228
9-9-80
JLB

Lh. 1723

MASTER

DEVELOPMENT OF A GLASS POLYMER COMPOSITE SEWER PIPE FROM WASTE GLASS

FINAL REPORT
FEBRUARY 1980

R. RAYFIEL AND L.E. KUKACKA

DEPARTMENT OF ENERGY AND ENVIRONMENT

BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

MASTER

DEVELOPMENT OF A GLASS POLYMER COMPOSITE SEWER PIPE FROM WASTE GLASS

**FINAL REPORT
FEBRUARY 1980**

R. RAYFIEL AND L.E. KUKACKA

**PROCESS SCIENCES DIVISION
DEPARTMENT OF ENERGY AND ENVIRONMENT
BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.**

**UNDER CONTRACT NO. DE-AC02-76CH00016 WITH THE
UNITED STATES DEPARTMENT OF ENERGY**

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$6.00; Microfiche \$3.00

CONTENTS

ABSTRACT.	v
FIGURES	vi
TABLES.	vii
EXECUTIVE SUMMARY	ix
I. INTRODUCTION	1
II. PROCESS DEVELOPMENT.	4
A. Bench Scale.	6
B. Pilot Plant and Field Trials	12
III. PROPERTIES AND SPECIFICATIONS.	22
A. Compressive Strength	25
B. Tensile Strength	25
C. Mold Release Stress.	27
D. Density.	29
E. ASTM Specifications.	32
IV. PROCESS AND EQUIPMENT.	40
A. Description of Process	40
B. Material and Energy Requirements	44
C. Selection of Equipment	46
V. CAPITAL COST	48
A. Bases.	48
B. Equipment List and Costs	48
C. Total Capital.	48
VI. OPERATING COST	52
A. Fixed.	52
B. Variable	52
VII. ECONOMICS.	56
A. Market Information	56
B. Return on Investment	56

CONTENTS (Cont'd)

VIII.	ENERGY CONSERVATION.	58
	A. GPC Requirements	58
	B. Comparison with Vitrified Clay Pipe.	60
IX.	SUMMARY AND RECOMMENDATIONS.	60
	A. Status of Process and Product Development.	62
	B. Economics.	62
	C. Problem Areas.	63
	D. Process and Product Improvements	64
	E. Energy Conservation.	64
	ACKNOWLEDGMENTS	64
	REFERENCES.	65

ABSTRACT

Brookhaven National Laboratory has developed a range of polymer-aggregate composites for applications in industry which appear to be economically attractive and contribute to energy conservation. Waste glass is the aggregate in one such material, which is called glass-polymer-composite (GPC). This report assays the economics and durability of GPC in piping for storm drains and sewers.

The properties of the pipe are compared statistically with the requirements of industrial specifications. These establish the raw materials requirements. The capital and operating costs for producing pipe are then estimated. Using published sales values for competing materials, the return on investment is calculated for two cases.

The ultimate energy requirement of the raw materials in GPC is compared with the corresponding requirement for vitrified clay pipe. The strengths of GPC, reinforced concrete, vitrified clay and asbestos cement pipe are compared after extended exposure to various media.

Finally the status of process and product development is reviewed and recommendations are made for future work.

FIGURES

1. Conceptual process flow diagram for the production of GPC sewer pipe.	5
2. Size distribution of glass fractions before milling	9
3. Size distribution of milled glass	14
4. Size distributions of glass used in high-strength runs.	15
5. Size distribution of synthetic glass mixtures	15
6. GPC test mold, 8 in. i.d., variable o.d. (assembly drawing) . .	17
7. GPC test mold (variable o.d.) and completed GPC pipe section. .	18
8. GPC pipe mold for life tests.	20
9. GPC pipe mold and section used for field trial in Newark, N.J..	21
10. GPC pipe run for installation in Amsterdam Avenue, Newark, N.J.	23
11. End sections used to adapt GPC to vitrified clay pipe	23
12. GPC pipe and adapter for installation in Parkhurst Street, Newark, N.J..	24
13. Mean and 90% confidence limits of data on three-edge-bearing strength of GPC pipe.	36
14. Life tests of pipe in water at 65°C (149°F): retention of bearing strength vs time.	41
15. Life tests of pipe in 5% aqueous sulfuric acid at ambient temperature	42

TABLES

1. Composition of GPC mix at start and end of program (nominal) . .	7
2. Composition and particle-size distribution of Bureau of Mines glass fraction.	7
3. Composition and particle-size distribution of Baltimore County/MES glass fraction	9
4. Size distribution of glass used in high-strength runs	14
5. Compressive strength of GPC made from mixtures of glass size fractions	15
6. Compressive strength of GPC with decreasing monomer content . .	26
7. Split tensile strength compared with monomer content and three-edge-bearing strength	26
8. Mold release properties of cylindrical samples.	28
9. Mold release properties of pipe samples	28
10. Density and compressive strength of cylindrical samples	30
11. Density and bearing strength of pipe samples.	31
12. Three-edge-bearing strength of GPC pipe with varying wall thickness.	34
13. Wall thickness of GPC pipe to meet ASTM specifications.	36
14. Retained strength of pipe after aging in circulating water at 65°C (149°F)	39
15. Retained strength of pipe after aging in 5% aqueous sulfuric acid at ambient temperature	39
16. Coefficients of life test equations for pipes in warm water and sulfuric acid	42
17. Design inputs of raw materials per ton of GPC pipe output, including losses.	45
18. Design bases for resource recovery plant and GPC addition . . .	49
19. Distribution of sizes in design product mix	49
20. Installed cost of process equipment, base case.	50
21. Capital cost summary, base case	53
22. Operating costs, base case.	53

TABLES (Cont'd)

23.	Application of the design product mix to determine size distribution for the base case.	55
24.	Estimated sales value of product, base case	57
25.	Simplified calculation of return on investment, base case	57
26.	Simplified calculation of return on investment, full scale plant.	59
27.	GPC pipe dimensions for comparison with vitrified clay pipe . . .	61
28.	Comparison of ultimate energy requirements for GPC and vitrified clay pipe	61

EXECUTIVE SUMMARY

The glass fraction of municipal solid waste is an inert aggregate which may be used in composites. A glass polymer composite (GPC) has been developed at Brookhaven National Laboratory (BNL).

One proposed application of this material in the public and private sectors is to make pipe for storm drains and sanitary sewers. The objectives of this BNL study were: (1) to determine whether this application is economically attractive, and (2) to compare the energy usage and durability of GPC pipe with those of conventional materials.

In preliminary work performed in 1972, GPC pipe was made by laboratory procedures. The initial economics were favorable. Later, a National Science Foundation program was employed to transfer the technology to industry.¹⁻³

In the present work, started in July 1976, the composition and procedures approached those which would be used in a full-scale plant. All of the properties which are involved in industrial specifications were measured. Strength specifications were exceeded at reduced wall thicknesses. Other specifications were also met with further modifications in procedures.

Samples of GPC and three other types of pipe were stored under water at 65°C (149°F) and under 5% sulfuric acid at ambient temperature. The percentage of strength retained was measured for periods up to about 10,000 hours. GPC appears to retain more of its strength in both media than vitrified clay, asbestos cement, and reinforced concrete. In the acid, for example, GPC still had 82.7% of its original strength after 10,300 hours, while concrete retained only 63% after 984 hours.

When the process and product were considered acceptable, piping was made for field trials and the economics were refined. Capital and operating costs were calculated for a plant which would be located at an existing resource recovery complex in Baltimore County and would produce about 6900 metric tons (7600 short tons) of pipe per year. For this example it would also be equivalent to about 93 kilometers, or about 58 miles of pipe. The capital cost would be \$1.65 million, in April 1979 dollars. If the entire output were sold, the return on the investment would be about 11% after taxes.

A new facility for resource recovery would probably reclaim most of the glass in about 907 metric tons (1000 short tons) of municipal solid waste per day. The GPC section of such a plant would make about 24,400 metric tons (about 27,000 short tons) of pipe per year. In that case the capital would be \$3.44 million in April 1979 dollars, and the return would be about 32% after taxes.

The manufacture of raw materials absorbs most of the energy used in making pipe. Compared with vitrified clay, GPC offers savings of from 2.8 to 30.2%, depending on the size of the pipe.

I. INTRODUCTION

The nation is exploring methods of recovering resources from its municipal solid waste. Our aims are to conserve energy, use less land for ultimate disposal, and reduce the hazards and nuisances associated with present methods.

About 10.5%, or 12.2 million metric tons (13.5 million short tons), of the municipal waste in 1975 was glass.⁴ Manufacture of this glass requires about 2.6×10^{17} joules (2.46×10^{14} Btu, or 0.25 quads).

There have been many efforts to separate this glass and to re-use it. At first, the intent was to produce cullet (crushed glass) which could be added directly to the raw materials that are charged to the glass furnace. Major problems arose: (1) a mixed-color cullet could only be charged in small amounts; (2) low concentrations of stones, refractories, and other contaminants caused trouble in the manufacture of containers. Electronic color sorting and flotation have been used to meet these objections, but their economics have not been proved.

Other proposed uses for waste glass do not require color sorting or high purity. These applications include foam glass, fiber glass and building brick. The Bureau of Mines has pioneered in these areas.⁵⁻⁷ The application described in this report also does not require a purified glass fraction.

Brookhaven has studied the repair and improvement of concrete by use of polymer concrete (PC). This material is a mixture of a monomer and an aggregate; after mixing, the monomer is polymerized to form a strong

chemically resistant composite. A logical extension of this work was to use finely divided waste glass as the aggregate to make a glass polymer composite (GPC).

This product proved to be stronger and more durable in acid environments than portland cement concrete. Therefore it was considered as a possible replacement for concrete pipe in storm drains and in sanitary sewers, where hydrogen sulfide and sulfuric acid can attack concrete rapidly.⁸

Lengths of 203-mm-(8 in.) inside diameter pipe were made in 1972. Test sections met the ASTM strength and leakage specifications. Ten lengths were installed in a sewer system in Huntington, Long Island. Arthur D. Little evaluated the economics of GPC pipe and found them attractive compared with those of asbestos cement, vitrified clay, concrete, and plastic.^{1,2}

In 1974, Teledyne National began the design and construction of a resource recovery plant for Baltimore County and the Maryland Environmental Service (MES). They decided to work with Brookhaven to continue evaluation of GPC pipe as a possible outlet for the glass fraction. The initial objective was to design a full-scale process to produce the pipe and to test its economics for the Maryland project. Before these could be conducted, further bench scale and pilot plant work was required. Upon completion of these tasks, preliminary design and cost calculations were carried out.

The initial conclusions were that at a diameter of ~ 300 mm (11.8 in.) GPC was competitive with reinforced concrete pipe and up to about 250 mm (10 in.) it was competitive with vitrified clay. On the basis of these encouraging results, Brookhaven and Teledyne National continued work in an attempt to increase the competitive range. To do this it was necessary to reduce the usage of energy-intensive monomers and other raw materials. This would conserve energy directly by lowering the requirement for GPC. It might also conserve energy by reducing the output of more energy-intensive piping.

ERDA and subsequently, the U.S. Department of Energy, Division of Industrial Energy Conservation, sponsored the continuation of the work to promote conservation. To help obtain acceptance of the results, they also specified that the statistical reliability of the data be determined. This report describes the work done to achieve both objectives.

GPC is made by milling glass to the desired range of particle sizes, mixing it with a monomer or mixture of monomers and additives, then polymerizing the monomer(s). To make test samples and pipe, the mixture is cast with vibration into a mold and polymerized in place.

Several potential problems were addressed early in the program. In earlier work the glass was in the form of bottles and other containers; included with the glass were caps, labels, and residual contents. In addition to these components, the glass fraction of municipal solid waste contains putrescibles and other organics, stones, ceramics, and metals other than container closures. The new components were expected to affect the behavior during milling and polymerization. Therefore, it was planned to use the glass from municipal waste as soon as it became available.

One of the persistent problems in manufacture of plastic parts is release of the finished part from the mold. At first, samples of GPC pipe were made in molds which were lined with Mylar sheets. This was too expensive for commercial use, so alternative procedures and materials were sought in this project.

To assemble a run of piping, the individual lengths must have ends which can be joined tightly in the field. The ends of previous GPC sections were machined to mate with an existing pipe run and with each other. This is also too expensive, so we decided to develop a mating joint and adapters to match existing types of pipe.

