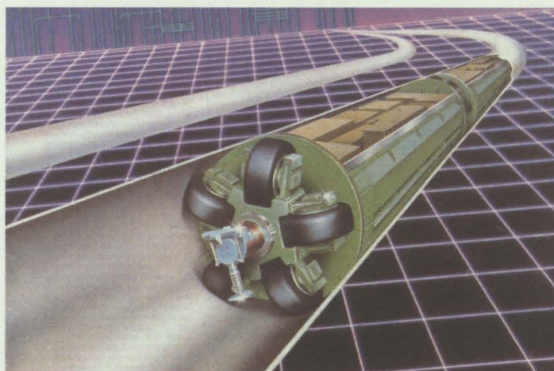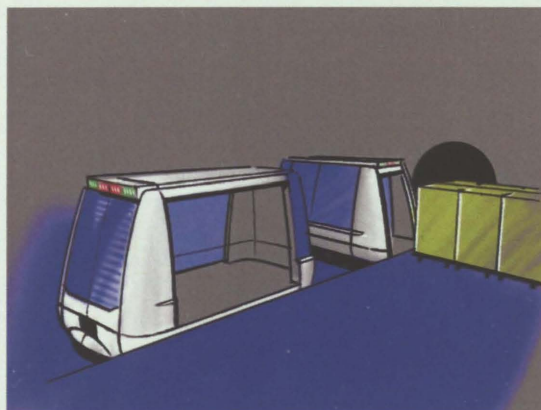Proceedings of the First
International Symposium on Underground Freight Transportation by Capsule Pipelines & Other Tube/Tunnel Systems
September 2-3, 1999
Columbia, Missouri, USA

Pneumatic capsule pipeline system designed and used by Sumitomo Metal Industries, Ltd. in Japan.

Automated guided vehicle for underground freight transportation of the future—This design was created for flower transport in the Netherlands.

Coal log pipeline pilot plant under construction—This technology promises to revolutionize the coal transport industry. This is a project of Capsule Pipeline Research Center, University of Missouri-Columbia, U.S.A.

A Group of Participants of the First
International Symposium on Underground Freight Transportation by
Capsule Pipelines and Other Tube Tunnel Systems
September 2-3, 1999, Columbia, Missouri, USA

Taking a few moments to pose for a group photo, participants are shown here visiting Capsule Pipeline Research Center's Pilot Plant--From left to right, FRONT ROW: P. Brink Weaver, Pneutrans Systems, Ltd., Toronto, Ontario, Canada; Arthur James, Texas A&M University-Galveston; Britta Schoesser, Ruhr University-Bochum Germany; Gene Russell (MATC representative), Kansas State University-Manhattan; Johan Visser, Research Inst. for Housing, Urban & Mobility Studies, Delft, the Netherlands; and Henry Liu, Capsule Pipeline Research Center, University of Missouri-Columbia. BACK ROW: Norm Hageman, Phillips Driscopipe, Richardson, Texas; Wolfgang Weller, Humboldt-University of Berlin, Germany; Sanai Kosugi, Sumitomo Metals, Ltd., Tokyo, Japan; John Sampson, Minnesota Dept. of Transportation, Oakdale, Minnesota; William Vandersteel, TUBEXPRESS, Alpine, New Jersey; Jyh-Cherng Jong, Sinotech Engr. Consultants, Taiwan; Gerard Arends, Delft University of Technology, the Netherlands; George Round, McMaster University-Hamilton, Ontario, Canada; Yuji Tomita, Kyushu Institute of Technology, Tobata, Japan; Ben Pielage, Delft University of Technology, the Netherlands; and Larry Vance, U.S. Dept. of Transportation, Volpe Transportation Center, Cambridge, Massachusetts.

PROCEEDINGS OF THE FIRST

International Symposium on Underground Freight Transportation by Capsule Pipelines & Other Tube/Tunnel Systems

Columbia, Missouri, U.S.A., September 2-4, 1999

Hosted by Capsule Pipeline Research Center
University of Missouri-Columbia

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Texas Transportation Institute
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Symposium Chairman

Henry Liu, Ph.D., P.E.
Director, Capsule Pipeline Research Center

Proceedings Edited by

Henry Liu, Editor
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NOTICE

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Copies of these <u>Proceedings</u> may be obtained from the Capsule Pipeline Research Center, University of Missouri-Columbia, E2421 Engineering Building East, Columbia, MO 65211-2200. (Cost $50.00, U.S., payment should accompany order).

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Workshop Recommendations

Two workshops were held simultaneously, one on **"Practice"** led by K. Thirumalia of U.S. Department of Transportation (DOT), and the other on **"Research"** led by Andrew Fowell of the National Institute of Standards and Technology (NIST). Gene R. Russell, Professor of Civil Engineering, Kansas State University, served as the chairman of the workshops and introduced the speakers. Many individuals spoke at these workshops and expressed their opinions and gave suggestions. A summary of five salient points and suggestions made is listed as follows:

1. *A strong need exists to educate the public, the policy makers, and the transportation planners about Underground Freight Transport (UFT) technologies and their economic and social values. Transportation planners have a special duty to consider UFT in future planning activities.*

2. *In the United States, the DOT Secretary should be contacted to request a panel, under the auspices of the National Academy of Science and Engineering, to study the issue of UFT and freight pipelines, and to issue a white paper. This will have a strong impact on bringing the needed national attention to and support for UFT.*

3. *Large underground pipeline systems for inter-city freight transport is not feasible without government help. Government help is justified due to the great economical, environmental and social benefits that such a system can bring, and its potential for solving highway congestion and safety problems. Government should help in R&D and demonstration of this new technology, and in providing eminent domain and other appropriate assistance.*

4. *In order to accelerate the use of the best systems of UFT, research is needed in many areas of UFT, such as an advanced pneumatic capsule pipeline (PCP) system driven by or augmented by Linear Induction Motors (LIMs). Problems that need to be looked at include how to design such an optimum system, how to restart after power failure, etc. Research is also needed on wheels and tires of PCPs and the associated wear, noise, and vibration, on the types of material to be used in UFT systems, and on the cost of the new systems.*

5. *There is a strong need for an early effort to set up a standard for various types of UFT systems, especially for large UFT systems that transport pallets and containerized cargoes. Government agencies such as DOT (Department of Transportation) and NIST (National Institute of Standards and Technology) should lead this effort.*

<u>Opening Remarks</u>
By Henry Liu, Symposium Chairman

Ladies and gentlemen, welcome to the International Symposium on Underground Transportation of Freight by Capsule Pipelines and Other Tube/Tunnel Systems, and welcome to Columbia, Missouri.

The purpose of this symposium is to bring the key players and stakeholders of capsule pipelines together from around the world not only to share experiences and research findings, but also to plan the future of capsule pipelines, in order to accelerate commercial use of various types of capsule pipelines. The five specific objectives of this Symposium are:

1. Review state-of-the-art and recent developments in the field of capsule pipelines.

2. Share research findings among researchers.

3. Bring stakeholders together to plan for the future of capsule pipelines.

4. Bring attention to the capability of capsule pipelines as an environmentally friendly, new mode of freight transport for the future.

5. Organize a worldwide network (coalition) to promote and accelerate commercial use of capsule pipelines.

Use of underground capsule pipelines and other tube/tunnel systems for freight transportation is important to the future of many nations due to the following advantages:

➢ It reduces the number of trucks on highways and hence reduces congestion, accidents and air and noise pollution caused by trucks.

➢ It reduces the damage to highway pavement and bridges caused by trucks, thereby reducing highway infrastructure maintenance cost.

➢ It conserves energy used in transporting freight, especially saves oil.

➢ Being mostly underground, pipelines do not compete for surface land use. For instance, farmers can plant crops right above pipelines.

➢ In countries such as the United States where pipelines are owned and operated by private companies, the use of pipelines to transport freight will not increase government expenditures. Rather, it increases the tax base or government revenue.

➢ Pipelines are weather proof, automated and hence most reliable, providing 24-hour-a-day, year-round delivery of freight.

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➤ Theft and loss of cargoes during transportation will be reduced.

➤ Lower freight cost.

In spite of the many advantages of underground freight transportation by pipelines, in general pipelines suffer from public neglect because they are underground and hence invisible—out of sight, out of mind. Therefore, it takes special efforts like this symposium to remind the public and government policy makers about the advantages of and need for underground freight pipelines.

This symposium is timely due to a number of important events that occurred recently, indicating a growing interest in using capsule pipelines and other tube/tunnel systems for freight transport. These events include, in chronological order, the following:

1991: National Science Foundation (NSF) funded the **Capsule Pipeline Research Center (CPRC)** at the University of Missouri-Columbia and Rolla. The center was funded for two successive four-year terms (1991-95 and 1995-99). Extensive R&D has been conducted in capsule pipelines over the last eight years under this major effort, resulting in great advancement in the knowledge and the state-of-the-art of capsule pipelines. During this period more than 15 faculty members and over 100 students from seven departments (civil engineering, mechanical engineering, chemical engineering, electrical engineering, industrial, engineering, mining engineering and law) were engaged in various aspects of capsule pipeline research. The total funding from NSF, State of Missouri (Department of Economic Development), an industry consortium, U.S. Department of Energy (Federal Energy Technology Center), and the Electric Power Research Institute, is approximately six million U.S. dollars.

1991: U.S. Congress passed the Intermodal Surface Transportation Efficiency Act (ISTEA). Section 6020 of the act is entitled **"Underground Pipelines."** It states: *"The Secretary of the Department of Transportation shall conduct a study to evaluate the feasibility, costs, and benefits of constructing and operating pneumatic capsule pipelines for underground movement of commodities other than hazardous liquids and gas."*

1994: Volpe National Transportation Systems Center in Cambridge, Massachusetts issued a report entitled **"Tube Transportation."** It is a report prepared for Federal Highway Administration to address Section 6020 of ISTEA. The report affirmed the technical and economic feasibility, and cited environmental and safety benefits of PCP. The principal author of that report, Dr. Larry Vance, is here today and will give a talk on his report in Session 2.

1996: American Society of Civil Engineers (ASCE) held a national workshop on Pipeline Research Needs. Various types of capsule pipelines made the list of needed research and were included in the workshop proceedings published by ASCE.

1997: National Science and Technology Council, which is an office under the U.S. President, issued a report entitled **"Transportation Science and Technology Strategy."** In this report, "capsule pipeline systems" were mentioned as a means to enhance goods and freight movement.

1997: The Institution of Civil Engineers and the Engineering Council of the United Kingdom issued a joint report, **"A Vision for Transport 2020."** This document has a section on pipeline transport, envisioning a national network of pneumatic capsule pipelines carrying freight, powered by linear induction motors.

1998: An interdepartmental government task force in the Netherlands published a report, **"Underground Freight Transport—A Challenge for the Future."** The report dealt with capsule and other tube/tunnel systems for underground freight transport. Key contributors of this study are present here today.

1998: U.S. Congress passed the **Transportation Efficiency Act (TEA-21).** In this act, the Congress authorized $1.125 million to Texas Transportation Institute (TTI) to conduct a freight pipeline study. Key researchers involved in this study are also here today.

1998: An ASCE Task Committee published its report, **"Freight Pipelines: Current Status and Anticipated Future Use"** in the <u>Journal of Transportation Engineering</u>, (Vol. 124, No. 4). This committee report gave detailed treatment of the state-of-the-art and anticipated future use of capsule pipelines.

The foregoing major events in the last eight years give concrete evidence to the growing realization, in various quarters of the world, of the important role that various types of capsule pipelines and other tube/tunnel systems can play, and are about to play in the future, to revolutionize freight transportation. Therefore, this symposium to bring key players together to plan for the future of freight pipelines is timely. It is expected to have a major positive impact on facilitating the future R&D and commercial use of capsule pipelines for underground transportation of freight.

In spite of the inevitability of growing interest and growing use of capsule pipelines in the 21st century, let us realize that progress and change will not come automatically. It will take a lot of effort by many dedicated people and especially if progress is to come rapidly. Therefore, only through the future efforts of many of you will rapid change be possible. I challenge each of you to consider how you can help or contribute to the further development of capsule pipelines and other tube/tunnel underground freight transport (UFT) systems. Your help is crucial because at this stage only a handful of people are involved or significantly concerned. However, everything starts small, like an acorn from which a giant oak tree grows. It always takes a dedicated group t push for a worthwhile cause. I am sure that all of you here, no matter whether you are optimistic or pessimistic about the future of capsule pipelines, share

the common belief that use of capsule pipelines and other tube/tunnel systems for underground freight transportation is beneficial to your country and good for the world. This belief will sustain you and me in our efforts, and insure our success. So, I am optimistic about the future—the inevitability of using capsule pipelines and other tube/tunnel systems for underground freight transportation in many nations. However, how soon this can be accomplished will depend to a large extent on government policies. Nations that encourage the use of UFT systems will first benefit from the use of such systems.

An important thing that we can do to facilitate the development and the use of UFT systems is to hold this Symposium on an annual basis in different nations which have strong interest in UFT. So, let me propose that during this Symposium, we organize an international steering committee for the next Symposium. The committee will take proposals from different nations, and consider final proposals for the next Symposium. To facilitate the formation of this committee, I urge we talk about this tonight at the dinner, so that the initial members of the committee can be selected. I am optimistic that with proper management of a strong steering committee, this Symposium will grow rapidly and continuously in future years.

I wish to recognize and thank the co-sponsors of this Symposium. Co-sponsors are those organizations which would like to encourage and endorse this Symposium. Most of them have at least one representative attending this Symposium. The co-sponsors are, in alphabetical order:

> American Society of Civil Engineering
> Chinese Mechanical Engineering Society
> Civil Engineering Research Foundation (CERF)
> Delft University of Technology, the Netherlands
> Florida Institute of Phosphate Research
> International Freight Pipeline Society
> Mid-America Transportation Center
> Minnesota Dept. of Transportation
> Missouri Dept. of Transportation
> National Institute of Standards and Technology
> National Science Foundation
> Sumitomo Metal Industries, Ltd.-Japan
> Texas Transportation Institute
> U.S. Department of Energy
> U.S. Department of Transportation

Finally, I wish to thank all the authors, co-authors and others who are present here. Without your interest and participation it would not have been possible to hold this Symposium. Thank you and have a nice symposium.

"Selling the Underground Pipe Dream[1]"

An Abstract
by Marshall M. Lih
National Science Foundation, Arlington, Virginia

With collaboration from colleagues in other fields, engineers have transformed everyday life and the face of the earth in this short century. Many products and services unimaginable a mere hundred years ago even in our wildest dreams are now commonplace. Examples can be readily found in virtually all fields such as transportation, space exploration, communication, computation, biotechnology, bioengineering, pharmaceuticals, materials, electronics, petro-chemicals, etc. Some advancements in speed, scale, and capacity have been as great as five orders of magnitude. An imaginary alien from outer space who visited us in 1900 and now returns might find us so different that he/she/it might think he/she/it is on the wrong planet!

This is how underground freight transportation (UFT) ought to be viewed in context. Those who think that the scale is so huge, the technology so daunting, and the costs so staggering should be reminded that our ability to envision the future and estimate our own capacity to rise up to challenges has historically been quite limited.

We need to consider UFT as an alternative or complement to the current systems of highways, railroads, and airfreight as a means of transporting goods and other kinds of material. We need to overcome the physical and mental barriers that stand in the way. We must realize, for example, that most of our highways, including the Interstates, were not designed to handle the present volume of freight traffic, let alone a certainly growing one. Under the current overuse, our roads are fast deteriorating, traffic increasingly congested, and accidents and fatalities multiplying. Concerns about aesthetics and the lack of open space limit our capacity to build more roads. A better way must be found.

Engineers need to work with colleagues in many fields on conceptual design, technological and economic feasibility, environmental and societal impact, etc. toward making this dream a reality. It also requires many of the non-technical skills identified in the ABET2000 criteria, such as communication, interpersonal, decision-making, cultural, teamwork, managing complexity and uncertainty, and the ability to advocate and influence, etc. We must give it our best shot.

This workshop is a good rallying point for this noble common cause. The breadth and depth of expertise represented here are impressive. We are also grateful to colleagues from overseas who are here to share their knowledge and experience with us. We hope that the discussions here will be stimulating and result in more collaboration with mutual benefits in the future. *May the force be with you!*

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[1] This title was co-inspired by Bill Vandersteel's self-effacing humorous reference to UFT as his "pipe dream" and by the bestseller *Selling the Dream* by Guy Kawasaki, 1991.

Symposium Program

1st Day (Sept. 2, Thursday)

Session 1: Opening Session (8:30-10:00 a.m., Ivy A Room)

Session Chair: **Henry Liu, Professor and Director, Capsule Pipeline Research Center, University of Missouri-Columbia**

8:30-8:35: Announcements
8:35-8:40: Columbia Mayor Pro Tem--Mr. Chris Janku's Welcome
8:40-8:45: University of Missouri Official Welcome--Associate Provost Lori Franz
8:45-8:50: Welcome from College of Engineering Dean—Dr. Jim Thompson
8:50-9:00: Opening Remarks by the Symposium Chair
9:00-9:45: **Keynote: Selling the Underground Pipeline Dream,** Dr. Marshall Lih, Director, Engineering Education & Centers Division, National Science Foundation, Arlington, Virginia, U.S.A.

Session 2: Technology Review (10:00 a.m.-12:00 p.m., Ivy A Room)

Session Co-Chairs: Andrew Fowell, Associate Director for Construction and Building, Building and Fire Research Laboratory, National Institute of Standards & Technology (NIST), Gaithersburg, Maryland; G. Michael Lloyd, Jr., Research Director, Chemical Processing & Phosphogypsum, Florida Institute of Phosphate, Bartow, Florida, U.S.A.

10:00-10:24: **Capsule Pipeline Technologies: Current Status and Potential Future Use,** Henry Liu, Capsule Pipeline Research Center, University of Missouri, U.S.A.

10:24-10:48: **Recent Developments in Coal Log Pipeline Technology,** T. R. Marrero, University of Missouri-Columbia, U.S.A. and J. W. Wilson, University of Missouri-Rolla, U.S.A.

10:48-11:12: **Electrical Capsule Pipeline System for Freight Transportation,** Y. J. Zhao and Thomas S. Lundgren, University of Minnesota, and John Sampson, Minnesota Department of Transportation, U.S.A.

11:12-11:36: **Tube Transportation,** Larry Vance, Volpe National Transportation Systems Center, U.S. Department of Transportation, Cambridge, Massachusetts, U.S.A.

11:36-12:00: **Review of Past and Current Research and Use of Capsule Pipelines in Japan,** Katsuya Yanaida, Kyushu Sangyo University and Yuji Tomita, Kyushu Institute of Technology, Japan

Luncheon (12:00-1:00, Missouri Room)

"Black Mesa Coal Slurry Pipeline—A Success Story," by Henry Brolick, President and CEO, Williams Technologies, Inc., Tulsa, Oklahoma, U.S.A.

Session 3: Existing Projects (1:20-3:00, Ivy A Room)

Session Co-Chairs: John Sampson, Director, Environmental Analysis of Compliance, Minnesota Department of Transportation; P. Brink Weaver, President, Pneutrans Systems Ltd., Ontario, Canada.

1:20-1:40: **Sumitomo Pneumatic Capsule Pipelines in Japan and Future Developments,** Sanai Kosugi, Pipeline & Thermal Plant Engineering Department, Sumitomo Metal Industries, Ltd., Tokyo, Japan.

1:40-2:00: **Electromagnetic Pipeline Transport Systems for the Phosphate Industry,** D. Bruce Montgomery, Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.

2:00-2:20: **Use of Linear Induction Motors for Pumping Capsules in PCP,** Henry Liu, Robert O'Connell, W. Plodpradista, and Kevin York, University of Missouri Columbia, U.S.A., and Alan Foster, Force Engineering, United Kingdom

2:20-2:40: **Feasibility and Design Considerations of Pipelines for Freight Transport along Selected Corridors -- A TEA-21 Study,** Steve Roop and Christine Jerko, Texas Transportation Inst., Texas A&M University, College Station, Texas, U.S.A.

2:40-3:00: **Underground Freight Transport in Urban Areas,** Johan Visser, OTB Research Institute for Housing, Urban and Mobility Studies, Delft University of Technology, and Martin Muller, Interdepartmental Underground Transport Task Force, the Netherlands

Session 4: Other Projects/Analyses (3:20-5:00, Ivy A Room)

Session Co-Chairs: Larry Vance, Volpe National Transportation Systems Center, U.S. Department of Transportation, Cambridge, Massachusetts, United States Department of Transportation, U.S.A.; Johan Visser, OTB Research Institute for Housing, Urban and Mobility Studies, Delft University of Technology, The Netherlands

3:20-3:40: **OLS-Schiphol, a Pilot Study for Automated Underground Freight Transport in the Netherlands,** Ben-Jaap A. Pielage, Mechanical Engineering Department, Delft University of Technology, The Netherlands

3:40-4:00: **Potential for Pneumatic Capsule Pipeline Systems in North America,** P. Brink Weaver, Pneumatic Systems Ltd., Toronto, Ontario, Canada and George F. Round, McMaster University, Hamilton, Ontario, Canada

4:00-4:20: **Transportation of Goods through Pipelines -- A Comprehensive Study,** Wolfgang Weller and Britta Schoessen, Ruhr-University of Bochum, Germany

4:20-4:40: **Megaships, Megaports and Landside Access Problems In the U.S. Port Industry--An Opportunity for Freight Pipelines,** Arthur P. James, Texas Transportation Institute, Texas A & M University, Galveston, Texas, U.S.A.

4:40-5:00 **Tubular Freight Transportation System Risk Assessment,** C. S. "Rocky" Shih, Bill Ingersoll and Albert Arroyo, University of Texas at San Antonio, Texas, U.S.A.

