illustration of the crack between points A and B, after the initial cutting away of part of the wrap. The following are combined observations made after initial exposure of the crack and after complete removal of the wrap:

1. The pipe beneath the wrap was found to be discolored and swollen. In contrast to the light grey color of the pipe, all portions of the outer surface of the pipe, in direct contact with the wrap, were dark brown. Those areas not in direct contact with the wrap, i.e., where overlaps between turns occurred, were light green in color. An example of this can be seem in Figure 3. The light colored, roughly longitudinal linear area passing below the letters C and D and extending to the area of point E resulted from lack of contact of the wrap with the pipe surface at the point where the second turn of the wrap passed over the starting end. The surfaces of the brown areas were slightly raised with respect to that of the green areas, indicating that the former were subjected to a greater degree of swelling.

2. There was a slight deviation in the linearity of the crack, in the form of a small arc, about 0.6 cm (0.25 in) from the end nearest the coupling, at point E in Figure 3.

3. The point of maximum swelling of the pipe occurred just beyond the arc on the side away from the coupling, i.e. just to the left of point E in Figure 3.

4. At about the midpoint of the length of the crack there was a dislocation in the form of a short, curved transverse crack approximately 0.08 to 0.10 cm (0.03 to 0.04 in) in length at point D in Figure 3.

5. Towards the outer end of the wrapped area, at a point just beyond the inner end of the metal pipe insert, at point C in Figure 3, there appeared to be two or three grains of sand, embedded deep in the crack. These particles protruded through the inner wall of the pipe, and felt hard and rather sharp to the touch.

6. Pressure exerted by the coupling had permanently compressed the pipe, to the extend that the O.D. was approximately 0.1 cm (0.04 in) less than the average O.D. of the pipe, in the area indicated by F in Figure 3.

7. There was a ballooned area on the bottom of the pipe, directly opposite of, and in the general area delineated by points C and D in Figure 3 of the crack. It was centered about 9 cm (3.5 in) from the coupling, and ranged from about 3.2 to 3.8 cm (1.25 to 1.50 in) in diameter.

<u>Examination of the Pipe Wrap</u>

The pipe wrap was a composite consisting of a thin, essentially transparent, backing film which had been coated with a relatively thick, black, bitumen-like "adhesive" layer of material. Infrared analysis indicated that the backing film was a poly(vinyl chloride/vinyl acetate) (PVCA) copolymer. The "adhesive" layer was composed predominantly of the same copolymer with some unidentifiable additives. There was visual evidence, in the form of brush marks on the surface of the "adhesive" and wrinkling of the backing film, that the pipe wrap had been treated with a primer prior to its application to the pipe and coupling, and that the materials in the wrap had been subjected to an active solvent. At the request of this laboratory, information was subsequently received from the Public Service Commission indicating that a primer, of unknown composition, was normally used to activate the surface of the adhesive layer. Acetone, or one of its higher boiling homologs, notably methyl ethyl ketone, is frequently used in this type of application since these ketones readily soften or dissolve PVCA copolymers, but have essentially no solvating action, at ambient temperatures, on rigid PVC homopolymers of the types used in pipe extrusion compounds. The use of any solvent-based primer in an application such as this could be expected to result in some permeation of solvent, or solvent vapor, into the pipe wall. Since specimens of this pipe failed the acetone immersion test which is discussed below, it is reasonable to assume that if ketone solvents, or any material with similar solvating action toward unfused PVC were present in the primer, normal permeation of such materials into the pipe wall would be expected to cause some swelling and also enhance migration, into the pipe wall, of soluble pipe wrap components. Such actions, if detrimental to improperly fused pipe could reasonably be expected to result in the swelling and staining noted in this sample. Thus, the brown stains were probably due to direct solvent action where the tape was in contact with the outer pipe surface, and the green stains to solvent vapor action. The maximum degree of swelling, believed to have been caused by the pipe wrap and excluding the ballooned area on the bottom of the pipe, occurred in the area just to the left of point E in Figure 3, which could be expected since this area was covered with the maximum thickness of the tapered wrap, and consequently was undoubtedly subjected to the highest concentration of solvent and solvent vapor, for the longest period of time. The maximum degree of out-of-roundness was on the top of the pipe, just beyond the small arc in the crack. Swelling caused the inner wall of the pipe, particularly the upper half, to pull away from the metal pipe insert, reducing its effectiveness as a reinforcing agent. This could be expected to result in the swollen portions, i.e., along the top, of the pipe being subjected to higher than normal tensile stresses due to the previously noted deformation of the adjacent longer section of the pipe. It also seems obvious that the previously noted reduction in the pipe diameter due to the adjacent compression fitting would induce inherent compression stresses that could feasibly produce a synergistic effect, in conjunction with adjacent tensile stresses, in reduction of the strength of the pipe. Since the above types of solvents are relatively volatile, it would appear most likely that the swelling began to occur almost immediately after the wrap had been applied; and as a result, swelling may well have occurred prior to the initial pressurization of the pipe.