There were several reasons for obtaining additional data on the properties of GPC pipe. More measurements of three-edge-bearing strength were needed for acceptable confidence limits. All previous strengths were for about 200-mm (8 in.) pipe. Therefore, at least one larger size had to be tested to allow extrapolation of the results to the competitive range. Since the smallest size of reinforced concrete pipe is about

300-mm-(12 in.), sections of at least that size were needed for field trials and customer acceptance test.

The first cost calculations for GPC pipe were based on analogies with concrete pipe and on mix compositions which have been revised. The second set used preliminary process and equipment designs, but most equipment costs were factored estimates from published data. To improve accuracy in the present work, we obtained vendors' quotations on most of the process equipment.

GPC and competing materials are produced from raw materials which require high energy inputs (monomers, glass, portland cement, steel, fired clay). Aside from economics, one material might be preferred if its components require less ultimate energy. These energy inputs were compared over a range of pipe sizes and usages.

Data on the long-term stability of any new product are required by prospective users. There are no specifications in this area for piping. We set up tests in circulating water at 65°C and 5% sulfuric acid at ambient temperature. The three-edge bearing strengths before and after exposure were measured for GPC, reinforced concrete, asbestos cement, and vitrified clay pipe.

II. PROCESS DEVELOPMENT

The GPC process and product were studied at the laboratory bench and in the pilot plant. The conceptual flow diagram (Figure 1) was the basis for deciding which steps must be piloted. Fortunately, most of the operations are conventional and can be tested in the laboratory or designed by standard methods. In the bench work mix compositions and procedures were evaluated, using ultimate compressive strength and release properties as the main responses.

Full-scale pipe sections and pipe lengths were cast in the pilot work. Different types of size reduction equipment were tested. Operating data were obtained on the preferred sledge mill during preparation of glass for production of GPC.

Figure 1. Conceptual process flow diagram for the production of GPC sewer pipe.

A. Bench Scale

Most of the laboratory work was performed using 76.2-mm-i.d. (3 in.) cylindrical aluminum tubes about 152.4-mm (6 in.) long. For molds, one end of each cylinder was sealed by caulking it with silicone rubber to a sheet of heavy gauge aluminum. The internal surface of this mold was treated with a release agent, which was usually baked on.

Additives and initiator were dissolved in the mixed monomer. This solution was combined with the dried milled glass in a change-can mixer (ref. 9, pp. 9-14). The prepared molds were placed on a vibrating table and the wet mix was transferred to them with scoops. Vibration continued until liquid appeared at the top of the molds and most, if not all, of the air and vapor had bubbled out of the mix.

The tops of the molds were then covered with light gage aluminum foil to minimize evaporation. They were placed in an electrically heated oven at 82°C (180°F) to initiate and complete polymerization. Usually this took four hours.

After air cooling to room temperature, the cylindrical samples were pressed out of the molds on a strength-testing machine. This yielded the shear strength of the bond between the cured GPC and the treated wall of the mold. Design of the equipment for removal of the full-scale pipe from its mold depended on such release data.

The ends of the cured samples were sliced off to eliminate the collar of unfilled resin and the rough edge due to caulking. In some runs the cylindrical sample was measured and weighed to determine its density.

Usually the ultimate compressive strength of each sample was determined. Split tensile tests were made on some samples because in earlier attempts to measure the direct tensile stress, the grips had failed before the sample.

1. Composition of GPC Mix. As a result of process improvements made during the program, the overall composition of the GPC formulation changed as shown in Table 1. The most significant change is in the total percentage of monomers and additives, which fell from about 12.83 to 10.27%.

Table 1
Composition of GPC Mix at Start and End of Program (Nominal), wt%

Run No.	257	342
Milled glass, wt%*	87.173	89.731
Styrene**	10.067	8.308
Polyester PPG-50293	1.868	--
Polyester PPG-50071	--	1.246
Polyester GR-13024	0.519	--
Polyester GR-13023	--	0.415
Initiator BPO-98	0.124	0.100
Bonding agent Silane A-174	0.124	0.100
Internal release agent Zelec UN	0.124	0.100
Total	99.999	100.000

*The basis for all percentages is the total weight of the GPC mix. This differs from the Brookhaven log, where percentages were sometimes based on the weight of the monomer or glass plus monomer.

**This is the percentage of styrene added as styrene; it does not include the styrene solvent of the polyesters.

Table 2
Composition and Particle Size Distribution
of Bureau of Mines Glass Fraction

Component		Wt%
Glass		88.90
Metal		0.09
Stones, ceramic, clay, dust		10.94
Organic		0.07
Total		100.00

Tyler sieve size, in.	U.S. Sieve, mm	Wt%
+3/8	+9.51	1.20
+4	+4.76	4.11
+6	+3.36	10.82
+8	+2.38	15.33
+10	+2.00	14.63
+14	+1.19	14.84
+20	+0.841	11.12
+28	+0.595	10.22
+35	+0.420	7.92
+48	+0.297	5.31
+65	+0.210	2.30
Pan	-0.210	2.20
		100.00

This improved the overall economics and energy conservation of GPC. New information was developed on the monomer requirement and on other components of the mix.

2. Characteristics of the Glass Fraction. Two sources of waste glass were used. Both originated in the municipal solid waste of Baltimore County, Maryland. One was separated in the Bureau of Mines pilot plant at Edmonston, Maryland, which uses a mineral jig (ref. 9, pp. 21-50). The other was separated in the Baltimore County/MES Secondary Separation facility in Cockeysville, Maryland, which uses an air table (ref. 9, pp. 21-51). The Bureau of Mines product had the composition and size distribution shown in Table 2. The size distribution is plotted in Figure 2.

The composition and size distribution of the Baltimore County/MES glass are shown in Table 3 and Figure 2. This glass was purer and contained less fines. To be conservative, it was used as the feed for design purposes. However, there was no noticeable difference in strength of the final product which was made from the two sources of glass.

Incoming glass was dried overnight (or longer) in an oven at 105°C (221°F). It was milled in a Sturtevant sledge mill and stored in open 55-gallon drums. This size reduction step and the required particle size range will be described in Section II-B.

At one point, because of an apparent erratic variation of the compressive strength of the GPC, some of the milled glass was redried and its performance compared with that of the stored glass. The ultimate compressive strengths, based on the average of four samples, are tabulated below.

Run No.	Glass status	Average ultimate compressive strength,	
		MPa	psi
336	Stored, redried	89.3	12,952
337	Stored, redried	74.7	10,833
338	Stored, not redried	49.3	7,153
339	Stored, not redried	19.3	1,794

Figure 2. Size distribution of glass fractions before milling.

Table 3
Composition and Particle-Size Distribution of
Baltimore County/MES Glass Fraction

Component		Wt%
Glass		95.62
Ceramics		1.03
Metals		0.21
Putrescibles		0.21
Plastic		0.06
Stones		2.87
Total		100.00

U.S. sieve size	mm	Wt%
+4	+4.76	8.81
+8	+2.38	25.66
+20	+0.841	58.17
+30	+0.595	6.51
+40	+0.420	0.62
+60	+0.250	0.06
Pan		0.17
		100.00

This indicated that the drop in strength might have been due to moisture. To determine whether the milled glass fraction would absorb moisture in storage, a dried sample of the -100 mesh fraction was stored in an open beaker in the laboratory for three months. The original moisture content (before drying) was 0.16%. During the storage period, the relative humidity varied between 49 and 72%. The final moisture content was 0.23%. This amount of adsorbed water could reduce strength by preventing formation of a strong bond between polymer and glass, by vaporizing during polymerization and producing voids, or by other mechanisms. It is important to mill dried glass and incorporate it in GPC as soon as possible.

3. Monomer Content of GPC Mix. The largest part of the cost of GPC pipe is the cost of the chemical raw materials. This in turn is sensitive to the monomer content of the mix and the wall thickness which is required to meet specifications. The wall thickness was determined by statistical methods applied to data on sections of varying diameter. Sufficient time was not available to follow this procedure on monomer content. However, the laboratory data showed little or no increase in ultimate compressive strength above 10.27% monomer and additives. (These data are summarized in Section III-A, Compressive Strength). Therefore, this monomer content was adopted for life tests.

4. Stabilization of Monomers. Tertiary-butyl catechol is added to industrial styrene to inhibit polymerization in shipment and storage. The concentration of inhibitor may be 12 or 50 parts per million. This concentration and possibly the moisture content of the styrene may affect the strength of the GPC.

In Run 328, the styrene contained 50 ppm of inhibitor and the average compressive strength was 55.0 MPa (7976 psi). Styrene from the same batch was passed through activated alumina to remove the original inhibitor and an amount equivalent to 12 ppm was added. This styrene was used in Runs 329 and 330; otherwise all components of the mix were the same as in Run 328. The average strengths were 63.4 and 76.6 MPa (9195 and 11112 psi).

Our conclusion is that styrene containing 12 ppm of inhibitor should be specified for GPC. However, there is some uncertainty because activated alumina also removes water from styrene, and adsorbed water in the glass also reduces the strength of GPC. In a full-scale plant the storage period for styrene would be minimized, so the lower concentration of inhibitor would not be likely to cause any losses.

On the other hand, some low strengths may have been caused by use of overage styrene or polyesters. This is also less likely to occur in a full-scale plant.

5. Characteristics of Polyesters. The earlier Pittsburgh Plate Glass polyester (PPG-50293) was chosen for its low viscosity and easier mixing. Since the later version (PPG-50071) contains less styrene, its viscosity is higher and its advantage is questionable.

Both of the resins from Grace Chemical (GR 13023 and 13024) contain a low profile additive. This cures with a smoother surface, which improves mold release. The additive is a polymer, and we tried introducing some polymers as part of the mix, but the results were poor.

6. Initiators and Additives. Benzoyl peroxide (BPO) and methyl ethyl ketone peroxide (MEKP) are satisfactory polymerization initiators. A solid form of BPO was chosen for design because of its low cost and ease of handling.

To bond the inorganic glass to the organic polymers, an agent with some characteristics of both phases is needed. Silane (A-174) or a similar compound is needed to give acceptable strengths. Liquids, soluble in the monomer but not in the polymer, are used as internal release agents. They leave the solid phase when it cures and form a lubricating film on the surface. Addition of 0.1% of DuPont's Zelec UN gave a 27% reduction in the shear strength of the bond between GPC and mold in Runs 303 and 304.

Varying percentages of all three of these compounds (initiators, bonding agent, and internal release agent) have been tried. The final recommendations of 1% (based on total weight of monomer) or 0.0997% (based on total weight of GPC) are not necessarily optimum but are believed to be conservative.

At the end of the project one additional additive and a procedure were tried. The additive was a wetting agent (Triton 100). The procedure was to reduce the pressure (to about 33,788 pascals absolute or a vacuum of 20 inches of mercury) over the GPC mix for about 5 minutes. Both the wetting agent and the vacuum improved the compressive strength. Sufficient data have not been obtained to incorporate either improvement in the design at this stage.

7. External Release Agents. In addition to the low profile resin and the internal release agent, a liquid external release agent was applied to the mold before it was filled with the GPC mix. This film was usually baked on and was always cooled before casting the mix. In some cases it lasted through several uses of the mold.

The best three agents from previous work were compared in Run 305. The shear strength of the GPC-mold bond was lowest (50,056 pascals or 7.26 psi) for Frekote 33. Bond strengths for the other agents averaged 172 and 173% higher. Although Frekote is more expensive, the increase in total cost is not significant, so Frekote was specified in design.

B. Pilot Plant and Field Trials

Methods of milling the raw glass were tested at the plant of an equipment vendor (Sturtevant). On the basis of these tests, a sledge mill was selected and installed at Brookhaven, where most of the glass was ground and where the rate of wear of the hammers was determined.

The pilot work at Brookhaven used three molds for production of pipe. Two were used for 304.8-mm-long (12 in.) sections with an inside diameter of 203.2-mm (8 in.), the other for 1524-mm-long (5 ft) lengths, including end joints, of 304.8-mm (12 in.) inside diameter. Monomer solutions were made in glassware, as in the bench scale work. Vibration required more powerful means than before. Release of the 203.2-mm (8 in.) sections was carried out on a strength-testing machine to obtain additional design data. Three edge-bearing strengths, before and after exposure to life test media, were determined for the 203.3-mm-i.d. (8 in.) sections. Most of the 304.8-mm-i.d. (12 in.) lengths were reserved for field trials.

