BNL--33019

DE83 015199

BNL-33019
INFORMAL REPORT

DESIGN AND FABRICATION OF POLYMER-CONCRETE-LINED PIPE

FOR TESTING IN GEOTHERMAL-ENERGY PROCESSES

FINAL REPORT

Albert O. Kaeding
Principal Investigator

NOTICE
PORTIONS OF THIS REPORT ARE ILLEGIBLE.

It has been reproduced from the best available copy to permit the broadest possible availability.

December 1981

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.

Prepared by the
POLYMER CONCRETE RESEARCH, INC.
FARGO, NORTH DAKOTA
Under Contract No. 529117-S

For the
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

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States nor the United States Department of Energy (DOE), nor Polymer Concrete Research, Inc., nor any of their employees, nor any of their contractors, subcontractors, or 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.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT -----	iii
LIST OF FIGURES-----	iv
LIST OF TABLES-----	vi
LIST OF APPENDICES-----	vii
EXECUTIVE SUMMARY-----	viii
I. INTRODUCTION-----	1
II. PROJECT PILOT PLANT AND LAB STUDIES-----	6
A. Pilot Plant Equipment-----	7
B. Lining Processes-----	16
C. Materials Properties Testing-----	39
III. A PC LINING PLANT FOR STEEL PIPE-----	60
A. Production Plant Specifications-----	60
B. Plant Production Process and Equipment-----	64
IV. THE ECONOMICS OF PC LINED PIPE-----	79
A. Capital Cost-----	79
B. Operating Costs-----	81
C. Return On Investment and Cost to End User-----	84
D. Market Information-----	85
E. Piping in a Geothermal Plant-----	90
V. PLANT SAFETY PROVISIONS-----	92
IV. CONCLUSIONS AND RECOMMENDATIONS-----	96
ACKNOWLEDGMENTS-----	99
REFERENCES-----	100
APPENDICIES-----	102

ABSTRACT

A specific polymer-concrete formulation was applied as a steel pipe liner in response to a need for durable, economical materials for use in contact with high temperature geothermal brine. Processes are described for centrifugally applying the liner to straight pipe, for casting the liner in pipe fittings, and for closure of field joints. Physical properties of the liner materials were measured. Compressive strengths of up to 165.8 MPa (24,045 psi) and splitting tensile strengths of 23.5 MPa (3408 psi) were measured at ambient temperature. Compressive strengths of 24 MPa (3490 psi) and splitting tensile strengths of 2.5 MPa (366 psi) were measured at about 150°C (302°F). A full-scale production plant is described which would be capable of producing about 950 m (3120 ft) of lined 305-mm-diam (12 in.) pipe per day. Capital cost of the plant is estimated to be about \$8.6 million with a calculated return on investment of 15.4%. Cost of piping a geothermal plant with PC and PC-lined steel pipe is calculated to be \$1.21 million, which compares favorably with a similar plant piped with alloy steel piping at a cost of \$1.33 million. Life-cycle cost analysis indicates that the cost of PC-lined steel pipe would be 82% of that of carbon steel pipe over a 20-year plant operating life.

LIST OF FIGURES

1. Temperature and pressure operating limits for various piping materials-----	3
2. Pilot plant PC mixer-----	8
3. Pilot plant pipe spinning machine, right end view-----	9
4. Pilot plant pipe spinning machine, diagonal view-----	10
5. Pilot plant pipe spinning machine, front view-----	11
6. Pilot plant pipe spinning machine, left end view-----	12
7. Pilot plant PC curing oven-----	15
8. Pilot plant curing oven temperature distribution-----	17
9. Section through centrifugally applied pipe lining-----	17
10. End cap and retaining ring-----	19
11. End view of lined pipe-----	20
12. General appearance of lined pipe-----	21
13. Waxed elbow core mold-----	23
14. Core mold being installed in elbow-----	24
15. Spacer cap being placed on elbow -----	25
16. Gauging and trimming end spacer cap-----	26
17. Mixing PC-----	27
18. Elbow mold ready to receive PC-----	28
19. Removing core mold after casting-----	29
20. Core mold partially removed-----	30
21. Components of tee core mold-----	31
22. Elbow and tee mold details-----	32
23. Field jointing coupler-----	34

24. Welding thermograph for coupling-----	34
25. Completed coupler joint-----	36
26. Welding thermograph: direct butt weld-----	37
27. Sawed section through butt welded joint-----	38
28. Field jointing detail-----	40
29. Pipe end with liner beveled for butt welding-----	41
30. Permeability tester for disc specimens-----	43
31. Permeability measuring apparatus for centrifugally cast pipe specimens-----	43
32. Compressive strength of PC vs test temperature after a 4 hour cure-----	46
33. Compressive strength of PC vs test temperature after a 7 hour cure-----	46
34. Compressive strength of PC vs test temperature after a 19 hour cure-----	47
35. Compressive strength of PC vs test temperature after a 90 or 113 hour cure-----	47
36. Splitting tensile strength of PC vs test temperature-----	49
37. Bond strength testing method-----	51
38. Production plant layout-----	62
39. PC pipe lining process diagram-----	65
40. PC mixing and pumping equipment diagram-----	70
41. Pipe filling equipment diagram-----	70
42. Pipe spinning velocities and radial accelerations-----	74
43. Piping spinning machine-----	74
44. Process curing oven-----	77

LIST OF TABLES

1. Elbow and tee liner permeability-----	44
2. Results of bond shear strength tests-----	51
3. Results of thermal shock tests-----	51
4. Production aggregate gradation-----	53
5. Grading requirements for silica aggregates-----	55
6. Design production plant specifications-----	63
7. Polymer concrete raw material useage-----	63
8. Plant equipment list-----	80
9. Plant capital cost estimate-----	82
10. Monthly raw material cost-----	82
11. Annual plant operating cost estimate-----	83
12. Simplified calculation of return on investment, full scale plant-----	86
13. PC lined pipe selling price estimate-----	86
14. Comparative cost of piping-----	87
15. 20-Year life cycle cost comparison-----	89
16. Life cycle cost comparison-----	91
17. PC lined pipe data-----	91
18. Geothermal plant piping cost comparison-----	91
19. Hazard characteristics of chemicals-----	93
20. Process Safety Design Criteria -----	95

LIST OF APPENDICES

Appendix A - Results of Mechanical Properties Tests

A1. Effects of curing time and type of peroxide used on high temperature compressive strengths

A2. Splitting tensile strength at various temperatures

Appendix B - Partial list of material sources

EXECUTIVE SUMMARY

One of the more serious technical problems encountered in economic utilization of geothermal energy is severe corrosion and scaling of the geothermal fluid piping. As fluid pressure and recovery temperatures are increased (improving efficiency), dissolved solids content increases producing high corrosion rates and excessive scaling of carbon steels and many alloy steels. To alleviate these problems, Brookhaven National Laboratory (BNL) developed and tested a specific polymer concrete (PC) capable of withstanding brine, flashing brine, and steam at temperatures up to about 260°C (500°F).¹

Polymer Concrete Research, Inc. (PCR), under this contract, developed equipment and procedures to produce full-scale PC-lined steel pipe for continued testing in geothermal environments. This report describes the details of a full-scale pipe lining plant capable of producing up to about 1,500 m (5000 ft) per day of PC-lined steel pipe. Capital investment to construct a plant of this scale is estimated to be about \$8.6 million (Autumn, 1981 dollars) with a return on investment of approximately 15.4% if all product produced is sold. Applying the PC liner to schedule 40 carbon steel pipe would increase its selling price by 73%. However, when schedule 10 steel pipe with a PC liner is used in place of schedule 40 pipe, where the extra wall thickness is provided as a corrosion allowance, the price to the user may be as much as 20% less for the lined pipe.

During the course of the project, various mechanical properties of the PC liner material were tested at ambient and at elevated temperatures. Ambient temperature compressive strengths of about 165 MPa (24,000 psi) were measured with about 9, 7, and 4% strength retention at 121°C (250°F),

150°C (302°F), and 200°C (392°F), respectively. Splitting tensile strengths of 25.4 MPa (3681 psi) at ambient temperature with 11% retention at 160°C (320°F) and bond strengths to the steel pipe of 3.5 MPa (510 psi) were also measured. Bond strengths of 2.59 MPa (375 psi) were measured about five thermal shock cycles where pipes preheated to 260°C (500°F) were immersed in 4°C (40°F) fluid. The results of these tests indicate that acceptable performance in service may be expected.

The selected lining method entails centrifugal application of the PC liner to the steel pipe at spinning velocities of about 1700 rpm. Elbows and tees were also lined successfully by using an interior form and casting the liner under vibration. Three different methods of field jointing are available, including direct butt welding, standard steel flanges, and a special steel coupler which is assembled and welded in the field.

I. INTRODUCTION

As the result of a recognized limit to U.S. and worldwide petroleum reserves over the past several years, the U.S. Government and private industry have been researching alternative energy sources. One such source being investigated is the extraction of heat energy from the earth, or geothermal energy. Worldwide commercial utilization of geothermal energy was reported to be over 7000 megawatts (thermal) in 1979.² A 1980 survey performed by EPRI indicated that current geothermal electricity generation in North American was 663 megawatts and projected a growth to about 10,000 megawatts by the year 2000. In addition, potential direct utilization of geothermal energy by a wide range of industries was indicated.³

One of the more serious technical problems encountered in economic utilization of geothermal energy is severe corrosion and scaling of the geothermal fluid piping. As fluid pressure and recovery temperatures are increased (improving efficiency), the potential for high salt content also increases. The dissolved solids produce high corrosion rates and excessive scaling of carbon steels and many alloy steels.

Corrosion studies of several different steels exposed to high temperature, high salinity wellhead brine flow in the Salton Sea Geothermal

Field were made by the Lawrence Livermore Laboratory. A mild steel specimen (AISI 1009) indicated corrosion rates of 1,65 mm/year (65 mil/year) while a chrome moly steel (ASTM A 387-9) indicated 0.13 mm/year (0.5 mil/year). This test was performed using a six-month exposure. Chrome-moly steels, however, cost about four to six times as much as the carbon steels, substantially increasing plant construction costs.³ Other studies have related corrosion to fluid pH and temperature and indicate that the use of expensive special materials is warranted when fluid pH is less than 6 and the temperature is about 120°C (248°F).³

Potential industrial application of geothermal energy using fluids at 40°C to 70°C (104°F to 158°F) can use various forms of plastic piping which are not subject to corrosion by the fluids. Low temperature space heating, greenhousing, and various other agricultural applications can make use of systems at these temperatures. Various curing and drying applications along with high temperature space heating require fluid temperatures up to 90°C (194°F). Normal plastic piping systems are not recommended above about 70°C (158°F), but fiber-reinforced plastic (FRP) piping is available that can operate at temperatures of up to 90°C (194°F). Again, corrosion resistance of FRP piping is good. Above 90°C (194°F), serviceable piping has been limited to metallic types. Many industrial processes require fluid in this temperature range. For electricity generation, fluid temperatures of 140°C to 150°C (284°F to 302°F) are required. Mild and alloy steels are acceptable within the constraints discussed earlier. But, in contrast to plastic, corrosion is a major problem.

The operating limits of various kinds of piping are illustrated graphically in Figure 1. Data for this figure were obtained from product literature of manufacturers producing the various types of pipe. Limits

Figure 1. Temperature and pressure operating limits for various piping materials.

shown for PC-lined steel pipe were taken from the requirements of this contract.

In 1972, BNL demonstrated that a polymer-silica sand-portland cement-aggregate composite (PC) with a particular formulation was suitable for service up to temperatures of 175°C (347°F). Since then, formulation changes have resulted in a PC material capable of withstanding brine, flashing brine, and steam at temperatures up to 260°C (500°F).²

BNL has completed extensive laboratory studies of this material and have long-term test data available. The generic name for the family of materials which are polymer-silica sand-portland cement-aggregate composites is polymer concrete (PC). The particular formulation exhibiting acceptable properties selected for this application consists of the following ingredients.

Monomer portion (12 wt. % of total mix)	
Styrene	52.6 wt. % (of monomer)
Acrylonitrile (ACN)	34.4 wt. % (of monomer)
Trimethylpropane trimethacrylate (TMPTMA)	8.6 wt. % (of monomer)
Silane A-174	1.0 wt. % (of monomer)
Benzoyl peroxide (BP)	1.9 wt. % (of monomer)
di-tert-butyl peroxide (DTBP)	0.5 wt. % (of monomer)
Dimethyl aniline (DMA)	1.0 wt. % (of monomer)
Aggregate portion (88 wt. % of total mix)	
Blended silica sand	70.0 wt. % (of aggregate)
Type III portland cement	30.0 wt. % (of aggregate)

For high temperature, 250°C (482°F), applications currently requiring chrome-moly steel piping, this PC provides an economical substitute. For operating pressures up to 1000 kPa (145 psig), properly constructed PC pipe can be used.⁴ In pressure regions of 1000 to 4000 kPa (145 to 580 psig), the PC can be applied as a liner to mild steel pipe. For this application, the PC provides corrosion and scaling protection, while the steel pipe contains the forces generated by the internal pressure.

PC production processes are similar to portland cement concrete production processes, with a few notable exceptions. First, PC cures much more rapidly with initial set occurring in 2 to 4 hours; 80 to 90% of the final strength is obtained within this time. Final set is accomplished in a process oven in approximately 8 hours at 180° to 190°C (356° to 374°F).