Microscopic Examination of the Crack

In order to study the surfaces of the crack, as well as the inner wall of the pipe, the cracked section was opened by making transverse cuts through the pipe at points A and B (Figure 3), and a longitudinal cut opposite the crack, on the bottom of the pipe. Microscopic examination of the crack surfaces indicated that a stress crack probably was initiated at the small arc, point E (Figure 3), which was located between the point of maximum swelling and the area that had been compressed by the coupling seal. However, microscopic examination of the surface and surrounding areas of the small transverse crack, located near the midpoint, point D (Figure 3), indicated that this was also a possible point of a stress crack initiation. There was also the possibility that the transverse crack was a junction of two adjacent, parallel, slightly overlapping, longitudinal cracks. A small piece of the outer pipe wall was missing at this point. In addition, there was a small indentation at the inner wall that could have been due to the presence of a void or a foreign occlusion. This indentation was approximately equal in width to the length of the transverse crack.

The small sand-like particles, observed embedded in the crack, fell out and were not recovered during attempts to remove the metal pipe insert. The insert was quite difficult to remove due to the extremely tight seal, affected by the compression seal, between it and the plastic pipe. However, the location of the particles had previously been marked on the outer pipe surface. Subsequent microscopic examination of the crack surfaces revealed the presence of two discrete cavities on each side of the pipe wall at and near the inner surface. The sharpness of detail of the cavities indicated that they were apparently present in the molding compound at the time the pipe was extruded, as opposed to having fallen into the crack after it had formed. Examination of the crack surfaces surrounding the pits did not reveal any visual evidence that their presence resulted in the initiation of a stress crack, but their presence could reasonably be expected to be conducive to propagation of a crack, initiated at some other point in the vicinity of the particles.

The ballooning observed in the bottom wall of the pipe was apparently caused by use of an excessive amount of pipe cement in joining the cracked section to the socket. Cement had flowed along the bottom of the pipe and collected in a pool between the metal insert and the inner wall of the plastic pipe. In addition excess cement had flowed into the metal insert for approximately 11 cm (4.5 in). Analysis of this material indicated that it was a PVC homopolymer. It is not unusual for this type of cement to contain cyclohexanone and/or dimethyl formamide as active solvents for the PVC homopolymer pipe compound. Such solvents attack or partially solvate the pipe surface, ensuring a strong bond between pipe and fitting. However, these solvents have low volatilities and if entrapped, such as between the metal insert and the plastic pipe, would tend to migrate into the plastic and soften it. Therefore, it is highly possible that ballooning occurred during the initial pressure testing of the pipe assembly, even though this may have occurred up to several days after installation. Under such circumstances, immediate rupture of the pipe might have been prevented because: 1) the test pressure was too low, with respect to the degree of softening of the pipe; or 2) the pipe wrap exerted sufficient counterpressure to limit the degree of ballooning. Although the ballooning was the obvious result of poor assembly techniques, there seemed to be no direct connection between it and the general swelling of the remainder of the wrapped area presumed to have been due to the components of the wrap or wrap primer. Although the general swelling of the upper half of the pipe could have been caused by solvent vapors from the pipe cement, which usually consists of about 75 percent solvent, this possibility was essentially ruled out after visual inspection of the inner surface of the pipe, and examination of cross sections of the pipe wall. These inspections revealed that both the inner surface and the pipe wall were light green in all areas opposite the brown-stained areas on the outer surface of the pipe, and that those areas of the inner surface, opposite of the light green areas on the outer surface, were unchanged in color from the natural light grey color of the pipe. This indicated staining from the outside of the pipe, i.e., due to solvent from the pipe wrap primer. Whereas, the solvent used in the pipe cement, excess of which was present within the socket fitting and along the bottom of the short, cracked section of the pipe from the butt weld within the socket to the wrapped area of the pipe, caused no discoloration of the inner wall of the pipe.