1. Size Reduction of the Glass Fraction. In the earlier phase of this work a hammer mill in the pilot plant at Mikropul Corporation was used. In one pass through this mill, the size distribution shown in Figure 3 was obtained which produced GPC with adequate strength, but Mikropul concluded that the wear on hammers was too severe for them to recommend the equipment. Other methods to approach the same size distribution were then sought.

Rolls crushers were tried at the Bureau of Mines facility in Edmonston, Md., and later at the pilot plant of Sturtevant Corporation. The first output approached the required distribution, but hard particles that lodged between the rolls after a short period increased the clearance. As a result the product became too coarse.

A sledge mill at Sturtevant gave particle-size ranges that straddled the distribution obtained earlier at Mikropul (see Figure 3). This mill was subsequently purchased for use with a 1.6-mm (1/16 in.) bar grate at Brookhaven.

As a result of these observations, the particle size was monitored more frequently. The results of runs which gave good compressive strength for known size distributions are shown in Table 4 and plotted in Figure 4.

A series of experiments were made in which the size distribution was varied while all other variables were held constant. Monomer concentration was at the design value, the glass was dried just before use, and the styrene contained only 12 ppm of inhibitor. The size distributions and compressive strengths are displayed in Table 5 and in Figure 5.

All of these size distributions fell within the envelope of high strength distributions shown in Figure 4. All made satisfactory GPC. Runs 344 and 345 may approach an optimum size distribution: higher percentages of fines in the other runs gave reduced strengths. The envelope of distributions in Figure 4 is considered a valid guideline for milling glass for GPC.

To keep the output within this range required frequent replacement or refacing of the hammers in the mill. To estimate the operating cost, data were obtained on the rate of wear.

Figure 3. Size distribution of milled glass.

Table 4
Size Distributions of Glass Used in High-Strength GPC Runs

Run	Average ultimate compressive strength		Wt% on U.S. Screen Size						
	MPa	psi	20	30	40	80	100	140	Pan
276	131.8	19,115	4.04	6.34	11.62	39.50	3.48	10.62	24.5
278	103.5	15,016	9.09	10.44	13.28	31.46	3.01	8.73	23.99
279	94.5	13,704	8.46	9.06	12.89	30.98	3.23	9.02	26.35
280	83.7	12,134	17.94	14.68	14.94	27.55	2.74	6.33	16.04
286	84.9	12,310	20.36	14.71	13.71	25.98	3.08	6.25	15.91
287	88.9	12,897	8.79	10.08	12.87	30.92	3.05	8.22	26.07
292	105.7	15,329	13.56	12.60	13.50	27.55	3.13	7.10	22.46

Figure 4. Size distribution of glass used in high strength runs.

Figure 5. Size distribution of synthetic glass mixtures.

Table 5
Compressive Strength of GPC Made from Mixture of Glass Size Fractions

Run	Average ultimate compressive strength		Wt% on U.S. Screen Size					
	MPa	psi	20	30	40	80	100	Pan
343	96.6	14,009	12	12	10	30	3	33
344	110.4	16,008	13	13	12	28	4	30
345	112.2	16,275	14	14	13	26	5	28
346	98.2	14,241	5	7	12	38	3	35

The present mill is a Sturtevant Model OOSM 25, belt driven at about 2300 rpm by a 7-1/2-hp motor. The hammers are low alloy steel, Hiten B-3, containing 0.6% carbon and 0.6% manganese, hardened to 50-55 Rockwell. At a feed rate of about 816.3 kg/hr (1800 lb), one set will mill a total of about 1360 kg (3000 lb) to the acceptable range. The design feed rate is slightly higher, but at present it is assumed that the hammers wear at the same rate per unit weight of feed.

Teledyne National tried to increase the operating life of the hammers by facing a set with a harder alloy. Small cracks appeared on cooling and there was no apparent increase in life. Sturtevant suggests a shorter hammer, of low carbon steel, to allow for more facing with less likelihood of cracking. There has been no opportunity or time to test this alternative.

2. Pipe of Varying Wall Thickness. A pipe mold was designed with a single inner sleeve and three interchangeable outer sleeves. This made it possible to fix the inside diameter of the GPC pipe at 203.2 mm (8 in.) while selecting an outside diameter of 235.0, 254.0 or 279.4 mm (9.25, 10.00, or 11.00 in.). The mold (Figures 6 and 7) was made of aluminum and suffered distortion when release was difficult. In future work the mold parts which are stressed during release should be made of stainless steel.

The weight of the filled molds exceeded the capacity of the table vibrator. To supplement the tables, pneumatic units supplied by the Martin Concrete Engineering Company were attached to the base and top plate of the mold with C-clamps.

Curing time at 82°C (180°F) was increased to 5 to 6.5 hours. All other procedures were the same as those used for the cylindrical laboratory samples. The strength data which were measured on the pipe sections are discussed in Section III.

3. Pipe for Life Tests. The data obtained by varying the outside diameter were used to calculate the wall thickness of 203.2-mm-i.d. (8 in.) pipe which was needed to meet industrial specifications. This was necessary because results of life tests depend on penetration by the

Figure 6. GPC test mold, 8 in. i.d., variable o.d.

Figure 7. GPC test mold (variable o.d.) and complete GPC pipe section.

est media, and the effect of penetration is a function of wall thickness. The calculated thickness of 19.0 mm (3/4 in.) was incorporated in a stainless steel mold (Figure 8). The procedure for making pipe in this mold was similar to that used with the mold of variable wall thickness. When it was found that the product often failed the hydrostatic test, improved vibration was obtained by coupling an electric finger vibrator to the mold in addition to the pneumatic units.

Two media were used for life tests: water at 65°C (149°F) and 5% aqueous sulfuric acid at ambient temperature. The water bath was in a stainless steel vessel. Steam was sparged in through a temperature control valve. The water in the bath was continuously pumped from bottom to top to prevent stratification. This also had the effect of removing the boundary layer around the test pieces and maximizing the effects of exposure. The sulfuric acid bath was in glass battery jars; the acid content was occasionally corrected for evaporation.

Fifteen-cm-long (6 in.) sections of GPC, reinforced concrete, vitrified clay, and asbestos cement pipe were compared. The three-edge-bearing strengths of three control samples of each were determined. Then the ends of the remaining sections were coated with epoxy to minimize penetration. (This was done because cut ends would not normally be exposed to media in use, and any penetration at the ends in these tests might give misleading results.) The sections were immersed in the baths with identifying tags, removed at scheduled times, and broken in the three-edge tests. The results are described in Section III.

4. Pipe for Field Trials. GPC pipe has been tested in the field since October 1972, when about 10.7 m (35 ft) of 203.2-mm- i.d. (8 in.) pipe was installed in a sewage system in Huntington, New York. Visual inspections have not shown any failures or other problems. However, the composition of the GPC and its method of manufacture differ from those now in use.

In December 1975, a 3.1 m (10.0 ft) section of 304.8-mm- i.d. (12 in.) pipe was installed in an industrial sewer on Amsterdam Avenue in Newark, New Jersey. One section of the pipe and the steel-aluminum mold used in fabrication are shown in Figure 9.

Figure 8. GPC pipe mold for life tests.

Figure 9. GPC pipe mold and section
used for field trial in Newark, N.J.

The charge for this mold exceeded the capacity of the change-can mixer, so a concrete mixer was used instead. The mold was suspended from a hoist and filled with the aid of three pneumatic vibrators. (In future work a finger vibrator, like the one which was used later on the life test mold, would probably speed filling and reduce porosity.)

The mold was cured in an 82°C (180°F) oven for six hours or longer. On removal from the oven, the inner sleeve was sprayed with cold water until it shrank away from the GPC (there was an audible crack). The inner sleeve could then be hoisted out of the mold. Jack screws and hydraulic jacks were used to separate the GPC pipe from the rest of the mold.

The two pipe sections were adapted at the ends to vitrified clay pipe of the same inside diameter. Figures 10 and 11 show the finished pipe and adapters.

Originally the waste water in the Amsterdam Avenue line had a pH of about 5.4 (weakly acidic). However, the process which made the acid effluent was moved to another plant, and the pH became 7.4 (slightly alkaline.)

In September 1976 and April 1978, the Amsterdam Avenue piping was inspected internally with a television camera. There was no evidence of pipe distortion or failure, infiltration through the joints, or leakage through the pipe wall itself.

To subject the GPC to acid conditions, a new site was selected at Parkhurst Street in Newark, New Jersey. Two sections and an increaser-adapter were installed in June 1978 (Figure 12). The pH of the effluent is 2.4. This section of pipe has not been inspected, but the Newark Engineering Department had not received any complaints as of August 1979.

III. PROPERTIES AND SPECIFICATIONS

Some properties of GPC, its raw materials, and the intermediate process streams must be known for design of the process and its equipment. Values of other properties must be measured to check conformance with specifications.

Figure 10. GPC pipe run for installation
in Amsterdam Avenue, Newark, N.J.

Figure 11. End sections used to adapt GPC to vitrified clay pipe.

Figure 12. GPC pipe and adapter for installation
in Parkhurst Street, Newark, N.J.

In some cases a property value is useful for control purposes. It is impractical to destroy all the output by measuring its three-edge-bearing strength. Instead some other property, which can be measured quickly on a small sample, may indicate whether the bearing-strength value will be satisfactory.

There are other properties which may be of interest to producers and consumers. For example, although there is no consensus on methods of measuring probable length of service, it is desirable to have comparative values. And some properties, like tensile strength, may suggest new uses for the product.

A. Compressive Strength

This property was determined during 88 runs in the course of this program. Usually there were three or four samples per run and the strengths were averaged. The results are summarized in Table 6 as averages of the run averages.

There are no consistently higher strengths at concentrations above 10.0% monomer, and there is apparently no justification to go lower. There is some indication of an optimum concentration of monomer as reported previously.¹⁰ Based on the total weight of the GPC mix, it leads to the concentration of 10.27% monomer and additives which is the current design basis.

B. Tensile Strength

When samples were tested in direct tension, the grips failed before the samples. Split tensile strengths were measured instead, and comparatively few values were obtained. This property is not related directly to the anticipated mode of failure in buried low-head pipelines. However, it might be of interest if GPC is proposed for pressure piping.

The tensile splitting results are given in Table 7, in order of increasing strength. They are compared with the failure stress in three-edge bearing, when it is known. The method of calculating this latter stress will be described in Section III-E-1, of this report. There is no apparent correlation with any of the other variables.

Table 6
Compressive Strength of GPC With Decreasing Monomer Content

Wt% of monomer, glass + monomer basis	Ultimate compressive strength,		No. of runs
	MPa	psi	
15.4	52.8	7660	1
14.9	59.8	8675	1
13.7	99.0	14,364	5
13.0	79.8	11,572	2
12.5	61.4	8908	29
12.4	35.9	5202	1
12.3	98.8	14,326	1
12.1	52.7	7650	1
11.75	60.8	8814	8
11.6	48.0	6938	1
11.5	62.5	9064	2
10.8	38.6	5602	2
10.3	40.3	5840	1
10.2	67.9	9844	1
10.0	71.7	10,398	27
9.5	37.7	5468	3
9.25	37.3	5404	1
8.5	70.3	10,198	1

Table 7
Split Tensile Strength Compared With Monomer Content
and Three-Edge-Bearing Strength

Run No.	Wt% monomer, glass + monomer basis	Split tensile strength,		Three-edge- bearing strength,		Failure stress in three-edge bearing,	
		MPa	psi	Newton	lb	MPa	psi
				m-mm	ft-ft		
270	12.5	4.12	597	--	--	--	--
316	9.5	4.97	721	205.6	4294	22.3	3240
282	11.75	5.07	735	686.3	14333	18.6	2704
312	13.0	5.23	759	--	--	--	--
272	12.5	6.54	948	--	--	--	--
271	10.8	7.05	1023	111.9	2337	17.5	2539
297	12.1	7.09	1028	77.5	1619	12.1	1759
310 CD	11.6	8.42	1221	--	--	--	--
269	15.4	9.78	1419	122.6	2561	19.2	2782
298	13.7	11.9	1729	113.0	2360	17.7	2564
279	13.7	12.1	1759	696.4	14544	18.9	2743
311	13.0	13.1	1897	--	--	--	--
309	11.5	13.5	1958	--	--	--	--
278	13.7	13.8	2005	138.0	2883	21.6	3132
299	12.3	14.4	2087	699.0	14600	19.0	2754
276	13.7	16.8	2438	169.8	3546	26.6	3853

C. Mold Release Stress

This property is a function of some variables which we did not measure or record: smoothness of metal surfaces, taper of mold (if any), and number of pulls per coating. There is an additional complication in comparing releases between cylindrical and pipe samples: shrinkage of the GPC during polymerization may make release of the core harder and release of the outer pipe surface easier.