Monomer constituents of the mix are tenacious adhesives to most materials. This property is a definite asset in bonding the PC liner to the steel pipe but has the disadvantage of causing the PC to stick to mold materials. Also, the monomeric components are generally classed as flammable liquids which require the use of explosion-proof equipment, non-sparking tools, and various other safety-related procedures and equipment.

Acrylonitrile, a major component of the mix, has been classified as a carcinogen by the National Institute of Occupational Safety and Health (NIOSH). Atmospheric vapor levels and personnel exposure are severely restricted by the OSHA standards. These require the use of specific personal protective gear as a minimum during prototype work. Design of production equipment suitable for total enclosure is warranted for personnel safety.

Lining carbon steel pipe with PC has been successfully demonstrated by ENL on a laboratory scale. Field trials by ENL have shown that the PC formula described can protect carbon steel from corrosion and lessen the adherence of calcite-type scale when exposed to geothermal fluid and process conditions.²

Because economical, corrosion-resistant piping for geothermal plants is needed, this project was undertaken to demonstrate new materials with potential to fill this need. In order to be a successful commercial product, PC-lined steel pipe has to meet several criteria. First, the product must be competitive with acceptable alternatives and producible in a

manufacturing plant, and it must consistently meet certain physical standards in production. It must also be suitable for field installation by contractors normally engaged in plant construction and maintenance. Finally, its durability must be demonstrated in full-scale field trials.

The goals of this project were to formulate, test, and demonstrate these capabilities of PC-lined steel pipe. Finally, should this product gain acceptance within the geothermal energy development industry, a source for the pipe is required. PCR, as a part of its pilot plant work on this project, has developed the capability to manufacture and supply this pipe to industry.

II. PROJECT PILOT PLANT AND LABORATORY STUDIES

Since use of the specified PC formulation as a pipe liner had only been achieved by ENL on a laboratory scale to date, equipment procedures for large-scale pipe production had to be developed. Development of special processing methods and equipment to match the laboratory methods were required. Fundamentally, the process consisted of, first, mixing together all the specified ingredients. Next, the mixed PC was applied to the inside of steel pipe which had been prepared by sandblasting. A 4- to 8-hour primary curing period at ambient temperature followed, and then the lined pipe was heated to 180°C (374°F) for 8 hours for elevated temperature secondary curing. After primary curing, post-cure finishing was done by grinding bevels onto the liner ends for field jointing and grinding radiuses into the liner at form intersections in the tees. These surfaces were then dressed with a PC slurry after secondary curing.

A. Pilot Plant Equipment

Three special pieces of process equipment were required for the Pilot Plant to prepare and install the PC liner: a PC mixer, a pipe spinning machine, and a process curing oven. In addition, other equipment requirements included monomer and chemical handling facilities, aggregate storage and batching equipment, batching scales, and ventilation equipment. In-plant and off-the-shelf equipment was used.

1. The PC Mixer. For the small quantities required for each trial run, a paddle-type batch mixer was used as shown in Figure 2. This mixer uses a polyethylene drum capable of holding approximately 30 kg (65 lb) of PC. The paddle is lowered into the mix and turned at 115 rpm using the 746-W (1 hp) explosion-proof motor with a right-angle drive. This mixer had a pneumatically actuated raising and lowering mechanism to remove the mixer paddle from the batch. The drum diameter was 30 cm (12 in.) and the height was 37 cm (14.5 in.).

2. The Pipe Spinning Machine. Figures 3 to 6 illustrate the pipe spinning machine used for this project. The machine consists principally of a rigid base frame, a driving shaft with a variable speed motor, and an idler shaft. Each shaft has a set of steel trunions which support the pipe during spinning. There is also a booster motor to begin spinning and to distribute the PC mix throughout the pipe before the high-speed spinning takes place. In Figure 3 the variable speed motor and the drive control unit are visible, along with one end of the pipe being spun and the pipe support trunions.

Figure 4 shows the side of the machine where the booster motor is apparent with the driving shaft and its support bearings. The vertical guards and braces provide a safety confinement for the pipe while it is spinning. A rod is passed through the holes in the top of the guards above the pipe being spun to prevent the pipe from jumping out of the machine during the high rpm phase of the spinning.

Figure 2. Pilot plant PC mixer.

Figure 3. Pilot plant pipe spinning machine, right end view.

Figure 4. Pilot plant pipe spinning machine, diagonal view.

Figure 5. Pilot plant pipe spinning machine, front view.

Figure 6. Pilot plant pipe spinning machine, left end view.

Figure 5 shows a direct side view where the proportions of the machine are apparent. The section of pipe resting in the machine is 305 mm (12 in.) diameter by 1.5 (5 ft) long.

Figure 6 shows the starting motor assembly. This motor is hinged with its weight providing belt-tightening capacity for a belt running from the motor to the driving shaft. Raising the motor releases the belt so that the variable speed motor can take over drive functions. The output of this motor is 115 rmp through a right-angle gear box. Also visible in this photo is a bearing adjustment for the idler shaft. Adjustment is necessary to assure that the driving and idler shafts are exactly parallel. If they are not parallel, the pipe will drift in one direction or another during spinning.

Since this machine was built for experimental prototype work, an additional fixture was attached to the end of the driven shaft, as seen in Figure 6. This fixture is set up to receive a short section of pipe for testing purposes.

During early spinning trials, the variable speed dc motor used to drive the machine appeared to be inadequate for initially accelerating the pipe to the correct spinning speed. For this reason, the starter motor described was added. Subsequent work on the motor controller for the variable-speed motor revealed that the motor was improperly fused. Installation of larger fuses corrected the machine start-up problems and the booster motor was no longer required, although its use provided a stabilizing effect on start-up.

The spinning machine was constructed with several features which permit considerable flexibility in the placement process. The driving shaft is powered by a direct-coupled variable speed dc motor so that radial acceleration is continuously adjustable from 0 to 500 g. The trunions on both shafts can be changed to different diameters. This permits spinning pipes with a large variety of sizes.

All rotating components of the spinning machine must be carefully balanced, since they have a very high mass and inertia. Spring-mounted and dampened containment rollers above the pipe should be included on a production machine to assure safety during spinning. Stationary portions of the machine must have a mass at least twice that of all rotating components to further assure stability.

Accessories to the machine include a direct reading optical tachometer and speed controls to operate the motor over its entire range.

3. The Process Curing Oven. Secondary curing was done with a batch oven constructed for the project. The oven's internal dimensions measured 2.4 m (7 ft 10 in.) wide by 0.9 m (3 ft) high by 0.6 m (2 ft) deep. The oven was equipped inside with pipe rests to support the pipes and with three 1500-W heating elements, each controlled by a thermostatic controller with a probe in the oven. It also had an internally circulating fan to distribute the hot air evenly throughout the oven. The shell of the oven was insulated with 6 inches of high-temperature insulation. In Figure 7, the oven control box is evident in the upper left corner. The entire front of the oven was removable for loading and unloading specimens. On the upper right-hand corner, the oven was supplied with an air fitting and regulator so that ventilating air could be introduced to limit styrene vapor buildup.

During initial trials, the curing oven constructed for the project performed well. During the fourth curing cycle, however, oven temperature control was lost and samples being cured were inadvertently heated to temperatures over 205°C (400°F) for 8 to 10 hours. As a result, the sample surfaces were degraded.

To remedy this problem and to control temperature stratification within the oven, the single controller was replaced with two controllers,

Figure 7. Pilot plant PC curing oven.

each controlling one heating element. One of the three heating elements initially installed in the oven was disconnected. Finally, the circulating fan noted above was added inside the oven to prevent air stratification. Temperature measurements were taken at several points within the oven to determine differentials after these modifications. As shown in Figure 8, the highest temperature recorded was 170°C (338°F) directly above one of the heating elements, and the lowest temperature was 162°C (324°F) measured above the circulating fan location. The oven is therefore operating with a $\pm 4^{\circ}\text{C}$ ($\pm 7^{\circ}\text{F}$) differential, or $\pm 2\%$ of the set temperature.

B. Lining Processes

1. Straight Pipe Lining. All straight pipe liners were applied centrifugally using the equipment illustrated previously. Each 1.5-m-long (5 ft) by 304.8-mm (12 in.) pipe section was sandblasted prior to lining. Preweighed 6.0-kg (13.2 lb) PC batches were mixed and placed inside the pipe. The end caps were then attached and the pipe was spun, first at 115 rpm to distribute the material and then at 1700 rpm for 2 minutes to compact the PC. It was found that even when the PC was prepared with 9 wt % monomer content, a fluid slurry of monomer and cement remained in the pipe after compaction. Approximately 0.5 kg (1.1 lb) of this slurry was drained from the pipe immediately after spinning. Actual polymer content of the finished liner was determined to be 4.45 wt % based on loss on ignition tests. A 4- to 8-hour primary cure at ambient temperature was then done with the end caps left in place. Even with the end caps on, some monomer depletion occurred at the surface, leaving a 1.6-mm (1/16 in.), or less, layer of dry fines over the inside surface of the pipe, as shown in Figure 9. This layer is easily removed with a light honing after the primary cure is completed.

Figure 8. Pilot plant curing oven temperature distribution.

Figure 9. Section through centrifugally applied pipe lining.

The pipe was then placed in the secondary curing oven where the temperature was raised to 180°C (374°F) over a period of 3 hours. This temperature was maintained for 8 hours, after which the pipe was cooled to ambient conditions inside the closed oven.

Figure 10 shows the end of a 304.8-mm-diam (12 in.) pipe specimen prepared for spinning. The collar evident was attached to the pipe with set screws to limit lateral drift of the pipe during spinning. After the PC mix is introduced into a pipe section, the end cap (shown in place) is attached, using a rod that extends through the pipe to the opposite end. This cap is plate steel with alignment dogs around its perimeter, and a sheet lead gasket between the pipe surface and the cap. Figures 11 and 12 show the appearance of the liner in place after primary and secondary curing.

2. Elbow and Tee Lining. Initially, an attempt was made to line the elbows and tees by troweling on a PC mortar. This process had been successfully demonstrated with a portland cement mortar. While trowel application of a portland cement mortar could be duplicated, successful application of a PC mortar could not be achieved. The PC formulation specified was modified within limits permitted by BNL during these attempts. Mixes with low (<10 wt %) monomer content would not properly wet out the pipe surface resulting in loss of bond during curing. Mixes with higher monomer contents would sag on overhead and vertical surfaces before primary cure occurred, even when small amounts (0.2 wt %) of thixotropic agents were added.

After the work to develop a trowel-on liner was completed, efforts to develop a molded liner were begun. Two approaches were undertaken, one to develop a disposable inside mold and the other to prepare a removable core. Both methods were successfully applied.

The disposable molds were made up of paraffin-impregnated paper or cardboard. After casting and initial curing of a liner, the mold was

Figure 10. End cap and retaining ring.

Figure 11. End view of lined pipe.

Figure 12. General appearance of lined pipe.

peeled off the inside surface. Removal can be facilitated by heating the pipe to the melting point of the paraffin. This method has good potential for production operations, as individual liners are inexpensive and easy to use. Special forming mandrels are required to make up the elbow molds, however, so trials were made only on tees.

Removable and reusable cores were made of fiberglass with a paraffin separating layer. Building the elbow molds was accomplished by first lining a pipe elbow with a layer of paraffin that was about 1.3 cm (0.5 in.) thick. A fiberglass core was built up against this wax liner using hand layup methods. The completed core was removed by melting the wax and sliding the core out.

Before each use, the fiberglass cores were coated with a 0.65-cm (0.25 in.) layer of paraffin (Figure 13) to facilitate removal after casting. This core was then inserted into a sandblasted fitting (Figure 14) and fiberglass end spacers applied (Figure 15). Figure 16 illustrates the end spacers being fabricated. PC was then mixed (Figure 17) and placed into the fitting. Compaction was accomplished by attaching a vibrator to the surface of the fitting (Figure 18). After the primary cure was completed, the fitting was heated to melt the paraffin parting layer and the core was removed (Figures 19 and 20).

Tees were lined in a manner similar to that used on the elbows illustrated except that a two-part core was used (Figure 21). This resulted in a sharp-edged turn being formed at the intersection of the two core segments as shown in the cutaway detail in Figure 22. This sharp edge must then be ground to a suitable radius before secondary curing. Sectional details of both the elbow and the tee molds are shown in Figure 22.

3. Field Jointing Methods. Methods to provide liner continuity in the field were also studied. Six different basic configurations were

Figure 13. Waxed elbow core mold.

Figure 14. Core mold being installed in elbow.

Figure 15. Spacer cap being placed on elbow.

Figure 16. Gauging and trimming end spacer cap.

Figure 17. Mixing PC

Figure 18. Elbow mold ready to receive PC.

Figure 19. Removing core mold after casting elbow liner.

Figure 20. Core mold partially removed

Figure 21. Components of tee core mold.

Cutaway of Tee Showing 2 Part
Mold Assembly

Cutaway of Elbow Showing Mold Assembly

Figure 22. Elbow and tee mold details.

examined, and three were tested. To be considered satisfactory, a joint procedure must provide impermeable continuity for the liner and must be simple enough to be applied consistently under field conditions.

Two of the methods considered required shop fabrication at each pipe end and some form of compressible gasket to seal the liner ends at the time of field installation. The first method was conventional forged steel pipe flanges.

