(a) Heat Transfer Under Pressure

A 0.92 m long section was cut from a 0.46 m diameter schedule 40 steel pipe. A SDR 26 HDPE liner; 2.44 m long, 0.41 m diameter and 15.6 mm thick; was placed inside the test section leaving approximately 0.76 m of the liner extending outside each end of the setup. Teflon insulted thermocouples were placed inside the liner and on its inside skin to measure the steam and skin temperatures. Each thermocouple was connected to an electronic digital thermometer. The liner was then inflated inside the steel pipe according to the steam injection method used in the field. Pressure inside the liner was increased gradually from 0 to 165.5 kN/m^2 over a 35 minutes period until the liner was completely reformed. Pressure was measured by a mechanical gauge installed on the steam inlet. Temperature measurements were taken every 5 minutes from the two thermocouples. The ambient temperature at the start of the test was 17 °C. Steam temperature was raised gradually to 107 °C in the first 5 minutes of the test and was held between 107 and 124 °C in the next 30 minutes.

(b) Temperature Gradients in Thick Liners

The second test series was conducted to examine temperature gradients within the thick liner wall. Tests were conducted to examine the influence of liner thickness, thermal heating and cooling, type of polyethylene and location within the pipe length. The new liner sections were all less than 2.44 m long so that temperature could be controlled with greater accuracy. One end of the liner was sealed with two plywood circular disks attached with steel angles and screws. A 25.4 mm diameter hole was drilled at the center of the disks.

Six thermocouples connected to electronic digital thermometers were installed in full contact with the liner at different locations. One thermocouple was placed inside the liner to measure the inside air temperature. Temperatures within the liner wall thickness were measured by thermocouples attached on the inside and outside surfaces of the wall and three thermocouples inserted in holes spaced 25.4 mm apart that were drilled from the outside surface of the liner to depths of 0.75t, 0.5t, and 0.25t, where t is the liner thickness. In some tests, this setup was implemented at two sections along the liner length to determine the temperature differences with respect to the cooling of air as it moved along the pipe. Readings were taken from the thermometers at 1 min intervals. An oil-fired turbo heater capable of providing

100,000 BTU was used to blow hot air through the open end of the liner while allowing the air to flow out through the hole at the opposite end. No internal pressure was used in this series of tests.

A total of 11 tests were conducted on the new setups. The setup was allowed to cool down to ambient room temperature of about 27 °C prior to commencing the following test. Air temperature inside the liner was raised or lowered at various rates in order to provide a wide spectrum of measurements. The duration of the tests ranged from 35 to 180 minutes.

Results of the Tests:

Testing conditions were not identical to actual field conditions but were sufficient enough to provide insight on heat transfer characteristics of thick PE liners. Tests were conducted on relatively short sections and the results may differ in a long pipeline. In addition, temperature distribution tests were conducted using hot air rather than pressurized steam which is used in the field. Ambient conditions in the field may also vary significantly from one site to another. In addition, most field installation involve thinner liners.

(a) Heat Transfer Under Pressure

The results shown in Table 1 indicate that temperature of the inside skin of a liner is not the same as the steam temperature. Temperature of the inside skin of the liner continued to increase gradually from 35 °C at the beginning of the test to a maximum of 99 °C at the end. Figure 1 indicates that temperature of the inside skin would have reached a steady-state in approximately 50 to 60 minutes if the steam temperature were held at 121 °C, but the test was halted after 35 minutes when the liner has been completely reformed to closely fit the host pipe. The drop in steam temperature during the test was reflected on the measured liner temperature after about 5 minutes. Accordingly, a time difference can be expected in the response of a HDPE liner to a measurable change in the steam temperature. Time difference is a function of several parameters including material density and liner thickness. Temperature ratio of the inside skin to steam (I/S) increased drastically after 10 minutes to about 0.66. The final I/S ratio reached 0.83 when the liner was completely reformed and the pressurized steam had been released.

