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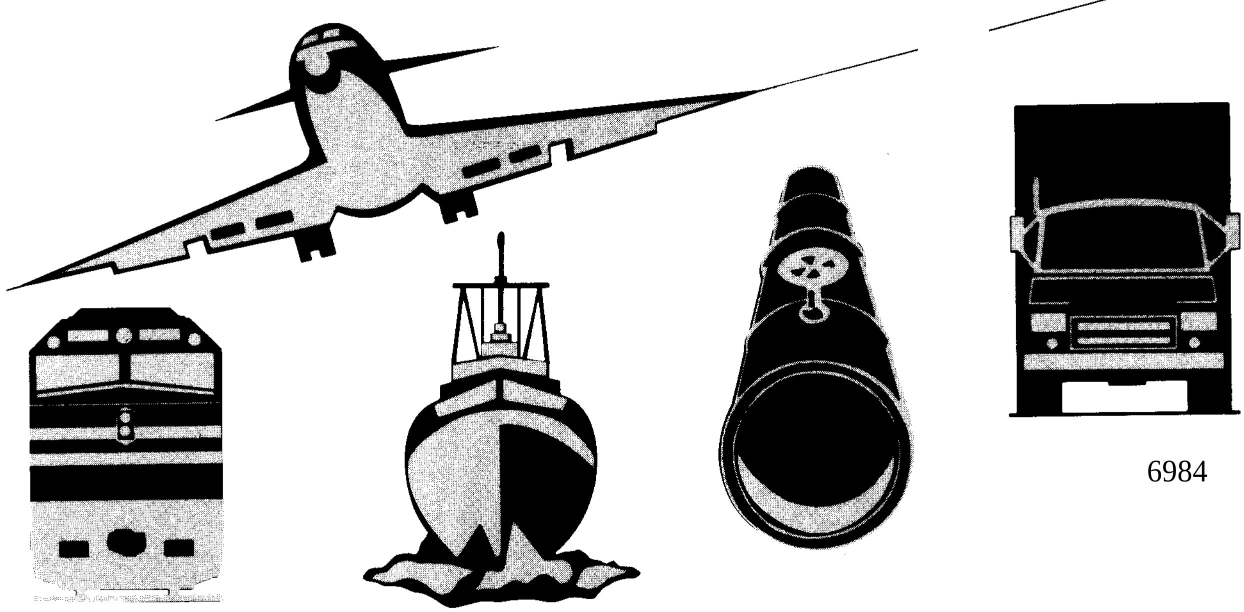
NATIONAL TRANSPORTATION SAFETY BOARD

WASHINGTON, D.C. 20594

SPECIAL INVESTIGATION REPORT

BRITTLE-LIKE CRACKING IN PLASTIC PIPE FOR GAS SERVICE



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Abstract: Despite the general acceptance of plastic piping as a safe and economical alternative to piping made of steel or other materials, the National Transportation Safety Board notes that a number of pipeline accidents it has investigated have involved plastic piping that cracked in a brittle-like manner. This special investigation report concludes that the procedure used in the United States to rate the strength of plastic pipe may have overrated the strength and resistance to brittle-like cracking of much of the plastic pipe manufactured and used for gas service from the 1960s through the early 1980s. As a result, much of this piping may be susceptible to premature brittle-like failures when subjected to stress intensification, and these failures represent a potential public safety hazard.

The safety issues discussed in this report are the vulnerability of plastic piping to premature failures due to brittle-like cracking; the adequacy of available guidance relating to the installation and protection of plastic piping connections to steel mains; and performance monitoring of plastic pipeline systems as a way of detecting unacceptable performance in piping systems.

As a result of this special investigation, the National Transportation Safety Board issued recommendations to the Research and Special Programs Administration, the Gas Research Institute, the Plastics Pipe Institute, the Gas Piping Technology Committee, the American Society for Testing and Materials, the American Gas Association, MidAmerican Energy Corporation, Continental Industries, Inc., Dresser Industries, Inc., Inner-Tite Corporation, and Mueller Company.

The National Transportation Safety Board is an independent Federal agency dedicated to promoting aviation, railroad, highway, marine, pipeline, and hazardous materials safety. Established in 1967, the agency is mandated by Congress through the Independent Safety Board Act of 1974 to investigate transportation accidents, determine the probable causes of the accidents, issue safety recommendations, study transportation safety issues, and evaluate the safety effectiveness of government agencies involved in transportation. The Safety Board makes public its actions and decisions through accident reports, safety studies, special investigation reports, safety recommendations, and statistical reviews.

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NATIONAL TRANSPORTATION SAFETY BOARD

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INTRODUCTION

The use of plastic piping to transport natural gas has grown steadily over the years because of the material's economy, outstanding corrosion resistance, light weight, and ease of installing and joining. According to the American Gas Association (A.G.A.),[1] the total miles of plastic piping in use in natural gas distribution systems in the United States grew from about 9,200 miles in 1965 to more than 45,800 miles in 1970. By 1982, this figure had grown to about 215,000 miles, of which more than 85 percent was polyethylene.[2] Data maintained by Office of Pipeline Safety (OPS), an office of the Research and Special Programs Administration (RSPA) within the U.S. Department of Transportation (DOT), indicate that, by the end of 1996, more than 500,000 miles of plastic piping had been installed. Plastic piping as a percentage of all gas distribution piping installed each year has also grown steadily, as illustrated in figure 1.

Despite the general acceptance of plastic piping as a safe and economical alternative to piping made of steel or other materials, the Safety Board notes that a number of pipeline accidents it has investigated have involved plastic piping that cracked in a brittle-like manner.[3] (See table 1 for information on three recent accidents.) For example, on October 17, 1994, an explosion and fire in Waterloo, Iowa, destroyed a building and damaged other property. Six persons died and seven were injured in the accident. The Safety Board investigation determined that natural gas had been released from a plastic service pipe that had failed in a brittle-like manner at a connection to a steel main.

[1]See appendix B for brief descriptions of the organizations, associations, and agencies referenced in this report.

[2]Watts, J., "Plastic Pipe Maintains Lion's Share of Market," *Pipeline and Gas Journal*, December 1982, p. 19, and National Transportation Safety Board Special Study--*An Analysis of Accident Data from Plastic Pipe Natural Gas Distribution Systems* (NTSB/PSS-80/1).

[3]The body of the report will make clear the distinction between brittle-like and ductile fractures.

The Safety Board also investigated a gas explosion that resulted in 33 deaths and 69 injuries in San Juan, Puerto Rico, in November 1996.[4] The Safety Board's investigation determined that the explosion resulted from ignition of propane gas that had migrated under pressure from a failed plastic pipe. Stress intensification at a connection to a plastic fitting led to the formation of brittle-like cracks.

The Railroad Commission of Texas investigated a natural gas explosion and fire that resulted in one fatality in Lake Dallas, Texas, in August 1997.[5] A metal pipe pressing against a plastic pipe generated stress intensification that led to a brittle-like crack in the plastic pipe.

A Safety Board survey of the accident history of plastic piping suggested that the material may be susceptible to brittle-like cracking under conditions of stress intensification. No statistics exist that detail how much and from what years any plastic piping may already have been replaced; however, as noted above, hundreds of thousands of miles of plastic piping have been installed, with a significant amount of it having been installed prior to the mid-1980s. Any vulnerability of this material to premature failure could represent a serious potential hazard to public safety.

In an attempt to gauge the extent of brittle-like failures in plastic piping and to assess trends and causes, the Safety Board examined pipeline accident data compiled by RSPA. The examination revealed that the RSPA data are insufficient to serve as a basis for assessing the long-term performance of plastic pipe.

[4]National Transportation Safety Board Pipeline Accident Report--*San Juan Gas Company, Inc./Enron Corp., Propane Gas Explosion in San Juan, Puerto Rico, on November 21, 1996* (NTSB/PAR-97/01).

[5]Railroad Commission of Texas Accident Investigation No. 97-AI-055, October 31, 1997.

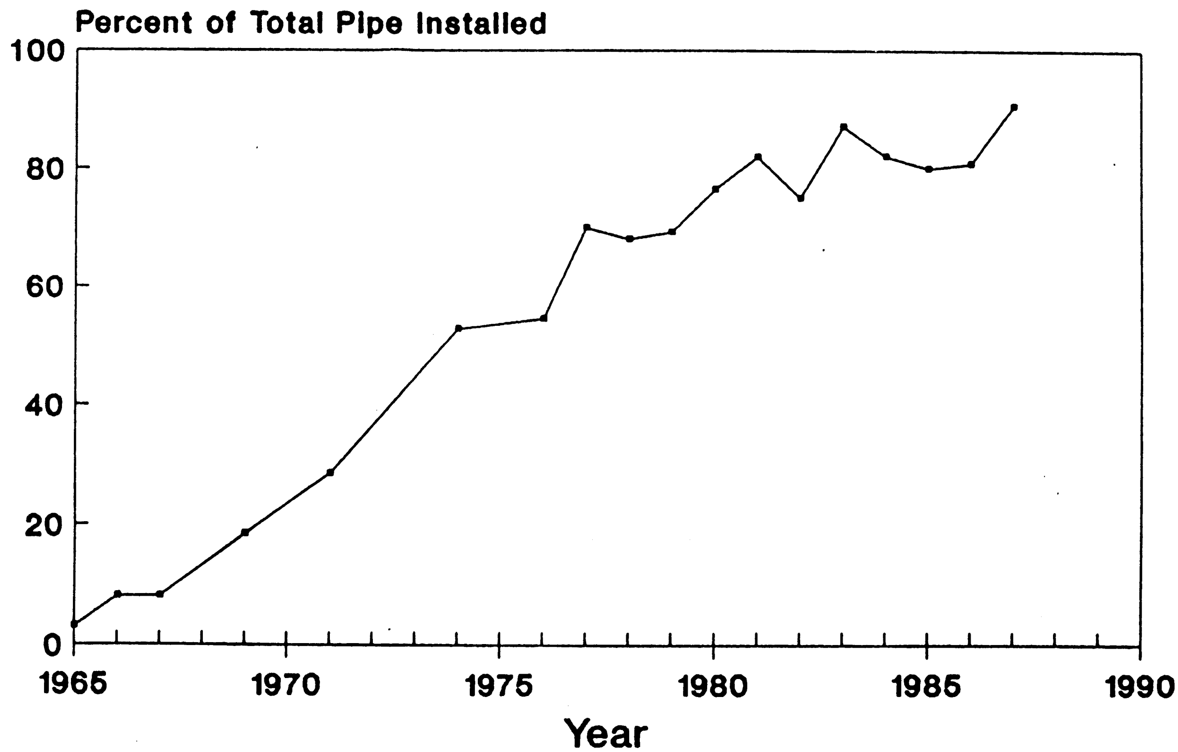

Figure 1 -- Plastic pipe as a percentage of all piping used in gas distribution. (*Source:* Duvall, D.E., "Polyethylene Pipe for Natural Gas Distribution," presented at the Transportation Safety Institute's Pipeline Failure Investigation course, 1997. Data from *Pipeline & Gas Journal* surveys.)

Lacking adequate data from RSPA, the Safety Board reviewed published technical literature and contacted more than 20 experts in gas distribution plastic piping to determine the estimated frequency of brittle-like cracks in plastic piping. The majority of the published literature and experts indicated that failure statistics would be expected to vary from one gas system operator to another based on factors such as brands and dates of manufacture of plastic piping in service, installation practices, and ground temperatures, but they indicated that brittle-like failures, as a nationwide average, may represent the second most frequent failure mode for older plastic piping, exceeded only by excavation damage.

The Safety Board asked several gas system operators about their direct experience with brittle-like cracks. Four major gas system operators reported that they had compiled failure statistics sufficient to estimate the extent of brittle-like failures. Three of those four said that brittle-like failures are the second most frequent failure mode in their plastic pipeline systems. One of these operators supplied data showing that it experienced at least 77 brittle-like failures in plastic piping in 1996 alone.

As an outgrowth of the Safety Board's investigations into the Waterloo, Iowa, San Juan, Puerto Rico, and other accidents, and in view of indications that some plastic piping, particularly older piping, may be subject to premature failure attributable to brittle-like cracking, the Safety Board undertook a special investigation of polyethylene gas service pipe. The investigation addressed the following safety issues:

- The vulnerability of plastic piping to premature failures due to brittle-like cracking;
- The adequacy of available guidance relating to the installation and protection of plastic piping connections to steel mains; and

Table 1 -- Recent pipeline accidents involving brittle-like cracking

Accident Location	Pipe Manufacturer	Year Pipe Manufactured	Year of Accident
Waterloo, Iowa	Amdevco/Century	1970	1994
San Juan, Puerto Rico	DuPont	1982	1996
Lake Dallas, Texas	Nipak	1970	1997

- Performance monitoring of plastic pipeline systems as a way of detecting unacceptable performance in piping systems.

As a result of its investigation, the Safety Board makes three safety recommendations to the Research and Special Programs Administration, one safety recommendation to the Gas Research Institute, three safety recommendations to the Plastics Pipe Institute, one safety recommendation to the Gas Piping Technology Committee, two safety recommendations to the American Society for Testing and Materials, one safety recommendation to the American Gas Association, two safety recommendations to MidAmerican Energy Corporation, two safety recommendations to Continental Industries, Inc., and one safety recommendation each to Dresser Industries, Inc., Inner-Tite Corporation, and Mueller Company.

INVESTIGATION

Accident History

On October 17, 1994, a natural gas explosion and fire in Waterloo, Iowa, destroyed a building and damaged other property. Six persons died and seven were injured in the accident. The Safety Board investigation determined that the source of the gas was a 1/2-inch-diameter plastic service pipe that had failed in a brittle-like manner at a connection to a steel main.[6]

Excavations following the accident uncovered, at a depth of about 3 feet, a 4-inch steel main. Welded to the top of the main was a steel tapping tee manufactured by Continental Industries, Inc. (Continental). Connected to the steel tee was a 1/2-inch plastic service pipe. (See figure 2.) Markings on the plastic pipe indicated that it was a medium-density polyethylene material manufactured on June 11, 1970, in accordance with American Society for Testing and Materials (ASTM) standard D2513. The pipe had been marketed by Century Utility Products, Inc. (Century). The plastic pipe was found cracked at the end of the tee's internal stiffener and beyond the coupling nut.

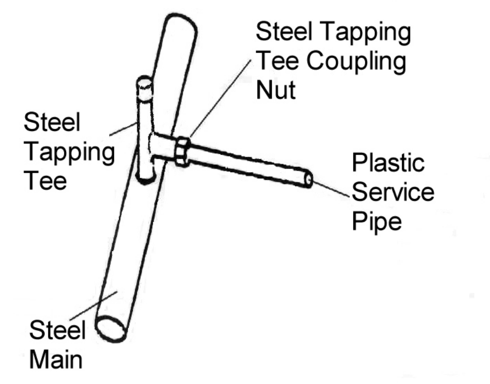

Figure 2 -- Typical plastic service pipe connection to steel gas main. Many connections are protected against shear and bending forces by a plastic sleeve that encloses the service pipe-to-tee connection on either side of the coupling nut.

The investigation determined that much of the top portion of the circumference of the pipe immediately outside the tee's internal stiffener displayed several brittle-like slow crack initiation and growth fracture sites. These slow crack fractures propagated on almost parallel planes slightly offset from each other through the wall of the pipe. As the slow cracks from different planes continued to grow and began to overlap one another, ductile tearing occurred between the planes. Substantial deformation was observed in part of the fracture; however, the initiating cracks were still classified as brittle-like.

Samples recovered from the plastic service line underwent several laboratory tests under the supervision of the Safety Board. Two of these tests were meant to roughly gauge the pipe's susceptibility to brittle-like cracking. These tests were a compressed ring environmental stress crack resistance (ESCR) test in accordance with ASTM F1248 and a notch tensile test known as a PENT test that is now ASTM F1473. Lower failure times in these tests indicate greater susceptibility to brittle-like cracking under test conditions. The ESCR testing of 10 samples from the pipe yielded a mean failure time of 1.5 hours, and the PENT testing of 2 samples yielded failure times of 0.6 and 0.7 hours. Test values this low have been associated with materials having poor performance histories[7]

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[6]For more detailed information, see Pipeline Accident Brief in appendix A to this report.

[7]Uralil, F. S., et al., *The Development of Improved Plastic Piping Materials and Systems for Fuel Gas Distribution—Effects of Loads on the Structural and Fracture Behavior of Polyolefin Gas Piping*, Gas Research Institute Topical Report, 1/75 - 6/80, NTIS No. PB82-180654, GRI Report No. 80/0045, 1981, and Hulbert, L. E., Cassady, M. J., Leis, B. N., Skidmore, A., *Field Failure Reference Catalog for Polyethylene Gas Piping, Addendum No. 1*, Gas Research Institute Report No. 84/0235.2, 1989, and Brown, N. and Lu, X., "Controlling the Quality of PE Gas Piping Systems by Controlling the Quality of the Resin," *Proceedings Thirteenth International Plastic Fuel Gas Pipe Symposium*, pp. 327-338, American Gas

characterized by high leakage rates at points of stress intensification[8] due to crack initiation and slow crack growth typical of brittle-like cracking.

In late 1996, the Safety Board began an investigation of a November 1996 gas explosion that resulted in 33 deaths and 69 injuries in San Juan, Puerto Rico. The investigation determined that the explosion resulted from ignition of propane gas that, after migrating under pressure from a failed plastic pipe at a connection to a plastic fitting, had accumulated in the basement of a commercial building. The Safety Board concluded that apparent inadequate support under the piping and the resulting differential settlement generated long-term stress intensification that led to the formation of brittle-like circumferential cracks on the pipe.

The Railroad Commission of Texas investigation of a fatal natural gas explosion and fire in Lake Dallas, Texas, in August 1997 determined that a metal pipe pressing against a plastic pipe generated stress intensification that led to a brittle-like crack in the plastic pipe.

The Waterloo, San Juan, and Lake Dallas accidents were only three of the most recent in a series of accidents in which brittle-like cracks in plastic piping have been implicated. In Texas in 1971, natural gas migrated into a house from a brittle-like crack at the connection of a plastic service line to a plastic main.[9] The gas ignited and exploded, destroying the house and burning one person. The investigation determined that vertical loading over the connection generated long-term stress that led to the crack.