To simplify the comparison, values for cylindrical samples are summarized separately in Table 8, in order of increasing shear stress. In all cases Frekote 33 was applied to the mold and Zelec UN was dissolved in the monomers at a concentration of 1.0% by weight, based on the total weight of monomers. The ratios of the individual monomer concentrations to each other were constant, assuming the vendors' polyesters did not change chemically during this period.

There is no strong correlation of the release stress with monomer content or strength in compression for cylindrical samples. Qualitatively lower monomer content (down to 10%) and higher strength lead to improved release.

Table 9 shows release data for pipe samples. All of the constant conditions for the cylindrical samples were also fixed for the pipes. The effect of shrinkage of the GPC is evident in all runs except No. 302. There is some indication of a correlation of higher compressive strength with improved release, but no noticeable correlation with monomer content.

For design purposes we have assumed that the core would be chilled with water to break the inner bond. To separate the shell from the pipes which contained 10.0% monomer required an average shear stress of 3654 MPa (0.53 psi). For the largest pipe made (1219-mm or 48-in. i.d.), it would take a force of 5.6 MT (6.2 short tons) to release the shell. A hoist with a capacity of 7.3 MT (8 short tons) was used in design. This is based on the assumption that we would get more reproducible stresses in a continuously operated plant and that they would be at the lower end of the range.

Table 8
Mold Release Properties of Cylindrical Samples

Run No.	Wt% monomer, glass + monomer basis	Ultimate compressive strength,		Shear strength of bond, GPC to mold,	
		MPa	psi	Pa	psi
336	10.0	89.3	12952	36267	5.26
310 EF	8.0	--	--	36956	5.36
340	10.0	70.7	10249	45023	6.53
310 AB	12.5	46.3	6712	48057	6.97
341	10.0	83.9	12168	48126	6.98
305 1A, B	12.5	66.1	9588	50056	7.26
310 C, D	11.6	48.0	6958	59157	8.58
334	10.0	66.4	9631	67569	9.8
307 E, F	12.5	50.5	0190	111834	16.22
313 H, I	8.5	70.3	10198	115005	16.68
308 C, D	12.5	52.1	7555	125348	18.18
308 E, F	12.5	53.5	7760	137965	20.01
312	13.0	69.5	10085	141068	20.46
307 C, D	12.5	52.8	7652	151548	21.98
313 F, G	10.0	71.3	10345	160925	23.34
313 A, B	11.5	51.9	7528	174576	25.32
307 A, B	12.5	52.8	7662	179747	26.07
306 1, 2, 3	12.5	67.5	9789	233458	33.86
308 A, B	12.5	59.1	8568	235113	34.10
306 4, 5, 6	12.5	65.6	9514	302061	43.81

Table 9
Mold Release Properties of Pipe Samples

Run No.	Wt% monomer, glass + monomer basis	Ultimate compressive strength,		Shear strength of bond, GPC to mold,			
		MPa	psi	Core		Shell	
				Pa	psi	Pa	psi
312	13.0	69.5	10085	46264	6.71	32819	4.76
325	10.0	73.0	10586	78463	11.38	2620	0.38
338	10.0	49.3	7153	115143	16.7	5378	0.78
324	10.0	72.4	10508	116040	16.83	483	0.07
318	9.5	35.3	5115	120383	17.46	276	0.04
264	13.7	60.1	8722	126864	18.4	13790	2.0
335	10.0	33.4	4852	131691	19.1	3034	0.44
326	10.0	67.9	9844	141274	20.49	7446	1.08
339	10.0	19.3	2794	234423	34.0	3103	0.45
315	9.52	52.4	7594	460021	66.72	41162	5.97
316	9.50	25.5	3695	463882	67.28	260623	37.80
301	12.4	35.9	5202	475741	69.0	12066	1.75
302	10.3	40.3	5840	571579	82.9	1054215	152.9
342	10.0	57.7	8371	717059	104.0	315782	45.8

D. Density

If there were no voids in GPC, its density would be a function of the polymer content and the densities of the individual phases. The density of the polymer has been measured at about 1.06 g/cm³ (66.0 lb/ft³). Common glass ranges from 2.4 to 2.8 g/cm³ (150.0 to 174.7 lb/ft³). Using the higher figure, to allow for metallic contamination, the average density may be expressed as:

$$\rho_{av} = \frac{18477.9}{108.7M + 6600} \quad \text{g/cm}^3 \quad (1)$$

$$= \frac{1153020}{108.7M + 6600} \quad \text{lb/ft}^3, \quad (2)$$

where M is the weight percent of monomer and additives in the mix, based on total weight of glass, monomer, and additives. For monomer contents in the experimental range, the calculated densities are

M, wt%	9	10	11	12	13
ρ_{av} , g/cm ³	2.44	2.40	2.37	2.34	2.31
lb/ft ³	152.2	150.0	147.9	145.9	143.9

The actual densities are always lower than the calculated values, indicating that voids are present. Instead of decreasing as the monomer content increases, the densities tend to increase. The reason may be that the additional monomer is likely to fill more of the voids.

The densities of cylindrical samples are listed in Table 10 in order of increasing monomer content. The ultimate compressive strengths are included. Both the density and the strength go through minimums at about 10.8% monomer.

Similarly the densities of pipe samples are shown in Table 11 in order of increasing monomer content. The three-edge-bearing strength and the calculated failure stress in three-edge bearing are also listed for comparison. The pipe densities are close to those of the cylinders, but the minimum in the failure stress appears at a higher monomer content.

Table 10
Density and Compressive Strength of Cylindrical Samples

Wt% monomer, glass + monomer basis	Run No.	Ultimate compressive strength,		Density,	
		MPa	psi	g/cm ³	lb/ft ³
10.0	333 A, B	53.2	7712	1.702	106.2
	334	66.4	9631	1.784	111.3
	333 C, D	68.2	9897	1.844	115.1
	337	74.7	10833	1.923	120.0
	340*	69.8	10122	2.000	124.8
	343	96.6	14009	2.037	127.1
	346	98.2	14241	2.042	127.4
	344	110.4	16008	2.045	127.6
	347	93.8	13604	2.046	127.7
	330	76.6	11112	2.067	129.0
	349	99.6	14453	2.070	129.2
	336	89.3	12952	2.072	129.3
	332 A, B	40.2	5828	2.086	130.2
	348	97.6	14148	2.086	130.2
	332 C, D	39.5	5728	2.090	130.4
	345	112.2	16275	2.102	131.2
	329	63.4	9195	2.147	134.0
	340	70.7	10249	2.296	143.3
	341	83.9	12168	2.343	146.2
	Average	79.1	11482	2.041	127.4
10.8	274	40.2	5838	1.768	110.3
	271	37.0	5367	1.836	114.6
Average		38.6	5602	1.802	112.4
12.5	258 A	47.0	6814	1.920	119.8
	257 B	51.4	7451	1.936	120.8
	257 A	55.8	8094	1.952	121.8
	258 B	41.6	6029	1.965	122.6
	275	119.9	17394	2.264	141.3
Average		63.1	9156	2.007	125.3
13.7	279	94.5	13704	2.146	133.9
	276	131.8	19115	2.292	143.0
	278	103.5	15016	2.312	144.3
	298	105.2	15261	2.348	146.5
Average		108.8	15774	2.275	141.9

*The low density samples of Run 340 were cast in glass, the high density ones in aluminum molds.

Table 11
Density and Bearing Strength of Pipe Samples

Wt% monomer, glass + monomer basis	Run No.	Three-edge- bearing strength,		Failure stress in three-edge bearing,		Density,	
		Newton's m-mm	lbs ft-ft	MPa	psi	g/cm ³	lb/ft ³
10.8	274	102.4	2138	16.0	2323	1.768	110.3
	271	111.9	2337	17.5	2539	1.836	114.6
Average		107.2	2238	16.8	2431	1.802	112.4
11.75	283	236.4	4938	14.4	2096	2.002	124.9
	282	686.3	14333	18.6	2704	2.034	126.9
	296	282.2	5895	17.2	2502	2.083	130.0
Average		401.6	8389	16.7	2434	2.040	127.3
12.0	268	271.0	5661	16.6	2402	1.954	121.9
12.1	297	77.5	1619	12.1	1759	2.287	142.7
12.3	299	699.0	14600	19.0	2754	2.128	132.8
13.7	279	696.4	14544	18.9	2743	2.146	133.9
	276	169.8	3546	26.6	3853	2.292	143.0
	278	138.0	2883	21.6	3132	2.312	144.3
	298	113.0	2360	17.7	2564	2.348	146.5
		309.2	6459	18.9	2744	2.210	137.9
Average							
15.4	269	122.6	2561		2782	1.960	122.3

E. ASTM Specifications

To gain acceptance, GPC pipe must meet the standards which apply to competing materials. These are included in the 1978 Annual Book of ASTM standards, Part 16.¹¹

Up to and including 381-mm-i.d. (15 in.), vitrified clay pipe is in common use for acid effluents. Sulfur compounds in sewage are oxidized to acids under some conditions, and vitrified clay is often specified for these cases also. The relevant standards are

C 700-77 Standard Specification for Vitrified Clay Pipe, Extra Strength, Standard Strength, and Perforated

C 301-78a Standard Methods of Testing Vitrified Clay Pipe

At larger sizes, especially where heavy loads are expected, reinforced concrete is called for. The standards are

C 76-77 Standard Specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe

C 497-77 Standard Methods of Testing Concrete Pipe, Sections, or Tile

For small and medium sizes, asbestos cement pipe is a third alternative. Its use is governed by the following standards:

C 428-77a Standard Specification for Asbestos-Cement Nonpressure Sewer Pipe

C 500-77 Standard Methods of Testing Asbestos Cement Pipe

There are several more ASTM specifications for low-pressure pipe and culvert. All of them are less stringent or depend on separate agreements between buyer and seller. If GPC pipe is made to conform with the specifications listed above, it should also meet the provisions of the other specifications.

1. Three-Edge Bearing. This is also called the external load crushing strength. A test specimen of piping is supported horizontally on two hard, rigid bearing strips which are parallel to its longitudinal axis. The length, spacing and other characteristics of the strips are specified. Vertical load is applied through a bearing block on top of the pipe section, also aligned parallel to the longitudinal

axis. The load is increased at a specified rate. When it produces a 0.3 mm (0.01 in.) crack, and again when the pipe fails completely, the size of the load is recorded. The larger of these loads is called the ultimate load, or D_{ult} . It may be expressed in lb (force) per linear foot per foot of diameter or in newtons per linear meter per millimeter of diameter.

One of our main tasks was to determine the wall thickness of GPC pipe needed to meet the specified values of D_{ult} for all sizes. We combined two methods to do this.

The first method was statistical. Samples of GPC pipe were made with constant inside diameter (203.2 mm or 8 in.) and varying wall thickness (15.9, 25.4, and 38.1 mm or 5/8, 1, and 1-1/2 in.), as described in Section II-B-2 above. The values of D_{ult} for all samples are given in Table 12.

For each of the three wall thicknesses, the limits of the 90% confidence interval were calculated. These compare with the mean values as shown below.