Properties of the Pipe

The only requirements in CS 237-61, that were applicable to the size of the sample and could be checked on the finished pipe, involved dimensional requirements and chemical composition of the basic pipe compound. The pipe was found to comply with the dimensions and tolerances set forth in CS 237-61. Qualitative infrared spectrographic analysis indicated that the pipe compound was based on a PVC homopolymer and probably contained an aliphatic hydrocarbon, elastomeric polymer, such as polybutadiene, to act as an impact modifier. This analysis indicated that the pipe was fabricated from the stated Type 2, Grade 1 PVC based compound.

Although not required in CS 237-61, the pipe was subjected to flattening tests for resistance to cracking, and to an extrusion quality test for PVC pipe, both of which are tests included in current plastic pipe specifications, issued either as ASTM Standards or as NBS Voluntary Product Standards. Test specimens passed the current requirements for the flattening tests, but failed the extrusion quality tests. The former test requires that the pipe specimen exhibit no splitting, cracking or related defects, when compressed to 40% of its actual outside diameter. The latter test is currently used to determine whether the extruded pipe compound is properly fused, by immersing specimens in anhydrous acetone for 20 minutes at room temperature. Although its use is limited to certain types of PVC pipe only, it includes the type of compound used in this pipe. Properly fused PVC homopolymer pipe compound will show no evidence of splitting, cracking, flaking, or the like on completion of this test. However, when specimens of this pipe were subjected to this test, the central portion, representing about one-third of the total wall thickness, was rapidly disintegrating within 6 to 8 minutes, followed by further gross cracking and splitting of the material comprising the remaining inner and outer portions of the pipe wall. To the best of our knowledge, including information in the latest ASTM version of this test, there is, as yet, insufficient data to provide a correlation between failure in this test and other physical and chemical properties of PVC pipe.

Conclusions

On the basis of this analysis, it is apparent that the failure of the pipe was due to a combination of several factors. The pipe was chemically attacked by one or more components in the pipe wrap or primer, resulting in swelling of the pipe. The swelling appeared to have been enhanced by the apparent poor quality of the extruded material, as indicated by its poor resistance to acetone. Separation of the swollen pipe from the metal insert, particularly along the top of the pipe, reduced the effectiveness of the insert in preventing undue strain on the plastic pipe adjacent to the coupling, such as the obvious tensile stresses created along the upper portion of the pipe by the nearby creep-type deformation of the long section of pipe. The nature of the stress crack indicated, to a high degree of probability, that embrittlement resulted, in part, from fatique stresses, such as those due to expansion and contraction of the soil, and to vibrations from overhead traffic, on the excessively swollen area of the wrapped section of the plastic pipe, immediately adjacent to the affixed, rigid coupling. In addition, the presence of a small cavity in the inner wall, at the small transverse crack, near the middle of the longitudinal crack, whether caused by an occluded particle, or not, as well as the cavities produced by the presence of the occluded sand-like particles, near the outer end of the crack, could have contributed to crack propagation. In both cases the presence of the cavities effectively reduced the wall thickness, and general experience indicates that the consequence would be a significant reduction in the mechanical strength of the pipe.

Figure 1. Damaged section of pipe, including attached components of coupling, pipe wrap, and socket fitting. Point A is outer end of visible stress crack in the pipe; point B is outer limit of crack in pipe wrap tape.