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Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

ADVANCED THERMOPLASTIC MATERIALS FOR DISTRICT HEATING PIPING SYSTEMS*

by

D. T. Raske and D. E. Karvelas**

Materials and Components Technology Division
**Energy and Environmental Systems Division

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ABSTRACT

The work described in this report represents research conducted in the first year of a three-year program to assess, characterize, and design thermoplastic piping for use in elevated-temperature district heating (DH) systems. The present report describes the results of a program to assess the potential usefulness of advanced thermoplastics as piping materials for use in DH systems. This includes the review of design rules for thermoplastic materials used as pipes, a survey of candidate materials and available mechanical properties data, and mechanical properties testing to obtain baseline data on a candidate thermoplastic material extruded as pipe. The candidate material studied in this phase of the research was a polyetherimide resin, Ultem 1000, which has a UL continuous service temperature rating of 338°F (170°C). The prototype pipes were obtained as a collaborative effort between Argonne National Laboratory, the General Electric Company, and PLEXCO.

The results of experiments to determine the mechanical properties between 68 and 350°F (20 and 177°C) were used to establish preliminary design values for this material. Because these prototypic pipes were extruded under less than optimal conditions, the mechanical properties obtained are inferior to those expected from typical production pipes. Nevertheless, the present material in the form of 2-in. SDR 11 pipe (2.375-in. O. D. by 0.216-in. wall) would have a saturated water design pressure rating of ~35 psig at 280°F.

I. INTRODUCTION

In district heating and cooling, a community energy systems concept, thermal energy from a central source in the form of hot water, steam, or chilled water is distributed through insulated pipes to serve commercial, residential, institutional, and industrial energy needs for space heating, cooling, and industrial purposes.

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District heating (DH) systems have not captured a significant portion of the space heating market in the U.S. primarily because of the high cost of building and maintaining DH thermal distribution systems. District heating systems are capital intensive. Depending on the project, up to 70% of project capital cost may be attributed to the thermal transmission and distribution system. In a typical DH system, more than 10% of the heat energy is lost because of inefficiencies in the thermal distribution system.

The financial feasibility of DH systems is significantly affected by the front-end costs and maintenance costs of the thermal distribution systems. Innovative piping systems and materials that can improve the long-term economic performance of DH systems are critical to the industry's future growth.

District heating hot water thermal distribution systems in the U.S. and Europe are designed for efficient operation at temperatures of up to 290°F (~140°C). Steam thermal distribution systems operate at temperatures above 250°F (120°C), with the condensate return temperature below 200°F (~90°C). In both of these heat distribution system designs, installation and operating costs are high in the U.S. because of high labor costs associated with the installation and maintenance of DH piping systems in which steel is the carrier pipe material. Thermoplastic materials suitable for operating temperatures above 250°F (120°C) would be a cost-effective alternative to steel for the DH hot water carrier pipe material and the steam condensate carrier pipe material because of their corrosion resistance and relative ease of installation, joining, and repair. Currently available thermoplastic DH piping materials suitable for temperatures up to 200°F are listed in Table 1.¹ Recently, several new thermoplastic materials have been developed, which appear to offer the elevated-temperature mechanical strength necessary for DH pipe systems.

The objective of the Argonne National Laboratory (ANL) program is to develop reliable and cost-effective non-metallic piping material and engineering design information for use in DH systems operating between 250 and 350°F. The material selected for study during this initial phase of the program is a polyetherimide resin, Ultem 1000, which was developed by the General Electric Company (GE) and introduced in 1982. This material was developed to provide a structural thermoplastic with improved elevated-temperature (~300°F) mechanical, electrical, and processing properties. The material and extruded pipe were obtained as part of a collaborative research effort between ANL, GE, and PLEXCO.

II. SCOPE

This report contains a review of the ASTM standard practice for qualifying thermoplastic materials as pressure pipes and the results of a survey on candidate elevated-temperature thermoplastic piping materials. Also included are results of laboratory experiments to provide basic data on mechanical properties of prototypic

pipe extruded from Ultem 1000 resin. The report also contains design guides and recommendations for future research on Ultem 1000 as a DH piping material, and an assessment of the potential of other advanced thermoplastic resins for use in DH piping systems.