DINNER: (6:00-7:00, Missouri Room)

2nd Day (Sept. 3, Friday)

Session 5: Other Projects/Analyses (8:00-9:20, Ivy A Room)

Session Co-Chairs: Jim Murray, Head, Research, Development & Technology, Missouri Department of Transportation, Jefferson City, Missouri, U.S.A.; Britta Schößer, Ruhr University-Bochum, Germany

8:00-8:20: **Feasibility of Underground Pipeline Transport of Freight in the City of Leiden,** A. J. van Binsbergen, Faculty of Civil Engineering and Geosciences, Transportation Section, Delft University of Technology, the Netherlands

8:20-8:40: **Benefits and Capabilities of Medium to Long Distance Tube Transportation Systems,** Stephen Catha and Carl Peterson, Cross Roads Technology, New Orleans, Louisiana, U.S.A.

8:40-9:00: **Horizontal Directional Drilling and Microtunneling: Current Status and Potential Future Use,** Mohammed Najafi, Associate Professor of Environmental Technology, Missouri Western State College, St. Joseph, MO, U.S.A.

2nd Day (Sept. 3, Friday)

Session 5 (Cont.)

9:00-9:20: **Analysis of Pneumatic Capsule Pipeline Systems with Branches,** Yuji Tomita, Kyushu Institute of Technology, Japan

Session 6: Panel Discussion: Need for Freight Pipelines (9:40-10-40, Ivy A Room)
Panelists Tom Canter, Arthur P. James, Henry Liu, Marvin Phillips, Larry Vance and John Whitley, J.C. Jong (Taiwan), Sanai Kosugi (Japan), Ben-Jaap Pielage (Netherlands), Wolfgang Weller (Germany)

Luncheon (12:00-1:00, Missouri Room)

"Pneumatic Mail Tubes: New York's Hidden Highway and Its Development,"
by Robert Cohen, Postal Inspector, U.S. Postal Service (New York Office)

Session 8: Workshop: Planning Freight Pipelines for the 21st Century (1:20-2:20, Ivy A Room)   **Group Spokesman:** Andrew Fowell

Session 9: Workshop: Facilitating UFT—Making it Happen (2:40-3:40, Ivy A Room)

2:40-3:00: **Group Spokesman:** K. Thirumalai

Session 10: Tour--Capsule Pipeline Labs (4:00-5:00)

3rd Day (Sept. 4, Saturday)

**Tour of State Capitol and Lake of the Ozarks
Riverboat Cruise on The Tom Sawyer**

A One-Day Short Course on Capsule Pipelines
Holiday Inn East (Holidome)
Columbia, Missouri, September 1, 1999
ECR Room

Course Content

A.M.	Subject
8:00 - 8:50	Basic Concepts and Design of HCP
8:50-9:00	Break
9:00-9:50	Hydrodynamics of HCP
9:50-10:00	Break
10:00-10:50	Coal Log Pipeline (CLP) Technology
10:50-11:00	Break
11:00-11:50	Economics of Transporting Coal and Grain by Capsule Pipeline
12:00-1:00	Luncheon

P.M.	
1:00-1:50	Basic Concepts and Design of PCP
1:50-2:00	Break
2:00-2:50	Fluid Mechanics of PCP (Part 1: Short Pipelines-Incompressible)
2:50-3:00	Break
3:00-3:50	Fluid Mechanics of PCP (Part 2: Long Pipelines-Compressible)
3:50:4:00	Break
4:00-4:50	Questions, Answers and Discussion
4:50	End of Short Course

(Note: The short course was taught by Dr. Henry Liu, Director of Capsule Pipeline Research Center. A set of lecture notes were handed out as part of the course.)

Individual Papers

(Note: All papers are listed in the order of the Program)

Capsule Pipeline Technology: Current Status and Potential Future Use

Henry Liu, Capsule Pipeline Research Center,
University of Missouri-Columbia, U.S.A.

ABSTRACT

Three types of capsule pipelines are discussed in this paper: pneumatic capsule pipeline (PCP), hydraulic capsule pipeline (HCP), and coal log pipeline (CLP). They are suitable for transporting different materials (freight) under different conditions. PCP has been used extensively for more than a century to transport mail, parcels and many other small-size products. PCPs of 1 m diameter are being used currently in Japan for transporting limestone to a cement plant, and construction materials at construction sites. Anticipated future use of PCP includes intercity freight transport by using pipes of 1.2 to 2.0 m diameter.

HCP has been under intensive research since 1960, and it is approaching commercialization pending last stage research focused on capsule preparation and handling, and electromagnetic pumping. Anticipated future use of HCP includes 0.5 m to 1.0 m diameter pipelines for transporting grain, solid wastes, and construction materials. In contrast to PCP, HCP uses water instead of air, its capsule speed is low, its freight capacity is high due to high linefill, and it uses less energy.

The CLP technology has been under intensive research since 1991 at the University of Missouri-Columbia. It is approaching commercialization pending a pilot plant test program currently underway. Potential use of CLP is not limited to transporting coal. The same technology can also be used to transport certain other minerals, certain wastes (such as power plant ashes), and petroleum coke.

INTRODUCTION

Capsule pipeline is the transport of freight by "capsules" which are vehicles or containers containing the material to be transported, or slugs (logs) made of the material, moving through a pipeline filled with a fluid—either a liquid or a gas. The fluid, pumped through the pipeline, provides the driving force to push the capsules forward in the pipeline. When the fluid in the pipe is a gas, most commonly air, the system is called **pneumatic capsule pipeline (PCP)**. When the fluid is a liquid, most commonly water, the system is called **hydraulic capsule pipeline (HCP)**. A special type of HCP is **coal log pipeline (CLP)** in which the capsules are made of coal compressed into the shape of solid cylinders (logs) which are both water-resistant and wear resistant and hence can be transported hydraulically through pipe for a significant distance without much deterioration or degradation. The CLP technology is also applicable to transporting many materials other than coal—including most minerals and certain solid wastes such as power plant ashes.

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Capsule pipelines have unquestionable safety and environmental values, mostly derived from the fact that the pipelines are underground, and that the vehicles (capsules) move inside a closed conduit—the pipe. Use of underground pipelines instead of trucks or trains to transport freight reduces traffic jam, accidents, noise and air pollution generated by trucks and trains. Therefore, it is appropriate to refer to capsule pipelines as an **"environmentally friendly"** or **"green"** technology in the transportation field. It is also the safest of all transportation modes. In many situations, freight can also be transported more economically by capsule pipelines than by trucks, trains and other competing transportation modes. Therefore, it is important to realize the full potential of capsule pipelines, and to develop various types of capsule pipelines to their full potential. After giving a brief account of the past and current use and study of capsule pipelines, this paper will focus on future possible usages of various types of capsule pipelines—what is each type most promising for, and what needs to be done for each type before it can be used, or more extensively used, to benefit the society. This paper is based in part on a 1998 task committee report of the American Society of Civil Engineers [1].

HISTORY & CURRENT USE

PCP (Pneumatic Capsule Pipeline)

The technology of PCP has been used throughout the world, especially in Europe and the United States, over the past 180 years. For instead, according to Zandi [2], as early as 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 PCP was built in London, England by the Pneumatic Dispatch Company. Since then, many PCP systems have been built and used successfully in various parts of the world for transporting mail, parcels and telegraphs. They are generally referred to as "pneumatic tubes." For instance, by 1875, London already had 28 km of PCPs, and by 1975 the British Postal Department operated 968 km of PCPs, 64 km of which was in London [3]. Paris, France started to use PCP in 1866. By 1899, the city had a total of 269 km of PCPs, and by 1966 it had 452 km. Berlin, Germany started to use PCP for mail transport in 1865. By 1899, Berlin had 118 km of PCPs.

In the early half of the 20th century, PCP was used in five U.S. cities (New York, Boston, Philadelphia, Chicago, and St. Louis) for transporting mail and parcels between main post offices and branch offices.

Since about 1970, a new generation of small PCPs (less than 300 mm in diameter), highly automated and modernized, has been used widely in the U.S. at drive-in banks, hospitals, airports, and large factories. They are all for short distances—within a large building or between neighboring buildings.

Since 1980, large systems of PCP (of 1 m diameter and 3 to 20 km length), have been used in the former Soviet Union, and in Japan. The most successful and famous PCP system, built by the Sumitomo Metal Industries in Japan for transporting limestone to a cement plant, is shown in Fig. 1. The system has been in operation smoothly and reliably since 1980, achieving an availability of over 95% [4]. Another successful and interesting Japanese project was a temporary PCP built for moving materials in and out of a long tunnel during the tunnel construction [5]. The system was dismantled after the tunnel was constructed. Two interesting

features of this PCP for tunneling are: (1) the system used rectangular cross-sectional pipe made of precast concrete plates, and (2) the PCP length was extended along the tunnel as tunnel construction progressed. These features show the great flexibility of the PCP systems—can be tailored to fit specific needs.
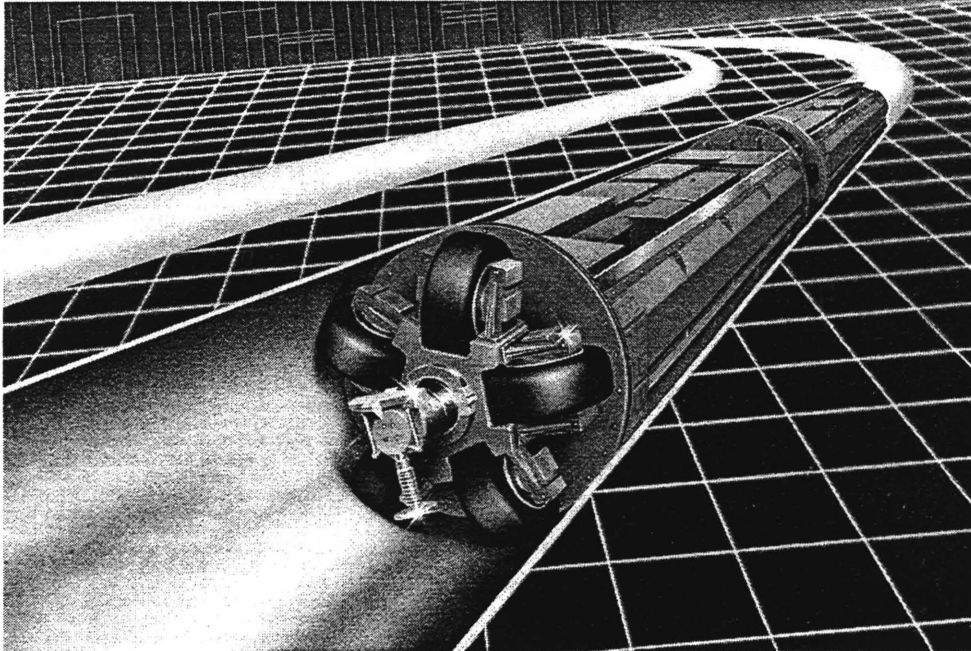
Fig. 1 PCP of Sumitomo Metal Industries in Japan

In spite of the success of the large PCP systems used in Japan, still only a few of them have been used to date commercially around the world, including Japan. The main reason for its sparse use is that current PCP systems are only marginally cost-effective when compared to other more established transportation modes such as truck, railroad, barge, and conveyor belt. When there is not a clear economic advantage in favor of PCP, transportation planners and users feel more comfortable with (due to more knowledge in) traditional modes of transportation. This means that for any major new technology such as PCP to make a significant inroad in the marketplace, it is not good enough for the new technology to be able to perform the same function as that of conventional freight transport modes at about the same cost. The new system must be far more cost effective, or much superior in providing services, than the conventional transportation modes before it will be accepted. Just being more environmentally friendly and much safer for the public is not good enough. In the choice of transporting modes, few shippers pay much attention to public safety and the environment. Therefore, the key to wide-spread use of PCP in the future is to improve the PCP technology and make it significantly more cost effective than conventional modes of freight transport. As will be shown later in this paper, this is possible by using electromagnetic capsule pumps and off-line loading/unloading of capsules.

HCP (Hydraulic Capsule Pipeline)

As compared to PCP, HCP has a much shorter history and is not yet ready for commercial use without further R&D on capsule design and handling, electromagnetic pumping,

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and pilot plant testing of an entire HCP system, an effort currently underway at the Capsule Pipeline Research Center, University of Missouri-Columbia in U.S.A.

The concept of HCP was first considered for possible use for transporting ammunition and other military supplies during World War II [6]. However, serious research in HCP did not occur until 1960 in Canada by some chemical engineers studying the two-phase flow of oil slugs moving in a water pipe [7]. These researchers discovered that the slugs travel at a speed higher than the water flow, and the pressure gradient along the pipe for the slug flow is less than that of the supporting fluid (water) when the flow was turbulent. This discovery encouraged the researchers to propose the idea of HCP—using solid capsules to replace the oil slugs for freight transport. Due to the foregoing discovery and subsequent analyses, the Alberta Research Council in Canada carried out an extensive research program in HCP over the period 1960-1975 [8, 9]. Research in HCP also spread to other nations including U.S.A. [10-12], Japan [13, 14], South Africa [15], the Netherlands [16, 17], Australia [18], and the Czech Republic [19].

In 1991, the National Science Foundation (NSF) of the United States of America established the Capsule Pipeline Research Center (CPRC) at the University of Missouri-Columbia. The Center has since conducted eight years of extensive R&D in HCP [20-22], especially in the coal log pipeline (CLP) technology for transporting coal [23-25]. This has brought both HCP and CLP close to commercial use, pending the testing of a large pilot plant currently under construction in Columbia, Missouri—see Fig. 2. The pilot plant pipeline can also be used to demonstrate and test the transport of many other materials, such as grain and solid wastes, by using water-proof containers (capsules).
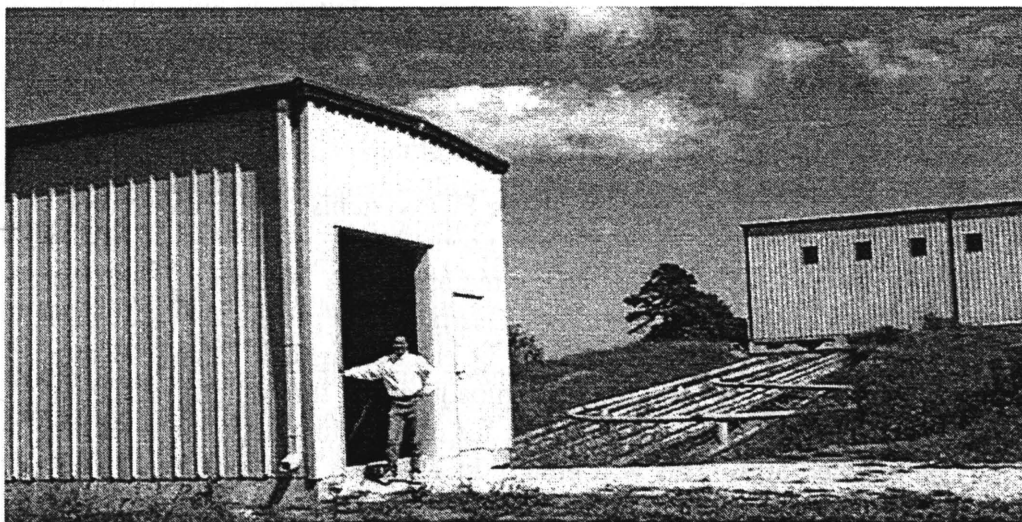
Fig. 2. CLP Pilot Plant Under Construction in Columbia, Missouri

CLP (Coal Log Pipeline)

The technology of CLP was invented by Liu and Marrero in U.S.A. in 1985 [26]. CLP is based on the concept of HCP except that the material to be transported, coal, is compressed in

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the shape of cylindrical capsules for hydrotransport in pipelines. To be successful, the logs (i.e., the compressed coal capsules) must be both water-resistant and wear-resistant.

Much of the research in CLP has been directed toward compaction of water-resistant and wear-resistant logs, and mass production of such logs at the lowest possible cost. To date, the best logs produced survived over a distance of 322 km in a recirculating pipe loop with only 5% weight loss. A machine has also been designed and tested successfully to produce 135 mm diameter coal logs in laboratory at the rate of one per 20 seconds [27]. Another machine, based on the rotary press concept, has been designed for producing 135 mm logs at the rate of one per second. A pilot plant CLP, consisting of a 940 m length, 152 mm diameter steel pipe recirculating loop, a coal log injection/ejection system, a pump bypass, and an automatic control system, are currently under construction in Columbia, Missouri, U.S.A. It can also be used for testing HCP.

The pilot plant is a costly but necessary step before the CLP technology can be and should be used commercially [28]. Its purpose is not only to demonstrate an entire system of CLP, but also to acquire the engineering data needed for the design and operation of the first future commercial CLP project.

Two years of extensive testing of the pilot plant is being planned to acquire the needed engineering data. The tests to be conducted using the pilot plant include coal log wear, pump bypass operation, automatic control system, drag reduction degradation, and testing certain components such as a novel coal log sensor [29].

FUTURE DEVELOPMENT AND APPLICATIONS

PCP

The main reason that contemporary large PCP systems such as those used in Japan is not cost competitive is that the system has only about 3% linefill. This means only 3% of the pipeline length is filled with capsules, the remaining 97% is empty. This greatly limits the throughput (freight capacity) of the system, as illustrated in a proposed Washington, D.C. to New York PCP to be discussed later. With the use of electromagnetic capsule pumps to propel the system [30], and the use of off-line loading/unloading, the throughput of current PCP systems can be increased at least fourfold, and the cost for transporting each tonne of coal over a given distance may be reduced 50%. This will greatly increase the economic competitiveness of PCP, reducing its cost to far below those charged by truck and train. Therefore, future R&D in PCP should be focused on LIM capsule pump and off-line loading/unloading. The LIM pump works only for capsules having a metallic wall. Good efficiency of the pump depends on small air gap between the capsule and the inner surface of the LIM. For best efficiency, the bore of the LIM must be slightly smaller than the inner diameter of the pipe.

Many potential future applications of PCP are expected. In the area of small and short systems of PCP, there will be increased use in large buildings and between large buildings, especially in large factories for materials that cannot be transported by pneumatic conveying,

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such as machine parts and many food products. There may even be a future underground PCP network of pipes in cities for food delivery from supermarkets to individual homes, in much the same manner water is delivered to homes today, except for using larger diameter tubes, of the order of 200 mm.

Increased use of large diameter PCP, of the order of 1 m diameter and less than 50 km long, is expected for transporting raw materials—such as limestone—to cement plants, for transporting rocks, sand and other materials to major construction sites, for transporting minerals from mines or processing plants, and for transporting municipal solid wastes from collection or processing centers to power plants (for burning the combustible part of the waste), and to landfills to dispose of the non-combustible part of the waste.

Larger diameter (of the order of 1.2 to 2 m) PCPs may be used in the future for inter-city transport of general cargo or freight in much the same manner as freight is transported by trucks today. Such large PCPs will be built along major highways in areas where the highways are already congested with cars and trucks, or to be congested in the future. An example of such anticipated large and long future PCP systems is one between Washington, D.C. and New York City, with terminals serving four other major cities along the route. An analysis [30] showed that based on current technology, this PCP system of 1.22 diameter can transport 2.5 million tonnes of cargoes per year at any given point in the line, and the cost of freight transported by such a pipeline is approximately $11 (U.S. dollars in 1997 value) per tonne of cargo transported for a distance of 160 km. This cost figure already includes a 12.5% after-tax return (profit). The cost can be significantly reduced if the system uses electromagnetic pumps for propulsion, and off-line loading and unloading of capsules.

HCP

Future development of HCP should be focused on the design, construction and handling of the capsules (cargo-laden containers)—how to make them water-proof, to withstand the high pressure generated in a long-distance pipeline, and to be easily opened and closed at pipeline terminals for automatic loading/unloading of freight. Electromagnetic capsule pumps should be used not only to simplify pumping but also to reduce the high pressure in the HCP so that the capsules will not need very thick walls. Due to the low cost nature of such pumps, they can be mounted at relatively short intervals along a long pipeline without excessive costs. Such pumps, based on the principle of linear induction motor (LIM), has been researched before but has not yet been demonstrated in large scale for HCP [31, 32]. They should be demonstrated before used.

The most likely future applications of LIM-based HCP is for transporting grain, minerals, solid wastes and heavy construction materials such as rocks over long distances (longer than 10 km), using pipelines of 0.3 to 1.0 m diameter. For very short lines (say, less than 10 km), HCP is uneconomical due to relatively high cost associated with capsule loading/unloading. An economic study has been performed to establish the economic feasibility of using LIM-based HCP to transport grain in the United States [33, 34].

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CLP

The most immediate need in developing CLP is to complete the construction of a pilot plant currently underway in Columbia, Missouri. The heart of the system is a recirculating loop of pipeline of 152 mm diameter and 915 m long, equipped with a special pump bypass, a coal log injection/ejection subsystem, and an automatic control system using PLCs and a SCADA. The system also includes a specially designed coal log fabrication machine which supplies 135 mm diameter logs for testing in the loop. At the time of this writing, the pilot plant construction is 80% complete, with the remaining construction planned for completion in December 1999. Then, the system will be tested. An extensive test program has been planned. It includes testing of coal log abrasion, operation of pump bypass, automatic control, sensor reliability, degradation of drag reduction in CLP, etc. Upon completion of the test program in two years, the CLP technology will be ready for commercial use.

Future R&D in CLP should also include testing of a second-generation coal log machine based on the concept of rotary press which is most suitable for low-cost, mass production of large-diameter logs. Finally, optimum processes to compact various kinds of coals, coal fines, solid wastes, minerals, and petroleum coke should be developed.

CONCLUSION

While PCP is an existing technology that has been widely used commercially for over a century, HCP and CLP are relatively new and are still in their final stages of development before they can be used commercially.

All the three types of capsule pipelines can be improved through research. In the case of PCP, drastic improvement can be made by using electromagnetic capsule pumps, and off-line loading/unloading. This is expected to increase the PCP's throughput by several times, thereby reducing the cost for transporting a unit weight of cargo through this pipeline. Anticipated future use includes large diameter PCPs for intercity freight transport.

In the case of HCP, further research is needed on capsule design, handling capsules at pipeline terminals, and economic and market analyses of such systems. Anticipated future use of HCP includes transporting grain, minerals, construction materials and solid wastes.

For CLP, remaining necessary R&D includes pilot plant tests and the test of a rotary press for mass production of coal logs. The CLP technology will be used not only for transporting coal but also for transporting petroleum coke, power plant ashes, mine tailings and many other minerals.