Table 1. Results of the Pressure Test

t	P_i	Steam		Skin		I/S
		T	Δ	T	Δ	
1	0	107	162	35	11	0.42
5	69	107	0	38	5	0.44
10	35	102	-4	61	42	0.66
15	103	107	5	69	11	0.70
20	152	121	11	74	6	0.66
25	152	118	-2	86	13	0.76
30	159	121	2	94	7	0.80
35	166	124	2	99	5	0.83

t = Elapsed time in minutes, P_i = Internal pressure in kN/m^2, T = temperature in °C, Δ = Change from previous reading in percent, I/S = Ratio of inside skin temperature to steam temperature.

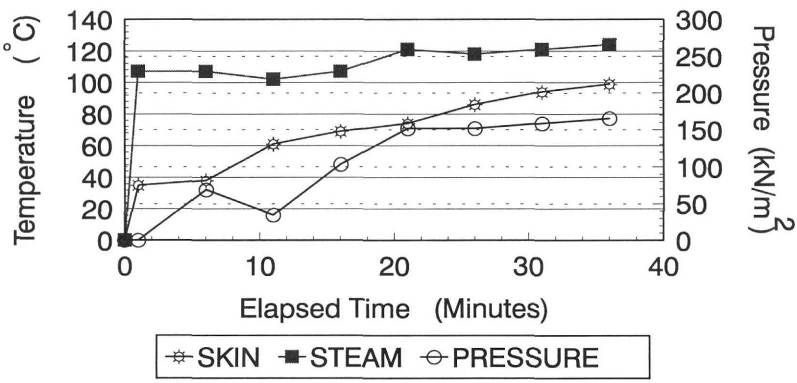

Figure 1. Heat Transfer During a Pressure Test

(b) Temperature Gradients in Thick Liners

Typical curves of internal air temperature and temperatures along the liner thickness are shown in Figure 2. As shown, a steep increase in the internal air temperature after approximately 18 minutes does affect the temperatures along the liner thickness for 10 to 15 min. After heating for 90 to 100 minutes, temperature of the liner walls appear to approach a steady-state at temperatures slightly below the internal air temperature. As expected, temperature was not distributed uniformly across the thickness of the liner in all tests. For the particular test shown, there is a measurable difference between the internal and external skin temperatures of approximately 9 °C. This may not be the case in much thinner liners.

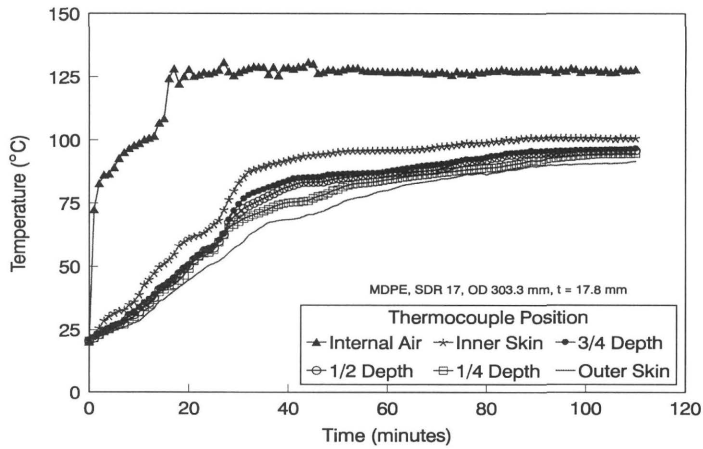

Figure 2. Temperature Gradient in a no Pressure Test

Table 2 summarizes the results of four tests conducted on thick HDPE liners and seven tests on thick MDPE liners. Results of all tests were similar to those presented in Figure 2. Temperatures decreased gradually within the liner wall where the deeper points closer to the inside skin were much warmer that the points near the outside skin. In a short duration test, the temperature difference between the inner skin of the liner and its outer skin was over 38 °C after two minutes, but the difference dropped to about 5 °C at the end of the test. In longer tests, the temperatures differences between the outside and inside surfaces of the liner were much less as a steady-state was reached. The difference in response can be attributed to the slower heating of the liner in the longer tests which allowed the distribution to become more uniform within the material.