Table 1. Commercial Piping Materials for Hot Water DH Systems¹

System Type	Maximum Temp., °F	Carrier Pipe Material	Jacket Pipe Material	Application
Aquawarm	250	Copper	Corrugated HDPE ^a	Small users
Flexalen	194	PB ^b	Corrugated HDPE	Small users
Teletherm	194	PB	HDPE	Small users
VVF ^c specification	250	Steel	HDPE	Universal
Moller EZbend	250	Steel	Corrugated HDPE	Small users
Wirsbo	194	PEX ^d	Urethane shell	Not in current use
Fiber-reinforced glass	220	Glass fiber	Various	Condensate
Minitherm	194	HDPE/Al foil	PEX foam	Small users

^a HDPE = high-density polyethylene.

^b PB = polybutylene.

^c VVF = Varne Verks Foreningen.

^d PEX = cross-linked polyethylene.

III. PRESSURE DESIGN OF THERMOPLASTIC PIPING

A. Background

The current procedure to obtain the hydrostatic design basis for thermoplastic pipe materials is given by ASTM Standard Method D 2837. The scope of this method is stated as follows:

This method describes a procedure for obtaining a hydrostatic design basis for thermoplastic pipe materials, by evaluating stress rupture test data derived from testing pipe made from the subject material. The method is applicable to all known types of thermoplastic pipe and for any practical temperature and medium.²

This standard uses laboratory experiments to obtain internal pressure versus time-to-failure data on short lengths (12 to 30 in.) of the candidate material.³ The tests range from 10 h to at least 10^4 h duration, and estimates of the long-term hydrostatic strength (LTHS) are obtained by extrapolation of a regression analysis of the experimental data to 10^5 h. A summary of this procedure is given in Table 2.

Table 2. ASTM Procedure for Pressure Rating of Thermoplastic Pipe

Step	ASTM Standard
1. Obtain Hydrostatic Burst Test Data	D 1598
2. Determine the Long-term Hydrostatic Strength (LTHS)	D 2837
3. Calculate the Hydrostatic Design Stress (HDS) HDS = LTHS × safety factor Water service safety factor = 0.5 Gas service safety factor = 0.32	D 2513
4. Determine Pressure Rating ^a	F 645
$P = \frac{2 t (\text{HDS})}{(D - t)}$	

^a P = internal pressure, t = pipe wall thickness, and D = outside diameter of pipe.

Although this procedure is commonly used by the U. S. fuel gas industry to qualify new polyethylene (PE) plastic piping materials, the method has three major drawbacks that limit its usefulness both as a qualification test germane to service experience and also as a practical tool to quickly screen new thermoplastic pipes:

1. The internal pressure burst test does not simulate the fractures obtained on pipes in service, i.e., failure by flaw initiation and growth. Therefore, the ASTM burst test does not provide a relevant measure of the material properties necessary to characterize a thermoplastic material for pressure pipe service.

2. The procedure requires testing of at least three specimens beyond 6×10^3 h (8.2 months), and at least one specimen for up to 10^4 h (1.1 years). As a consequence, the procedure requires a significant investment in testing time that may not produce useful data.
3. Since the pipe samples are under internal pressure, the testing facilities and support equipment are relatively intricate and expensive compared to other methods for assessing the mechanical behavior of materials.

B. The Constant Tensile Load (CTL) Test

In 1977, Battelle Columbus Division (BCD) began a study, funded by the Gas Research Institute (GRI), to develop new methods to evaluate the mechanical properties of PE fuel gas piping materials.⁴ This study was primarily directed to testing that would evaluate the stress-crack resistance of PE materials, and to providing a basis for developing a simple and inexpensive test that could be used by the fuel gas industry to evaluate new PE pipe materials.