A 1973 natural gas explosion and fire in Maryland severely damaged a house, killed three occupants, and injured a fourth.[10] The Safety Board's investigation revealed that a brittle-like crack occurred in a plastic pipe as a result of an occluded particle that created a stress point.

The Safety Board's investigation of a natural gas explosion and fire that resulted in three fatalities in North Carolina in 1975[11] determined that the gas had accumulated because a concrete drain pipe resting on a plastic service pipe had precipitated two cracks in the plastic pipe. Available documentation suggests that these cracks were brittle-like.

A 1978 natural gas accident in Arizona destroyed 1 house, extensively damaged 2 others, partially damaged 11 other homes, and resulted in 1 fatality and 5 injuries.[12] Available documentation indicates that the gas line crack that caused the accident was brittle-like.

A 1978 accident in Nebraska involved the same brand of plastic piping as that involved in the Waterloo accident. A crack in a plastic piping fitting resulted in an explosion that injured one person, destroyed one house, and damaged three other houses.[13] The Safety Board determined that inadequate support under the plastic fitting resulted in long-term stress intensification that led to the formation of a circumferential crack in the fitting. Available documentation indicates that the crack was brittle-like.

A December 1981 natural gas explosion and fire in Arizona destroyed an apartment, damaged five other apartments in the same building, damaged nearby buildings, and injured three occupants.[14] The Safety Board's

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Association, Gas Research Institute, Battelle Columbus Laboratories, 1993.

[8]Stress intensification occurs when stress is higher in one area of a pipe than in those areas adjacent to it. Stress intensification can be generated by external forces or a change in the geometry of the pipe (such as at a connection to a fitting).

[9]National Transportation Safety Board Pipeline Accident Report--*Lone Star Gas Company, Fort Worth, Texas, October 4, 1971* (NTSB/PAR-72/5).

[10]National Transportation Safety Board Pipeline Accident Report--*Washington Gas Light Company, Bowie, Maryland, June 23, 1973* (NTSB/PAR-74/5).

[11]National Transportation Safety Board Pipeline Accident Brief--"Natural Gas Corporation, Kinston, North Carolina, September 29, 1975."

[12]National Transportation Safety Board Pipeline Accident Brief--"Arizona Public Service Company, Phoenix, Arizona, June 30, 1978."

[13]National Transportation Safety Board Pipeline Accident Brief--"Northwestern Public Service, Grand Island, Nebraska, August 28, 1978."

[14]National Transportation Safety Board Pipeline Accident Brief--"Southwest Gas Corporation, Tucson, Arizona, December 3, 1981."

investigation determined that assorted debris, rocks, and chunks of concrete in the excavation backfill generated stress intensification that resulted in a circumferential crack in a plastic pipe at a connection to a plastic fitting. Available documentation indicates that the crack was brittle-like.

A July 1982 natural gas explosion and fire in California destroyed a store and two residences, severely damaged nearby commercial and residential structures, and damaged automobiles.[15] The Safety Board's investigation identified a longitudinal crack in a plastic pipe as the source of the gas leak that led to the explosion. Available documentation indicates that the crack was brittle-like.

A September 1983 natural gas explosion in Minnesota involved the same brand of plastic piping as that involved in the Waterloo and Nebraska accidents.[16] The explosion destroyed one house and damaged several others, and injured five persons. The Safety Board's investigation determined that rock impingement generated stress intensification that resulted in a crack in a plastic pipe. Available documentation indicates that the crack was brittle-like.

One woman was killed and her 9-month-old daughter injured in a December 1983 natural gas explosion and fire in Texas.[17] The Safety Board's investigation determined that the source of the gas leak was a brittle-like crack that had resulted from damage to the plastic pipe during an earlier squeezing operation to control gas flow.[18]

A September 1984 natural gas explosion in Arizona resulted in five fatalities, seven injuries, and two destroyed apartments.[19] The Safety Board's investigation determined that a reaction between a segment of plastic pipe and some liquid trapped in the pipe weakened the pipe and led to a brittle-like crack.

During the course of the investigation of the accident at Waterloo, Iowa, the Safety Board learned of several other accidents, not investigated by the Safety Board, that involved cracks in the same brand of plastic piping as that involved in the Waterloo accident. Three of these accidents, which occurred in Illinois (1978 and 1979) and in Iowa (1983), resulted in five injuries and damage to buildings.[20] A 1995 accident in Michigan also involved a crack in this same brand of pipe.[21] Available documentation indicates that the cracks were brittle-like.

Strength Ratings, Ductility, and Material Standards for Plastic Piping

During the 1950s and early 1960s, when plastic piping was beginning to gain acceptance as an alternative to steel piping for the transport of water and gas, no established procedures existed for rating the strength of materials intended for use in plastic pressure piping.

In November 1958, the Thermoplastic Pipe Division of the Society of the Plastics Industry organized a group called the Working Stress Subcommittee.[22] The subcommittee, in January 1963, issued a procedure (hereinafter referred to as the PPI procedure) that specified a uniform protocol for rating the strength of materials used

[15]National Transportation Safety Board Pipeline Accident Brief--"Pacific Gas and Electric Company, San Andreas, California, July 8, 1982."

[16]National Transportation Safety Board Pipeline Accident Brief--"Northern States Power Company, Newport, Minnesota, September 19, 1983."

[17]National Transportation Safety Board Pipeline Accident Brief--"Lone Star Gas Company, Terell, Texas, December 9, 1983."

[18]Plastic pipe is sometimes squeezed to control the flow of gas. In some cases, squeezing plastic pipe can damage it and make it more susceptible to brittle-like cracking.

[19]National Transportation Safety Board Pipeline Accident Report--*Arizona Public Service Company Natural Gas Explosion and Fire, Phoenix, Arizona, September 25, 1984* (NTSB/PAR-85/01).

[20]Illinois Commerce Commission accident reports dated September 14, 1978, and December 4, 1979. Iowa State Commerce Commission accident report dated August 29, 1983.

[21]Research and Special Programs Administration Incident Report—"Gas Distribution System," Report No. 318063, January 8, 1996.

[22]This subcommittee was subsequently made into a permanent unit and was renamed the Hydrostatic Stress Board.

in the manufacture of thermoplastic pipe in the United States. In March 1963, the Thermoplastic Pipe Division adopted its current name, the Plastics Pipe Institute (PPI).

On July 1, 1963, the PPI established a voluntary program of listing the material strengths of plastic piping materials, specifically, those materials designed for water applications. To apply for a PPI listing, applicants sent strength test data to the PPI, often accompanied by the manufacturer's analysis of the data and a proposed material strength rating. The PPI would analyze the data and, if warranted, list the material for the calculated strength. The PPI did not certify or approve the material received or validate the data submitted, nor did it audit or inspect those submitting data.[23]

In simplified terms, the PPI procedure, which is performed by the materials manufacturers themselves, involves recording how much time it takes stressed pipe samples to rupture at a standardized temperature of 73 °F. The stresses used in the tests are recorded as "hoop stress," which is tensile stress in the wall of the pipe in a circumferential orientation (hence the term "hoop") due to internal pressure. Although hoop stress is expressed in pounds per square inch, it is a value quite different from the pipe's internal pressure.

The testing process involves subjecting pipe samples to various hoop stress levels, and then recording the time to rupture. For some samples at some pressures, rupture will occur in as little as 10 hours. As hoop stress is reduced, the time-to-failure increases. At some hoop stress level, at least one of the tested specimens will not rupture until at least 10,000 hours (slightly more than 1 year). After the rupture data points (hoop stresses and times-to-failure) for this material have been recorded, the data points are plotted on log-log coordinates as the relationship between hoop stress and time-to-failure. (See figure 3.) A mathematically developed "best-fit" straight line is correlated with the data points to represent the material's resistance to rupturing at various hoop stress levels.

Once the best-fit straight line is calculated to 10,000 hours, it is extrapolated to 100,000 hours (about 11 years). The hoop stress level that coincides with the point at which the line intersects the 100,000-hour time line represents the calculated long-term hydrostatic strength of that particular material.

To simplify the ratings and facilitate standardization, the PPI procedure grouped materials with similar long-term hydrostatic strength ranges into "hydrostatic design basis" categories. For example, those materials having long-term hydrostatic strengths between 1200 and 1520 psi were grouped together and assigned a hydrostatic design basis of 1250 psi. Those materials having long-term hydrostatic strengths between 1530 and 1910 psi were grouped together and assigned a hydrostatic design basis of 1600 psi.

To help ensure the validity of the mathematically derived line, the PPI procedure required the submission of all rupture data points. It further specified the minimum number of data points and minimum number of tested lots. The procedure employed statistical tests to verify the quality of data and quality of fit to the mathematically derived line. These measures excluded materials when the data demonstrated excessive data scatter due to either inadequate quality of data or deviation from straight line behavior through 10,000 hours.[24]

The PPI procedure, after some refinement, was issued as an ASTM method in 1969 (ASTM D2837). The PPI adopted a policy document[25] for PPI's listing service in 1968, which remained under PPI jurisdiction.

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[23]As a result of Safety Board inquiries to the PPI about its inability to verify the actual data submitted, the institute, in 1997, revised its policy document for its listing service to require a signed statement from applicants that data accompanying applications for a PPI listing are complete, accurate, and reliable.

[24]The PPI procedure also had restrictions on the degree of slope of the straight line so that the material's strength would not excessively diminish beyond 100,000 hours.

[25]Plastics Pipe Institute, *Policies and Procedures for Developing Recommended Hydrostatic Design Stresses for Thermostatic Pipe*, PPI-TR3-July 1968.

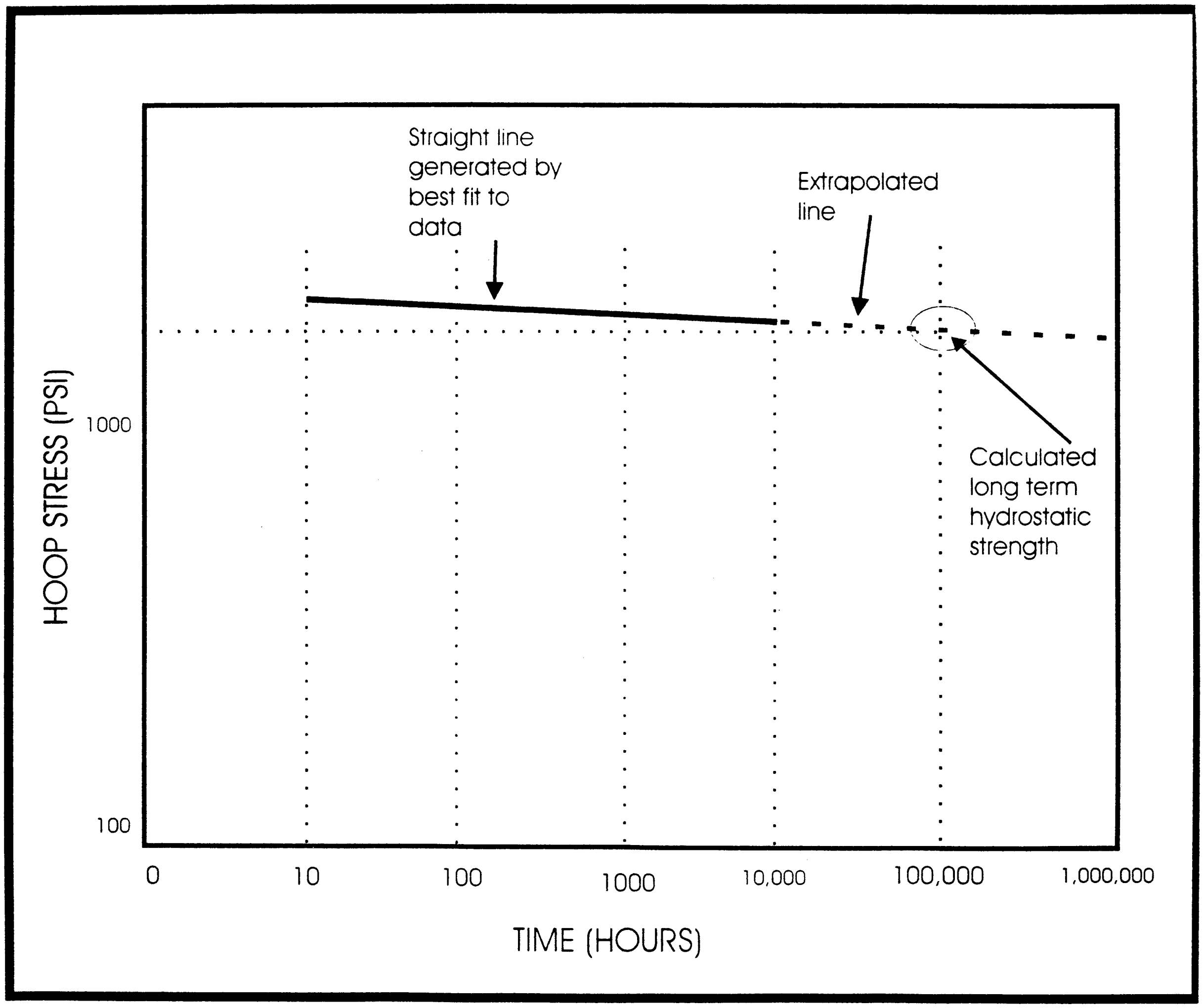

Figure 3 -- Stress rupture data plotted as best-fit straight line and extrapolated to determine long-term hydrostatic strength. (Derived from *A.G.A. Plastic Pipe Manual for Gas Service.)*

When polyethylene pipe fails during laboratory stress rupture testing at 73 °F, it fails primarily by means of ductile fractures, which are characterized by substantial visible deformation (see figure 4). During stress rupture tests, if hoop stress on the test piping is decreased, the time-to-failure increases, and the amount of deformation apparent in the failure decreases.[26] In pipe subjected to prolonged stress rupture testing, slit fractures[27] may begin to appear at some point (depending on the specific polyethylene resin material). Figure 5 shows a slit fracture that resulted from a stress rupture test. The PPI procedure did not differentiate between ductile and slit failure types, and, based on most available laboratory test data (at 73 °F),[28] assumed that both types of

[26]Mruk, S. A., "The Ductile Failure of Polyethylene Pipe," *SPE Journal*, Vol. 19, No. 1, January 1963.

[27]Because of the frequent lack of visible deformation associated with them, slit fractures are also referred to as brittle-like fractures.

[28]Kulhman, H. W., Wolter, F., Sowell, S., Smith, R. B., *Second Summary Report, The Development of Improved Plastic Pipe for Gas Service, Prepared for the American Gas Association*, Battelle Memorial Institute, covering the work from mid-1968 through 1969. Stress rupture tests were performed using methane and nitrogen as the internal pressure medium and air as the outside environment. Some experts have advised the Safety Board that stress rupture testing showing time-to-failure in the slit mode may vary with different pressure media and

Figure 4 -- Ductile fracture resulting from stress rupture test. Note substantial deformation (ballooning) at the failure.

failures would be described by the same extrapolated (straight) line.

In 1963-64, the National Sanitation Foundation[29] amended its standard for plastic piping used for potable water service to require that manufacturers furnish evidence of having an appropriate strength rating in accordance with the PPI procedure. Manufacturers then decided to utilize the PPI listing service, having determined that this was the most convenient way to furnish the required evidence.

In 1966, the ASTM issued ASTM D2513, the society's first standard specification covering polyethylene plastic piping for gas service.[30] ASTM D2513 made reference to long-term hydrostatic strength and hydrostatic design stress and included an appendix defining these terms in accordance with the PPI procedure.[31] It also required that polyethylene pipe meet certain requirements of ASTM D2239 (a polyethylene pipe specification for water service), which also included references to the PPI procedure. ASTM D2513 did not explicitly require materials to have a PPI listing.

environments and that Battelle Memorial Institute's choices for these fluids may have contributed to the slow recognition in the United States of a downturn in the stress rupture line.

[29]Now known as NSF International.

[30]This standard also included plastic piping materials other than polyethylene.

[31]Although adherence to ASTM appendixes is not mandatory, the PPI procedure was the only industry-accepted mechanism to determine long-term hydrostatic strength and hydrostatic design stress.

Figure 5 -- Slit fracture resulting from a stress rupture test conducted at 100 °F. Note lack of deformation visible in the fracture. This pipe was manufactured by DuPont in 1977. After failing Minnegasco's incoming inspection tests, the pipe was subjected to stress rupture testing. (*Source:* Henrich, R.C., and Funck, D.L., "Effects of ESCR Variation on Some Other Properties of Plastic Pipe." *Proceedings, Eighth Annual Plastic Fuel Gas Pipe Symposium, 1983.)*

Even without an explicit requirement, some manufacturers voluntarily obtained PPI listings for their resin materials[32] intended for gas use, and some others,[33] as noted above, obtained PPI listings for their resins that were intended for water use (but were similar to their resins intended for gas service) as a way of meeting National Sanitation Foundation requirements.

In 1967, the United States of America Standards Institute B31.8 code,[34] *Gas Transmission and Distribution Piping Systems*, for the first time recognized the suitability of plastic piping for gas distribution service and included requirements for the pipings' use. The 1966 issuance of ASTM D2513 and the 1967 inclusion of plastic piping within B31.8 cleared the way for the general use of plastic piping for gas distribution.[35] B31.8 included a design equation (see discussion below), and although the code, like the ASTM standard, did not explicitly require a PPI listing, it did require that material used to manufacture plastic pipe establish its long-term hydrostatic strength in accordance with the PPI procedure.

[32]Resins are polymer materials used for the manufacture of plastics.

[33]For example, E. I. du Pont de Nemours & Company, Inc., and Union Carbide Corporation.

[34]Now known as ASME B31.8.

[35]*A.G.A. Plastic Pipe Handbook for Gas Service*, American Gas Association, Catalog No. X50967, April 1971.

On August 12, 1968, the Natural Gas Pipeline Safety Act was enacted, requiring the DOT to adopt minimum Federal regulations for gas pipelines. In December 1968, the DOT instituted interim Federal regulations by federalizing the State pipeline safety regulations that were in place at the time. The DOT, having concluded that the majority of the States required compliance with the 1968 version of B31.8, adopted that version of the code for the Federal regulations covering those States not yet having their own natural gas pipeline safety regulations.