Wall thickness,		Three-Edge-Bearing Strength, D_{ult}					
		Newtons/mm-m			lb/ft-ft		
<u>mm</u>	<u>in.</u>	<u>Upper</u>	<u>Mean</u>	<u>Lower</u>	<u>Upper</u>	<u>Mean</u>	<u>Lower</u>
15.9	5/8	155.5	140.0	124.4	3248	2923	2598
25.4	1	301.9	283.4	265.1	6305	5920	5536
38.1	1-1/2	704.6	693.9	683.2	14717	14492	14268

To extrapolate these results to pipe with higher diameters, a different method was used. The following dimensional equation for the three-edge-bearing strength is adapted from one cited by Lindstrom and Milgrom²:

$$D_{ult} = \frac{37.7 S_{failure} t^2}{R^2}, \quad (3)$$

where

D_{ult} is in lb (force)/ft length-ft i.d.,

$S_{failure}$ is the failure stress in lb (force)/in.²,

t is the wall thickness in inches,

R is the inside radius in inches.

Table 12
Three-Edge-Bearing Strength of GPC Pipe With Varying Wall Thickness

Specimen size, 12 in. long x 8 in. i.d. Test procedure, ASTM C-497					
Batch No.	Wall thickness, in.	Three-edge-bearing strength, lb/ft _L -ft _{i.d.}	Mean	Standard deviation	Coefficient of variation
276	0.625	3510			
		3582			
278		3010			
		2870			
		2770			
298		2051			
		2670			
Entire series			2923	522	0.18
283	1.0	4656			
		4808			
		5349			
286		6159			
		6036			
		6609			
292		6810			
		7011			
296		5727			
		5602			
		6356			
Entire series			5920	776	0.13
279	1.5	14703			
		14587			
		14340			
282		14714			
		13915			
		14370			
		15341			
		14153			
		14308			
Entire series			14492	410	0.03

In metric units, the equation becomes

$$D_{ult} = \frac{261.8 S_{failure} t^2}{R^2},$$

Where

D_{ult} is in newtons/meter length-mm i.d.,

$S_{failure}$ is in megapascals,

t is in mm,

R is in mm.

The inside radius is constant at 101.6 mm (4 in.) in the runs with variable wall thickness. Therefore, a logarithmic plot of the three-edge-bearing strength as ordinate against the wall thickness as abscissa should be a straight line with a slope of 2.0. The mean and limiting values of D_{ult} are plotted in Figure 13. When a straight line of the proper slope is drawn through the ranges of the confidence limits, as shown, the failure stress can be calculated by substituting data for wall thickness and strength.

The calculated failure stress in three-edge bearing is 18.4 MPa (or 2675 psi). This value was used to calculate the required wall thicknesses of all sizes of GPC pipe. It compares with an average failure stress of 22.3 MPa (3240 psi) and a minimum of 19.5 MPa (2830 psi) for Run 316, which is close to the design composition.

For each pipe size the specified three-edge-bearing strength, the inside radius, and the failure stress were substituted in Eq.(3) and the wall thickness was calculated. The resulting thickness was then rounded off to a common fraction of an inch, as shown in Table 13. Six to 15-in. i.d. sizes were selected by reference to the specification for extra strength vitrified clay pipe; 15- to 48- in. sizes were selected to meet the strength requirement for Class III reinforced concrete pipe.

2. Hydrostatic. This governs the allowable leakage through the pipe wall at low values of hydrostatic pressure. There is no specified leakage for reinforced concrete pipe in ASTM Specification No. C-76-77. (In practice concrete pipe may crack when loaded. Leakage occurs, but the pipe still supports the load because of its reinforcement.) For vitrified clay pipe in C-700-77, there is a range of test times at an

THREE-EDGE BEARING STRENGTH OF GLASS POLYMER PIPE

Figure 13. Mean and 90% confidence limits of data on three-edge-bearing strength of GPC pipe.

Table 13
Wall Thickness of GPC Pipe To Meet ASTM Specifications

Size, i.d., in.	Crushing strength, lb (force)	D_{ult} , lb (force)	Wall thickness,		Outside diameter, in.
	lineal foot	lineal ft-ft i.d.	calculated in.	rounded in.	
6	2000	4000	0.5975	0.625	7.25
8	2200	3300	0.7235	0.750	9.5
10	2400	2880	0.8450	0.875	11.75
12	2600	2600	0.9634	1.000	14.00
15	2900	2320	1.1375	1.25	17.5
15R	--	2000	1.0562	1.125	17.25
18	--	2000	1.2674	1.375	20.75
21	--	2000	1.4787	1.5	24.0
24	--	2000	1.6899	1.75	27.5
27	--	2000	1.9011	2.0	31.0
30	--	2000	2.1124	2.125	34.25
33	--	2000	2.3236	2.375	37.75
36	--	2000	2.5348	2.625	41.25
42	--	2000	2.9573	3.000	48.00
48	--	2000	3.3798	3.375	54.75

internal hydrostatic pressure of 68.9 kPa (10 psig) above atmospheric. During these time periods (7 to 21 minutes, depending on wall thickness), moisture may appear as beads on the surface but may not run down the surface of the pipe.

Some samples of 203.2-mm (8 in.) and 304.8-mm (12 in.) GPC pipe met the hydrostatic test requirement. None of the full lengths of 203.2-mm pipe which were made for life tests passed this test, although some 152.4-mm (6 in.) lengths were satisfactory. This is probably due to increased porosity at reduced monomer concentration, an effect noted in the discussion of the density data above (Section III-D). The life test samples were made with the low design monomer content and reduced wall thickness. This reflects the low cost that would be necessary in commercial production. The resulting pipe met strength requirements but not the hydrostatic test.

Pipe which failed the hydrostatic test in previous work was made acceptable by applying a thin film of initiated monomer and curing it. As a result, a coating step was added to the process flow sheet. It was planned to apply a 0.762 mm (0.03 in.) film of monomer and additives to the inside wall of all GPC pipe in the size range where it competes with vitrified clay. The pipe would then be returned to the oven to cure the coating.

3. Joint Tightness. There is no specified rate of leakage at the joints in the standards for vitrified clay or reinforced concrete pipe. ASTM C-425-77, which covers compression joints for vitrified clay pipe and fittings, states that joints shall not leak under a 3.05-m (15 in.) head of water, whether straight, deflected by a specified amount, or under a specified shear load.

The sections of 304.8-mm (12 in.) GPC pipe for field trials were designed with an O-ring joint. This did not meet the C-425-77 requirements. The groove and O ring were probably not adequately sized to correct for out-of-roundness of the pipe.

Since this pipe was to be installed in Newark, New Jersey, their Engineering Department was asked to specify the maximum leakage at the joints. They set the rate at 100 gallons per inch of diameter, per mile of pipe per day at a hydrostatic head of 2 feet (equivalent to 9.26 cubic meters per millimeter of diameter per kilometer of pipe per day at a hydrostatic head of 0.610 meters).

A joint was assembled using General Electric RTV 102 white silicone rubber instead of the O ring. After the rubber was cured, the jointed section was clamped in a jig which had been made for this test at Brookhaven. Water was added to cover the joint and a controlled air pressure was maintained on the surface to keep a static head of 2 feet at the joint. The water level was monitored with a manometer.

After five days the level had dropped about 3.2 mm (1/8 in.), which corresponds to about 0.1 cubic meters per mm per kilometer per day (or 1.08 gallons per inch per mile per day). Newark accepted the pipe on this basis.

F. Accelerated Aging

The environment attacks waste water piping by dissolving components and thus weakening its structure, effects usually noticeable only after long periods. To accelerate the process we took two steps. Some samples were stored under circulating water at 65°C (149°F). The circulation and the increased temperature tended to increase the rate of solution. Other samples were stored under 5% aqueous sulfuric acid. This relatively strong acid was much more aggressive than most residential or commercial wastes.¹²

Unexposed samples of the same batches of pipe were tested in three-edge bearing. The results were averaged and used as a baseline.

Exposed samples were removed from the baths after various periods of time and tested in the same way. The new strength value was expressed as a percentage of the original average and plotted against the time of exposure.

Reinforced concrete, vitrified clay, and asbestos cement pipe were tested in the same way. The results are shown in Tables 14 and 15 and

Table 14
Retained Strength of Pipe After Aging
in Circulating Water at 65°C (149°F)

Run No.	Time, hr	Strength retained, %	Run No.	Time, hr	Strength retained, %
GPC 309E	2	110.5	RC 5	6672	42.9
309B	4	99.7	RC 6	6672	53.1
302B	10	97.2	VC 7	2	50.5
302A	30	88.2	8	10	61.3
301E	100	119.3	9	95	46.0
301B	270	119.8	4	1729	103.5
309C	836	95.1	6	10920	72.8
311A	836	99.1			
301A	1000	92.0	TR 15	2	89.1
324III	2500	88.7	16	10	84.9
301C	3200	91.8	17	95	72.1
335IIA	6672	37.7	7	1150	79.4
309A	10000	84.7	13	1512	75.5
301F	10920	71.7	8	2039	80.6
309F	10920	78.4	14	3200	93.4
RC 4	2500	135.3	10	5216	95.9

Key: GPC is glass polymer composite
RC is reinforced concrete
VC is vitrified clay
TR is asbestos cement

Table 15
Retained Strength of Pipe After Aging in 5% Aqueous
Sulfuric Acid at Ambient Temperature

Run No.	Time, hr	Strength retained, %	Run No.	Time, hr	Strength retained, %
GPC 324 I	112	106.2	VC 10	4	60.2
324 II	960	105.0	11	30	66.9
301D	1300	118.9	13	890	47.7
325 II	6650	55.9	12	6570	69.7
311 II	10300	82.7			
RC 7	4	79.8	TR 6	4	101.0
8	30	77.8	9	30	91.0
9	112	105.7	11	100	88.3
10	984	63.0	4	1009	64.5

Key: GPC is glass polymer composite
RC is reinforced concrete
VC is vitrified clay
TR is asbestos cement

plotted in Figures 14 and 15. The abbreviations are RC for reinforced concrete, VC for vitrified clay, and TR for asbestos cement (Transite is a trade name).

The project was terminated before all tests were completed. The data that were obtained show the pronounced scatter which is common in tests of this type.¹² Regression analysis was used to establish the coefficients of the straight lines which represent the data as closely as possible. The general equation of these lines is

$$R = b_0 - b_1 \log t, \quad (5)$$

where R is the retention of bearing strength, %, b_0 and b_1 are constants for a type of pipe and a set of conditions, and t is the length of exposure, hr.

The values of the coefficients are compared in Table 16. The data for GPC in water are fairly close to Baker's results with polymer concrete.¹² His coefficients are 82.4 and 5.29 compared with the values 111.6152 and 7.6110 given in Table 16.

The scattered data points for other types of pipe do not lead to firm conclusions. However, compared to the other materials, it is apparent that GPC retains more of its strength over most of the 10,000-hr test period in water. In the 5% sulfuric acid, a significant degree of improvement is indicated.

IV. PROCESS AND EQUIPMENT

A. Description of Process

The flow diagram in Figure 1 shows three main process lines: a glass line, a monomer line, and a product line. The waste glass is prepared in the glass line. Monomers, additives, and initiator are dissolved in the monomer line. When these lines join they form a product line in which the GPC is formed and finished. There are auxiliary items of equipment for dust collection, solvent cleaning, and product handling.

The glass line begins at the export chute from the existing Secondary Separation System. A hopper feeds the raw glass to a belt conveyor which carries it to a silo outside the GPC plant. From the silo it is transferred to a bucket elevator which raises it to permit flow by gravity through the dryer and mill. The prepared glass falls directly from the mill into a hopper from which it is metered into a planetary mixer.

Figure 14. Life tests of pipe in water at 65°C (149°F).

Figure 15. Life tests of pipe in 5% aqueous sulfuric acid at ambient temperature.

Table 16
Coefficients of Life Test Equations for Pipes
in Warm Water and Sulfuric Acid

Medium	Type of Pipe	b_0	b_1
Water at 65°C	GPC	111.6152	7.6110
Water at 65°C	Vitrified clay	46.5575	-9.5988
Water at 65°C	Asbestos cement	82.4218	-0.5748
Water at 65°C	Reinforced concrete	830.5789	204.6294
Aqueous sulfuric acid ambient	GPC	104.1934	1.2754
Aqueous sulfuric acid ambient	Vitrified clay	60.7306	-0.1784
Aqueous sulfuric acid ambient	Asbestos cement	112.5286	14.8684
Aqueous sulfuric acid ambient	Reinforced concrete	89.1141	4.2346

Monomers and additives are all liquids, which are stored in tanks and drums. Individual pumps meter them into one of two mix tanks. Solid initiator is stored in a refrigerator in weighed packages and added by hand to the blended contents of the mix tank. The initiated monomer mix is pumped into the glass charge in the planetary mixer.