Flanged joints are very adaptable to lined-pipe installation. Initially, this was the preferred method of jointing. Installation is simple and positive. A seal is provided by compressing a gasket into the joint space as the joint is assembled in the field. Since the mating flange faces are machined, the PC liner must be ground and dressed to provide a suitable gasket land. This method is relatively expensive to use. The flanged joint was not selected for detailed testing for this reason.

The other prefabricated joint consisted of a steel coupler which is field welded to steel retainer rings on the pipe spools. Details of this joint are shown in Figure 23.

One of the expected drawbacks to field welding was the damage that might be done to the PC liner immediately adjacent to the weld line by the welding heat. The advantage of the welded coupler joint is the separation and shielding between the welding point and the pipe liner. This method was tested and thermographs were taken to determine the maximum temperature encountered at the steel-liner interface. A thermo-couple probe was embedded at the interface, approximately 2.5 cm (1 in.) to the side of the weld line. The maximum temperature recorded (Figure 24) was about 155°C (311°F), which is within the operating temperature limits of the PC liner.

Figure 23. Field jointing coupler.

Figure 24. Welding thermograph for coupling.

This joint is installed by inserting the pipe ends in the coupler and hydraulically closing the joint to compress a molded gasket which is on the inside of the coupler.⁵ The standard coupler is supplied with an elastomeric gasket unsuitable for use at high temperature,⁵ but the manufacturer stated that another gasket material was available which would provide service at the required temperatures. Figure 25 shows a completed coupler joint. This method of assembly is used commonly in plastic-lined pipelines and also for jointing cement-lined pipe in some oil field recovery piping.

During the course of the project, a poll was taken of potential users on their preferred field jointing methods.⁶ The consensus was that a standard butt-welded field joint would be preferred. Since relatively low temperatures were encountered in the coupler welding tests, a similar test was conducted for direct butt-welded joints. Thermographs were again taken and the results are shown in Figure 26. The maximum temperature recorded was about 170°C (338°F) after the third welding pass. The highest single pass temperature rise was 95°C (170°F), so that if the weld line was cooled to ambient temperature between passes, relatively low temperature rises within the PC may be maintained.

After welding, the joint was sawed to examine the PC-steel interface. Delamination was noted approximately 1.3 cm (0.5 in.) to each side of the weld line. The PC did not appear to be charred or otherwise degraded (Figure 27).

Field closure of the PC liner must be performed to provide liner continuity. This was done by inserting an inflatable bladder at the joint and sealing it to the liner by inflating it. A PC slurry was then injected into the joint and allowed to polymerize, completing the joint. The PC slurry used consisted of 33% Type III portland cement, 33% silica flour,

Figure 25. Completed coupler joint.

Note: Butt welding test performed on 6 inch diameter steel pipe lined with 3/8 inch polymer concrete. Thermocouple sensor located at steel-pc interface, 1 inch from weld line.

Figure 26. Welding thermograph:direct butt weld.

Figure 27. Sawed section through butt welded joint.

and 34% of the specified monomer. This procedure is illustrated in Figure 28. Drawbacks to this closure method include the need to leave the bladder in place until initial polymerization has taken place (1 hour) and the possibility of voids and cracking in the slurry. Another is the need to handle a PC mixture in the field. Figure 29 shows the liner and pipe ends prepared for butt welding.

C. Materials Properties Testing

Since the steel shell of the pipe can be expected to carry all or most of the mechanical stresses, high physical strengths are not of primary concern, but were measured for purposes of quality control. Bond strength between the PC and the steel pipe is important, however, since a securely bonded liner is less likely to crack during thermal cycling in service.

1. Permeability. Since the purpose of the liner is to provide a barrier between the geothermal fluid carried in the pipe and the mild steel shell, the permeability coefficient of the lining material is important. Permeability was measured on samples that represent material as placed in the elbows and tees and on materials representative of the centrifugally applied pipe lining. The difference in the two materials was in the method of compaction of the liner. The elbow and tee liners were compacted using vibration applied to the steel shell during and after filling. Compaction of the straight pipe liner was by the centrifugal force applied during spinning.

For the tests on the elbow and tee lining material, cylindrical specimens, 76.2-mm diam by 142.4-mm long (3 by 6 in.), were cast and vibrated using the lining material.

A 76.2-mm (3 in.) disk, about 10-mm (0.4 in.) thick, was sliced out of the cylinders and mounted in the apparatus shown in Figure 30. The permeability coefficient was calculated, using Darcy's Law, to be 22 x

Figure 28. Field jointing detail.

Figure 29. Pipe end with liner beveled for butt welding.

10^{-12} cm/sec (817×10^{-12} in./sec). Earlier tests on PC that visually exhibited a large number of voids had a permeability coefficient of 28×10^{-12} cm/sec (11×10^{-12} in./sec), while samples with few visible voids had a coefficient of 13×10^{-12} cm/sec (5.1×10^{-12} in./sec).⁷ The permeability of normal portland cement concrete is about 5.12×10^{-10} cm/sec or about 23 times more permeable.⁸

Specimens representative of centrifugally applied lining were prepared by spinning 142-mm-diam (6 in.) pipe sections, removing the liner from the steel shell, and slicing off 142-mm-long (6 in.) segments. These segments were then mounted in the apparatus shown in Figure 31 and tested under a constant head of 42.8-m (142 ft) H_2O . Usable data were not obtained from this test since a watertight joint between the apparatus and the pipe could not be obtained. After several trials the test procedure was abandoned. Data and results from the permeability tests are shown in Table 1.

2. Compressive Strength. Although the liner will not be required to withstand high physical stresses, it must maintain its integrity while conducting high temperature flowing brine. PC formulations with the same ingredients in mix ratios similar to those used for this project have been tested by ENL. Samples exposed to flowing brine at $135^{\circ}C$ for 16 months did not exhibit any appreciable deterioration. Specimen strength increased to approximately 200% of its initial value (88.5 MPa) (12,835 psi) during the exposure. This increase is attributed to gradual hydration of the portland cement when immersed in the hot brine. After exposure, compressive strength of 136 MPa (19,735 psi) was measured at $150^{\circ}C$ ($302^{\circ}F$) test temperature. Before exposure, the compressive strength of a similar formulation was about 55 MPa (7,980 psi) at $150^{\circ}C$ test temperature.⁹

PCR prepared PC formulations for the liners using the material ratios indicated. After curing, compressive strengths were measured, using methods similar to ASTM C-39, on cylindrical specimens, 76.2-mm-diam by

Figure 30. Permeability tester for disc specimens.

Figure 31. Permeability measuring apparatus for centrifugally cast pipe specimens.

Table 1
Elbow and Tee Liner Permeability

7.62 cm diam (3 in.) disk specimens

Test No.	Thickness, cm	Avg vol flow, cc/sec	Density, kg/m ³	Permeability coefficient, cm/sec
1	1.11	1.94×10^{-6}	2355	13.32×10^{-12}
2	1.19	3.04×10^{-6}	2329	22.38×10^{-12}
3	0.95	4.74×10^{-6}	2231	27.86×10^{-12}
4	0.95	16.30×10^{-6}	--	37.80×10^{-12} *

*The permeometer is suspected of leaking during the test.

142.4-mm long (3 x 6 in.), at temperatures varying from ambient to 260°C (500°F).¹⁰ The results of these tests are shown in Figures 32 through 35. While ambient temperature strengths were higher than reported by BNL, 165.8 MPa (24,045 psi) versus 88.5 MPa (12,836 psi), they were only about 44% of the reported strength at 150°C. At a test temperature of 260°C, compressive strengths of 3.9 to 6.4 MPa (566 to 926 psi) were measured. This is approximately 40 to 65% those reported by BNL at this temperature.⁹ Lindsey Industries reported compressive strengths of 55 MPa (8,000 psi) at 150°C (302°F) compared with strengths up to 24 MPa (3490 psi) determined in PCR tests. Lindsey Industries also reported low strength retention in earlier tests with 24 MPa (3500 psi) at 150°C (302°F). Researchers at Lindsey Industries determined that these lower strengths were the result of inadequate secondary curing at elevated temperature.⁴

In an attempt to determine if inadequate secondary curing may also be affecting compressive strengths determined by PCR, curing times were extended and additional measurements taken. Ambient temperature strength improvements were noted when the curing time was extended from 4 to 7 hours. Additional curing time, up to 113 hours, showed no additional improvement at ambient temperature. At 260°C (500°F), there was a gradual strength improvement as the curing times were extended.

After curing at 180°C (374°F) for 66 hours, a strength of 6.1 MPa (884 psi) was determined compared with 3.6 MPa (519 psi) after only 4 hours at curing temperature. In another series, only a 3% improvement was noted for a 113-hour vs a 4-hour cure. This improvement is not statistically significant, as sample variability was +15% at this test temperature.

PCR used two different forms of BP for initiating polymerization. One form, BP-40, contained 60% of an organic plastisizer. Since this is

Figure 32. Compressive strength of PC vs test temperature after a 4 hour cure.

Figure 33. Compressive strength of PC vs test temperature after a 7 hour cure.

Figure 34. Compressive strength of PC vs test temperature after a 19 hour cure.

Figure 35. Compressive strength of PC vs test temperature after a 90 or 113 hour cure.

a significant portion of the total mix, a series of comparison tests were made to determine if the plastisizer might be affecting the elevated temperature strengths: No such effect was apparent in the results and it therefore appears that the two peroxides may be used interchangeably.

3. Splitting Tensile Strength. Splitting tensile strengths were also measured on 76.2-mm-diam by 142.4-mm-long (3 x 6 in.) cylinders at temperatures varying from 21°C (70°F) to 260°C (500°F), using methods described in ASTM C 496.¹¹ Again, while ambient temperature strengths were 23.5 MPa (3,415 psi), a significant loss in elevated temperature strengths was noted, down to 2.5 MPa (366 psi) at 160°C (320°F). Results show in Figure 36 compare with those obtained by Lindsey Industries when samples were cured at 149°C (300°F) for 4 hours. Lindsey Industries reported substantial strength improvements after curing temperatures were increased 195°C (383°F). PCR cured all samples in this series at 180°C (374°F) indicated oven temperature. An odor of ammonia was emitted by broken samples, indicating conversion of monomers to polymers, but conversion may not have been complete.⁴

PCR was unable to determine a specific cause for the lower elevated temperature strengths measured. As noted, significant changes in PC strength could not be attributed to the type of BP used, and while curing time did affect the strengths measured, low strengths were still evident after extended (113 hr) curing periods. Factors not investigated that may affect elevated strength measurements include curing temperature used, length of specimen exposure to dry elevated temperatures before testing, and exact handling procedures and timing during elevated temperature testing. PCR had insufficient time remaining in the project to research this problem further and suggest that more experience and additional testing under plant conditions may be required to determine the exact cause of the lower strengths.

Figure 36. Splitting tensile strength of PC vs test temperature

Elevated temperature compressive and splitting tensile strengths measured should be adequate for the proposed service since high physical stresses will not be applied to the liner. Another factor considered was a noticeable decrease in the brittleness of the PC when tested at elevated temperatures. Considerably more deformation occurred prior to failure which would permit the PC to yield and transfer the load to the steel pipe wall. In addition, as the portland cement hydrates in service, compressive strengths will increase, improving service durability further.

4. Bond Strength and Thermal Shock. Bond strength between the PC liner and the steel pipe was also tested. Sections of 152.4-mm-diam (6 in.) pipe, centrifugally lined with PC, were loaded in a compression testing machine as shown in Figure 37. Bond strengths were found to be about 3315 kPa (510 psi) under ambient conditions as shown in Table 2. Test number 5 was made on a specimen which included a welded and grouted joint. Similar specimens were subjected to 5 and 10 thermal shock cycles to determine the effect of rapid temperature change on the bond strength. Results shown in Table 3 indicate that 5 cycles of 256°C (460°F) temperature change decreased the bond strength to 35% of its initial value and 10 cycles decreased the bond strength to 22% of its initial value. Results of these tests were extremely variable, with strengths of 345 and 1220 kPa (50 and 177 psi) resulting after 10 cycles. Debonding near the specimen ends is suspected, resulting in a very large end effect. Continuous pipe runs should be able to redistribute the stresses developed more readily and consequently should have higher bond strength retentions.

BNL reported bond strengths of 10.3 MPa (1508 psi) after 90 days' exposure to 280,000 ppm flowing brine at 235°C. No deterioration of the PC or loss of bond to the steel was apparent after the exposure.¹² These results indicate that bond strengths should improve with immersion

Figure 37. Bond strength testing method.

Table 2
Results of Bond Shear Strength Tests

Test No.	Specimen size		Load, KN(kips)	Bond stress, kPa(psi)
	length, cm (in.)	diam, cm (in.)		
1	15.24 (6.0)	15.24 (6.0)	247.3 (55.6)	3392 (492.0)
2	15.24 (6.0)	15.24 (6.0)	266.9 (60.0)	3658 (530.5)
3	17.78 (7.0)	15.24 (6.0)	311.4 (70.0)	3658 (530.5)
4	15.24 (6.0)	15.24 (6.0)	244.7 (55.0)	3354 (486.4)
5	35.3 (13.9)	15.24 (6.0)	427.1 (96.0)	2608 (378.0)

Table 3
Results of Thermal Shock Tests

Test No.	No. cycles	Specimen length, cm (in.)	Temperature range		ΔT °C	Bond stress kPa(psi)
			Upper, °C(°F)	Lower, °C(°F)		
1	0	15.24 (6.0)	control	specimen, ambient	256	3392(492.0)
2	5	19.82 (7.8)	260(500)	4(40)	256	2581(374.3)
3	5	16.76 (6.6)	260(500)	4(40)	256	777(40.2)
4	5	19.05 (7.5)	260(500)	4(40)	256	683(99.0)
5	10	19.82 (7.8)	260(500)	4(40)	256	1220(177.0)
6	10	16.00 (6.3)	260(500)	4(40)	256	345(50.0)

time as the compressive strength did and that end effects are less in greater segment lengths.