Most of these Federal interim standards were replaced in November 1970 by 49 *Code of Federal Regulations* (CFR) 192; however, the interim provisions concerning the design, installation, construction, initial inspection, and initial testing of new pipelines remained in effect until March 1971. At that time, 49 CFR 192 incorporated the design equation for plastic pipe from B31.8 and also required that plastic piping conform to ASTM D2513.[36]

The 1967 version of B31.8 introduced fixed design factors[37] (subsequently incorporated into 49 CFR 192) as a catch-all mechanism to account for various influences on pipe performance and durability. These influences included external loadings, limitations of and imprecision in the PPI procedure, variations in pipe manufacturing, handling and storage effects, temperature fluctuations, and harsh environments.[38] A design equation was used to determine the allowable gas service pipe pressure rating based on the hydrostatic design basis category, pipe dimensions, and design factor.[39] The design basis for plastic pipe thus used internal pressures as a design criterion but did not directly take into account additional stresses that could be generated by external loadings, despite the fact that field failures in plastic piping systems were frequently associated with external loads but were rarely attributable to internal pressure effects alone.[40]

Kulmann and Mruk have reported that no direct basis was established to design for external loads because:

- The industry had no easy means of quantifying external loads and their effects on plastic piping systems;[41] and

- Many in the industry believed that plastic piping, like steel and copper piping, behaved as a ductile material that would withstand considerable deformation before undergoing damage, thus alleviating and redistributing local stress concentrations that would crack brittle materials such as cast iron. This belief resulted from short-term laboratory tests showing that plastic piping had enormous capacity to deform before rupturing.[42]

Because of plastic piping's expected ductile behavior, many manufacturers believed it safe to base their designs on average distributed stress concentrations generated primarily by internal pressure and, within reason, to neglect localized stress concentrations. They believed such stress would be reduced by localized yielding, or deformation. Mruk and Palermo have pointed out that design protocols were predicated on the assumption of such ductile behavior.[43]

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[36]RSPA reviews revised editions of ASTM D2513 for acceptability before referencing them in 49 CFR 192.

[37]A design factor is similar to a safety factor, except that a design factor attempts to account for other factors not directly included within the design equation that significantly affect the durability of the pipe.

[38]Reinhart, F. W., "Whence Cometh the 2.0 Design Factor," Plastics Pipe Institute, undated, and Mruk, S. A., "Validating the Hydrostatic Design Basis of PE Piping Materials."

[39]The design equation (with the current design factor, 0.32) can be found in 49 CFR 192.121, although 192.121 erroneously references the long-term hydrostatic strength instead of the hydrostatic design basis category. RSPA is currently conducting rulemaking activities to correct this error.

[40]Kulmann, H. W., Wolter, F., Sowell, S., "Investigation of Joint Performance of Plastic Pipe for Gas Service," *1970 Operating Section Proceedings*, American Gas Association, pp. D-191 to D-198.

[41]Kulmann, Wolter, and Sowell.

[42]Mruk, S. A., "Validating the Hydrostatic Design Basis of PE Piping Materials."

[43]Mruk, S. and Palermo, E., "The Notched Constant

Figure 6 -- Slit fracture on a polyethylene pipe manufactured by DuPont that was found leaking and removed from a gas piping system.

In contrast, cast iron piping has recognized brittle characteristics. The design basis for cast iron therefore does not assume that localized yielding or deformation will reduce stress intensification. As a result, the design protocol for cast iron includes the quantification and direct input of external loading factors that can generate localized stress intensification.[44]

Failures in polyethylene piping that occur under actual service conditions are frequently slit failures; ductile failures are rare.[45] Figure 6 shows a slit (brittle-like) fracture in a pipe that was found leaking and had to be replaced. A rock pressing against the plastic pipe generated long-term stress intensification that led to the formation of the brittle-like crack. Slit failures in polyethylene, whether occurring during stress rupture testing or under actual service conditions, result from crack initiation and slow crack growth and are similar to brittle cracks in other materials in that they can occur with little or no visible deformation.[46]

Tensile Load Test: A New Index of the Long Term Ductility of Polyethylene Piping Materials," summary of presentation given in the Technical Information Session hosted by ASTM Committee F17's task group on Project 62-95-02, held in conjunction with ASTM Committee F17's November 1996 meetings, New Orleans, LA.

[44]Mruk and Palermo and Hunt, W. J., "The Design of Grey and Ductile Cast Iron Pipe," *Cast Iron Pipe News*, March/April 1970.

[45]Mruk, S. A., "Validating the Hydrostatic Design Basis of PE Piping Materials," and Bragaw, C. G., "Fracture Modes in Medium-Density Polyethylene Gas Piping Systems," *Plastics and Rubber: Materials and Applications*, pp. 145-148, November 1979.

[46]Mruk and Palermo have quantified and discussed the deformation in brittle-like failures in: Mruk, S. and Palermo, E., "The Notched Constant Tensile Load Test: A New Index of the Long Term Ductility of Polyethylene

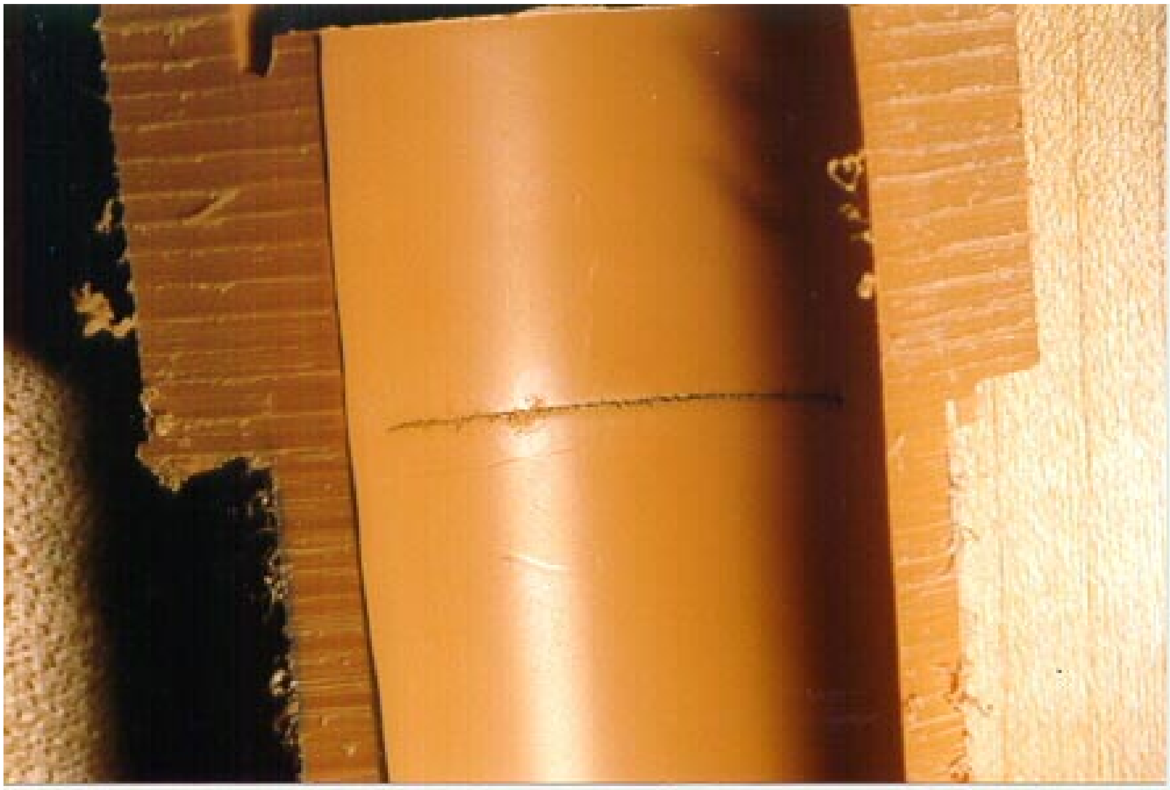

Figure 7 -- Interior of polyethylene pipe from San Juan pipeline accident showing brittle-like crack with no visible deformation.

Figure 7 illustrates brittle-like cracking that was found in a plastic pipe involved in the fatal propane gas explosion in San Juan, Puerto Rico, in November 1996. That pipe was manufactured in 1982 by E. I. du Pont de Nemours & Company, Inc., (DuPont) at its Pencador, Delaware, plant. Apparently, differential settlement resulting from inadequate support under the piping generated long-term stress intensification that led to the formation of brittle-like cracks in the pipe.

Figure 8 shows a brittle-like crack that was found in a plastic pipe involved in the fatal natural gas explosion and fire in Lake Dallas, Texas, in August 1997. That pipe was manufactured in 1970 by Nipak, Inc. A metal pipeline pressing against the plastic pipe generated long-term stress intensification that led to the crack.

During the 1960s and 1970s, some experts began to question the validity of the PPI procedure's assumption of a continuing, gradual straight-line decline in strength (figure 3). [47] By the late 1970s and early 1980s, the plastic piping industry in the United States realized that

Piping Materials," summary of presentation given in the Technical Information Session hosted by ASTM Committee F17's task group on Project 62-95-02, held in conjunction with ASTM Committee F17's November 1996 meetings, New Orleans, LA, and Mruk, S. A., "Validating the Hydrostatic Design Basis of PE Piping Materials," pp. 202-214, 1985.

[47]The 1971 *A.G.A. Plastic Handbook for Gas Service* noted that the cause and mechanisms of brittle fractures sometimes found with long-term stress rupture testing was not yet well established. Two of the pioneering papers in the United States to suggest a downturn in long-term hydrostatic strength with brittle-like failures or in elevated temperature testing were: Mruk, S. A., "The Ductile Failure of Polyethylene Pipe," *SPE Journal*, Vol. 19, No. 1, January 1963, and Davis, G. W., "What are Long Term Criteria for Evaluating Plastic Gas Pipe?" *Proceedings Third A.G.A. Plastic Pipe Symposium*, American Gas Association, pp. 28-35, 1971.

Figure 8 -- Brittle-like crack in pipe involved in August 1997 accident in Lake Dallas, Texas. The crack extends from the left to upper right of the area defined by the ellipse.

testing piping materials at elevated temperatures was a way to accelerate failure behavior that would occur much later at lower temperatures (such as 73 °F). Based on data derived from elevated-temperature testing, the industry concluded that the gradual straight-line decline in strength assumed by the PPI procedure was not valid. Instead, two distinct failure zones were indicated for polyethylene piping in stress rupture testing. (See figure 9.) The first zone is characterized by the gradual straight-line decline in strength accompanied primarily by ductile fractures. The first zone gradually transitions to the second zone, which is characterized by a more rapid decline in strength accompanied by brittle-like fractures only. The time and magnitude of this more rapid decline in strength varies by type and brand of polyethylene. Piping manufacturers have worked to improve their products' resistance to slit-type failures and thus to push this downturn further out in time. The PPI procedure did not account for this downturn, and the difference between the actual falloff shown in figure 9 and the projected straight-line strengths shown in figure 3 for listed materials became more pronounced as the lines were extrapolated beyond 100,000 hours.

As manufacturers steadily improved their formulations to delay the onset of the downturn in long-term strength and associated brittle-like behavior, PPI and ASTM industry standards were upgraded to reflect what the major manufacturers were able and willing to accomplish.[48] Accordingly, and because a consensus of manufacturers recognized the relationship between

[48]Both the PPI and the ASTM work on a consensus principle, meaning that requirements are put into place only when a consensus of voting members is reached. The PPI is a manufacturers' organization. With respect to the ASTM technical committee that generates requirements for plastic piping, the major piping manufacturers participate actively in the committee and are in a position to influence ASTM strength rating requirements.

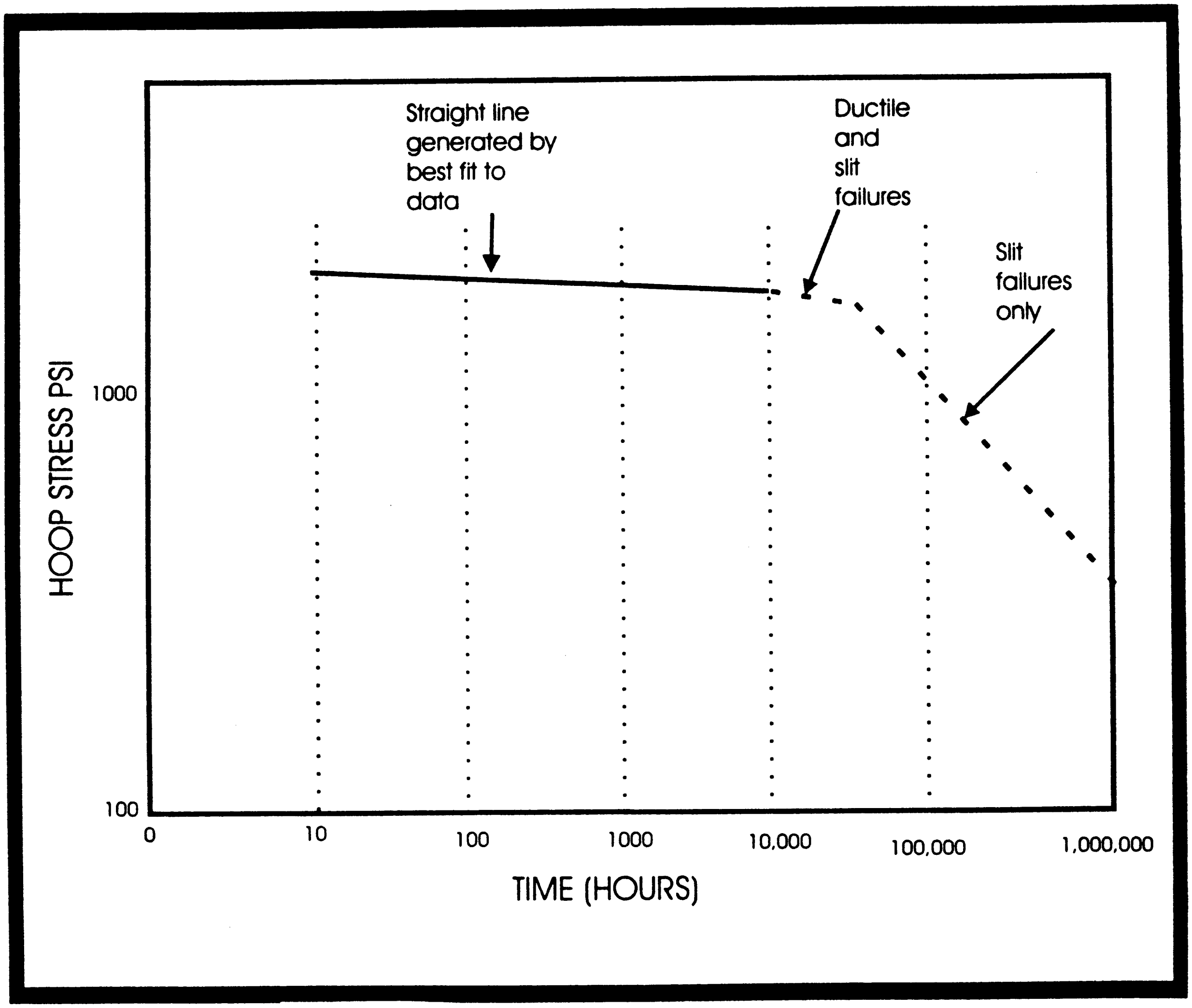

Figure 9 -- Stress rupture data plotted as best-fit straight line transitioning to downturn in strength. (Derived from *A.G.A. Plastic Pipe Manual for Gas Service.*)

improved elevated-temperature properties and improved longer term pipe performance, the PPI in 1982 recommended that ASTM D2513 specify a minimum acceptable hydrostatic strength at 140 °F. In 1984, ASTM D2513 included a statement in its non-mandatory appendix that gas pipe materials should have a specified long-term hydrostatic strength at 140 °F. In the 1988 edition, this requirement was moved to the mandatory section of the standard. This strength at 140 °F was calculated the same way that the 73 °F strength was calculated—data demonstrating a straight line to 10,000 hours was assumed to extrapolate to 100,000 hours without a downturn.

Gradually, more manufacturers obtained PPI listings for their resins intended for gas service, and by the early to mid-1980s, virtually all resins used for gas service had PPI listings. At that time, a consensus of manufacturers supported a change within ASTM D2513 to require PPI listings. In 1985, ASTM D2513 was revised to require that materials for gas service have a PPI listing.

By 1985, manufacturers reached a consensus to exclude materials that deviated from the 73 °F extrapolation before 100,000 hours. The PPI adopted this restriction and advised the industry that, effective January 1986, all materials not demonstrating straight-line performance to 100,000 hours would be dropped from its listing.[49] In 1988, ASTM D2837 also included the restriction.[50] The new PPI and ASTM requirements had no effect on pipe installed prior to the effective date of the requirements.

On August 20, 1997, after manufacturers reached a consensus, the PPI issued notice that, effective January 1999, in order for materials to retain their PPI listings for long-term hydrostatic strength at temperatures above 73 °F (for example, at 140 °F), these materials will have to demonstrate (mathematically, via elevated-temperature testing) that a downturn does not exist prior to 100,000 hours or, alternatively, if a downturn does exist before 100,000 hours, the strength rating will be reduced to reflect the point at which the calculated downturn in strength intercepts 100,000 hours. An ASTM project has been initiated to incorporate this requirement within ASTM D2837. The Safety Board also notes that the PPI has endorsed a proposal to have ASTM D2513 require polyethylene piping to have no downturn in stress rupture testing at 73 °F before 50 years, as mathematically determined in elevated-temperature tests.

All available evidence indicates that polyethylene piping's resistance to brittle-like cracking has improved significantly through the years. Several experts in gas distribution plastic piping have told the Safety Board that a majority of the polyethylene piping manufactured in the 1960s and early 1970s had poor resistance to brittle-like cracking, while only a minority of that manufactured by the early 1980s could be so characterized.[51] Several gas system operators have told the Safety Board that they are aware of no instances of brittle-like cracking with their own modern polyethylene piping installations.

[49]Mruk, S. A., "Validating the Hydrostatic Design Basis of PE Piping Materials."

[50]*A.G.A. Plastic Pipe Manual for Gas Service*, American Gas Association, Catalog No. XR 9401, 1994.

[51]A number of these experts considered material to have poor resistance to brittle-like cracking if the material was shown to have a downturn in strength associated with brittle-like fractures in stress rupture testing (at 73 °F) before 100,000 hours.