ACKNOWLEDGMENT

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Recent Developments in Coal Log
Pipeline Technology

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ABSTRACT

This report describes the present status of coal log pipeline (CLP) technology that is under development at the University of Missouri. For the last eight years, the National Science Foundation, Missouri Department of Economic Development, and an industrial consortium have sponsored this development program. CLP developments include: (1) preparation of coal log samples from various types of coal, with and without the use of binders or heat, (2) design, construction and use of a large, single-punch, high-pressure press, (3) design, construction and test of a bench-scale system that injects coal logs into a pipeline, (4) design, construction and operation of a bench-scale pump bypass system, (5) conduct a field test using coal logs in a 5 mile long, 6 inch diameter, water pipe and (6) estimate the costs of a CLP system to transport approximately 3 to 18 million tons of coal per year over various distances. In this report the current status of a CLP Pilot Plant, and recent tests on large diameter coal logs, are presented.

INTRODUCTION

The coal log pipeline technology is a specific type of hydraulic capsule pipeline that is being developed at the University of Missouri as a new means for transporting coal. For example, run-of-mine coal is formed into logs, injected into a water-filled pipeline, and then transported through a subsurface pipeline to a power plant. At the power plant the coal logs are separated from the carrier water, crushed, and fed to boilers in a steam-electric power plant. The purpose of this report is to summarize selected recent developments in the coal log pipeline R & D program. In order to place these developments in perspective, a hydraulic capsule pipeline system is initially outlined; then the coal log pipeline (CLP) concept is presented with a brief listing of R & D achievements at the University of Missouri. The third part of this report is a description of CLP achievements over the last year. This report does not contain extensive mathematical formulas or bibliography. For this information, the reader is referred to the literature [1,2].

HYDRAULIC CAPSULE PIPELINE

The concept of a hydraulic capsule pipeline for the transportation of freight was suggested for use in the Asian Theater of operations during World War II. Though never implemented during the war, the concept of moving solid cylinders or loading materials into hollow containers, through liquid-filled pipelines, seemed practical. With this concept, cargo could be practically moved across mountainous terrain.

In 1962, the Alberta Research Council of Canada began to report results of systematic experimental and theoretical investigations of a hydraulic capsule pipeline [2]. Subsequently, engineering studies were conducted in South Africa (University of Cape Town) and the Netherlands (Twente University). Recent investigations have been reported by a select number of investigators in the Czech Republic, Japan, and the United States. Most of the recent developments in the hydraulic capsule pipeline concept have originated in the United States from the Capsule Pipeline Research Center [3]. These developments have been focused on studies related to the coal log pipeline, a patented system for transporting coal in the form of right-solid cylinders through long, water-filled pipelines.

Briefly, the concept of a hydraulic capsule pipeline is as follows [4]: When water flows at "lift-off velocity" a sufficient hydrodynamic lift is generated that causes the capsules (cylinders) to levitate or to become suspended. The capsule diameter to pipeline diameter ratio is slightly less than one and the capsule specific gravity is greater than that of the motive water, but theoretically, it can be less. In a hydraulic capsule pipeline the capsules are the dominant portions of the cross-sectional area of pipe. In other words, capsules are conveyed in a moving ring of water that permits the solid-to-water ratio to be much greater than one. The hydrodynamics of hydraulic capsule pipeline has been recently described [5].

A number of methods have been carefully considered to pump solid capsule-liquid mixtures [6] and two pumping systems have been found to be feasible. First, it is possible to use conventional water pumps that separate capsules from a liquid by means of lock systems. This type of pumping system can also include the use of multiple valves and a single pump; and is the outcome of the research carried out at the Alberta Research Council. The second system uses pumps that allow the capsule and liquid mixture to pass through the pump. The various pumping systems that have been tested for hydraulic capsule pipelines have been documented in the literature [3,6].

Hydraulic capsule pipeline studies in the United States have been pioneered by Liu et al. at the University of Missouri [3]. The initial studies carried out during the late 1970's and early 1980's evaluated hydraulic capsule pipeline energy intensiveness and pumping systems based on the principle of a linear induction motor to pump capsules made with metallic walls. Subsequently, an idea was developed to form a capsule by the compaction into a cylindrical form and be sufficiently strong to enable stable travel for days through water-filled pipe. This idea was applied to coal and called the "coal log pipeline" system. One reason for this choice of application is that the annual amount of coal mined, transported and used is enormous with a total exceeding one billion tons in China and the United States.

COAL LOG PIPELINE

The coal log pipeline is a special type of hydraulic capsule pipeline, and facets of this coal log pipeline system have been researched and developed for more than ten years. These university level investigations have substantiated the theoretical basis for hydraulic capsule flow, developed compaction methods for samples of both bituminous and sub-bituminous coals, tested apparatus to produce coal logs, inject and convey coal logs through water-filled pipelines, and

crush the coal logs that they exit a pipeline. In addition, extensive studies have been made of (1) the legal aspects pertinent to the use of coal log pipelines in each state of the United States, and (2) the costs of transporting coal by means of a coal log pipeline system. Since there are many facets of coal log pipeline technology, a detailed explanation of any one of these is beyond the scope of this summary report. The major coal log pipeline areas of interest include hydrodynamics, coal log formation processes, coal log flow attributes, pipeline systems, lift-cycle costs, and special issues such as environmental, legal, and safety. In addition, an independent market analysis for the application of the coal log pipeline was conducted. These studies have been summarized elsewhere [1,3].

In the area of hydrodynamics, studies have been made to better understand flow-regimes, incipient velocity, lift-off velocity, tilt velocity, capsule (log) velocity and pressure gradient, core annular flow, drag reduction, water hammer, and headloss. These studies reflect directly on coal throughput and the required pumping power. Consideration of all these items is an indication of the theoretical and experimental efforts to develop the coal log pipeline technology to a level that will provide an operational commercial system.

Detailed studies of other topics have also been conducted and are described elsewhere [3].

The major technical achievements to-date of coal log pipeline technology are as follows:

1. A much clearer understanding of coal log pipeline hydrodynamics, including the effects of lift-off velocity on pressure gradients, and the potential value of drag reducing agents and water hammer.

2. The formulation and compaction of bituminous and sub-bituminous coals with and without the use of binders and heat, in small and large diameter single punch presses.

3. The design, construction and testing of computer controlled systems capable of injecting coal logs into a pipeline and then pumping (coal logs) using a single pump with multiple valves.

4. The field test in which coal logs were pumped over a five-mile length of pipeline of nominal six inches diameter.

RECENT DEVELOPMENTS IN COAL LOG PIPELINE

Over the last year or so, the activities conducted at the University of Missouri on CLP research have been focused on, but not limited to, the following areas: designing and testing coal log manufacturing machines on a commercial scale, investigating factors that affect rapid-compaction of coal logs, scaling the CLP system from lab-size to commercial-size, conducting coal log train studies, continuing the hydraulics and hydrodynamics aspects of CLP, and the planning and construction of a CLP pilot plant. Some activity details follow:

A new 250-ton hydraulic press was installed and tested at the Holstein Farm, University of Missouri-Columbia, for making large coal logs of 5.4-inches in diameter. This machine is shown in Figure 1. The machine was designed to make one log in under a 3-second compaction time. After several technical problems were solved, such as the control of compaction back-pressure, the machine has reached design objectives in terms of speed and maximum compaction force. Thus, good-quality coal logs have been produced when using high-ranked coal. In addition, a large rotary press has been designed to produce 5.4-inch diameter coal logs at a rate of one log per second. It is believed that a rotary press can produce coal logs at a much higher rate than a hydraulic press by keeping a high pressure on logs for a longer period of time. The main differences between this new-designed machine and available commercial rotary presses are that for the new machine, the compaction pressure is 2 to 5 times higher, the diameter of compaction is at least 2 to 4 times larger, and the length of compaction is 5 to 10 times longer. This second-generation machine is expected to greatly reduce the cost of manufacturing commercial coal logs, thereby contributing to the economic competitiveness of the CLP technology.

In the coal log fabrication study, it was demonstrated from the lab-scale experiments that rapid compaction can produce strong coal logs only if the moisture of the coal mixture is at or below the equilibrium moisture, which is a function of compaction pressure. Therefore, it has been concluded that moisture content is the most important factor in affecting the quality of coal logs when a rapid compaction process is used. For example, with 6% moisture for a bituminous coal (Mettiki coal), high-quality coal logs were produced with a 5-second compaction time, as little as 0.5% binder, and with a compaction pressure of only 10,000 psi. A mathematical model is under development to predict the effect of excess moisture in coal mixture on coal log compaction. This model will enable the prediction of the effect of excess moisture on rapid compaction of coal logs that cannot be tested in a laboratory, such as rapid compaction of large-size commercial coal logs.

In order to project the behavior of coal logs in a commercial CLP, a scale-up study was carried out by comparing a small system (1.8-inch coal logs travelling in a 2-inch loop) and a large system (5.4-inch coal logs travelling in a 6-inch loop). Figure 2 outlines the 6-inch pipeline test loop built at the Experimental Mine at the University of Missouri-Rolla (UMR). Both strength characteristics and abrasion performance of coal logs were studied by scaling-up compaction and transportation processes. It was found that there was good correlation between the tensile strength of small and large coal logs when compacted under the same conditions. However, large coal logs suffered more weight loss than small logs in tests of degradation. This difference was partially attributed to the dissimilarities between the small loop and the large loop.

The effect of the number of coal logs in a train on coal log wear in a pipe, was investigated by forming a log-train with 5, 10, and 15 coal logs. These tests were carried out in a 6-inch loop with and without the use of dummy logs to lead and trail 5.4-inch coal logs. Some coal logs used in coal log train tests are shown in Figure 3. From those tests it was concluded that the longer the coal log-train, the less the weight loss per coal log. In addition, dummy logs appeared to make no significant difference on the weight loss of coal logs forming a train. It was further inferred from the test data that the minimum coal log abrasion rate could be reached with

trains of about 15 to 20 logs, and the minimum would be constant when there were more than 20 logs in a train. In future commercial operation of CLP, each train is expected to contain hundreds of logs, and its abrasion rate in a pipeline is expected to be about the same as that of a train with approximately 20 logs.

The extensive studies on hydraulics and hydrodynamics in a CLP are continuing. The effect of pipe bends on coal log behavior was studied experimentally in a 2-inch diameter transparent pipe having a 180° bend, for both single capsules and capsule trains. It was observed that capsules rotate about their own center-lines in a preferred direction as they pass through the bend. The capsules were also found to move faster through the bend than through straight sections of the pipe. This is due to the reduction in the pipe cross-sectional area at the bend, which in turn is due to the ovality of the pipe cross section caused by bending the pipe. The pressure gradient along the bend was also measured for comparison with theory. In addition, a new laboratory scale pipeline was built to investigate capsule (coal log) behavior in vertical slopes. Recently, an alternative drag reduction study was completed. This method uses a poly (ethylene oxide) slurry in a poly (ethylene oxide) solution. The results indicate that: (1) a polymer slurry is effective in maintaining drag reduction in a coal log pipeline; (2) a polymer slurry allows increased throughput when compared to traditional drag reduction methods; and (3) a polymer slurry can be directly injected into a water-filled pipeline without the use of adverse solvents.

The most recent developments in the coal log pipeline project are dominated by efforts to complete the construction of a pilot plant at the CPRC Field Station for demonstrating and pilot testing a CLP system. This pilot plant facility will be a 3,000-ft-long, 6-inch-diameter steel pipe circulating loop with a pump bypass and injection system. The pipeline inlet and outlet will be located in a building that also houses the 250-ton hydraulic press and auxiliary equipment used for coal log preparation. The pipeline was constructed; several companies assisted, including the digging of the trenches and laying pipe. The coal logs for this loop will be produced by a machine that can make up to 100 logs at the rate of 3 logs per minute. This pilot plant is expected to be operational late this year. Figure 4 is the construction site of the pilot plant at the UMC.

With the purpose of controlling and monitoring the CLP pilot plant, a sensor system was designed and laboratory tested at UMC on the 6-inch loop at UMR. The experiments showed that the sensor is adequate for detecting coal logs, dummy logs, and steel capsules. More than thirty such sensors have been installed at various places in the pilot plant pipe loop. They were attached to the pipe through a special type of fitting (T-O-R) welded to the pipe, as shown in Figure 5.
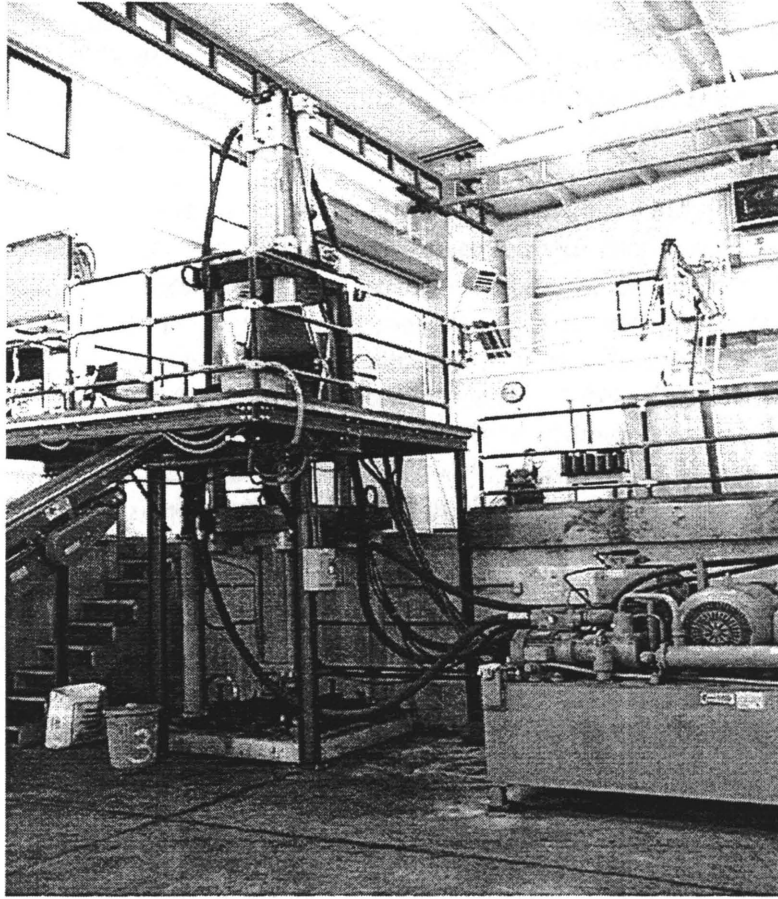
Figure 1. 250-Ton Coal Log Compaction Machine at UMC
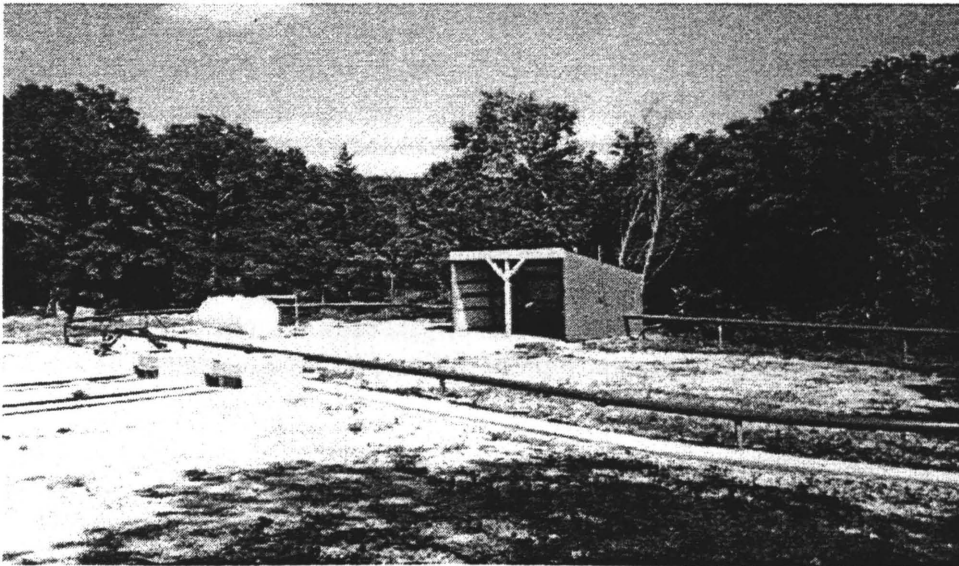
Figure 2. Six-Inch Pipeline Test Loop at UMR

Figure 3. 5.4-Inch Coal Logs for Log-Train Tests
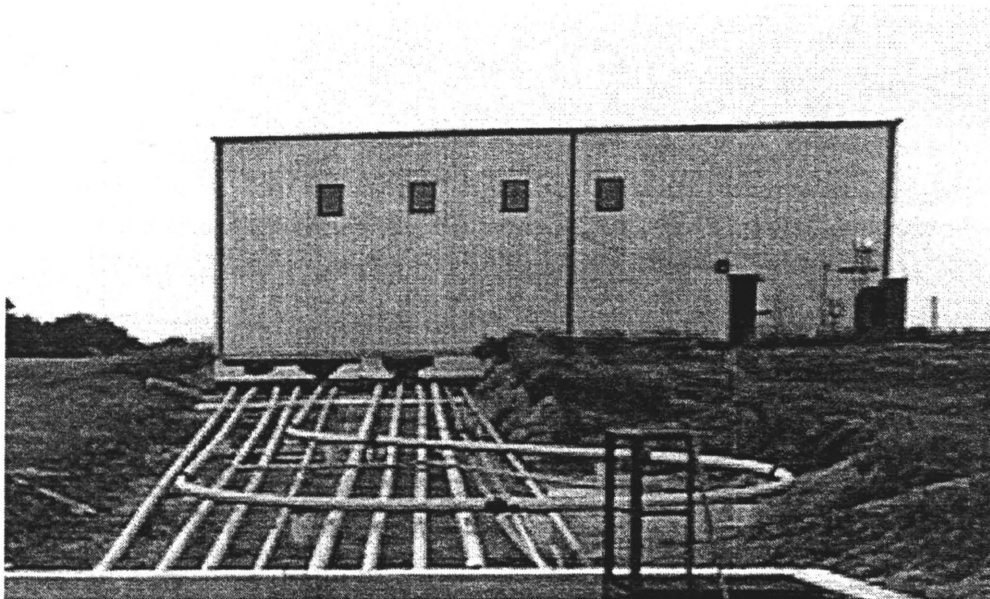
Figure 4. Construction Site of CLP Pilot Plant

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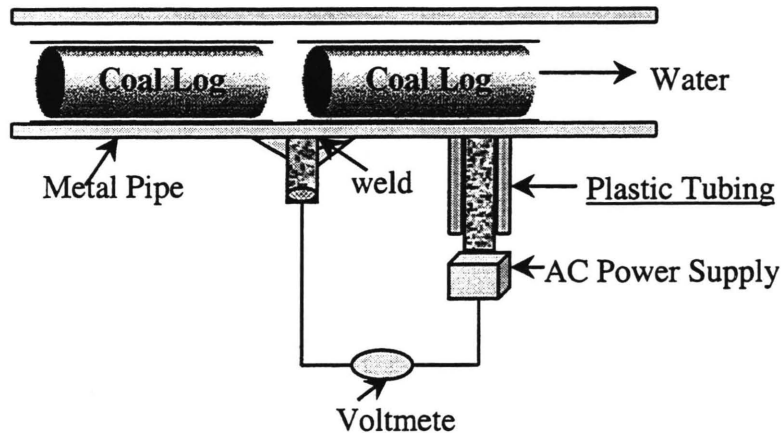
Figure 5. Installation of Coal Log Testing Sensor

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Electrical Capsule Pipeline System for Freight Transportation

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ABSTRACT

This paper examines the concept of electrical capsules in which capsules are driven by linear electric motors. Based on models of individual force components on a capsule and the comparison of several configurations, a linear induction motor pipeline system with moving primaries is selected. Preliminary designs of capsule and pipetubes are conducted. It is shown that electrical capsule pipeline systems offer intrinsic advantages, in terms of energy use, over pneumatically propelled systems. Numerical simulations of the system operations show that it is advantageous to connect two-bore pipelines with adits or open vents. If there is not a sufficient number of capsules for operating at full capacity, an efficient strategy is to run platoons of capsules followed by long intervals with no traffic.

INTRODUCTION

The last several decades have witnessed significant increase in both surface and air traffic[1]. At this point, both the highway system and air traffic system are approaching saturation. It has become important to examine new transportation infrastructure concepts.

Any future alternative transportation system should be able to provide highly reliable, safe, and secure transportation of people and/or freight. It is desirable that such a system can be operated with full automation, and regardless of weather conditions. In addition, a proposed system should produce little pollution and intrusion to the environment, be energy-efficient, and decrease the current ground/air traffic congestion.
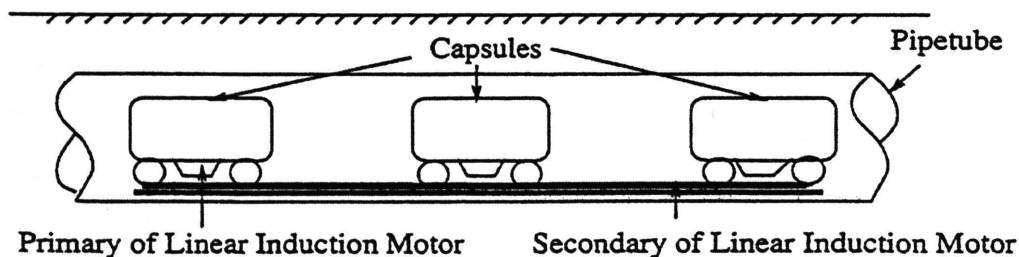
Figure 1. An Electrical Capsule Pipeline System

This paper examines a system concept that can potentially achieve these qualities. In such a system, capsules are propelled through pipelines by linear electric motors. To distinguish from traditional pneumatic pipeline systems, the capsule pipeline system directly powered by linear electric motors will be called **electrical capsule pipelines**. Figure 1 shows a schematic drawing of an electrical capsule pipeline system.

