Capsule Pipeline Research Center (CPRC)

College of Engineering
University of Missouri-Columbia

Self Evaluation Report

By Henry Liu and
Terry Maynard

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PREFACE

The Capsule Pipeline Research Center (CPRC) is a State/Industry University Cooperative Research Center (S/IUCRC) approved and funded by the National Science Foundation (NSF) in 1991. It is the only NSF research center in the State of Missouri, and the only pipeline research center at U.S. universities.

CPRC's core program received annual funding not only from NSF but also from the State of Missouri (Department of Economic Development) and industry. Each of the three sources provided over $1,875,000 to CPRC in the 8-year operation of CPRC. NSF policy requires that each S/IUCRC be supported for no more than two four-year terms. September 1, 1999 is the expiration date of NSF and State grants for supporting CPRC for the second term. During its eight-year operation, CPRC was also supported by four non-core projects from the U.S. Department of Energy and one from EPRI (Electric Power Research Institute), totaling over one million dollars. So, the total research funding received by CPRC during its 8-year operation is close to $7 million.

Following NSF approval of CPRC in 1991, the University of Missouri (both the Campus and the University System) approved the CPRC as a University of Missouri Research Center, giving it the privileges and recognition of a University center, including a separate budget. All University centers require periodic evaluation on a 5-year basis. In 1993, in conjunction with the Missouri Department of Economic Development (MDED) and industry sponsors, NSF conducted a detailed evaluation of CPRC, including a 2-day site visit. The Site Visit Team talked not only to CPRC faculty and students, but also to College and Campus administrators, including the Chancellor. The evaluation report was favorable to CPRC, and the Center received a second four-year funding from NSF. Due to this external evaluation, the Campus Administration decided not to conduct any internal evaluation of CPRC until the Center has completed its 8-year term under NSF sponsorship. In spite of that, the University system, under the auspices of then Vice President Richard Wallace, conducted an independent evaluation of the cost effectiveness of coal log pipeline and its potential market value in order to determine whether to continue to seek State funding for the Center. The independent evaluation, conducted by two consulting firms (Foster Associates and J. D. Energy), was again positive. The evaluation helped in getting continued State matching fund for CPRC until the end of its 8-year term.

The current evaluation of CPRC is timely due to the completion of the NSF and State support on September 1, 1999.

This self-evaluation report is prepared to provide the information needed for the external reviewers to determine whether CPRC has fulfilled its mission, and whether the University should continue to provide internal support and recognition to CPRC after August 31, 1999.

For any question about this report or for additional information, please contact Henry Liu by phone at (573) 882-2779 or by e-mail at liuh@missouri.edu.

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A. Overview

CPRC is a National Science Foundation (NSF) State/Industry University Cooperative Research Center (S/IUCRC). Section B of this self-evaluation report contains NSF statements about the purpose and mission of the S/IUCRCs (taken from the NSF Web site). These provide a framework to assess the outcomes that CPRC has produced since its existence.

Section C looks at CPRC's statement of its mission, vision and plans—again, taken from the NSF Web site—to see what it had hoped to accomplish with the time and resources that it had been given.

Section D discusses the most significant CPRC technical achievements; Section E discusses the economic impact of CPRC; Section F discusses the educational accomplishments of CPRC; and Section G describes the CPRC's plan for commercialization of the CLP technology.

Section H describes the history of two outside evaluations of CPRC conducted since the establishment of CPRC. Section I provides an overall self-assessment of the Center's work. Section J discusses the Center's future plan for commercializing the CLP technology, and for expanding research and educational activities. It also shows the efforts that have been made such as submitting two proposals to NSF, one for the establishment of an Engineering Research Center (ERC) on Pipeline Infrastructure, and the other for collaboration with a small firm in the R&D of a coal-log/capsule sensor. Ways that the Campus/University can facilitate CPRC's efforts, such as having an enlightened policy that allows industry sponsors to share patent royalty, lobbying for a government program in capsule pipeline research, and approaching private foundations and philanthropists for donation, are also pointed out.

Finally, some important documents referred to in this report are included in the Appendix for easy access by reviewers.

It can be concluded that CPRC has fulfilled its mission—as established by NSF and by itself. All of its stakeholders—NSF, the state of Missouri, the University of Missouri-Columbia and its industrial partners—have benefited from the Center's accomplishments. They have received significant benefits in return for their support of the Center.

B. The NSF S/IUCRC Program

1. Purpose of the S/IUCRC:

The S/IUCRC Program was established by NSF following an understanding reached in 1990 between NSF and the National Governors Association Science and Technology Council. A S/IUCRC is a University-Based Research Center that receives base funding of an equal amount from NSF and a state government. Industry contributions in cash and in kind must at least equal the NSF or State contribution. (http://www.eng.nsf.gov/eec/0-intro.htm)

2. Mission of the S/IUCRC

Although diversity is encouraged, each center is required to carry out at least the following tasks:

a. Conduct a "core" research program of generic, fundamental research relevant to industrial needs.

b. Conduct a "non-core" program of proprietary research and development projects sponsored by industrial firms.

c. Work closely with industry (including small businesses) to facilitate diffusion of center research results and technology innovation with a view to impacting economic development. Technology transfer and implementation is considered part of the core program.

The total funding received by an S/IUCRC supports both the core and non-core programs, although the NSF and the State funds are used in support of the core research only. The core research and technology transfer programs permit non-exclusive, royalty-free patent rights to member companies and early dissemination of publications to industry sponsors. For non-core, sponsored projects, exclusive licenses are permitted.

Each S/IUCRC acts as an economic agent for its State while also serving important national needs. These centers are already being seen as a model for other joint Federal/State cooperative efforts. Harnessing academic research more productively to the service of economic growth is the wave of the future, and the S/IUCRCs are clearly in the forefront. (http://www.eng.nsf.gov/eec/0-intro.htm)

C. Capsule Pipeline Research Center (CPRC) at the University of Missouri-Columbia

1. Introduction

CPRC was funded as a S/IUCRC as a result of winning a two-stage open competition conducted first by the Missouri Department of Economic Development, and then by the National Science Foundation. It was one of the first four S/IUCRC funded by NSF in the nation. It was funded by NSF and Missouri for two full terms, each for four years. It is scheduled to reach its statutory 8-year limit and will expire on September 1, 1999. CPRC is devoted to performing basic and applied research on capsule pipelines—both hydraulic capsule pipelines (HCP) and pneumatic capsule pipelines (PCP)—so that this emerging technology can be developed for use to transport solids such as coal, grain and other agricultural products, solid wastes (including hazardous wastes), machine parts, and a host of other materials and commodities. Funding received since 1991 came from the National Science Foundation, the State of Missouri (Department of Economic Development), the U.S. Department of Energy (Pittsburgh Energy Technology Center), the Electric Power Research Institute (EPRI), and the Coal Log Pipeline (CLP) Consortium, which consists of pipeline companies, electric utilities, coal companies, and small business participants including equipment companies and consulting firms.

2. Vision

In spite of environmental concerns (e.g., acid rain and the greenhouse effect) over the burning of coal and other fossil fuels, the nation will continue to rely heavily on coal for many years to come. This is due to the fact that coal is the prime source of energy for the U.S.—approximately 70% of the electricity in the U.S. is generated from coal. Also, coal is the most abundant domestic source of energy—the nation has a known coal reserve of 500 years! Therefore, finding ways to reduce the cost and environmental impacts associated with using coal is of the utmost importance to the public. The use of coal log pipelines not only would reduce coal transportation costs; it also would mitigate environmental impacts such as noise and air pollution, as well as transportation accidents associated with the use of coal trucks and trains. CLP is an environmentally friendly technology that contributes to environmental improvement.

After the capsule pipeline technology has been developed and used successfully for transporting coal logs, it will be adapted for transporting grain, solid wastes, and many other materials. These follow-on applications promise even greater benefits to the nation and the world than the CLP technology does. The Center's vision is that, in the 21st century, the United States will have in place an underground network of large-diameter capsule pipelines connecting major cities for freight shipment, in much the same manner that petroleum products and natural gas are transported by pipelines today.

3. Mission

The first four years of the Center's operation were devoted to research, development, and technology transfer toward a specific type of capsule pipeline—the coal log pipeline for transporting coal. Once the development of the CLP is completed, the Center will expand its program to include other types of capsule pipelines, both hydraulic and pneumatic. These can be used to transport grain and other agricultural products, solid wastes, machine parts, and other cargoes. Almost anything that can be fitted inside a "capsule," which is a cylindrical container of a diameter slightly smaller than the pipe diameter, can be transported by a capsule pipeline. Capsule pipeline is a new generation of pipelines for transporting freight (solids) in the 21st century.

There are several reasons for concentrating on CLP during the first four years of CPRC. First, the CLP technology will greatly benefit the nation, the region and the State of Missouri; it has immediate commercial applicability. Second, once CLP is developed, the knowledge generated can be applied to other types of capsule pipelines. This means that early development of CLP will accelerate the development of other types of capsule pipelines. Third, the companies which supported the CPRC consist of electric utilities, coal companies, and pipeline companies. The first two groups are interested in transporting only coal, not other products. In the future, grain companies and firms in other industries will be recruited to finance the Center's development of the kinds of capsule pipelines needed for transporting grain, solid wastes, and other products.

Capsule pipelines will be a major transportation technology in the future. This is supported by the view of a recently published Task Committee Report of the American Society of Civil Engineers (ASCE), and by other documents included in Appendix 1. The Center's program will make the United States the world leader in this new technology, enhancing our national competitiveness. Furthermore, the use of CLP in the United States will reduce coal transportation cost, making U.S. coal more economically competitive in the world market. It also helps to reduce the cost of electricity, thereby benefiting many other industries and the public. Finally, use of capsule pipelines reduces the society's reliance on trucks and rails for transportation of freight. This helps to reduce traffic congestion on highways and railroads, improves transportation safety, and reduces air and noise pollution generated by trucks and trains.

4. Financial Support

The Center's core program received financial support from three external sources: the National Science Foundation, the State of Missouri (Department of Economic Development), and from private companies. Each source has contributed $250, 000 each year since 1993. For the first two years, each source contributed $175,000 (in 1991), and $200,000 (in 1992). In some years the private companies have exceeded the one-third share. The contributions from companies include both cash and in-kind contributions. The in-kind contribution is for needed equipment, materials or services. The in-kind contributions in 1998 and 1999 are especially important as they are for the final development of the Coal Log Pipeline Pilot Plant currently under construction at the University of Missouri-Columbia's Holstein Farm, approximately 10 miles northwest of Columbia (see Appendix 2).

Additional funding for non-core projects has been received. The total non-core funds received has been $621,442. This figure does not include the new Grand Challenge Biomass Research project the Center has won in an open competition conducted by the U.S. Department of Energy. The two phases of this DOE project are expected to receive more than $2,000,000 from DOE and industry, and it will take three and one-half years to complete.

As to internal (University) support, the Center during its first four years of operation received strong internal support including not only equipment funds from the College of Engineering averaging more than $50,000 per year, but also a general operating budget which included the Center Director's salary, and E&E of $33,000 per year which can be used for research assistants, technicians, secretaries and other miscellaneous expenses. As a result of such strong internal support, the Center's operation was at its peak, as reflected by hiring more than 20 students each year to serve as research assistants. However, starting 1995, the Center has no longer been given any equipment fund, nor a general operating budget. To make up for the cuts, the Center had to cut back on research assistants by approximately half, relying more on a few experienced professionals (post doctoral fellows and research associates) to take care of research need. Education (training) suffered as a result.

5. CPRC Technical Programs

The Capsule Pipeline Research Center's immediate goal is to develop the coal log pipeline technology for coal transport. This development program includes all aspects of CLP, with the aim of making this new technology available for commercial use in the beginning of the 21st century.

A major accomplishment of the Center is the development of binderless and low-binder (less than 3%) coal logs. While the binderless process requires compaction of coal logs at 150°C in order to produce the strongest coal logs, the process using 1%-3% binder can produce good-quality logs at room temperature. An extrusion process was also studied, but it was found to be inferior to the compaction process for making coal logs. The Center's accomplishments also include: design, construction and testing of a coal log compaction machine; understanding how to design, automate, and control a CLP; completion of a detailed economic study of CLP systems; and a legal review of water rights, eminent domain, and easement rights related to coal pipeline use in the United States. Each of these areas is explained briefly next.

a) **Hydrodynamics of HCP.** The hydrodynamics of HCP, the same as that for CLP, has been studied in detail in order to understand how to design and operate such pipeline systems. The study has greatly enhanced the understanding and the prediction of the wear (abrasion) of coal logs in CLP and how to minimize it, the effects of bends and slopes, the head loss is HCP and CLP, water hammer and unsteady flow generated by pump bypass, drag reduction by using polymer in HCP and so forth.

b) **Binderless and Low-Binder Coal Logs.** In the search for ways to make good binderless or low-binder coal logs, several promising methods have been investigated and perfected. These include: binderless underwater extrusion, hot-water compaction of binderless high-strength coal logs, vacuum compaction of coal logs, hydrophobic coal logs, and compaction of binderless logs of moderate strength. Surface treatments of dry coal logs to make them impermeable to water also have been investigated, but the result was not promising and hence the effort was terminated. Current efforts are focused on scaling up coal log fabrication to make high-quality large logs, controlling back pressure to make high-quality logs, and on design and testing of a machine that will mass produce high-quality coal logs.

c) **Automation and Control.** In the area of automation, a scale model CLP system has been designed, constructed, tested, and demonstrated in the laboratory. The system has some key elements of a commercial CLP system and is operated (controlled) by a computer. It works smoothly, and has been demonstrated to various visitors and groups. The knowledge and experience gained in working with this scale model are essential for designing a prototype commercial CLP system. Current effort in this area is to test an automatic control system for the large coal log pipeline pilot plant under construction.

d) **CLP Economics**. The economics of coal log pipeline is not only an important subject in itself, it also affects the direction of technical research and development. For instance, in a comprehensive economic study completed by the Center, it was found that the economics of CLP depends greatly on the amount of binder used in fabricating coal logs. Based on that finding, coal log manufacturing research was refocused on making logs with less than 3% binder or no binder at all (the binderless process). The economic study also indicated specific conditions under which CLPs are less costly than trucks or trains for coal transportation. This information will help future users to select economically attractive sites for CLP. The economic model developed passed scrutiny of three sources: first, by our industrial sponsors who carefully evaluated it; then, by the two consulting firms hired by the University administration to evaluate it; and finally, by publication in a refereed journal.

e) **Legal Issues.** The Center's legal research has identified legal and institutional obstacles that may impede future implementation of coal log pipelines, and has found ways to remove or reduce such obstacles. Subjects studied include water rights, eminent domain rights, the right to cross railroads, transfer of the right to convert ordinary oil or gas pipelines to coal log pipelines, the procedure for pipelines to acquire right-of-way across federal land, constraints on water rights transfers, etc.

In addition to the five areas of work and accomplishments outlined above, several other technical achievements have been made. These include a successful test of coal logs through a 5-mile long commercial pipeline in Conway, Kansas, and completion of an EPRI-sponsored study which assessed the details of coal log handling and effluent water treatment at power plants, including the costs of these operations. Details of these studies are reported in the more than one hundred publications listed in Appendix 3.

D. Most Significant Technical Accomplishments

1. Coal Log Pipeline Cost Model

For CLP to be accepted commercially, its economic and market potential must be determined. An engineering cost model of a complete CLP system was developed and programmed for use on a PC. The model defines unit freight transportation cost as the cost of transporting a ton of coal for any prescribed distance in $/T (dollars per ton). It includes not only capital and operational costs, but also a reasonable built-in profit for the investor. Thus, the unit freight transportation cost of coal log pipeline transportation can be compared with the current tariffs for coal transportation charged by railroads, trucks and barges to determine whether it is economically competitive in a given situation. The cost model is detailed in a 180-page report. An abbreviated version of the report is published in 1998 as an article in TRANSPORTATION RESEARCH (A), (Vol. 32A, No. 4), an international journal.

2. Demonstration Site

A survey of more than 100 coal and utility companies—nationwide—was conducted in 1995-96 to suggest sites where a CLP might be constructed to demonstrate the performance and benefits of the technology. These companies were asked to nominate sites where the coal transport distance is less than 100 miles and the volume shipped is less than five million tons per year. Fourteen sites were submitted to the Center for consideration. Of these 14, seven were judged to be economically feasible. These seven were further evaluated by Williams Technologies, Inc., an industrial sponsor of CPRC having an extensive experience in evaluating energy projects. The utilities that owned the two most promising sites were contacted. One joined the CPRC-CLP consortium.

3. Coal Log Manufacture

The coal log manufacturing process is one of the keys to commercial success of CLP. Without coal logs that can withstand the rigors of pipeline transportation over long distance, CLP would not be technically feasible. A number of potential coal log manufacturing processes were investigated. Laboratory tests were conducted on each to find the most promising ones. Several highly promising CLP manufacturing processes have been developed; they are all based on mold compaction rather than extrusion.

Compaction processes have been tested for both bituminous coal – mostly found in the eastern U.S.—and for sub-bituminous coal—mostly found in the Powder River Basin in Wyoming. The compaction tests were conducted at different temperatures, pressures, hold times, moisture contents, binder concentrations, and mold shapes. The results from the testing program have confirmed that it is possible to produce high-quality coal logs. The best coal logs produced survived transportation in a 2-inch-diameter steel pipe in the laboratory over a distance of 200 miles.

4. Coal Log Machine Design

Because coal logs cannot be manufactured at sufficiently low cost by using existing commercially available machines, CPRC designed and constructed a coal log manufacturing machine for testing. This special machine is a hydraulic press that uses a vertical mold to hold the coal. Upper and lower pistons compress the coal into logs. The logs are ejected by the lower piston pushing the logs out of the top of the mold. One of the unique and critical features of the machine is the ability to apply pressure to the log as it exits the mold. This pressure—called back pressure—is essential to the production of high-quality logs. At such high compaction pressures, back pressure delivered by the machine preserves the structural integrity of the coal log, and prevents crack formation.

Based on CPRC research findings and input from members of the industrial consortium and outside companies that make industrial presses, the design of the coal log hydraulic press was completed in 1996. The design is very unique, and it was featured in MECHANICAL ENGINEERING—the main publication of the American Society of Mechanical Engineers (See Appendix 4). The bid to construct the machine was won by the T. J. Gundlach Company, one of the Center's small business participants. In 1997, the machine was delivered to the CLP pilot plant facility on the University of Missouri-Columbia's Holstein farm west of Columbia. In January 1998, the machine was accepted from the manufacturer subject to fixing a minor oil leak. Since that time the machine has gone through extensive testing and improvements. It allowed researchers to test the back pressure feature of the machine for manufacturing high-quality logs.