Century Pipe Evaluation and History

The Safety Board's investigation of the Waterloo, Iowa, accident determined that the pipe involved in the accident had been manufactured by Amdevco Products Corporation (Amdevco) in Mankato, Minnesota. Amdevco's Mankato plant first began producing plastic pipe in 1970, with plastic piping for gas service as its only piping product. Amdevco made the pipe from Union Carbide's Bakelite DHDA 2077 Tan 3955 (hereinafter referred to as DHDA 2077 Tan) resin material. Century Utility Products, Inc., marketed the pipe to Iowa Public Service Company,[52] and Century's name was marked on the pipe. Century and Amdevco formally merged in 1973. The combined corporation went out of business in 1979.

Because Amdevco/Century no longer exists, Safety Board investigators could locate no records to indicate the qualification steps Amdevco may have performed before Century marketed its pipe to Iowa Public Service Company. A plastic pipe manufacturer would normally have obtained documentation from its resin supplier indicating that the resin material had a sufficient long-term hydrostatic strength. Code B31.8 required and ASTM D2513 recommended that polyethylene pipe manufacturers perform certain quality control tests on production samples, including twice-per-year sustained pressure tests.

Like many gas operators of that time, Iowa Public Service Company (now MidAmerican Energy Corporation), which had installed the Waterloo piping in 1971, had no formal program for testing or evaluating products. According to MidAmerican Energy, the company accepted representations from a principal of Century, a former DuPont employee, who portrayed himself as being intimately involved with the development and marketing of DuPont's polyethylene piping. MidAmerican Energy has reported that these representations included assertions that Century

[52]Because of a series of organizational changes and mergers, the name of the owner/operator of the gas system at Waterloo, Iowa, has changed over the years. In 1971, Iowa Public Service Company installed the gas service that ultimately failed. At the time of the accident, the gas system operator was Midwest Gas Company. The current operator is MidAmerican Energy Corporation.

plastic pipe met industry standards and had the same formulation as DuPont's plastic pipe. In 1970, according to MidAmerican Energy officials, Century offered Iowa Public Service Company attractive commercial terms for its product, with the result that, in 1970, when Amdevco first started to manufacture pipe, Iowa Public Service Company began purchasing all of its plastic pipe from Century.[53]

Before the Waterloo accident, a previous accident involving Century pipe had been reported in the Midwest Gas (the operator at the time of the accident) system. That accident occurred in August 1983 in Hudson, Iowa, and resulted in multiple injuries. Midwest Gas, attributing this accident to a rock pressing into the pipe, considered it an isolated incident. During 1992-94, the company had two significant failures with pipe fittings involving brittle-like cracks in Century pipe. Sections of the failed pipe were sent to the two affected pipe fitting manufacturers, and one responded that nothing was wrong with the fitting, suggesting instead that the problem might rest with the piping material.

MidAmerican Energy reported that, as a result of these two failures, Midwest Gas directed inquiries to other utilities operating in the Midwest and, in May 1994, learned of one other accident involving Century pipe. In June 1994, Midwest Gas decided to send samples of Century polyethylene piping to an independent laboratory for test and evaluation. The sample collection was in process at the time of the Waterloo accident. In August 1995, Midwest Gas issued a report, based on the laboratory testing, concluding that the Century samples had poor resistance to slow crack growth.

Subsequent to the accident, Midwest Gas worked to determine if its installations with Century plastic piping had had higher rates of failure than those with piping from other manufacturers. After analyzing the data, Midwest Gas concluded that the piping installations with Century piping had failure rates that were significantly higher than those installations with plastic piping from other manufacturers. Based on this analysis, as well as on other factors—including the severity and consequences of leaks involving Century piping, the laboratory test results, recommendations from two manufacturers of pipe fittings cautioning against use of their fittings with Century pipe because of the pipe's poor resistance to brittle-like cracking, and interviews with field personnel—MidAmerican Energy (the current operator) has replaced all its known Century piping with new piping, completing the replacement program in 1997.

Safety Board investigators found little additional documentation regarding qualification tests of Century plastic pipe by other gas system operators having Century pipe in service. A reference was found to a 1971 Northern States Power Company Testing Department progress report stating that Century pipe complied with ASTM D2513, and that the pipe was acceptable for use with DuPont polyethylene fittings. The actual progress report and records of any tests that may have been performed were not located.[54]

Union Carbide DHDA 2077 Tan Resin -- The resin used to manufacture the pipe involved in the Waterloo accident was DHDA 2077 Tan. To examine how Union Carbide qualified this material requires some background.

During the late 1960s, several companies manufactured plastic resin and plastic pipe for the gas distribution plastic piping market. At that time, Union Carbide began a process of modifying its DHDA 2077 Black resin (for water distribution) in order to create a DHDA 2077 Tan resin for the gas distribution industry.

Before Union Carbide could market its DHDA 2077 Tan resin material for natural gas service, it needed to generate stress rupture data, in accordance with the PPI procedure, that would support the long-term hydrostatic

[53]Iowa Public Service Company continued to purchase DuPont plastic piping fittings until fittings were available from Century. MidAmerican Energy made technical procurement decisions via a Gas Standards Committee. According to company officials, the company has implemented a process to ensure that it continues to receive quality products once the products have passed an initial qualification process.

[54]Northern States Power is based in St. Paul, Minnesota.

strength rating it was assigning to the material (a requirement of the interim Federal regulations effective at that time).[55] The company had three resources to draw upon to support the hydrostatic design basis category: (1) internal stress rupture data on its DHDA 2077 Tan resin, (2) a PPI listing already obtained on its similar black resin, and (3) additional internal stress rupture data on its black resin.

On June 11, 1968, Union Carbide began stress rupture testing on specimens of pipe made from a pilot-plant batch of its newly developed DHDA 2077 Tan resin. The results of this testing supported Union Carbide's declared hydrostatic design basis category for DHDA 2077 Tan. The number of data points generated by these stress rupture tests for the DHDA 2077 Tan was less than that required by PPI procedure; however, Union Carbide began to market the product for use in gas systems based on these tests and on additional testing performed on the company's black resin material.

Because Union Carbide had not developed the PPI-prescribed number of data points on its DHDA 2077 Tan resin before marketing the product, Safety Board investigators reviewed the data the company developed on its black resin. A review of Union Carbide's laboratory notebooks revealed that a number of adverse data points Union Carbide developed for its black resin were not submitted to the PPI when the company applied for a PPI listing for the black material.[56]

Union Carbide first made a commercial version of its DHDA 2077 Tan resin during the spring of 1969, and in April 1970, a first shipment of 80,000 pounds of DHDA 2077 Tan resin was shipped to Amdevco's Mankato plant. The next shipment of the material to Amdevco was not until 1971. Based on Amdevco's June 11, 1970, manufacturing date for the Waterloo pipe, Union Carbide manufactured, sold, and delivered the resin used to make the Waterloo pipe between the spring of 1969 and June 11, 1970, and the resin used to make the pipe involved in the Waterloo accident probably was included in the April 1970 shipment.

Union Carbide began, on December 3, 1970, additional stress rupture tests on its commercial DHDA 2077 Tan resin. These tests generated the results to further support its claimed long-term hydrostatic strength and also provided the number of data points required by the PPI procedure. Additional stress rupture tests on the commercial DHDA 2077 Tan resin beginning on December 28, 1970, and again on January 6, 1972, further supported the material's long-term hydrostatic strength.

During the late 1960s and 1970s, Minnegasco, a gas system operator based in Minneapolis, Minnesota, routinely employed a 1,000-hour sustained pressure test at 100 °F detailed in ASTM D2239 and a 1,000-hour sustained pressure test at 73 °F detailed in ASTM D2513 to qualify plastic piping for use in its system. Minnegasco went beyond the requirements of ASTM standards by continuing both versions of the testing beyond 1,000 hours until eventual failure occurred. The company used this information to evaluate the relative strengths of different brands of piping.

In 1969-70, Minnegasco began a series of tests on samples from five different suppliers of plastic piping made from DHDA 2077 Tan resin. On March 3, 1972, Minnegasco's laboratory issued an internal report that contained the results of its latest tests on piping made from the resin and referenced earlier tests on several brands of piping (including Amdevco/Century) that were also made from it. Based on this report, Minnegasco rejected for use in its gas system the DHDA 2077 Tan resin. According to the report, the company rejected the material because (1) none of the pipe samples made from this resin could consistently pass the 1,000-hour sustained pressure test at

[55]The company was required to follow the PPI procedure in developing the necessary stress rupture data, but no requirement existed for those data to be submitted to the PPI or for the PPI to assign a listing before the tested material could be marketed.

[56]Although the PPI procedure required the submission of all valid data points for statistical analysis, the Union Carbide employee who managed the data indicated that he believed he could discard data that, in his judgment, did not adequately characterize the material's performance. Union Carbide has contended that the non-submitted data may have been invalid because of experimental error, uncompleted tests, or other reasons.

100 °F, and (2) the pipe samples had lower performance in 73 °F sustained pressure tests than similar plastic piping materials already in use in the company's gas system.

In 1971, Union Carbide acknowledged to a pipe manufacturer that piping material manufactured by DuPont had a higher pressure rating at 100 °F than did its own DHDA 2077 Tan. Union Carbide laboratory notebooks examined by the Safety Board showed test results for the DHDA 2077 Tan material that generally met the 1,000-hour sustained pressure test value at both 100 °F and 73 °F, although, in the case of the 100 °F test, not by a wide margin. The notebooks also showed that the material had an early ductile-to-brittle transition point in stress rupture tests.[57]

Information Dissemination Within the Gas Industry

The OPS reports that more than 1,200 gas distribution or master meter system[58] pipeline operators submit reports to the OPS. Additionally, more than 9,000 gas distribution or master meter system pipeline operators are subject to oversight by the States.

As noted earlier, a frequent failure mechanism with polyethylene piping involves crack initiation and slow crack growth. These brittle-like fractures occur at points of stress intensification generated by external loading acting in concert with internal pressure and residual stresses.[59]

A 1985 paper[60] analyzed, for linear (straight line) behavior up to 100,000 hours, the stress rupture test performance (by elevated-temperature testing) of six polyethylene piping materials. The results were then correlated with field performance. This paper found that those materials that did not maintain linearity through 100,000 hours had what the author characterized as "known poor" or "questionable" field performance. On the other hand, those materials that maintained linearity through 100,000 hours had what the author characterized as "known good" field performance through their 20-year history logged as of 1985.

By the early to mid-1980s, the industry had developed a method to mathematically relate failure times to temperatures and stresses during stress rupture testing.[61] In the early 1990s, the industry developed "shift functions," another mathematical method to relate failure times to temperatures and stresses.[62]

One study[63] pointed out that using mathematical methods to calculate the remaining service life of pipe under the assumption that the pipe would only be exposed

[57]The data from the laboratory notebooks suggest that this material's early ductile-to-brittle transition would not have met today's standards.

[58]*Master meter system* refers to a pipeline system that distributes gas to a definable area, such as a mobile home park, a housing project, or an apartment complex, where the master meter operator purchases gas for resale to the ultimate consumer.

[59]Kanninen, M. F., O'Donoghue, P. E., Popelar, C. F., Popelar, C. H., Kenner, V. H., *Brief Guide for the Use of the Slow Crack Growth Test for Modeling and Predicting the Long-Term Performance of Polyethylene Gas Pipes*, Gas Research Institute Report 93/0105, February 1993. Because, after extrusion, the outside of the pipe cools before the inside, residual stresses are usually developed in the wall of the pipe.

[60]Mruk, S. A., "Validating the Hydrostatic Design Basis of PE Piping Materials."

[61]Bragaw, C. G., "Prediction of Service Life of Polyethylene Gas Piping System," *Proceedings Seventh Plastic Fuel Gas Pipe Symposium*, pp. 20-24, 1980, and Bragaw, C. G., "Service Rating of Polyethylene Piping Systems by the Rate Process Method," *Proceedings Eighth Plastic Fuel Gas Pipe Symposium*, pp. 40-47, 1983, and Palermo, E. F., "Rate Process Method as a Practical Approach to a Quality Control Method for Polyethylene Pipe," *Proceedings Eighth Plastic Fuel Gas Pipe Symposium*, pp. 96-101, 1983, and Mruk, S. A., "Validating the Hydrostatic Design Basis of PE Piping Materials," and Palermo, E. F., "Rate Process Method Concepts Applied to Hydrostatically Rating Polyethylene Pipe," *Proceedings Ninth Plastic Fuel Gas Pipe Symposium*, pp. 215-240, 1985.

[62]Popelar, C. H., "A Comparison of the Rate Process Method and the Bidirectional Shifting Method," *Proceedings of the Thirteenth International Plastic Fuel Gas Pipe Symposium*, pp. 151-161, and Henrich, R. C., "Shift Functions," *1992 Operating Section Proceedings*, American Gas Association.

[63]Broutman, L. J., Bartelt, L. A., Duvall, D. E., Edwards, D. B., Nylander, L. R., Stellmack-Yonan, M., *Aging of Plastic Pipe Used for Gas Distribution, Final Report*, Gas Research Institute report number GRI-88/0285, December 1988.

to stresses of internal operating pressures would result in unrealistically long service-life predictions. As noted earlier, polyethylene piping systems have failed at points of long-term stress intensification caused by external loading acting in concert with internal pressure and residual stresses; thus, to obtain a realistic prediction of useful service life, stresses from external loadings need to be acknowledged.

Over a number of years, the Gas Research Institute (GRI) sponsored research projects investigating various tests and performance characteristics of polyethylene piping materials. Among these projects was a series of research investigations directed at exploring the fracture mechanics principles behind crack initiation and slow crack growth. These investigations led to the development of slow crack growth tests. The research studies frequently identified the piping and resins studied by codes rather than by specific materials, manufacturers, or dates of manufacture.

In 1984, the GRI published a study[64] that compared and ranked several commercially extruded polyethylene piping materials produced after 1971. Again, the materials tested were identified by codes. Stress rupture tests were performed using methane and nitrogen as the internal pressure medium and air as the outside environment. Several stress rupture curves showed early transitioning from ductile to brittle failure modes.

The A.G.A.'s Plastic Materials Committee periodically updates the *A.G.A Plastic Pipe Manual for Gas Service*, which addresses a number of issues covered by this Safety Board special investigation. In 1991, the committee formed a task group to gather and then disseminate to the industry information regarding the performance of older plastic piping systems. The task group disbanded in 1994 without issuing a report.

In 1982 and 1986, DuPont formally notified its customers about brittle-like cracking concerns with the company's pre-1973 pipe. Safety Board investigators could find no record of either Century/Amdevco, Union Carbide, or any other piping or resin manufacturer formally notifying the gas industry of the susceptibility to premature brittle-like failures of their products. Nor does any mechanism exist to ensure that the OPS receives safety-related information from manufacturers.

Regarding Federal actions on this issue, the OPS has not informed the Safety Board of any substantive action it has taken to advise gas system operators of the susceptibility to premature brittle-like failures of any older polyethylene piping.[65]

Installation Standards and Practices

The discussion in this section is intended to present a "snapshot" of the regulations and some of the primary standards, practices, and guidance to prevent stress intensification at plastic service connections to steel tapping tees. The appendix to this report includes a description of the connection in the Waterloo accident, and figure 10 provides a close-up view of the failed fitting.

Federal Regulations **--** The OPS establishes, in 49 CFR 192.361, minimum pipeline safety standards for the installation of gas service piping.

Paragraph 192.361(b) reads as follows:

> *Support and backfill.* Each service line must be properly supported on undisturbed or well-compacted soil….

Paragraph 192.361(d) reads:

> *Protection against piping strain and external loading.* Each service line must be installed so as to minimize anticipated piping strain and external loading.

[64] Cassady, M. J., Uralil, F. S., Lustiger, A., Hulbert, L. E., *Properties of Polyethylene Gas Piping Materials Topical Report (January 1973 - December 1983)*, GRI Report 84/0169, Gas Research Institute, Chicago, IL, 1984.

[65] The Safety Board asked the OPS for information about its actions in regard to older piping, after which, in 1997, the OPS notified State pipeline safety program managers of several issues regarding Century pipe and solicited input on their experiences with this particular piping.

Figure 10 -- Close-up view of failed plastic pipe connection to steel tapping tee from site of Waterloo, Iowa, accident. A portion of the fractured plastic service line (light-colored material) remains attached to the tee.

Subsequent to the Waterloo accident, personnel from the Iowa Department of Commerce, after discussions with OPS personnel, stated that the Waterloo installation was not in violation of the Federal regulation. They further stated that, while they agree that the installation of protective sleeves[66] at pipeline connections is prudent, a specific requirement to install protective sleeves is beyond the scope of Part 192 and is inconsistent with the regulation's performance orientation.

The Transportation Safety Institute (TSI), part of RSPA, conducts training classes for Federal and State pipeline inspectors. TSI instructors advise class participants that many of the performance-oriented regulations within Part 192 can only be found to be violated if the gas system fails in a way that demonstrates that the regulation was not followed. The TSI acknowledges the difficulty of identifying violations under paragraph 192.361(d). A TSI instructor told the Safety Board that, in the case of the failed pipe at Waterloo, an enforcement action faulting the installation would be unlikely to prevail because of the poor brittle-like crack resistance of the failed pipe and the length of time (23 years) between the installation and failure dates.

GPTC Guide for Gas Transmission and Distribution Piping Systems -- After the adoption of the Natural Gas Pipeline Safety Act in August 1968, the American Society of Mechanical Engineers, after discussions with

[66]Protective sleeves are intended to help shield the pipe at the connection point from bearing loads and shear forces and to limit the maximum pipe bending.

the Secretary of Transportation, formed the Gas Piping Standards Committee (later renamed the Gas Piping Technology Committee) to develop and publish "how-to" specifications for complying with Federal gas pipeline safety regulations. The result was the *GPTC Guide for Gas Transmission and Distribution Piping Systems* (GPTC Guide). The GPTC Guide lists the regulations by section number and provides guidance, as appropriate, for each section of the regulation.

In its investigation of the previously referenced 1971 accident in Texas, the Safety Board determined that protective sleeves were too short to fully protect a series of service connections to a main. The Safety Board noted that a protective sleeve must have the correct inner diameter and length if it is to protect the connection from excessive shear forces. As a result, and in response to a Safety Board safety recommendation,[67] the 1974 and later editions of the GPTC Guide included guidance that "a protective sleeve designed for the specific type of connection should be used to reduce stress concentrations." No guidance was included as to the importance of a protective sleeve's length, diameter, or placement.[68]

The GPTC Guide does not include recommendations to limit bending in plastic piping during the installation of service lines under 49 CFR 192.361. Although the guide references the *A.G.A. Plastic Pipe Manual for Gas Service*, and this manual does provide recommendations on bending limits, the GPTC Guide does not reference this manual in its guidance material under 49 CFR 192.361.