5. Raw Material Section. Altogether, 12 different raw materials were used directly in the production mix. Particular characteristics and purities were required for each material to obtain the specified PC liner. Characteristics which will be helpful in specifying and purchasing raw materials are outlined. ASTM references are given in some cases. When using these ASTM standards, they must be qualified by the particular requirements noted for polymer concrete in order to obtain suitable materials. Sources for some of these materials are listed in the Appendix.

6. Aggregates. The durability of PC to geothermal fluids is highly dependent upon the composition of the aggregate. An aggregate blend of mineral silica (SiO_2) and Type III portland cement is required. The silicas should be naturally rounded as sharp-edged particles may adversely affect the strength of the PC.

Proper aggregate grain-size distribution is necessary to obtain a workable mix rheology to obtain low monomer contents and to lessen segregation under centrifugal compaction. For this project, four separate aggregates were blended in the PC mixer. These aggregates consisted of a coarse and a fine silica, a silica flour, and Type III portland cement. The grain-size distribution of each of the aggregates is shown separately in Table 4 as is the calculated combined gradation.

The aggregates should not contain more than 3.0 wt % of clay, friable particles, organic material, or other deleterious substances. Surface moisture on the aggregates will severely reduce the quality of the PC and should, therefore be limited to less than 1.0 wt % of the aggregate. It is recommended that aggregate supplies be routinely tested

Table 4
Production Aggregate Gradation

Aggregate Name	No. 10 silica sand	No. 5 fdry* silica sand	Silica flour	Type III cement	Production blend
wt % of total aggregate	32.4	32.4	5.0	30.0	100.0
10 (20.000)	99.9				100.0
16 (11.800)	86.8				95.5
18 (10.000)	45.3				82.1
20 (0.8500)	2.1				68.1
30 (0.6000)	0.0	100.0			67.4
40 (0.4250)		99.8			67.4
50 (0.3000)		81.6			61.4
60 (0.2500)		55.1			52.9
70 (0.2120)		41.2			48.3
100 (0.1500)		11.2	100.0		38.6
140 (0.1060)		3.6	97.0		36.1
200 (0.0750)		3.2	93.0	100.0	35.7
(0.0050)		0.0	86.0	90.6	31.5
400 (0.0038)			78.0	84.8	29.3
(0.0030)				75.6	22.7
(0.0020)				60.0	18.0
(0.0010)				34.6	10.4
(0.0004)				26.0	7.8

* fdry=foundry

for moisture content by drying samples in an oven to constant weight. Maximum grain size should be limited to one-third the least dimension of the liner being cast. Particle size distribution for the silica portion of the aggregates should be within the limits shown in Table 5. This gradation is best obtained by blending two or more separate aggregates. Addition of a fine silica flour may also be required to obtain the necessary fine gradations. ASTM C 39 may be used for judging the characteristics of the aggregates in other respects.¹⁰

Portland cement is used as a reactive portion of the aggregates, but it is not hydrated as it would be in portland cement concrete. The required reaction appears to take place between tricalcium silicate ($3\text{CaO} \cdot \text{SiO}_2$) in the cement and the vinyl monomers used.² Type III portland cement is high in tricalcium silicate and is an economical source of this material, and for this reason, it is used. Cement is available from many commercial sources and should meet the requirements of Type III portland cement as specified in ASTM C 150.¹³

Selected aggregates should be handled and stored separately. Metering of each aggregate should be by weight, or weight-calibrated volumes using a consistent set of standard conditions for density and volume. After the different grades of aggregates have been mixed, care must be taken during any subsequent handling to prevent segregation.

7. Monomers. Three different monomers are required. All are reactive and flammable organic compounds requiring special handling and storage. A Material Safety Data Sheet (MSDS) and other safety procedures should be obtained from the supplier at the time of purchase. Some detailed safety information is provided in a subsequent chapter. Each monomer should be manufactured to meet applicable standards of quality and should be shipped with adequate levels of the correct polymerization inhibitor.

Table 5
Grading Requirements for Silica Aggregates

Standard sieve size	% passing
2.36 mm (No. 8)	100
1.18 mm (No. 16)	72-90
600 um	48-66
300 um	32-46
150 um	16-32
75 um	4-18

a. Acrylonitrile (ACN)

Formula	$\text{CH}_2 = \text{CH-CN}$
Molecular weight	53.06
Density, g/cc @ 25°C	0.8004
Boiling point, °C @ 760 mm Hg	77.3
Purity, wt % min.	97.0
Inhibitor type	methyl ether of hydroquinone
Inhibitor content	35-45 ppm
Appearance	clear liquid
Odor	faintly pungent
Flash point (tag open cup)	$(0 \pm 2.5)^\circ\text{C}$
Ignition temperature	481°C (898°F)
Viscosity, cP @ 25°C	0.34
Vapor density (Air = 1.0)	3.05 to 17.0

b. Styrene

Formula	$\text{C}_6\text{H}_5\text{CH}:\text{CH}_2$
Molecular weight	104.16
Density, g/cc @ 20°C	0.9059
Boiling point, °C @ 760 mm Hg	145
Purity	97.0
Inhibitor type	<u>tert</u> -butylcatechol
Inhibitor content	10-12 ppm
Appearance	clear liquid
Flash point (tag closed cup)	31°C (87°F)
Explosive limits (Vol % in air)	1.1 to 6.1

c. Trimethylpropane trimethacrylate (TMPTMA)

Formula	$\text{CH}_3-\text{CH}_2-\text{C}-(\text{CH}_2-\text{O}_2\text{C}-\text{C}_2\text{H}_3=\text{CH}_2)_3$
Molecular weight	338.39
Density, g/cc	0.998
Boiling point, °C @ 760 mm Hg	greater than 200
Purity, wt %	97.0
Inhibitor type	hydroquinone
Inhibitor content	60-100 ppm
Appearance	amber, clear liquid
Flash point (Pensky-Martins)	greater than 100°C
Viscosity, cP @ 25°C	25-75

8. Initiators. The polymerization reaction is initiated by the addition of certain organic peroxides. These peroxides decompose in solution with the addition of heat energy to form free radicals which initiate polymerization sites to begin polymer chain growth. Two organic peroxides are required for the specified PC formulation, benzoyl peroxide (BP), and di-tert-butyl peroxide (DTBP).

Benzoyl peroxide is a white granular solid in its pure state. When pure, it is relatively unstable and is, therefore, normally supplied in the presence of a plasticizer which makes it safer to handle. Two forms of BP were used and each is described. When determining the quantity required in a formulation, only the equivalent weight of active BP is considered, i.e., two-and-one-half times as much 40 wt % compound is used as would be used of a 98 wt % compound.

a. Benzoyl peroxide (BP-98)

Form	dry granules
% active oxygen	6.3 minimum
Decomposition point	103° - 105°C
Purity	98%
Formula	$(C_6H_5CO)_2O_2$

b. Benzoyl peroxide (BP-40)

Form	heavy white emulsion
Benzoyl peroxide content	40%
Plasticizer	diisobutyl phthalate
Viscosity @ °C	7000 cP
Specific gravity	1.152
Flash point (SETA Closed)	greater than 93°C

c. Di-tert-butyl peroxide (DTBP)

Form	Clear, water white liquid
Active oxygen, %	10.6 minimum
Viscosity, cP @ 25°C	0.8

Purity	97%
Flash point	Below 27°C
Boiling point, 760 mm Hg	111°C
Formula	$C_8H_{18}O_2$
Boiling point	167°C
Specific gravity	0.785

9. Promoter. The organic peroxide initiators used require the addition of energy to promote free radical formation. For the ambient temperature portion of the curing cycle, a chemical promoter is used to decompose the peroxides. This chemical is dimethyl analine (DMA). Note: Caution must be exercised at all times to prevent DMA from coming in contact with an organic peroxide when not in a dilute solution. Concentrated contact of these two families of chemicals will result in violent or explosive decomposition which is extremely hazardous.

Dimethyl analine (DMA)

Formula	$(CH_2)_2^N Ca H_5$
Appearance	straw to brown liquid
Boiling point	193°C
Density	4.17
Flash point, closed cup	63°C

10. Coupling agent. A chemical coupling agent is added to the PC mix to provide a chemical bond between the silica aggregates and the polymer binder. This coupling agent has reaction sites which are attracted to the surface of the silica grains and other sites which react with the growing polymer chains during polymerization. The characteristics of the coupling agent used are:

Trade name:	A-174 Silane Coupling Agent
Chemical name:	gamma-methacryloxypropyltrimethoxysilane
Formula:	$CH_2=C/CH_3/-C/O/-OCH_2CH_2Si(OCH_3)_3$
Appearance:	straw-colored clear liquid

Specific gravity @ 25°C	1.044
Boiling point @ 760 mm Hg	255°C (491°F)
Flashing point (Pensky-Martins)	88°C (190°F)

11. Polystyrene. All of the monomers used in the PC mix are very low in viscosity (0.34 to 75 cP) which results in a fluid mix. During vibration or compaction, the mix may segregate since the aggregate grains are quite mobile in the low-viscosity monomers. The viscosity of the mix may be increased to lessen this problem by replacing up to 9 wt % of the styrene monomer with polystyrene. Added polystyrene may be specified as follows:

Vicat softening, °C	100 or higher
Tensile strength, MPa	55 or higher
Flexural strength, MPa	85 or higher
Tensile elongation, %	3.0
Rockwell hardness	70
Specific gravity	1.05

12. Steel Pipe. Steel pipe for high pressure/ high temperature applications is available in A53 and A106 ASTM steel grades. Sources contacted indicated that A106 grades are a little more expensive than A53. Normal spool length purchased by users is 12.2-m (40 ft). For 305-mm-diam (12 in.) and larger, a 9.53-mm (0.375 in.) wall is more commonly used than Schedule 40 (10.21-mm wall). Diameters larger than 305-mm (12 in.) are also more commonly purchased with an even English system fractional wall thickness than an actual ASTM schedule wall thickness.

Flanges are available in several classes and styles. Slip-on flanges are forged with a socket to receive the pipe end and then the flange is welded into place using fillet welds. Weld neck flanges are forged to match the pipe end and the welded joint is prepared by a V groove weld at the intersection of the two units. All flange styles are available in

several weight classes with the 300-lb class being suitable for the temperature and pressure conditions specified. At the high operating temperatures and pressures specified, mill test reports should be required. Pipe used for this project was certified as follows:

ASTM A53 GR B

Carbon content, %	0.27
Manganese content, %	0.67
Phosphorus content, %	0.008
Sulfur content, %	0.023
Silicon content, %	—
Ultimate strength	68,600 psi
Yield strength	42,200 psi
Minimum hydrostatic	1540 psi
Elongation, % 50 mm (2 in.)	40.0

III. A PC LINING PLANT FOR STEEL PIPE

The principal objective of this part of the project was to develop and test any special equipment and processes required in a full-scale PC pipe lining plant. Basic requirements of such a plant include the ability to produce a product of consistent quality as simply and economically as possible. As a part of this report, a full-scale production plant has been outlined. Plant layout and equipment selection were based on the results of prototype work done during the course of this project. Wherever possible, off-the-shelf or existing manufacturing equipment was selected for the plant layout.

A. Production Plant Specifications

Potential production capacity was based upon a centrifugal lining operation limited by the use of one machine for spinning the pipe. Normally, steel pipe is available in lengths varying from 6.1 to 18.3 m (20 to 60 ft). By selecting a spinning machine with a bed slightly

longer than 18.3-m(60 ft), pipe of any commercially available length may be lined. Assuming that one pipe spool can be lined every five minutes, and using 6.5 production hours per day, approximately 78 pieces 12.2-m (40 ft) long could be lined per day. This is approximately 950-m (3120 ft) of straight pipe. Associated elbow and tee lining processes were sized and planned for approximately 30 elbows and 30 tees, which resulted in a production plant of the size described. Table 6 gives the operating specifications of this production plant. For this analysis, the product was assumed to be nine different steel pipe sizes with diameters ranging from 152.4-mm (6 in.) to 609.6-mm (24 in.).

Using the production plant layout shown in Figure 38, approximately 6500 square meters (70,000 square ft) of plant floor space would be required. A crew of about 30 men operating on three daily shifts would be needed to operate the plant.

The plant was as fully mechanized as possible for two reasons: to lessen the operating manpower requirements and to improve safety and handling of the various chemicals required for the process. Wherever possible, monomer and the resulting PC mix handling were done in mechanized processes with closed-loop ventilation to protect in-plant workers from exposure. Any part of the PC handling operation that can be mechanized reduces personal exposure to potentially hazardous chemicals.

A plant operating at these daily output levels would use raw materials at the rate indicated in Table 7. Raw material storage facility sizes were based upon available delivery sizes for the various ingredients and a suitable operating inventory.