External release agent is pumped from its storage drum and sprayed on the contact surfaces of the mold, which is then assembled and baked. When it is cooled, the vibrators are attached and the mold is ready for filling.

The filled can of the planetary mixer is hoisted above the vibrating mold and the GPC mix is transferred into the mold through a chute. During this step the chute is moved around the top of the mold to distribute the charge. After filling, the vibration is continued until liquid resin appears on top and essentially all the trapped air and vapor have bubbled through this layer. Then the mold is covered and placed in the oven at 82°C (180°F).

After the GPC is cured in the oven the mold is removed and its inner core is chilled with water until it shrinks away from the casting. The core is hoisted out and the casting is set aside to cool.

After cooling, the GPC pipe is hoisted out of the shell of the mold. All sections larger than 381 mm (15 in.) are taken to field storage. Sections of smaller pipe are placed on coating rolls. Initiated monomer (including additives) is sprayed on the inside surface of the pipe. During this step the pipe rotates and the spray nozzle travels its length to distribute the film. Then the pipe returns to the oven for a short curing period. (A promoter may be added to permit curing at room temperature if the oven is full.) Finally the small sections are taken to field storage.

Dust is generated in at least four process steps: when the glass fraction falls into the silo and when it is dried, milled, and mixed. The silo, dryer, mill, and mixer are connected through ducts to a bag-type dust collector. Air is drawn through these individual items of equipment by a fan downstream from the dust collector, and the air is then vented to the atmosphere. The dust is collected in fiber drums and returned batchwise to the glass hopper to be incorporated in the GPC product.

During plant shutdowns and some maintenance work, it will be necessary to remove monomer and polymer residues from tanks, piping, and other equipment. A solvent tank, pump and piping are included in the design to permit as much cleaning as possible without opening the equipment. Liquid waste from this operation (washdowns and spills) goes to a sump and is pumped to a waste treatment plant (not included in this process).

There will also be losses of raw materials (spills, leakage, holdup in equipment on shutdown, polymerized residues of monomers) and of intermediates and finished product as off-grade. To simplify the flow diagram these losses are not shown.

B. Material and Energy Requirements

Raw material requirements will exceed the minimum amounts, because of the losses in the process, which were listed in the Section IV-A above. It is difficult to estimate these losses individually, because of lack of experience with this type of plant, but it has been assumed that 5% of the total input of each raw material will be lost in the process. The resulting inputs per unit weight of GPC pipe produced are listed in Table 17. These inputs are based on Run 342. The equipment designs are based on the composition of Run 316, which used a slightly lower percentage of monomer (9.5% instead of 10%, based on the weight of glass plus monomer).

The inputs of monomers and additives for sealing smaller sizes of pipe and the input of external release agent for coating the molds for all pipe will depend on the product mix. They can be expressed approximately in terms of the internal wall area to be sealed or the internal and external wall area to be released.

For example, the seal coat is 0.762 mm (0.03 in.) thick. The density of the mixed monomers is about 0.925 g/cm^3 (57.7 lb/ft^3). The minimum input for coating would be about 705 g/m^2 (0.144 lb/ft^2). Allowing for 5% losses, the actual input would be about 742 g/m^2 (0.152 lb/ft^2).

The external release agent is applied at the rate of about $57.0 \text{ cm}^3/\text{m}^2$ ($1.4 \text{ gal}/1000 \text{ ft}^2$). In some cases we have used a single coat for two or three releases. The suppliers of one agent blame occasional poor performance on accumulation of coating material due to excessive use. For conservatism we have assumed a single coat at the above rate per release.

Table 17
Design Inputs of Raw Materials Per Ton
of GPC Pipe Product, Including Losses

Raw materials	Input	
	kg/metric ton	lb/short ton
Glass fraction	944.535	1889.070
Styrene	87.457	174.914
Polyester PPG-50071	13.119	26.238
Polyester Grace 13023	4.373	8.745
Initiator BPO-98	1.050	2.099
Bonding agent Silane A-174	1.050	2.099
Internal release agent Zelec UN	1.050	2.099

In Section VI, the requirements for coating and sealing will be given for a specific product mix.

Energy requirements also depend on the product mix and other local plant conditions. For example, both the glass dryer and the curing oven can use low level waste heat if it is available. If not, natural gas, oil, and LPG are alternatives. At the location we have used for design, waste heat and natural gas are not available now. Oil would require storage facilities and LPG is approaching electricity in cost. Since all the users in this process are relatively small, we have used electric power for heating and instrumentation as well as drives.

The total manufacturing energy requirement is 223.6 kWh/metric ton (202.8 kWh/short ton) of GPC. For the design case, 37.6% is for drives, 53.3% is for process heat, and 9.1% is for lighting, instrumentation, compressed air, and miscellaneous uses.

C. Selection of Equipment

Most of the equipment that would be used in a full-scale plant can be designed from published information or data from the laboratory or pilot plant work. The scope and accuracy of some of the data should be improved in future work, but we believe that they will yield conservative designs at present.

Raw glass is transferred in a covered belt conveyor and stored in a concrete stave silo to keep it as dry as possible. The bulk density for design purposes is 1.90 g/cm^3 (118.6 lb/ft^3).

Moisture content of the BuMinex raw glass ranges from 0.12 to 0.14%. For design of the dryer it was assumed to be 0.2%. (In a dry process plant it could be assumed to be lower.) The design exit moisture content was 0.01%. The unit is a stainless steel belt dryer, with an air preheat section to conserve energy.

The capacity of the sledge mill which was bought for the pilot plant is adequate for the design case. Since hammers must be replaced after one shift, an installed spare and parallel conveyors were included. The bulk density of the product is 1.6 g/cm^3 (99.8 lb/ft^3).

Change-can mixers of the type used in the pilot plant have been replaced in industry by planetary mixers. The cycle time, based on pilot plant work, is 20 minutes. At a batch size for the design case of 383 kg (845 lb), the mixer volume is 0.28 m^3 (75 gallons) and a 20-hp motor is required.

The molds would be 4 m (13 ft) long and would be made from commercial sizes of pipe and tubing. End joints would be of the O-ring type, like those of the 304.8 mm (12 in.) pilot plant mold, except that the grooves would be deeper. An average cycle time of 15 hours includes the following steps:

<u>Operation</u>	<u>Time, hr</u>
Fill	1.0
Cure	6.0
Break core bond	0.5
Cool	4.0
Release pipe	1.0
Coat with external agent	0.5
Reassemble	1.0
Bake & cool	1.0
	<u>15.0</u>

In the pilot plant, pneumatic vibrators clamped to a suspended mold have been used. The rule of thumb for this type of device is to provide one unit of vibrational force for 10 weight units of contents. To allow for energy lost in liquid viscosity, we have used one force unit for five weight units of the loaded mold. It was assumed that vibrators would be transferred between molds as required.

This vibration system could probably be improved, at least for the larger sizes, by using finger vibrators. Another possibility is that the pneumatic units could be used at the start of the operation when the level is low, and supplemented or replaced at the end by finger vibrators.

The design of the curing oven is based on an average cure time of 6 hours and an operating temperature of 82°C (180°F). The maximum temperature is 150°C ($\sim 300^\circ\text{F}$) for baking the coating of external release agent. A $340\text{-m}^3/\text{hr}$ ($\sim 200 \text{ ft}^3/\text{min}$) fan is provided to remove monomer vapor which leaks through the cover. (This would be vented with the dust collector air stream.) These requirements lead to a 65 kW oven for the design case.

V. CAPITAL COST

A. Bases

Since the GPC pipe plant is designed to use the glass fraction output of a specific resource recovery plant, the design conditions for the source plant and the GPC plant are summarized together in Table 18. The yields and recoveries are limited by the efficiencies of existing equipment and by the sizing of experimental trains for separation of certain fractions. A more fully integrated case will be discussed in Section VI of this report.

The product mix is based on the pipe used for sewers and storm drains in projects of the Department of Public Works of Baltimore County, Maryland, in the fiscal year 1971-1972.¹³ The 152- to 381-mm (6 to 15 in.) pipes were made of extra-strength vitrified clay. The 381-mm and larger (15 in.) pipes were of concrete. Lengths of each size are given in Table 19.

The design output of the GPC plant is derived from the assumed yield of glass fraction and the assumed recovery of glass fraction in the GPC. This yields an output of about 6871 metric tons (7575 short tons) of GPC pipe per year. Outputs of individual sizes are then calculated from the percentages in the assumed product mix, using the weight per unit length for each size.

B. Equipment List and Costs

Preliminary quotations were obtained for the major process equipment. Other items were priced from data in books by Bauman, Guthrie, and Moselle.¹⁴⁻¹⁶ All these prices were escalated to April 1, 1979, using the Marshall and Swift Equipment Cost Index, as published in Chemical Engineering.¹⁷

The installed costs of the items, listed in Table 20, include delivery, placement on foundation, structural steel supports, connection to wiring, piping and instrumentation, and insulation and painting where necessary.

C. Total Capital

The final cost of the plant includes nonprocess items in addition to the installed cost of the process equipment. A sketch was made of the

Table 18
Design Bases for Resource Recovery Plant and GPC Addition

Source plant bases:

MSW* input, metric tons/day	1088
short tons/day	1200
Operating hours/day	10
Operating days/year	300
Primary fraction to separation system	37.5%
Yield of glass fraction from primary fraction	5.3%

GPC plant bases:

Operating hours/day	24
Operating days/year	350
Operating factor (onstream time at capacity)	90%
Recovery of raw materials in GPC	95%

*Municipal solid waste

Table 19
Distribution of Sizes in Design Product Mix

Diameter,			Length,		% of total
mm	in.	m	ft		
152.4	6	8965	29414		13.56
203.2	8	32808	107639		49.61
254.0	10	1545	5070		2.34
304.8	12	2056	6746		3.11
381.0	15	768	2520		1.16
381.0	15R*	4984	16350		7.54
457.2	18	6601	21657		9.98
533.4	21	2146	7042		3.24
609.6	24	1462	4796		2.21
685.8	27	948	3109		1.43
762.0	30	1266	4154		1.91
838.2	33	295	968		0.45
914.4	36	1009	3309		1.52
1066.8	42	499	1638		0.75
1219.2	48	787	2581		1.19
Total		66139	316993		100.00

*R designates the usage of concrete pipe of this size.

Table 20
Installed Cost of Process Equipment, Base Case

Item	Component	Installed cost, \$
1	Raw glass conveyor	33,000
2	Raw glass silo	50,000
3	Transfer conveyor	2,400
4	Glass elevator	13,000
5	Glass dryer	77,200
6	Mill feed conveyor	2,400
7	Glass mill	10,800
8	Glass hopper	3,500
9	Planetary mixer	29,500
10	Molds	102,000
11	Vibrators	4,100
12	Curing oven	62,200
13	Coating rolls	1,200
14	Sump pump	900
15	Forklift truck	39,200
16	Trolley hoist	14,000
17	Styrene tank	16,800
18	Styrene pump	2,400
19	Polyester No. 1 tank	4,800
20	Polyester No. 2 tank	3,100
21	Polyester No. 1 pump	1,200
22	Polyester No. 2 pump	1,000
23	External agent tank	300
24	Internal agent tank	2,200
25	Bonding agent tank	200
26	Bonding agent pump	1,700
27	Internal agent pump	1,700
28	External agent pump	1,400
29	Mix tank	7,000
30	Mix pump	2,000
31	Solvent tank	3,600
32	Solvent pump	1,500
33	Dust collector	30,700
34	Dust collector blower & stack	6,700
35	Mold storage (included in building)	--
Total		\$533,700

equipment arrangement. This gave area requirements, building areas and height, foundation volume, structural steel volume, and lengths of runs of piping, ducting, and wiring. The nonprocess costs were then estimated, using refs. 9, 14, 15, and 16.

Site preparation in this case includes soil tests, storm drains, grading, foundation excavations, landscaping, and paving for truck access and field storage. The cost of concrete is for foundations, since the building slab is included in the cost of the building. Some of the usual services during construction would be supplied by the existing plant.