A.G.A. Plastic Pipe Manual for Gas Service -- The most recent edition of the *A.G.A. Plastic Pipe Manual for Gas Service*[69] identifies the connection of plastic pipe to service tees as "a critical junction" needing installation measures "to avoid the potentially high…stresses on the plastic at this point." The manual recommends proper support and the use of protective sleeves. Although the manual recommends following manufacturers' recommendations, no guidance is included on the importance of a protective sleeve's proper length, diameter, or placement. The manual includes, without elaboration, the following sentence:

> Installation of the tee outlet at angles up to 45° from the vertical or along the axis of the main as a 'side saddle' or 'swing joint' may be considered to further minimize…stresses.

The 1994 edition adds that manufacturers' recommended limits on bending at fittings may be more restrictive than for a run of piping alone.

A.G.A. Gas Engineering and Operating Practices (GEOP) Series -- The preface to the current *Distribution Book D-2* of the GEOP series states that the intent of the books is to offer broad general treatment of their subjects, and that listed references provide additional detailed information.

Figure 11 reproduces an illustration from *Book D-2*. This figure shows a steel tapping tee with a compression coupling joint connected to a plastic service. The illustration shows a protective sleeve and includes a note to extend the protective sleeve to undisturbed or compacted soil or to blocking. But the figure also shows the blocking positioned so that either the edge of the blocking or the edge of the protective sleeve might provide a fixed contact point on the plastic service pipe if the weight of backfill were to cause the pipe to bend down. Additional illustrations within this GEOP series book show this same positioning of the blocking with respect to the plastic pipe.

ASTM -- The most recent ASTM standard covering the installation of polyethylene piping was revised in 1994.[70] This standard addresses

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[67] Safety Recommendation P-72-64 from National Transportation Safety Board Pipeline Accident Report--*Lone Star Gas Company, Fort Worth, Texas, October 4, 1971*.

[68] The correct positioning of the protective sleeve has a bearing on its effective length.

[69] *A.G.A. Plastic Pipe Manual for Gas Service*, American Gas Association, Catalog No. XR 9401, 1994.

[70] ASTM D2774-94, *Standard Practice for Underground Installation of Thermoplastic Pressure Piping*, American Society for Testing and Materials, 1994.

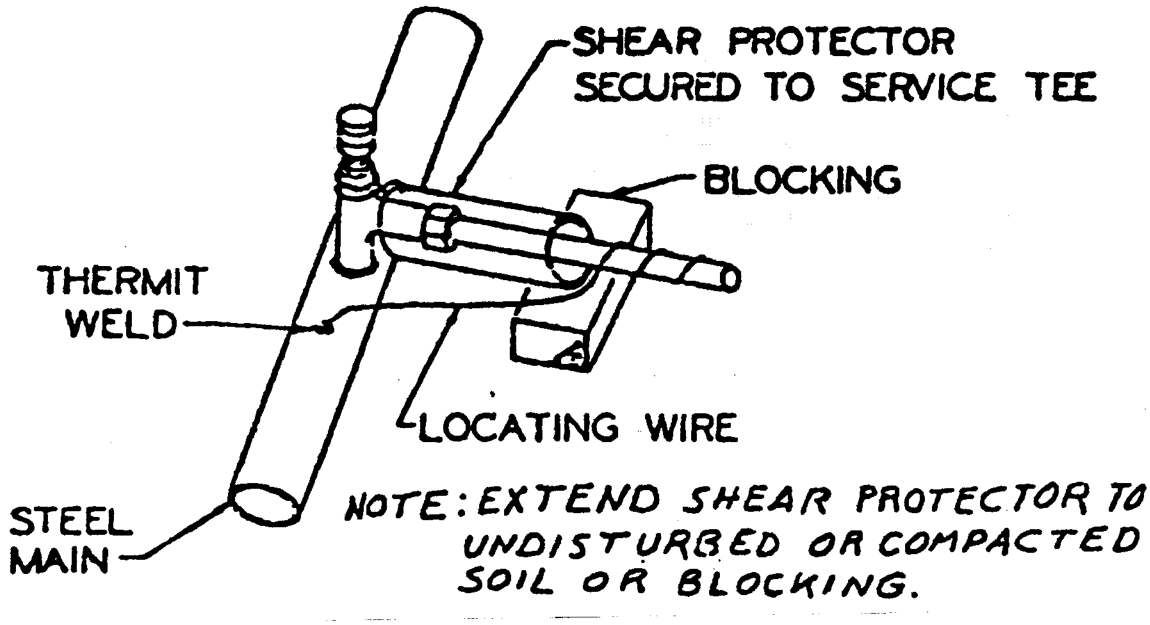

Figure 11 -- Reproduction from A.G.A. GEOP series illustrating application of protective sleeve. (Hand-scribed notation from the original.)

the vulnerability of the point-of-service connection to the main.

This standard, advising consultation with manufacturers, recommends taking extra care during bedding and backfilling to provide for firm and uniform support at the point of connection. In addition, the document recommends minimizing bends near tap connections, generally recommending that bends occur no closer than 10 pipe diameters from any fitting and that manufacturers' bend limits be followed. Similar recommendations for avoiding bends close to a fitting can be found in the forward to a water industry standard.[71]

This ASTM standard further recommends the use of a protective sleeve if needed to protect against possible differential settlement. Currently, manufacturers that provide protective sleeves have their own criteria for designing sleeve lengths and diameters for their fittings. Some manufacturers' criteria are based on limiting stress to a maximum safe value,[72] while one manufacturer has advised the Safety Board that its sleeve is not designed to limit bending, but only to guard against shear forces at the connection point.

Guidance Manual for Operators of Small Natural Gas Systems -- The OPS/RSPA *Guidance Manual for Operators of Small Natural Gas Systems* notes that plastic pipe failures have been found at transitions between plastic and metal pipes at mechanical fittings. The manual states the need to firmly compact soil under plastic pipe, advises following manufacturers' instructions for proper coupling procedures, and shows protective sleeves on connections of plastic services to steel tapping tees. The manual indicates that a properly designed protective sleeve should be used. The manual does not caution against bending the piping in proximity to a connection.

[71]Forward to American Water Works Association Standard C901-96, *AWWA Standard for Polyethylene (PE) and Tubing, ½ In. (13 mm) Through 3 In. (76 mm) for Water Service*, effective March 1, 1997.

[72]Allman, W. B., "Determination of Stresses and Structural Performance in Polyethylene Gas Pipe and Socket Fittings Due to Internal Pressure and External Soil Loads," *1975 Operating Section Proceedings*, American Gas Association, 1975.

Manufacturers' Recommendations -- As noted earlier, both the *A.G.A. Plastic Pipe Manual for Gas Service* and ASTM D2774 specifically refer the reader to manufacturers for further guidance on limiting shear and bending forces at plastic service connections made to steel mains via steel tapping tees.

Bending and Shear Forces -- Safety Board investigators contacted representatives of the four principal companies that marketed plastic piping for gas service to determine to what extent plastic piping manufacturers were providing recommendations for limiting shear and bending forces at plastic service connections to steel mains via steel tapping tees. The four manufacturers contacted were CSR PolyPipe, Phillips Driscopipe, Plexco, and Uponor Aldyl Company (Uponor).

Three out of four of these manufacturers had published recommendations addressing these issues. These three manufacturers have historically emphasized heat fusion fitting systems[73] instead of field-assembled mechanical fitting systems. Representatives of these manufacturers indicated that mechanical fittings manufacturers should provide installation instructions covering their systems. Accordingly, one of the manufacturers' published literature referred the reader to the manufacturers of mechanical fittings for installation instructions. Nonetheless, these three major polyethylene pipe manufacturers did, in fact, provide recommendations to limit shear and bending forces, and these recommendations can apply to plastic service connections to steel mains via steel tapping tees.

With respect to the specific issue of limiting bends, DuPont, in January 1970, issued recommendations to limit bends for polyethylene pipe. DuPont/Uponor[74] later published bend radius recommendations that differentiated between pipe segments consisting of pipe alone and those with fusion fittings. The recommendations specified much less bending for pipe segments with fusion fittings; however, DuPont/Uponor did not provide bend limits for mechanical fittings. Two of the other major manufacturers (Phillips Driscopipe and Plexco) provide bend limits and differentiate between pipe alone and pipe with fittings, without specifying the type of fittings. None of the manufacturers' literature discusses bending with or against any residual bend remaining in the pipe after it is uncoiled. (See "Pipe Residual Bending" below.)

Of these four major polyethylene gas pipe manufacturers, only CSR PolyPipe had no published recommendations for limiting shear and bending forces at plastic service connections to steel mains via steel tapping tees. Although the company does not manufacture steel tapping tees with compression ends for attachment to plastic services, it does manufacture pipe that will be attached to steel tapping tees via mechanical compression couplings. The company has been supplying polyethylene pipe to the gas industry since the 1980s[75] and is thus relatively new to that business compared to the other three major manufacturers. When CSR PolyPipe entered the market, plastic materials were vastly improved compared to earlier versions with respect to resistance to crack initiation and slow crack growth. For this reason, according to CSR PolyPipe personnel, the company saw less need to publish installation recommendations.

The Safety Board attempted to identify every U.S. steel tee manufacturer that currently manufactures steel tees with a compression end for plastic gas service connections.[76] The Safety Board identified and contacted representatives of Continental Industries (Continental), Dresser Industries, Inc. (Dresser), Inner-Tite Corp. (Inner-Tite),[77] and Mueller Company (Mueller).

[73]Heat fusion fittings are used to make piping joints by heating the mating surfaces and pressing them together so that they become essentially one piece.

[74]Uponor purchased DuPont's plastic pipe business in 1991.

[75]CSR Hydro Conduit Company purchased PolyPipe in 1995. PolyPipe began supplying polyethylene pipe to the gas industry in the 1980s.

[76]J. B. Rombach, Inc., which manufactures M. B. Skinner Pipeline products, told the Safety Board that it no longer manufactures or markets its "Punch-It-Tee" line of steel tapping tees. Chicago Fittings Corporation told the Safety Board it no longer manufactures or markets its line of steel tapping tees. The Safety Board therefore made no further inquiry with these companies.

[77]Inner-Tite did not manufacture steel tees; it purchased them, affixed its own compression connections,

Only Continental and Inner-Tite offered protective sleeves to their customers as an option. None of these manufacturers has published installation recommendations to limit shear and bending forces on the plastic pipe that connects to their steel tapping tees.

On another issue related to protective sleeves, Safety Board examination of a protective sleeve offered by Continental to its customers revealed that the sleeve that did not have sufficient clearance to allow the application of field wrap (intended to protect the steel tee from corrosion after it is in the ground) to that portion of the steel tee under the sleeve. This observation was confirmed by a Continental representative.

Pipe Residual Bending -- The service involved in the Waterloo accident was installed with a bend at the connection point to the main. (See illustration in appendix A.) The plastic service pipe leaving the tee immediately curved horizontally. The pipe was cut out and brought into the laboratory, at which time the bend had a measured horizontal radius of approximately 34 inches. Based on field conditions and photos, MidAmerican Energy estimated the original installed horizontal bend radius to have been about 32 inches. This bend is sharper than that allowed by current industry installation recommendations for modern piping adjacent to fittings.

An issue related to recommended bend radius is residual pipe bending. Plastic pipe often arrives at a job site in banded coils. After the bands are released, the coiled pipe will partially straighten, but some residual bending will remain. The water industry already recognizes that bends *in* the direction of the residual coil bend should be treated differently than bends *against* the direction of the bend;[78] however, gas industry field bend radius recommendations do not address residual coil bending.

A former Iowa Public Service Company employee stated that Iowa Public Service Company, in an effort to reduce stress at connection points, generally attempted to install polyethylene services at an angle to the main to match the residual bend left after uncoiling the pipe. This former employee stated that no set time was specified to allow for complete relaxing of the pipe, but that the pipe would be placed in the ditch, and the crews would weld the tee at what they judged to be the appropriate angle.

MidAmerican Energy Installation Standards -- As a result of the Waterloo accident, Safety Board investigators examined some of MidAmerican Energy's construction standards for minimizing shear and bending forces at plastic service connection points to steel mains. Specifically, Safety Board investigators examined MidAmerican Energy's standards pertaining to providing firm support, using protective sleeves, and limiting bends at plastic service connections to steel mains.

According to the company, MidAmerican Energy no longer installed steel tapping tees with mechanical compression ends to connect to plastic service pipe. Instead, it employed steel tapping tees welded at the factory to factory-made steel-to-plastic transition fittings. It then field-fused the plastic ends from the transition fittings to the plastic service pipe.

MidAmerican Energy advised the Safety Board that it had no standard calling for firm compacted support under plastic service connection points to steel mains.

MidAmerican Energy designed, constructed, and installed its own protective sleeves for installation on its purchased steel tapping tee/transition fitting assemblies. MidAmerican Energy required its protective sleeves to be a minimum of 12 inches long; however, MidAmerican Energy could provide no design criteria for this length. MidAmerican Energy has reported that the company's unwritten field practice was to install the smallest diameter sleeve that will clear the field wrapped fitting, but MidAmerican Energy had no written requirements or design criteria for the diameter of its protective sleeves. The company's standard showed the sleeve as approximately centered over the steel-to-plastic transition, and no

and marketed the complete assembly.

[78]Forward to American Water Works Association Standard C901-96.

criteria or instructions were provided for the correct positioning of the sleeves.

The Safety Board notes that manufacturers that provide factory-made steel-to-plastic transition fittings will also provide protective sleeves along with the transition fittings and will provide positioning guidance for their use.

Effective January 27, 1997, MidAmerican Energy instituted minimum bend radii requirements that differentiated between pipe segments consisting of pipe alone and pipe with fittings.

Gas System Performance Monitoring

This section examines gas system performance monitoring largely in the context of the Waterloo accident.

Federal regulations (49 CFR 192.613 and 192.617) require that gas pipeline system operators have procedures in place for monitoring the performance of their gas systems. These procedures must cover surveillance of gas system failures and leakage history, analysis of failures, submission of failed samples for laboratory examination (to determine the causes of failure), and minimizing the possibility of failure recurrences.

Prior to the Waterloo accident, Midwest Gas had two systems for tracking, identifying, and statistically characterizing failures. The first system was the leak data base, which tracked the status of leak reports, documented actions taken, and recorded almost all gas system leaks. The data base received input from two primary sources: leak reports from customers and leak survey results. The data base parameters classified the general type of piping material that leaked (such as "plastic," "cast iron," "bare steel"), and indicated whether the leak occurred in pipe or certain fittings. The parameters did not include manufacturers, manufacturing or installation dates, sizes,[79] or failure conditions commonly found with plastic piping (for example, poor fusions, bending force failures, insufficient soil compaction, rock impingement failures, and lack or improper use of protective sleeves). The data base indicated that the performance of plastic piping overall was comparable to other piping materials. MidAmerican Energy stated that the parameters chosen for this data base were those required for reporting to the DOT. The company said the parameters were also chosen on the premise that pipe meeting industry specifications would perform similarly.

The second system used by Midwest Gas for tracking failures was the company's material failure report data base, which was intended for use in evaluating the quality and performance histories of products installed in the company's gas system. Input to the data base was by way of a form (or, in some cases, a tag) filled out by field personnel. The form included categories such as the manufacturer, size, and an internal material identification number of the affected pipe or component. It also included areas for a narrative description of the failure. The form did not include dates of manufacture or installation dates or failure conditions commonly found on plastic piping. Field personnel sent the failed item, along with the completed form or tag, to engineering personnel, who examined the item and accompanying information to determine the need for corrections. Midwest Gas personnel then transcribed the narrative description of the failure word-for-word into the data base without attempting to determine and categorize causes of failure. Engineering personnel compiled the available data into periodically issued material summary reports. The company said engineering personnel from time to time sorted available data fields to determine trends.

The material failure report data base included only a portion of the leaks in the Midwest Gas system. For example, if Midwest Gas field personnel corrected a leak by replacing an entire line segment without digging up the leaking component (which the company said was a frequent occurrence with bare steel, cast iron, and certain plastic piping that was difficult to join), the material failure report data base system was not used. Also, field personnel were not required to use the reporting system if they determined that the failed item was related to an operating problem, such as excavation damage, rather than to a material problem.

[79] While sizes of the piping, along with a drawing of the piping assembly, were normally written or drawn on the forms, piping size was not captured in the data base generated by these forms.

Additionally, the company indicated that the system did not enjoy full participation from field personnel.

When, after the Waterloo accident, Midwest Gas attempted to determine if installations with Century plastic piping had higher rates of failure than those with piping from other manufacturers, it found that its material failure report data base's incomplete coverage of gas leaks made that data base unsuitable for the purpose. The company decided instead to use the leak data base, which the company believed included almost all leaks. But because the leak data base did not list the manufacturers of plastic piping, Midwest Gas took several months to correlate entries in the leak data base with records showing the manufacturers of plastic piping. Midwest Gas, in 1995, concluded that piping installations with Century piping had failure incidence rates that were significantly higher than the balance of its plastic piping system. The company did not correlate entries with the years of installation.

Since the Waterloo accident, the current Waterloo gas system operator, MidAmerican Energy, in addition to replacing all its Century pipe, has added parameters such as piping size, installation date, and pressure to the forms used for input into its leak data base. Also since the accident, MidAmerican Energy has added parameters such as installation date, pressure, and component location and position to its form for input into its material failure report data base. The company has also worked to determine if any other plastic piping manufacturers can be linked to piping with unacceptable performance.

The current (1994) edition of the *A.G.A. Plastic Pipe Manual for Gas Service* recommends the use and provides a sample of a form for recording information on plastic piping failures. The manual recommends collecting this information and then performing a visual examination or, in some cases, a laboratory analysis, to determine the type and cause of failure.

ANALYSIS

General

The common thread in a series of plastic pipeline accidents investigated by the Safety Board and others since the early 1970s—as well as in a number of reports of other, non-accident, plastic pipeline leaks—is the indicated presence of brittle-like cracking leading to eventual pipe failure. The number and similarity of these brittle-like failures seem to indicate that the long-term durability of plastic piping, which was premised on the pipe's ductility, may have been overstated by the method used to rate the long-term strength of plastic piping materials.