5. Hydrodynamics of CLP

Researchers at the Center have greatly advanced the hydrodynamics of coal log transport in a pipe. They developed a four-regime theory and equations to predict coal log behavior in pipelines. They also assessed and demonstrated the effects of polymer to reduce drag in a CLP, discovered ways to reduce coal log wear in pipe, and clarified the effects of bends and slopes on coal log behavior in pipelines.

6. Injection, Ejection and Pumping of Coal Logs

A fully automated, operational model of a CLP system was put together in the Civil Engineering Hydraulics Laboratory. Experience gained from this model system will be extremely valuable in avoiding mistakes and making improvements when designing commercial systems. It forms the basis for a manual of practice in coal log pipeline operations.

7. Commercial Pipeline Coal Log Test

In September 1994, coal logs were tested in a 6-inch-diameter, 5-mile-long commercial pipeline in Conway, Kansas. Twenty four coal logs were run through the pipe three at a time; some went through the pipe twice. The best (strongest) logs lost less than 1% weight due to abrasion; the worst broke up in the pipe but did not cause jamming. The results indicate that coal logs can be made robust enough to withstand travel for miles, and the pipe has an ability to pass broken logs. The tests also revealed the need to eliminate girth weld protrusions in future commercial CLPs. This test was an important verification of the feasibility of CLP and the log manufacturing processes that the Center had developed. Since then, much better logs have been made by new processes and the new machine. It is expected that logs made today (in 1999) behave much better than those tested in Conway in 1994.

8. Legal Issues Study

A thorough study of the legal issues associated with the use of CLP was conducted. Issues researched were eminent domain rights for coal pipelines, water rights and permits, rights to cross railroads right-of-way, and the possibility of using the easement of liquid or natural gas pipelines for CLPs. Research results were published in legal journals, and a legal manual for CLP was completed. One law professor and six law students participated in the project.

9. Heating and Drying of Coal Logs

A detailed study was conducted to determine the most practical method to heat coal for compaction as part of the coal log manufacturing process. Several approaches were compared; the most practical method was found to be fluidized-bed heating. A separate study was also performed to determine how to predict the cooling and drying rates of coal logs. A sophisticated mathematical model was developed which couples heating with moisture change. Moisture content is a critical variable to the manufacture of quality coal logs.

10. Construction of a Full Scale CLP Pilot Plant

A CLP pilot plant system is under construction. It consists of the coal log manufacturing machine, coal preparation (grinding and mixing) equipment and handling systems, a 3,000 ft pipeline complete with a pump bypass system, injection and ejection systems, and automatic control systems. Successful test of the pilot plant will pave the way for commercial use of CLP. The system can also be used for future tests of grain pipelines and other hydraulic capsule pipeline studies.

E. Economic Impacts

1. Economic Development

Commercial deployment of CLP will bring significant economic benefits to University of Missouri, state of Missouri and the nation. Such economic developments are approaching reality with the ongoing construction of the pilot plant.

To date, the Center has already contributed toward economic development of the University of Missouri and state of Missouri. In the last 7½ years, the state of Missouri has invested $1.8 million in the Center's work. Outside funds from NSF and private companies (both cash and in-kind contributions) will total in excess of $4 million by the end of August 1999. In addition, more than $621, 000 have been received from non-core research projects. And with the win of the DOE Biomass fuel project, the Center will receive more than $2 million over the next 3½ years.

The millions of dollars that the Center has attracted have paid for the salaries of faculty, student research assistants, skilled trades people, contractors and employees, and for materials purchased from local businesses. The Center has produced substantial economic benefits for the University of Missouri, and for the state of Missouri. Much greater benefits will result from future commercial use of the technologies developed by CPRC.

2. Commercial Partnerships and Technology Transfer

Since the establishment of the CPRC, strong partnerships have been forged between the Center and companies interested in the development of CLP and other capsule pipeline technologies. This partnership is reflected by the funds—cash and in-kind contributions—that these companies have provided the Center, and by research participation by industry. For instance, Williams Technologies Company has helped the Center develop an industry acceptable cost model for evaluating the economic feasibility of possible CLP projects. It has also evaluated more than ten potential CLP demonstration sites proposed by electric utilities. The MAPCO Company allowed the Center to test coal logs in a 5-mile-long stretch of its pipeline located in Conway, Kansas, and participated in the test. The Williams Pipe Line Company constructed a 340-ft long pipeline at Rolla, Missouri for the Center's UMR team. It is now constructing a 3,000-ft long CLP pilot plant in Columbia for CPRC. The Gundlach Machine Company, a small business participant, fabricated the new coal log compaction machine under contract to the University of Missouri using the Center's design. The T. D. Williamson, Inc., donated pipeline pigs and special fittings, participated in the Conway test by sending a crew for three days, and participated in the development of the dielectric coal log sensor for use in coal log pipelines. The Nova Tech, Inc. helped the Center to develop the computer the computer control system for operating coal log pipelines. The COMPACTCONSULT guided the Center in its coal compaction result. And several others also provided equipment, materials and services for the Center's research. All of these partnerships demonstrated strong collaboration between CPRC and its industrial sponsors. All these partnerships contributed greatly to the success of the Center's R&D.

3. Intellectual Property

Since the Center's inception in 1991, five inventions have generated: two resulted in U.S. patents, and three other patents are pending. In addition, one license agreement has been executed by one of the companies that was a member of the Center's industrial consortium, and five others have license under consideration. These five companies have earned the rights for licenses, but have not signed the licenses yet due to their objections to the University's licensing terms.

4. Spin-off Technologies

CPRC has invented and developed several technologies that can be applied to other fields. These spin-off technologies include the following:

a) A compaction machine that can be used for compacting many materials other than coal. These include compaction of biomass solid wastes for use as power plant fuel, compaction of wood waste to make to make high valued products, and compaction of certain other solid wastes such as flyash for environmentally safe disposal.
b) A novel method, based on vacuum principle, for rapid dissolution of powder in water and other liquids.
c) A sensor, based on dielectric principle, that can be used for sensing pipeline pigs and scrappers.
d) A device to prevent weld protrusion into pipe during girth welding.

F. Educational Achievements

1. Student Participation

More than 64 graduate students, 6 law students, 42 undergraduate students and 2 exceptionally qualified high school students were paid and trained by CPRC. All of them finished their degrees.

2. Hands-on Experience

All the graduate students who serve as research assistants on any CPRC project are required to write a thesis (for M.S.), or a dissertation (for Ph. D.), on a coal log or capsule pipeline topic closely related to their work. This policy has resulted in close integration of research with graduate education. Many undergraduates also wrote honor's reports on coal log related studies. For instance, Bill Knowles, a former undergraduate in Chemical Engineering, studied vacuum dissolution of Polyox in water as an honors project. The study resulted in an invention disclosure with patents pending. Bill is now employed by Dow Chemical Company. Since the Fall semester of 1999, three undergraduates with GPA higher than 3.6 (Jamie Graham, ChE; Jamie Kiesler, CEE, and Amy Morgan, CEE) have been participating in the DOE biomass compaction program under NSF sponsorship—research experience for undergraduates (REU).

Research results on CLP and HCP have also been incorporated into the curriculum of CE/MAE 345 Pipeline Engineering. Chapter seven of the course is on capsule pipelines. The course notes are being expanded into a textbook.

G. Plan for Commercialization of CLP

The Center's plan for commercialization is a three-prong program consisting of a commercial demonstration project, a full-scale test/demo facility and a medium sized pilot plant. In 1994, questionnaires were sent to all the major utilities and major coal companies in the U.S.. The purpose of the questionnaire was to determine the most promising site for commercial demonstration of the CLP technology. A total of 17 projects were received and evaluated. Seven projects were selected for further evaluation by Williams Technology, Inc. (WTI). Using the Center's CLP Cost Model and Williams Technologies' expertise operating the Black Mesa pipeline, the only operating coal slurry pipeline in the U.S., WTI evaluated all these projects, and selected two most promising projects for possible development.

A full-scale test/demo facility consisting of a 12-mile-long , 8-inch-diameter CLP has been planned. The total cost of such a facility was estimated to be $15 million, and the time to complete the project was estimated to be three years. Such a facility would enable the Center to test a full-scale CLP system under conditions that might be encountered in commercial operation. Land for the facility has been offered to the Center by the Associated Electric Cooperative, a sponsor of CPRC. However, at this time, lack of funds has put this project on hold indefinitely. Efforts to get the U.S. Department of Energy to fund this project did not materialize.

A medium size CLP pilot plant is currently under construction. It consists of 1) an automated coal log machine that can mass produce 6 in (5.4 in-diameter) coal logs at the rate of one log every 20 seconds, 2) coal preparation and handling equipment, 3) a metal building to house the equipment and machine, and 4) a 3,000-ft-long 6-inch-diameter pipeline recalculation loop CLP complete with a coal log injection system, pump bypass system, coal log ejection system, and an effluent water treatment system. At present, the machine and building are in place and the 3,000 foot loop is under construction. Materials and components for the pump bypass and control systems are being procured—mainly through donations. The MU Research Board has approved to provide $98,780 to CPRC to purchase and install the equipment needed for coal and biomass preparation and handling. The pilot plant should be completed by September 1, 1999.

The pilot plant is critical to the commercial success of CLP. Industrial companies supporting CPRC (including both electric utilities and pipeline companies are risk adverse and frugal when spending R&D dollars. Completion of the pilot plant will enable the Center to demonstrate the technical and economic feasibility of using CLP for shipping coal. This should lead to greater willingness by pipeline and utility companies to invest in commercial use of CLP.

H. Outside Evaluation of CPRC

CPRC has had two external evaluations in the past 7½ years—one conducted by NSF and the other commissioned by the President of the University of Missouri.

The NSF evaluation was conducted in 1993 during the first 4 years of operation of CPRC. The purpose of the evaluation was to help NSF determine whether to fund CPRC for the second four-year term. The evaluation team was organized and coordinated by Dr. Win Aung of NSF. Five outside members were appointed by NSF, including two from industry, two from academia and one from government (Bureau of Mines). The team visited the Campus for two days, talking to CPRC Director, Associate Director, faculty, research assistants, and administrators—including the Dean of Engineering, Provost and Chancellor. The final report was generally supportive of the accomplishments of the Center. It resulted in NSF's decision to fund CPRC for the second four-year term.

In 1995, the President of the University of Missouri, George Russell, commissioned Foster Associates to do an independent assessment of the CLP technology being developed by CPRC. The matter was handled through Vice President Richard Wallace, who is currently MU's Chancellor. This evaluation was focused on the economics of coal log pipelines and their commercial potential. Foster with the help JD Energy—both companies have vast, in-depth experience and expertise in the fields of coal transportation and power generation—reached the following conclusions:

- CLP is technically feasible. Because the coal log manufacturing machine had not yet been built and tested, the report stated that the successful development of the coal log manufacturing machine is a condition for the technical feasibility.

- Private industry has interest in advancing the project—citing the interest of Williams Company, Union Electric and EPRI.
- Market opportunities exist with U.S. consumers for large quantities of coal, and demand for coal is expected to rise. The Clean Air Act (Phase I) should improve CLP's viability. A large number of electric utilities have characteristics that favor CLP use (at least 2 million tons per year and served by one railroad or by truck). A total of 145 plants, consuming 75 percent of the total U.S. coal, have these characteristics. Foreign markets offer prospects for U.S. coal export and CLP transport of indigenous coal.
- The best market conditions for the economics of CLP include the following: distances of 50 to 100 miles from the coal source to the power plant, truck routes where roads are circuitous and/or speed levels are low, end-users with limited sunk costs in their current transportation and delivery equipment, plants that can no longer use traditional coal sources as a result of Phase II of the Clean-Air act, and captive end-users who are suspicious of long-term rail rates.
- Commercialization of CLP for long-haul distances is not as promising because of competitive, economic, water supply and right-of-way factors.
- After suggesting revisions to the Center's economic model and using its own model, Foster concluded that CLP can offer competitive rates on a site-specific basis.
- Using four specific sites, Foster stated that CLP transportation is generally competitive with trucks on a unit cost basis for both direct (shorter) and indirect (longer) routes. With respect to rail competition, CLP can compete effectively in situations where CLP distances are shorter than rail distances and/or volumes are high enough to result in substantial economies of scale. CLP is particularly competitive under those conditions where the capital cost is less than 15 percent (e.g., 13 percent with the use of partial debt financing).

In addition to economic issues, commercialization of CLP will depend on overcoming certain impediments: railroads will probably reduce rates in response to the threat of CLP competition, CLP will require long-term commitment either under long-term ownership or contract, large volume deliveries to multiple points result in logistical problems, and water supply is a problem in some states. Foster believes that these issues are not insurmountable.

Foster report concluded that CLP commercialization is feasible. Shorter haul projects where CLP may have a niche have a higher probability of going forward than longer haul projects, particularly because of the ability of railroads to reduce rates. International markets without existing railroad infrastructures may also provide a promising market opportunity for CLP transportation service.

I. Overall Assessment

Table1 shows how the Center took full advantage of NSF State/IUCRC opportunities. It planned and managed robust core and non-core research programs which were fruitful across technology, economic, legal and educational areas.

Table 1: Capsule Pipeline Research Center Programs and Accomplishments

Core Research	**CPRC Technical Programs (pps. 5-7)**	**Most Significant Technical Accomplishments (pps. 7-9)**
	Hydrodynamic of HCP	Hydrodynamics of CLP
	Binderless and Low-binder Coal Logs	Coal Log Manufacture
		Coal Log Machine Design
		Commercial Pipeline Coal Log Test
		Heating and Drying of Coal Logs
	Automation and Control	Injection, Ejection & Pumping of Coal Logs
	CLP Economics	CLP Cost Model
		Demonstration Site Evaluation
		Construction of Medium Size CLP Pilot Plant
	Legal Issues	Completed Study for Coal Pipelines
Non-Core Research	**Project Title**	**Project Sponsor**
	CLP System Development	US DOE
	End-of-Pipeline Study	EPRI
	Used Energy Related Lab Equipment – multiple projects	US DOE
	Consortium for CLP Research	US DOE Pittsburgh Technology Center
	Patricia Robert Harris Fellowships	US Department of Education
	Advanced PCP System for Transporting Freight	US DOT's Mid-America Transportation Center.
	Biomass Compaction	DOE Federal Energy Tech Center
	Research Experience for Undergraduates (REU)	NSF Education and Center Division
Economic Impacts	**Sponsor**	**Amount (approx.)**
	NSF	$ 2,000,000
	State of Missouri	2,000,000
	CLP Industrial Consortium	(cash + in-kind materials & services) 2,000,000
	Non-Core Projects – completed or nearly complete	621,000
	Non-Core Projects (DOE) - starting	(over next 3.5 years) Up to 2,000,000
Intellectual Property	2 patents; 3 patents pending	
Spin-off Technologies	Unique compaction machine that can be used on materials other than coal	
	A device to prevent weld protrusion into pipes during girth welding	
	A dielectric based sensor that can be used in sensing pipeline pigs and scrappers	
	An efficient method of rapid dissolution of powder in water and other liquids	
Educational Achievements	**Participants**	
	64 Graduate Students	
	6 Law Students	
	42 Undergraduate Students	
	2 Exceptionally gifted High School Students	

EPRI = Electric Power Research Institute
USDOE = United States Department of Energy
USDOT = United States Department of Transportation

Considering NSF guidelines, the Center's own mission and vision as the measuring sticks and using the Center's accomplishments to measure, CPRC has performed well. The Center has been the main contributor to the advancement of capsule pipeline technology in the world. The technical accomplishments are accompanied by significant economic development and educational achievements. In today's educational and economic environment, it is very difficult to maintain a balance among the technical, economic and education goals. However, CPRC has managed successfully to maintain the balance and to achieve in each area—as it should be expected to perform.

CPRC's performance and direction were also affirmed by outside professionals as in the Foster Report. Knowledgeable industrial consultants agreed in the potential for CLP technology and concurred with the Center's development claims and assessment tools. The Foster Report validated CPRC's mission and performance at a critical time of the Center.

Since the Foster report, the Center has continued to make progress toward its ultimate goal of commercializing CLP. The pilot plant currently under construction is the final step in preparation for commercial readiness. It will enable industry to see CLP in operation and the Center to prove the efficacy of CLP and HCP for freight transport.

In conclusion, the Center has fulfilled its commitments to NSF, the state of Missouri, the University of Missouri-Columbia and industrial partners. NSF received a working S/IUCRC: technology was developed, partnerships were formed and students received invaluable experience while participating in CPRC projects. The University and the state of Missouri benefited from the prestige and notoriety that the Center has brought by being one of only a handful of S/IUCRC centers in the nation, and the only NSF center in Missouri. It is also the only pipeline research center in the U.S. The state and the University also benefited from the additional funds the Center received, and from the extensive educational experience the Center's students received. The industrial partners also received technical benefits that could well improve their products and competitive position. It is believed that utility companies in Missouri already benefited from receiving the lowest rates for transporting coal from Wyoming by rail. The threat of CLP has apparently affected rail rates in the last ten years, prompting railroad companies to offer lower rates for coal transportation in places where the threat of CLP is the greatest. Because Missouri's major utilities have supported CLP R&D, they have been offered the lowest rates by railroads, in an effort to keep them away from using CLP. CPRC has fulfilled its mission and obligation, and most if not all of its stakeholders have benefited from its solid performance.

J. Future Plan

1. Plan for Completing CLP Development

Even though great progress has been made in the development of the CLP technology for commercial use, the development work is still incomplete because the technology is not yet ready for commercial use. What remains to be done includes: (a) completing the pilot plant pipeline test, (b) constructing and testing a coal log machine based on the concept of rotary press, and (c) completing a commercial CLP demonstration project.

The main reason that these three remaining tasks were not done in the past is their high costs. The support for CPRC in the past was insufficient even to complete task (a). Tasks (b) and (c) were not undertaken at all due to their high costs, and their dependency on task (a). It is expected that by using industry donated materials, equipment and services, the CLP pilot plant construction will be completed by September 1, 1999, the expiration of the NSF and State grants. However, an additional one million dollars, approximately, is required to complete the tests planned for this facility which can be completed in two years.

Task (b), constructing and testing a coal log compaction machine based on a rotary press, is needed because the current machine, based on the hydraulic press concept, will be expensive for commercial use which requires mass production of coal logs at low cost. The hydraulic press machine is very versatile and hence is suitable for use as a laboratory test machine to test the compaction of coal logs and biomass waste logs under various conditions, but it is too expensive for commercial coal log mass production. The most promising type of machine for commercial low-cost mass production of coal logs is one based on the rotary press concept. It is now being designed, and the design will be completed by September 1, 1999. However, one unit of such a new machine must be built, tested and demonstrated, before it can be used commercially. The cost for building such a machine to mass produce 5.4-inch diameter coal logs for testing in the 6-inch-diameter pilot plant pipeline is estimated to be approximately $500,000. The machine is designed to produce one log per second which is twenty times faster than the hydraulic press machine which has only a single stationary mold. Another $500,000 is needed to test the rotary press machine for two years after construction. Therefore, the total cost for testing and completing the rotary press study is approximately $1 million.