One of the tests developed by BCD was the constant tensile load (CTL) test. This test uses ring-type specimens cut directly from extruded pipe, and provides a measure of the material's resistance to a crack-like defect (provided by a razor notch) similar to that found to have caused service failures of existing PE pipes. This test was also evaluated and subsequently adopted by ANL in 1983 as part of a GRI-funded program to characterize and optimize PE pipe for fuel gas service.⁵ As a consequence, the CTL test has been used by both ANL and BCD as a research tool to characterize and evaluate many of the commercial PE pipes currently used for fuel gas service. The current data base consists of over 400 experiments on 30 different lots of PE pipe, and has demonstrated the applicability of the CTL test as a research tool as well as its potential to be used as a quality assurance test.⁶ At present, the CTL test is used by several gas utilities and pipe manufacturers to assess new and existing pipe, and is being documented for submission as a proposed ASTM test method. In addition, the CTL test procedure is simple to conduct, provides relevant data relatively quickly, and uses an inexpensive testing apparatus. A schematic diagram of the CTL test arrangement and specimen design is given in Fig. 1, and typical CTL test data obtained from a PE fuel gas pipe material are shown in Fig. 2. The data in Fig. 2 exhibit a bilinear fracture distribution. This distribution is phenomenologically related to a transition from high-stress ductile fracture to low-stress brittle fracture, which are the fracture mechanisms generic to pressure pipes made from thermoplastic materials.

Part of the current GRI-funded research at ANL has been directed toward developing an interpretation of CTL test data that can be used to estimate the LTHS value of thermoplastic pipe materials. One approach is to extrapolate the relatively short-term laboratory data ($<10^4$ h) to 10^5 h (as in ASTM D 2837), and to use the

(a)

(b)

Fig. 1. Constant tensile load (CTL) specimen design (a), and arrangement of components for the CTL test (b).

resulting nominal stress as a basis to estimate the LTHS value. Another strategy is to relate CTL data obtained at some intermediate brittle failure time (e.g., 10^3 h), augmented with tensile strength, to the LTHS. An example of the latter approach is provided by the PE pipe data shown in Table 3. For this material, the ratio of average LTHS to average ring tensile strength (RTT) is 0.44,* and the ratio of LTHS to average 10^3 h CTL strength is 0.76. Thus, a new PE pipe material might be assigned an LTHS value equal to the lesser of 0.44 times the RTT or 0.76 times the 10^3 h CTL strength. Or, within the 95% confidence intervals, the LTHS value would be the lesser of 0.38 times the RTT or 0.65 times the 10^3 h CTL strength. This is the approach adopted in the present study to obtain the LTHS value of candidate DH piping materials.

Fig. 2. Typical CTL data obtained for a commercial PE pipe material showing the transition from ductile, high-stress failures to brittle, low-stress failures (normalized stress is defined as the nominal stress divided by the ring tensile strength).

* For comparison, the average value of this ratio for the eleven thermoplastic gas pressure pipe materials listed in ASTM D 2513⁷ is 0.49.

Table 3. Comparison of ASTM Ring Tensile Strength (RTT), ASTM Long-term Hydrostatic Strength (LTHS), and Constant Tensile Load (CTL) Test 10³-hr Strength for 11 Lots of Polyethylene Gas Pipe Materials

Material	Lot	ASTM RTT, psi ^a	ASTM LTHS, psi ^b	LTHS/RTT Ratio	CTL 10 ³ -hr Strength, psi	LTHS/CTL Ratio
PE2306	31	2972	1250	0.42	2020 ^c	0.62
PE2306	1	3170	1250	0.39	2020 ^c	0.62
PE3408	19	3674	1600	0.44	1940 ^c	0.82
PE3408	32	3347	1600	0.48	1870	0.86
PE2306	16	2970	1250	0.42	1920 ^c	0.65
PE2306	20	2776	1250	0.45	1390	0.90
PE3408	33	3347	1600	0.48	1300	1.23
PE3406	5	3292	1250	0.38	1240	1.01
PE2306	6	2900	1250	0.43	1190	1.05
PE2306	11	3124	1250	0.40	780	1.60
PE3408	3	3027	1600	0.53	60	>20
Average ^d		3092	1377	0.44	1810	0.76

^a ASTM D 2290.

^b From ASTM D 2513.

^c Ductile failure data.

^d Mean values for all lots studied.