An interesting point can also be seen at the internal and external interfaces. While the temperature difference between the 0.75t point and the 0.5t point was less than 1 °C and the temperature difference between the 0.25t and the 0.5t points was 2 °C at the end of the test, the temperature flux across the internal and external surfaces were 6 and 5 °C, respectively. This is a result of film coefficients and is indicative of temperature drops that often occur at phase change locations (Carslaw and Jaeger, 1959). All tests showed the presence of a time difference between the response of the liner to a given change in the internal air temperature. This was more evident with the major drop in temperature experienced during one of the shorter tests. As expected, the inner surface of the liner had a shorter time difference and was more sensitive to the changes in hot air temperature than the other points within and on the outside skin.

Table 2. Thermal Gradients in a no Pressure Test.

	Time	Temperature °C					
	min	Air	I	3/4	1/2	1/4	O
A	50	128	108	105	103	101	99
A	35	127	102	101	97	NA	95
A	51	129	109	108	107	111	106
B	34	NA	122	113	107	102	99
C	180	128	78	76	71	68	66
C	110	128	101	97	97	95	92
C	60	128	91	87	85	84	82
D	75	127	104	102	101	NA	92
D	70	129	103	NA	101	99	96
D	110	132	122	NA	NA	NA	117
C	180	129	112	NA	NA	NA	102

I = Inside skin temperature, O = Outside skin temperature.
A = SDR 24 HDPE liner 0.30 m in diameter and 12.7 mm thick.
B = SDR 26 HDPE liner 0.41 m in diameter and 15.8 mm thick.
C = SDR 17 MDPE liner 0.30 m in diameter and 17.8 mm thick.
D = SDR 17 MDPE liner 0.20 m in diameter and 11.7 mm thick.

Summary and Conclusions:

Tests were conducted to examine heat transfer characteristics of thick HDPE and MDPE liners during reforming process. It was found that the inside skin temperature reaches about 80 percent of the temperature of the steam used in the process upon completion of reforming in a laboratory setup. The tests also indicated that the temperature on the outside skin is lower than that on the inside skin and that the difference becomes smaller with time when the internal temperature is maintained at a constant level. Temperature distribution within the skin of thick liners remains non-uniform throughout the processing period. At near steady-state conditions a smaller temperature variation is present. The time to reach steady-state varies with liner material and its thickness. Disruptions or sudden increases in the internal air temperature will take approximately 15 minutes to effect a thick liner.

Results of the heat transfer tests are currently being used in conjunction with the results of buckling tests on PE liners to develop a constitutive model for the use in finite element analysis of PE liners. A comprehensive paper containing the results will be published upon the completion of the study.

Acknowledgments:

This work was funded by a research grant provided by the Louisiana Education Quality Support Fund (LEQSF) and Pipe Liners, Inc. under contract No. LEQSF(93-96)-RD-3-12. The authors would like to express their gratitude to Ivan Mandich, Keith Hebert, San Hla Aung, Chunduru Suryanarayana, and John Taylor, Sean Pechon for their assistance in the laboratory work and analysis of this project.

Appendix - References:

_____ (1994) Existing Sewer Evaluation & Rehabilitation, Manuals and Reports on Eng. Practice No. 62, 2nd edition, ASCE, New York, NY, Manual of Practice FD-6, WEF, Washington, D.C.

_____ (1991) Handbook - Sewer System Infrastructure Analysis and Rehabilitation, Rep. No. EPA/625/6-91/030, US Environmental Protection Agency, Ctr. for Env. Res. Info., Cincinnati, OH.

Bakeer, R.M., M.E. Barber, R. Subramanian, and I.C. Mandich, (1994). "Effect of Different Fluids on Mechanical Properties of a U-Liner", Proc. Conf. Localized Damage, Udine, Italy, June 21-23.

Bakeer, R.M. and M.E. Barber, (1995). "Evaluation of the U-Liner Technology for Trenchless Sewer Rehabilitation," Interim Report to Louisiana Education Quality Support Fund (LEQSF), Baton Rouge, LA.

Carslaw, H.S. and J.C. Jaeger, (1959). *Conduction of Heat in Solids*, 2nd Ed., Oxford Univ. Press, Oxford, England.