Since the application of PC linings to steel pipe is a new process, some of the equipment required had to be custom designed and built to perform properly. The features of these special pieces of equipment are

- A. Incoming Pipe Storage
- B. Sandblasting Equipment
- C. Prepared Pipe Storage
- D. PC Placement Rack
- E. Primary Curing Storage
- F. PC Delivery Lance
- G. PC Mix Pump
- H. PC Mixer
- I. Pipe Curing Ovens
- J. Fitting Curing Ovens
- K. Fitting Lining Shop
- L. Fitting Form Removal & Primary Curing
- M. Fitting Molding Shop
- N. Flammable Liquids Storage
- O. Q.C. Lab
- P. Tool Shop
- Q. Crew Amenities
- R. Plant Office
- S. Monomer Storage
- T. Aggregate Storage
- U. 10T Overhead Crans
- V. Finished Product Storage
- W. Pipe Transporter
- X. Building Walls
- Y. Pipe Spinning Machine

62

Figure 38. Production Plant Layout
Approx. Scale: 1 in. = 18.3 m (60 ft)

Table 6
Design Production Plant Specifications

Plant floor area	6,500 m ³ (70,000 ft ²)
Yard area	20,000 m ³ (214 ft ²)
Operating day, lining operations	1- to 8-hr shift
Operating day, curing operations	3- to 8-hr shifts
Production line crew, day shift	22 men
Production line crew, swing shift	4 men
Production line crew, night shift	3 men
Maximum PC mixing and handling capacity	725,000 kg/mo (800 Tons/mo)
Plant output	

Item No.	Pipe diam, mm (in.)	Length, m (ft)	PCS/Day	Total length m (ft)	PC output, kg/day (lb/day)
6	152.4 (6)	18.3 (60)	84	1536 (5040)	15,875 (35,000)
8	203.2 (8)	18.3 (60)	84	1536 (5040)	20,865 (46,000)
10	254.0 (10)	12.2 (40)	84	1024 (3360)	17,690 (39,000)
12	305.0 (12)	12.2 (40)	84	1024 (3360)	2,320 (47,000)
14	355.6 (14)	6.1 (20)	78	475 (1560)	10,890 (24,000)
16	406.4 (16)	6.1 (20)	78	475 (1560)	12,700 (28,000)
18	457.2 (18)	6.1 (20)	78	475 (1560)	14,515 (32,000)
20	508.0 (20)	6.1 (20)	72	439 (1440)	14,970 (33,000)
24	609.6 (24)	6.1 (20)	72	439 (1440)	18,140 (40,000)
Average				825 (2708)	16,330 (36,000)

Table 7
Polymer Concrete Raw Material Usage

Material	Maximum daily use kg (lb)	Average monthly use kg (lb)
10-20 Silica sand	6272 (13,830)	96,000 (212,000)
No. 5 Foundry sand	6272 (13,830)	96,000 (212,000)
Silica flour	968 (2,130)	14,800 (32,600)
Type III cement	5807 (13,800)	89,000 (196,200)
Polystyrene	173 (380)	2,650 (5,800)
Stryene	880 (1,940)	13,500 (29,700)
ACN	690 (1,520)	10,500 (23,300)
TMPTMA	173 (380)	2,650 (5,800)
BP-98	38 (85)	590 (1,300)
DTBP	9 (20)	130 (290)
DMA	19 (40)	290 (650)
A-174 silane	19 (40)	290 (650)

described to provide an understanding of their function. This equipment included the PC mixer, handling equipment to deliver the mix to the pipe and fittings, the pipe spinning machine, and the secondary curing equipment.

B. Plant Procution Process and Equipment

The full production process is shown in Figure 39. The major areas are liquid handling, aggregate handling, PC mixing, mix application to the pipe, primary and secondary curing, and post curing operations. Each selection was reviewed for available alternative methods, available equipment, and levels of sophistication and reliability which would be desirable. Tests were then formulated to define and resolve unknowns and to provide data for final process selection.

1. Raw Material Handling. Two types of raw material handling are required for the process: one for the dry aggregates, and the other for the fluids such as monomers, initiators, and promoters. Dry materials were assumed to consist of four descreet components which must be metered and delivered in the correct blend. Delivery may be accomplished by batch weighing each component if a batch mixing system is selected, or by pneumatic or calibrated conveyor systems if a continuous mixing system is used. Both pneumatic and calibrated conveyor methods are volumetric. Volumetric metering has been found to be very accurate in a continuous process, but it is not reliable in a batching (stop-start) system. For safety reasons, all monomers were assumed to be piped from storage tanks to the mixing station. Here again, metering is dependent on the mixing process chosen. Continuous mixing is well suited to volumetric measure by the use of constant displacement pumps, and a batch system might use calibrated batch volumes with good reproducibility.

The selected aggregate system consists of a blend of four different materials. The effect of preblending some or all of these materials

Figure 37. PC pipe lining process diagram.

prior to delivery to the mixer was studied. Segregation was noted if all the ingredients were premixed, but the cement and silica flours could be preblended without segregation. The two sands could not be preblended, however, without segregation occurring. For the design plant, liquid storage, handling, and transfer stations consist of tanks sized to receive a normal batch of replacement material, and a working reserve including related pumps and piping. Separate tanks for styrene, TMPMA, ACN, the initiators, and the promoter are required. In addition, there are tanks for silane, for mold release agents, and a tank to hold cleaning solvent. Each of these tanks has an attached delivery pump. In the case of mix chemicals, the pumps are constant displacement, with variable speed drives. Operator control of the pumps permits metered output rates to a chemical blending unit, which blends styrene, TMPMA, ACN, and polystyrene pellets. Blender time must be sufficient to allow complete dissolution of the polystyrene and mixing of the component chemicals.

The blended monomer is then piped to the PC mixer. The initiators and promoter are also delivered by individual pipes to the PC mixing unit, as is the solvent.

Aggregates are maintained in separate storage silos sized to hold normal delivery loads and working reserves. Four silos are required, one each for coarse aggregate, fine aggregate, fine material, and portland cement. Each of these silos is equipped with a variable speed metering conveyor at its discharge chute capable of adjustable flow rates from the hopper to a transfer conveyor. By balancing the output rate of the various silos, the desired blend of aggregates is delivered to the PC mixer in a continuous stream. The PC mixer itself meters the quantity of combined aggregate required for the PC mix. Various pneumatic metering and conveying systems are also commercially available, but they were not evaluated during this project.

2. PC Mixers. PC mixing may be accomplished by either batching or by the use of continuous mixing machinery. Batch mixing is well suited to small-scale operations but its applicability is limited by requirements for frequent cleaning, added personnel exposure to the monomers, and machinery scale. Continuous mixing, on the other hand, is not well suited to intermittent or small-scale production, but above the level of about 9-kg/min (20 lb/min) output, continuous mixing becomes very economical.

A major consideration in the selection of any mixing process is safety and reliability. Whether continuous or batch methods are selected, the process should include automatic procedures which prevent inadvertent mixing of initiators and promoters. Mixing procedures must also assure that all of the required mix components are added in the correct proportion at all times.

In the pilot plant, mixed PC was placed in the pipe by hand and the ends were then capped prior to spinning. Since the method of mixing and placing takes about 15 minutes, there was some concern over the working time, or pot life, of the PC. Laboratory trials were performed to verify the gel time of the mix. It was found that the mix could be safely worked for about 30 minutes, depending on ambient temperature. This is fully adequate for both pilot and production applications.

Plant design assumed that the PC would be mixed in a continuous production mixer, which receives a continuous feed stock of preblended aggregate. In addition, preblended monomers and separate initiator, promoter, and solvent fluid streams are delivered to the mixer. Final metering and mixing of all of the blended components then takes place within the mixer.

After mixing, the PC is delivered to a conventional concrete pump. Modifications required to this pump include explosion proofing, enclosing

the receiving hopper and connecting it to the mixer output chute; adaptation of a solvent tank; and a discharge port for the elbow and tee production area. Since PC hardens quite rapidly (within 1 to 2 hr), the equipment would have to be cleaned out whenever the mixing and pumping operation is shut down for more than a few minutes. In the mixer, this could be done by direct introduction of solvent through the mixing apparatus. For the pump and the PC delivery lines, a slurry of fine aggregate and solvent will provide the best cleaning medium. This medium should carry a very strong dye so that it is evident when the line is filled with solvent. The solvent-aggregate slurry could be recovered at the down stream end of the delivery lines and reintroduced to the hopper above the concrete pump. A schematic of this equipment is shown in Figure 40.

3. Liner Placement and Forming. Several methods of mix placement were studied. For straight section of pipe, liner may be applied by installing an interior form and filling the annulus under vibration, or by placing material in the pipe and then spinning it at high rates of revolution which levels and compacts the liner by centrifugal force. Centrifugal application is advantageous in that no interior form must be built, maintained, removed, or cleaned.

Lining the fittings posed different problems. First of all, centrifugal application is not possible. Two other methods were considered. One consisted of troweling a lining into place by hand in each fitting, and the other of preparing interior forms and again filling the annulus under vibration. Since the fittings (elbows and tees) include compound inside curves, form removal presented special problems. Considerable effort was, therefore, expended in attempting to arrive at a trowelable variation of the specified formula. This could not be accomplished, so the form and

and fill method was developed. A low-cost disposable form liner system would be ideal for these fittings. A solid liner coated with a heavy, disposable surface is another possibility. Both methods were tested.

A solid liner mold with a 6 to 10-mm (0.24 to 0.39 in.) paraffin surface was used for pilot plant work. The mold was then removed by heating the fitting to melt the paraffin, and then sliding the mold out of the fitting. Reapplying the paraffin each time is very time consuming, however, and thus this method would not be a good production procedure. A disposable liner made of wax-impregnated cardboard was found to be much easier to install and remove. For a production plant, these disposable liners could be pre-made on mandrels designed for this purpose.

A separate section of the designed plant was set up for all fitting lining operations. The selected process consists of sandblasting the fitting, installing a disposable mold to form the inside surface of the liner, and filling the annulus with polymer concrete delivered by a skip hoist mechanism from the mixer.

After approximately 2 hours, the inside forms are removed from the fittings and curing is continued for another 2 to 4 hours prior to being loaded into the secondary curing oven. Cleanup and preparation of the molds for reuse after they have been removed from the fitting is also accomplished in this area. Disposable liners may be purchased from an outside source. Companies now making cardboard concrete test cylinder molds have the necessary equipment to produce these liners at a reasonable cost.

Figure 40. PC mixing and pumping equipment diagram.

Figure 41. Pipe filling equipment diagram.

Downstream of the PC pump, delivery to the pipe spools is also required. Since some pipe spools may be 18.2-m (60 ft) long and as little as 152-mm (6 in.) in diam,, delivery must be by an insertable lance. A successful method for doing this consists of mounting the lance on a power-driven carrier. The lance is then inserted into the pipe spool and withdrawn at a controlled rate while the concrete pump is operating, This distributes the PC mix uniformly throughout the length of the pipe. Figure 41 shows the details of such assembly. During filling operations, a special pipe end cap is applied, with a connection to the exhaust scavenger system. This assures minimal losses of monomer vapors to the plant and resulting exposures to workmen in the area.

4. Centrifugally Applied Liner. Initially, PCR studied the process equipment required. Similar industrial operations were reviewed and centrifugal lining processes were selected for production testing. The first was the centrifugal casting method used for precast, prestressed portland cement concrete piling and pole manufacturing. The second was the process currently used to line cast iron and ductile iron pipe with a cement slurry.

The centrifugal, or spin, casting method generally consists of rotating a cylindrical form with the spin axis placed horizontally. Concrete is introduced into the form from a hopper at one end and screeded or allowed to flow along the length of the form. A splash shield and waste hopper are located at the opposite end. Concrete is introduced while the form is turning at a velocity which produces 1 to 5 g acceleration and allowed to distribute over the form surface. After the concrete is distributed, tangential velocity is increased to provide 500 to 600 g radial acceleration. Concrete mixes used in this process are typically of very low slump. Figure 42 shows the effect of increasing

the spinning velocity on acceleration obtained. The effects of pipe diameter are also indicated. Ranges of spin velocities used for various industrial processes are noted.

The other form of the centrifugal lining process studied was that of applying a portland cement slurry to steel pipe as a liner.¹⁴ This process consisted of the following steps:

1. A cement slurry was pumped into a pipe section and distributed over its length while the pipe was resting in a work cradle.
2. The ends of the pipe were capped and sealed.
3. The pipe section was then placed in a spinning machine and rotated to produce 50 g of radial acceleration for 2 to 3 minutes.
4. After spinning, the pipe section was removed from the spinning machine, the end caps were removed, and the bleed water was flushed out. (During spinning, the solids in the slurry had been so tightly compacted against the pipe wall that they were free standing and could be trimmed with a knife.)
5. After flushing, the ends of the liner were trimmed and dressed by hand to the correct dimension.
6. The pipe section was then removed to be cured.
7. All fittings were lined by hand. The material was worked and kneaded into place by a workman wearing rubber gloves.
8. Successive material application and spreading was repeated until a complete liner had been installed. The surface was worked by hand until the correct dimension and degree of finish had been achieved. (Experienced workmen accomplished this installation quickly and efficiently.)

A process similar to that used for the cement slurry application was selected for both the pilot plant work and for the design plant.