Based on the available evidence, any public safety threat posed by possible premature failure of plastic piping appears to be limited to locations where stress intensification exists. This special investigation examines in detail one installation configuration—plastic pipe mechanical connections to steel mains via steel tapping tees—where great potential exists for the generation of stress intensification. At these connections, certain poor installation practices have been known to create stress that is greater than the pipe can withstand. Thus, inadequate or improper installation of piping connections, in combination with brittle piping, represents one identifiable public safety hazard associated with the thousands of miles of older plastic piping now in service nationwide.

Gas system operators need to have an effective surveillance and data analysis (performance monitoring) program to determine the extent of the possible hazard associated with their pipeline systems, including plastic piping. Such a program must be adequate to detect trends as well as to identify localized problem areas, and it must be able to relate poor performance to specific factors such as plastic piping brands, dates of manufacture (or installation dates), and failure conditions.

The major safety issues developed during this special investigation are as follows:

- The vulnerability of plastic piping to premature failures due to brittle-like cracking;
- The adequacy of available guidance relating to the installation and protection of plastic piping connections to steel mains; and
- Performance monitoring of plastic pipeline systems as a way of detecting unacceptable performance in piping systems.

The remainder of this analysis addresses each of these major safety issues, as well as a number of other issues affecting the safety of plastic piping for gas service.

Durability of Century Utility Products Piping

Iowa Public Service Company, the company that installed the Century pipe involved in the 1994 Waterloo, Iowa, pipeline accident, began purchasing all of its plastic pipe from Century in 1970, when Amdevco/Century had just started to manufacture plastic pipe. These purchases were made without Iowa Public Service Company's having a testing or technical evaluation program and without Century/Amdevco having a successful track record. Iowa Public Service Company decided on the Century product because Century offered favorable commercial terms for a product it claimed was virtually identical to the DuPont plastic piping that had previously been used.

The Safety Board has investigated two other pipeline accidents, one in Nebraska in 1978 and one in Minnesota in 1983, that involved Century piping. The Safety Board is also aware of four other accidents that it did not investigate that involved the same brand of piping. Moreover, laboratory testing of Century product samples from the Waterloo accident determined that the material had the same brittle-like crack properties that have been associated with materials having poor performance histories.

Laboratory examination also revealed evidence of slow crack growth typical of brittle-like cracking.

The Century pipe involved in the Waterloo accident was made from Union Carbide’s DHDA 2077 Tan resin. Although Union Carbide’s laboratory data indicated that the material had the strength required by existing government and industry requirements, the Safety Board’s review of the same data showed that the material had an early ductile-to-brittle transition, indicating poor resistance to brittle-like fractures.

In the early 1970s, a Minnesota gas system operator tested a number of piping products made from DHDA 2077 Tan resin, including those marketed by Century, as part of its comprehensive specification, testing, and evaluation program. The company rejected piping made from the Union Carbide product for use in its system based on the results of sustained pressure tests. Union Carbide, in 1971, acknowledged that its DHDA 2077 Tan resin material had a lower pressure rating at 100 °F than did DuPont’s polyethylene pipe material.

Midwest Gas, the Waterloo, Iowa, gas operator at the time of the explosion and fire, had experienced at least three other significant failures involving Century pipe. The most recent failures, occurring between 1992 and 1994, prompted the company to collect samples of the Century material for independent laboratory testing. Samples were being gathered for testing at the time of the Waterloo accident. The subsequent laboratory report indicated that the Century piping had poor resistance to slow crack growth.

Midwest Gas’s subsequent analysis of the company’s leakage history concluded that its installations with Century piping had failure rates significantly higher than those with piping from other manufacturers. Midwest Gas had received warnings from two pipe fitting manufacturers against use of their products with Century pipe because of Century pipe’s susceptibility to brittle-like cracking. The current operating company in the Waterloo, Iowa, area, MidAmerican Energy, has, since the accident, replaced all the identified Century piping in its gas pipeline system.

The Safety Board concludes that plastic pipe extruded by Century Utility Products, Inc., and made from Union Carbide’s DHDA 2077 Tan resin has poor resistance to brittle-like cracking under stress intensification, and this characteristic contributed to the Waterloo, Iowa, accident.

The Safety Board believes that RSPA should notify pipeline system operators who have installed polyethylene gas piping extruded by Century Utility Products, Inc., from Union Carbide Corporation DHDA 2077 Tan resin of the piping’s poor brittle-crack resistance. The Safety Board further believes that RSPA should require these operators to develop a plan to closely monitor the performance of this piping and to identify and replace, in a timely manner, any of the piping that indicates poor performance based on such evaluation factors as installation, operating, and environmental conditions; piping failure characteristics; and leak history.

Strength Downturn and Brittle Characteristics

While Century piping has been identified specifically as being subject to brittle-like cracking (slow crack growth), evidence suggests that much of the early polyethylene piping, depending on the brands, may be more susceptible to such cracking than originally thought and thus may also be subject to premature failure.

The principal process used in the United States to rate the strength of plastic piping materials has been, and remains, the procedure this report has referred to as the PPI procedure. The PPI procedure, which was developed in the early 1960s, involved subjecting test piping to different stress values and recording how much time elapsed before the piping ruptured. The resulting data were then plotted, and a best-fit straight line was derived to represent the material’s decline in rupture resistance as its time under stress increased.

To meet the requirements of the PPI procedure, at least one tested sample had to be able to withstand some level of hoop stress without rupturing for at least 10,000 hours, or slightly more than 1 year. The straight line plotted describing the data for this material was extrapolated out by a factor of 10, to 100,000 hours (about 11 years). The point at which the sloping straight line intersected the 100,000-hour point indicated the appropriate hydrostatic design basis for this material.

A key assumption characterized the assignment of a hydrostatic design basis under the PPI procedure: The procedure assumed that the gradual decline in the strength of plastic piping material as it was subjected to stress over time would always be described by a straight line. In the early 1960s, the industry had had little long-term experience with plastic piping, and a straight line seemed to represent the response of the material to laboratory stress testing. With little other information on which to base strength estimations, the straight-line assumption appeared valid.

As experience grew with plastic piping materials and as better testing methods were developed, however, the straight-line assumptions of the PPI procedure came to be challenged. Elevated-temperature testing indicated that polyethylene piping can exhibit a decline in strength that does not follow a straight line path but instead describes a downturn, as shown in figure 9. The difference between the actual (falloff) and projected (straight line) strengths became even more pronounced as the lines were extrapolated beyond 100,000 hours. The timing and slope of the downturn varied by pipe formulation and manufacturer.

Piping manufacturers addressed this issue by improving their formulations to delay onset of the downturn in strength. At the same time, the PPI procedure was improved to reflect the fact that elevated-temperature testing, by accelerating the fracture process, provided a good representation of the true long-term strength of the tested material at 73 °F. By 1986, the PPI adopted a requirement to exclude any materials that deviated from the straight-line path to at least 100,000 hours at 73 °F.

The combination of more durable modern plastic piping materials and more realistic strength testing has rendered the strength ratings of modern plastic piping much more reliable. Unfortunately, much of the early plastic piping was sold and installed with expectations of strength and long-term performance that, because they were based on questionable assumptions about long-term performance, may not have been valid. This is borne out by data from a variety of sources. The history of strength rating requirements, a review of the piping properties and literature, and observations of several experts with extensive experience in plastic piping, all suggest that much of the polyethylene pipe, depending upon the brands, manufactured from the 1960s through the early 1980s fails at lower stresses and after less time than originally projected. The Safety Board therefore concludes that the procedure used in the United States to rate the strength of plastic pipe may have overrated the strength and resistance to brittle-like cracking of much of the plastic pipe manufactured and used for gas service from the 1960s through the early 1980s.

Another important assumption of the design protocol for plastic pipe involved the ductility of the materials. It was assumed, based on short-term tests, that plastic piping had long-term ductile properties. Ductile material, by bending, expanding, or flexing, can redistribute stress concentrations better than can brittle material, such as cast iron. Notable from results of tests performed under the PPI procedure was that those short-term stress ruptures in the testing process tended to be characterized by substantial material deformation in the area of the rupture. This deformation described a material with obvious ductile properties. Under prolonged testing, however, as time-to-failure increased, some stress ruptures in some materials occurred as slit failures that, because they were not accompanied by substantial deformation, were more typical of brittle-like failures. These slit or brittle-like failures were characterized by crack initiation and slow crack growth. The PPI procedure did not distinguish between ductile fractures and slit fractures and assumed that both failures would be described by the same straight line.

The assumption of ductility of plastic piping had important safety ramifications. For example, a number of experts believed it was safe to design plastic piping installations based on stresses primarily generated by internal pressure and to give less consideration to stress intensification generated by external loading. Ductile material reduces stress intensification by localized yielding, or deformation.

As noted previously, laboratory data supported the strength rating assigned to DHDA 2077 Tan resin by the process used at the time to rate strength; nevertheless, the material showed evidence of early ductile-to-brittle transition. The fact that the process used to measure the long-term durability of piping materials did not reveal the premature susceptibility to brittle-like cracking of the DHDA 2077 Tan material highlights the weaknesses of the process in use at the time. More significantly, it calls into question the durability of other early materials that were rated using the same process and that remain in service today. This concern is heightened by the fact that, in addition to the Waterloo accident involving Century pipe and DHDA 2077 Tan resin, numerous other accidents investigated or documented by the Safety Board have suggested that brittle-like cracking occurs in older plastic piping at significant rates.

Stress intensification has been an element common to many plastic gas pipeline accidents investigated by the Safety Board. The premature transition of plastic piping from ductile failures to brittle failures appears to have little observable adverse impact on the serviceability of plastic piping except in those instances in which the piping is subjected to external stresses. Rock impingement, soil settlement, and excess pipe bending are among the potential sources of stress intensification, and the combination of brittle piping and external stresses can lead to significant rates of failures. These failures can, in turn, lead to serious accidents. The Safety Board therefore concludes that much of the plastic pipe manufactured and used for gas service from the 1960s through the early 1980s may be susceptible to premature brittle-like failures when subjected to stress intensification, and these failures represent a potential public safety hazard.

The Safety Board believes that RSPA should determine the extent of the susceptibility to premature brittle-like cracking of older plastic piping (beyond that piping marketed by Century Utility Products, Inc.) that remains in use for gas service nationwide. RSPA should then inform gas system operators of the findings and require them to closely monitor the performance of the older plastic piping and to identify and replace, in a timely manner, any of the piping that indicates poor performance based on such evaluation factors as installation, operating, and environmental conditions; piping failure characteristics; and leak history. Because materials other than polyethylene have been used in plastic pipe for gas service, and even though the Safety Board has not examined those materials in depth, RSPA would do well to address those other plastic piping materials still in gas service.

The Safety Board further believes that RSPA should immediately notify those States and territories with gas pipeline safety programs of the susceptibility to premature brittle-like cracking of much of the plastic piping manufactured from the1960s through the early 1980s and of the actions that RSPA will require of gas system operators to monitor and replace piping that indicates unacceptable performance.

Information Dissemination Within the Gas Industry

As noted earlier, much of the polyethylene pipe, depending upon the brands, from the 1960s through the early 1980s may be susceptible to premature brittle-like failures when subjected to stress intensification. Poor resistance to crack initiation and slow crack growth in the face of stress intensification can translate into a higher incidence of leaks and a decrease in public safety.

Premature brittle-like cracking in plastic piping is a complex phenomenon. Those pipelines operators who wish to study the phenomenon can gain a basic understanding of brittle-like cracking by researching the technical literature, but without direct and straightforward communication to pipeline operators about brands of piping and conditions that increase the likelihood of brittle cracking, many pipeline operators may not have the knowledge to make good decisions affecting public safety. Some of these key decisions include how often to conduct leak surveys and whether to repair or replace portions of pipeline systems.

Frequently, piping manufacturers, because they can receive feedback from a number of customers, are the first to learn of systemic problems with their products. For small operators, contact with a manufacturer may be the major source of outside communication about poorly performing products. Unfortunately, while manufacturers have a high degree of technical expertise regarding their products, they may also tend to aggressively publicize the best performance characteristics of their products while only reluctantly acknowledging weaknesses. The Safety Board is aware of only a very few cases in which manufacturers of resin or pipe have formally notified the gas industry of materials having poor resistance to brittle cracking.

Thus, although reputable manufacturers commonly provide essential technical assistance and serve as partners to pipeline operators, operators are still responsible for evaluating and determining which products are most likely to maintain the integrity of their pipeline systems. Furthermore, perhaps because the possibility of premature failure of plastic piping due to brittle-like cracking has not been fully appreciated within the industry and the scope of the potential problem has not been fully measured, the Federal Government has not provided information on this issue to gas system operators. The Safety Board concludes that gas pipeline operators have had insufficient notification that much of the plastic pipe manufactured and used for gas service from the 1960s through the early 1980s may be susceptible to brittle-like cracking and therefore may not have implemented adequate pipeline surveillance and replacement programs for their older piping.

In the view of the Safety Board, manufacturers of resin and pipe should do more to notify pipeline operators about the poor brittle-crack resistance of some of their past products. The PPI is the manufacturers' organization that covers most of the major resin and pipe producers, many of whom have manufactured resin and pipe for several years. Although manufacturers of some of the worst performing materials and piping products may not have survived and therefore may not be current members of the PPI, the current members of the PPI have produced much, if not most, of the plastic piping and materials used in the manufacture of plastic piping over many years. The Safety Board therefore believes that the PPI should advise its members to notify pipeline system operators if any of their piping products, or materials used in the manufacture of piping products, currently in service for natural gas or other hazardous materials indicate poor resistance to brittle-like failure.

In the interest of public safety and in order for the Federal Government to fully exercise its oversight responsibilities, the Safety Board believes that RSPA should, in cooperation with the manufacturers of products used in the transportation of gases or liquids regulated by the OPS, develop a mechanism by which the OPS will receive copies of all safety-related notices, bulletins, and other communications regarding any defect, unintended deviation from design specification, or failure to meet expected performance of any piping or piping product that is now in use or that may be expected to be in use for the transport of hazardous materials.

Over a number of years, the GRI has developed a significant amount of data on older plastic piping, but it has published the data in codified terms. Without a way to associate codes with specific products, the average gas pipeline operator could not make effective use of the data. The Safety Board concludes that, even though the GRI has developed a significant amount of data about older plastic piping used for gas service, because the data have been published in codified terms, the information is not sufficiently useful to gas pipeline system operators. The Safety Board believes that the GRI should publish the codes used to identify plastic piping products in previous GRI studies to make the information contained in these studies more useful to pipeline system operators.

Installation Standards and Practices

Because of the large safety factor[80] used in the design equation, even many of the materials

[80]Technically, this term should be "design factor."

having early downturns in strength appear, absent stress intensification, to have the capacity to provide good service. Unfortunately, stress intensification, which can take many forms, has been found in a number of gas piping systems.

Almost all of the plastic pipeline accidents the Safety Board has investigated involving brittle-like cracking have been linked to stress intensification generated by external forces acting on the pipe. Examples of conditions that can generate stress intensification include differential earth settlement, particularly at connections with more rigidly anchored fittings; excessive bending as a result of installation configurations, especially at fittings; and point contact with rocks or other objects.

As discussed below, much of the guidance available to gas system operators for limiting stress intensification at plastic pipeline connections to steel mains is inadequate or ambiguous. It is particularly significant that none of the steel tapping tee manufacturers had published recommendations to safely limit shear and bending forces at connections where their products are used. Based on its review of this guidance and on the history of the plastic pipeline accidents it has investigated, the Safety Board concludes that, because guidance covering the installation of plastic piping is inadequate for limiting stress intensification at plastic service connections to steel mains, many of these connections may have been installed without adequate protection from shear and bending forces. The specific limitations of existing guidance are addressed in the sections that follow.

Federal Regulations -- RSPA acknowledges that the regulation that requires gas service lines to be installed so as to minimize anticipated piping strain and external loading lacks performance measurement criteria. The Safety Board pointed out in a previous accident investigation report[81] that, although the OPS considers many of its pipeline safety regulations to be performance-oriented requirements, many are no more than general statements of required actions that do not establish any criteria against which the adequacy of the actions taken can be evaluated. The Safety Board has further stated that regulations that do not contain measurable standards for performance make it difficult to determine compliance with the requirements. The Safety Board therefore previously recommended that RSPA:

> P-90-15
> Evaluate each of its pipeline safety regulations to identify those that do not contain explicit objectives and criteria against which accomplishment of the objective can be measured; to the extent practical, revise those that are so identified.

As a result of this safety recommendation, the OPS asked the National Association of Pipeline Safety Representatives liaison committee to review the 20 regulations deemed to be the least enforceable due to lack of clarity. The Safety Board has encouraged RSPA to make such a review a periodic effort so that all of the regulations, not just the specified 20, are continually clarified. The last correspondence to the Safety Board from the OPS regarding this recommendation was on March 8, 1993, and the recommendation has remained classified “Open--Acceptable Response.” In an October 31, 1997, letter to the OPS, the Safety Board inquired as to the status of 28 open safety recommendations to RSPA, including P-90-15. The OPS has not yet provided a written response to the request for the status of P-90-15. The Safety Board will continue to follow the progress and urge completion of this recommendation. In the meantime, other elements of the gas pipeline industry can take steps to enhance the protection of vulnerable piping at connections, as outlined below.

A.G.A. Plastic Pipe Manual for Gas Service -- A protective sleeve helps to shield the pipe at the connection point from bearing loads and shear forces, and controls the maximum bending. The *A.G.A. Plastic Pipe Manual for Gas Service* recommends installing protective sleeves at connections of plastic pipe, but it does not directly address designing the sleeve to have the correct inner diameter and length, or the need to position the sleeve

[81] National Transportation Safety Board Pipeline Accident Report--*Kansas Power and Light Company Natural Gas Pipeline Accidents, September 16, 1988, to March 29, 1989* (NTSB/PAR-90/03).

properly. Instead, it includes a sentence recommending that manufacturers' instructions be followed carefully. Such advice presumes that the manufacturers' instructions address designing the sleeve to have the correct inner diameter and length, as well as positioning the sleeve properly, in order to limit the shear and bending forces at the connection. Unfortunately, since none of the steel tapping tee manufacturers recommend any precautions to limit shear and bending forces at the connection point, gas pipeline operators may not realize the importance of determining these parameters.