The commercial demonstration project, task (c), will be very expensive. Depending on the project selected for demonstration, the cost can range from about $20 million to about $50 million. The pipeline will have a diameter in the 6-inch to 10-inch range, and the length will be between 20 miles and 100 miles. Even though such a demo project is very costly, it has economical value because it is a commercial project. As long as it can be shown that the unit coal transportation cost for the demo project is less than the cost of transporting the same coal by trucks and trains, the project is economically feasible, and it will be able to attract the needed capital. The demo project can be completed in two years.

With sufficient money, both task (a)—the pilot plant test, and task (b)—the rotary press, can be pursued simultaneously and independently. However, to minimize risks and maximize success, the demo project should not be conducted until the pilot plant test and the rotary press tests are completed. This means with sufficient money ($2 million), the research and development (R&D) of the CLP technology can be completed in two years. The commercial demo project can be built in another two years. This means at the earliest one may see the use of the CLP technology for transporting coal in a commercial project (the demo project) in four years.

Where would the money come from for completing the development of the CLP technology and for demonstrating it in the first commercial project? Because the NSF and the state funding for coal log R&D will expire on September 1, 1999, the remaining work in CLP development/demonstration must be 100% privately financed. No private entity will invest the money needed unless it has sufficient economic incentive. In accordance with the NSF guidelines, the Center already has promised all its current and past industrial sponsors the right for royalty-free usage of any invention resulting from the Center's R&D. About ten companies will gain such rights by September 1, 1999. So, allowing royalty-free or reduced royalty rate is no longer an incentive to our existing sponsors, and is only marginally attractive to new industrial sponsors due to the fact that so many companies already have such non-exclusive rights. The University is unable to offer any company exclusive rights.

However, the University so far has not promised any company the right to share future royalties generated from CLP transportation of coal and other related inventions of CPRC. This remains to be the most single powerful incentive that the University can offer to industry to attract the money needed for completing future tasks (a) and (b). It is proposed that the University raise the needed $2 million to complete tasks (a) and (b) by promising companies the right to share at least 50% of the future royalty with the University. Our current and past industrial sponsors will be given the first right to accept or refuse such a deal. If the money cannot be raised from current and past industrial sponsors, it will be raised from other companies—utility companies, EPRI, pipeline companies, coal companies, and if necessary, investment companies and venture capitalists.

To promote the rapid development of a commercial demo project, task (c), the University should guarantee that the royalty to be paid by the owner of the first project will be very low—no more than 5 cents per ton of coal transported by CLP, over the life of the project. Before September 1, 1999, the Center plans to conduct another survey of utilities and coal companies to determine possible new commercial demo projects. A free evaluation will be provided for each submitted project, assessing its technical and economic feasibility, in the same way as done before (in 1995). This will enable the determination of the most promising demo project and the owners' current interest in it. This time, the survey will cover not only the United States but also China, as there has been strong interest in using the CLP technology for transporting coal in China. China is also the largest coal producing nation in the world. However, any demo project in China will be conducted only with U.S. industry participation. There is at least one company in the U.S. that has strong interest in building coal pipelines in China. To protect U.S. and University of Missouri intellectual rights in China, the University should apply for a CLP patent in China. So far, the University is reluctant to pay for the cost of such patent application.

2. Plan for Other Areas of Capsule Pipeline Research

While the completion of coal log pipeline development must rely entirely on industry funding, there is great opportunity for government sponsored research in other types of capsule pipelines that are so far unexplored by CPRC and other entities or individuals. The two most promising types are pneumatic capsule pipeline (PCP) for future intercity freight transportation, and hydraulic capsule pipeline (HCP) for transporting grain and other agricultural products. Both have strong industrial and public interests.

A proposal has been submitted to the National Science Foundation (NSF) to establish an ERC (Engineering Research Center) on Pipeline Transportation Infrastructure Center. The Center is to be funded for five years with the likelihood of a second five-year term. Should this proposal be funded, the Center will be in an excellent position to conduct the needed PCP and grain pipeline research. With such an ERC from NSF, the Center researchers can concentrate on research in the next five to ten years, instead of focusing on endless fund-raising which takes away a great deal of the researcher's time for research. This will cause rapid development of the technology and possible commercial use of PCP and grain pipelines within the next five to ten years.

Other opportunities will and should also be explored. Because there is an increasing national and international interest in PCP for freight transportation in order to reduce traffic congestion on highways caused by trucks, sooner or later the U. S. Department of Transportation will be involved in sponsoring R&D in PCP. This can be hastened through federal legislation. A freight pipeline research bill is being considered by two congressmen from Missouri for possible introduction in the Congress. Should the bill be successful, it will speed up PCP research in the future. CPRC, being the leader in this field, is expected to play an important role in such R&D. The University can help greatly by including this in the University's priority list for legislative action.

As to the grain pipeline R&D, an industry consortium will be organized to support the NSF-ERC proposal. The U. S. Department of Agriculture will also be contacted for possible help. This action will be most successful by involving the College of Agriculture in a joint effort.

Finally, CPRC has recently received a large grant from the U. S. Department of Energy to do R&D in biomass compaction—an adaptation of the coal log compaction technology developed by CPRC for compacting biomass solid waste materials such as sawdust, wood chips, waste paper, and municipal solid waste. The first phase of the project is for 18 months, and the 2nd phase is for two years. This will also be an important research area of CPRC in the coming years. An industry consortium is being formed to participate in this R&D.

Another spin-off technology also resulted in a proposal submitted to a special NSF program called Research Center/Small Firm Collaborative Research. The proposal was submitted with the T. D. Williamson, Inc. in Tulsa. The proposal, based on a CPRC invention, is to test and develop a special sensor for detecting capsules and coal logs passing through pipes. It can also be used for detecting pipeline "pigs"—scrapers that move through pipelines.

3. Education Plan

CPRC has conducted a national survey on pipeline education—see document in Appendix 5. It is clear from this survey that there is a general lack of adequate training of engineers in the pipeline area, and this includes M.U. Due to MU's strong research capability and reputation in the pipeline field, it should be relatively easy for MU to take a lead in developing a model pipeline education program in the nation. Such a program, focused on graduate education, can attract the most talented young people and some employees of pipeline companies interested in receiving graduate education and training in pipeline. Such a program has been proposed to NSF in the ERC proposal. If funded, MU will become the nation's education/training center for pipeline engineers.

4. Seeking Donation from Foundations/Philanthropists

The Campus development office and the College of Engineering Development Office can help the Center by seeking donations from private foundations and philanthropists. Due to the fact that capsule pipeline is an environmentally friendly new technology of great implications to the nation, and due to the fact that University of Missouri is clearly the national leader in this field, it should be possible for the University to obtain one or more than one large donation for CPRC. The money can be used for a new office/lab/classroom building, to be located where the new pilot plant is located on the Holstein Farm. Part of the donation can also be used for pipeline scholarships, and a chaired professorship in pipelines. Such a donation will help to insure the existence of a permanent center for capsule pipelines at MU, well into the 21st century.

K. Conclusion

CPRC has made great strides in the last 7½ years, in research, development, technology transfer, and training students. It has also helped in the economic development of the State although much greater economic benefits remain to be fulfilled through commercialization of the coal log technology and other spin-off technologies developed by CPRC.

Even greater opportunities exist for CPRC in the future. The Center will seek to expand activities into new areas such as compaction of solid wastes and other materials, pneumatic capsule pipeline for intercity freight transportation, hydraulic capsule pipelines for transporting grain and other agricultural products, pipeline education, etc.

Strong support from industry, government agencies (both federal and state agencies), and the University (including Department, College, Campus and System administrations) are needed for CPRC to fulfill its vision and mission. University support (internal support) is especially crucial for the Center to succeed and to increase its training and education mission.

APPENDICES:

1. ASCE Task Committee Report on Freight Pipelines
2. Coal Log Pipeline Pilot Plant
3. CPRC Publication List
4. Article on Coal Log Compaction Machine Design in ASME journal, MECHANICAL ENGINEERING.
5. Article on Pipeline Education

APPENDIX 1:

ASCE Task Committee Report on Freight Pipelines

FREIGHT PIPELINES: CURRENT STATUS AND ANTICIPATED FUTURE USE

By the ASCE Task Committee on Freight Pipelines of the Pipeline Division

(Reviewed by the Pipeline Division)

ABSTRACT: This report is issued by the Task Committee on Freight Pipelines, Pipeline Division, ASCE. Freight pipelines of various types (including slurry pipeline, pneumatic pipeline, and capsule pipeline) have been used throughout the world for over a century for transporting solid and sometimes even package products. Recent advancements in pipeline technology, aided by advanced computer control systems and trenchless technologies, have greatly facilitated the transportation of solids by pipelines. Today, in many situations, freight pipelines are not only the most economical and practical means for transporting solids, they are also the most reliable, safest, and most environmentally friendly transportation mode. Increased use of underground pipelines to transport freight is anticipated in the future, especially as the technology continues to improve and surface transportation modes such as highways become more congested. This paper describes the state of the art and expected future uses of various types of freight pipelines. Obstacles hindering the development and use of the most advanced freight pipeline systems, such as the pneumatic capsule pipeline for interstate transport of freight, are discussed.

INTRODUCTION

Freight pipeline is the generic term for all pipelines that transport freight—solids, bottled liquid, or bottled gas. There are three general types of freight pipelines: pneumatic pipelines, slurry pipelines, and capsule pipelines.

Pneumatic pipeline has been used extensively throughout the world for transporting hundreds of types of bulk materials such as minerals, grain, cement. In recent years, it has been used for collecting refuse from apartment complexes and from entertainment centers, such as Disney World in Florida. Because pneumatic conveying is energy intensive, it is practical only for short distances—generally not more than a few kilometers, usually much shorter.

There are two general types of pneumatic pipelines. The first is the suction or negative-pressure type in which a fan or blower is located near the end of a pipe to suck solids through the pipe, as in the case of a vacuum cleaner. Each stage of a suction type system is limited to a pressure difference less than one atmospheric pressure, and hence is applicable only for relatively short distances, such as 100 m. If several pipes are used to transport solids from different locations to a common place, a suction system can be operated with a single fan or blower located at the end of the system.

The second type is the positive-pressure or simply "pressure" system. It can develop pressure differentials much greater than those in a suction system, and hence can be used for conveying solids much longer distances than suction systems. Some positive-pressure pneumatic pipelines are longer than 1 km. A common fan or blower can be used to transport solids from a single location to different destinations by using a set of branching pipes.

Slurry pipelines transport solid particles mixed in water or another liquid. They can be subdivided into two categories: (1) coarse slurry pipelines; and (2) fine slurry pipelines. The coarse slurry pipeline transports solids composed of large particles. It is both energy intensive and abrasive to pipe. Because of this, as in the case of pneumatic conveying, the coarse slurry pipeline is used only for relatively short distances. Examples of common use of the coarse slurry pipeline include underground mining, dredging, and hydraulic conveying of construction materials such as sand and crushed rock. A relatively new use of coarse slurry pipeline currently popular with contractors is concrete pumping, which pumps wet concrete to bridge decks and the upper floors of high-rise buildings to facilitate construction.

The fine slurry pipeline transports fine solids (particles of less than approximately 1 mm in size). Because fine particles can be suspended by water at low velocity, the operational velocity of fine slurry pipelines is low (usually less than 2 m/s), and hence the energy intensity is also relatively low, especially for large pipelines. This and the fact that grinding minerals to powder and dewatering fine slurry are both energy intensive and expensive make the fine slurry practical only for large pipelines over long distances, unless dewatering is not required, as in the case of the disposal of mine tailings.

Capsule pipeline technology is the most versatile type of freight pipelines, capable of transporting almost any cargo, including solids and packaged products, of a size slightly smaller than the diameter of the pipe through which the cargo moves. There are two general types of capsule pipelines: (1) the pneumatic capsule pipeline (PCP); and (2) the hydraulic capsule pipeline (HCP). Whereas PCP uses air or an inert gas as the transporting fluid, HCP uses a liquid (usually water). Because water is one thousand times denser than air at standard atmospheric conditions, large buoyancy and lift forces are generated on hydraulic capsules, making it possible to suspend capsules by the water in the pipe at relatively low velocities. This alleviates the need for wheels for hydraulic capsules. The capsule in an HCP is either a cylindrical container that contains the cargo or a cylinder made of the material to be transported. In the latter case, the cargo is to be made into a solid cylinder, and it must not chemically interact with or dissolve in water. An example is the coal log pipeline, which will be discussed later.

In contrast, because of the lightness of air and other gases, the fluid in a PCP cannot develop significant buoyancy and lift forces to suspend capsules, especially those carrying heavy cargoes. Consequently, large PCP capsules that carry heavy cargoes are usually vehicles with wheels rolling in the pipe. The capsules are propelled by the thrust or drag generated by the air moving through the pipe. However, PCP has the advantage of using air instead of water. Air exists everywhere on earth, costs nothing, and does not wet the cargo. Also, PCP

Note. Discussion open until January 1, 1999. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on March 18, 1998. This paper is part of the ***Journal of Transportation Engineering***, Vol. 124, No. 4, July/August, 1998. ©ASCE, ISSN 0733-947X/98/0004-0300–0310/$8.00 + $.50 per page. Paper No. 17948.

is much faster than HCP and hence is more suitable for cargoes that must be quickly dispatched.

HISTORY AND CURRENT USE

Pneumatic Pipelines

According to Stoess (1981), as early as 1866 Sturtevant developed a pneumatic pipeline system for conveying lightweight materials such as wood shavings, sawdust, and waste papers. In 1886, W. E. Allington invented a dust collector for woodworking plants, formed a company in Michigan, and developed a pressure-type pneumatic pipeline system based on the Allington charger, which is a rotating vertical cylinder divided into chambers. In 1890, F. E. Duckham in England produced the prototype of modern-suction grain unloaders and marine unloaders for bulk materials. In 1906, the Englishman A. H. Mitchell devised methods for substantial reduction in the power consumption of unloaders, from 5 horsepower per ton to 1.5 horsepower per ton. By 1914, most of the imported grain in England and continental Europe was handled pneumatically.

The early pneumatic suction systems used either a reciprocating piston pump or a turboexhauster. The development of the rotary positive blower, invented by Roots in 1859, greatly enhanced pneumatic conveying. However, further development and use did not occur until the 1900s—decades after P. H. Roots' invention. By 1920, the rotary positive blower had become popular. Meanwhile, many experiments were conducted to eliminate the fire and explosion hazards in pneumatic conveying of pulverized coal. The fluid-solids pump was invented by A. G. Kinyon, and its first commercial use was in 1919. Initial attempts to use fluid-solids pumps in 1926 to convey Portland cement were unsuccessful. The cement was too abrasive to the variable-pitch screw of the pump. However, this problem was solved by J. H. Morrow of the Fuller–Lehigh Company, by using welding rods to coat the screw pump. Subsequently, the fluid-solids pump became standard for pneumatic transport of cement and many other materials.

At about the same time, high-pressure blow tanks were developed by F. L. Smith & Co. using a Fluxo pump. In 1933, the system was used for transporting cement pneumatically over a distance of 1.8 km at the Hoover Dam construction site. Later, similar equipment was used to convey cement for a distance of 2.1 km for constructing the Grand Coulee Dam.

The next industry-wide use of pneumatic pipelines after cement was in the brewing industry. After prohibition was lifted in 1933, practically all large brewers in the United States invested in a pneumatic pipeline unloader for malt and grits. During World War II, much emphasis was placed on pipelining catalysts for the high-octane gasoline program and on handling other war materials. After the war, many industries (paper, baking, plastics, animal feed, etc.) began using pneumatic pipelines. This was facilitated by the development of special hopper cars designed for pneumatic loading and unloading.

At present, practically all industrial plants that produce powdered or granular solids, or use powdered or granular materials in large quantity, use pneumatic pipelines. One of the biggest users is the plastics industry. The use of pneumatic pipelines to handle materials such as polyvinyl chloride and polyethylene not only cuts costs but also prevent product contamination and reduce dust problems. Other industries that use pneumatic pipelines extensively include bakeries, the pulp and paper industry, sawmills, plywood plants, cement plants, and metal plants.

Slurry Pipelines

In the United States, the first application of hydraulic dredging was in 1855 (Huston 1970). In 1891, a U.S. patent was granted to W. C. Andrews for a method of pumping coal with water (Thompson and Wasp 1968). The first experimental study of slurry hydraulics was reported by Hazen and Hardy (1906). Blatch (1906), reported that the pressure gradient of slurry flow in pipe was minimum at a velocity corresponding to the transition from a stationary bed of solids to fully suspended solids for a given solids concentration. Additional tests on slurry hydraulics were reported by Gregory (1927), Howard (1934), and O'Brien and Folsom (1937). Worster (1952, 1954) correlated his experimental results and those of other workers and made theoretical contributions. The most extensive work and design correlations were reported by Durand and coworkers (Durand and Condolios 1952; Durand 1953). Their correlations are extensively used in the design of slurry pipelines. Newitt et al. (1955) derived an equation for head loss based on semitheoretical arguments. Since the late 1960s, a considerable amount of experimental and theoretical work related to slurry hydraulics has been reported. However, because of large variations in the properties of the solids to be transported and the complex nature of interactions between solids and water in a slurry, no universal correlation has been established.

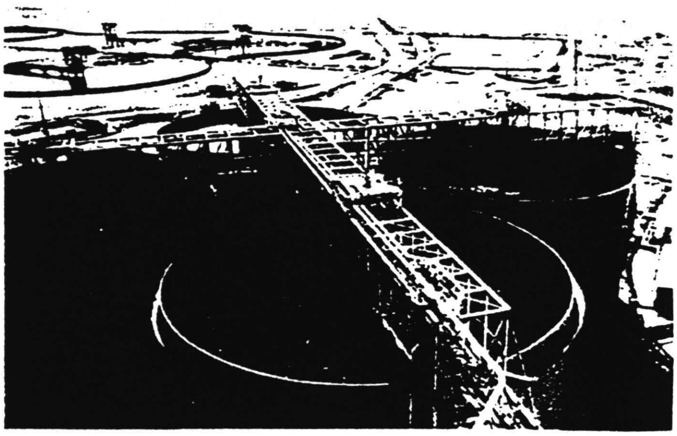


FIG. 1. Slurry Dewatering Facility at Mohave Power Plant (Laughlin, Nevada) (Slurry Is Delivered by 438-km-long Black Mesa Pipeline, which Gets Coal from Black Mesa Coal Mine in Arizona)

In 1957, a 187-km-long 152-mm-(6-inch) diameter gilsonite slurry pipeline was put into operation in the United States (Fulkerson and Rinne 1959). In the same year, a 174-km-long 254-mm-diameter (10-inch) coal slurry pipeline was put into operation in Ohio (Halvorson 1964). Over the last three decades, a number of long-distance slurry pipelines have been built to transport coal, iron concentrate, copper concentrate, phosphate, kaolin, limestone, fly ash, and various types of tailings from the mineral processing industry. The longest slurry pipeline built to date is the 438-km-long 456-mm-diameter (18-inch) Black Mesa Coal slurry pipeline in the United States (Fig. 1). The largest diameter slurry pipeline is the 500-mm-diameter (20-inch) Samarco iron concentrate pipeline in Brazil. A list of major slurry pipelines around the world is given by Thompson and Aude (1981).