Schrock, B.J. (1992). "Pipeline Rehabilitation: A Guide to a Growing Market," NUCA, August, pp. 14-21.

Yang, G. (1995). "Effect of heat on the Behavior of Polyethylene Pipes," MS Thesis, Tulane Univ., New Orleans, LA.

Deformation Measurement of Liners During Buckling Tests

Alexander C. Aalders[1], Reda M. Bakeer[2], and Michael E. Barber[3]

Abstract:

Several methods were employed to measure the deformation of a polyethylene liner during a buckling test. In the test, a deformed (folded) liner is reformed back to closely fit a steel casing pipe then it is subjected to a uniform radial pressure. The test simulates a field situation where uniform pressure is being exerted on a liner by the groundwater seeping through the defects in a deteriorated host pipe. Simple methods, such as shining a strong light through one end of the pipe or videotaping, were found to be adequate to record failure patterns; but not accurate enough to provide exact measurement of deformation. Volumetric changes were detected by filling the liner with water and measuring the amount of water being squeezed out of the liner under the applied pressure. A mechanical device was specially designed to provide a 3-D scan of the longitudinal profile of the liner during loading. Measurements are taken every 40 degrees along the pipe's axis using an internal electro-mechanical unit connected to a data acquisition system.

Introduction:

The term trenchless technology encompasses a wide variety of methods used for inspection, installation, replacement, or rehabilitation of utility lines; or for leak detection with minimum ground excavation. Rehabilitation of sewer networks using a polyethylene

---

[1] Grad. Stud., Dept. of Civ. and Env. Engrg., Tulane Univ., New Orleans, LA 70118.
[2] Assoc. Prof., Dept. of Civ. and Env. Engrg., Tulane Univ., New Orleans, LA 70118.
[3] Asst. Prof., Dept. of Civ. and Env. Engrg., Washington State Univ., Pullman, WA 99164.

(PE) deformed/reformed liner is one of many methods currently available in the growing trenchless technology market.

This paper gives a summary of an ongoing research on the buckling characteristics of deformed/reformed PE liners. Several buckling tests under uniform radial pressure were conducted on polyethylene liners (Bakeer and Barber 1997). A buckling test simulates the situation of a deteriorated underground gravity sewer line fitted with a flexible liner and subjected to a uniform groundwater pressure. In a buckling test, a liner is reformed inside a steel chamber pipe then subjected to a uniform radial pressure. Three types of buckling tests were performed in this study (Pechon, 1996); namely short-, medium- and long-term tests. These tests may not fully represent the exact field situation due to some factors such as the differences between a typical underground host pipe and the tested specimens with respect to boundary conditions, length and integrity. However, the tests provide useful insight with regard to buckling performance of polyethylene liners. This simulation allows for examining various parameters such as collapse pressure, safe design pressure, volume reduction, cross-sectional changes, and deformation. Different methods were used to measure the deformation of the PE liner during buckling tests. These methods included: light projection, videotaping, laser beams, strain gages, water measurement, and an electro-mechanical measuring device.

Buckling Tests:

A typical buckling test setup consists of a rigid steel chamber pipe fitted with threaded inlet holes. Two circular steel rings are welded to each end of the steel casing pipe, as shown in Figure 1. The testing chamber is then fitted with a PE liner of appropriate length. Liners with Standard Diameter Ratio (SDR) of 32.5 and 26 were mostly used in the tests as these are the most common sizes used in the field. SDR is an industry standard which defines the required minimum thickness of a pipe wall as a function of its diameter. The liner is reformed to closely fit the casing using a process that is as close as possible to the field installation procedure. A second steel ring is then bolted to the welded ring on each end. The two rings hold in-place the flared ends of the PE liner to create a tightly sealed annular space between the outside surface of the liner and the inside surface of the casing. This condition will produce some restraint at the liner's ends which may not be present in the field, but it is necessary to create the tightly sealed space. The threaded holes on the steel casing are used to apply, regulate and measure the air pressure in the annular space. An air compressor is used to supply the required pressure. Mechanical dial gages are used for pressure measurements and are calibrated prior to each test.