The idea of electrical capsule pipeline transportation is not completely new. In 1984, Ampower Corporation of Alpine, New Jersey proposed a capsule pipeline system powered by linear induction propulsion [2]. Swiss researchers proposed a cross-country high-speed pipeline transportation system for passengers, powered by linear induction motor and magnetic levitation, and assisted by tunnel evacuation [3]. Researchers in the Netherlands are also developing an electrical capsule pipeline system for transporting freight out of the Amsterdam International Airport to a suburban warehouse [4]. Liu and his associates have examined the use of electromagnetic pumps for capsule pipelines [5-7]. Fujisawa et al. have constructed and tested a prototype pipeline transportation system powered by linear synchronous motors [8, 9]. Recently, Zhao, Lundgren & Sampson reported results of analysis on electrical capsule pipeline systems [10]. This paper presents key results from that report.

AERODYNAMIC ADVANTAGES OF ELECTRICAL PROPULSION

In a pneumatic system, simply stated, a pump/blower raises the pressure on one end of the tube and blows the capsules through the tube. Under ideal operating conditions the capsules are moving at the same speed as the pumped air and there is no aerodynamic drag on the capsules. The pressure difference required across the ends of the tube is the same as required to pump air at that speed, namely

$$\Delta\rho A_T = \tfrac{1}{2}\rho V^2 2\pi R_T C_f \tag{1}$$

where Δp is the pressure difference, A_T is the tube area, ρ is the density of the air, V the capsule speed, R_T and L_P the pipetube radius and length and C_f is a friction coefficient. The power required is

$$P_{pn} = \tfrac{1}{2}\rho V^3 2\pi R_T C_f \tag{2}$$

This is independent of the number of capsules in the tube. This formula neglects rolling friction, which would require an additional pressure drop across each capsule to overcome this friction, and a consequent air speed in the tube which is greater than the capsule speed.

In an electrical pipeline system, each capsule is individually driven by the motor force and is resisted by aerodynamic drag. In a tube, which is open to the atmosphere at both ends, the moving capsules force part of the air to pass through the gap between the capsule and the tube wall and also force some air to flow through the tube. The balance between these effects is determined by the size of the gap. If the gap is very small more air is pushed through the tube. In this sense the linear electric motor takes the place of the pump in the pneumatic system. The pressure distribution in the tube, proceeding in the direction of motion, consists of pressure increases along each capsule and pressure drops between the capsules because of the air friction with the tube walls.

The force on a single capsule is given by

$$\tfrac{1}{2}\rho(V-w)^2 AC_D \tag{3}$$

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It may be shown that

$$V - w = \frac{V}{(1 + \phi)} \qquad (4)$$

where

$$\phi = \sqrt{\frac{\beta R_T n C_D}{2 L_P C_f}} \qquad (5)$$

Here n is the number of capsules in the tube and $\beta = A/A_T$ is the blockage ratio. The formula takes into account the frictional resistance of the pushed air which, depending on parameters, can offer less resistance than forcing the air through the gap.

The total power required to drive n capsules is

$$P_{li} = \tfrac{1}{2} \rho V^3 A n C_D / (1 + \phi)^2 \qquad (6)$$

and therefore the two power requirements may be compared by the efficiency ratio

$$\frac{P_{li}}{P_{pn}} = \frac{\phi^2}{(1 + \phi)^2} \qquad (7)$$

where ϕ is the relative friction parameter defined above. This ratio is always less than one. Under maximum traffic conditions (large n) it approaches one. However, when there are only a few capsules in the tube, it becomes much smaller than one. This is because the pneumatic blower has to maintain the same power independently of the number of capsules, in order to keep the speed up. One may therefore conclude that the linear electrical system is always the more efficient, and can be much more efficient when the traffic is light.

CONCEPTUAL DESIGN
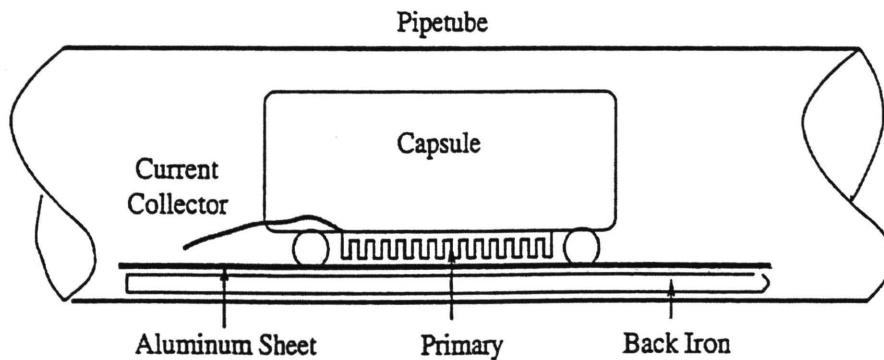
Figure 2. A Moving Primary Linear Induction Motor System

The best pipeline configuration depends on the requirements of a specific application. For capsules operating with speeds less than 200 miles per hour, a wheel-on-rail configuration can be used. Reference 10 lists several possible design configurations that use either linear induction motors or linear synchronous motors, and compares these configurations in terms of initial development cost, system operating efficiency, maintenance cost, ac supply requirement, capsule speed control requirement, requirements on capsule-ground communications, and future expandability. A moving primary linear induction motor system, as shown in Figure 2, is selected for medium to long range transportation. This moving primary LIM concept is the basis of the Japanese HSST 03 system, the maglev transit link in Birmingham, and the transit system in Vancouver [11].

In this system, three-phase primary windings are mounted on capsules, whereas secondary metal sheet and ground ac supply are placed on the pipeline (passive guideway). Power supply to the moving capsule is from a variable-frequency converter, which receives electricity from the ground via a current collector. The variable-frequency converter, together with an on-board radar unit, capsule speed detector, and computer, serves as the capsule speed control unit. On-board radar can detect the relative distance between one capsule and the capsule ahead, and speed control can be adjusted automatically to avoid collisions with the capsule ahead. A desired steady-state operating speed can be pre-set in the on-board computer, before the capsule is injected into the pipeline. If the system contains many capsules distributed over a range inside a pipeline, each capsule can control its own speed. A close spacing can be achieved to take advantage of the drafting effect without physical chains, so that each capsule has the freedom to head for different destinations when necessary.

Capsule design needs to consider capsule interior, exterior, door, capsule speed control, and emergency strategies. In a pneumatic pipeline system, capsules are moved by drag forces created by blowers [12]. In an electrical pipeline system, on the other hand, capsules are moved by electric propulsion and capsule drag becomes a resistance to capsule motion. Therefore, it is important to minimize aerodynamic drag in capsule design. Figure 3 shows a candidate capsule design with a square cross section [10]. The same reference also contains a candidate pipetube design.
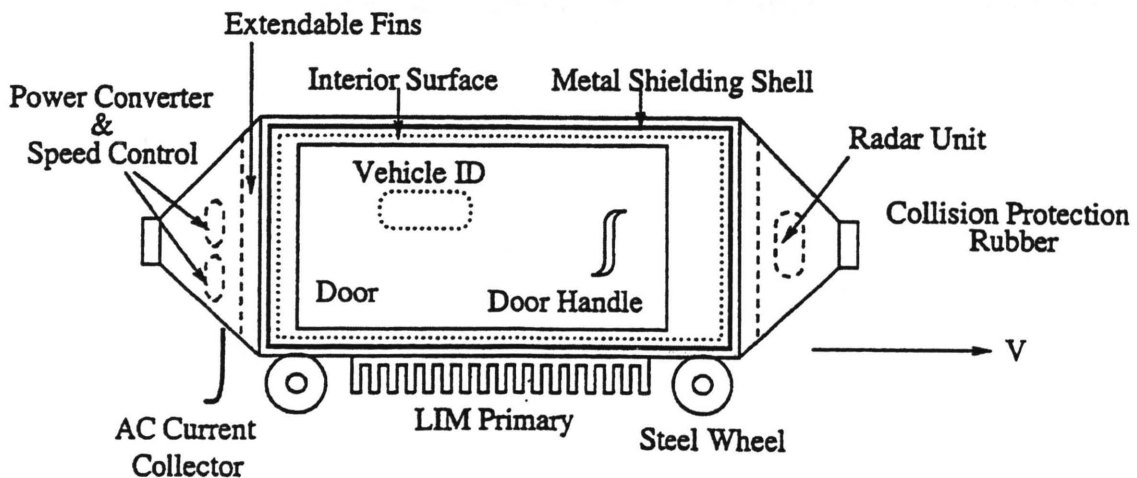
Figure 3. A Candidate Capsule Design: Side View

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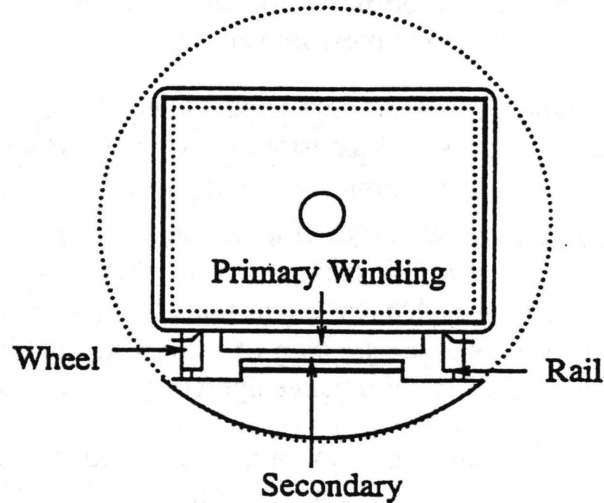
Figure 4. Candidate Capsule Design: Rear View

EQUATIONS AND OPERATING COST

We consider a two-bore freight pipeline system consisting of parallel tubes, connected at regular intervals by pressure relief tunnels (Figure 5). These tunnels can be opened up to external environment as vents or just adits. The moving capsules cause flow in the tubes and through the adits. The part of pipeline between two adits is called a section.

To obtain a set of tractabile equations of motion, it is assumed that the flow inside the pipetube is incompressible turbulent flow, the capsule length is short compared to the distance between adits (or section length), and adits are ideal and without headloss.
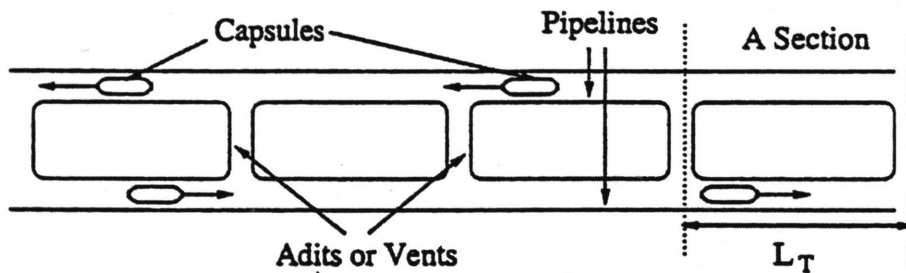
Figure 5. Layout of a Two-Bore Pipeline System

Let us assume there are N sections (or N − 1 adits or vents) in the two-bore pipeline, N_{cr} capsules in the right bore, and N_{cl} capsules in the left bore. Equation variables for a pipeline system include capsule velocities, velocities of fluid flows in the pipeline, and pressure variables. There are a total of $(2N + N_{cr} + N_{cl}) + (N + 1)$ variables. To solve for these variables, the same number of differential and/or algebraic equations are derived, and appropriate initial conditions are identified. Detailed equations are derived in [10]. This set of equations is strongly coupled since the drag force on a capsule depends on the flow velocity for the section and bore it is in,

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and the flow velocity in turn depends on the velocities of all the capsules in the system. In addition, there is also coupling through the pressure variables.

Before numerical simulations can be conducted, as set of system design parameters need to be specified. These parameters include dimensions of pipeline system and capsules: blockage ratio β, pipetube interior cross-sectional area $A_T = \pi R_T^2$, total pipeline length L_P, number of sections N which in turn determines the length of a section $L_T = L_P/N$, pipeline grade geometry $\phi(x)$, capsule length l, capsule hydraulic diameter d so that $A = \beta A_T$. In addition, some parameters are needed to specify the physical environment of pipeline operations, such as air density ρ, kinemataic viscosity v, and acceleration of gravity g. Finally, models of LIM thrust force F and normal force F_N as functions of pipeline operating conditions are needed [10].

Total cost of a pipeline system consists of initial construction cost, maintenance cost, and operating cost. A measure of operating cost can be defined as the amount of electrical energy required to transport one unit of payload over one unit of distance. Mathematically,

$$\mu = \frac{1}{M_p g L} \int_o^{t_f} P_{in} dt = \frac{1}{M_p g} \frac{\int_o^{t_f} P_{out}/\eta_e dt}{\int_o^{t_f} V dt} = \frac{1}{M_p g L} \int_o^{t_f} FV/\eta_e dt \qquad (8)$$

where t_f is the amount of time required to travel over distance L, η_e is the efficiency of the linear electric motor, and the LIM output power is $P_{out} = FV$. This expression can be simplified for steady-state operation, in which both V and F are constant.

SYSTEM OPERATION DESIGN

Under optimum steady-state operating conditions, there is an equal number of capsules moving in each bore; each with the same load velocity and with the same spacing between them. Under such "design conditions" there are the same number of capsules in each bore section. In Ref. 10, methods of steady-state capsule speed design and sizing of linear induction motors are presented. Details are omitted for simplicity. In the following, we have adopted a Vandersteel's model [13] which has a 2m diameter tube carrying 10-ton capsules (of which 8 tons are payload), propelled at 25 m/s. At these design conditions, a 2 sec headway would give a continuous freight rate of 4 tons/sec, or 100 million tons per year, which is about 10 times the annual truck freight tonnage carried between Minneapolis and Chicago, but is not an unreasonable rate for some heavily used corridors. Table 1 summarizes the base line operation design parameters.

CONTROL OF CAPSULE SPEED AND POSITION

Capsules are designed to operate at a certain speed. However, actual systems always differ from models that are used in system design and analysis. In an actual system, a capsule's operating speed is determined by the balance of its linear induction motor thrust force, aerodynamic drag, rolling friction, weight thus pipeline grade, and miscellaneous forces on the capsule. This speed, called an equilibrium speed of the capsule differs from the designed capsule speed due to modeling uncertainties and disturbances. It also differs from capsule to capsule, because different capsules have different payloads, and experience different aerodynamic drags

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and rolling frictions. It is desirable that the equilibrium speed is close to the design speed for a capsule.

Table 1. Baseline Pipeline Design Parameters

$R_T = 1$ m	interior radius of the pipetube
$\theta_d = 0$	pipeline average grade
$V_d = 25$ m/s	steady state capsule speed
$l = 3$ m	capsule length
$d = 1.25$ m	capsule hydraulic diameter
$\beta = A/A_T = 0.5$	blockage ratio
$1/q_d = 2$ sec	capsule headway times
$M_d = 10$ tons $= 9071.8$ kg	capsule weight
$M_p = 8$ tons $= 7257.4$ kg	capsule payload
$L_T = 250$ m	section length
$L_P = 20$ km	total pipeline length
$N = 80$	number of sections (adits)
$V_d/q_d -= 50$ m	spatial headway
$N_{cl} = N_{cr} = 400$	number of capsules in each bore
$N_c/N = 5$	number of capsules in each section

In operation, an individual capsule can maintain its speed in a certain range around the equilibrium speed without active feedback control. This is due to the nature of linear induction motor force. An increase in capsule speed results in a decrease in motor thrust and vice versa. On the other hand, capsule positions in the pipetube are expected to deviate from the position histories corresponding to the equilibrium speed. This is because positions are integrations of capsule speed, and deviations of capsule speeds from the designed value can cause a finite change in capsule position from designed time history. These deviations will cause the relative distance between any pair of capsules to increase or decrease gradually over time. Because of the low pressure region behind each capsule, a capsule approaching from behind will be sucked into the wake region of the lead capsule if the relative separation becomes sufficiently small.

To control a capsule speed or position to a prescribed value, a feedback control logic can be used that reduces the linear motor thrust force if the actual speed is larger than the desired speed, and increase the linear motor thrust force otherwise. A feedback control law determines how fast and how much the motor thrust force is changed. The capsule motion system is a nonlinear dynamical system with fairly large ranges of speed change. As a result, **nonlinear** feedback control laws must be used. Details of feedback control laws are reported in Ref. 10.

COMPUTER SIMULATION STUDIES

A comprehensive computer program is coded using C language to simulate pipeline operations. This computer program essentially solves the differential/algebraic equations developed above. A major challenge to the development of this simulation program is that capsules must be allowed to enter and/or leave the pipeline system with **arbitrary** schedules. As a result, the number of capsules in the pipeline system and thus the number of solution variables can change from time to time. In numerical implementations, a set of logics has to be devised

that can detect when a new capsule enters into the pipeline system, and when a capsule exits the system. An array of variable dimensions is implemented with dynamic memory allocations.

In [10], numerical simulations are used to compare the efficiencies of different pipeline system configurations such as adits and vents under off-design conditions. The relative merits of intermittent versus platoon operations under off-design conditions are also compared. Key results are now summarized below. For these results, the insertion of new capsules into the system was done by a simple freight periodicity condition for convenience.
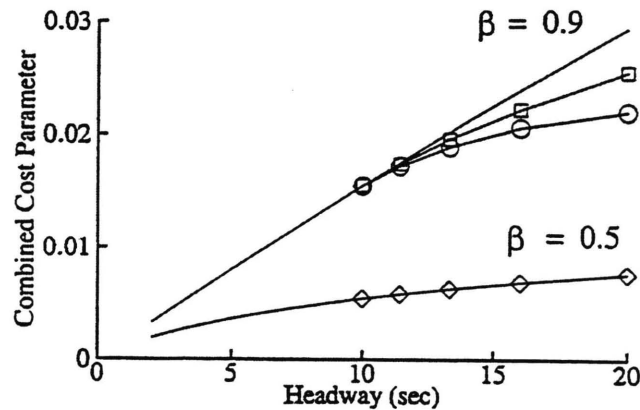
Figure 6. Cost Parameter vs. Headway

Note: Circle for Vents, Square for Adits, Diamond for Both, Solid Line for Without Adits or Vents

Figure 6 compares the cost of transporting the standard 10-ton capsules, with 8-ton payloads, for configurations without adits, with adits or vents. It is assumed for intermittent operation that capsules are evenly spaced but the headway between the capsules is greater than the 2-second design value. It is also assumed that the motor force is available to keep the speed of each capsule at 25 m/s. In Figure 6, the combined cost parameter $\mu \cdot \eta_e$ is plotted versus headway time for the range 2 seconds to 20 seconds, i.e., the tonnage rate varies from 4 ton/sec on the left side of the figure to .4 ton/sec on the right. For $\beta = .9$ the cost increases by a factor of 9 over this range, while for $\beta = .5$ it increases by a more moderate factor of 4. At the higher blockage value the cost increases almost linearly with headway time, most of the resistance coming from air friction in the linearly lengthening distance between capsules. With the use of adits or vents, any headway increase does not affect the cost as long as there is at least one capsule in each adit section. That is, there is no effect up to a headway time of 10 sec, and this is also the case if there is no traffic in the other tube; at longer headway we begin to see an effect. The results for adits are disappointing. For $\beta = .5$ there is no effect over the range shown, while for $\beta - .9$ there is only a small improvement. When the capsules are spaced out like this there is only a small opportunity for air to be shunted through the other tube. For simple lossless vents to the atmosphere, at the same spacing as for the adits, the results are somewhat better for the larger blockage, but still have no effect for $\beta = .5$.

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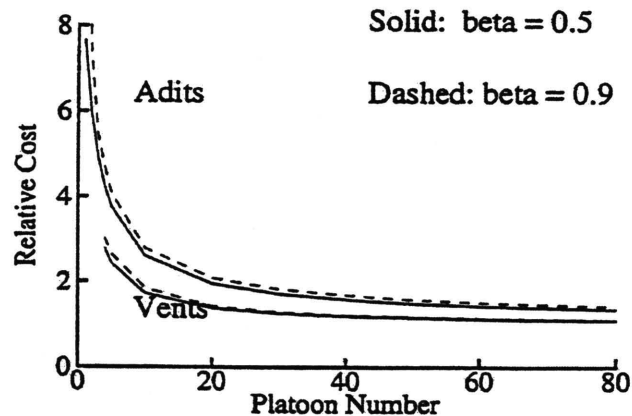
Figure 7. Relative Cost vs. Platoon Number

In Figure 7, we consider platoons of from one to 80 capsules, with 25 m/s speed and 2 sec headway in a 20 km pipeline with 250 m between adits or vents. The other tube is empty. The results are shown in Figure 7 as relative cost versus platoon length for $\beta = .5$ and $\beta = .9$. Relative cost is the cost divided by the cost under design conditions. If the platoon length were increased to 400 for this pipeline, the relative cost would be one. If the capsules in a 40-capsule platoon were spaced out evenly they would have headway of 20 seconds; the situation would be the same as the right hand side of Figure 6. The advantage of platoon operation over intermittent operation is clear from these figures. The physical reason is that with a platoon, it is not necessary to pump air through the entire tube; the adits work as intended, circulating the air through the other tube. Vents work even better. Vents are preferred from a heat circulation point of view. It is interesting that the *relative* results are almost independent of blockage.

The forces required to keep all the capsules moving at the design speed are much larger for the lead capsule in a platoon, which must accelerate the air as they enter a new adit section, thus providing drafting for the following capsules. For $\beta = .5$ the (time average) force on the lead capsule in a long platoon is about 3.5 times average force; for $\beta = .9$ it is about 5.5 times the average. This requirement can be handled in one of two ways. Sufficient reserve forces can be designed into each capsule. Alternatively, a special "lead capsule" can be designed that has a larger LIM thrust force capability than other follower capsules.

CONCLUSIONS

There is an intrinsic advantage, in terms of energy use, of electrical capsule pipeline systems over pneumatically propelled systems if the capsules have moderate blockage, since some of the air set in motion by the capsules can pass over the capsules. For a blockage of .5, which can be achieved without making the tube larger by using capsules of square section, the aerodynamic cost is about half that for pneumocapsules.