PCP

PCP is a technology of long history and frequent usage. According to Zandi and Kim (1974) and Zandi (1976), in 1810, Danish engineer George Medhurst wrote a pamphlet explaining how letters and goods can be transported in small tubes at speeds as high as 160 km/h. In 1861, a large-scale PCP was built in England by the Pneumatic Dispatch Company. Since then, many PCP systems have been built and used successfully in various parts of the world. At the turn of the

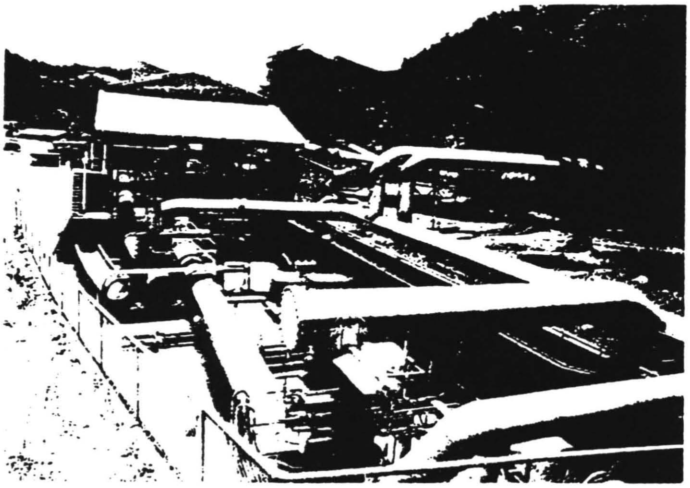


FIG. 2. Capsule Loading Station of Sumitomo Pipeline (Japan)

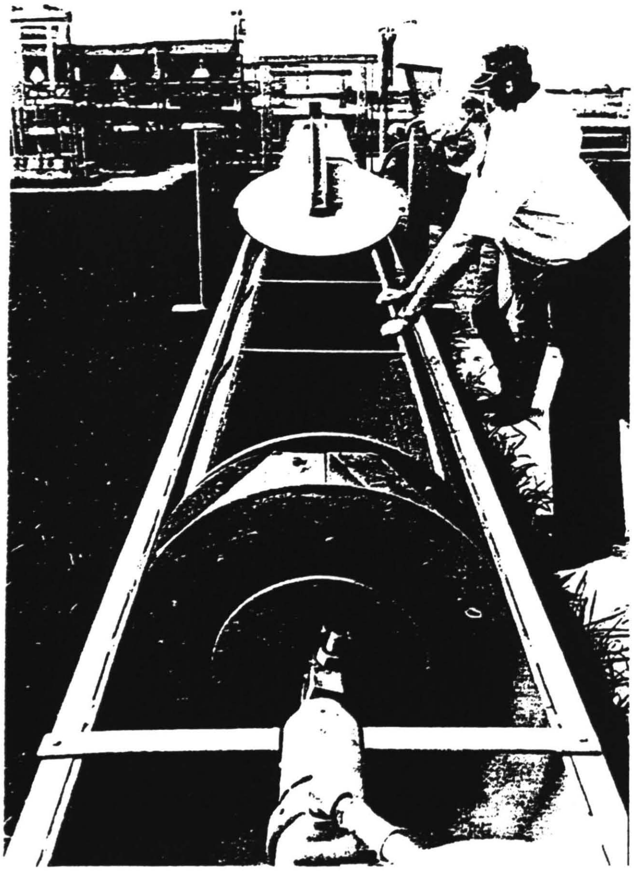


FIG. 3. Tubexpress PCP System Developed in United States (Standing by Capsule Is Prof. Robert Carstens, Developer of Tubexpress PCP System)

century, five U.S. Post Offices (Philadelphia, New York, Boston, St. Louis, and Chicago) had PCP systems linking main offices to branch offices.

The old PCP systems were crude, mechanically unreliable, and troublesome to use. In the last 50 years, they have mostly been replaced by automobiles, conveyor belts, and other means of transportation. Meanwhile, a new generation of PCP has emerged, using modern pipeline technology and computer control. Such new PCP systems have found increased use in hospitals to transport blood samples, medicine, and supplies between buildings, in drive-in banks to transfer cash and receipts, in factories to transport machine parts and materials, and at airports for transporting tickets and documents between buildings (Liu 1993b).

Large and long PCP systems for transporting minerals have been built and used in both the former Soviet Union (Jvarsheishvili 1981) and Japan (Kosugi 1992). The largest and longest is LILO-2 in the Republic of Georgia. This is a 17 km long 1.22-m-diameter (48-inch) pipeline for transporting rock (Jvarsheishvili 1981). Since 1983 in Japan, Sumitomo Metal Industries has successfully operated a large (1-m-diameter) PCP system for transporting limestone from a mine to a cement plant, a distance of more than 3.2 km (Kosugi 1992). Fig. 2 shows the loading of capsules at the intake station of this Japanese pipeline. Success in this project has prompted Japan to undertake other PCP projects. In the United States, the Tubexpress System in New Jersey developed and marketed a large PCP system (Fig. 3). Unfortunately, the system has not been used commercially. Further improvement of this system is needed to make it more cost competitive with trucks, trains, and conveyor belts. The potential of using PCP in North America has been established by Round and Marcu (1987).

In the ISTEA (Intermodal Surface Transportation Efficiency Act) legislation, the U.S. Congress asked the U.S. Department of Transportation to conduct an assessment of the PCP technology for freight transport. This report was prepared by the Volpe National Transportation Systems Center (Vance and Mattson 1994).

HCP

HCP is a relatively new concept first proposed during World War II by Jeffrey Pyke to transport war materials to China through Burma (Lampe 1959). The proposal was never implemented because the technology had not been developed at that time. It was reinvented independently in Canada in 1959 (Brown 1987). Since then, extensive research in HCP has been conducted in Canada at the Alberta Research Council (Jensen et al. 1975); the United States, primarily at the University of Missouri–Columbia (Liu, 1981; Liu 1982; Assadollahbaik 1984; Assadollahbaik and Liu 1986); and in several other nations including Australia (Graze and Dzadey 1984), South Africa (Lazarus 1979), Japan (Sakamoto et al. 1976; Yanaida 1982), and The Netherlands (van der Kroonenberg et al. 1979).

In 1991, the National Science Foundation established a capsule pipeline research center at the University of Missouri–Columbia. The current focus of the center's research is to develop coal log pipeline (CLP) technology for commercial use by the year 2000 (Fig. 4). CLP is a special type of HCP that uses compacted coal logs for hydraulic transport via pipeline (Liu 1996). This new type of HCP for transporting coal has

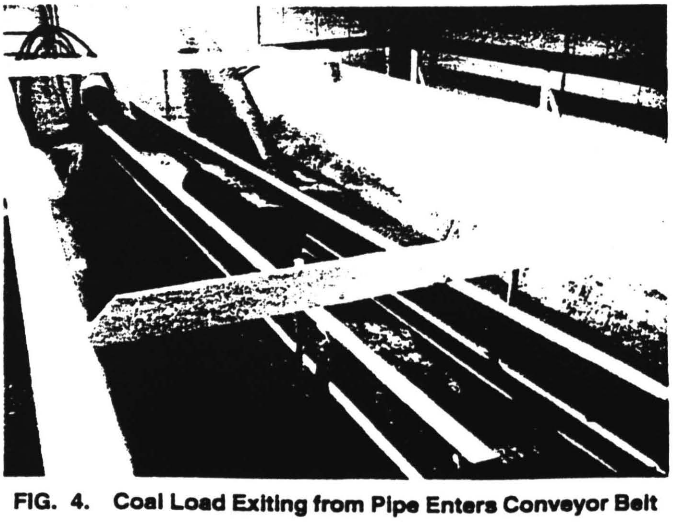


FIG. 4. Coal Load Exiting from Pipe Enters Conveyor Belt

several advantages over the coal slurry pipeline—lower cost, less water needed, and larger throughput of coal (Liu 1994).

Comparison of HCP with PCP

A comparison of HCP with wheeled large PCP systems for transporting heavy cargoes is provided next.

Main Advantage of Wheeled PCP

1. The capsules in PCP move much faster than in HCP—more than 10 m/s as compared with fewer than 3 m/s for HCP. This does not mean a larger throughput (i.e., cargo volume) or smaller pipeline diameter because it is difficult to achieve high line fill (linear concentration) of capsules at high speed. However, it means fewer capsules are running in the pipeline and this reduces the system cost. Also, higher capsule speed means shorter travel time for each capsule. This is important for perishable cargo or mail, which must be transported speedily. For nonperishable cargo such as coal, being transported in a continuous operation, shorter travel time has no significant advantage.
2. PCP uses air, which exists everywhere and is free except for compressor costs. Furthermore, handling air is easier than handling water, and air cannot accidentally wet the cargo in capsules.
3. In crossing mountains, the large change of elevation in hydraulic pipeline can cause problems such as column separation at summits (which results in the "slack flow") and excessive line pressure in low places. Sophisticated designs must be made in HCP to overcome these problems.

Main Advantages of Wheelless HCP

1. Without wheels, the cost of each capsule is less, and the system has no problems and costs associated with wheels.
2. The low velocity of HCP means lower energy consumption per unit weight of cargo transported.
3. HCP can have any slope including infinite (vertical) slope, as illustrated by the study of Hwang et al. (1980). In contrast, the slope of PCP is normally limited to about 20%.
4. For any HCP that transports water-resistant and wear-resistant compacted solids such as coal logs (see later description), no capsules (containers or vehicles) are needed to carry the cargo and no return pipeline is required to carry empty capsules.

STATE OF THE ART

Pneumatic Pipeline

Modes of Transport

Although negative-pressure or suction-type pneumatic conveyance is usually restricted to dilute-phase solids transport, long-distance and dense-phase transports usually require the positive-pressure type. Much attention has been paid lately to dense-phase transport in which the solid-to-air loading ratio is often greater than 100. While dense-phase transport can occur at lower velocities (fewer than 5 m/s), thus preserving the particle and pipe integrity, there are several trouble spots, such as booster-air-application location. Conveying fine particles in dilute phase also presents a challenge due to the cohesiveness of particles and electrostatic charges. The accumulation of charges on combustible fine particles such as coal or grain can cause fire and explosions. It must be treated with great care.

Basic Transfer Operations and Analysis

Current design practice in dilute-phase conveying relies on the principles of linear combination of the energy requirements of the gas and solids phases. This additive property has been challenged recently by Weber (1991). Some applications of the newer nonlinear interactions have been verified for high-pressure conveying and dense-phase conveying (Plasynski et al. 1994).

A concept that has received some additional attention in the dilute-phase conveying field is the pickup and saltation (deposit) velocities of the material. These velocities can be used for the establishment of conveying velocity. They are dependent on the type of material being conveyed. For example, fine particles that are cohesive will have a relatively high pickup velocity because of the agglomerates that they form. The deposit velocity is generally lower than the pickup velocity.

Dense-Phase Conveying

Modeling dense-phase conveying is very material-dependent because there is intimate contact between particles and between the particles and the wall. Some materials are suitable for this type of conveying, namely plastic pellets, which easily form plugs themselves without too much assistance. Generic sand, however, does not form plugs and probably should not even be subjected to this type of conveying.

Konrad et al. (1980) did one of the first analyses of the dense-phase plug conveying. They modeled the system using the particle-wall and particle-particle friction using the classic shear cell measurements. Other researchers have followed a similar approach—Legel and Swedes (1984), Aziz and Klinzing (1990), and Destoop (1993). Tsuji and colleagues (1990) have had considerable success in modeling dense-phase flow by using a kinetic model accounting for individual particle-particle interactions. In dense-phase pulsed piston transport, there is a minimum length of a plug that can be conveyed before the plug loses integrity. Meanwhile, the pressure loss across these moving plugs increases exponentially as the plug length increases. There is obviously an optimum plug length. Some success has been achieved by using booster air to help limit the size of the plug.

Challenges in Pneumatic Conveying

Pneumatic Conveying of Cohesive Particles. Pneumatic transport of fine particles that are cohesive presents a special challenge due to the complexity of the matter, especially if the surface forces are electrical in nature or if moisture is present on particles. Because the subject is poorly understood, more research is needed.

Attrition. Even though attrition can be reduced significantly through the reduction of the gas velocity by using dense-phase conveying, most existing systems cannot be changed easily to a dense-phase operation to take advantage of this concept. One is faced with addressing the dilute-phase system and trying to redesign the piping arrangement to cut down on attrition. Another source of large attrition are the cyclone separators, which are often used to collect particles at the end of transfer operations. Often the cyclone will provide more than 80% of particle attrition. How to further reduce attrition of particles to be transported pneumatically remains a challenge to researchers.

Dense Phase. Dense-phase conveying is not for all materials. The misapplication of dense-phase conveying has often resulted in solutions that have turned the dense-phase system into a dilute-phase operation. The use of booster air to control the size of the plug in a dense-phase system is a viable technology, but its application is often overused. Often, vendors will solve these problems but not offer the purchaser any clue to the strategy in arriving at a solution, or whether the solution has maintained the dense-phase concept of the original design. Because of a lack of published studies in this area, more published information is highly desirable.

Wall Interactions. As with attrition, the higher the velocity of gas, the more erosion of the piping system takes place. A properly designed pneumatic pipeline system should have the straightest path between the entrance and the outlet of the pipeline. The fewer bends there are the better the design. More information is needed on the selection of pipe materials that produce the least wear.

Electrostatics. Generation of static electricity can often occur in a conveying system causing fire and explosion if the material conveyed is combustible. Several means exist to prevent charge build-up and hazards, such as using metal pipe and equipment and grounding the system electrically, using moist air or inert gas, cleaning pipe interior frequently to prevent dust build-up and so on.

A review of the subject of electrostatic hazards in pneumatic conveying is given by Soo (1981). Jones and King (1991) have compiled a useful book on practical solutions to problems with powders and electrostatics. Most lacking at present are theoretical models that can predict electrostatic charge accumulation and threshold levels of charge that cause fire and explosion in a given situation. More research is needed in this area.

Feeding and High Pressure. Introduction of solids into a pneumatic conveying system is a major task. When the system is operating at high pressure, this task is even more challenging. The fluid-bed combustors are a case in point. There are a few technologies on the market, but nothing yet that is simple, reliable, and low cost. Development of a better means to introduce solids into high-pressure pneumatic conveying systems represents a challenge to would-be inventors.

Measurements. Meters for measuring the flow properties in pneumatic conveying are sadly lacking. A simple device is needed to measure the flow rate, so that the process of pneumatic conveying can be better controlled. Likewise, in handling solids, a reliable means for measuring the solid level in tanks and silos would help with the inventory analysis of such systems.

Data Sharing. Over the years there have been many designs of pneumatic conveying systems for challenging materials and materials of unique design. They remain proprietary information of various firms and are not shared with other companies and academia. As a result, a large amount of money has been spent to redesign similar systems. If the technology had been available through the literature, a significant amount of money could have been saved and spent on answering more basic questions. It has been suggested that the practitioners of pneumatic conveying band together in a consortium to share information so that the technology can advance more rapidly.

Slurry Pipelines

Slurry Flow Behavior

Flow of a solid-liquid suspension in a horizontal pipe gives rise to varying types of solids movement depending upon the flow velocity. The various flow regimes are classified as homogeneous, heterogeneous, moving bed, and stationary bed.

In homogeneous flow, the solids are uniformly distributed across the pipe cross section. This type of flow is encountered with slurries of high solids concentration and fine particle size or relatively high velocities. The presence of solids can result in significantly different rheological behavior of slurry compared with carrier fluid. This type of flow occurs with finely ground mineral concentrates such as copper, iron, phosphate, limestone, chalk, and kaolinite.

In heterogeneous flow, solids are not evenly distributed and a pronounced concentration gradient exists along the vertical axis of the pipe. Heterogeneous flow is encountered with slurries of low concentration and large particle size, or at low velocities. This type of flow is encountered in dredging operations and in many tailing pipelines.

In the moving-bed flow regime, the fluid turbulence is insufficient to keep the particles in suspension for a prolonged period of time. The particles travel by making successive jumps downstream—saltation. A moving bed of sliding or rolling solids may also be present. This type of flow occurs with large particles or at low flow velocities. It is encountered in the pumping of coarse coal, coarse sand, and gravel.

Flow with a stationary bed occurs when the velocity of flow is lower than that required for moving bed. This type of flow must be avoided because it results in no transportation of solids and clogging of pipeline.

Most of the naturally occurring materials show a wide range of particle size. Therefore, in a practical situation, the coarse fraction of the solids may be carried in the heterogeneous or saltation flow regime, whereas the finer fraction may be carried in the homogeneous regime.

Turian and Yuan (1977) have developed correlations for estimating velocities at which transitions from one regime to another take place.

Slurry Hydraulics

In slurry transport by pipelines, turbulent flow must be maintained to prevent settling of solids in the pipeline. For homogeneous slurries that behave like a Newtonian fluid, transition from laminar to turbulent flow occurs at a Reynolds number of approximately 2,400, based on the viscosity of the slurry. The head loss (pressure drop) along the pipe can be calculated from the conventional Darcy-Weisbach formula in which the resistance factor f can be determined from either the Moody diagram, Fanning diagram, or the Colebrook equation.

For slurry that behaves like a Bingham plastic fluid, transition from laminar to turbulent depends on both the Reynolds number and the Hedstrom number. The method proposed by Hanks and Pratt (1967) can be used to estimate the transition Reynolds number. The pressure drop along the pipe can still be determined by the Darcy-Weisbach formula, but the resistance factor f depends on both the Reynolds number and the Hedstrom numbers (Thompson and Aude 1981).

For slurries that behave like a pseudoplastic or dilatant fluid, other equations are available to predict the hydraulic behavior of the slurries (Govier and Aziz 1972).

Slurry Preparation

In many applications, slurry is prepared as a part of mineral beneficiation. In the case of coal slurry the solids are specifically ground to obtain a size suitable for pipeline transportation. The slurry preparation involves grinding of large size (50 mm top size) coal solids using cage mills to obtain minus 6 mesh (smaller than 3.36 mm) products. Finally, rod mills are used to obtain the desired (minus 1.4 mm) size distribution. When a large amount of fine fraction must be generated, as in the case of coal-water mixtures, ball mills may be used instead of rod mills.