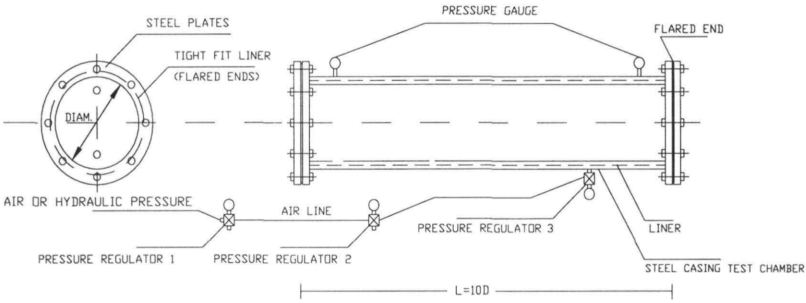

Figure 1. A Typical Testing Setup.

A short-term test is performed by increasing the uniform pressure in equal increments until the liner collapses which occurs typically within an hour or more. In the field, this condition simulates the gradual application of a load; such as a temporary surcharge or a rise of the groundwater table. In a medium-term test, a new pressure increment is applied every 24 hours to allow the liner to adjust to the applied pressure. The medium-term test requires several days to complete and it is terminated when the liner collapses. This test models a slowly applied load such as the construction of an embankment over an underground line. Collapse in both tests is defined by the loss of function of the pipeline due to either excessive deformation or structural failure of the liner. A long-term test is performed over a 10,000 hour period using a low pressure representing a typical service condition. In a long-term test, the liner is not expected to collapse, but it would experience some volumetric deformation and creep under the service pressure.

Several tests were performed on confined liners with different length-to-diameter ratios, deformed cross sections, and SDR's to establish their collapse pressure as well as to design the ultimate testing setup and procedure. The tests revealed that a setup with a length-to-diameter ratio of 10:1 is adequate to eliminate end effects (Bakeer and Barber 1997). The influence of end restraints is severe on the performance of shorter setups, while the tested longer setups yielded similar results as the 10:1 setups. Accordingly, use of a setup with a 10:1 ratio was deemed adequate to represent the much longer pipelines in the field with respect to buckling behavior.

Light Projection:

A strong light source was projected through one end of the pipe on a translucent plastic plate mounted on the opposite end. A sheet of engineering paper was affixed to the plastic plate which allowed for the shadow of the deformed liner to be traced during each pressure increment. The traced shadow was then transformed into a computer image and the deformed area was calculated using an electronic digitizer and a CAD software. This method had its limitations. Failure occurred at a very fast pace in short-term tests which made it extremely difficult to trace the deformed shape. Calculation of the deformed cross-sectional area of the liner using the traces proved to be too simple, but was equally crude. This is due to the non-uniform deformation pattern along the liner span. The projected light always cast the shadow of the most deformed section. Accordingly, when this area was used to calculate the reduction in the volume of the liner pipe it yielded an overestimated value. In addition, the liner's deformation becomes excessive during collapse such that it prevents any light from passing through.

A short-term test was performed on a SDR 26 HDPE liner installed in a steel pipe 1.6 m long with an inside diameter of 0.27 m. The liner was loaded over a 5 minute period with consecutive pressure increments of 36 kN/m^2 until the liner collapsed at 144 kN/m^2 (14 m of water head). Collapse was defined as loss of function due to excessive deformation, but the liner did not rupture. The collapse pattern was non-uniform where the liner bulged inward at the middle of the setup on one side and near both ends on the opposite side. The traced shadows showed that the reduction in the cross sectional area of the liner was less than 2% under a pressure of 72 kN/m^2 (7 m of water). The cross sectional area decreased by about 36% under a pressure of 108 kN/m^2 and 65% at collapse. It should be noted that this test was extremely quick and high pressure increments were used. This procedure was used in the early stages of this research to develop the setups and testing procedures. In later stages, similar liners have shown much higher collapse pressure in slower tests and under lower pressure increments (Bakeer and Barber, 1997).

Video Taping:

A video camera was used to record the liner's deformation during buckling tests. Video taping provided