Preliminary designs are conducted for electrical capsule pipeline systems with moving primaries mounted on capsules. Potential cost problems arise when the system is not operating at full capacity; the aerodynamic cost per ton-mi would be 4 to 9 times the optimum if the traffic

were at 10% of capacity. This situation is much improved if the tubes are connected by adits or are vented, provided the traffic management strategy is to run platoons of capsules at the design headway, followed by long intervals with no traffic. The advantage comes from circulating the driven air through the other tube, or diverting it to atmosphere, eliminating the necessity of pushing it at high speed all the way through the tubes.

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The Technical and Economic Feasibility of Tube Freight Transportation Systems

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ABSTRACT

Periodically the United States Department of Transportation (DOT) assesses the feasibility of "new" transportation system concepts. Tube freight transportation systems (also referred to as capsule freight pipelines) have been the subject of at least two DOT studies in the last twenty-five years. The last study [1], completed in 1994, is the basis for this paper. This study was sponsored by the Federal Highway Administration as a part of its assessment of future freight transportation requirements and was prepared in response to a congressional request in the ISTEA legislation. The Volpe National Transportation Systems Center performed the study. This paper examines current tube freight transportation proposals and discusses their general economic and technical feasibility.

Since World War II a number of tube freight systems have been built and operated in regular service. In addition a number of systems have been proposed, particularly for general merchandise movement. This paper surveys the range of these proposals with emphasis on proposals in the United States. A quick review is also made of foreign activities known to DOT.

This study concludes that tube freight transportation systems are technically feasible based on almost two hundred years of prototypes and operational systems. The early systems were almost all based on the use of pneumatic propulsion, which is still in use today. Some recent proposals anticipate use of linear induction motors for propulsion [2-5]. Although design and limited development will be required for any specific application, there appear to be no fundamental technological barriers to the introduction of the proposals which have been made known to DOT.

With respect to economic feasibility, the study concludes that in spite of some favorable general analyses of economic feasibility based on many assumptions, economic feasibility can only be estimated in a convincing manner for a specific technology operating over defined routes. This recognizes that economic feasibility is sensitive to tunneling costs and to the likely demand for the service, both of which are highly site specific. Therefore, economic feasibility remains to be estimated in detail and subsequently demonstrated.

INTRODUCTION

The U.S. DOT's Federal Highway Administration, with the support of the Volpe National Transportation Systems Center is examining the technical and economic feasibility of tube transportation as an alternative to increasing capacity for long-haul trucking on the nation's highways. Tube transportation is a class of transportation systems in which close fitting capsules or trains of capsules move through tubes between terminals. Pneumatics is a consideration in such systems even if they are not pneumatically powered. All historic systems were pneumatically

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powered and were often referred to as pneumatic capsule pipelines. Recently it has been proposed that such systems might be more productive if powered by another means; use of linear induction motors is one recommendation.

Tube transportation systems have a number of attractive features which make them worthy of evaluation as alternatives for increasing national long-haul freight capacity. Such systems are, and always have been inherently automated; they are, as a result, more productive than trucking and railroading. Because they are enclosed, they are unaffected by weather and not subject to most common rail and highway accidents. The tubes can be placed above or below ground. Underground locations are useful in environmentally sensitive areas and are important where surface congestion makes surface right-of-way difficult and/or expensive to obtain. All modern, proposed systems are electrically powered: thus, they are not a direct source of air pollution. Their energy efficiency appears to be better than trucking and comparable to railroads.

Tube transportation, formerly referred to as pneumatic tube systems or pneumatic capsule pipelines (as they were universally pneumatically powered), have been providing reliable freight transportation around the world for over 150 years. Some systems have operated for over 75 years in essentially continuous use. Common applications before World War II were in the high priority movement of documents and parts in industrial environments and movement of letters and telegrams under city streets to bypass congestion. These systems were built with tubes ranging from 2 to 8 inches in diameter. Such systems are still being built today to expedite small shipments.

After World War II larger pneumatic systems were developed and built in Japan [6] and Russia [7] to move bulk materials such as limestone and garbage. These systems had considerably greater throughput as a result of both their increased diameter (3 to 4 feet) and their mode of operation which allowed more capsules to be moving through the tube at one time. By the early 1970's several groups began to give consideration to the use of these pipeline designs for common carrier, general merchandise freight applications using tubes 4 to 6 feet in diameter.

CURRENT PROPOSALS

By 2015, surface transportation is expected to grow beyond current traffic levels with significant constraints on construction of new capacity. New transportation routes are likely to be difficult to obtain to accommodate this traffic increase. Thus, emphasis will be placed on increasing the capacity of existing facilities and construction of new facilities on/under existing transportation rights-of-way. Any new facilities will likely be required to have increased safety and minimal environmental impact. For expansion of surface freight, some have recommended construction of "pipeline" type new facilities on existing highway or other rights-of-way. The essential concepts are:
1. Freight facilities using highway or other rights-of-way (primarily underground).
2. Completely automated operation. No personnel on board vehicles.
3. Electric power.
4. Complete grade separation.
5. Very high reliability service.

These concepts, in addition to expanding national freight capacity, claim the following benefits:

1. Increased safety due to substantial removal of long-haul trucks from the highways

2. Reduced emissions from trucks.

3. Reduced wear and tear on existing highways and bridges resulting in lower maintenance costs.

4. Potential savings of operating cost due to automation.

5. Higher reliability than existing alternatives.

6. Very high productivity.

7. Lower energy costs.

8. Increased control over delivery schedules.

No standard definitions of "tube transportation" or "pneumatic powered transportation" appear in the literature. For the purposes of this study we have adopted the following definitions:

TUBE TRANSPORTATION is a class of transportation systems for passengers or freight in which vehicles (or capsules) are propelled through essentially continuous tubes between terminals. TUBE TRANSPORTATION is differentiated from other transportation systems using tunnels by the use of vehicles which are a close fit in the tubes. Pneumatic considerations are important in these systems even if they are not directly propelled by differential air pressure.

PNEUMATIC POWERED TRANSPORTATION is any transportation system which uses differential air pressure to power its vehicles . The vehicles can be self-powered or passive. All historic tube transportation systems were pneumatic powered in that they used passive vehicles propelled through tubes by differential air pressure. The International Freight Pipeline Society refers to these systems as pneumatic capsule pipelines. Other pneumatically powered systems were not tube transportation systems. Examples of the latter include compressed air powered locomotives used by common carrier railroads and mining concerns and the atmospheric railways built in the nineteenth century which were pulled by a piston operating in a tube (generally around 15 inches in diameter) placed between the running rails.

It should be noted that the preceding definitions explicitly do not include the much broader range of pipeline systems which supply "transportation" in the broad sense. There are many examples. Oil and gas pipelines in many cases provide interstate transportation. Coal and other slurry pipelines often operate over extended distances. Water and sewer systems transport their commodities. Air pressure is used to load, unload and move such bulk commodities as grain and cement through pipes. Also excluded from this discussion are hydro capsule pipelines which have been proposed. These pipelines would use water or another fluid to propel the capsules through the pipe.

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Worldwide, several groups are proposing common carrier tube transportation systems at this time including:

- SUBTRANS, a freight pipeline concept developed by Mr. William Vandersteel of North Bergen, New Jersey would ultimately provide a national system for transportation of general merchandise. He has prior experience with the TUBEXPRESS system developed by Transco Corporation of Houston Texas, a pneumatic system for dedicated movement of bulk commodities in special markets. Vandersteel currently owns 50% of the TUBEXPRESS Corporation.

- A proposal similar to SUBTRANS was made by the British Hydro-mechanics Research Association (BHRA) in the early 1970's for a British national tube transportation system for general commodity freight. The only major difference from the SUBTRANS proposal was that the British proposed to use pneumatic propulsion. Although the British are no longer actively promoting this technology we assume they, as well as others who are still active in the field remain interested in general cargo applications. The Transport and Road Research Laboratory also participated in the development of this concept.

- Mr. W. H. Chapman, a consultant from El Paso, Texas has recently proposed to the Secretary of Transportation that a pneumatic tube transportation system for general merchandise be built between El Paso and Dallas Texas. Few specifics are available.

- The Swiss are evaluating a proposed cross-country, high-speed, maglev, tube transportation system for passengers. In this case the tube is evacuated to minimize air resistance.

- NASA has proposed "The New Millennium Transportation System" which includes a hyper-velocity tube transportation system for both passengers and freight. The hyper-velocity component would achieve approximately a travel time of 1 hour coast to coast. This system would use an evacuated tube similar to the Swiss proposal above.

- A proposal, for underground collection and distribution of freight in Tokyo, is significant because it shares some common features with the proposals above although it does not meet the definition of tube transportation adopted for this paper.

TECHNICAL FEASIBILITY

The purpose of this section is to demonstrate that tube transportation has a long history of successful applications in niche markets, a fact that is generally unfamiliar to the public.

Tube transportation has a history which extends back at least 200 years. During this period systems for both passengers and freight have been built and operated. Some are in operation today. In addition, there have been many more proposed systems which were never built. All of the historical tube transportation systems were pneumatically powered. A number of pneumatic systems were built which were not tube transportation systems as defined here. These systems are mentioned briefly here for completeness. Three sections follow. Large diameter systems, smaller diameter freight systems and non-tube transportation pneumatic systems (Atmospheric Railways).

George Medhurst, a London businessman, is considered the earliest proponent of pneumatic powered railways although there were a few earlier, brief suggestions from others. He first published a freight proposal in 1810, a passenger proposal in 1812 and a more comprehensive set of proposals in 1827. These included a suggested speed of 60 miles per hour (at a time when steam locomotives had not reached 30 miles per hour!) [8-10]. The latter proposals envisioned all three of the general categories to be discussed below.

LARGE DIAMETER PASSENGER/FREIGHT TUBE TRANSPORTATION SYSTEMS

There have been many proposals for large diameter tube transportation systems (diameters ranging between about 6 feet and 15 feet). Medhurst proposed a rectangular tube 6 feet high by 5 feet wide for a passenger system in 1812. Generally the large tube systems were "large" to accommodate passengers. Carriage of freight was usually incidental to the basic proposal [8].

Only four demonstration systems are known to have been built and operated in passenger carrying service. In 1826-1827 John Vallance built in Brighton, England a 150-ft long, nearly 8-ft diameter tube in which he operated a 20-passenger vehicle. The 22-ft long vehicle was propelled through the tube at 2 miles-per-hour by air pressure from two steam driven pumps. The carriage ran on rails in the tube and was steadied by lateral wheels [9].

The second system was built in London for the Crystal Palace Exposition and placed in operation in August, 1864. This 1800-ft long line used a relatively standard, broad gauge railway carriage with a capacity of 35 passengers. The carriage ran in a brick arch tube roughly 10 feet by 9 feet. The carriage was moved in one direction by the pressure from a 22-ft diameter, steam driven fan. For the return run the fan was reversed creating a slight vacuum in the tube, so that atmospheric pressure propelled the carriage. The system operated successfully for 2 years. The line included several curves and a grade of 1 in 15. As a result of this demonstration, a number of proposals were made for application of the technology to transportation needs. One proposed application, the Waterloo and Whitehall Railway Co., actually began construction of a half mile crossing of the Thames River in 1865. This railway was privately financed. The river crossing was to be by 12-ft long, 9-inch wide (inside diameter) iron tubes sunk and covered in an excavated trench in the river bottom. Even though three of the 221-ft tube sections had been constructed, the financial panic of 1866 stopped all construction and it was never resumed. This project was the closest the Crystal Palace technology came to a real transportation application.

Pneumatically powered systems are clearly feasible because they have been built and operated in the past, although not in general merchandise service. Although the largest system built to date has a diameter of about 4 feet, we see no technical problems in scaling such systems to a 6-ft diameter. Linear induction motor powered systems are also technically feasible although such systems have not been demonstrated or, in fact, designed in detail as yet. These systems are not off-the-shelf: They will require specific designs for specific applications. Also better definition of cost and performance is required for a number of system elements to improve the reliability of economic estimates. More detailed conceptual designs for linear motors, switching mechanisms and terminals are examples.

ECONOMIC FEASIBILITY

The economic feasibility of tube transportation systems carrying general merchandise is unknown at this time as no such system has been built and operated in revenue service. A study of the economics of tube transportation performed in the later 1970's sponsored by the U.S. Department of Transportation indicates tube transportation may be competitive with long-haul truck and some railroad operations. This study by the University of Pennsylvania was performed without detailed tube designs and associated cost data. Such data for currently proposed tube transportation concepts is also lacking as noted above. As a result, engineering development studies and concept demonstrations are needed to provide refined estimates of the system economics. Cost estimates need to be made for specific routes since a major part of the capital requirement covers tunneling costs which are highly variable and site specific. Port or urban core access corridor lines appear to be likely candidates for study where high land values and surface congestion would enhance the value of the tube transportation approach. Package delivery firms, less-than-truckload trucking firms and the U.S. Post Office are also candidates for such a system [4].

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Review of Past and Current Research and Use of Capsule Pipelines in Japan

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ABSTRACT

In the initial stage of capsule pipeline research the drag coefficient and the pressure drop were experimentally and theoretically studied for concentric and eccentric capsules held stationary in the pipe. In the early 1970's industries started applied research to establish the design method for a large-scale system, gathering the necessary data. In 1977, the first large-scale pneumatic system was introduced in a steelworks to transport burnt lime 20,000t per month over 1.5km by using 609.6mm diameter pipeline. Later on there appeared a demand for exactly predicting the capsule motion to hydrodynamically control the motion near the destination. Various feasibility studies and investigations have been performed on the capsule pipelines. To hoist manganese nodules from a deep sea, basic research was started on the motion of capsule in an air lift pipe. A tube transport system using a linear motor has been also investigated. As a new application of hydraulic capsule, research has been carried out on the transport of spherical ice capsules as a transport medium for a heat storage system.

INTRODUCTION

One of the authors (K.Y.-M.) reported on capsule pipeline research in Japan at the 4th International Symposium on Freight Pipelines in 1982 [1]. In the present paper we review the same topic for work extending over a period of 30 years. Pneumatic capsule pipelines have been used to transport documents in buildings for a long time. However, the role of information in hard copy form, has been gradually replaced by electronic communication. The remaining and emerging roles are transport of sample material in works, commodities in buildings and a large-scale transport of bulk materials. The merit of capsule pipelines is isolation of transport from the environment. Thus, the environment is not affected by the transport and *vice versa*. Furthermore, since the transported material is contained in the capsules, the degradation of materials is minimized. The principle of capsule pipeline is old. Although there were various problems in design of a large-scale system, it was not practical to restrict this conventional practice to small-scale pipelines. To solve these problems much research has been carried out in various fields. This paper reviews the basic research related to capsule motion in a pipeline and then describes the practical use of pneumatic capsule pipelines.

FLUID FORCE ON THE CAPSULE

When fluid is the driving medium of the capsule the effective use of fluid force is important; but when the capsule is driven by other means, the fluid in the pipeline is generally obstructive. In either case, however, the precise estimation of fluid force on the capsule is important. The fluid force to drive the capsule (fluid drag) F generally consists of pressure and shear forces, and is characterized by the drag coefficient C_D as

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important. The fluid force to drive the capsule (fluid drag) F generally consists of pressure and shear forces, and is characterized by the drag coefficient C_D as

$$C_D = \frac{F}{1/2 \rho v_o^2 A_c}$$

(1)

where ρ represents the fluid density, v_o the fluid velocity relative to the capsule and A_c the cross-sectional area of the capsule.

Yanaida [2, 3] derives the drag coefficient for cylindrical capsule held concentrically in the pipeline based on the boundary layer theory as

$$C_{df} = 1.628 - (1-k^2)^2 + 0.6225\left(\frac{1}{k} - 1\right) + \frac{96l/d}{\left(1/k - 1\right)^2 Re}$$

(2)

for laminar flow of Re $(l/d) < 5 \times 10^5$ and

$$C_{df} = 1.013 - (1-k^2)^2 + 0.293\left(\frac{1}{k} - 1\right) + \frac{0.322l/d}{(1/k - 1)^{5/4} Re^{1/4}}$$

(3)

for turbulent flow. In these equations, l represents the capsule length, $k = d/D$, d the capsule diameter, D the pipe inside diameter, $Re = v_{mf}d/v$, $C_{df} = C_D (1-k^2)^2$ and v_{mf} the mean fluid velocity relative to the capsule in the annulus. Figure 1 shows his correlation of drag coefficient, which includes the experimental results. In the figure, s is the density ratio of capsule to fluid.
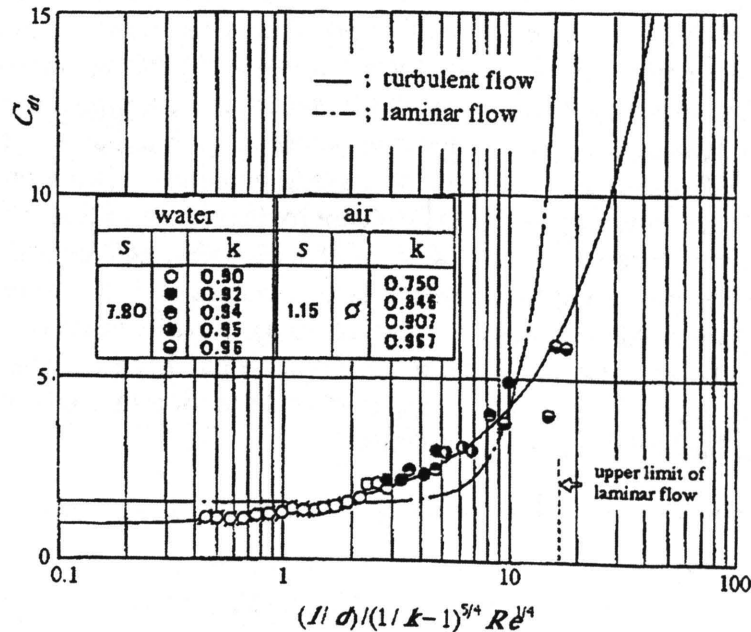
Figure 1. Drag coefficient versus characteristic number.

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Tsuji *et al.* [4] also derives the drag coefficient for the concentric cylindrical capsule as

$$C_D = \frac{1 + \zeta_r + 4\lambda_p \, (l/d)/(1-k)}{(1-k^2)^2} \qquad (4)$$

where

$$\lambda_p = \frac{0.0376}{Re_{an}^{1/6}}, \quad Re_{an} = \frac{v_o D}{2(1+k)} \qquad (5)$$

and ζ_r the loss coefficient for abrupt contraction due to the capsule. They [5] also give the drag coefficient for the cylindrical wheeled capsule with end plates.

Hisamitsu *et al.* [6] measured the drag coefficient for various wheeled capsules with end plates and obtained the following convenient equation

$$C_D = \left(\frac{2k_s^2}{1-k_s^2} \right)^2 \qquad (6)$$

where k_s is the square root of area ratio between the end plate and the pipe.

Ohashi and Yanaida [7] show that since in the equilibrium state of capsule motion, the fluid drag becomes equal to the retarding force on the capsule C_D in the horizontal pipeline is expressed as

$$C_D = 2fk(l/d) \, (s-1) \, Fr^{-2} \qquad (7)$$

where Fr is the Froude number defined by $v_o/\sqrt{gD}$ and f is the sliding friction factor of the capsule.
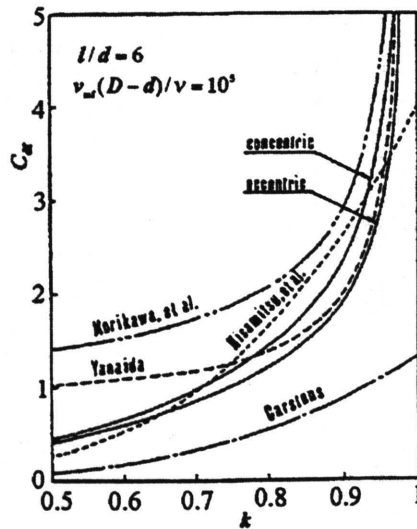
Figure 2. Drag coefficients.

PRESSURE DROP DUE TO THE CAPSULE

Fluid flow dissipates the energy when driving the capsule. The energy loss due to the capsule per unit fluid volume is expressed as the pressure loss due to the capsule Δp and is characterized by the pressure loss coefficient ζ_c which is defined by

$$\zeta_c = \frac{\Delta p}{1/2 \rho v_o^2} \tag{8}$$

Since there is pressure recovery when the fluid emerges from the capsule, C_D is slightly larger than ζ_c. However, C_D is usually substituted by ζ_c. The pressure loss due to the capsule consists of the friction loss, abrupt contraction loss and abrupt expansion loss. It is known that the friction loss of eccentric capsule is smaller than that of concentric one. Tachibana and Matsumoto [8] and Ohashi and Yanaida [9] studied the pressure loss due to the concentric and eccentric capsules and give the correlation equations of pressure loss for both capsules. Figure 2 shows the drag coefficient by several researchers.