The *A.G.A. Plastic Pipe Manual for Gas Service* does not provide an explanation for the following sentence:

> Installation of the tee outlet at angles up to 45° from the vertical or along the axis of the main as a 'side saddle' or 'swing joint' may be considered to further minimize…stresses.

This sentence is subject to different interpretations and does not explain how stresses might be reduced. Moreover, many gas system pipeline operators recognize that installing services 90° from the main helps with future locating of the pipe and reduces the likelihood of excessive bending, which could generate excessive stress. In the view of the Safety Board, this sentence does not provide useful guidance as it is written, and the A.G.A. Plastic Materials Committee would be well advised to either expand on or delete this sentence.

A.G.A. Gas Engineering and Operating Practices Series -- Illustrations from the GEOP series show protective sleeves extending to undisturbed or compacted soil or to blocking. But these figures show the blocking positioned so that, under some conditions, either the edge of the blocking or the edge of the protective sleeve might provide a fixed contact point on the service pipe. The Safety Board notes that B31.8 and ASTM D2774 discourage supporting plastic pipe by the use of blocking. In the view of the Safety Board, these illustrations would provide better guidance if they were revised to eliminate showing the possibility of blocking or other fixed contact point supporting plastic pipe.

The Safety Board believes that the A.G.A. should revise its *Plastic Pipe Manual for Gas Service* and the *Gas Engineering and Operating Practices* series to provide complete and unambiguous guidance for limiting stress at plastic pipe service connections to steel mains.

GPTC Guide for Gas Transmission and Distribution Piping Systems -- The Safety Board has previously noted that a protective sleeve's correct inner diameter and length are important to protect the piping from excessive forces. The Safety Board even issued a safety recommendation that the GPTC Guide be modified accordingly. As a result of this safety recommendation, the GPTC Guide now includes guidance under 49 CFR 192.361 to install protective sleeves "designed for the specific connection…to reduce stress concentrations." Designing protective sleeves for the specific connection is presumed to include designing the sleeve for the correct inner diameter and length, and may also include positioning the sleeve correctly, since positioning the sleeve affects its effective length. However, if steel tapping tee manufacturers do not address the parameters for sleeve design and positioning, gas pipeline operators may not realize the importance of determining these parameters. The guidance would be much more useful to gas pipeline operators if the GPTC included in the guide a specific statement of the need to design protective sleeves so that they will have the correct inner diameter and length, as well as the need to properly position the sleeves.

Although the guide references the *A.G.A. Plastic Pipe Manual for Gas Service* in various locations, and this manual provides recommendations on bending limits, the guide does not reference this manual under the guide material under 49 CFR 192.361. Therefore, the Safety Board believes that the GPTC should revise the guide to include complete guidance for the proper installation of plastic service pipe connections to steel mains. The guidance should emphasize the need to limit pipe bending and should include a discussion of the proper design and positioning of a protective sleeve to limit stress at the connection.

ASTM -- ASTM D2774 recommends the use of a protective sleeve, if needed to protect against possible differential settlement. The standard practice additionally advises consultation with manufacturers, which would presumably address designing the sleeve with a proper diameter and length, as well as positioning the sleeve correctly. However, as noted previously, none of the steel tapping tee manufacturers has recommended precautions to limit stresses at the service to main connection; therefore, gas pipeline operators may not realize the importance of determining these parameters. Consequently, the Safety Board believes that the ASTM should revise ASTM D2774 to emphasize that a protective sleeve, in order to be effective, must be of the proper length and inner diameter for the particular connection and must be positioned properly.

Currently, manufacturers that provide protective sleeves have their own criteria for sleeve lengths and diameters. Some manufacturers' criteria are based on limiting stress to a maximum safe value,[82] while one manufacturer has advised the Safety Board that its sleeve is not designed to limit bending but only to guard against shear forces at the connection point. A published common criteria would better motivate a wider spectrum of manufacturers and gas operators to apply scientific reasoning to their decisions on protective sleeve use. A published common criteria would additionally provide guidance to gas operators who provide their own sleeves rather than using manufacturer-supplied sleeves. The Safety Board therefore believes that the ASTM should develop and publish standard criteria for the design of protective sleeves to limit stress intensification at plastic pipeline connections.

Guidance Manual for Operators of Small Natural Gas Systems -- The expressed purpose of RSPA's *Guidance Manual for Operators of Small Natural Gas Systems* is to assist nontechnically trained persons who operate small gas systems. However, the manual provides no caution against bending close to a plastic service connection to a steel main. The manual recommends following manufacturers' instructions and indicates that a properly designed sleeve should be used at this connection, which would address designing the sleeve with the proper diameter and length. However, as noted previously, none of the steel tapping tee manufacturers has recommended precautions to limit stresses at the service to main connection; therefore, nontechnically trained persons may not realize the importance of determining these parameters.

Because manufacturers' recommendations in the above areas are also currently inadequate, the Safety Board believes that RSPA should revise its *Guidance Manual for Operators of Small Natural Gas Systems* to include more complete guidance for the proper installation of plastic service pipe connections to steel mains. The guidance should address pipe bending limits and should emphasize that a protective sleeve, in order to be effective, must be of the proper length and inner diameter for the particular connection and must be positioned properly.

Manufacturers' Recommendations -- Reliance on manufacturers' recommendations is a common theme running through many of the primary published sources of industry guidance for limiting stress intensification on plastic piping. CSR PolyPipe was relatively new to providing polyethylene pipe to the gas market. When CSR PolyPipe entered the market, the three other major polyethylene piping manufacturers had already published installation recommendations to limit stress intensification, and plastic materials were vastly improved compared to earlier versions with respect to resistance to crack initiation and slow crack growth. CSR PolyPipe therefore saw less need to develop extensive recommendations. And although CSR PolyPipe does not manufacture steel tapping tees with compression ends for attachment to plastic services, it does manufacture the pipe that will be attached to steel tapping tees via mechanical compression couplings. To facilitate the safe use of plastic piping, the Safety Board believes that the PPI, of which all four of the major piping producers are members, should advise its plastic pipe manufacturing members to develop and publish recommendations for limiting shear and bending forces at plastic service pipe connections to steel mains.

[82] Allman, W. B., "Determination of Stresses and Structural Performance in Polyethylene Gas Pipe and Socket Fittings Due to Internal Pressure and External Soil Loads," *1975 Operating Section Proceedings*, American Gas Association, 1975.

Compared to plastic piping manufacturers, steel tapping tee manufacturers may have much less technical expertise regarding the strength and failure modes of plastic pipe; however, steel tapping tee manufacturers, who have designed their rigid steel tees to connect to flexible plastic gas pipe, have a responsibility to provide recommendations for the safe use of their products. If a steel tee manufacturer believes that installation options are dependent on the type of plastic to be connected and that these options can be addressed only by the pipe manufacturer, the tee manufacturer has a responsibility to state that in its literature and to provide the gas system operator with direction for best using its product safely.

The Safety Board therefore believes that Continental, Dresser, Inner-Tite, and Mueller should develop and publish detailed recommendations and instructions for limiting shear and bending forces at locations where their steel tapping tees are used to connect service pipe to steel mains. While gas system operators have the option of not accepting manufacturers' recommendations, many gas system operators rely on manufacturers to provide installation recommendations for the safe use of their products. With published recommendations, gas system operators may be far less likely to overlook prudent construction practices, such as providing proper compaction and support, limiting bends, and using protective sleeves. Tee manufacturers may wish to make these published recommendations even more effective by packaging them with each tee shipped, thus ensuring that the gas operator or the tee installer, or both, will have ready access to them.

A Continental representative told the Safety Board that the protective sleeve it provides to customers as an option does not provide sufficient clearance to allow field wrap to be applied to the metallic portion under the sleeve as a way to prevent corrosion. The Safety Board concludes that the use of Continental tapping tees with Continental protective sleeves may leave the tapping tees susceptible to corrosion because the sleeves do not provide sufficient clearance for the application of field wrap to the metallic steel tapping tee. The Safety Board therefore believes that Continental should provide a means to ensure that use of Continental-designed protective sleeves with the company's steel tapping tees at plastic pipe connections to steel mains does not compromise corrosion protection for the connection.

Installation Issues at Site of Waterloo Accident -- Safety Board examination of the fracture surface and the failed pipe from the Waterloo accident revealed evidence of stress intensification. For example, the upper portion of the inside of the pipe showed the impression of the edge of the tee stiffener, indicating that the top of the pipe had been pressed down. The failure of the pipe can be directly associated with this stressed area, which was characterized by several brittle-like slow crack growth fractures that originated on or near the pipe inner wall just outside the depression associated with the tip of the tee stiffener. These slow crack fractures propagated through the wall of the pipe.

The stress intensification noted in the Waterloo pipe was consistent with the pipe's having been subjected to shear and bending forces generated primarily by soil settlement.[83] Soil settlement is a common source of stress intensification for buried plastic pipelines, and it can occur and contribute to a piping failure even though no observable voids are noted during a subsequent excavation. Ultimate settlement of backfill can take many years, and sometimes it only occurs after periods of heavy rains (such as the area experienced the previous year) or under additional external loading (such as that represented by truck traffic over the connection).

The accident investigation could not determine whether the ground settlement at Waterloo occurred because of inadequate compaction and support under the connection at the time it was installed, or whether it occurred despite initial adequate compaction and support. Nor could it be conclusively determined whether the amount of soil settlement was slight and generated relatively low stresses over a long

[83]The failed pipe also showed signs that the installed horizontal curve may have generated horizontal bending forces. Other factors contributing to stress at the connection included the pipe's internal pressure and may have included residual stresses inside the wall of the pipe resulting from the manufacturing process.

period of time, or whether the soil settlement was substantial and generated relatively high stresses over a relatively short period of time. Because of these uncertainties, investigators could not determine how much more resistance to crack initiation and slow crack growth the pipe would have needed to have successfully resisted the stresses to which it was subjected.

MidAmerican Energy, at the time of this accident investigation, had no installation standard that called for firm compacted support under plastic service connection points to steel mains. MidAmerican Energy connected plastic service pipe to mains via factory-joined plastic-to-steel transition fittings. As noted previously, the manufacturers for these specialty fittings, unlike steel tapping tee manufacturers, have protective sleeves available. Although MidAmerican Energy designed its own protective sleeves for this application, it did so without a design criteria for length or inner diameter, or for positioning the protective sleeves. Without such criteria, MidAmerican Energy may reduce the sleeve’s effectiveness in limiting stress intensification. The Safety Board concludes that, because MidAmerican Energy’s gas construction standards do not establish well-defined criteria for supporting plastic pipe connections to steel mains or for designing or installing its protective sleeves at these connections, these standards do not ensure that connections will be adequately protected from stress intensification. The Safety Board believes that MidAmerican Energy should modify its gas construction standards to require (1) firm compacted support under plastic service connections to steel mains, and (2) the proper design and positioning of protective sleeves at these connections.

The service involved in the Waterloo accident was installed with a horizontal bend that was sharper than that recommended by current gas industry guidance recommendations; however, the bend may have been installed in the direction of the residual coil bend. Gas industry recommendations do not address residual bending in the pipe, even though plastic piping is often delivered to job sites in banded coils, which leaves some residual bending in the piping even after the bands are removed. Installing coiled pipe with any necessary bending in the direction of the residual bend may be a good practice to limit stresses. Conversely, bending pipe against the direction of the residual coil bend, even if the resulting bend is in accordance with gas industry recommendations, will induce greater stresses.

Plastic piping manufacturers continue to have the best combination of technical expertise and practical knowledge for determining bend radius recommendations. Therefore, the Safety Board believes that the PPI should advise its plastic pipe manufacturing members to revise their pipeline bend radius recommendations as necessary to take into account the effects of residual coil bends in plastic piping.

Gas System Performance Monitoring

Federal regulations require that gas pipeline system operators have in place an ongoing program to monitor the performance of their piping systems. Before the Waterloo accident, Midwest Gas developed only a limited capability for monitoring and analyzing the condition of its gas system. For example, the company did not statistically correlate failure rates to the amounts of installed pipe provided by specific manufacturers. The design of the program meant that the relatively few areas with high failure rates (for example, those with Century pipe) were aggregated with and therefore masked by the large number of plastic piping installations that had low failure rates. Thus, the Midwest Gas surveillance program did not reveal the high failure rates associated with Century pipe. Only after the accident did Midwest Gas identify the Century pipe within its pipeline system as having high failure rates, even though the company could have collected and processed the same type of data and reached the same determination before the accident. If Midwest Gas had further correlated its data to years of installation, it may have also been able to examine the effects of its changing installation methods or changes in performance with different manufacturers through the years.

The Safety Board concludes that, before the Waterloo accident, the systems used by Midwest Gas Company for tracking, identifying, and statistically characterizing plastic piping failures did not permit an effective analysis of system failures and leakage history. The Safety Board further concludes that if, before the Waterloo accident, Midwest Gas had had an effective surveillance program that tracked and identified the high leakage rates associated with Century piping when subjected to stress intensification, the company could have implemented a replacement program for the pipe and may have replaced the failed service connection before the accident.

Since the accident, MidAmerican Energy has revised its systems, adding parameters to provide the company with added capability to sort failures. However, MidAmerican Energy has not chosen parameters that will allow an adequate analysis of its plastic piping system failures and leakage history. For example, the generic "improper installation" is a parameter to be linked to leaks; however, no parameters have been added for the presence, lack, improper design, or improper placement of a protective sleeve. And no parameters have been added to link leaks to squeeze locations, improper joining, or items to differentiate between insufficient support and excessive installed bending. The Safety Board therefore concludes that MidAmerican Energy's current systems for tracking, identifying, and statistically characterizing plastic piping failures do not enable an effective analysis of system failures and leakage history.

The Safety Board believes that MidAmerican Energy should, as a basis for the timely replacement of its plastic piping systems that indicate unacceptable performance, review its existing plastic piping surveillance and analysis program and make the changes necessary to ensure that the program is based on sufficiently precise factors such as piping manufacturer, installation date, pipe diameter, geographical location, and conditions and locations of failures.

An effective surveillance program would include the data base inputs that would allow the company to adequately monitor and characterize the types and causes of plastic piping field failures. The *A.G.A. Plastic Pipe Manual for Gas Service* recommends the use of a form for recording necessary information on plastic piping failures; this form may be helpful to MidAmerican Energy as it decides which data fields would be necessary to provide for an adequate analysis of its plastic piping system failures and leakage history. The *A.G.A. Plastic Pipe Manual for Gas Service* further recommends collecting this information, then performing visual examinations of the type and cause of failure and, in some instances, a laboratory analysis. The above steps may help MidAmerican Energy comprehensively monitor and address parts of its plastic pipeline system—other than those installations with Century pipe—that may also indicate unacceptable performance.

In a previous accident investigation report,[84] the Safety Board pointed out that many operators had not established procedures to comply with Federal regulations requiring surveillance and investigation of failures. The Safety Board recommended that RSPA:

> <u>P-90-14</u>
> Emphasize, as a part of OPS inspections and during training and State monitoring programs, the actions expected of gas operators to comply with the continuing surveillance and failure investigation, including laboratory examination requirements.

In a letter to the Safety Board, RSPA responded that the TSI had increased emphasis on gas surveillance and failure investigation in the operations block of its industry seminars held across the country. The letter stated that the TSI would incorporate a discussion of accident analysis into a new hazardous liquids seminar that was to be presented for the first time in FY 1992. Additionally, RSPA noted that it planned to place additional emphasis on continuing surveillance and failure investigation requirements in its new inspection forms at the time of the next revision. Based on this response, the Safety Board classified Safety Recommendation P-90-14 "Closed—Acceptable Action."

Despite the RSPA response to this safety recommendation, for a variety of reasons—including the inadequate performance monitoring

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[84]National Transportation Safety Board Pipeline Accident Report--*Kansas Power and Light Company Natural Gas Pipeline Accidents, September 16, 1988, to March 29, 1989* (NTSB/PAR-90/03).

programs found at Midwest Gas/MidAmerican Energy, the susceptibility to brittle cracking of much of the polyethylene piping installed through the early 1980s, deficiencies noted in gas industry communications regarding poorly performing brands of polyethylene piping, and differences noted in the performance of different types and brands of polyethylene piping—RSPA may need to do more. Gas system operators may need to be advised once again of the importance of complying with Federal requirements for piping system surveillance and analyses. As is the case with older piping, an effective general pipeline surveillance program would be based on factors such as piping manufacturer, installation date, pipe diameter, operating pressure, leak history, geographical location, modes of failure (such as bending, inadequate support, rock impingement, or improper joining), location of failure (such as at the main to service or at pipe squeeze locations), and other factors such as the presence, absence, or misapplication of a sleeve. An effective program would also evaluate past piping and components installed, as well as past installation practices, to provide a basis for the replacement, in a planned, timely manner, of plastic piping systems that indicate unacceptable performance.

CONCLUSIONS

1. Plastic pipe extruded by Century Utility Products, Inc., and made from Union Carbide's DHDA 2077 Tan resin has poor resistance to brittle-like cracking under stress intensification, and this characteristic contributed to the Waterloo, Iowa, accident.

2. The procedure used in the United States to rate the strength of plastic pipe may have overrated the strength and resistance to brittle-like cracking of much of the plastic pipe manufactured and used for gas service from the 1960s through the early 1980s.

3. Much of the plastic pipe manufactured and used for gas service from the 1960s through the early 1980s may be susceptible to premature brittle-like failures when subjected to stress intensification, and these failures represent a potential public safety hazard.

4. Gas pipeline operators have had insufficient notification that much of the plastic pipe manufactured and used for gas service from the 1960s through the early 1980s may be susceptible to brittle-like cracking and therefore may not have implemented adequate pipeline surveillance and replacement programs for their older piping.

5. Even though the Gas Research Institute has developed a significant amount of data about older plastic piping used for gas service, because the data have been published in codified terms, the information is not sufficiently useful to gas pipeline system operators.

6. Because guidance covering the installation of plastic piping is inadequate for limiting stress intensification at plastic service connections to steel mains, many of these connections may have been installed without adequate protection from shear and bending forces.

7. Because MidAmerican Energy Corporation's gas construction standards do not establish well-defined criteria for supporting plastic pipe connections to steel mains or for designing or installing its protective sleeves at these connections, these standards do not ensure that connections will be adequately protected from stress intensification.

8. Before the Waterloo, Iowa, accident, the systems used by Midwest Gas Company for tracking, identifying, and statistically characterizing plastic piping failures did not permit an effective analysis of system failures and leakage history.