Slurry Pumps

Slurry pumps are similar to ordinary liquid pumps in principles and types, except that they are designed to handle a large amount of solids in the flow—slurry—and hence are far more costly than corresponding liquid pumps. The type of pumps to be used in any slurry pipeline application depends on the maximum particle size and pumping pressure requirement. Gandhi et al. (1980) developed general guidelines and a chart for selecting the type of pump for a given particle size and discharge pressure.

Centrifugal slurry pumps have high flow capacity per pump, but the head developed per pump is limited to about 45 m. The pumps can be arranged in series to increase the total pump head. The maximum pump head is limited by the casing pressure limit, which is about 5,170 kPa (750 psig). Booster pump stations will be needed if the total pressure drop along a pipeline exceeds this limit. Centrifugal pumps are easy to maintain and are lower in cost compared with positive displacement pumps, especially at high flow rates and low pumping pressures. The efficiency of centrifugal slurry pumps (below 80%) is generally low as compared with positive displacement pumps (more than 90%). The centrifugal pump's flow rate decreases with an increase in head. Thus, with an incipient plug, a centrifugal pump may give rise to progressively slower flow until a blockage develops. Use of variable speed drives can reduce this problem to some extent.

Positive displacement pumps provide constant flow rate at a given speed, independent of pipeline pressure. This property of the positive displacement pumps makes the slurry pipelines that use such pumps less likely to develop blockage. Furthermore, due to their high pressure capability (as high as 15,000 kPa in a single stage), and higher efficiency compared with centrifugal pumps, such pumps have been used extensively in long-distance slurry pipelines. Their initial costs are higher than centrifugal slurry pumps, and skilled labor is required to maintain them. The positive displacement pumps generally used include piston, plunger, and diaphragm types. The piston pumps are used with materials having a Miller number below 60. The Miller number is a measure of slurry abrasiveness, with materials having Miller numbers above 60 being considered highly abrasive. For abrasive slurries, either a plunger pump or a diaphragm pump is used. High-pressure clear water is pumped between the plunger and packing to reduce wear of the plunger type pump. A diaphragm driven by a piston operating in clear hydraulic fluid is used in a diaphragm pump. The diaphragm pump has the minimum number of wear parts compared with a piston or a plunger pump. Diaphragm pumps have the lowest maintenance costs, but their initial cost is about 50% higher than the plunger or piston pumps.

Slurry Dewatering

Dewatering is generally a part of the mineral processing requirement and, therefore, is not considered a part of the pipeline system. In the case of a coal slurry pipeline, however, dewatering is considered as a part of the pipeline system in cost analyses. Vacuum filters and flyash driers were used in the Ohio coal pipeline system for dewatering the slurry at the power plant. Centrifuges are used at the Mohave Power Plant in Nevada, which receives the coal delivered by the Black Mesa coal slurry pipeline. The Mohave plant was specifically designed to receive pipeline-delivered coal and, therefore, the centrifuge cake is directly fed to boilers.

If a slurry pipeline is used to deliver coal to an existing power plant that is designed to burn coal delivered by a railroad, then additional conditioning of the dewatered cake and centrifuge effluent will be needed. The primary centrifuge effluent is fed either to secondary centrifuges or belt filter presses to capture all of the coal solids. The primary centrifuge cake and the secondary centrifuge or belt filter press cakes are mixed and dried in a fluidized bed dryer to control the cake moisture in the final product. The cake moisture is controlled to achieve mass flow in boiler feed hoppers and at the same time prevent a dusting problem that may occur if the cake moisture is too low.

Instrumentation

A slurry pipeline system can be controlled in the same manner as a conventional liquids pipeline system. Magnetic flow meters are used for flow measurement. The slurry density is measured using nuclear density meters. Both of these meters must be installed in a vertical section of pipe to eliminate problems resulting from solids settlement in horizontal sections of pipe.

Pressure transducers are used to measure pressures. Special measures should be taken to prevent plugging of pressure taps. This can be done by purging the pressure taps with water. A better method is to mount a diaphragm near the pressure tap and connect the diaphragm to the pressure sensor using a sealed capillary tube. The slurry level in the slurry storage tank can be measured using conduction probes or ultrasonic transmitters. The slurry temperature can be measured using a temperature probe installed in a thermowell connected to the pipe.

PCP

Design

Currently, use of digital computers is essential for the design of most engineering systems, including PCP. Designers of PCP such as TUBEXPRESS Systems in the United States and Sumitomo Metal Industries in Japan have all developed software programs for the design of PCP systems. For instance, TUBEXPRESS has a simplified mathematical model assuming that the pipeline slope is constant between terminals, the flow of air and of capsules is steady, and the air expands in accordance with "ideal gas laws." Another program developed by TUBEXPRESS is a spreadsheet economic model. The third is a software program in which the operation of a given system is simulated. The first two of these programs are used to select the optimum mass rate of flow of air and diameter of pipelines. The third program is a lengthy numerical analysis in which calculations proceed upstream by each capsule and intervening air pocket, and are repeated at small increments of time. The simulation program involves calculating and recording a detailed history of capsule position, capsule velocity, and acceleration and history of air-pocket length, density, and pressure. The simulation program is used to determine whether any instabilities will develop, the maximum power input required, and the system behavior during a power outage and during the subsequent startup.

System Components

All current commercial PCP systems use rubber tires. The following description pertains mainly to the PCP system developed by TUBEXPRESS Systems in New Jersey. The TUBEXPRESS capsules are four-wheeled rubber-tired vehicles with the open-topped cargo container being built as a unit. The wheels at each end are spaced 90° apart. The rubber tires that deform laterally as rubber contacts the pipe are responsible for maintaining the capsules in an upright position as the capsule rolls through the pipeline. In as much as the capsules are propelled by the flowing air and are braked aerodynamically, the vehicles are completely passive and are designed to be as lightweight as possible. Each capsule is designed to produce maximum drag to minimize the leakage of air past the capsule. To increase the coefficient of drag, flexible seals are attached to the rear of the capsule. These seals are slightly smaller in diameter than the inner diameter of the pipe, so that solid-to-solid contact friction does not occur as the capsule rolls along. Because rubber tires are limited in weight-carrying capacity, steel-tired wheels can be used with a resultant reduction in rolling friction, but with an increase in noise, which may not pose serious problems for underground pipeline systems. The only particular requirements of the pipeline are that the welds are to be exterior welds, the bottom one-third of the pipe should be well aligned with any offsets being forced to the top two-thirds of the pipe, and pipe joints must have a smooth interior surface.

At the end of the pipeline, capsules are directed into a dead-end chamber and the air is directed out of the top of the pipe along a separate path, either to be vented into the atmosphere or to be piped to the intake side of the blowers. The dead-end chamber is plugged at the downstream end by four or five capsules, which are restrained by means of a chain drive. The vehicles are decelerated in the dead-end chamber by the low speed of the chain drive, which matches the speed of the carousel loader or unloader.

Both the loading and unloading systems are horizontal carousels that pick up capsules from the downstream end of the dead-end chamber and carry each succeeding capsule in a semicircular path around to the entry of the opposing pipeline. While the carousel is rotating through 180° the capsules are loaded at the loading station or are unloaded at the unloading station. The peripheral speed of the carousel is locked to match the speed of the drive chain at the dead-end chamber. Originally, capsules were coupled into four-capsule trains with each train being loaded or unloaded simultaneously. With this scheme, the unit process time was somewhat in excess of 30 s or an effective headway between capsules of about 7.5 s. Using the carousel concept, the headway between capsules has been reduced to about 3.5 s.

The pump stations at the terminals are equipped with Roots-type blowers powered by electric motors. The air discharge from the blowers is fed into the main pipeline through a series of ports along the bottom of the pipe. The pipeline upstream from these ports is plugged by at least four or five capsules, which are moved forward by means of a chain drive. The speed of this chain drive is also locked to match the peripheral speed of the carousel. The foregoing description is based on a special TUBEXPRESS PCP system to transport bulk cargo (coal) where all capsules are loaded at one terminal and all are unloaded at the other terminal. More complex arrangements can be made for transporting cargoes that must be loaded and unloaded at many stations.

A new concept related to PCP is "tube transportation," in which freight-laden vehicles (capsules) move on rails inside large diameter tubes or pipe. In this system, capsules are propelled by linear electric motors rather than air. The capsules act as pistons to move the air. The concept was investigated by Zhao and Lundgren (1996) and is being promoted by TubeFreight of Dallas, Texas.

Economics

Application of the economic model for various designs using 1993 cost estimates, a capital payoff period of 10 years, and an interest rate of 15% indicates that under the most favorable conditions the cost of hauling by PCP is not likely to be less than $0.07 per ton/km ($0.10 per ton/mile). Because this cost is not particularly favorable for PCP as compared with conveyor belts or even trucks, adoption of PCP systems will depend upon other factors such as environmental considerations. Further development of this technology to increase the throughput can make the system more economical. Also, large-diameter PCP systems required for interstate transport of freight are more economically competitive due to economy of scale (Zandi 1976).

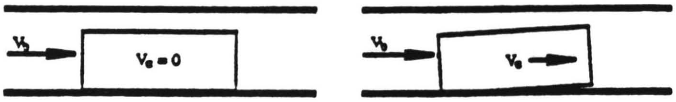
HCP

Much progress has been made in HCP since 1980, resulting in rapid state-of-the-art advancement.

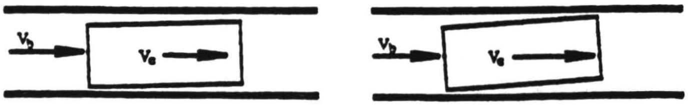
In the understanding of the basic hydraulics of HCP, it is now realized that accurate prediction of the head loss (pressure drop) across a capsule in HCP is possible only if the flow is divided into four regimes with different equations applicable to different regimes (Liu 1993). The four regimes are illustrated in Fig. 5; the predicted average pressure gradient along a capsule is compared with the experimental data in Fig. 6.

The four regimes of the flow are arranged in ascending order of velocity. Regime 1 exists when the bulk velocity, V_b, of the fluid (water) is very low—less than the incipient velocity, V_l, which is the bulk velocity that initiates capsule motion. In this case, a denser-than-fluid capsule will remain stationary on the bottom of pipe with the fluid passing around it. The flow around the capsule is similar to that around an obstacle fixed to the pipe interior, such as a partially closed valve. By dividing the flow into several regions, including a convergent flow upstream of the capsule, flow separation at the entrance, parallel annular flow along the remainder of the capsule, and a sudden expansion flow at the capsule downstream end, the pressure variation along the stationary capsule can be predicted from the one-dimensional energy, momentum, and continuity equations. Because of the eccentricity of the flow, the energy correction factor and the momentum correction factor are both greater than 1.0. Their correct values must be used for accurate prediction of the pressure variation along the capsule. Equations for Regime 1 are presented in Liu and Richards (1994). The pressure drop across a capsule in Regime 1 increases with velocity squared because it is similar to turbulent flow across a partially closed valve.

In Regime 2, the velocity of the fluid exceeds the incipient velocity slightly, and the capsule starts to slide along the pipe floor. This causes the relative velocity of the fluid with respect to the capsule to decrease, and the pressure drop across the capsule to reduce from that of a stationary capsule. However,



(a) Regime 1 ($V_b < V_l$, $V_c = 0$) (b) Regime 2 ($V_l < V_b < V_L$, $V_c < V_b$)



(c) Regime 3 ($V_l < V_b < V_L$, $V_c > V_b$) (d) Regime 4 ($V_b > V_L$, $V_c > V_b$)

FIG. 5. Classification of Capsule Motion into Four Regimes

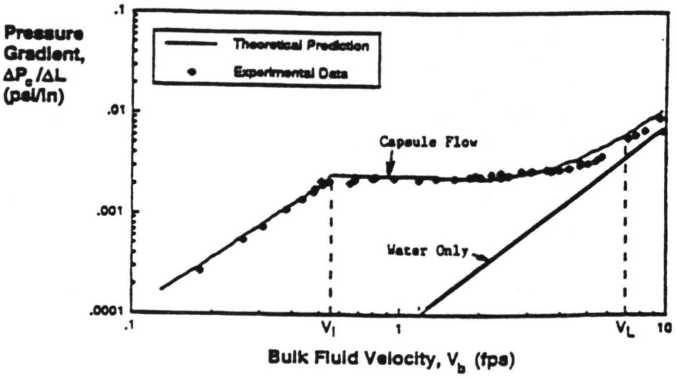


FIG. 6. Variation of Pressure Gradient with Fluid Velocity: Comparison of Theory with Experimental Data in 2-Inch (51 mm) ID Pipe

because little lift is developed in this case due to low velocity, the contact friction between the capsule and the pipe floor is high and it dominates the head loss along the capsule. This can be seen from Fig. 6 in which the average capsule pressure gradient is much higher than the fluid pressure gradient in Regime 2. Equations for predicting pressure drop across the capsule in Regimes 2–4 can be derived by using one-dimensional energy, momentum, and continuity equations with respect to a coordinate system moving with the capsule.

In Regime 3, the velocity of the fluid is significantly higher than in Regime 2, and a significant lift is developed on the capsule. This causes the contact friction between the capsule and the pipe to decrease, whereas the head loss caused by the turbulence in the flow around the capsule increases with velocity. Depending on capsule density and fluid velocity, the combined head loss due to turbulence and contact friction may either increase, decrease, or remain approximately constant as the velocity increases.

Regime 4 begins when the fluid velocity is so great (greater than the liftoff velocity V_L) that the capsule becomes totally suspended by the fluid. The liftoff velocity can be predicted from an equation derived by Liu (1982). In Regime 4, head loss is dominated by turbulence, and it increases directly with velocity squared. The average capsule pressure gradient in Regime 4 approaches that of the fluid as shown in Fig. 6.

Note that the same equations for predicting capsule pressure gradient in the four regimes also yield the capsule velocity. The capsule velocity, V_c, in Regime 1 is zero; it is less than the fluid velocity, V_b, in Regime 2, is slightly greater than V_b in Regime 3, and is much greater (15–20% greater) than V_b in Regime 4. Not only can steady flow of capsules be predicted accurately from the equations, the unsteady capsule flow also can be predicted by using the method of characteristics (Lenau and El-Bayya 1993; El-Bayya 1994). The method has been used for analyzing and optimizing the behavior of capsules in the injection system (Wu 1994) and through booster pumps (Wu et al. 1994).

Rapid advancement in the state of the art has happened since 1991, when the National Science Foundation (NSF) established the Capsule Pipeline Research Center at the University of Missouri–Columbia. The advancement is not limited to hydraulic aspects. Hardware and computer control of injection and pumping systems have been studied (Sun 1993; Du 1996), and an operational small-scale system of HCP including capsule injection, pumping, ejection, and computer control has been designed, built, and tested in a laboratory (Shieh 1993).

Great strides have also been made since 1991 in the development of the CLP, which is a special type of HCP for transporting coal. In CLP the capsules consist of coal compressed into solid cylinders called "coal logs." The logs can be directly injected into and transported through pipe without having to use containers to separate the coal from the water and without needing a separate pipeline to return empty capsules (containers). Water-resistant and wear-resistant coal logs have been developed that can be transported over long distances through pipelines with insignificant wear or weight loss. For instance, some coal logs were circulated through a closed-loop pipeline in laboratory for 12,000 cycles (equivalent to 274 km) with less than 4% weight loss (Cheng 1994).

Several processes have been developed to make strong (water-resistant and wear-resistant) coal logs. One is a binderless process that requires compressing coal at approximately 150°C (Gunnink and Liang 1993; Kananur 1994). Another is at room temperature, but requires the use of 1–3% of asphalt emulsion as a binder (Wilson and Ding 1993). A third combines moderate temperature (about 90°C) with a binder of 1–3% asphalt emulsion (Cheng 1994). In all these processes, the compression pressure is between 3.5×10^4 kPa (5,000 psi) and 1.4×10^5 kPa (20,000 psi). The cost of making such coal logs, when mass produced in commercial operations, is estimated to be less than $3 per ton of coal. The compacted logs absorb little water due to the small porosity of the logs. Even with 3% asphalt emulsion, the logs were found to be easy to crush and grind for combustion in power plants (Marrero and Wilson 1993).

Much is known today about how to make good coal logs at low cost and how to minimize wear loss. For instance, it is known that minimum wear loss happens when the pipeline is operated at 15–20% below the liftoff velocity. At such velocities, wear happens mainly at the rear end of the logs, and hence compacting logs with a beveled rear end helps in reducing wear. Finally, the aspect ratio (i.e., the length-to-diameter ratio) also was found to have a profound effect on coal log wear—larger aspect ratio (greater than 1.6) gives less wear. Many more factors affect the wear of coal logs; they are reported in Liu (1996).

Finally, not only are engineering aspects of HCP and CLP well understood today, the economics of HCP and CLP have also been thoroughly explored (Wu 1989; Liu et al. 1995). Legal issues surrounding coal pipelines, such as the right of eminent domain, water rights, and railroad crossing rights have been thoroughly explored (Davis 1992; Davis and Liu 1996). It was found that railroads cannot disallow coal pipelines or other types of freight pipelines to cross railroads without violating laws. Water needed for coal pipelines and other freight pipelines can be obtained in Western states according to the doctrine of "prior appropriation" and in the Eastern states according to "riparian rights." In regions of severe water shortage such as Wyoming or Utah, desalinated saline or brackish water can be used. Use of such water does not compete with irrigation and other uses of water, thereby avoiding conflicts with farming and other interest groups. The small amount of water needed by CLP coupled with recent advancements in desalination technology based on reverse osmosis has made it economically feasible for CLP to use desalinated brackish water (Liu et al. 1995).

EXPECTED FUTURE USE

Freight pipelines will find growing use in the future because of the following:

1. Lowest cost for freight transport as compared with other transportation modes in many situations.
2. Public desire to reduce reliance on trucks and trains due to serious pollution and safety problems, and increased congestion of highways and streets.
3. Damage caused by trucks to highway infrastructure and the associated high maintenance cost of the infrastructure.
4. Desire to have a reliable, weatherproof, around-the-clock cargo delivery system.
5. Free from cargo theft during transportation.
6. Advantage of underground pipelines from a land use standpoint.
7. Increased population and increased demand for freight transportation.
8. Advancements in freight pipeline technology and computer control, making it feasible to use improved and reliable freight pipeline systems hitherto not feasible. Such advancements include better welding technology to prepare steel pipe with smooth joints, better pipe bending technology to produce bends of smooth radius and least pipe ovality, better control of corrosion, advanced pigging technology and inspection of pipe interior, trenchless technologies (computer guided directional drilling) for construction of underground pipelines to cross roads,

rivers, and other obstacles, computer control of pipeline systems, and so on.