Ohashi and Yanaida [7] divide the total pressure drop due to the capsule pipeline into the one due to the fluid flow alone Δp_o and the one due to the capsule Δp_c, and they propose the following correlation for Δp_c after the Durand correlation for a liquid-solid two phase flow:

$$\phi_c = \phi_c (\psi_c) \tag{8}$$

where

$$\phi_c = \Delta p_c / k^2 \Delta p_o, \quad \psi_c = F_r \sqrt{2fk(l/d)/(s-1)} \tag{9}$$

Figures 3 shows experimental result by this correlation.
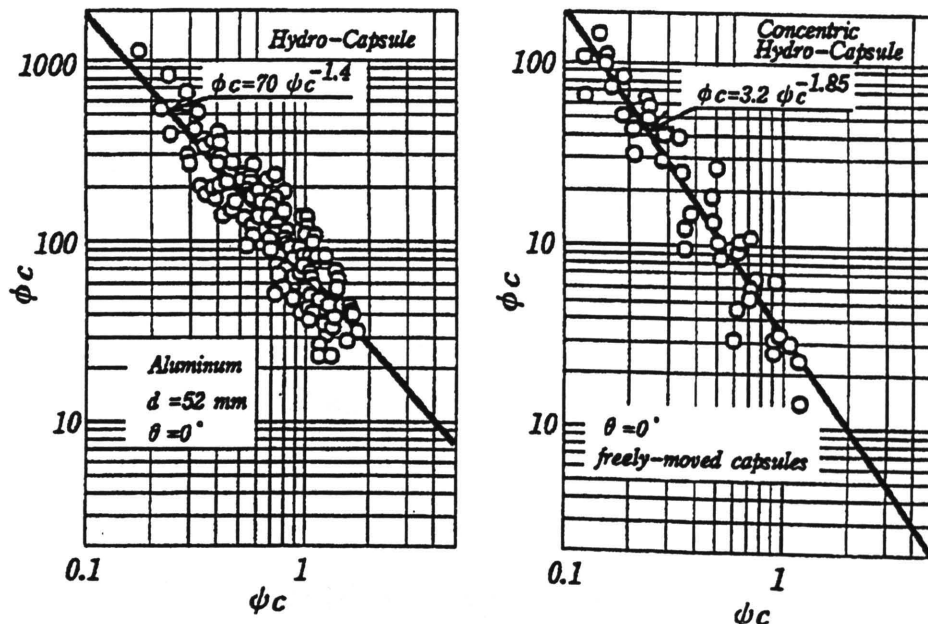
Figure 3. Correlation of pressure drop.

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Fujiwara *et al.* tried to reduce the pressure drop in a hydraulic capsule pipeline by adding a small amount of polymer (See Figure 4) to water flow [10] and by carving helical ribs on the capsule surface [11].
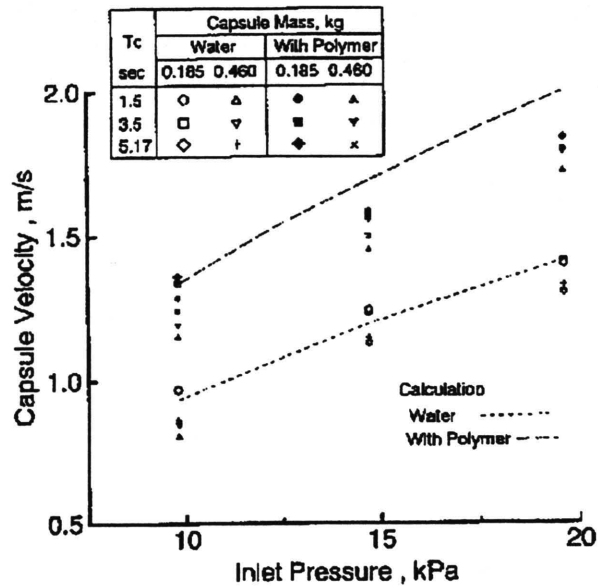
Figure 4. Effect of polymer additives

CAPSULE TRAJECTORY

It is important to stop the capsule slowly to prevent it from being destroyed by the collision with the stopper at the destination. For a soft landing the braking effect by air between the capsule and the stopper can be utilized. Collisions between capsules should also be avoided. Figure 5 shows the brake effect of air between wagons. If the capsule trajectory is known, the handling of capsules becomes easy. For this purpose many researchers have been studying the capsule motion in the pipeline.
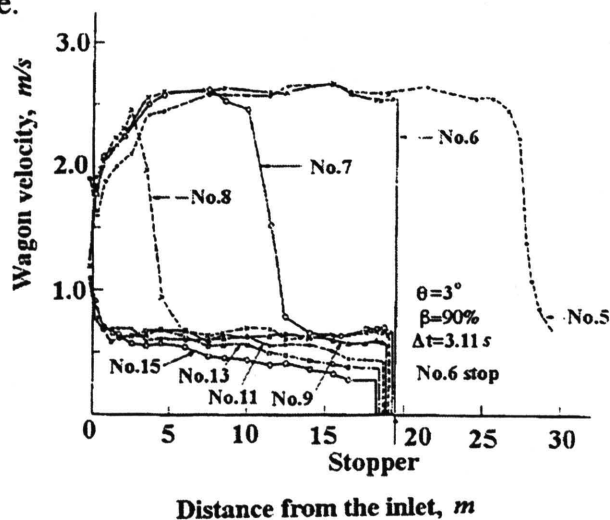
Figure 5 Brake effect of air between wagons.

Yamamoto [12] numerically examined a tube-freight-system in which wagons, which will be driven by a linear motor system, transport freight in a tube between cities like Tokyo and Osaka. His results show that the braking effect increases with increasing k and decreases with increasing wagon number. Furthermore, the braking effect is weak to control automatically the wagon intervals. Fukuchi et al. [13] proved the Yamamoto's analysis by the measurement that was done in a 100mm diameter inclined tube of 30m in length. Fifteen wagons were put into the pipeline. The wagon was driven by gravity.

Ohtaki [14] numerically studied a pneumatic capsule pipeline where capsules with different mass and end plate were put into the pipeline. The measurement taken in a 100mm diameter horizontal straight pipeline of 8m in length proved his numerical prediction. Tsuji et al. [5] and Chono et al. [15] carried out the numerical analysis and proved it by their detailed measurements.
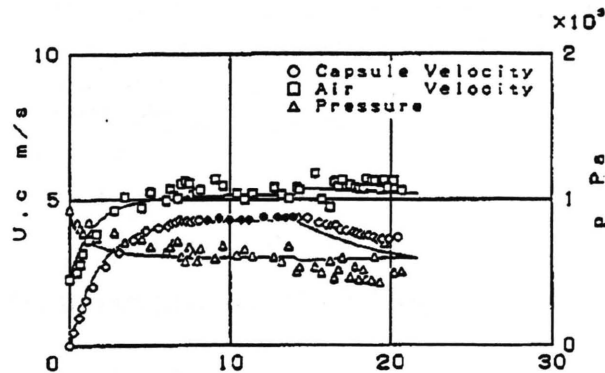
Figure 6. Capsule velocity control by changing the area of the end plate.

Abe et al. [16] introduced a new calculating method which was invented by Lurie [17]. He calculated the compressible unsteady gas flow by the method of characteristics. Thereafter, many calculations were reported by this method [18-23]. Ohba et al. [24] extended this method to include a shock wave. Tomita et al. [25-28] applied this method to a hydraulic capsule pipeline.

Tsuji et al. [29] show numerically and experimentally that in a pneumatic capsule pipeline the capsule motion can be controlled by changing the area of end plates (see Figure 6). Yanagisawa and Kosugi [30] studied the velocity control of capsule at the loading or unloading site by adjusting the valves at both ends so as to make the capsule move according to the reference velocity pattern (Figure 7). Fujiwara et al. [31] numerically show that the capsule velocity can be controlled by an air release valve placed on the pipeline (Figure 8).
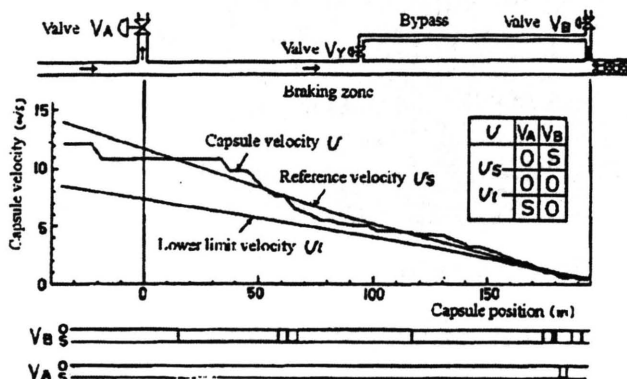
Figure 7. Control of capsule velocity by valves.
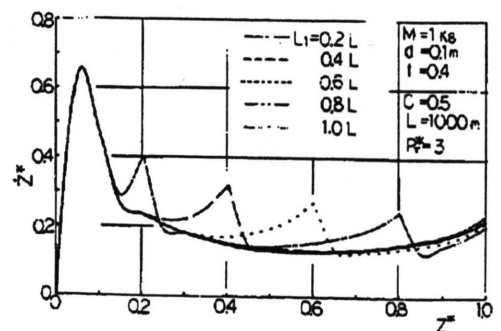
Figure 8. Effect of air release on the capsule velocity.

Tachibana [32] analyzed the incipient velocity and the power required at incipience in an inclined hydraulic pipeline.

PNEUMATIC CAPSULE PIPELINES

As a practical realization of pneumatic capsule pipelines, Japanese companies started research and development by introducing technology from the U.S.A. and former U.S.S.R. in the early to mid 1970's. They constructed a large-scale pilot plant up to a pipeline of 900mm in diameter and 1500m in length including upward and downward routes (up to 8°). They obtained running characteristics of capsule, developed the reliability and durability of the system on a prototype level, improved the control method and mechanism and proved heavy loading operation. They established the optimum property and size of the running wheel of capsule and structure of the wheel suspension system. They found that the reduction of noise and vibration could be realized by means of underground pipeline.

The first demonstrating pneumatic capsule pipeline was introduced into Nippon Steel's Muroran Works in 1977. The system was jointly developed by Nippon Steel Corporation and Daifuku Machinery Works Ltd. and was used to transport burnt lime. The main specifications of the system were:

(a) The transport material was a lump burnt lime of 10 to 30mm in size, of which bulk density was 1070kg/m³.

(b) The monthly transport volume was 14,000t and the monthly operating time was 500h. The maximum annual transport volume was 300,000t.

(c) The pipeline was 1.5km in length and with an inside diameter of 609.6mm and was laid on 7 to 8m in height above ground.

(d) The unit consisted of a two-capsule train and the dispatch intervals were 60s (45s in minimum). The unit transport volume was 500kg/train and the capsule running speed was 6 to 8m/s. The total mass of the unit was 1000kg/train.

(e) The air sources consisted of one unit of main blower of 75kW and each 6 units of auxiliary blowers of 2.2kW and 3.7kW, respectively.

The similar system but single track was employed for a cotton mill to transport bobbins and empty bobbins between two works. The main specifications were:

(a) The capacity was 37.5case/h.

(b) The pipeline was 230 m in length and with a width of 500mm and a height of 700mm.

(c) The unit was consisted of a three-capsule train and the dispatch intervals were 288s. The unit total transport volume was 200kg/train and the capsule running speed was 4.5m/s.

(d) The air source consisted of two units of blowers of 3.7kW.

In 1978, Mitsubishi Heavy Industries Ltd. installed a vacuum type of pneumatic capsule pipeline of single track for dry paint sludge. The main specifications were:

(a) The daily transport volume was 4800kg and the daily operating time was 8 h.

(b) The pipeline was 120m in length with a diameter of 600mm and was laid 8m above ground.

(c) The dispatch intervals were 6min and the capsule running speed was 1.5m/s. The carrying capacity of the capsule was 60kg.

(d) The air source consisted of a blower of 3.7kW.

In 1981 Sumitomo Cement Co., Sumitomo Steel Co., Kashima Civil & Construction Co. and Niigata Engineering Co. Ltd. jointly developed a pneumatic capsule pipeline system for transport of limestone. In 1983 the first commercial system was installed from Karasawa mine to Tochigi mill of the Sumitomo Cement Co., and the system is still in operation. The main specifications are:

(a) The transport material is limestone under 50mm in size, of which bulk density is 1600kg/m^3.

(b) The annual transport volume is 2,000,000 tonnes.

(c) The pipeline, which was laid on the remains of discontinued railroad line, is 3.2km in length and has an inside diameter of 998mm. The maximum gradient is 9.5%.

(d) The unit consists of a three-capsule train and the dispatch intervals are 50s. In the line 23 trains are used. The capsule running speed is 9m/s. The total mass of the unit was 16,000kg.

(e) The air source consists of two units of main blower of 800kW for loading and two units of main blower of 840kW for unloading.

Sumitomo Metal Industries found a new application to move drilled mud at the construction site of their tunnel. The capsule transported the mud over about 10km from the tunnel face (drilling site of the tunnel) to the dump yard. On the return trip concrete mix was fed to the empty capsule at the tunnel inlet and was transported to the face over 7km at the maximum. When the tunnel was completed and there was no longer a need for transportation, the transport system was removed. The main specifications were:

(a) The transport volume of the tunnel mud was 100m^3/h and that of the concrete mix was 40 m^3/h.

(b) The length of pipeline in the gallery was 7km in the maximum and that in the outside was about 3km. The section of the line was square with a side of 900mm. The gradient in the gallery was 3%.

(c) The unit consisted of a three-capsule train and the dispatch intervals are 120s. The capsule running speed is 7m/s. The total mass of the unit was 2,000kg.

(d) The rotary positive blower of 1360 m^3/h was used.

One of the authors (K.Y.-M.) joined the project to vertically hoist drilled mud from underground below 15m at the construction site. The planned specifications were:

(a) Transport volume is 7,500kg/h.

(b) The length of pipeline is 30m and the inside diameter is 1000mm.

(c) The dispatch intervals are 190s.

(d) The air flow rate is 280m^3/min, the pressure is 710mmAq and the power is 55kW.

While the introduction of large-scale pneumatic system has not increased as expected during the past twenty years, freight transport by pneumatic capsule pipeline is still forecast as a key technology in future transport system. Various feasibility studies and investigations have been performed for urban garbage transport in a district.

HYDRAULIC CAPSULE PIPELINES

Since the hydraulic capsule pipeline has larger driving force compared with the pneumatic capsule pipeline, it can take advantage of the buoyancy; therefore, it is more suited to long distance and large-scale transport of heavy material as well as transport in steep gradient lines. Japanese companies started the research and development of hydraulic capsule pipeline from the-mid 1970's as well. Sumitomo Metal Industries constructed a large-scale loop pilot plant for the hydraulic capsule pipeline of which total length was about 1,300m and the pipe diameter was 302mm. Hitachi Zosen Co. constructed two experimental facilities: (1) a straight horizontal pipeline 46m in length and with an inside diameter of 95mm, and (2) a large-scale loop pilot plant of which length and diameter were 200m and 304.7mm, including 45° inclined lines. Yokogawa et al. [33] obtained many useful results by using these apparatus, obtaining new data on correlation of capsule velocity, pressure loss, scale-up method, design data and safe operation methods (See Figure 10). The experimental work is near completion and a trial design has been implemented for the practical system [34]. However, no commercial pipeline exists in Japan yet.
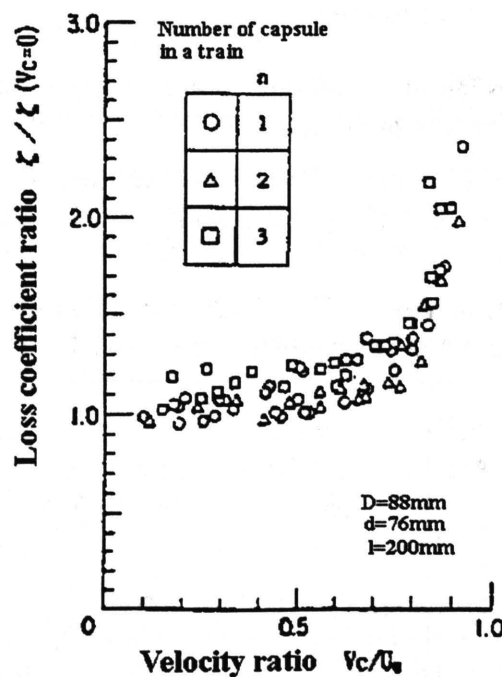
Figure 9. Loss coefficient of a capsule.

MISCELLANEOUS

In 1989, a project was initiated to construct a micro gravity experimental facility of about $10^{-4}g$ level by using an abandoned mineshaft. The diameter and depth of the shaft are 4.8m and 820m, respectively. The drop shaft uses the lower 730m, in which the free fall section is 500m for about 10s duration and the rest is used for a braking section. The size of capsule that contains experimental apparatus is 1.8m in diameter and 8m in length. To obtain high quality of micro gravity operation, it was necessary to minimize the fluid drag on the capsule in the test section, and at the same time, the capsule had to be smoothly stopped in the braking section. For the latter purpose, the capsule was introduced into a pipe 200m in length with an inside diameter of 1.895m to take advantage of air braking effect. The mass of the capsule was about 5,000kg and the velocity at the pipe inlet was about 100m/s. The huge kinetic and potential energies of the capsule were absorbed by the compressibility of air in the pipe. For this project related technology was used and many research projects were performed, which produced useful results [35,36].

In relation to hoisting manganese nodules from a deep sea, one of the authors (K.Y.- M.) is investigating a gas lift capsule transport [37]. Yanaida established that voidage is a governing parameter in the correlation of drag coefficient [1].

A tube transport system using a linear motor has been investigated as a possible transport system in future. In 1993, NKK Co. constructed a test loop line 56m in total length, which included a 5.2m vertical, a 45° inclined and a branch section. The tube sizes are 300 and 500mm. The current maximum speed of the capsule is 10m/s in the horizontal section when the carrying capacity was 10kg [38]. The system consists of a linear tube and a linear capsule. The conception for application is as follows:

(a) In small size tubes between 200 and 350mm, transport of small commodities like medical charts and documents in buildings.

(b) In middle size tubes between 400 and 700mm, supply of parts from automatic warehouse to works through an underground corridor and delivery of goods from stores to residential houses.

(c) In large size tubes between 750 and 1200mm, high speed and mass transport like freight between cities and urban garbage through underground pipeline.
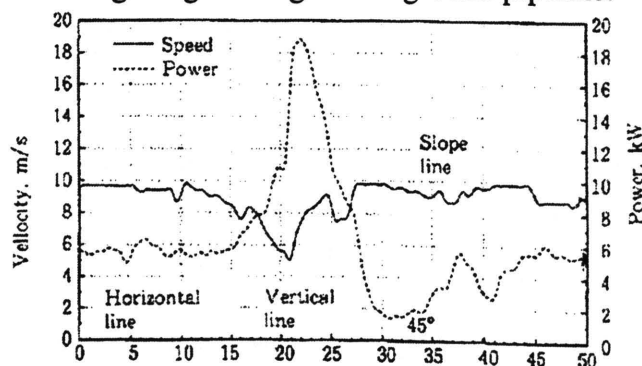
Figure 10. Capsule velocity in a linear tube transport.

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In an ice heat storage system, spherical capsules filled with water are frozen to store energy and hydraulically transported through a pipeline to a destination [39]. The spherical ice capsules are a transport medium of heat storage system. Capsule size is from about $1\mu m$ to 3 cm. The requirement is high-density transport of energy and reduction of transport power. At present, various approaches are considered for the effective transport.

CONCLUSIONS

While it seems that the basic research on the capsule pipeline is mostly established, such unstable and unsteady problems as the capsule rotation and stoppage and water flow in hydraulic capsule pipelines are hydrodynamically interesting topics to be investigated. Although the spread of capsule pipeline is slow, people seem to be recognizing the merits of the system. Therefore, now is now an important time for us to strongly appeal to the world concerning the advantages of this technology with constant effort.

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NOMENCLATURE

<u>English</u>

A_c = cross-sectional area of the capsule;

C_D = drag coefficient of capsule;

C_{df} = drag coefficient of capsule referred to the clearance velocity;

D = inner diameter of pipe;

d = outer diameter of capsule;

F = fluid force to drive the capsule;

Fr = Froude number defined by $v_o/\sqrt{gD}$;

f = sliding friction factor of the capsule against the pipe wall;

k = diameter ratio (d/D);

l = length of capsule;

Δp = pressure drop due to the capsule;

Re = Reynolds number defined by $v_{mf}d/v$;

Re_{an} = Reynolds number defined by $v_oD/2(1 + k)$;

s = density ratio of capsule to fluid;

v_{mf} = mean fluid velocity relative to the capsule in the annular region;

v_o = fluid velocity relative to the capsule;

<u>Greek</u>

v = kinematic viscosity of fluid;

λ_p = friction factor in the clearance flow;

ρ = fluid density;

ζ_c = pressure loss coefficient due to capsule.

Pneumatic Capsule Pipelines in Japan and Future Developments

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ABSTRACT

This paper presents a review of development in the pneumatic capsule pipeline (PCP) system and its potential future applications. Two commercial PCP systems have been installed in Japan. One is to transport 2 million tons of limestone annually from the mine to the cement works (3.2 km). It has been operated since 1983 without serious trouble and environmental pollution with its availability being as high as 94 - 98 %. The other was commissioned for tunneling of the Japan's bullet train from 1991 to 1994. It transported hourly 100 cubic meters of excavated earth from the excavating machine in the tunnel to the disposal area (3 - 6 km) and ready mixed concrete in return. This application is an epoch-making tunneling project with its cleanliness and safety. One of recent potential applications in Japan is for highway construction in the thickly populated area where highway is of ditch configuration in order to avoid noise and dust. The construction requires transportation of huge volume of excavated earth. The project is to be launched in 1999. Sumitomo Metal Industries, Ltd. (SMI) is also studying the application of the PCP system to municipal solid wastes, parcels, etc. It is anticipated that the 21st century will see widespread uses of the PCP system by virtue of its effectiveness without environmental impacts.

INTRODUCTION

The PCP system has a long history from the point of feasibility study and engineering-design since its invention in the 19th century, however its use for commercial operations is very limited. Recent industrial concern and trend such as environmental issues, political deregulations have enhanced the attention of the PCP system due to its environmental friendliness and its effectively diversified applications. This paper firstly traces SMI's experiences and operation scheme, as well as SMI's recent potential application, then explains the future development of application with political deregulation in Japan.

EXPERIENCE OF OPERATION

Up to now two commercial PCP systems have been installed in Japan. One is to transport limestone from the mine to the cement works and the other is to transport excavated earth from the excavating machine to the disposal area and ready mixed concrete in return.

1. Limestone Transportation

The first and largest capsule transport system in the western industrialized countries was installed at the Karasawa Mine of Sumitomo Cement Co., Ltd. in Kuzuu-City, Tochigi Prefecture. It commenced commercial operation in April, 1983.

1.1. Background of Introduction

The limestone had been originally transported by railway from the mine to the cement plant. Year by year, however, problems caused by the railway transportation became increasingly serious, such as noise, earth vibration, traffic congestion at road crossing and traffic accidents. Furthermore, the railway transportation capacity was limited, and it was difficult to cope with the increasing amount of production. As the railway transportation's future was considered limited because of noise/vibration, traffic problems, limited capacity and no foreseeable labor productivity improvement, through several studies the belt conveyor system and the pneumatic capsules transport system were raised as possible alternatives. The latter was chosen based on the following comparisons :

(1) **Right of way:** The belt conveyor system was not able to use the railway route because it required a straight line and, therefore, a new right of way had to be obtained. In addition, a curved belt conveyor system had difficulties in road or railway crossings.