IV. THERMOPLASTIC PIPING MATERIALS

Table 4 provides a summary of the available thermoplastics that possess adequate elevated-temperature mechanical properties and are capable of being extruded to pressure piping.^{8,9} At the present time, none of these materials, with the exception of chlorinated polyvinyl chloride (CPVC), is commercially available as extruded pipe suitable for use in DH systems. Nevertheless, all of these materials have been extruded as research-grade pipe, and if the economic incentives are present, they can be manufactured as commercial pipe and fittings.

As was stated previously, the material selected for the present study is polyetherimide, provided by GE under the name Ultem 1000. The basis for this selection was that Ultem 1000 possessed superior strength, stiffness, and thermal

expansion properties, and was available as heavy-wall extruded pipe. In addition, the UL-rated continuous service temperature of 338°F for this material makes it a primary candidate for DH service. A handbook summary¹⁰ of the room-temperature mechanical properties of Ultem 1000 is given in Table 5, and a plot of tensile strength and elastic modulus versus temperature is shown in Fig. 3.¹¹

Table 4. Room-temperature Mechanical Properties of Thermoplastic Materials for DH Piping Applications

Material	Tensile Strength, ^a ksi	Elastic Modulus, ^a 10 ⁵ psi	Thermal Exp., ^b 10 ⁻⁵ in./in./°F	Heat Dfl. Temp. ^c at 264 psi	UL Cont. Service Temp.,°F
Chlorinated					
Polyvinyl Chloride	~8.2	4.2	7.2	218	210
Polybutylene	4.1	0.3	15.0	275	225
Polysulfone	10.2	3.6	5.4	345	~320
Polyetherimide (GE Ultem 1000)	15.2	4.3	3.1	392	338
Polyethersulfone	12.2	3.5	5.5	397	~345
Polyarylsulfone	13.0	3.7	4.7	400	356
Polyphenylene (Phillips PPS)	14.0	-	4.0	221	~400
Phillips PAS-2	9.8	-	7.0	383	~400

^a ASTM Standard D 638.

^b ASTM Standard D 696.

^c ASTM Standard D 648.

V. EXPERIMENTAL PROGRAM

A. Materials and Specimens

The material used in this study was obtained from an injection molding grade of Ultem 1000 resin provided by GE and extruded to pipe by PLEXCO. The pipes were extruded to 1- and 4-in. nominal size, with wall thicknesses of approximately 0.20 and 0.44 in., respectively.

The test specimens used for the CTL and RTT tests were 0.5-in.-wide rings that were cut from a section of pipe. The specimens used for the RTT measurements were made in accordance with the ASTM D 2290 standard practice.¹² These specimens have reduced test sections parallel to the circumference of the pipe, which act like miniature tensile bars. These experiments measured the circumferential tensile strength of the material.

For the CTL tests, razor notches were cut at both the inner and outer surfaces of the pipe ring at the location of the minimum thickness, and at 180° from this notch. The notch depth was adjusted to be equal to approximately one-fourth the nominal wall thickness for each pipe size. Thus, for 1-in. pipe the notch depth was 0.050 in., and for 4-in. pipe, 0.100 in. All notching was done in a fixture that locks the razor blade and assures uniform and consistent notch depths. The fixture is designed so that the specimen is drawn over both the inside and outside blade, which has a gradual projection from zero to the desired notch depth. In this way, the specimens are notched without excessive localized deformations.

Table 5. Mechanical Properties of General Electric Ultem 1000 Resin at 23°C

Property	ASTM Test	Ultem 1000	Units
Tensile Yield	D 638	15.2	10 ³ psi
Tensile Modulus	D 638	430	10 ³ psi
Elongation at Yield	D 638	7-8	%
Elongation at Ultimate	D 638	60	%
Flexural Strength	D 790	21	10 ³ psi
Flexural Modulus	D 790	480	10 ³ psi
Compressive Strength	D 695	20.3	10 ³ psi
Compressive Modulus	D 695	420	10 ³ psi
Izod Impact	D 256		
notched		1.0	ft lb/in.
unnotched		25	ft lb/in.
Ultimate Shear Strength	...	15	10 ³ psi
Rockwell Hardness	D 785	M109

Fig. 3. General Electric data showing the effect of temperature on tensile strength and elastic modulus.