Structural steel costs include supports for conveyors, silo, dryer, hoist, and dust collector, as well as access ladders and platforms to all overhead equipment.

The building is a three-story structure, 18.3 x 22.9 m (60 x 75 ft), with a total volume of 5098 m³ (180,000 ft²). A concrete slab, steel siding, and roof conform with the other buildings in the existing plant. The building cost includes its own lighting and other electrical fixtures, heating and ventilating, and fire protection. These costs are factored on the building cost. A high factor is used for fire protection because styrene and the polyesters are flammable. Here again some services would be supplied by the existing plant, e.g., laboratory, shop, office, and sanitary facilities.

Most of the storage tankage is outside the building. The styrene is in a diked area across the plant road loop. This accounts for most of the piping, which is Schedule 10S to minimize corrosion and contamination. Since the instrumentation is electronic and the dust collector supplies its own backwash air, there is no need for a dry air supply from the existing plant.

Electrical costs include a transformer, switchgear, circuit breakers, and motor control center with all the necessary starters. Internal and external conduit and wiring, and yard lighting are also included.

Instrumentation, field expense, and painting are factored estimates, based on the cost of the installed process equipment. All insulation in this plant is included in the cost of equipment. Home office expense is based on a one-year design and construction schedule. Installed and

warehouse spares are critical items and those which are subject to most wear, with an added 25% for miscellaneous spare parts. The contingency is assumed to be about 20% of the other nonprocess costs, to give a rounded total. The capital cost figures are listed in Table 21.

VI. OPERATING COST

Equipment design, and, therefore, capital cost, are based on the composition of Run 316. In that run the monomer content of the GPC mix was 9.5% based on the weight of glass plus monomer. To calculate operating costs, the slightly more conservative basis of Run 342, where the monomer content is 10.0% on the same basis, was used. The calculations are described below and the results are summarized in Table 22.

A. Fixed Costs

Amortization is based on straight line depreciation for ten years, with no salvage value. Working capital is not depreciated. For this plant it consists of inventories of raw materials and finished product. The raw glass is assumed to be worth \$22.05/metric ton (\$20.00/short ton). The unit cost of styrene is obtained by interpolation in data published by Ponder.¹⁸ Other raw material prices are based on 1974 quotations, brought up to date by use of the index of prices of industrial chemicals.

One week's production is stored in the plant. Its value is based on the assumed product mix and prices per unit length from ref. 16.

Insurance and ordinary maintenance are both factored estimates, based on installed capital. The costs of replacing one set of hammers for the sledge mill during each shift is added to the ordinary maintenance cost.

B. Variable Costs

Unit prices of raw materials are the same as those used to calculate working capital. They are multiplied by the GPC output and composition, and divided by the fractional recovery (0.95) to get annual costs of the raw materials in the GPC mix.

Additional amounts of chemical raw materials are used to coat the molds for release and to seal the walls of the smaller-sized pipe. These quantities depend on the product mix, given in Table 19.

Table 21
Capital Cost Summary, Base Case

Item	Cost, \$
Installed process equipment	533,700
Site preparation	10,000
Concrete	44,500
Structural steel	22,000
Building	221,000
Piping and ductwork	13,000
Electrical	40,000
Instrumentation	107,000
Painting	15,000
Insulation and fire protection*	--
Home office expense	190,000
Field expense (including startup)	98,000
Spares and spare parts	27,000
Contingency	328,800
Total	1,650,000

*Included in cost of equipment and building.

Table 22
Operating Costs, Base Case

Fixed costs	Annual cost, \$
Amortization	165,000
Insurance (2% of installed capital)	33,000
Maintenance (7% of installed capital)	115,500
Replacement hammers (1050 sets @ \$15.89)	16,690
Total fixed	\$ 330,190
Variable costs	
Glass (7155.0 short tons @ \$20)	143,100
Styrene (1,390,081 lb @ \$0.25)	347,520
PPG50071 (208,518 lb @ \$0.66)	137,622
GR13023 (69,501 lb @ \$0.68)	47,261
BPO 98 (16,681 lb @ \$1.69)	28,191
Silane A-174 (16,681 lb @ \$3.93)	65,556
Zelec UN (16,681 lb @ \$1.82)	30,359
External release (2954.4 gal @ \$26.53)	78,380
111 Trichloroethane (800 gal @ \$2.87)	2,296
Total raw materials	\$ 880,285
Operators (16,800 M.H. @ \$7.75)	130,200
Utility men (8,400 M.H. @ \$6.75)	56,700
Fringe benefits (35% of direct labor)	65,415
Supervision (20% of direct labor)	37,380
Total labor	\$ 289,695
Electricity (1,536,024 kWh @ \$0.049)	75,265
General & administrative (15% of other variable costs)	186,787
Total variable	\$1,432,032

The product mix indicates relative usages of various sizes of pipe. To translate this into the lengths of these sizes to be produced, the wall thicknesses in Table 13 were used. The average density of GPC in the design composition range is 2.04 g/cm³ (127.4 lb/ft³). For any size the weight per unit length can be calculated as follows (neglecting the ends of the sections):

$$\frac{\text{short tons}}{\text{mile}} = \frac{\pi}{4} \frac{(\overline{\text{o.d.}}^2 - \overline{\text{i.d.}}^2)}{144} \frac{5280 (127.4)}{2000}$$

$$= 1.8344 (\overline{\text{o.d.}}^2 - \overline{\text{i.d.}}^2)$$

where $\overline{\text{o.d.}}$ and $\overline{\text{i.d.}}$ are in inches.

An arbitrary total length of pipe per year (100 miles, for example) is assumed and the corresponding total weight is calculated from the individual percentages and unit weights. Using the ratio of this total weight to the design weight output of GPC, the weight and length of each size are calculated. The results in Table 23 apply to the design case.

The usage of external release agent is calculated from the loading per unit area (57.0 cm³/m² or 1.4 gal/1000 ft²) and the total internal and external surface of each size of pipe produced in a year:

$$\frac{\text{gal}}{\text{yr}} = \frac{\text{miles}}{\text{yr}} \times 5280 \times \frac{\pi(\overline{\text{o.d.}} + \overline{\text{i.d.}})}{12} \times \frac{1.4}{1000} = 1.935 \times \frac{\text{miles}}{\text{yr}} \times (\overline{\text{o.d.}} + \overline{\text{i.d.}})$$

where $\overline{\text{o.d.}}$ and $\overline{\text{i.d.}}$ are outside and inside diameters in inches. Applying this to the mileage and diameter figures in Table 23 gives the annual usage of external release agent.

The usage of monomer and additives for coating the smaller sizes is calculated from the thickness of the coating (0.762 mm or 0.03 in.), its density (0.925 g/cm³ or 57.7 lb/ft³), and the internal surface of each of the smaller sizes produced in a year. Assuming 5% of the monomer is lost in handling, the gross usage for any size is

$$\begin{aligned} \frac{\text{lb}}{\text{yr}} &= \frac{\text{miles}}{\text{yr}} \times 5280 \times \frac{\pi(0.12 \overline{\text{i.d.}} - 0.0036)}{144} \times 57.7 \times 1.05 \\ &= 1744.7 \times \frac{\text{miles}}{\text{yr}} \times (0.12 \overline{\text{i.d.}} - 0.0036). \end{aligned}$$

About 4.7% of the monomer usage is for coating.

Table 23
Application of the Design Product Mix To Determine
Size Distribution for the Base Case

Size (i.d.) inches	o.d. inches	Short tons/mile	Miles/ 100 miles	Short tons/ 100 miles	Short tons/yr	Miles/yr
6	7.25	30.38	13.56	411.95	237.27	7.81
8	9.5	48.15	49.61	2388.72	1375.85	28.57
10	11.75	69.82	2.34	163.38	94.10	1.35
12	14.0	95.39	3.11	296.63	170.85	1.79
15	17.5	149.05	1.16	172.90	99.59	0.67
15R	17.25	133.11	7.54	1003.65	578.08	4.34
18	20.75	195.48	9.98	1950.89	1123.66	5.75
21	24.0	247.65	3.24	802.39	462.16	1.87
24	27.5	330.66	2.21	730.76	420.90	1.27
27	31.0	425.59	1.43	608.59	350.53	0.82
30	34.25	500.92	1.91	956.76	551.07	1.10
33	37.75	616.49	0.45	277.42	159.79	0.26
36	41.25	743.98	1.52	1130.85	651.34	0.88
42	48.0	990.60	0.75	742.95	427.92	0.43
48	54.75	1272.30	1.19	1514.04	872.05	0.68
				13151.88	7575.16	57.59

The usage of cleaning solvent (1, 1, 1 trichloroethane) is based on the assumption that there will be four shutdowns per year. Each shutdown will require about 200 gallons of solvent to rinse all the equipment that contained the monomer mix.

Labor is the most important variable cost after raw materials. Two operators and one utility man per shift would operate the GPC plant, with part-time supervision supplied from the resource recovery facility. Hourly rates are those for the same jobs in that facility in April 1979. Fringe benefits and supervisory costs are factored on direct labor. The unit cost of electricity is also taken from figures for the existing facility in Maryland. General and administrative costs are assumed to be 15% of the preceding variable costs.

VII. ECONOMICS

The design case, for a semiworks plant in an existing facility, is evaluated by calculating the anticipated return on investment. A new plant, in which the full output of glass would be converted to GPC pipe, is evaluated by comparison with the design case.

A. Market Information

Funds and manpower were not available to conduct a market survey for the area within hauling distance of the Maryland plant. Instead, material costs cited in ref. 16 for vitrified clay and Class III reinforced concrete pipe were used. It was assumed that there would be no selling cost, since the county could specify the use of its own GPC pipe output. This leads to the sales values in Table 24.

B. Return on Investment

For the design case, the simplified calculation of ROI is shown in Table 25.

The design case is unusual, since it assumes that only part of the glass fraction of solid waste is recovered as GPC. If the market for pipe will support it, the plant should be designed to minimize production costs by maximizing the recovery of glass.

It may be assumed that a 907-metric-ton/day (1000 short ton/day) plant for recovery of resources from municipal solid waste is a practical

Table 24
Estimated Sales Value of Product, Base Case

Size (i.d.) inches	Lineal ft/yr	Sales value	
		\$/lin. ft	\$/yr
6	41,237	3.10	127,834
8	150,840	4.80	724,078
10	7,128	7.00	49,896
12	9,451	9.30	87,896
15	3,538	13.30	47,050
15R	22,915	7.10	162,698
18	30,360	8.60	261,096
21	9,874	10.60	104,660
24	6,706	13.30	89,184
27	4,330	15.30	66,243
30	5,809	17.70	102,802
33	1,373	19.80	27,181
36	4,646	23.00	106,867
42	2,270	29.10	66,069
48	3,590	34.90	125,305
			\$2,148,859

Table 25
Simplified Calculation of Return on Investment, Base Case

Installed capital	\$1,650,000
Working capital	61,405
Total capital	1,711,405
Fixed costs	330,190
Variable costs	1,432,032
Total annual costs	1,762,222
Sales value of products	2,148,859
Income	386,637
Income tax (50%)	193,318
Income after tax	193,319
Return on investment	11.3%

minimum size. It would probably recover 90% of the input as a non-magnetic fraction and about 9% of the nonmagnetic material as a crude glass stream, suitable for GPC. If the operating times were the same as those for the design case, its output would be about 23,335 metric tons/year (25,727 short tons/year), or about 3.4 times that of the existing experimental plant.

In the absence of a detailed estimate, installed plant capital is usually assumed to be proportional to the output to the 0.6 power. Fixed costs may be derived from this capital as they were in the design case.

Raw material and electricity costs will increase roughly in direct proportion to output, though there might be some savings due to increased efficiency. The larger plant would probably require three operators and two utility men. Fringe benefits, supervision, and general and administrative costs may be calculated as before. The results are given in Table 26.

VIII. ENERGY CONSERVATION

As a first approximation, the ultimate energy requirement of GPC pipe is that of the chemical raw materials. (This neglects the ultimate energy requirement of the waste glass and the energy used to manufacture the GPC, in comparison with the high ultimate energy requirement of the polymer.) A corresponding energy usage is calculated for vitrified clay pipe.