(2) **Cost:** The belt conveyor construction cost was slightly higher than the capsule cost.

(3) **Noise/vibration problem:** Belt conveyor's noise and vibration is controlled by using pipe girder, low noise rubber and firm foundations. The capsule pipeline noise is affected by characteristics of rubber tire, laying condition, ground condition, capsule velocity, etc. It was reduced about 20 dB by burying the pipeline. Capsule pipeline vibration was controlled by using thick rubber tire and pipe connection gap control.

(4) **Safety:** The pipeline, which is the major part of capsule transport system, is maintenance free. Both the loading station and the unloading station are fully automatic operation. The capsule pipeline system is extremely safe, much safer than the belt conveyor system which requires line maintenance and roller replacement.

1.2. Outline

The system is designed to transport limestone at the rate of 2 million tons per year between the mine and the cement plant for a distance of 3,200 meters. Since commencing operation the system has been in continuous use at average 6,000 hours per year. Table 1 and Figure 1 provide the operating parameters and the outline of the system which functions as follows [1]:

The three-capsule trains, operating at an average speed of 9 m/s are slowed down in the braking zone located between the first air outlet and the second outlet (braking valve) with back-pressure created by subsequent capsule train(s) previously decelerated. By the control of the braking valve, the velocity of each capsule train in the braking zone is controlled to stay within prescribed limits. In this way capsule trains are decelerated so that succeeding trains can be connected with controlled impact velocity. Once the trains operate in a continuous stream, they are loaded or unloaded with limestone with the capsule motion controlled by a chain conveyor. Once the trains exit the loading or unloading station, the connecting link between trains is released and each train is sequentially inserted in the launching device by a suction blower and,

once the launching tube is shifted to the return line, the main blower pressure is used to accelerate the train out of launch tube.

The capsule, as shown in Figure 2, has two five-wheel assemblies at each end of the capsule body. Three capsules are connected together to make up one capsule train. Each wheel assembly has five equally spaced wheels mounted on a bearing at the central axis of the capsule. As the center of gravity of the capsule body is below the point of rotation, the capsule body will remain stable preventing cargo spillage. Rubber tires are used to minimize noise and soil vibration along the pipeline route.

1.3. Performance

This system has been operated for 16 years without any serious trouble. The required energy is about 2.5 kWH per unit metric ton. Its availability was between 94% and 98% and it was operated 16 hours everyday in shifts of 8 hours each by 8 persons. Since November of 1991, it has been operating 24 hours every day in shifts of 8 hours each by 8 persons totally. Although its availability was reduced to 90 – 94% initially, it recovered its availability to 94 – 98%.

2. Earth Handling for Tunneling

2.1. Background of Introduction

Excavated earth in tunneling construction is conventionally carried out by shuttle truck transportation. Air ducts to remove exhausted gas of trucks out of tunnel occupy large portion of the tunnel section. The shuttle truck transportation in narrow tunnel space always has considerable risks, such as traffic accidents and personnel injuries.

In the case of belt conveyor application in earth transportation, there are other problems such as maintenance work along belt conveyor, cleaning of spilt material off the conveyor belt and accidents of entrapping person in conveyor belt. In the case of railway application, increase of traffic accidents and operational person error is reported due to the elongation of transporting distance. Conventional railway transportation cannot ever meet excavating speed in this case and there is the possibility of increasing accidents due to the difficulty in braking in approximate 3% steep gradient of the tunnel. In construction conditions in mountainous area, it is not so easy to obtain enough passby space for shuttle trucks. It is also difficult to install belt conveyor facilities in curve sections along the mountainous road. In addition, environmental restrictions on dust, noise and vibration have become more stringent than ever. To overcome the difficulties of the conventional transportation method, the PCP system was spotlighted to solve the problems in tunneling construction in mountainous area, and Japan Railway Construction Public Corporation determined to adopt the PCP system in the Hokuriku Shinkansen Akima Tunnel Construction. Akima Tunnel is a mountain tunnel with large section of almost 90 square meters in cross-sectional area. They use the Extruded Concrete Lining (ECL) Method as a tunneling method and use the PCP system for earth and concrete transportation as subsystem to the ECL Method [3]. Ready-mixed concrete is transported from the tunnel head to the ECL machine and excavated earth from the tunnel face to the dumping zone 3 km away from the tunnel head.

2.2. Outline

The outline of the PCP System is shown in Figure 3 and Table 2. This system transports 100 cubic meter of excavated earth and 40 cubic meter of ready-mixed concrete every hour at the launching interval of 150 seconds [2]. The following shows the six components:

1) Capsule vehicle (Figure 4)
2) Station Inside Tunnel (SIT; Figure 3)
3) Station at Tunnel Head (STH; Figure 3)
4) Station at Dumping Zone (SDZ: Figure 3)
5) Pipeline inside Tunnel: Pipeline between SIT and STH is extended in accordance with the progress of ECL machine. The tunnel slope is 3%.
6) Pipeline outside Tunnel: Pipeline between STH and SDZ is installed underground, on the ground or on trestle.

Three capsule vehicles form one train and carry ready-mixed concrete from the concrete plant to ECL machine and excavated earth from ECL machine to the dumping zone. Excavated earth or ready-mixed concrete is loaded from the top of capsule and dumped out by opening the bottom lid. Reinforced concrete boxes of 1.5-2.0 m long (inner height and width are 0.9m each) are used for the most of the pipeline. This system has a unique moving station SIT:

After decreasing its speed by the dead end effect, train stops at the stopper installed in the pipe after the preceding train. When the next train arrives, the stopper is released and the preceding train moves out of the pipeline and onto the capsule transfer conveyor. Then the capsule transfer conveyor moves to the loading and unloading unit carrying its newly loaded train. This train moves to discharging unit where ready-mixed concrete is dumped into a concrete mixer. Ready-mixed concrete is unloaded by opening the bottom lid of capsule. When finished unloading ready-mixed concrete, train moves to loading unit where capsules are loaded with measured volume of excavated earth. Then it moves to capsule transfer conveyor, launching unit into the pipeline. The travelling distance of capsule transfer conveyor is extended in accordance with progress of excavation. But the extended distance is put back to the original by adding pipe pieces between the end of pipeline and launching & braking unit. The adjustment work of the distance is carried out once a day by shutting down the operation of the system.

2.3. Performance

This system applied in the tunnel construction for the first time is unique in the aspects of moving station (SIT) and different materials transported (earth and ready mixed concrete). Tunnel construction was finished in August, 1994 after excavating 3,800 m. The progress of construction went without serious trouble though collapsible rocks sometimes disturbed the progress of tunneling machine. Use of the PCP System resulted in a higher level of safety and cleanliness in construction than could be obtained from other construction methods such as truck and railway transportation. The PCP System is expected to see more use in tunnel construction as the utilization of underground space becomes more realistic. To establish the economical application of the PCP system, it is necessary to reuse the system in different construction projects, or to design pipeline as a part of foundation of tunnel structure for other utility lines.

RECENT POTENTIAL APPLICATION

1. Earth Handling for Highway Construction

1.1. Background of Application

Japan Highway Public Corporation (JHPC) has been planning several highways around Tokyo in order to relieve the traffic congestion. Such highways are required to be installed underground or in big ditch to reduce environmental impact such as noise and dust to the surrounding thickly populated area. Such kind of highway configuration produces a huge volume of excavated earth to be transported and at the same time, this transportation shall be carried out with a minimum environmental impact. This requirement suggests application of the PCPs instead of trucks.

1.2. Outline

Figure 5 shows highway connecting junction K (JCT-K) and interchange T (IC-T) through interchanges S and C (IC-S, IC-C). Excavated earth shall be gathered to JCT-K and disposed at the disposed area. Construction of this highway starts from JCT-K and spreads to IC-T. Earth from Spread 1 is disposed directly through JCT-K. Earth from Spread 2 is gathered to the loading station 1 (LS1) located at the center of Spread 2 and that from Spread 3 and 4 is gathered to the loading station 2 (LS2) at Spread 3. The PCP project's Phase 1 in the former 3 years used unloading system (US) near JCT-K, loading station LS2 and pipeline. Loading station LS2 and pipeline are constructed by the end of the third year. Earth from Spread 2, 3 and 4 is transported from LS1 and LS2 in the latter 3 years (Phase 2). The pipeline diameter is 0.7 m which is rather large comparing total freight volume of 4 million tons in 6 years in order to cope with high peak volume of 130,000 ton/month.

1.3. Performance

JHPC requested a consulting company conduct an econo-technical feasibility study in 1998. This study concluded that existing road capacity does not allow usage of trucks and the PCP system is more technically feasible and much more economical than the belt conveyor system. JHPC will proceed with this project using the PCPs, which is to be launched at the end of this year.

FUTURE DEVELOPMENTS

1. New Target – Municipal Solid Waste Transportation

Several studies have been carried out on application of the PCPs for materials other than ore or rocks. Henry Liu [4], Capsule Pipeline Research Center, has determined the preliminary economic feasibility of using the PCPs to transport mail and other products along the East Coast corridor stretching from Washington D.C. to New York City. His study found out that PCPs can

transport mail and other cargoes at about half of the cost by trucks. On the other hand, SMI has studied the economic feasibility of using the PCPs to transport municipal solid wastes for a large city area and for a newly developed small areas [5].

1.1. Background of introduction

The cost of collection and transportation of municipal solid wastes has been rapidly increasing because of the increase in the amount of wastes and traffic congestion. Current needs of municipal solid wastes management require drastic measures. However, to change whole systems of waste collection-transportation in large cities brings about large problems and troubles in budgets and labor issues. A newly developed urban district in Japan was chosen as a target area for this study. This represents the first step toward gradual application of a new pipeline system, and a large city area was chosen for the second step.

1.2. Outline

Municipal solid wastes are processed through two stages, collection and transportation. The PCP system is to be used for transportation of wastes as shown in Figure 7. The bulk specific gravity of solid wastes is so low (0.15-0.25) that it is not efficient to transport wastes under this bulky state. Solid wastes are, therefore, compressed up to a bulk specific gravity of 0.5 and fed into capsules. The capsule vehicles are simplified in their structure by packing solid wastes into cylindrical capsules in advance. Outside views of capsule and capsule vehicle are shown in Figure 8. The capsule train consists of several capsule vehicles and its load is exchanged between capsules filled with solid wastes and empty ones at the stations.

1.3. Performance

The PCPs can actualize the cleanliness of solid waste transportation. From an economical point of view, its feasibility will be suggested by the result that the transportation cost for a small area application, which is 300 T/day in volume and 6 km in distance, is about 30 dollars per ton. However, for a large city area application of 4,000 T/day in volume and 25 km in distance, transportation cost is much less--about 10 dollars per ton.

2. Technology

Technological improvement will enlarge the application area of the PCPs by decreasing its cost. The following developments are underway:

2.1. Top-Dumping Unloading

Bottom dumping requires bottom lids of capsule vehicle as shown in Figure 2. On the other hand, capsule body for top-dumping can be cylindrical shape as shown in Figure 6. Comparison between Figure 2 and 6 suggests that capsule capacity for top dumping system becomes larger than that for bottom dumping system. Its difference is about 30% in our design and this means the pipeline diameter and the cost can be reduced by 15% and 30%, respectively. Furthermore, the configuration of capsule vehicle is simpler in top dumping system, which reduces maintenance as well as fabrication cost for capsule vehicles. We have developed the top

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dumping unloading system through performance experiment and the system is to be applied in the before-mentioned highway earth transport project.

2.2. Linear Motor Control/Drive

The capacity of the PCPs increases linearly to the inverse of its launching interval as well as the conveying speed of capsule vehicles in stations. This conveying speed is limited by the stability of mechanical drive control. The use of linear motor control can be regarded to increase this convey speed. Capsule Pipeline Research Center (CPRC) and SMI have been developing this new system. This increase in capacity of PCPs means decrease in their pipeline diameter and therefore in its capital cost.

In addition to this cost reduction, the use of linear motor drive can contribute to stable operation in re-start after the power failure. Power failure can cause several trains of capsule vehicles to gather at the bottom of valley shaped pipeline profile. Blower has to move these trains at the bottom in the current system, and this operation causes transient and unstable motion of trains. Trains can be moved one by one if the linear motor drive is installed along the valley slope.

3. Political Deregulation in Japan

3.1. Land-Ownership

The highest hurdle in applying the PCPs in Japan lies in the difficulty to acquire right-of-way due to legally protected land-ownership. It is, therefore, very difficult to acquire right-of-way on private land. On the other hand, laying pipeline/tunnel under the road is not allowed unless designated for gas, electricity, telecommunication, sewage, and railway. The effort to acquire approval to pass under roads is very hard because of a complex government regulatory system. For example, the governing body in charge of transporting wastes is different from that for road maintenance. Recent tendency toward government deregulation in Japan is a good sign for the future of PCPs.

3.2. Multi-Department Task Force

Activities of governmental bodies in Japan are highly sophisticated, and they are separated from each other. For example, the municipal solid waste processing is governed by the Ministry of Health and Welfare, maintenance of national road is managed by the Ministry of Construction, and that of local roads by the local government; all environmental issues are controlled by the Ministry of Environment and so on. It is desirable this situation will be improved and multi-Department task forces will be established in the near future.

3.3. Utilization of Underground Tube Networks

Several underground tube networks for electricity, telecommunication and sewage have been established independently in the metropolitan areas of Japan. It will be profitable if they can be allowed to install the PCPs.

CONCLUSIONS

In the 20th century the PCP system proved to be a highly effective method with least environmental impacts by many companies and institutes. We are sure that SMI has made high contribution in this respect and paved the way for wide utilization of the PCP system through its operational performance of the two commercial installations. The 21st century will see its widespread uses by strengthened efforts to find out new opportunities while keeping abreast with technological developments and political deregulation movements.

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Table 1 Specification of Limestone Capsule Pipeline

Items	Description
Material Transported	Limestone
Travel Distance	3,200 m
Annual Volume of Freight	2,000,000 ton
Annual Working Hour	6,000 H
Pipeline Diameter	0.998 m
Capsule / Live Load	1.6 ton
Number of wheels	5×2
Launching Interval of Trains	50 sec (3-capsule train)
Availability	94 – 98 %

Table 2 Specification of Excavated Earth & Concrete Transportation

Items	Description	
Material Transported	Excavated Earth	/ Ready Mixed Concrete
Travel Distance	Max 10km	/ Max 7km
Capacity	100m^3/H	/ 40m^3/H
Pipeline	0.9m×0.9m Rectangular Concrete	

Table 3 Specification of Excavated Earth Capsule Pipeline for Highway Construction

Items	Description
Material Transported	Excavated Earth
Freight Volume	4 million ton / 6years
Pipeline Diameter	0.7 m
Capsule / Live Load	0.6 ton
Number of wheels	4×2
Launching Interval of Trains	45 sec (6-capsule train)
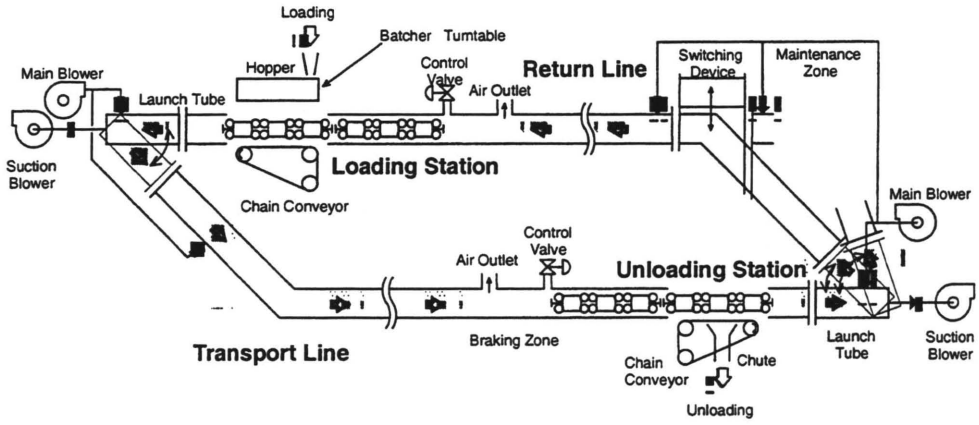
Figure 1   The Limestone Transport System
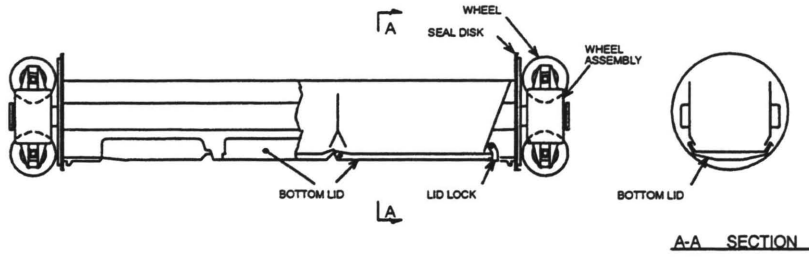
Figure 2   Capsule Vehicle for Limestone Transportation
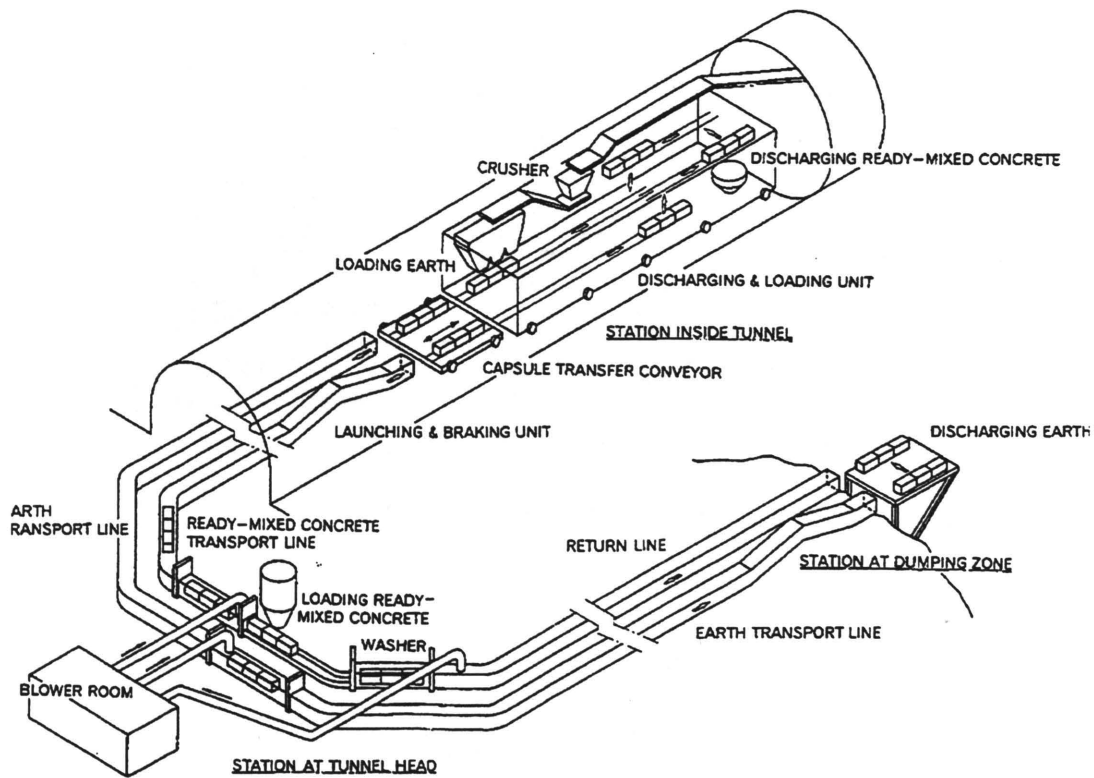
Figure 3   The Tunnel Earth Handling System
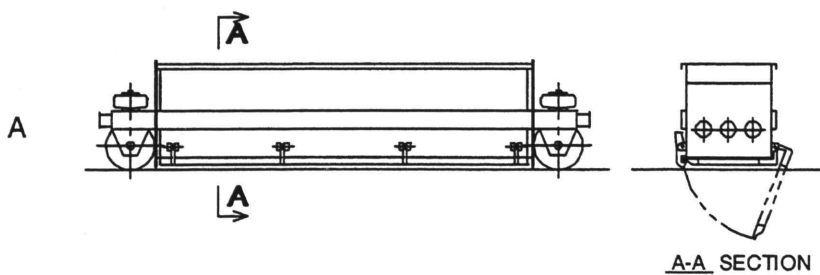
Figure 4   Capsule Vehicle for Tunnel Earth Handling
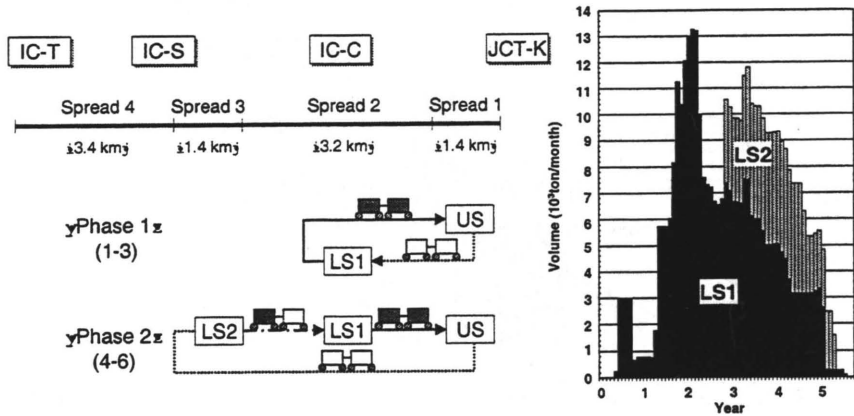
Figure 5 Highway Earth Transport System