Stress-rupture specimens were also made from both the 1- and 4-in. pipes. These specimens were typical pin-loaded, straight gage-section specimens with a gage length of 0.75 in. and a cross-section of 0.90 in. width and 0.65 in. thickness. Specimens from the 4-in. pipe were oriented both longitudinally to the extrusion direction (parallel to the pipe axis) and circumferentially. These specimens are referred to as U-4CL-x and U-4CC-x (x being the individual specimen number) for longitudinal and circumferential specimens, respectively. Because of the relatively thin wall of the 1-in. pipe, only longitudinal specimens were fabricated. These carry the designation U-1CL-x. All of the stress-rupture specimens were annealed at 200°C (~400°F) for 4 h after machining.

Because Ultem tends to absorb water from the environment (which may cause a reduction in mechanical properties),¹³ a number of the various test specimens were preconditioned to obtain saturation prior to testing by soaking the specimens in a boiling-water bath for 400 h. For storage, these specimens were kept in a water bath at room temperature. In the sections that follow, the specimens that were water saturated are so identified.

B. Apparatus and Test Procedure

All RTT experiments were conducted in accordance with the procedures specified in the ASTM D 2290 standard¹² except that the tensile loading rate was 0.39 in./min (10 mm./min) rather than the recommended 0.50 in./min (12.7 mm./min). Since most engineering thermoplastic materials exhibit a loading-

rate sensitivity,¹⁴ the tensile value data obtained with this loading rate are probably somewhat lower (1-3%) than values obtained at the slightly higher, ASTM-recommended loading rate.

In the CTL test, a constant tensile load is applied to the notched specimen by a split stainless steel disk that fits within the inside diameter of the pipe ring, and the load is applied by weights through a rod and clevis arrangement, depicted in Fig. 1. The time to failure, defined as specimen separation, is automatically recorded by a timer. The commercial single-edge stainless steel razor blades used to provide the simulated flaws are replaced after notching a single specimen. The tip radius of a typical new blade was optically determined to be $\sim 10^{-4}$ in. (3 μ m). The data obtained from the CTL test are (1) the nominal stress over the actual thickness of uncut pipe wall ligament, and (2) the time to failure. These data were correlated by the methods described in section VII.

The stress-rupture tests were conducted in a standard creep/stress-rupture test system and, as in the CTL tests, the dead load corresponding to the test section stress was applied gradually to avoid impact loadings after the entire system reached equilibrium at the test temperature. For all elevated-temperature experiments, the actual test temperature was maintained within 2% ($\pm 5^\circ\text{F}$) of the desired temperature.

VI. EXPERIMENTAL RESULTS

A. Ring Tensile Tests

A summary of the data obtained for the 1- and 4-in. pipes used in this study is given in Table 6. These data are compared in Fig. 4 with GE's tensile strength data¹¹ on laboratory plaques. Except for the 1-in. data at 250°F, Fig. 4 shows that the tensile strength of extruded pipe is generally lower than that of straight tensile coupons made from molded plaques. The reason is twofold. First, the local stress distributions in the RTT specimens and the flat tensile coupons are different; this can affect the results. Second, the processing (cooling, etc.) of plaques and pipe may be sufficiently different to alter the molecular structure and hence the mechanical properties of these specimens.

The data in Fig. 4 also show that preconditioning the specimens in boiling water will generally reduce the RTT strength. This is attributed to a plasticization of the material that degrades its mechanical properties.¹⁵ General Electric data on water absorption indicate that Ultem will experience a weight gain of approximately 1.5% after prolonged exposure (>350 h) to 100°C water. The results of the present study indicate a weight gain of 3.2% for 1-in. pipe and 1.3% for 4-in. pipe after exposure for 400 h. The difference in RTT strength for the 1- and 4-in. pipes is due to differences

in processing during extrusion. Because these pipes were extruded only as preliminary, demonstration products, not intended for commercial use, the lower strength of the thicker-walled 4-in. pipe is not unexpected and can probably be corrected by optimizing the extrusion parameters.⁸