It is expected that all types of freight pipelines, large or small, long or short, will find increasing use in the future. In the pneumatic pipeline area, the main future growth is expected to be in the handling of household refuse. It is not difficult to envision that in the next century, pneumatic conveying of refuse will be a part of the standard plumbing system of many buildings, be it at home, hospital, an apartment, or an office building. Instead of using trucks to collect refuse, the refuse will be pneumatically conveyed to processing stations. Pneumatic conveying of refuse is expected to be a fast-growing industry.

In the future, slurry pipelines will continue to be used in mining, dredging, and transport of construction materials. The biggest growth is expected, however, for transporting sludge from water and sewage treatment plants or factories to processing plants or disposal sites. This is rarely done by pipeline today, but is likely to become a standard practice in the future. If and when the coal water fuel, currently being developed in the United States and other nations, becomes cost competitive with oil, it is only logical to expect that the coal water fuel, which contains purified and concentrated fine coal particles suspended in water, some containing as much as 70% coal and 30% water by weight, will be transported by pipelines.

In the HCP area, six main uses are envisioned: (1) CLPs for transporting coal from mines to power plants, seaports, or barge terminals, for distances between 50 and 2,000 km. The economic feasibility of CLP in this range for larger throughputs (over one million metric tons per year) has been established by a recent study (Liu et al. 1995). (2) Transport of power plant waste (ash and sludge) from the plant to a coal mine or another place for disposal. This can be done either by using the same pipeline that delivers coal or by a separate pipeline using the same right of way. The waste can be compacted into logs for pipeline transportation in the same manner coal is transported in the log form by CLP. (3) Transport of biomass (such as alfalfa hay and chickweeds) and biomass wastes (such as sawdust, wood chips, and soybean hulls). This again can be done by compacting such materials into logs and transporting the logs by pipelines. (4) Refuse logs pipelines for transporting processed municipal refuse, especially the combustible part, from processing plants to incinerators or power plants. The feasibility of this application was established by a study conducted by the Sanford Research Institute more than two decades ago (Boettcher 1971). Unfortunately, lack of technical development to perfect the system has prevented its use so far. (4) Transportation of grain by HCP from storage (elevators) to barge terminals, seaports, and large cities. The grain must be sealed in large waterproof capsules or cylindrical containers to prevent cargo wetting during the journey through pipelines. The economics of grain transportation by using large-diameter HCP (greater than 300 mm) have been established by Liu and Wu (1990). (6) Transportation of hazardous waste, including nuclear wastes, to the storage site. However, the economic feasibility of this application has not yet been studied and ascertained.

As to the future of PCP, it is anticipated that small and short systems of PCP will find increasing use in banks, warehouses, factories, hospitals, office buildings, transportation terminals, and apartment complexes. Large systems of PCP have a unique role to play in transporting heavy freight over long distances. Although it is difficult for such PCP systems to compete with CLP for transporting coal and to compete with HCP for transporting grain and waste materials, the much higher speed of PCP (greater than 10 m/s) as compared with HCP and CLP (less than 3 m/s) makes PCP uniquely suitable for transporting perishable materials such as meat, vegetables, fruit, and other commodities (perishable or nonperishable) that must be dispatched, such as mail and parcels.

Therefore, major future applications of large PCP systems are envisaged. At first, a few large-diameter mail (postal) pipelines will be constructed between some major population centers or cities, such as between Washington, D.C. and New York City. The pipe diameter will be 1–2 m, so that many commodities including mail and parcels can be transported through such a pipeline. After such pipeline projects have demonstrated their success, more and larger PCP systems will be in demand and built. The largest of such pipelines, for interstate transportation of freight, may have rectangular cross sections, resembling large and extra long wind tunnels. Many containers loaded with various cargoes can be transported through the pipeline (tunnel). Upon reaching their destination, truck drivers pick up the containers at each tunnel outlet and make short-distance delivery of goods. The trucks will then be driven back to the pipeline terminal to deliver a new load of cargo (containers) for transportation through a separate return pipeline. This will greatly reduce the need for driving trucks on highways for long distances.

OBSTACLES TO FUTURE DEVELOPMENT

Pipelines in the United States have traditionally been in private hands, serving the nation while paying taxes instead of relying on government subsidy to exist. Although this is expected to continue with freight pipelines, those pipelines for long-distance transportation of freight, and those that require expensive research and development before they can be used reliably, will not be developed without government help for the following reasons:

1. Most U.S. pipeline companies are profiting from operating their existing pipelines and from building new pipelines for transporting liquids and natural gas, without having to engage in any research. There is a lack of incentive for pipeline companies to invest in research and development (R&D) in general and in new freight pipelines in particular. The investment in R&D by U.S. pipeline companies is very low—less than 1% of their revenues. Many large pipeline companies do not have a single individual doing research. The situation is distinctly different from that which exists in the electronic, computer, automobile, aerospace, chemical, and pharmaceutical industries, which invest heavily in research and hire a large number of PhD researchers.
2. It is difficult for small business and venture capitalists to invest in new freight pipeline technologies because of the high cost and the long-term nature of the needed R&D before the technologies can be used and because of the risks of such investment.
3. Long-distance pipelines cannot be built without crossing many private properties and railroads, which are also privately owned in the United States. Without eminent domain rights and without explicitly authorized rights to cross railroads, one individual land owner and a single railroad company can block the construction of an interstate pipeline. Although most oil pipelines and natural gas pipelines do enjoy either federal or state eminent domain rights and are accepted by railroads, the same cannot be said of freight pipelines. This is most vividly illustrated by the ETSI (Energy Transportation System Incorporated) case, in which a long coal slurry pipeline was planned to transport Wyoming coal to Texas and Arkansas, via Colorado and Oklahoma. In this case, although all these states had eminent domain rights for coal pipelines or all types of pipelines, railroads refused

to allow the ETSI pipeline to cross in order to eliminate competition. ETSI had to go to court for each rail crossing. Although ETSI won each court case, years of delays in the courts killed the project. More than 100 million dollars was wasted as a result. This shows that without explicit legislation that grants freight pipelines the right to cross railroads, any future freight pipelines may be at the mercy of railroad companies against which the freight pipelines are in competition. Legal issues are discussed at greater length by Davies and Liu (1995).

Because of these obstacles, government encouragement in the form of R&D support in certain types of freight pipeline technologies appears justified. This is especially true for freight pipelines that have not sufficiently been developed to warrant commercial use, and those of far-reaching implications to the nation, such as pipelines for transporting solid waste and interstate transport of mail and general cargoes. Freight pipelines should also be granted eminent domain rights and the right to cross railroads.

CONCLUSION

Freight pipelines are economical in many situations, reliable, automatic, environmentally friendly, energy efficient, and safe to people and the ecosystem. Advancements in pipeline technology and computer control systems have greatly facilitated the development and use of freight pipelines. The greatest future growth areas of freight pipelines are expected to be in the use of pneumatic pipelines to transport refuse from buildings; use of slurry pipelines to transport the sludge generated at water and wastewater treatment facilities; use of small PCP systems to transport goods in, to, and between buildings; use of HCP or CLP to transport coal, grain, and solid wastes; and use of large PCP systems as a general cargo carrier between major cities.

There is no doubt that freight pipelines have a bright future. However, it is uncertain how soon freight pipeliness can make a substantial contribution to the nation and the world. This depends to a large extent on government policies and on private and government investment in R&D. Pipeline companies mut be willing to make significant investment in R&D before new advanced freight pipeline systems can be developed and made reliable. The government must not only support research in freight pipelines, but also provide regulatory relief and encouragement, such as granting eminent domain right to long freight pipelines, granting explicit rights for freight pipelines to cross railroads, and reducing the red tape required for acquiring various permits from government to construct such pipelines. Finally, due to the importance of freight pipelines to the engineering profession, especially the civil engineer, the ASCE should play a leadership role in promoting and advancing the state of the art of freight pipelines.

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APPENDIX 2:

Coal Log Pipeline Pilot Plant

MU ENGINEERING WEEKLY

-News of the people and events in the College of Engineering-Dec. 1, 1998-

Industry gives major boost to CPRC plant

Donations include pipe, fittings, labor

CE Professor Henry Liu is smiling these days, and with good reason: More than a half-dozen companies are chipping in to help build a costly pilot plant to further the development of coal log pipeline technology.

"I am gratified by the generous industry donation of materials, equpment and services toward this project," says Liu, director of the Capsule Pipeline Research Center. "This new facility will be used not only to complete the development of coal log pipeline technology, but also to test and develop related technologies such as grain pipeline and compaction of solid waste."

The pilot plant is being built on MU's Holstein Farm in Boone County, a few miles west of Columbia. "The goal is to test and demonstrate an entire CLP system, from coal log manufacturing to pipeline transportation," Liu says.

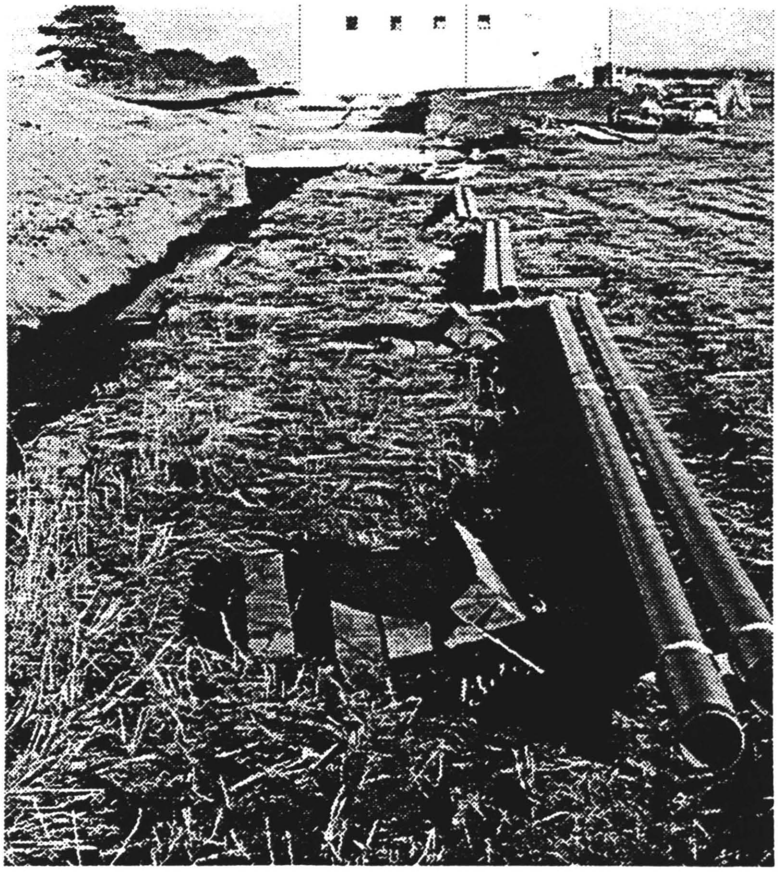
One of the principal parts of the plan is a pipeline 3,000 feet long that loops, making it possible to recirculate coal logs indefinitely for testing. At the Holstein Farm, the ditches have been dug and the pipe is being put into place now.

"We have a lot of people to thank for this," Liu says. To wit:

•**The Maverick Tube Corp.** in St. Louis has donated 4,000 feet of steel pipe.

•**VALVTECHNOLOGIES** of Houston, Texas, has donated the expensive ball valves.

•**The Rotork Co.** of Rochester, N.Y., has donated the actuators for controlling the valves.



The pipes for the 3,000-foot 'loop' at the Holstein Farm wait to be placed. With such a large loop, researchers can recirculate coal logs indefinitely for testing.

•**The Tulsa Tube Bending Co.** has donated service to do the necessary bending of the pipes.

•**The Commercial Resin Co.** of Tulsa will coat the pipe with fusion-bond epoxy.

•**The Garney Cos.** in Kansas City are doing the ditching and other earth work.

•**The T.D. Williamson Co.** of Tulsa is donating certain special pipe fittings for sensor mounting.

•And last but certainly not least, **the Williams Energy Group** (formerly the Williams Pipeline Co.) is building the pipeline.

The pilot plant is the final stage of the coal log pipeline development that Liu and CPRC Associate Director Tom Marrero began nearly 10 years ago. Their research center is the only one in Missouri sponsored by the National Science Foundation.

The technology uses underground pipelines for transportation of coal compacted into slug or cylindrical form, directly from coal mines to power plants. Use of CLP instead of trucks and trains could not only save money, but most likely would reduce traffic congestion and accidents on highways and railroads.

The estimated cost of the pilot plant is $1.5 million. In addition to Liu and Marrero, others integral to the project are Charles Lenau, CE professor; Yuyi Lin, MAE associate professor; Bill Burkett, ChE research associate; and Terry Maynard, project manager.

SHORT TAKES

Congratulations to MAE Associate Professor **Yuyi Lin** and his wife Donhua, as their son Qi recently accomplished a rare feat. Qi, a senior at Hickman High, scored a perfect 1,600 on the SAT test, one of only 673 students across the nation to do so. Qi says he may consider engineering as a career, and is looking at several universities for his study, including MU. Some in the College may remember that Qi took first place in the state MATHCOUNTS competition a few years ago . . . The College has received quite a bit of favorable publicity recently. Students of CE's **Kristen Sanford** were featured in a *Columbia Daily Tribune* story as they built replicas of Francis Quadrangle and the St. Louis Arch as part of the CANstruction competition; Diversity Director **Michael Lee** was quoted in a *Tribune* article on graduate students the College hopes to attract as part of a new National Science Foundation project; Research Director **Andy Blanchard** was quoted and the SAE Formula car was pictured in a story in *MIZZOU* magazine, which goes to all MU alumni; and Undergraduate Recruitment and Career Services Director **Bob Jones** was part of two articles: one that he wrote for the fall newsletter of the JETS Report, "Hosting a Successful TEAMS Competition," and as part of an article on job interviewing for the *Engineering Times*, published by the National Society of Professional Engineers. Also, word on the street is that Jones and his successful recruiting techniques will be featured in an upcoming issue of *Mizzou Weekly*.

COMING UP

Dec. 11 — CEP Commencement Ceremony, 1 p.m., UMKC campus.

Dec. 12 — Stop Day.

Dec. 20 — Engineering Convocation, 5 p.m., Jesse Auditorium. Reception to follow.

Send your news items for *The MU Engineering Weekly* to Terry Jordan, communications coordinator, at W1000 EBE, call 2-3221, or email JordanT@missouri.edu.

APPENDIX 3:

CPRC Publication List

CAPSULE PIPELINE RESEARCH CENTER (CPRC)
University of Missouri-Columbia
Publications List
(1991-1998)

A. Theses/Dissertations and Student Papers:

Bahr, M., Rapid Compaction of Bituminous Coal Logs, M.S. Thesis, Department of Chemical Engineering, May 1996, 126 pages, (Adviser: Richard Luecke).

Bennett, J., EPRI Water Absorption Tests, B.S. Chemical Engineering, University of Missouri-Columbia, July 1992, 12 pages, (Adviser: Thomas R. Marrero).

Berg, D.M., Hot Extrusion of Coal Logs, M.S. Thesis, Department of Chemical Engineering, University of Missouri-Columbia, August 1993, 187 pages, (Adviser: Thomas R. Marrero).

Carney, D., Water Impervious Coatings for Coal Logs, M.S. Thesis, Department of Chemical Engineering, December 1996, 106 pages, (Adviser: Richard Luecke).

Chen, F., Advances in Coal Log Fabrication for Coal Log Pipelines, M.S. Thesis, Department of Civil Engineering, University of Missouri-Columbia, May 1995, 106 pages, (Adviser: Brett W. Gunnink).

Chen, S.H., Effects of Particle Size, Binder Concentration and Compaction Pressure on Selected Properties of Coal Logs, M.S. Thesis, Department of Chemical Engineering, University of Missouri-Columbia, August 1993, 102 pages, (Adviser: Thomas R. Marrero).

Cheng, C.C. Wear and Damage of Coal Logs in Pipeline, Ph.D. Dissertation, Department of Civil Engineering, University of Missouri-Columbia, December 1994, 347 pages, (Adviser: Henry Liu).

Chiao, Victor Kuo-Ping, Internal Corrosion Control of Steel Pipeline For Transporting Coal Logs, M.S. Thesis, Department of Civil Engineering, University of Missouri-Columbia, July, 1991, 78 pages, (Adviser: Dr. Shankha K. Banerji)

Deng, Q., Analysis of Coal Log Extrusion, M.S. Thesis, Department of Civil Engineering, University of Missouri-Columbia, December 1995, 184 pages, (Adviser: Henry Liu).

Ding, Y., Characterization of Pyrite Surface and Evaluation of Effect of Absorbed Depressants on Pyrite Floatation Ph.D. Dissertation, Department of Mining Engineering, University of Missouri-Rolla, May 1992, 180 pages, (Adviser: John Wilson).

Du, H., Issues Related to Reliable Operation of Pump Bypass System for Capsule Pipeline,, Ph.D. Report, Department of Mechanical Engineering, University of Missouri-Columbia, August 1996, 219 pages, (Adviser: Satish Nair).

El-Bayya, Majed, Unsteady Flow of Capsules in a Hydraulic Pipeline: Theory and Experiment, Ph.D. Dissertation, Department of Civil Engineering, University of Missouri-Columbia, May 1994, 189 pages, (Adviser: Charles W. Lenau).

El-Bayya, Majed, Transient Flow in Hydraulic Capsule Pipeline, M.S. Thesis, Department of Civil Engineering, University of Missouri, May, 1991, 113 pages, (Adviser Charles W. Lenau).

Garber, L., Water Quality Effects of Drag Reduction Polymers, M.S. Thesis, Department of Civil Engineering, University of Missouri-Columbia, May 1995, (Adviser: Shanka Banerji).

Hjelmfelt, A., Water Quality and Treatment of Coal Log Pipeline Effluent, M.S. Thesis, Department of Civil Engineering, University of Missouri-Columbia, May 1995, (Adviser: Shanka Banerji).

Huang, X., Polymer Drag Reduction in Hydraulic Capsule Pipeline (HCP), M.S. Thesis Department of Civil Engineering, University of Missouri-Columbia, August 1994, 137 pages, (Adviser: H. Liu).

Ji, G., Research and Design of Coal Log Fabrication Machine, M.S. Thesis, Department of Mechanical & Aerospace Engineering, University of Missouri-Columbia, May 1995, 142 pages, (Adviser: Yuyi Lin).

Kananur, J.J., Compaction of High Strength Binderless Coal Logs for Pipeline Transportation, M.S. Thesis, Department of Civil Engineering, University of Missouri-Columbia, May 1994, 106 pages, (Adviser: Brett W. Gunnink).

Kuhlman, G.S., Polymer Slurry Drag Reduction in Capsule Pipeline, M.S. Thesis, Department of Chemical Engineering, May 1998, (Adviser: Thomas R. Marrero).

Li, H., Research on Mechanical Design Methodology and Automation Tools With Application to a Hydraulic Press, M.S. Thesis, Department of Mechanical Engineering, UMC, December 1996, 126 pages, (Adviser: Y. Y. Lin).