A. GPC Requirement

The ultimate energy requirement for polystyrene is 134,533 M-J/metric ton (115.67×10^6 Btu/short ton).¹⁹ Since polystyrene usually includes catalysts and additives, we have assumed that this figure applies to the entire added organic content of GPC. For pipe of any size, the ultimate energy requirement per unit length is the product of the weight per unit length, the polymer concentration, and the ultimate energy requirement for the polymer.

$$\begin{aligned} \frac{\text{Btu}}{\text{mile}} &= \frac{\text{short tons}}{\text{mile}} \times 0.102692 \times 115.67 \times 10^6 \\ &= \frac{\text{short tons}}{\text{mile}} \times 11.88 \times 10^6 \end{aligned}$$

Table 26
Simplified Calculation of Return on Investment,
Full-Scale Plant

Installed capital	\$3,440,000
Working capital	209,000
Total capital	<u>3,649,000</u>
Fixed costs	710,000
Variable costs	<u>4,282,000</u>
Total annual costs	4,992,000
Sales value of products	7,298,000
Income	2,306,000
Income tax (50%)	1,153,000
Income after tax	1,153,000
Return on investment	31.6%

However, the weights per unit length in Table 23 are not all based on the strengths of corresponding sizes of vitrified clay (sizes 15R and above are based on the specified strengths of reinforced concrete). The procedures of the preceding sections were applied to the strength requirements of ASTM C 700-77 to calculate the dimensions and weights in Table 27.

B. Comparison with Vitrified Clay Pipe

The ultimate energy requirement for fired clay is 10469 M-J/metric ton (9×10^6 Btu/short ton).²⁰ We have no information on the energy used in manufacture and transportation of vitrified clay pipe, so we neglect it in comparison with that of the clay.

Unfortunately the dimensions of extra-strength vitrified clay pipe are not standardized, so its energy requirement per unit length is not easy to establish. ASTM Standard C 700-77 does not specify wall thickness. Perry⁹ gives minimum wall thickness for standard and extra-strength pipe, but measurement of pipe in the field indicates that these minimums are exceeded.

We used the following procedure. Five samples of vitrified clay pipe were selected in the Baltimore County storage yard in Cockeysville, Maryland. The sizes were 152.4, 203.2, 254.0, 304.8, and 381.0 mm (6, 8, 10, 12, and 15 inches). The wall thicknesses were measured and two samples were weighed. The weights and volumes of the weighed samples gave an average density of 1.91 g/cm^3 (119.3 lb/ft^3). The wall thicknesses were compared with those calculated from the minimum dimensions in Perry.⁹ All wall thicknesses were larger; the ratio ranged from 1.135 to 1.448 and averaged 1.271. This average ratio was applied to all of the minimum dimensions in ref. 9 to calculate pipe wall thicknesses. Then weights and energy requirements per mile were calculated and are compared in Table 28 with the results for GPC.

IX. SUMMARY AND RECOMMENDATIONS

Many cities and regions are now recovering resources from municipal solid waste and others are considering doing so. In most cases plans are being made to separate components of the waste to do this.

Table 27
GPC Pipe Dimensions for Comparison With
Vitrified Clay Pipe

Size (i.d.) inches	B ₃ , lb ft, ft	Wall thickness, inches		o.d., inches	Short tons/mile
		calculated	rounded		
6	4000	0.5975	0.625	7.25	30.38
8	3300	0.7236	0.75	9.5	48.15
10	2880	0.8450	0.875	11.75	69.82
12	2600	0.9634	1.0	14.0	95.39
15	2320	1.1375	1.25	17.5	149.05
18	2200	1.3293	1.25	20.5	176.56
21	2200	1.5508	1.625	24.25	269.78
24	2200	1.7724	1.875	27.75	355.99
27	2089	1.9430	2.0	31.0	425.58
30	2000	2.1124	2.125	34.25	500.92
33	2000	2.3236	2.375	37.75	616.48
36	2000	2.5348	2.625	41.25	743.97
39	2031	2.7673	2.875	44.75	883.39
42	2000	2.9573	3.0	48.0	990.59

Table 28
Comparison of Ultimate Energy Requirements of GPC
and Vitrified Clay Pipe

Vitrified Clay					GPC	GPC
Size (i.d.) inches	Wall thickness, inches	o.d., inches	Short tons/mile	Btu/ mile $\times 10^{-6}$	Btu/ mile $\times 10^{-6}$	Saving, %
6	0.874	7.748	41.27	371.43	360.9	2.8
8	1.112	10.224	69.60	626.4	572.0	8.7
10	1.271	12.542	98.41	885.7	829.5	6.3
12	1.509	15.018	140.03	1260.3	1133.2	10.1
15	1.906	18.812	221.35	1992.2	1770.7	11.1
18	2.383	22.766	333.67	3003.0	2097.5	30.2
21	2.860	26.72	468.77	4218.9	3205.0	24.0
24	3.178	30.356	593.33	5340.0	4229.2	20.8
27	3.495	33.99	732.15	6589.4	5055.9	23.3
30	3.813	37.626	885.67	7971.0	5950.9	25.3
33	4.131	41.262	1053.69	9483.2	7323.8	22.8
36	4.448	44.896	1235.90	11123.1	8838.4	20.5
39	4.766	48.532	1432.89	12896.0	10494.7	18.6
42	5.084	52.168	1644.38	14799.4	11768.2	20.5

The major component in these plans at present is refuse-derived fuel, or RDF, which is a minor answer to the current fuel shortage. Several problems have appeared in the use of this fuel. Conveying equipment is subject to erosion and personnel are exposed to a dust hazard. Slagging in furnaces and boilers reduces their performance. All of these problems are traceable in part to a high glass content in the fuel.

This will probably increase emphasis on recovery of the glass fraction itself, a process that will become increasingly attractive as more uses are developed for the glass fraction. This report has dealt with one such use.

A. Status of Process and Product Development

Brookhaven has made a potentially useful structural material, glass polymer composite (GPC), from milled waste glass and polymers. In collaboration with Teledyne National, we have developed a process for production of low-head water pipe for sewers and storm drains from GPC.

The GPC composition and the particle size of the glass have been established for purposes of process design. Methods of handling the feeds, the monomer mix, and the cast product are also firm. With this information it has been possible to select and size process equipment and to estimate material and energy requirements.

The product meets ASTM specifications for other types of pipe in the same service. Lengths of pipe in the field also satisfy the leakage requirements at joints. In aging tests under 65°C (149°F) water and 5% aqueous sulfuric acid, it retained its strength at least as well as its competitors. Pipe runs which have been in service in the field since 1972 have performed satisfactorily.

B. Economics

The attractiveness of an investment in resource recovery depends on the conditions at a particular site. These range from site characteristics through availability of utilities to the type and concentration of markets for the products.

We have based one set of economics on a semiworks plant in an existing resource recovery complex in Baltimore County, Maryland. Most of the local conditions were known, but there was no opportunity for a market survey. The plant would produce about 6900 metric tons or 93 kilometers (7600 short tons or 58 miles) of GPC pipe per year. A preliminary estimate of the installed capital is \$1.65 million. The return on this investment would be about 11% after taxes.

The smallest full-scale plant would probably make about 24,400 metric tons (27,000 short tons) of GPC pipe per year. Scaling up from the previous estimate, its installed capital would be about \$3.44 million and the return on investment would be about 32% after taxes.

C. Problem Areas

When the monomer concentration is reduced to cut costs, the pipe retains its strength, but it often develops small leaks under low pressure. To pass the hydrostatic test we have provided for a seal coat in the smaller sizes, where wall thicknesses are low. Improved vibration might be a more economical answer, but this has not been proved.

Vibration itself remains a problem. The greatest length of pipe we have cast to date is 1.52 m (5 ft). Coupling vibrators to a 3.96-m (13 ft) casting might require methods different from those currently in use. Finger vibrators would probably be the most direct method, at least for the larger-sized pipe.

The O-ring joint which is incorporated in the present 304.8-mm-i.d. (12 in.) pipe section did not satisfy the leakage requirement. Although we were able to meet specifications by calking the joint, this would probably be more expensive than redesigning the joint to take a larger O ring.

The rate of wear in the glass mill was the subject of one set of runs and this covered only the hammers. For a firmer estimate of mill maintenance, longer runs and study of other parts of the mill are required.

D. Process and Product Improvements

New polyesters and monomers of other types come on the market frequently. These should be screened, using cylindrical samples. If compressive strength and release stress are close to those of the present mix, they should be tried in pipe samples and a rough economic comparison should be made.

Preliminary tests to evaluate the GPC mix modified by the addition of a wetting agent looked promising. These tests should be reproduced and then extended to pipe samples.

Centrifugal casting might reduce voids and improve the orientation of the glass particles to handle the bearing stress. This in turn might permit reductions in wall thicknesses which would pay for the cost of the casting equipment and improve the economics.

E. Energy Conservation

A preliminary comparison shows that the ultimate energy requirement for the raw materials in GPC pipe is between 2.8 and 30.2% lower per unit length than vitrified clay pipe, depending on the size. Further reductions in monomer content or wall thickness of GPC are likely at this early stage in its development. They would make this comparison more favorable.

ACKNOWLEDGMENTS

The authors wish to acknowledge the helpful aid in program planning of Meyer Steinberg, Head, Process Sciences Division, Brookhaven National Laboratory, and Robert S. Turley, President, Teledyne National. Thanks are also due to Jack Fontana, James Amaro, George Arnold, Barry Galen, and Donald Horne of Brookhaven National Laboratory for their work in monomer selection, sample fabrication, and performance of tests on the numerous specimens prepared during the course of the experimental effort.

REFERENCES

1. M. Beller and M. Steinberg, Glass Polymer Composite, BNL 17555, January 1973.
2. R. S. Lindstrom and J. Milgrom, Glass Polymer Composite Sewer Pipe, an Initial Evaluation of its Commercial Potential, Arthur D. Little, Inc., C-74228, 1972.
3. M. Steinberg, L. E. Kukacka, M. M. Small, and B. Manowitz, Promoting the Utilization of Solid Waste Glass Polymer Composite Technology in the Public and Private Sector, BNL 19394, October 1974.
4. Fourth Report to Congress - Resource Recovery and Waste Reduction, EPA Office of Solid Waste, SW-600, August 1, 1977.
5. K. J. Liles and M. E. Tyrrell, Waste Glass as a Raw Material for Lightweight Aggregate, Bureau of Mines Report of Investigation 8104, 1976.
6. P. W. Johnson and J. A. Barclay, Economic Studies of the Use of the Glass Fraction from Municipal Incinerator Residues, Bureau of Mines IC 8567, 1973.
7. A. H. Goode and M. E. Tyrrell, Trans.AIME 256, 303 (1974).
8. U. S. Patent 3,856,054, Glass Polymer Composites, M. Steinberg, P. Colombo, and G. Farber, assigned to U.S. AEC, December 24, 1974.
9. R. H. Perry and C. H. Chilton, Editors, Chemical Engineers' Handbook, Fifth Edition, McGraw Hill, New York, 1973.
10. Development of a Glass Polymer Composite Sewer Pipe from Waste Glass, Progress Report No. 7, January-March 1978, p. 8. BNL 50835, 1978.
11. 1978 Annual Book of ASTM Standards, Part 16, American Society for Testing and Materials, Philadelphia, 1978.
12. Baker, C. A., Polymer Concrete: A Chemically Inert Structural Material, Humes Limited, Melbourne, Australia, 1973.
13. Baltimore County Department of Public Works, Annual Report for Fiscal Year 1971-1972.
14. H. C. Bauman, Fundamentals of Cost Engineering In the Chemical Industry, Reinhold, New York, 1964.
15. K. M. Guthrie, Process Plant Estimating, Evaluation and Control, Craftsman Book Company of America, Los Angeles, 1974.
16. G. Moselle, Editor, National Construction Estimator, 27th Ed. Craftsman Book Company, Solana Beach, California, 1978.

REFERENCES (Cont.)

17. Chemical Engineering, Economic Indicator, All Issues, McGraw Hill, New York.
18. T. C. Ponder, U.S. Styrene: More Growth with Less Plants, Hydrocarbon Processing, 137, July 1977.
19. Gordian Report, PB-243614, Vol 3, p. 13, June 1974
20. M. D. Goldberg, Editor, Energy Model Data Base, BNL 19200, 1975.