Table 6. Results of ASTM D 2290 Ring Tensile Tests on Pipes Extruded from Ultem 1000 Resin

Specimen No.	Pipe Size, in.	Test Temp., °F	Material Condition ^a	Tensile Strength, psi
U-1-5	1	RT ^b	As Rec'd	12000
U-1-8	1	RT	Saturated	8600
U-1-12	1	250	As Rec'd	8230
U-1-13	1	250	Saturated	8230
U-1-6	1	350	As Rec'd	4600
U-1-7	1	350	Saturated	4020
U-4-5	4	RT	As Rec'd	4130
U-4-8	4	RT	Saturated	5700
U-4-6	4	350	As Rec'd	4260
U-4-7	4	350	Saturated	3200

^a As Rec'd = stored and tested in standard laboratory air;
Saturated = pre-soaked 400 h in boiling water, tested in standard laboratory air.

^b RT = room temperature.

The RTT strength data on the saturated 1-in. pipes can be used for preliminary design studies in the approximate relation

$$S_u = 10.3 - 0.015 (T), \quad (1)$$

where S_u is the tensile strength in ksi and T is the temperature in °F.

Fig. 4. Comparison of tensile strength data obtained on pipes (ANL) with data obtained for specimens made from cast plaques (GE).

B. CTL Test Experiments

The results of the CTL experiments are given in Table 7. Because of the poor mechanical properties for the preproduction 4-in. pipe discussed in the previous section, these experiments focused on the 1-in. pipe samples. In order to maximize the design data within the limited scope of the present program, these tests were conducted primarily on water-saturated samples at the maximum expected use temperature of 350°F.

The apparent decrease in CTL life at nominal stresses below 1200 psi indicates that extrusion-induced defects present in the 4-in. pipes also manifest themselves in the 1-in. material. These defects result in thumbnail-shaped, subsurface cracks that lead to premature failure. Imbedded cracks were observed during the posttest examination of specimens U-1-4, U-1-11, and U-1-16. The 4-in. pipe samples did not exhibit these cracks, but the fracture surfaces were characteristic of brittle, cleavage-like failures, whereas the fracture surfaces of all the 1-in. pipes exhibited some evidence of ductile tearing. A plot of the 1-in. data in Fig. 5 shows both the data considered valid and also the data for pipes that failed prematurely, perhaps due to imbedded cracks. This figure also shows one test that is still in progress, which will presumably result in valid data.

Table 7. Results of Constant Tensile Load (CTL) Tests at 350°F on Pipes Extruded from Ultem 1000 Resin

Specimen No.	Pipe Size, in.	Material Condition ^a	Nominal Stress, psi	Time to Failure, h
U-1-1	1	As Rec'd	3200	0 ^b
U-1-2	1	As Rec'd	1600	2.2
U-1-3	1	Saturated	1400	0 ^c
U-1-4	1	Saturated	1400	9.7
U-1-9	1	Saturated	1200	35.0
U-1-10	1	Saturated	1000	25.6
U-1-11	1	Saturated	800	34.8
U-1-16	1	Saturated	600	16.8
U-1-17	1	Saturated	400	>400 ^d
U-4-3	4	Saturated	1400	0 ^b
U-4-4	4	Saturated	1200	0 ^b

^a As Rec'd = stored and tested in standard laboratory air;

Saturated = presoaked 400 h in boiling water, tested in standard laboratory air.

^b Failed instantly; load too high.

^c Failed instantly; broken razor in specimen.

^d Test in progress.

C. Stress-Rupture Tests

Table 8 summarizes the stress-rupture data obtained in this study. These data were originally intended to augment the RTT strength and CTL test data to obtain an estimate of the LTHS value for Ultem 1000. However, the extrusion-induced defects present in these preproduction pipes led to macrocrazes that effectively precluded obtaining meaningful data. Although these specimens were annealed prior to testing, internal defects and/or persistent residual stresses caused numerous craze cracks to form at the edges of the gage section during specimen heating. Only two of the samples tested (U-4CC-1 and U-1CL-3) showed no evidence of gage section edge cracks. One sample, U-1CL-3, failed at what appeared to be a machining-induced surface crack, and another sample, U-4CC-3, survived for over 1100 h, but also had several edge cracks in the gage section away from the final fracture surface. The results for sample U-4CC-1 appear to be the only valid data obtained on these pipes. This test exceeded 1200 h, and the tensile creep strain at fracture was 22%. (The creep strain for U-4CC-3 was 14%.)