Li, W., Progress in Faster Compaction of Coal Logs, M.S. Thesis, August 1998, (Adviser: Brett W. Gunnink).

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**Visiting Scholar

APPENDIX 4:

Article on Coal Log Compaction Machine Design in
ASME Journal, MECHANICAL ENGINEERING

From ASME Monthly Magazine, MECHANICAL ENGINEERING, Vol. 117, No. 11, Dec. 1997

Compacting coal into logs

Eons and enormous pressure are still needed to transform coal into diamond, but a new hydrauli machine can compact the black rock quickly into transportable logs. **By Yuyi Lin, Guoping Wen, Huachao Li, and Kang Xue**

RESEARCHERS AT THE UNIVERSITY of Missouri in Columbia have designed a 300-ton hydraulic press for the fast compaction of coal logs, which will be transported through water-filled pipelines. The press can also be used to manufacture other products from wet granular mixtures.

Commercially available, PC-based, design-optimization tools and finite-element-analysis software were used to create the press. This new procedure can automatically generate design alternatives and find an optimized design based on a user-specified objective function and constraints. Results to date show that the procedure is an efficient, flexible, low-cost, and powerful design tool.

Because the pressure of the water inside the pipe can be as high as 1,500 pounds per square inch and the pipeline can be as long as 1,000 miles, the quality of coal logs made for such a transportation system is very important. After five years of research and development, the Capsule Pipeline Research Center at the university can make low-cost coal logs with a compressive strength approaching that of low-grade concrete. The required compaction pressure can be as high as 20,000 pounds per square inch. For a 6-inch pipeline, each coal log is 5.4 inches in diameter and 10.8 inches long, and weighs approximately 12 pounds. The net compaction force required is approximately 230 tons.

In addition to size and force requirements, the operational speed of the compaction machine is important. A production rate of about eight logs per second is required to feed a 6-inch pipeline to capacity. If a compaction machine can make a coal log in 3 seconds, 24 such machines will be needed in the manufacturing plant. This speed requirement conflicts with the quality of a coal log, which i usually improved with longer compaction time.

Many compaction and material-testing machines already on the market can provide the needed force but not th speed. Most of these large machines have one main cylinder that can perform only single-action compaction. Double-action compaction, which requires two movin pistons, produces better products.

The need to design and manufacture a special machine is therefore justified. This machine will be used to test mass production of coal logs at a rate of up to one log every 1 seconds and to collect data for commercial machine design. Based on the test results obtained from this machine, bette hydraulic or nonhydraulic systems can be designed fo commercial applications.

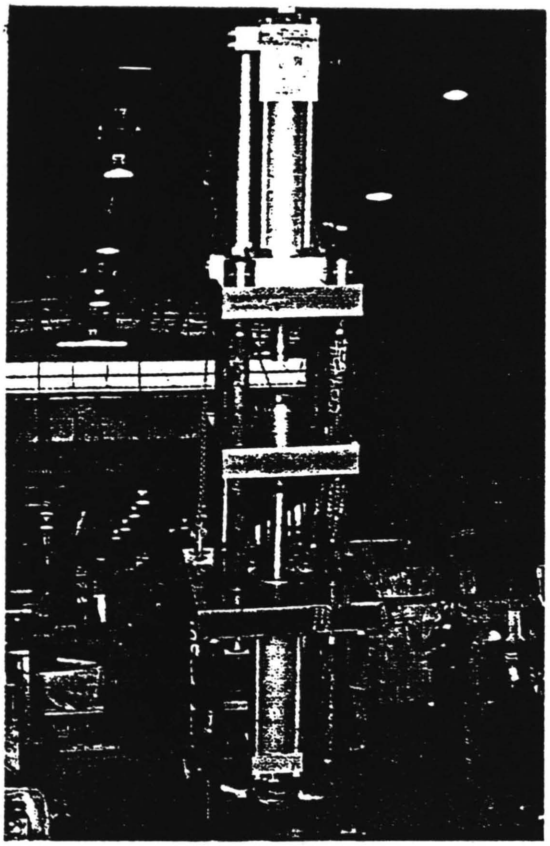
MACHINE FRAME

To reduce manufacturing time, time-consuming operations are commonly divided into several stages. A three-stage production process, for example, can be performe on one multiple-stage machine or on three separate machines. The first stage in the production of coal logs is t precompact the loaded materials into the mold at low pressure, the second is to compact the logs at high pressure (20,000 pounds per square inch), and the third is to eject them. The press we have designed is a single-stage machin that can simulate a three-stage machine, for a productio rate of one log in 10 seconds.

Two distinctly different designs have been taken into consideration. The first is a two-plate frame with three 8-inch-thick platforms sandwiched in between; the second is a four-column structure with three platforms fastened o the columns. Unlike material-testing machines, the platforms do not need to move on the columns, but two cylinders are required to achieve the double-action compacting For the plate frame, stress, deformation, and the stress relie shapes (the corners of the two windows on each plate in the two-plate design) must be carefully analyzed. Because o

Yuyi Lin is an associate professor in the Department of Mechanical and Aerospace Engineering at the University of Missouri in Columbia. Guoping Wen and Kang Xue are research assistants in the department's Capsule Pipeline Research Center. Huachao Li is a design engineer with Caterpillar Inc. in Peoria, Ill.

frame analysis is relatively easy.



With this four-column frame structure, pipe spacers ensure the parallelism of the platforms and reduce both column-cutting and assembly costs.

The two types of frames were compared on the basis of manufacturing considerations. First, the machine needs to be easily disassembled, transported, and reassembled. Both types of frame are quite satisfactory for this need, since each can be assembled by bolts and nuts without welding. In each design alternative, the maximum weight of a single component is less than 4 tons, making it practical for transportation and assembly.

The second design concern is to maintain parallelism among the three platforms during assembly and under loading conditions. The four-column design with steel pipes as spacers between two plates seems easier to manufacture than the plate frame, which will require large numerical-control machine tools.

The third concern is piston alignment. Since each cylinder can be adjusted when fastened to the platform, either design alternative is satisfactory. After the cylinder is mounted and aligned, dowel pins should be used for fixation.

Taking advice from press manufacturers, we chose the four-column structure for the final design. The two hydraulic cylinders are mounted on the upper and lower platforms. The compaction mold is secured on the middle platform. The total weight of the machine frame is about 10 tons. The compaction mold is stationary while the two pistons move into the mold, where the coal is compacted, and the log is ejected upward from the top of the mold.

HYDRAULIC POWER AND CONTROL

The hydraulic power system consists of one 200-horsepower electric motor, four hydraulic pumps, two 12-inch-bore hydraulic cylinders, control valves, and other accessories. Each cylinder can generate the 230-ton net compaction force under a cylinder pressure of 4,455 pounds per square inch. A regenerative circuit is used for the upper cylinder, so the fastest moving speed for the upper hydraulic cylinder will be 15 inches per second during rapid advance. Each variable-displacement piston pump has a capacity of 25 gallons per minute, and the pressure can reach 5,000 pounds per square inch. Each gear pump has a capacity of 50 gallons per minute and will be offloaded when the system pressure reaches approximately 1,500 pounds per square inch. Reservoir capacity is 400 gallons with water cooling.

The compressibility of the oil under high pressure must be considered. For every 1,000 pounds per square inch of pressure, oil may have a 0.5-percent compressibility. For or shock-absorbing component is important. To keep the cost down, an accumulator is not used; special decompression valves are specified.

When solenoids S1 and S4 are energized, both the upper and lower cylinders are moving forward and compacting the coal into logs within the mold. When the pressure reaches 1,500 pounds per square inch, the gear pumps will be unloaded. When the pressure reaches 4,455 pounds per square inch, the piston pumps will be fully compensated. The pressure in the mold can be held at maximum for a short period if necessary. Holding pressure is a required function for high-quality compaction, and it can be achieved by a delay of up to 10 seconds by the programmable logic controller (PLC) after receiving the maximum pressure signal and before the ejection sequence.

When solenoids S4, S5, S6, and S7 are energized, the bottom piston will push the log against the top piston, moving both the log and the top piston upward. The oil flows from the back of the upper cylinder to the front through a directional valve operated by S5. The back pressure can be adjusted by the relief valve next to the valve controlled by S6.

Two position sensors are mounted on each hydraulic cylinder to measure the position of the pistons. The position sensor signal will be sent to the PLC for control and to the data acquisition board for monitoring.

The pressure switch sends a signal to the PLC when 4,455 pounds per square inch is reached. Pressure transducers are used to monitor the pressure in the cylinders and the compaction pressure. Both manual and automatic control of the two main three-position directional valves are desirable. Four press-button switches, SW1 to SW4, are used to advance or retract the pistons manually during machine adjustment. The PLC enables these four buttons only if S1 to S7 are not energized.

Selection of the hydraulic cylinders is based on speed and pressure requirements. Large-bore cylinders allow a lower working pressure inside the hydraulic system, which is a desirable condition. However, to reach the desired speed of compaction, a large-bore cylinder requires large hydraulic pumps to supply the compressed oil. For this press, the largest compaction force needed is about 504,000 pounds.

The choice of the cylinders was between those having 12- and 16-inch bores. If 12-inch-bore cylinders are used, a flow of 150 gallons per minute will be sufficient for the speed requirement, but the system pressure has to be as high as 4,455 pounds per square inch. Given the application's speed requirements and the cost savings in a higher-pressure, lower-volume pump, the 12-inch cylinders were chosen for this design.

INTEGRATED DESIGN SYNTHESIS

After more than 30 years of development, most general-purpose, large-scale FEA programs include an optimization capability. These programs are usually based on high-performance workstations. With the rapid advancement of computer technology, the capability of PC-based FEA codes such as Algor from Pittsburgh-based Algor Inc. has greatly improved, and many engineers are using PC-based FEA programs in their design process. Algor does not have an imbedded optimization program, but it does have a module called Eagle, a control and interface program designed to run a predetermined number of alternative analyses in batch mode. Eagle is useful in that it provides an interface to the user-supplied programs.

Integrated FEA and optimization software generates design alternatives and determines the best one.

The program described here is an attempt to interface commercial FEA and optimization programs to achieve optimal shape design. The program couples the Design Optimization Tools (DOT) developed by G. N. Vanderplaats and available from V&RD Inc. with the PC-based code Algor. The model-geometry generator and communication deck between DOT and Algor have been developed to automate the design process.

The optimization algorithms in DOT are mostly derivative-based. In general, results found by such algorithms are local optima. Genetic Algorithm (GA), developed by Z. Michalewicz, and others are theoretically capable of finding global optima. To determine if there is a globally better optimum than that obtained by DOT, we have also integrated a genetic optimization algorithm with Algor.

To achieve this integration, we simply let the optimization program calculate all needed sensitivity information by repeatedly calling the FEA program. The objective function and the stress constraints are implicit with respect to the design variables, and they are computed using Algor. The main program is written in Eagle, the macro control language of Algor.

A graphic interface is designed to parametrically generate the mold geometry and a model input file for Algor. The mold geometry can be shown on the screen so the user can view and interact with the optimization process. Supergen, Algor's automatic mesh generator, is then invoked to generate the symmetric mesh. Boundary conditions are applied through an Algor script file.

A finite-element model of the mold has been set up to facilitate the analysis and optimization. The mold has axial symmetry. The internal compaction pressure and the clamping force are assumed to be axisymmetric. Therefore, axisymmetric elements are used in this model instead of solid elements to save computation time. It takes [illegible] analysis of the axisymmetric element model on an 80486-66-based personal computer. If hexahedron solid elements are used, the analysis time will be increase to 30 minutes for a quarter of the mold. Model simplification is important for a finite-element-based design optimization tool on a PC, because optimization programs—especially the global algorithms such as the genetic and simulated annealing algorithms—make many function calls before reaching the optimum.

MOLD DESIGN

The compaction mold has been designed using the developed design automation tool. (This mold is still only for laboratory use.) The most suitable and cost-effective manufacturing method would be to use high-strength, low-alloy thick-wall steel pipe with boring and possibly some welding, but not forging or casting. Based on the ratio of volumes of coal before and after compaction as well as on the hydraulic system of pipeline transportation, we determined that the mold should be 24 inches long. The diameter of the bore is 5.4 inches.

Based on the results of an initial stress analysis and the application requirements, high-strength, low-alloy structural steel (ANSI 4340) is chosen for this mold. If a safety factor of 3 is considered, the maximum allowable stress of the mold material is 45,000 pounds per square inch. The design problem is to minimize the total volume and the maximum deformation, while the von Mises stresses must be less than or equal to 45,000 pounds per square inch. There are six design variables and 10 constraints.

When DOT is used as the optimizer, the nonlinear design optimization problem is solved by means of sequential linear programming (SLP). Although SLP is considered to be a poor method in a strict mathematical sense, the well-coded SLP algorithm in DOT has proven very powerful. The SLP method uses a move-limit strategy to deal with the constraints, and so the optimization process will not converge if there are significant constraint violations. The design optimization process will continue until all the constraints are satisfied.

The optimized shape is obtained after 13 iterations. The optimization process converged quickly.

When GA is used as the optimizer, the formulation of the problem is similar to that employed with DOT. Since the initial design is generated by the GA program itself, no input variables are required for this method. For each iteration of FEA called, 500 generations were calculated to find the optimal design. The design objective function converges after 12 iterations. Nevertheless, a comparison shows that results from DOT and Algor are slightly better than those from GA and Algor. ▪

This article is adapted from a paper presented at the 1996 ASME International Mechanical Engineering Congress and Exhibition in Atlanta.

APPENDIX 5:

Paper on Pipeline Education

Paper presented at the International Conference on
Engineering Education (ICEE), Rio de Janeiro, Brazil, August 1998

Pipeline Engineering Research and Education at Universities in the United States

Henry Liu and Thomas R. Marrero
College of Engineering
University of Missouri-Columbia
Columbia, Missouri 65211-2200

Abstract—*A national survey on pipeline engineering research and education at engineering and mining colleges of U.S. universities was conducted in 1996-97. It was found that only 12 schools offer pipeline related undergraduate courses, and 15 offer pipeline-related graduate courses. Only one university offers Pipeline Engineering or any other similar introductory course exclusively on pipelines. A strong need exists to have more of such courses offered at universities so that civil, chemical, mechanical, mining and other engineers who use pipelines to transport liquids, gases and solids will be better prepared to plan, design, construct and operate various types of pipelines in the future upon graduation from universities.*

While pipeline-related research covers a wide spectrum of subjects, only 25 schools reported to have pipeline-related research projects in the last five years. Only two existing research centers are focused on pipeline technologies: the Capsule Pipeline Research Center (CPRC) at the University of Missouri-Columbia, and the Trenchless Technology Center at Louisiana Tech University. A need exists to expand pipeline research at universities not only to generate new knowledge but also to provide opportunities for graduate training.

*This paper will also discuss the experience learned in teaching **"Pipeline Engineering"** at the University of Missouri-Columbia. The course has been taught by the first author for fourteen years, and much experience has been gained from this teaching involvement. During the past two years (1997-98), this course was taught using telecommunication equipment. Both ITV (Instructional Television) and ISDN (Integrated Services Digital Network) were used. This paper will also compare the two delivery systems with each other and with traditional classroom teaching.*

Justification of Survey

In the United States and throughout the world, pipelines are used extensively to transport many commodities: water, waste water, sewage, gas, petroleum products, chemicals, and many other products including solids. Recent (1995) statistics indicate that the total operating revenues of the oil- and gas-pipeline industries in the United States are $17 billion. These industries employ 200,000 people. Through more than one million miles of pipelines, 2 billion tons of oil and gas are transported each year in the United States [1].* The importance of pipelines for transporting water and sewage even surpasses that of oil and natural gas pipelines. The total amount of liquid and gas (including oil, natural gas, water, sewage and many other fluids and solids) transported by pipelines in the United States is estimated to be 2.7 trillion ton-miles. This is more than the freight transported by truck (0.9 trillion ton-miles) and railroad (1.2 trillion ton-miles) combined. Pipeline is also by far the safest mode of freight transportation, and is highly reliable and energy efficient. Since pipeline is critically important to any modern nation for the conveyance of critically needed materials such as water and oil, and since many industries use pipelines, it is legitimate to ask how are colleges and universities preparing today's and tomorrow's engineers and managers dealing with pipelines. Is there a course or option in pipeline engineering? What research is being conducted at universities to improve pipeline performance and to develop new pipeline technologies? This survey was conducted to answer these questions.

The Survey

The survey was conducted in November 1996 through December 1997 [2]. A survey form (questionnaire) was drawn up and sent to 225 deans of the engineering and mining colleges or schools in the United States. The cover letter asks the recipient—the Dean—to pass on the survey form to those faculty members in his (her) college who have pipeline-related research projects or educational activities. The survey form was intentionally made brief (a single page), in order to encourage responses. The form simply asks the respondent to list the research projects, courses (both graduate and undergraduate) and other activities related to pipeline by his (her) group or institution within the last five years. The respondents were requested to list only those research and educational activities directly

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* Numerals in [ ] represent corresponding items in REFERENCES.

related to pipeline. They were told specifically not to list general courses in fluid mechanics, even though such courses usually cover pipe flow, pumps, flowmeters, etc. which are closely related to pipeline. It is the intent of this survey to determine from what courses other than general fluid mechanics do students learn about pipelines.

Of the 225 schools contacted, only 35 returned the form. They are presumed to be mostly from schools that have pipeline-related activities. Twenty-seven (27) of the 35 returns listed either pipeline-related courses or research projects, or both. The remaining 8 schools reported none of such activities. The survey result is based on the data provided by the 27 schools in the U.S. that have pipeline-related activities. They are listed in Table 1.

Survey Results

(a) Education

General courses in fluid mechanics in which pipe flow is covered are not counted as pipeline courses in this survey because they are generally known to exist at every engineering school. To list fluid mechanics will yield nothing new.

Thirteen schools reported that they had both courses and research in pipeline engineering related topics in the last five years. The universities that offered courses related to pipeline engineering are presented in Table 2. At 12 universities, a total of 17 undergraduate courses were offered. Of all these undergraduate courses, only one course has a title that includes the word "pipe" or "pipeline." As to graduate courses, a total of 27 were taught at 15 schools. Three of these graduate courses have the word "pipe" or "pipeline" in their title; one has the term "closed conduits" which is the same as pipe. None of the schools reported any ***department, major, minor, option*** or ***area*** in pipeline engineering.

(b) Research

The pipeline research topics at universities are quite varied—see Table 3. In addition to the 14 schools that had both research and courses, 9 schools had only research, but no pipeline engineering courses. The total number of studies (research projects) reported in the survey for the 5-year period preceding the survey is 58 at 25 universities. The number of projects listed (58) is somewhat an underestimate because some large projects (such as those at research centers) actually have several sub-projects under each having separate principal investigators and separate objectives. A majority of the reported studies are in the area of fluid dynamics. Sponsors of pipeline research are primarily federal agencies, most often the National Science Foundation (NSF). A number of projects were funded by industries and trade organizations such as Gas Research Institute (GRI) and American Water Works Association (AWWA).