PC mix from the mixer delivered to a concrete pump and controlled by a demand switch, provides a metered flow of PC to the pipe filling equipment. In addition, an outlet would be available to deliver mixed PC to a skip hoist in batch quantities for use in the elbow and tee molding shop.

PC delivered to the pipe filling lance would be introduced into the pipe spools, one at a time, at a rate matching the cycle time of the pipe spinning machine.

The pipe spool is then hydraulically conveyed to a spinning machine like that shown in Figure 43. The spinning machine consists essentially of two lines of rollers mounted on parallel shafts. One shaft is power driven and the other is an idler. The pipe spool rides between these roller pairs and is rotated by contact with the driven rollers. The driving motor must have variable speed capacity, as initial start-up should permit a short period of time at low rpm to distribute the PC mix. After the mix is evenly distributed along the pipe wall, the rotational speed is increased to the required compaction speed. This compaction speed must be held for 1 minute or more before the machine is allowed to coast to a standstill. During slowdown, the pipe must not be jarred or suddenly accelerated, since this may dislodge some of the PC.

Containment rollers are also required above the pipe to hold it in place. These rollers may be pneumatic and should be hydraulically activated. (The drive and idler wheels on the spinning machine, however, should be constructed of steel, since other materials will wear out very rapidly under the stresses encountered at the high spinning rpm.)

Experience with prototype work described earlier in the report, indicates

Note: Normal limits of cast iron and concrete centrifugal compaction processes shown for comparison.

Figure 42. Pipe spinning velocities and radial accelerations.

Figure 43. Pipe spinning machine.

that 1240 W of driving energy is required per meter of 305-mm pipe (1/2 hp per linear ft of 12-in. diam) with the PC material in it.

Operation of a spinning machine constructed in this manner, produces a noise level of about 120 dB within 1.8 m (6 ft) of the machine. For that reason, the spinning machine and associated equipment must be enclosed in a separate, soundproof room. Sound-absorbing materials should also be incorporated in the construction of the room to lessen noise transferred to other parts of the plant. The operator's station must be enclosed and separated from the spinning machine to protect the operator.

The actual spinning cycle consists of bringing the pipe up to 500 rpm over a period of 5 sec, holding the pipe at 500 rpm for 55 sec, and then increasing the velocity to 1700 rpm over a period of 10 sec and maintaining it for 100 sec. Following completion of compaction, the pipe is slowed down and brought to rest over a period of 60 sec. Removing the pipe and reloading the machine would take another 60 sec. Therefore, a complete spin cycle would be 5 minutes in duration.

5. Two-Step Polymerization. After spinning, the pipe would be hydraulically lifted from the spinning machine and deposited in the primary curing rack. This area serves as a buffer area for both primary curing and for cycling loads of pipe into the oven for the secondary curing process.

The specified PC formulation requires secondary curing at elevated temperatures. A production plant could do this by either passing the lined pipe sections through a continuous flow oven or by loading a number of sections into a batch oven. Batch ovens would occupy less plant floor space and have higher operating efficiency. For these reasons, batch ovens have been selected for both the pilot and the design plant.

After the primary curing period has been completed, the pipe end caps can be removed and the pipe momentarily connected to an air scavenger system to clear any residual vapor from within the pipe. The pipe is then transferred to racks and placed in the secondary curing oven for a period of 8 hours. Again on the basis of prototype work, approximately 3 kW/m (3/5 kW/ft) is required to raise a 305-mm-diam (12 in.) pipe to curing temperature within a reasonable period of time. Less power is required to maintain temperature during the curing cycle. Process ovens should be large enough to hold one-half day's production. The ovens must include an air scavenger system to clear out residual vapors being driven off during the secondary cure cycle.

Actual full-scale production oven heating requirements may be less than indicated for the prototype work since a larger oven would be more efficient. With a properly constructed and insulated oven, however, the heat required is more directly related to time required to raise the cool mass of the pipe and liner to the curing temperature. This rate must be controlled so that bringing the pipe up to curing temperature takes approximately 2 to 4 hours. Temperature rise in any case should not exceed 100°C (180°F) per hour to prevent thermal shock damage to the uncured liner. The curing oven should have internal dividing walls to limit heat loss during loading and unloading, and the heating elements should be outside the actual curing chamber with heated air being circulated into the curing space. Air quality must be monitored and maintained in the system with sufficient makeup air added to maintain permissible vapor levels within the oven. In no case should actual vapor levels be allowed to reach 75% of the lower explosive limit for any of the monomers present. Within the oven, separate chambers must also be provided for the pipe fittings. Figure 44 shows a proposed layout for a curing oven to match the process size described.

PLAN VIEW 15.2 x 30.5 m (50 x 100 ft)

SECTION VIEW

Figure 44. Process curing oven.

6. Post Cure Finishing. Although post cure finishing should be limited, several possible operations were considered. First, the straight pipe sections may require a light honing to achieve the desired surface finish. Pipe ends may also have to be ground or dressed by hand owing to the effects of rebound and flow around the end caps during spinning. Some grinding to achieve acceptable turn radiuses and clearances will also be required in the pipe tees if they are produced by forming.

For the design plant, pipe spool ends will be inspected, beveled with a grinder (for field jointing), and dressed with a PC slurry if necessary prior to secondary curing. Fittings will be ground to the correct dimensions and the ground surfaces will be dressed with PC slurry to provide the finished surfaces.

7. Miscellaneous Equipment. The pipe handling portion of the process involves an upstream pipe storage unit where unlined pipe would be stored. Moving from the pipe storage rack, the pipe is placed in a sandblasting nozzle is passed into and out of the pipe to clear out any oil or scale. After filling, the pipe is transferred to the spinning room and placed on the spinning machine.

Throughout the plant, wherever monomer vapors may be present, a scavenger air system must be connected to the unit. This scavenger system is collected through a central piping system and connected to a hydrocarbon scrubbing unit, which is selected and sized to remove ACN and styrene vapors from the air stream. In the vicinity of the aggregate hoppers and sandblasting operations, a dust cyclone must be mounted with air collection to remove dust created in this operation.

IV. THE ECONOMICS OF PC-LINED PIPE

In order to determine the economics and marketability of PC-lined pipe, cost estimates of the PC plant described in Section III were prepared. First a detailed equipment list was prepared and the costs of each piece of equipment determined. The cost of installing and making the equipment operational was also determined. These equipment cost estimates are shown in Table 8. Much of the auxiliary and support equipment required is similar to equipment currently in use at PCR, and costs were obtained through this experience. Local suppliers were contacted for costs of material handling and transporting equipment selected. Costs of specialized unit packaged equipment, such as the mixer, the air scrubber, the bridge crane, the dust cyclone, etc., were estimated by prospective suppliers. The cost of installing the equipment was estimated by in-house personnel familiar with construction estimating. Installation costs include contractor's overhead and profit based upon plant construction in Fargo, ND.

A. Capital Cost

To arrive at a total estimated capital requirement, costs for a plant facility and for plant design and start-up were determined. An inventory of spare parts and raw materials plus a contingency fund completed the items included in the starting capital required. The cost to build a 6500-m^2 ($70,000\text{ sq ft}^2$) plant and provide basic equipment was estimated to be $\$376/\text{m}^2$ ($\$35/\text{ft}^2$). Installation of the process equipment and related foundations, piping, plumbing, and electrical requirements was estimated to be about a 19-month project at a cost of about $\$1,125,000$. Start-up and debugging expenses were based on PCR's experience with new PC product development which indicates that lab work to verify process conditions, initial equipment running trials, and operator and crew training is about equivalent to 20% of the first year's running expenses. Home office expenses include process and plant engineering costs, general supervisory cost, and a

Table 8
Plant Equipment List

1 200-lb/min PC mixer	\$186,000
1 200-lb/min PC pump and lance	26,000
100-ft pipe spinning machine	65,000
1 sandblaster	16,000
40 x 100 x 9-ft curing oven	100,000
24 mobil pipe racks	24,000
8 fixed pipe racks	4,000
10 T bridge crane	30,000
200 pipe caps	4,000
60 fitting mods	30,000
1 250 T aggregate silo	60,000
1 120 T aggregate silo	35,000
2 10 T powder hopper	11,000
1 1500-lb fumed silica bin	15,000
3 600-gal monomer tanks	50,000
1 peroxide storage building, 10-drum capacity	4,000
1 promoter storage building, 2-drum capacity	1,500
1 700-lb polystyrene hopper	9,000
5 metering conveyors	20,000
1 pickup conveyor	8,000
1 lift conveyor	14,000
1 feeder conveyor	8,000
Dust separating cyclone	22,000
Air collector system	20,000
Activated carbon scrubber (5000 cfm)	50,000
Hydraulic pumps and motors	10,000
Misc. pumps	8,000
Monomer piping	8,000
Misc. tools and equipment	30,000
Total Installed Costs (Autumn 1981 Dollars)	\$863,500

share of general office costs allocated to plant construction activities. Spare parts requirements were assumed to be 10% of the plant equipment costs. During plant operations, a fixed raw material inventory equal to one month's production demand is generally required, and this cost was included in the starting capital. A finished product inventory of twice the value of the raw material inventory was also assumed. A contingency amount of about 20% of all other capital costs was included. The resulting total capital requirements are shown in Table 9.

Monthly raw material usage, shown in Section III, Table 2, was used to determine both the fixed inventory requirements and the annual raw material cost for plant operations. Plant output for the amortization period was assumed to be 75% of maximum. Each of the materials required was multiplied by a unit cost provided by suppliers. This unit cost was based on appropriate quantity purchase discounts and transportation costs where applicable. Total monthly raw material cost were then calculated and are about \$57,000 for 252,300 kg (540,200 lb) of PC produced per month. Details of individual component costs are shown in Table 10.

B. Operating Costs

Plant operating costs were estimated in three general categories; fixed costs, variable costs, and general and administrative costs. Operating costs are itemized in Table 11. Fixed costs include amortization and insurance. The five-year, straight-line depreciation method was used for simplicity. Insurance was assumed to be 1% of the replacement cost of the physical plant and installed process equipment.

Next, the variable operating costs were determined. Annual maintenance was budgeted at 20% of the value of plant equipment. Maintenance and replacement of air cleaning filters and media were taken separately from an estimate obtained for activated carbon scrubber media. This

Table 9
Plant Capital Cost Estimate

Plant process equipment	\$ 863,500
Physical plant	2,450,000
Process equipment installation	1,125,000
Start-up and debugging expenses	1,895,000
Home office expenses	633,000
Spare parts	86,000
Fixed raw material inventory	76,000
Contingency	1,361,500
Fixed finished product inventory	<u>152,000</u>
 Total Plant Capital (Autumn 1981 Dollars)	 \$8,642,000

Table 10
Monthly Raw Material Cost

Material	Fraction of mix	Monthly usage kg (lb)	Unit ^a cost, \$/lb	Monthly cost, \$
10-20 silica sand	0.2942	96,000 (212,000)	0.027	5724
No. 5 foundry sand	0.2942	96,000 (212,000)	0.013	2756
Silica flour	0.0453	14,800 (32,600)	0.090	2934
Type III cement	0.2723	89,000 (196,200)	0.040	7848
Polystyrene	0.0091	2,650 (5,800)	0.600	3480
Styrene	0.0413	13,500 (29,700)	0.650	19350
ACN	0.0323	10,500 (23,300)	0.500	11650
TMPTMA	0.0081	2,650 (5,800)	1.570	9106
BP-98	0.0018	590 (1,300)	2.600	3380
DTBP	0.0004	130 (290)	2.110	612
DMA	0.0009	290 (650)	2.580	1677
A-174 silane	0.0009	290 (650)	11.790	<u>7664</u>
		336,400 (720,290)		76136
x 0.75 ^b		252,300 (540,220)		57102

^aMaterial costs, FOB Fargo, ND, Autumn, 1981.

^bAssumed operating efficiency factor.

Table 11
Annual Plant Operating Cost Estimate

<u>Fixed</u>		
Amortization	\$1,728,400	
Insurance (1% of installed capital)	<u>70,000</u>	
		\$1,798,400
<u>Variable</u>		
Maintenance (10% of plant equipment)	172,700	
Air pollution control	22,260	
Raw materials	684,000	
Miscellaneous materials	342,000	
Plant labor	1,098,000	
Plant supervision	250,000	
R & D and Q. C.	200,000	
Utilities	300,000	
Selling Expenses	680,000	
Miscellaneous	<u>400,000</u>	
		4,126,700
<u>General and administrative</u>		
Management salaries	570,000	
General office costs	36,000	
Supplies	150,000	
Customer services	127,000	
General insurance	<u>48,000</u>	
		<u>931,000</u>
Total annual operating cost (Autumn 1981 dollars)		\$6,856,100

cost is listed as Air Pollution Control. Raw material costs were taken directly from Table 5. Miscellaneous materials, such as mold release waxes, solvents, small tool replacement, etc., were estimated to be about 50% of the known raw materials. Plant labor and supervision were based on crew requirements described in Section III plus supplemental labor of 50% for production line support. The average cost of production line labor was assumed to be \$12 per hour and the cost of plant supervisors was assumed to be \$20 per hour. These costs include all payroll taxes and fringe benefits. Ongoing product research and development and product quality control were based on three people and a nominal amount of lab equipment and supplies. Plant utilities include electricity, other fuels, and city services. Utility costs were based on PCR's PC plant operating experience. Selling expenses of a 10% commission on part of the total sales were used to allow for the use of manufacturer's agents.