9. If, before the Waterloo accident, Midwest Gas Company had had an effective surveillance program that tracked and identified the high leakage rates associated with Century Utility Products, Inc., piping when subjected to stress intensification, the company could have implemented a replacement program for the pipe and may have replaced the failed service connection before the accident.

10. MidAmerican Energy Corporation's current systems for tracking, identifying, and statistically characterizing plastic piping failures do not enable an effective analysis of system failures and leakage history.

11. The use of Continental Industries, Inc., tapping tees with the company's protective sleeves may leave the tapping tees susceptible to corrosion because the sleeves do not provide sufficient clearance for the application of field wrap to the metallic steel tapping tee.

RECOMMENDATIONS

As a result of this special investigation, the National Transportation Safety Board makes the following safety recommendations:

--to the Research and Special Programs Administration:

Notify pipeline system operators who have installed polyethylene gas piping extruded by Century Utility Products, Inc., from Union Carbide Corporation DHDA 2077 Tan resin of the piping's poor brittle-crack resistance. Require these operators to develop a plan to closely monitor the performance of this piping and to identify and replace, in a timely manner, any of the piping that indicates poor performance based on such evaluation factors as installation, operating, and environmental conditions; piping failure characteristics; and leak history. (P-98-1)

Determine the extent of the susceptibility to premature brittle-like cracking of older plastic piping (beyond that piping marketed by Century Utility Products, Inc.) that remains in use for gas service nationwide. Inform gas system operators of the findings and require them to closely monitor the performance of the older plastic piping and to identify and replace, in a timely manner, any of the piping that indicates poor performance based on such evaluation factors as installation, operating, and environmental conditions; piping failure characteristics; and leak history. (P-98-2)

Immediately notify those States and territories with gas pipeline safety programs of the susceptibility to premature brittle-like cracking of much of the plastic piping manufactured from the 1960s through the early 1980s and of the actions that the Research and Special Programs Administration will require of gas system operators to monitor and replace piping that indicates unacceptable performance. (P-98-3)

In cooperation with the manufacturers of products used in the transportation of gases or liquids regulated by the Office of Pipeline Safety, develop a mechanism by which the Office of Pipeline Safety will receive copies of all safety-related notices, bulletins, and other communications regarding any defect, unintended deviation from design specification, or failure to meet expected performance of any piping or piping product that is now in use or that may be expected to be in use for the transport of hazardous materials. (P-98-4)

Revise the *Guidance Manual for Operators of Small Natural Gas Systems* to include more complete guidance for the proper installation of plastic service pipe connections to steel mains. The guidance should address pipe bending limits and should emphasize that a protective sleeve, in order to be effective, must be of the proper length and inner diameter for the particular connection and must be positioned properly. (P-98-5)

--to the Gas Research Institute:

Publish the codes used to identify plastic piping products in previous Gas Research Institute studies to make the information contained in these studies more useful to pipeline system operators. (P-98-6)

--to the Plastics Pipe Institute:

Advise your members to notify pipeline system operators if any of their piping products, or materials used in the manufacture of piping products, currently in service for natural gas or other hazardous materials indicate poor resistance to brittle-like failure. (P-98-7)

Advise your plastic pipe manufacturing members to develop and publish recommendations for limiting shear and bending forces at plastic service pipe connections to steel mains. (P-98-8)

Advise your plastic pipe manufacturing members to revise their pipeline bend radius recommendations as necessary to take into account the effects of residual coil bends in plastic piping. (P-98-9)

--to the Gas Piping Technology Committee:

Revise the *Guide for Gas Transmission and Distribution Piping Systems* to include complete guidance for the proper installation of plastic service pipe connections to steel mains. The guidance should emphasize the need to limit pipe bending and should include a discussion of the proper design and positioning of a protective sleeve to limit stress at the connection. (P-98-10)

--to the American Society for Testing and Materials:

Revise ASTM D2774 to emphasize that a protective sleeve, in order to be effective, must be of the proper length and inner diameter for the particular connection and must be positioned properly. (P-98-11)

Develop and publish standard criteria for the design of protective sleeves to limit stress intensification at plastic pipeline connections. (P-98-12)

--to the American Gas Association:

Revise your *Plastic Pipe Manual for Gas Service* and your *Gas Engineering and Operating Practices* series to provide complete and unambiguous guidance for limiting stress at plastic pipe service connections to steel mains. (P-98-13)

--to MidAmerican Energy Corporation:

Modify your gas construction standards to require (1) firm compacted support under plastic service connections to steel mains, and (2) the proper design and positioning of protective sleeves at these connections. (P-98-14)

As a basis for the timely replacement of your plastic piping systems that indicate unacceptable performance, review your existing plastic piping surveillance and analysis program and make the changes necessary to ensure that the program is based on sufficiently precise factors such as piping manufacturer, installation date, pipe diameter, geographical location, and conditions and locations of failures. (P-98-15)

--to Continental Industries, Inc.:

Provide a means to ensure that the use of your protective sleeves with your tapping tees at plastic pipe connections to steel mains does not compromise corrosion protection for the connection. (P-98-16)

--to Continental Industries, Inc. (P-98-17):

--to Dresser Industries, Inc. (P-98-18):

--to Inner-Tite Corporation (P-98-19):

--to Mueller Company (P-98-20):

Develop and publish recommendations and instructions for limiting shear and bending forces at locations where your steel tapping tees are used to connect plastic service pipe to steel mains.

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April 23, 1998

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National Transportation Safety Board
Washington, D.C. 20594

Pipeline Accident Brief

Pipeline Accident Number:	DCA-95-MP-001
Type of System:	Gas distribution
Accident Type:	Explosion and Fire
Location:	Waterloo, Iowa
Date and Time:	October 17, 1994; 10:07 a.m. local
Owner/Operator:	Midwest Gas Company[1]
Fatalities/Injuries:	Six fatalities and seven non-fatal injuries
Damage:	$250,000
Material Released:	Natural Gas
Pipeline Pressure:	25 pounds per square inch, gauge (psig)
Component Affected:	1/2-inch plastic pipe at steel tapping tee mechanical compression connection to steel main

The Accident

At 10:07 a.m. central daylight savings time on Monday, October 17, 1994, a natural gas explosion and fire destroyed a one-story, wood frame building in Waterloo, Iowa. The force of the explosion scattered debris over a 200-foot radius.

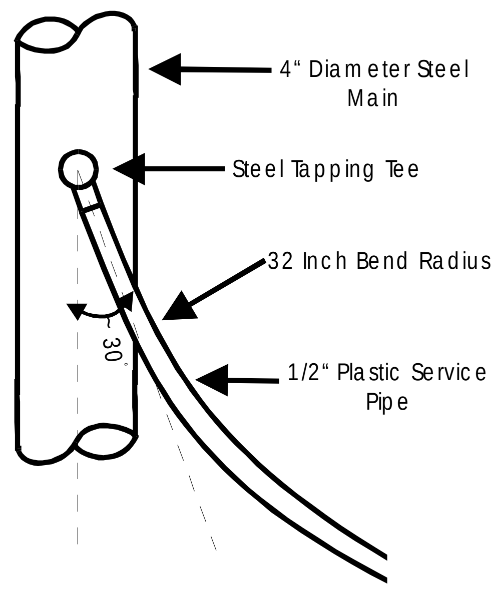
Six persons inside the building died, and one person sustained serious injuries. Three persons working in an adjacent building sustained minor injuries when a wall of the building collapsed inward from the force of the explosion. The explosion also damaged nine parked cars. A person in a vehicle who had just exited the adjacent building suffered minor injuries. Additionally, two firefighters sustained minor injuries during the emergency response. Two other nearby buildings also sustained structural damage and broken windows.

Site Information

The destroyed building was a neighborhood tavern known as Buzz's Bar. Adjacent to and east of the bar was Woodland Pattern Company, which was provided gas service by a 1/2-inch-diameter plastic polyethylene service pipeline. The service pipeline was installed by Iowa Public Service Company on September 3, 1971, and was operated at a maximum pressure of 25 psig.

[1] Because of a series of organizational changes and mergers, the name of the owner/operator of the gas system at Waterloo, Iowa, has changed over the years. In 1971, Iowa Public Service Company installed the gas service that ultimately failed. At the time of the accident, the gas system operator was known as Midwest Gas Company, while the current operator's name is MidAmerican Energy Corporation.

The underground pipeline connected with the steel gas main and entered the Woodland Pattern Company building between Buzz's Bar and the Woodland Pattern Company.



Service-to-main connection at site of Waterloo accident.

The area between Buzz's Bar and Woodland Pattern Company was unpaved and, according to those familiar with the location, was regularly used by beer trucks making deliveries to Buzz's Bar and by semitrailers delivering materials to Woodland Pattern Company. These trucks had been seen to drive over the area of the piping assembly that cracked. At various times, beer trucks servicing Buzz's Bar had been observed to park directly over the location of the pipe break. One witness stated that a beer delivery truck had been parked over the area of the pipe break at approximately 7:00 a.m. on the day of the accident.

Excavations following the accident uncovered a 4-inch-diameter steel main at a depth of about 3 feet. Welded to the top of the main was a steel tapping tee with markings indicating that the tee had been manufactured by Continental Industries, Inc. (Continental). Connected to the steel tee was a 1/2-inch-diameter plastic service pipe leading to Woodland Pattern Company. Markings on the plastic pipe indicated that it was a medium-density polyethylene material manufactured on June 11, 1970, in accordance with American Society for Testing and Materials (ASTM) standard D2513, and marketed by Century Utility Products, Inc. (Century). A circumferential crack through the plastic pipe was found at the tip of the tee's internal stiffener that protruded beyond the tee's coupling nut. A 1- to 2-foot-diameter "hard ball" surrounded the cracked pipe.[2]

Because Safety Board investigators did not arrive at the accident site until after excavation of the failed pipe, investigators had to consult several sources to determine the condition of the piping at the time of excavation. Photographs of the excavation, a Waterloo Fire Department video tape, and several witnesses all indicated that the downstream portion of the plastic pipe was found broken off and vertically displaced below the plastic pipe portion still attached to the steel tee. However, an Iowa State Fire Marshall's Office investigator, who directed and participated in the excavation, reported that the pipe was displaced by the excavation activities. That investigator also reported no observed voids in the soil under the failed assembly.

Service-to-main connection at site of Waterloo accident.

MidAmerican Energy estimated that the steel tee on the steel main was installed so that the polyethylene pipe exited the tee at an approximate 30° angle to the steel main. (See figure.)

[2]A "hard ball" is a term used in the gas industry for a soil condition where leaking natural gas over a period of time dries and hardens the soil adjacent to the leak.

The plastic service pipe leaving the tee immediately curved horizontally. After a portion of the pipe was taken to the laboratory for testing, the bend radius was measured at about 34 inches. Based on field conditions and photos, MidAmerican Energy has estimated the original installed horizontal bend radius to be approximately 32 inches.[3] This bend is sharper than currently recommended by industry guidelines for modern piping adjacent to fittings. However, a former Iowa Public Service Company employee stated that Iowa Public Service Company, in an effort to reduce the stress at the connection point, often attempted to install polyethylene services at an angle to the main to match the residual bend left after uncoiling the pipe.[4] This former employee stated that no set time was prescribed to allow for complete relaxing of the pipe, but that the pipe would be placed in the ditch, and the crews would weld the tee at what they judged to be the appropriate angle, in consideration of the natural bend of the pipe.

Also immediately from the tee outlet, the polyethylene bent downward. The tee outlet did not have a protective sleeve to reduce shear and bending forces at the connection.

Tests and Examination

Samples recovered from the plastic service line underwent several laboratory tests under the supervision of the Safety Board. Two of these tests were meant to roughly gauge the pipe's susceptibility to brittle-like cracking. These tests were a compressed ring environmental stress crack resistance (ESCR) test in accordance with ASTM F1248 and a notch tensile test known as a PENT test that is now ASTM F1473. Lower failure times in these tests indicate greater susceptibility to brittle-like cracking under test conditions. The ESCR testing of 10 samples from the pipe yielded a mean failure time of 1.5 hours, and the PENT testing of 2 samples yielded failure times of 0.6 and 0.7 hours. Test values this low have been associated with materials having poor performance histories[5] characterized by high leakage rates at points of stress intensification due to crack initiation and slow crack growth typical of brittle-like cracking.

To facilitate identification, the fracture surfaces were divided into two regions, A and B, around the circumference of the failed pipe. If a cross section of the pipe, looking toward the tee, were superimposed on a clock face, region A would extend from approximately the 9:00 position up across the top and down to about 1:30, with the center of the region at about 11:15. Region B took up the remainder of the pipe surface, extending from about the 1:30 position down across the bottom and up to 9:00.

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[3]Polyethylene pipe installed with a bend often, over time, permanently deforms in the direction of the bend. This permanent deformation partially reduces the stresses generated by the bending forces. When the pipe is released from its installation configuration, the pipe can straighten to some extent.

[4]MidAmerican Energy has indicated that Iowa Public Service's plastic service pipe was received in coils from Century. After uncoiling the pipe, some residual bending remains. The amount of residual bending depends on the factory coiling conditions.

[5]Uralil, F. S., et al., *The Development of Improved Plastic Piping Materials and Systems for Fuel Gas Distribution—Effects of Loads on the Structural and Fracture Behavior of Polyolefin Gas Piping*, Gas Research Institute Topical Report, 1/75 - 6/80, NTIS No. PB82-180654, GRI Report No. 80/0045, 1981, and Hulbert, L. E., Cassady, M. J., Leis, B. N., Skidmore, A., *Field Failure Reference Catalog for Polyethylene Gas Piping, Addendum No. 1*, Gas Research Institute Report No. 84/0235.2, 1989, and Brown, N. and Lu, X., "Controlling the Quality of PE Gas Piping Systems by Controlling the Quality of the Resin," *Proceedings Thirteenth International Plastic Fuel Gas Pipe Symposium*, pp 327-338, American Gas Association, Gas Research Institute, Battelle Columbus Laboratories, 1993.

The fracture in region A was located immediately outside the tee's internal stiffener. The crack was perpendicular to the pipe wall and directly in line with the end of the tee's internal stiffener. The inside surface of the pipe throughout region A was characterized by a circumferential impression from the tip of the tee's stiffener. A similar impression was not found in region B. This impression was only found on the pipe segment that was still attached to the steel tee, and was not evident on any part of the pipe segment that was detached from the steel tee. Region A was characterized by several brittle-like slow crack growth fractures, each of which initiated on or near the pipe inner wall just outside the depression associated with the tip of the tapping tee's stiffener. These slow crack fractures propagated on almost parallel planes slightly offset from each other through the wall of the pipe. As the cracks from different planes continued to grow and began to overlap one another, ductile tearing occurred between the planes, which produced a jagged appearance in parts of the overall circumferential crack in region A Thus, even though substantial deformation was observed in part of the fracture, the initiating cracks were still classified as brittle-like.

Region B contained two brittle-like crack growth sections that initiated from each end of region A. Cracks from each end of region A propagated through region B on approximate 45° planes towards the tee (partially exposing the tee's stiffener) and met at the bottom (the 6:00 position). The remaining ligament tore with visible deformation at the bottom.

Laboratory comparisons showed that the fractures that initiated and grew in region A were consistent with fractures generated by long-term shear and bending forces at the end of the stiffener. The fractures in region B were consistent with a continuation of the same loading system described for region A but occurred subsequent to those in region A. The last ligament that fractured at the 6:00 position in region B was consistent with ductile tearing. Examination could not determine whether the last remaining ligament tore because of concentrated stresses prior to the excavation or because of excavation activities after the accident.

Other Information

Flooding was reported in the area during the summer of 1993. Midwest Gas's most recent leak surveys, performed in March 1994, did not detect a leak in this area. Records of odorant tests performed in September 1994 and on October 17, 1994 (two and a half hours after the accident), show odorant levels that met the level required by Federal standards.[6]

Probable Cause

The National Transportation Safety Board determines that the probable cause of the natural gas explosion and fire in Waterloo, Iowa, was stress intensification, primarily generated by soil settlement at a connection to a steel main, on a 1/2-inch polyethylene pipe that had poor resistance to brittle-like cracking.

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[6]Federal standards require the odorant in natural gas systems to be detectable at one-fifth of the lower explosive limit, which is typically at gas/air concentrations of 0.9 to 1.0 percent and above.

Organizations, Agencies, and Associations Referenced in this Report

American Gas Association (A.G.A.)
An organization dedicated to promoting and protecting the interests of its member natural gas local distribution companies. The A.G.A. has approximately 300 members, of which about 250 are natural gas local distribution companies.

American Society for Testing and Materials (ASTM)
An organization that provides a forum for producers, users, consumers, and others with a common interest, including representatives of government and academia, who come together to write standards for materials, products, systems, and services.

Gas Piping Technology Committee (GPTC)
An organization dedicated to the development of the *GPTC Guide for Gas Transmission and Distribution Piping Systems* (*GPTC Guide*). The purpose of the *GPTC Guide* is to provide assistance to gas pipeline system operators in complying with Federal regulations addressing the transportation of natural and other gases by pipeline.

Gas Research Institute (GRI)
A research, development, and commercialization organization dedicated to the interests of the natural gas industry. The organization's mission is to discover, develop, and deploy technologies and information that benefit gas customers and the industry.

Plastics Pipe Institute (PPI)
A manufacturers organization, the PPI is an operating unit of the Society of the Plastics Industry. Members of the PPI share a common interest in broadening market opportunities through the effective use of plastic piping in water and gas distribution, sewage and wastewater transport, oil and gas production, and in industrial, mining, power, communications, and irrigation applications.

Office of Pipeline Safety (OPS)
The Research and Special Programs Administration (see below) acts through the OPS to administer the U.S. Department of Transportation's national regulatory program to ensure the safe transportation of natural gas, petroleum, and other hazardous materials by pipeline. The OPS develops regulations and other mechanisms to ensure safety in design, construction, testing, operation, maintenance, and emergency response of pipeline facilities.

Research and Special Programs Administration (RSPA)
A part of the U.S. Department of Transportation, RSPA has responsibility for emergency preparedness, research and technology, and transportation safety. The agency's safety mandate is to protect the Nation from the risks inherent in the transportation of hazardous materials by all transportation modes, including pipelines. RSPA carries out its pipeline safety and training programs through the Office of Pipeline Safety (see above).