Interpretation of Survey Results

As a result of this survey, the following interpretations are made:

1. The fact that only 35 of the 225 universities that have been contacted actually filled out and returned the survey form is an indication of the low level of pipeline-related research and educational activities at most universities, including many major universities in the United States. It is possible that some Deans who had received the survey form did not pass on the form to the proper individuals in his (her) college for response. However, if pipeline research and education at those schools were known to the Dean, most deans would have done their jobs and forwarded the form to the proper individuals for response. It is likely that most schools did not respond because they have little to report in pipeline-related activities. Some omissions are certainly inevitable.
2. Twenty-seven (27) universities have reported pipeline-related activities—either research or courses or both. Even if half of the schools with pipeline activities were omitted and did not respond, this would still be a rather low number. Considering the importance of pipelines to the nation and to many industries, it is clear that most universities are not paying due attention to providing students with adequate training in pipelines. Two reasons may explain for this inadequacy: (a) not knowing the need, and (b) lack of research funding opportunities. Many universities and faculty members do not pursue any field with limited funding opportunities. They seem to forget that such opportunities can be created if more attention is given to pipeline by more universities. Recently, the American Society of Civil Engineers has published a list of needed pipeline research topics [3].
3. Of all the pipeline-related undergraduate courses reported, only one has the word "pipe," or "pipeline" or "closed-conduits" in its title. It is clear that most of the courses listed are not solely on pipelines and hence do not serve as an introductory course in pipelines, even though they do address important aspects of pipelines. Given the importance of pipelines to many industries including petroleum, natural gas, water, sewer, public works, electric utilities, chemical, mining, etc., and given the fact that many students upon graduation work for these industries, it is not difficult to justify for an introductory course in pipeline

engineering, to be taken by students who have taken fluid mechanics. Such a course is highly desirable for students in civil, chemical, environmental, mechanical, nuclear, petroleum, mining and agricultural engineering.

4. Graduate students in certain disciplines should also be exposed to the introductory pipeline engineering course if they never had it during their undergraduate years. The fact that only 15 universities reported graduate courses in pipeline-related areas is also of concern. All major universities with graduate programs in engineering should have some graduate courses related to pipelines. Again, this is justified by the wide-spread application of pipelines in many industries.

In conclusion, it can be said that inadequate attention is being given to pipeline engineering at universities in the United States. The essential absence of pipeline engineering courses means that the training of pipeline engineers is done by industry on-the-job. This has been confirmed through discussion with industry representatives. This practice, though apparently effective in maintaining continuity and the status quo, it is ineffective in bringing new ideas and developing new types of pipelines and technologies for transporting materials and goods. To continue sending university graduates into the marketplace with little pipeline training does not serve the best interest of the society, the students, and many industries that use pipelines extensively.

Recommendations

On the basis of this pipeline engineering survey, the following recommendations are made:

(1) Promote more pipeline engineering courses in engineering; have at least one introductory course on pipeline engineering for civil, environmental, mechanical, chemical, nuclear, agricultural, petroleum and mining engineering undergraduate students, either as an elective or required.

(2) Schools with strong research programs in pipeline should not only offer pipeline-related courses, but also allow students to choose pipeline engineering as a "minor," "option," or "area" under civil, mechanical and chemical engineering departments. This will enhance the employment opportunities for students enrolled in such programs.

(3) Provide more federal programs for supporting graduate students and research in pipeline engineering. Pipeline engineering is a critically needed area with insufficient number of highly-trained engineers to enter the workplace each year.

(4) Related industries should do more to support universities in pipeline education and research.

Pipeline Engineering: An Introductory Course

To be discussed next is an introductory course in pipeline engineering taught at the University of Missouri-Columbia (UMC), by the first author of this paper. It is discussed herein with the hope that other universities will develop a similar course to serve their students.

(a) Course Description

The course at UMC is CE/MAE 345 PIPELINE ENGINEERING. It is a 3-credit course serving as an elective for students in engineering. The course is co-sponsored by CE (Civil Engineering Department) and MAE (Mechanical & Aerospace Engineering Department). It is taken normally by seniors and graduate students in CE, MAE and some other departments. The purpose of the course is to provide a broad coverage in pipeline engineering so that the students will have a good background in pipelines for a variety of applications. The prerequisites of the course is CE/MAE 251 Fluid Mechanics.

(b) Contents

The course is divided into two parts. Part 1 is Pipe Flows, and Part 2 is Pipeline Technology. The part on Pipe Flows covers six chapters:

(1) Incompressible pipe flow—steady and unsteady, single pipe and pipe network.

(2) Compressible pipe flow—constant temperature, adiabatic, with friction and frictionless, for both ideal gas and real gas.

(3) Non-Newtonian Fluids—power-law fluids, Bingham plastic fluid, yield stress, laminar-turbulent transition, pressure drops, etc.

(4) Hydraulic transport of solids—pseudo-homogenous, heterogeneous, moving-bed and stationary-bed regimes, limit-deposit velocity, etc.

(5) Pneumatic Conveying—positive and negative pressure systems, dilute and dense phase transport, pressure gradient, electrokinetic effect on safety, etc.

(6) Capsule Transport—hydraulic capsule pipeline, pneumatic capsule pipeline, coal log pipeline, etc.

Part 2, Pipeline Technology, covers the following topics (chapters):

(1) Pipe Materials, Valves and Other Fittings—Comparison of various pipe materials including steel, other metals, plastic (especially PVC and PE), concrete (both low and high pressure types), clay, corrugated, etc.; nominal pipe size, schedule and strength; types of valves and pressure regulators, etc.

(2) Pipeline Planning and Construction—route selection and ditching, microtunneling, directional drilling, river crossing, pipe bending, welding, flanges, etc.

(3) Pipeline Protection and Safety—coating, lining, insulation, corrosion, cathodic protection, soil resistivity, pipe-to-ground potential, third-party damage, pipeline leak detection, integrity monitoring, pigging, etc.

(4) Design Considerations—internal load (hoop tension), external load (buckling), soil pressure on buried pipe, thermal stresses, etc.

(c) Textbook

There is no suitable textbook at present for this introductory course. However, through fourteen years of teaching this course, the writer has developed a rather detailed set of notes, homework problems, and exam problems. The notes and homework problems are printed and given to the students before they are discussed in the class. Eventually, the notes will be expanded into a textbook for publication by a commercial publisher. Prior to publication, arrangements can be made to use the notes for teaching at other universities. Those interested in doing that should contact the first author.

(d) Course Evaluation

Student response to the course, judged from student evaluation conducted near the end of each semester, appears favorable. Students seem to feel the course to be highly relevant.

(e) Distance Learning

Since 1997, the course was taught simultaneously to students both in Columbia, Missouri and Kansas City, Missouri, via telecommunications. Two different systems of telecommunications were used for delivery of the lectures: ITV (Instructional Television) System, and the ISDN (Integrated Services Digital Network). This created an opportunity to compare the two systems.

The best part of the ISDN system, from the student/instructor standpoint, is the electronic chalkboard. It allows the instructor to write or mark on the board with colors, and draw perfect circles and straight lines. Erasing a whole page can be done instantly by the touch of a button. However, the image is transmitted by Internet whose access is not guaranteed at all times. Therefore, two backup systems are used in the event the board is not functional. Furthermore, lecture notes and view graphs must be entered into a computer prior to the class by a technician. This requires early preparation of class materials, and is more demanding on the instructor's time than when he (she) uses the ITV system. Also, the resolution of the electronic chalk board is marginal, and there is a one-second delay (approx.) for writings to appear on the board. These two problems can be solved by using better equipment or a faster computer. An advantage of the ISDN System is that the equipment is portable. It can be rolled into and used in any room that has electrical and phone outlets.

The ITV system is less flexible but more reliable and easy to use. Instructors must sit or stand in a fixed place and write on a paper placed under an overhead camera. Equipment is attached to the room (permanently mounted) and hence not portable.

Both systems enable distance learning to take place with students and instructors being able to see each other and talk to each other via a TV set. Both systems should not be used unless distance learning is involved. Without distance learning, traditional teaching with an overhead projector is more convenient and just as effective.

(f) Conclusion

An introductory course, Pipeline Engineering, has been tried out successfully in the last 14 years at the University of Missouri-Columbia. It is recommended for students in engineering, especially civil, chemical and mechanical engineering, both undergraduates (seniors) and beginning graduate students. The course provides a sound background in pipeline engineering to students, and prepares the students for success in employment with many industries that use pipelines extensively, not just the pipeline industry. More universities need to seriously consider offering such a course to benefit their students. The course can be taught either in the traditional classroom lecture manner, or with ITV or ISDN for distance learning.

References

1) Gross, M. and Feldman, R.N., 1997, "National Transportation Statistics 1997," U.S. Department of Transportation/Bureau of Transportation Statistics, DOT-VNTSC-BTS-96-4, pp. 244-246.

2) Liu, H., Letter dated November 22, 1996, "National Survey on Pipeline Research and Education at Universities.
3) Pipeline Research Needs, American Society of Civil Engineers, Reston, Virginia, 1997, 153 pages.

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Table 1. Names of U.S. Universities That Offer Courses and/or Conduct Research Related to Pipeline Engineering.*

University of Alabama-Birmingham
Colorado School of Mines
Colorado State University
University of Florida
Georgia Institute of Technology
University of Idaho
University of Kentucky
Louisiana Tech University
Marquette University
University of Michigan
University of Minnesota
University of Missouri-Columbia
University of Missouri-Rolla
Montana State University
New Jersey Institute of Technology
New Mexico Institute of Mining & Technology
Oakland University
University of Oklahoma
Pennsylvania State University
University of Pittsburgh
Rensselaer Polytechnic Institute
Texas A&M University
Tulane University
University of Tulsa
University of Washington
Wayne State University
University of Wyoming

* Respondents to survey (Liu, 1996).

Table 2. Undergraduate and Graduate Pipeline Courses at U.S. Universities (1991-96).

Course	Cr.	School	Instructor	Dept.
Undergraduate				
Hydraulic Engineering	3	Colorado State University	Skinner	CE
Hydraulics	3	University of Idaho	Liou	CE
Applied Stress Analysis	3	Marquette University	Widera	ME/IE
Hydraulics	3	University of Michigan	Wright	CE
Hydraulic Design	3	"	"	CE
Pipeline Engineering	3	University of Missouri-Columbia	Liu	CE
Applied Fluid Mechanics	3	"	Lenau	CE
Advanced Hydraulic Engineering	3	Montana State University	Williams	CE
Production Engineering	3	New Mexico Inst. Mining & Tech.	Rajtar	PNGE
Production Process Engineering	3	Pennsylvania State University	Adewumi	PNGE
Solids Processing	3	University of Pittsburgh	Klinzing/Chiang	ChE
Infrastructure Engineering	3	Rensselaer Polytechnic Institute	Grivas	CE
Water &.Wastewater Infrastructure	3	"	Esler/Smith	EE
Corrosion	3	"	"	MSE
Welding Processes & Metallurgy	3	"	"	MSE
Production Design	3	University of Tulsa	Brill	PE
Fluid Mechanics (focused on pipelines)	4	University of Washington	Finlayson	ChE
Graduate				
Introduction to Offshore Technology	3	Colorado School of Mines	Chung	E
Marine Mining Systems	3	"	"	E
Operation of Hydraulic Systems	3	Colorado State University	Ruff	CE
Hydraulic Structures/Systems	3	"	Skinner	CE
Hydraulics of Closed Conduits	3	"	Rugg	CE
Hydromachinery	3	"	Skinner	CE

Table 2. . Undergraduate and Graduate Pipeline Courses at U.S. Universities (Continued)

Transport Phenomena in 2-Phase Flow	3	Georgia Institute of Technology	Ghiaasiaan	ME
Nuclear Reactor Technology II	3	"	"	ME
Biofluid Mechanics	3	"	Ku	ME
Fluid Transients	3	University of Idaho	Liou	CE
Mechanics of Liquid Flow in Pipes	3	University of Kentucky	Wood	CE
Stormwater Modeling	3	"	Ormsbee	CE
Design & Manuf. of Composite Materials	3	Marquette University	Widera	ME/IE
Hydraulic Transient	3	University of Michigan	Wylie	CE
Hydraulic Transport of Solids	3	University of Missouri-Columbia	Round	CE/MAE
Pipeline Engineering	3	"	Liu	CE/MAE
Advanced Hydraulics (Water Hammer)	3	"	Lenau	CE
Advanced Production Engineering	3	New Mexico Inst. Mining & Tech.	Rajtar	PNGE
Non-Newtonian Fluid Mechanics	3	University of Oklahoma	Shah	PNGE
Natural Gas Engineering	3	Pennsylvania State University	Adewumi	PNGE
Solids Processing	3	University of Pittsburgh	Klinzing/Chiang	ChE
Earthquake Processing	3	Rensselaer Polytechnic Institute	Papageorgiou	CE
Infrastructure Engineering	3	"	Grivas	CE
Advanced Production	3	University of Tulsa	Brill	PE
Two-Phase Modeling	3	"	Sarrca	PE
Transient Two-Phase Flow	3	"	Shoham	PE
Multi-phase Flow in Pipes	3	University of Wyoming	Sharma	CPE

Note: Acronyms for departments of engineering:
CE = Civil; ChE = Chemical; CPE = Chemical & Petroleum; E = Engineering; EE = Environmental;
IE = Industrial; ME = Mechanical; MSE = Material Science & Engineering; PE = Petroleum Engineering;
PNGE = Petroleum and Natural Gas.

Table 3. Research in Pipeline Engineering at U.S. Universities (1991-96).

Title	School	Investigator (PI)	Sponsor
High Performance Concrete Pipes	University of Alabama-Birmingham	Fouad	Industry
Cement Lined Ductile Iron Pipe	"	"	"
Deep-Ocean Pipe Dynamics	Colorado School of Mines	Chung	NSF
Impact on Offshore Pipelines	"	"	SAUDI ARAMCO
Two Phase Flows	"	"	Multi-National
Three Phase Flows	"	"	Multi-National
Hydromachinery	Colorado State University	Skinner	TVA/USBR
Valve Tests	"	Brisbane	Industry
Flow Meter Studies	"	Abt	Industry
User Friendly Models for Cathode Protection of Trans-Alaska Pipeline	University of Florida	Orazem	Alyeska
User-Friendly Models for Cathodic Protection of Pipelines	"	"	Industry
Fluid Dynamics of a Pressurizer Surgeline in a Reactor Pipeline System	Georgia Institute of Technology	Desai	--
Pipeline Leak Detection	University of Idaho	Liou	API
Leak Detectability	"	"	GRI
Modeling Dynamic Check Valves	"	"	Industry
Neural Networks Applied to Transients	"	"	--

Table 3. Research in Pipeline Engineering at U.S. Universities (1991-96) Cont.

Optimal Operation of Water Distribution Systems	University of Kentucky	Ormsbee	NSF
An Optimization Model for Rural Water Distribution Systems	"	Lingireddy	KWRRI
Trenchless Technologies Center (Various Projects)	Louisiana Tech University	Sterling	Industries Consortium
Internal Pressure Testing of Plastic Pipe	Marquette University	Widera	PVRC
External Pressure Testing of Plastic Pipe	"	"	PVRC
Analysis of Shell Intersections	"	"	PVRC
Unsteady Flow in Pipe	University of Michigan	Wylie	NSF & Other Sources
Surging During Surcharging of Storm Sewers	"	Wright	–
Metering of Flow in Storm Sewers	"	"	–
Lubricated Flows	University of Minnesota	Joseph	NSF & Oil Industry
Pneumatic Capsule Pipeline System Design	"	Zhao/Lundgren	Minnesota DOT
Hydraulic Capsule Pipeline R&D	University of Missouri-Columbia	Liu/Marrero/Others	NSF/State/Industry
Coal Log Pipeline R&D	"	"	"
Pneumatic Capsule Pipeline R&D	"	Liu/O'Connell	NSF/MATC/Industry
Coal Log Pipeline	University of Missouri-Rolla	Wilson	NSF/State/Industry
Factors Limiting Microbial Growth on the Distribution System	Montana State University	Camper	AWWA
Investigation of Biological Stability of Water in Treatment Plants & Distrbtn. Systems	"	"	AWWA
Interactions Between Pipe Materials, Corrosion Inhibitors, Disinfectants, Organics, & Distrbution System Biofilms	"	"	NWRI
Microbial Souring in Oil Formations (& Pipelines)	"	Sears	NSF/Industry
Pipeline Infrastructure Study	New Jersey Institute of Technology	Pignataro	U.S. DOT
Pipeline Leak Detection System for Oil and Gas Gathering Lines	New Mexico Inst. of Mining & Tech.	Rajtar	WERC
Develpmnt. of Non-Intrusive Laser Diagnostics for Measurements in Sediment-Laden Flows	University of Oklahoma	Parthasarathy	NSF
LDV Measurements in Fully-Developed Channel Flows of Non-Newtonian Liquids	"	Shah	GRI/DOE
Fracturing Fluid Characterization Facility	"	"	"
Transient Flow Surges & Low Frequency Flow Instabilities in Parallel-Tube	Oakland University	Wedekind/Blatt	NSF
Modeling PCB/Condensate Distribution in Gas Pipelines	Pennsylvania State University	Adewumi	Consortium of Agencies
Modeling Hydrate Deposition and Slury Transport in Pipelines	"	"	"
Pneumatic Conveying and Neural Network Analysis	University of Pittsburgh	Klinzing	NSF
Flow-Economizer for Long Distance Conveying	"	"	DOE
Lifeline Earthquake Engineering	Rensselaer Polytechnic Institute	O'Rourke	NSF/NCEER
Pipeline Monitoring Technologies	"	Savic	Industry
Pipeline Safety	Texas A&M	Mamora	DOT Ofc. of Pipeline Safety

Table 3. Research in Pipeline Engineering at U.S. Universities (1991-96) Cont.

Evaluation U-Liner Technology for Trenchless Sewer Rehabilitation	Tulane University	Bakeer/Barber	Louisiana EQSF
Test for Fluid Migration Between Host Pipe and Pile Liners	"	Bakeer/Guice	City of Baton Rouge
Paraffin Deposit in Pipelines	University of Tulsa	Brill/Volk	DOE, GRI and Industry Consortium
Oil Water Flow in Pipelines	"	Trullero	Consortium
Low Liquid Holdup Two-Phase Flow	"	Meng	"
Slug Characteristics in Pipeline	"	Marcano	"
SMARTE Enrichment Project	Wayne State University	Rathod	NSF
Tech-Prep 2000	"	"	Michigan
King-Chavez-Parks Program	"	Robinson	WSU
Summer Academy	"	Green	WSU