General and administrative costs were based on an eight-man management staff with associated space and supplies. Customer services supplied by the manufacturer would require an in-house engineer and two draftsmen.

Other insurance costs are listed as general insurance. For the plant described, producing about 148,000 m (486,000 lin. ft) of lined pipe per year, the annual operating budget would then be about \$7,000,000.

C. Return on Investment and Cost to End User

A return on investment was calculated to be 15.4% as shown in Table 12. Annual operating costs and the selling value of the PC liners were used based on prices in effect in the autumn of 1981. Actual selling prices of the liner would require annual adjustment to reflect changes in costs of raw materials and plant labor.

A probable market or selling price for PC lined pipe was then calculated. Table 13 shows the method of calculation. The price of each pipe size was

based on the total cost of raw materials required, the manufacturing expenses, the selling expenses, and a profit markup. Raw material usage was based on calculated PC volumes required for each pipe size. The manufacturing expenses were prorated from Table 12 after subtracting raw materials costs, since they are listed separately. As shown, the average selling price for the liner alone is then \$87.10 per meter (\$26.55 per ft). If the average selling price for the 9 pipe sizes considered is divided into the average price for lined pipe, the cost for lined pipe is about 173% of the unlined pipe price. The actual pipe cost on the job, however, may be less than the price for carbon steel pipe if the corrosion allowance is replaced by the PC liner, as explained in the next section.

D. Market Information

Two principal sources of information were reviewed to determine the cost of present piping systems that might be suitable for use in geothermal energy extraction plants. The first was a detailed article on the installed cost of corrosion-resistant piping in the chemical industry.¹⁵

This article provided detailed comparisons between a number of steel, steel alloy, and lined steel piping systems. Comparisons were made for two separate systems, one simple and one complex. Prices used were for the fourth quarter of 1980 in the U.S. Gulf Coastal Area.

The second source described in detail the itemized costs of a geothermal district heating system. Costs used in the presentation were based upon 1978 Means Mechanical Cost Data Guide and bids taken for the project in Klamath Falls, Oregon, prior to 1979.² All cost used from this source were factored by 130% to obtain a value comparable to the 1980 prices described above.

Table 14 shows a comparison of materials and installation costs for a wide variety of corrosion-resistant piping. Systems operating at 70°C

Table 12
Simplified Calculation of Return on Investment, Full Scale Plant

Installed capital	\$ 8,642,000
Working capital	<u>285,670</u>
Total capital	8,927,670
Fixed costs	1,798,400
Variable costs	4,126,700
General and Administrative	<u>931,000</u>
Total Annual Costs	6,856,100
Sales value of liners	9,611,100
Income	2,755,000
Income tax (50%)	1,377,500
Income after tax	1,377,500
Return on Investment	15.4%

Table 13
PC Lined Pipe Selling Price Estimate

Average annual production, m (ft)	110,200 (362,000)
Average annual raw material use, kg (lb)	3,027,600 (6,675,000)
Raw material cost	\$684,000
All other operating costs	\$6,172,100
Manufacturer's markup	\$2,742,000
Average liner selling price, \$/m (\$/ft)	\$87.10 (\$26.55)
Average pipe selling price, \$/m (\$/ft)	\$118.74 (\$36.19)
Average total price, \$/m (\$/ft)	\$205.84 (\$62.74)
Percentage increase over unlined pipe	73%

Table 14
Comparative Cost of Piping

Piping Materials	Material cost,* \$	Field labor cost,* \$	Total installed cost/ft	Cost ratio
PC-lined carbon steel, butt welds*	9,907	11,935	87	1.40
PC-lined carbon steel, couplers*	12,972	12,300	101	1.63
PC-lined carbon steel, flanged*	16,032	13,640	119	1.92
Sch 40 carbon steel*	4,914	10,973	62	1.00
Vinyl ester FRP	11,411	12,540	86	1.35
Rubber-lined Sch 40 Steel	18,097	13,640	99	2.16
Sch 10 aluminum*	5,143	9,680	105	1.69
Sch 40 aluminum*	6,679	10,423	105	1.69
304-L SS, Sch 10*	8,487	10,434	106	1.71
Polypropylene-lined steel	15,231	13,640	106	1.71
Saran-lined steel	16,710	15,070	114	1.84
316-L SS, Sch 10*	12,833	10,423	121	1.99
304-L SS, Sch 40*	15,634	11,220	139	2.24
Kynar-lined steel	29,979	13,640	158	2.55
316-LSS, Sch 40*	23,030	11,200	165	2.66
Glass-lined steel Sch 40*	32,480	22,605	201	3.24
FEP-lined steel	45,725	13,640	215	3.47
PTFE-lined steel	46,591	15,070	222	3.58
Alloy 20, Sch 10*	33,193	10,973	225	3.63
Nickel, Sch 10*	57,971	11,330	323	5.21
Alloy 20, Sch 40*	64,093	11,935	349	5.63
Hastelloy C-276, Sch 10*	93,103	11,330	421	6.79
Nickel, Sch 40*	112,354	12,375	562	9.06
Hastelloy C276, Sch 40*	171,824	12,375	704	11.35

*Based on a 400 ft long complex plant piping plan.

(160°F) and 1.03 MPa (150 psig) or less could be assembled with any of the materials listed. At temperatures above 70°C (160°F), only those materials marked with an asterisk (*) could be used.

Three different PC-lined carbon steel piping systems are listed. All are based on schedule 40 pipe. The "butt welds" entry is based upon 35 field-made butt welds and includes sealing each joint with a PC slurry after welding. Flanged joints and a joint using the Flexweight coupler are also listed. These two listings are based on substituting the respective joint for each of the 35 joints listed as field welds for the "butt welds" entry. As shown, the cost of PC-lined pipe compares very favorably with the majority of other corrosion-resistant piping.

In the Klamath Falls project, for a plant and distribution system estimated as having a total cost of about \$2.5 million, the primary and secondary distribution piping network was estimated at \$308,000. This piping cost was based on unlined carbon steel pipe. If, in fact, corrosion losses were such that the system required replacement in 10 years, whereas a lined system would have a 20-year life expectancy, the lined system would be \$40,000 per year less expensive. The initial cost of installation would increase the total project cost by about 3%, but the annual cost would be 25% less for the lined system. This analysis was based on an annual interest rate of 15% on the money used. The lined pipe was amortized over 20 years while the unlined pipe was amortized over 10 years for the initial installation and 10 years for the replacement costs. The cost of the lined pipe, installed, was assumed to be 173% of the cost of the carbon steel pipe installed. The details of this analysis are presented in Table 15.

Table 15
20-Year Life Cost Comparison

Item	Initial cost		Replacement cost (unlined)
	lined	unlined	
1237 m (4050 ft) 8-in. Sch 40 steel pipe	\$160,200	\$ 92,600	\$143,000
Fittings	20,000	11,700	18,000
Expansion joints	10,800	10,800	16,500
Pipe guides	7,700	7,700	
Pipe insulation	54,000	54,000	83,100
Concrete tunnel	233,300	233,300	
Excavation & backfill	175,600	175,600	270,200
Highway & RR crossings	59,800	59,800	
Expansion vaults	12,400	12,400	
Total Costs	\$733,800	\$657,900	\$530,800
Combined Initial and Replacement Costs for Unlined Carbon Steel			\$1,188,700
Annual Cost:	Lined	\$116,530	
	Unlined	\$156,540	

Another way to examine the costs of piping in service is to compare life-cycle costs. Corrosion losses in geothermal environments for various kinds of piping were compared in a study by McCright et al.³ Using the results of this study to calculate corrosion losses over a 10-year period, corrosion allowances can be determined. If the initial pipe selection is based on pipe sized with the appropriate allowance added to the wall thickness required for stresses, relative costs may be compared. Table 16 shows the results of this analysis. As shown, PC-lined steel pipe has 82 and 37% of the estimated life-cycle cost of carbon steel and chrome-moly steel respectively.

E. Piping in a Geothermal Plant

Production cost estimates and selling prices shown in Table 13 were based on the average of 9 different pipe sizes, from 152.4 to 609.6 mm diam (6 to 24 in.). Since any order for plant piping would include several pipe sizes, this estimating method is sufficiently accurate for determining preliminary pipe costs. Pipe and liner dimensions used these estimates are shown in Table 17..

A detailed breakdown of piping required in the Niland geothermal power generation plant, near Niland, California, was prepared by Burns & Roe Industrial Services Corporation.¹⁶ Using these data, a cost comparison between carbon steel piping and PC-lined steel or PC pipe was made and is shown in Table 18. The published costs for the steel pipe was factored from 1977 dollars to 1981 dollars on the basis of a 10% per year cost escalation. Prices for PC pipe were based upon estimated prices published by Lindsey Industries.⁴ Results indicate that a 9.9% savings in the initial cost of the piping may be realized if the normal steel corrosion allowance is replaced by PC-lined steel pipe and if PC pipe is substituted for steel pipe where operating conditions permit.

Table 16
Life-Cycle Cost Comparison

	Stress thickness, in.	Corrosion rate, in./yr	Corrosion allowance, in.	Design thickness, in.	Cost Factor
Carbon steel, 10 yr	0.135	0.053	0.530	0.665	39.53
Chrome moly steel	0.203	0.006	0.120	0.323	88.15
PC-lined steel	0.135	0.000	0.000	0.135	32.30

Table 17
PC Lined Pipe Data

Item No.	Schedule	Actual inside diameter		Cross section decrease, %	Liner weight kg/ft (lb/ft)
		Unlined, mm (in.)	Lined, mm (in.)		
6	40	154.2 (6.07)	135.1 (5.32)	30	3.1 (6.9)
8	40	202.7 (7.98)	183.6 (7.23)	22	4.2 (9.2)
10	40	254.5 (10.02)	235.5 (9.27)	17	5.3 (11.7)
12	0.375a	304.8 (12.00)	285.8 (11.25)	14	6.4 (14.1)
14	0.375	336.6 (13.25)	317.5 (12.50)	12	7.1 (15.6)
16	0.375	387.4 (15.25)	368.3 (14.50)	11	8.2 (18.0)
18	0.375	438.2 (17.25)	419.1 (16.50)	9	9.3 (20.4)
20	0.375	489.0 (19.25)	469.9 (18.50)	8	10.4 (22.9)
24	0.375	590.6 (23.25)	571.5 (22.50)	7	12.6 (27.7)

^aPipe wall thicknesses are normally specified in pipe diameters over 304.8 mm (12 in.). Therefore, 0.375 indicates a 9.53 mm (0.375 in.) pipe wall thickness.

Table-18
Geothermal Plant Piping Cost Comparison

Size, mm (in.)	Length, m (ft)	Steel pipe, \$	PC lined pipe, \$	PC pipe, \$
152.4 (6)	35.1 (115)	4,990		3,300
203.2 (8)	272.8 (895)	58,436		39,000
304.8 (12)	411.5 (1350)	193,435		128,000
508.0 (20)	56.4 (185)	33,872	32,964	
609.6 (24)	24.4 (80)	31,598	23,841	
914.4 (36)	349.0 (1145)	735,618	744,495	
1016.0 (40)	36.6 (120)	85,660	86,730	
1270.0 (50)	21.3 (70)	74,955	63,300	
1524.0 (60)	24.4 (80)	102,793	86,850	
Total (1981 Dollars)		1,326,356		1,208,480

Based on Niland Plant piping list.¹⁶

V. PLANT SAFETY PROVISIONS

The use of volatile organic chemicals in PC production makes it necessary to give careful consideration to safety. When properly planned and supervised, the required chemicals can safely and successfully be used. Personnel exposure to chemical vapors should be the primary consideration, but use of high temperature curing and high pressure equipment as well as various other pieces of manufacturing equipment also merit careful safety planning. Their personnel exposure and flammability data of the mix chemicals are given in Table 19.

In the production of PC-lined pipe, certain safety hazards will be encountered, but with planning, the severity of these potential hazards will be lessened substantially.

Some areas which will need special consideration are:

1. Chemical storage and handling.
2. Pipe spinning equipment.
3. High temperature curing chamber.

To protect against the hazards of the chemicals involved in the production of PC pipe liners, the following personal protection gear should be available and used as required:

- a. Full facepiece airline respirator systems.
- b. Personal air sampling systems.
- c. Protective outerwear.
- d. Safety shower.
- e. Eyewash stations.
- f. First aid stations.

A major consideration in any production process is the understanding that the work force has concerning the materials and equipment they work with.

Table 19
Hazard Characteristics of Chemicals

Chemical	TLV	Explosive limits, Vol %		Flash point, °C	Boiling point °C	Specific gravity
		LEL	UEL			
Acrylonitrile (1)	2ppm	3.05	17.0	-1	77	0.797
Styrene	100ppm	1.10	6.1	-1	145	0.903
TMPTMA	--	--	--	93	315	1.060
Silane	--	0.90	5.4	138	255	1.0447
BP-40	5mg/m ³	--	--	--	-(3)	1.152
DTBP	--	--(2)	--	27	167	0.785
DMA	5ppm	--	--	63	193	0.956
BP-98(4)	--	--	--	--	-(3)	--

(1) Carcinogenic hazard

(2) Difficult to extinguish

(3) Decomposes

(4) Granular solid

TLV Threshold limit valve

LEL Lower explosive limit

UEL Upper explosive limit

Safety considerations are integral with other criteria when processes using monomers are designed. A detailed plant safety plan should be prepared during plant design. This plan should contain provisions for limited personnel and environmental exposure to monomer liquids and vapors. Important to successful mass production of PC pipe liners is a process design that eliminates personnel contact with the monomers and contains atmospheric emissions. Specific areas where contact or emissions are likely and the process design criteria are indicated in Table 20. The process design detailed in Section III includes provisions for these criteria. Additional safety data on handling, mixing, and placing PC are discussed in a safety report by Fowler et al.¹⁷

A. Special Provisions for Safe ACN Handling

Manufacturers must provide, to the employee who will be exposed to ACN, an initial and annual medical examination. They should also have personnel trained in first aid available when ACN is in use.