Fig. 5. Constant tensile load (CTL) test data obtained on 1-in.-diameter Ultem 1000 pipe at 350°F.

Table 8. Results of Stress-rupture Tests at 350°F on Annealed^a Samples of Pipes Extruded from Ultem 1000 Resin

Specimen No.	Pipe Size, in.	Location in Pipe Wall ^b	Material Condition ^c	Stress, psi	Time to Rupture, h ^d
U-4CL-1	4	Long.	As Rec'd	3000	0
U-4CC-1	4	Circ.	As Rec'd	1000	1205
U-4CC-2	4	Circ.	As Rec'd	1400	0
U-4CC-3	4	Circ.	Saturated	1000	1122 ^e
U-1CL-3	1	Long.	Saturated	1400	0 ^f
U-1CL-4	1	Long.	Saturated	1200	1.2 ^e

^a Annealed 4 h at 200 °C.

^b Long. = longitudinal to the extrusion direction; Circ. = circumferential.

^c As Rec'd = stored and tested in standard laboratory air;
Saturated = presoaked 400 h in boiling water, tested in standard laboratory air.

^d Zero time to rupture indicates that the specimen failed at the time of loading because of multiple craze cracks along the edge of the gage section.

^e Specimen also had multiple craze cracks in the gage section.

^f Failure was caused by a surface flaw that could be due to a machining scratch.

VII. DISCUSSION

A. *Limitations and Assumptions*

In spite of the limitations imposed because the pipes used in the testing program were not representative of actual production materials, the data obtained can serve as a basis to establish a lower bound design value for polyetherimide in a DH piping system. These data can provide a rough, first-cut, LTHS estimate and can verify the premise that advanced thermoplastics are a viable alternative to steel for DH piping materials.

In establishing an estimate of the LTHS value, the design temperature was assumed to be 350°F (177°C). Although this temperature is slightly above the UL maximum use temperature of 338°F (170°C), it represents a reasonable upper bound value for DH service. If polyetherimide can be shown to be an acceptable alternative to steel pipe at 350°F, its acceptance at lower temperatures is straightforward.

B. *Design of DH Pipe Using Ultem 1000*

At 350°F, Eq. (1) gives a tensile strength of 5.05 ksi. (The GE data of Fig. 3 give 5.70 ksi.) Therefore, for the approximate lower bound ratio of 0.38, the LTHS estimate is 1.92 ksi. However, the limited stress-rupture data of Table 8 suggest that the maximum LTHS value should not exceed 1.0 ksi. Consequently, the CTL test data must be used to estimate a 10^3 -h failure stress. A simple linear regression analysis of the valid data in Table 8 gives an extrapolated 10^3 -h failure stress of 473 psi. For the ratio 0.65, this results in an estimated LTHS value of 307 psi. Then, with the ASTM D2513 water service safety factor of 0.5, the hydrostatic design stress (HDS) is estimated to be 150 psi.

During the next phase of this investigation, an agreement has been reached with PLEXCO¹⁶ to provide a supply of commercial-quality, 2-in. pipe with a wall thickness equivalent to a standard dimension ratio (SDR) of 11.* This pipe will have a nominal wall thickness of 0.216 in. and an outside diameter of 2.375 in. Substituting these values and the HDS value into the equation given in Table 2 gives a pressure rating of 30 psig at 350°F for the service pipe.

The pressure for saturated water at 350°F is 135 psia, which means that the water in the pipe will consist of both liquid and vapor, and the vapor will have ~ 76°F superheat. In order to contain only liquid, the pressure rating of the pipe would have to be 120 psig. This corresponds to a LTHS of 1200 psi, which, based on the results of the CTL and stress-rupture tests, appears to be beyond the capabilities of the present

* Standard dimension ratio is defined as the ratio of average outside diameter to minimum wall thickness, i.e., $2.375/0.216 = 11$.

pipe material. On the basis of saturation pressures of water, Fig. 6 shows a plot of the LTHS values required to provide 2-in. SDR 11 service pipes containing water in the liquid state only.