Special ACN First Aid Kits containing the following items must be on hand wherever ACN is being used.

- 1) Amyl nitrite pearls (2 dozen)
- 2) 2 ampules of sterile sodium nitrite solution
(10 ml of a 3% solution)
- 3) 2 ampules of sterile sodium thiosulfate solution
(50 ml of a 25% solution)
- 4) 2 sterile 40-ml syringes with intravenous needles
- 5) 1 sterile 40-ml syringe with intravenous needles
- 6) 1 tourniquet
- 7) 1 gastric tube (rubber)
- 8) 1 nonsterile 100-ml syringe.

Table 20
Process Safety Design Criteria

1. Bulk monomer unloading	1. Coupled and gasketed transfer lines. Vent line from tank to truck. Grounding.
2. Bulk monomer storage	2. Above ground tanks in vented enclosure and surrounded by an impervious dike.
3. Monomer mixing	3. Constituent transfer through enclosed lines to operating "blender." recirculating pump mixing.
4. PC mixing	4. Direct coupled line transfer of monomer to an enclosed and vented continuous mixer.
5. PC placement	5. Mix transferred through enclosed conduits to molds. Molds and conveyors vented to scrubber.
6. Second stage cure	6. High temp curing accomplished in enclosed and vented process oven.
7. Handling air/monomer vapor mixtures from all vents	7. Direct all exhaust ventilation air through an incenerator, air scrubber, a suitable filter, etc. to remove vapors. Ground all vessels during transfer.
8. Plant air quality	8. Threshold limit value air quality monitoring stations located in various parts of the plant.
9. Personnel protection	9. Use of personnel protective gear whenever and whenever monomer vapors may be present.

Medical records must be kept and maintained for 30 years after an employee's last exposure to ACN. These records must be available to a designated representative of the Secretary of Health, Education and Welfare, of the Secretary of Labor, of the employer and of the employee or former employee.

Concentration must be kept at or below 2 ppm of breathing zone air by the use of personal respirators and general plant ventilation. Personal air samplers should be worn by personnel when ACN is in use.¹⁸

B. Pilot Plant Vapor Exposure Surveys

In order to determine potential exposure to ACN during PC mixing and placing operations, organic vapor monitor badges were worn on various occasions, both inside the supplied air respirator helmet and on the outside of the coverall lapel. Results indicate less than 0.02 ppm (T.W.A.) of ACN contamination for breathing air exposures and less than 0.10 ppm styrene exposure. The sensors indicated exposure outside the helmets to be about 0.22 ppm of styrene. Sensors used were 3M brand, Model No. 3500, Organic Vapor Monitors. Badge analysis was performed by the Organic Chemistry Department, North Dakota State University.

VI. CONCLUSIONS AND RECOMMENDATIONS

Successful full-scale application of PC pipe liners has been demonstrated. Plant-scale centrifugal lining of straight pipe, and formed, cast, and vibrated fitting linings are possible. Equipment required for a full-scale plant is available "off-the-shelf" or may be fabricated readily. While any size for a full-scale lining plant may be selected, capacity matched to the output of one spinning machine bed was selected for analysis. A lower output plant would still require basically the same major equipment and would, therefore, have a similar capital cost.

A lower output design would consequently have a much lower return on investment. Larger plants would have improved efficiency and could be sized in multiples of each spinning machine bed installed. Equipment costs would be in a nearly direct ratio to the plant described with improved return on investment being based primarily on efficiency improvements.

The use of the specified PC liner in carbon steel pipe provides a very economical corrosion-resistant system for high temperature, high pressure applications. The durability of the PC in geothermal fluid environments has been demonstrated by extensive, long-term tests conducted by ENL. Estimates show that if the normal corrosion allowance provided in steel pipe design is replaced by a PC liner, the initial purchase price of the pipe may actually be lower. Life-cycle cost analysis demonstrates even more remarkable cost savings with a projected 26% annual cost reduction.

For this project, eight 305-mm-diam by 1.5-m-long (12 in. by 5 ft) straight pipe segments, four 305-mm (12 in.) elbows and two 305-mm (12 in.) tees were lined with a 9.53-mm-thick (0.375 in.) PC liner. These units will be installed in an operating geothermal energy plant for in-service durability evaluation. In addition, several 142-mm-diam (6 in.) pipe segments were lined with both bonded and unbonded PC liners for testing purposes. Mechanical properties, permeability, bond strength, and thermal shock durability were measured and determined to be acceptable for the intended service. Variations of standard ASTM testing procedures were used whenever possible. Where special tests were deemed appropriate, they were developed and are described in this report.

Mechanical test strengths of the PC at elevated temperature were much lower than those reported by ENL in earlier reports. While two possible causes for this were considered and tested, strength improvements were not obtained. Additional study and testing is suggested

to determine causes for elevated temperature strength loss and remedies determined which may be incorporated in future lining production specifications.

Three field jointing methods were described and tested which will provide satisfactory finished installation. The most economical method entails direct butt welding of the pipe spools in the field and then field grouting the liner joint. This method uses a PC slurry containing ACN, an extremely hazardous organic chemical. Additional research is recommended to eliminate the need to use this material on construction sites and, preferably, to eliminate all field grouting with a more dependable (and still economical) field joint. Because of the hazards described herein associated with field grouting, the use of the more expensive flanged joint with a gasket is recommended at this time.

Replacement of the normal corrosion allowance, added to steel pipe walls in design, with a PC lining is suggested to obtain the most economical piping system. Use of PC-lined carbon steel pipe should be adequate in all cases where the use of high alloy steel piping was indicated for corrosion resistance.

While work of this project was directed at geothermal fluid piping applications only, cross-over applications in many other industries faced with similar corrosion problems are possible. By addressing these other potential uses, sufficient market for the output of a PC lining plant of the scale suggested will be available sooner. This would permit earlier construction of a lining plant to make this product available on a commercial scale to the developing geothermal energy industry.

ACKNOWLEDGMENTS

The author gratefully acknowledges assistance from several people on this project. K. Collins, P. Collins, A. Berdal, and J. Huso, of PCR, assisted with lab and production work and with the cost and economic analyses. Dr. Z. Wicks, Dr. R. Koob, and several students at North Dakota State University contributed chemical expertise and chemical vapor survey analyses. Invaluable assistance was also furnished by L. Kukacka and J. Fontana of BNL, the program managers.

REFERENCES

1. Kukacka, Lawrence E., Polymer concrete materials for use in geothermal energy processes, Second International Congress on Polymers in Concrete, Symposium Proceedings, University of Texas at Austin, 1978.
2. Anderson, David N., and Lund, John W., Editors, Direct Utilization of Geothermal Energy: A Technical Handbook, Geothermal Resources Council Special Report No. 7, ISSN #0149-8991, ISEM #0-934412-07-03, 1979.
3. McCright, R.D., Frey, W.F., and Tardiff, G.E., Localized corrosion of steels in geothermal steam/brine mixtures, Geothermal: Energy for the Eighties, Transactions, Volume 4, Geothermal Resources Council, ISSN #0193-5933, ASEN #0-934412-54-5, Davis, California, 1980.
4. Schroeder, J.E., Design and Fabrication of Polymer Concrete Pipe for Testing in Geothermal Energy Processes, Final Report, Lindsey Industries Project Report, BNL 486337-S, 1981.
5. Schmigle, B.J., and Hemm, K.W., Testing of Flexweight Corporation's Perma Couples for Williams Brothers Engineering Company, Tulsa Division, North American Rockwell, 1974.
6. Unpublished report submitted to Brookhaven National Laboratory on a phone poll of six potential users of PC-lined pipe.
7. Kaeding, A., Design and Fabrication of Polymer Concrete Lined Pipe for Testing in Geothermal Energy Processes, Progress Report No. 3, April-June 1981, BNL 529117-S, 1981.
8. Design and Control of Concrete Mixtures, Twelfth Edition Portland Cement Association, Skokie, Ill. 1979.
9. Kukacka, L.E. et al., Alternate Materials of Construction for Geothermal Applications, Progress Report No. 18, BNL 51036, 1979.

10. Compression Strength of Molded Concrete Cylinders, ASTM C-39, American Society for Testing and Materials, Philadelphia.
11. Test for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM C-496, American Society for Testing and Materials, Philadelphia.
12. Kukacka, L.E. et al., Alternate Materials of Construction for Geothermal Applications, Progress Report No. 17, BNL 50979, 1978.
13. Specification for Portland Cement, ASTM C-150, American Society for Testing and Materials, Philadelphia.
14. Kaeding, A., Current Cementitious Pipe Lining Technology, Supplemental Report, Project Status Report No. 5, BNL 529117-S, 1981.
15. Barrett, O.J., Installed cost of corrosion-resistant piping, Chemical Engineering, McGraw Hill, Nov. 2, 1981.
16. Economic Assessment of Polymer Concrete Usage in Geothermal Power Plants, Burns and Roe Industrial Services Corporation, BNL 50777, 1977.
17. Fowler, D. et al., Safety aspects of concrete-polymer materials, Polymers in Concrete, International Symposium, American Concrete Institute, SP-58, Detroit, 1978.
18. Handling - Storage - Analyses of Acrylonitril, American Cyanamid Company, Wayne, New Jersey, 1970.

Appendix A

Results of Mechanical Properties Tests

Table A1. Effects of Curing Time and Type of Peroxide
Used on High Temperature Compressive Strengths

Table A2. Splitting Tensile Strengths at Various Temperatures

Table A1
Effects of Curing Time and Type of Peroxide Used on
High Temperature Compressive Strength

Test temp °C (°F)	Cure time, hr	Compressive strength			
		with 40% BPO MPa (psi)	No.	with 98% BPO MPa (psi)	No.
21(70)	4	129.2 (18740)	2	132.3 (19189)	3
	7	165.8 (24045)	2	159.9 (23196)	3
	19	158.0 (22913)	5	157.7 (22866)	3
	90	164.7 (23884)	3	159.7 (23167)	4
	113	113.1 (16407)	4	160.6 (23292)	3
38(100)	19	131.7 (19095)	2		
66(150)	19	116.1 (16832)	2		
121(250)	4	17.6 (2546)	1		
	7	15.6 (2262)	2		
	19	15.8 (2287)	6		
150(302)	4	8.8 (1282)	3	13.7 (1980)	3
	7	12.3 (1781)	2	20.8 (3017)	3
	66	12.0 (1744)	3	13.4 (1945)	4
	90	19.1 (2777)	4	24.1 (3489)	3
184(363)	66			11.0 (1591)	4
	90	12.8 (1852)	3	13.7 (1994)	1
200(392)	4	4.3 (617)	3	9.1 (1320)	3
	7	5.9 (854)	2	9.1 (1320)	3
	19	9.3 (1343)	3	12.0 (1745)	3
	113	7.8 (1132)	4	7.5 (1084)	3
260(500)	4	62. (896)	3	3.6 (519)	3
	7	6.4 (926)	4	3.9 (566)	3
	19	3.9 (569)	2	4.2 (613)	3
	66	4.9 (707)	3	6.1 (884)	4
	113	6.3 (920)	4		

No. - number of cylinders tested at each set of conditions.
Strength value given is the average of these tests.

Table A2
Splitting Tensile Strength at Various Temperatures

Test temp. °C (°F)	Splitting Tensile stress, KPa (psi)	% Retention	No. Tests
21 (70)	23,546 (3415)	100	18
93 (200)	15,541 (2254)	66	4
116 (240)	5,578 (809)	24	5
141 (285)	3,303 (479)	14	3
160 (320)	2,523 (366)	11	2
177 (350)	1,827 (265)	8	1
238 (460)	641 (93)	3	1
260 (500)	241 (35)	1	3

Appendix B

Partial List of Material Sources

Acrylonitrile:

American Cyanamid Company, Los Angeles, California

Styrene:

Worum Fiberglass Supply, St. Paul, Minnesota

Trimethylopropane Trimethacrylate:

Rohm and Haas Company, Philadelphia, Pennsylvania

Benzoyl Peroxide:

Noury Chemical Corporation, Burt, New York

di-tert-Butyl Peroxide:

Lucidal Division, Pennwalt Corporation, Buffalo, New York

Dimethyl Aniline:

Continental Fiberglass Corporation, Des Moines, Iowa

A-174 Silane:

Union Carbide Corporation, Chicago, Illinois

Polystyrene:

Mobil Chemical Company, Paramus, New Jersey

No. 10 Silica Sand:

Unimin Corporation, New Canaan, Connecticut

No. 5 Fdry Silica Sand:

Unimin Corporation, New Canaan, Connecticut

Silica Flour:

Smith-Sharpe Company, Minneapolis, Minnesota

Type III Portland Cement:

Lone Star Industries, Greenwich, Connecticut

Fumed Silica:

Degussa Corporation, New York