If the supply side water in a DH piping system must be saturated, the graph in Fig. 6 indicates that the present Ultem 1000 pipes are unacceptable for use at 350°F. Nevertheless, a lower acceptance temperature can be appraised by assuming a linear relationship between temperature, CTL resistance, and RTT strength, and by determining the point where these properties give an LTHS estimate that coincides with the curve in Fig. 6. This exercise results in a temperature of ~280°F (138°C), which is certainly acceptable for current DH service pipes. In addition, because the pipes used to obtain the design data were prototype, demonstration pieces only, known to be inferior to the actual production product, the present results provide ample evidence that Ultem 1000 can be a suitable DH piping material.

Fig. 6. Relationship between temperature and long-term hydrostatic strength (LTHS) required for 2-in. SDR 11 pipes to contain saturated water.

C. Recommendations for Future Research

The primary objective of any future research using Ultem 1000 should be to obtain data on elevated-temperature mechanical properties of high-quality, production-grade pipe. The data obtained in the present investigation are barely adequate for design purposes; more importantly, these data reflect the mechanical properties of prototypic piping, which, experience suggests, will be inferior to the actual production product. Thus, the present results provide an unfair appraisal of the elevated-temperature mechanical behavior of Ultem 1000 pipe.

In addition, experiments should be conducted on a thermoplastic that has already been established as an elevated-temperature piping material in order to provide a basis to correlate the CTL, LTHS, and RTT data. A suggested candidate for this aspect of the study is chlorinated polyvinyl chloride (CPVC).

VIII. SUMMARY AND CONCLUSIONS

The objective of this research is to investigate and assess the usefulness of advanced thermoplastic materials as pressure piping for DH service between 250 and 350°F. The work conducted during this phase of the program consisted of a review of the design rules for plastic piping, a survey of all available high-temperature thermoplastic materials suitable for pipe, and an initial study on the mechanical properties of a polyetherimide thermoplastic, Ultem 1000. Results from these experiments were used to estimate the elevated-temperature pressure capability of extruded Ultem pipe.

The results of the mechanical testing experiments on prototype 1- and 4-in. pipes made from Ultem 1000 resin suggest the following conclusions:

1. The 4-in. pipes had poorer overall mechanical properties than the 1-in. pipes. Because the pipe samples used in this study were the first ever extruded from Ultem 1000 resin, the processing variables were not optimal, and consequently the heavier-walled 4-in. prototypes contained more defects than did the 1-in. prototypes.
2. The tensile strength of extruded pipe is somewhat less than that of specimens made from cast plaques. This is due to differences in processing and in the test specimens themselves.
3. In an aqueous environment, Ultem 1000 pipe will absorb water. The maximum weight gain was ~3%, which is about twice the value reported by GE.

4. The prototypic pipes contained defects that made it difficult to obtain consistent results from the CTL tests. Nevertheless, sufficient data were obtained on the 1-in. prototypes so that an estimate of the CTL resistance could be used in calculating a LTHS value for this material.
5. The poor quality of these prototypic pipes affected the results of the stress-rupture experiments. On the basis of limited results, the stress-rupture data indicate that the LTHS value at 350°F should not exceed 1000 psi.
6. The results of the experiments to determine the mechanical properties of Ultem 1000 pipe at 350°F led to an estimate of the hydrostatic design pressure rating for 2-in. SDR 11 pipe of 30 psig at 350°F. For saturated water, Ultem 1000 pipes would be limited to a maximum temperature of ~280°F, which corresponds to a design pressure rating of 35 psig.
7. Elevated-temperature pipe made from polyetherimide plastic, e.g., Ultem 1000, appears to be a viable alternative to steel because of its good mechanical properties and superior corrosion resistance. However, Ultem 1000 is now relatively expensive, and further research on production-quality pipe is required before a definitive conclusion can be reached as to the value of using this material in DH service.

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