A-A SECTION
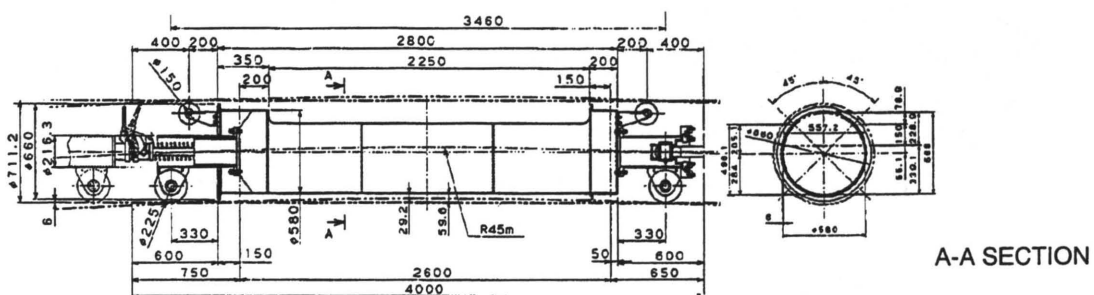
Figure 6 Capsule Vehicle for Highway Earth Transportation
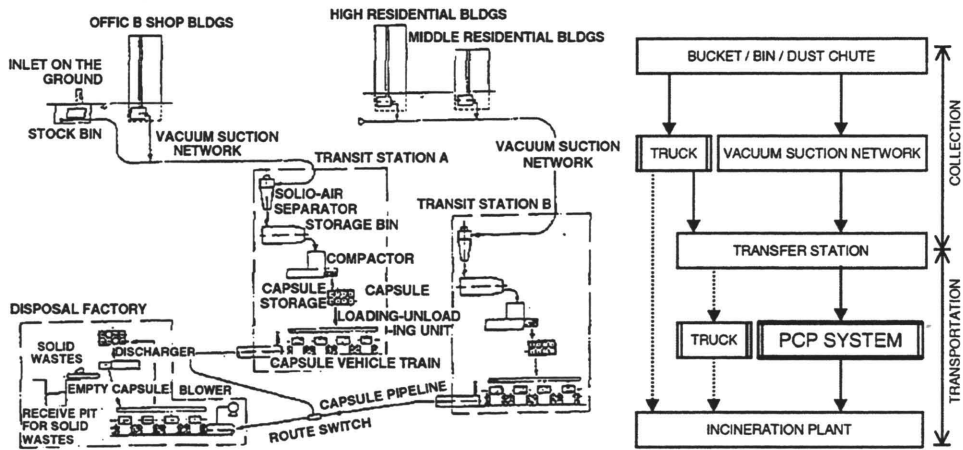
Figure 7   Concept of Municipal Solid Wastes Transportation
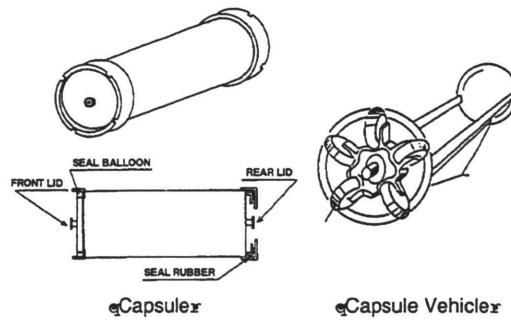
Figure 8   Capsule and Capsule Vehicle for Wastes Transportation

Electromagnetic Pipeline Transport Systems for the Phosphate Industry

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ABSTRACT

This paper presents a description and cost model results for a new bulk material pipeline transport system. A demonstration which uses a linear synchronous motor to move vehicles is under construction at the IMC-Agrico Company in Lakeland, FL. The demonstration utilizes 276 m (700 feet) of 610 mm (24 inch) diameter cylindrical cast "waste water" fiberglass tube, and contains a 79 m (200 foot) long accelerator/decelerator section, a switch, and load and unload stations. The test vehicle traverses back and forth, obtaining a peak speed of 17.9 m/s (40 MPH.) The 2.39 m (6 foot) wheelbase vehicle uses six-wheel assemblies at each end of a rotating hopper, and has a payload capacity of 273 kg (600 pounds). The vehicle carries an array of neodymium-iron boron permanent magnets which interact with the linear motor mounted on the outside of the tube to provide propulsion, and with external coils to provide an electromagnetic switch function. A preliminary economic model has been built to estimate total system cost and to investigate the trade-off between variables such as annual capacity goals, pipe diameter, vehicle speed, headway and number of coupled cars.

INTRODUCTION

Pneumatic capsule pipelines have a long history, and there are several large scale systems in current use. Conventional pneumatic systems use external blowers to move the column of air together with the capsules in the pipe. Full-diameter valves are used to control the injection, removal and subsequent return of capsules. Various practical limits tend to constrain the throughput of these systems and limit their cost effectiveness. This paper shows that the use of electromagnetics can lessen these constraints.

The original research impetus toward capsule pipelines was driven by a mandate from the Florida phosphate industry to find a cost-effective way to reduce the environmental impact of conventional transportation for their very large quantities of material. These industry leaders projected up to 27 million tonnes (30 million tons) per year of finished product will flow from the Port of Tampa. Trucks carry the bulk of current production, and place a burden on the region's already stretched feeder and highway infrastructure. A 48 km (30 mile) pipeline from the mining region to the port is a potential solution, but must be cost effective enough to compete with conventional transportation. Preliminary economic studies carried out during phase 1 were judged by the phosphate industry to be sufficiently promising to proceed with the demonstration project.

This capsule pipeline study has also generated expressions of interest from a large mining company interested in transport of ore from deep mines to their surface mills, and from a large

cement company interested in a viable alternative for their more difficult long-length conveyor belt applications.

PROTOTYPE SYSTEM DESCRIPTION

A cross section through the pipe containing a typical vehicle is shown in **Figure 1,** and the vehicle is shown separately in **Figure 2**. The linear synchronous motor "stator" winding is mounted on the outside of the tube leaving the inside of the tube free of obstructions. The permanent magnet assembly mounted on the vehicle consists of four poles, alternately north and south. A linear synchronous motor concept was chosen over a linear induction motor concept because it retains reasonable efficiency at large operating gaps. The gap between the magnet face and the effective centerline of the winding is 32 mm (1.25 inches).
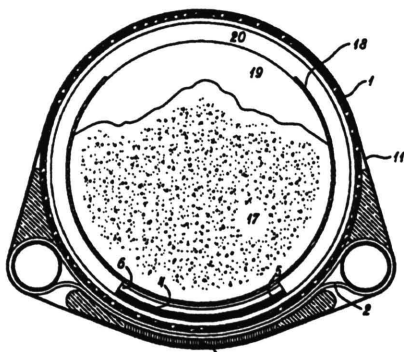
| Figure 1: Cross-Section Through Pipe and Capsule Mid-Section. | Figure 2: Capsule with 4-Pole Magnet Structure |
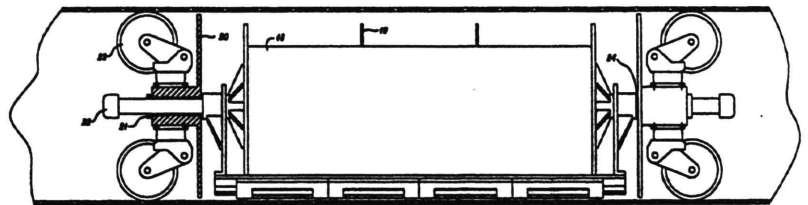
Pipe:

Because the winding is on the exterior of the tube, the tube must be made from a non-conducting material. A cast fiberglass "waste water" pipe product is used for the straight sections, and is supplied in 7.9 m (20 ft) lengths with a 15 mm (0.6 inch) wall. The curved sections are also fiberglass, but are built on an interior removable mandrel. The sections are joined by standard sealed couplings. The pipe can be run at ground level, in elevated sections, or underground.

Vehicle:

The vehicle consists of a cylindrical open-top hopper 508 mm (20 in) in diameter by 1,219 mm (48 in) long, attached to wheel carriers at each end through pivot bearings. This allows the hopper and the wheel assemblies to rotate independently around the pipe line central axis. The wheel carriers each have six wheels spaced at equal 60-degree angles. The wheels are 150 mm (6 in) diameter polyurethane coated standard industrial units with sealed ball-bearings. The overall length of the vehicle is 2.36 m (6 feet.) The magnet assembly occupies a 90 degree by 1,219 mm (4 foot) long sector at the bottom of the vehicle, and is hung from the central shaft at each end of the hopper section through bearing mounts, to allow rotation independent of both the hopper and the wheel assemblies. This feature is used in switching and unloading.

The fully loaded capsule weighs 545 kg (1,200 pounds), of which 273 kg (600 pounds) is payload. The ratio of payload to overall weight is lower than one might have postulated from conventional capsule systems. This is largely a consequence of the need to carry an on-board magnet system, which weighs 91 kg (200 pounds.) Additional tare weight reductions may be possible as the project moves beyond the prototype stage.

Magnet Assembly:

The magnet assembly consists of an array of individual blocks 5 cm x 5 cm x 1.9 cm deep (2" x 2" x 3/4"), magnetized parallel to the 1.9 cm dimension. They are located on a curved back-iron plate 610 mm by 1220 mm long by 12.7 mm thick (2 feet by 4 feet by 0.5 inches thick) which is hung from the central shaft at each end of the hopper section. The 80 individual magnet blocks are arranged in sets of 28 to form four poles, two north and two south. The poles have a "pole pitch" of 305 mm (12 inches), and a repeat pitch of 610 mm (24 inches.) The magnet blocks are magnetized prior to mounting on the back iron.

Linear Synchronous Motor Winding:

The linear motor windings are wound in 7.09 m (18-foot-long) modules and attached to the outside of individual 7.9 m (20-foot-long) pipe sections. Each module is wound from three continuous lengths of #6 copper cable, insulated for 600-volt outdoor service. Each length forms one phase of the three-phase winding, and is wound back and forth 14 times using special tooling. A single phase of the winding (artificially foreshortened) is illustrated in **Figure 3.** A laminated iron 12.5 mm thick backing is included outside the winding to double the effective permanent magnet field at the winding, reducing the power requirement by a factor of four.
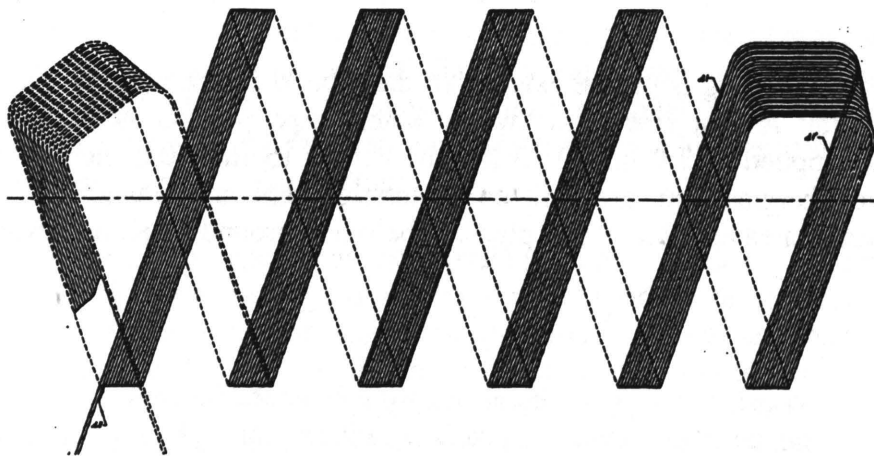
Figure 3: Single Phase of the 3-Phase Linear Synchronous Winding Module (Not Shown Full Length)

Power Conversion and Control:

A standard 100 HP commercial four-quadrant motor drive is used to drive the synchronous motor modules. The drives are outfitted with proprietary control systems to enable them to automatically synchronize the LSM, and to interface with the global control system. An output frequency of 30 hz is synchronous with 17.9 m/s (40MPH.) Ten modules in series are

required to accelerate a fully loaded vehicle to 17.9 m/s. In cruise sections of the pipe, periodically spaced motor modules are used to re-accelerate the capsules which have been slowed by wheel bearing and air friction. The impact of periodic windings on system operation and economics is discussed in later sections.

In most rotary and linear synchronous motor applications a feed-back loop is required between the position of the "rotor" and the phase of the stator magnetic traveling wave. In the pipeline capsule "freight" application, however, where the load is insensitive to the jerk which accompanies position hunting, the motor can be operated open-loop without difficulty as long as the phase angle is not advanced beyond a limit. This eliminates the need to continuously sense position of the vehicle. Instead, position and velocity are checked only at the entrance to each motor section as the car passes over a simple magnetic sensor.

A global control system is required to keep the capsules properly spaced. Each time a vehicle passes over a boost winding, the global controller adjusts the speed appropriately. A phase difference is maintained between the capsules assuring that all do not simultaneously pass over boost windings, thus smoothing out the power peaks. Information fed-back from the local drives can also modify the global system; for example, capsules that do not respond in an anticipated manner, and may require maintenance can be flagged.

Load and Unload Stations:

A load station consists of an accumulation hopper feeding a metering device, which in turn dumps on command through a chute into the at-rest hopper section.

The unload station needs to rotate the hopper 180 degrees, and have a clear path for the load to gravity dump. This requires that the magnet assembly be rotated out of the way, and that there be no vehicle support directly below the hopper. A preferred approach is to rotate the magnet assembly 180 degrees before entering the unload station using the same technique used in the switch, and to then use passive iron elements on the top of the tube to provide sufficient upward attractive force to carry the full weight of the loaded vehicle. The lower 180 degrees of the pipe can then be removed without loss of support. The magnet rotation is also used to rotate the load hopper.

Experimental dumps of phosphate rock with varying levels of moisture indicate that a minimum of 1.5 seconds is required to dump the load. To provide a time allowance for positioning the capsule and releasing it, we have set 2 seconds as the minimum time interval allowed for each capsule to spend within the unload station.

Capsules can be operated singly or in coupled sets. Coupling two capsules, for example, increases the launch interval by two, reducing the number of required parallel load and unload stations, but increases the complexity of those stations.

Switch:

Throughput of a given dimension pipeline can be increased as the time interval between capsules (or an articulated set of capsules) is decreased. If the time interval between capsules

becomes shorter than the minimum time required in an unload station, parallel unload stations must be added with switches to accommodate the increased throughput.

An external winding interacts with the magnet assembly on the capsule to provide the switch function. A "street Y" switch section in the pipeline is provided. Prior to entering the switch, the rotatable magnet assembly on the vehicle is swung to the horizontal position by an external winding on the pipe, and then held in that orientation by passive iron elements in the wall of the tube. The elements carry through the curved section of switch until the vehicle has safely re-entered the pipeline, at which point the magnet assembly rotates back to the bottom. In the default mode, the capsule travels directly through the straight branch, with any necessary lateral support provided by passive iron elements in that wall.

Demonstration Project:

A demonstration project is under construction to test the feasibility of the system concept and the various components. Two hundred seventy six meters (700 feet) of 610 mm (24 inch) diameter pipeline are being constructed. A vehicle is loaded and accelerated to 17.9 m/s (40 MPH), coasts to a stop in climbing a 24 m (60 foot) elevation hill; re-accelerates to 17.9 m/s (40 MPH) in descending the hill, is decelerated to zero, unloaded, and recycled through the process. The switch is located between the accelerator and the hill.

Preliminary systems integration tests were completed in March, 1999. Two motor modules were used to cycle a vehicle between the ends of an 80-ft pipeline section at a vehicle speed of 2.7 m/s (6 MPH.) A separate wheel test ran fully loaded wheels at 17.9 m/s (40 MPH) for 300 hours without noticeable wear.

The field installation began in July, 1999, and site integration tests will begin in September. The present phase of testing is scheduled to be complete in February, 2000. Photographs of several components are shown in **Figure 4.**

MOTOR COVERAGE

In a freight transport pipeline there is no need for the capsules to maintain a constant velocity, and therefore no need to cover the entire length of the line with motor windings. Rather the capsules can coast between periodically spaced motor modules which boost the speed lost to wheel friction and moving air in the pipe. As noted in the economic studies, the fraction of the pipeline occupied by motor windings has a significant impact on the overall system capital cost.

The fraction of motor coverage required is a function of the allowed loss of speed between motors, the capability of the motors, the pipeline and capsule characteristics and the velocity and spacing between capsules. For the prototype 610 mm (24 inch) pipeline and 545 kg (1200 pound) loaded capsule, the minimum percent coverage required on flat ground is 5% if vehicles are traveling at 1 second intervals and are permitted to lose 10% of their 17.9 m/s (40 MPH) speed before re-acceleration. Since two 7.9 m (20-ft) motor modules are sufficient to re-establish the velocity of a passing capsule, 5% coverage represents a pair of modules every 281 m (712 feet.)
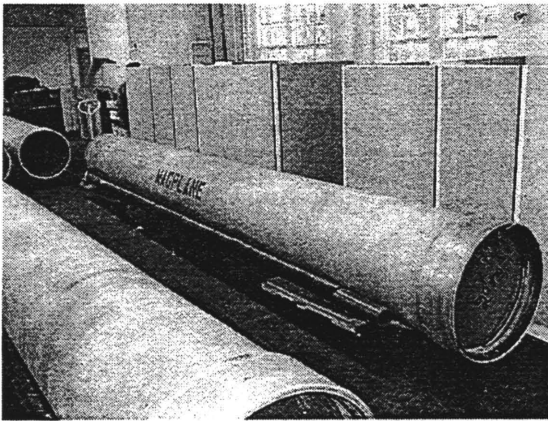
Figure 4a: Motor Module
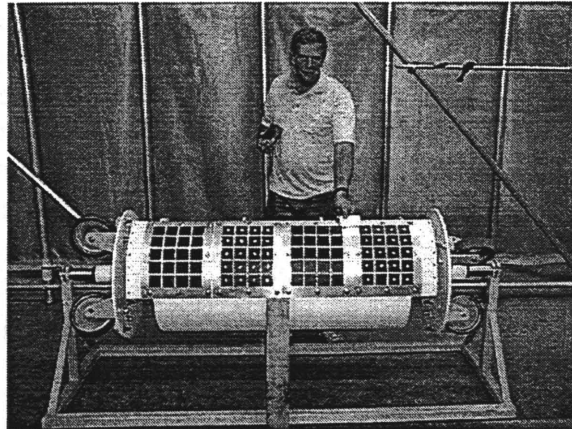
Figure 4b: Magnet Structure
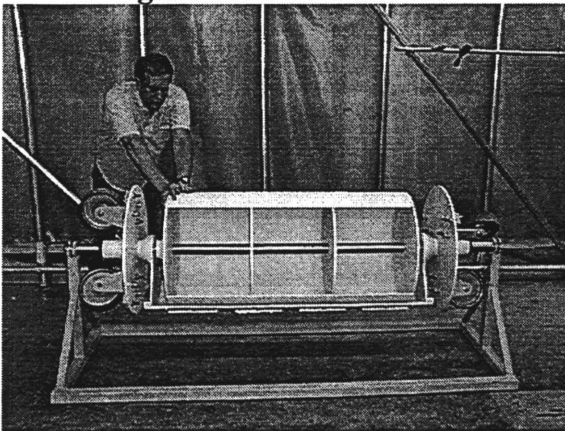
Figure 4c: Rotating Hopper

Figure 4d: Demonstration site

The individual capsule speed loss resulting from moving air in the pipeline, depends on how much air is being moved by each capsule, which in turn depends on the time interval between capsules. If the interval in the above example is lengthened from 1 to 3 seconds, each capsule must move 3 times as much air, and will have higher losses. A motor coverage of 8% is required in this case, requiring two motor modules every 175 m (443 feet.) At 3-second intervals, the losses due to moving air are comparable to the wheel friction losses, assuming a coefficient of friction of 0.01 for the wheels.

While limiting motor coverage to small percentages of the total pipeline has a beneficial economic effect, it presents a potential problem of system restart after a loss of power. In the above examples (assuming level ground) the 1 second spaced capsules would coast to a stop in 158 seconds, traveling a distance of 1,700 m (4,320 feet); at 3 second intervals (with larger losses per capsule) they would coast for 130 seconds, traveling a distance of 1,270 m (3,224 feet.) With these very small percent coverage of windings, the chance that any significant number of capsules would coast to a stop over a motor segment is very low, and therefore some other strategy for restart is required. The relatively long coast times, however, do allow normal recovery from the most common power failures which are only a few seconds in duration. The capsules would simply coast to a somewhat lower velocity before being automatically re-accelerated when the power was restored.

The restart strategy chosen would depend on an assessment of the expected frequency of long duration power outages. If it were once a year, a slow recovery could be tolerated; for example, motorized "recovery" capsules could clear the pipeline. If the expectation were for much more frequent outages, a more pro-active system would be required. By way of example, a bypass pipe containing an accelerator could be provided every 1,300 m (3,300 feet.) In the event of a long duration power failure, coasting capsules would be switched into the bypass and held until they could be re-accelerated and re-enter the main pipeline. Addition of a 79 m (200 feet) long accelerator every 1,700 m (4,400 feet), would add a 5% motor coverage penalty to the capital cost. The coupling of vehicles through the air column in the pipe would be used to advantage during the re-start.

The above discussion is based on a hypothetical level-ground installation. In cases where significant altitude changes must be accommodated, motor coverage must be further increased.

LINEAR SYNCHRONOUS MOTOR PERFORMANCE

The calculated performance of a pair of boost modules sufficient to restore a 10 % drop in velocity is given below, and is based on the prototype design. A commercial 100 HP conventional synchronous motor drive unit is sufficient to power a module. The performance of the two motors vary, reflecting the speed-dependent characteristics. The efficiency increases with speed, but the increased back EMF developed by the vehicle motion cuts into the maximum voltage limit on the drive, decreasing the current and thrust available.

Table 1. 1st Boost Motor and Drive at 60 Degree Phase Angle

Velocity in (m/s)	15.9	Efficiency (%)	55
Velocity out (m/s)	17	Power factor(%)	44
Time (s)	0.26	traction power (kW)	37
Acceleration (m/s^2)	4.5	input power (kW)	69
Thrust (N)	2,242	input power (HP)	93

Table 2. 2nd Boost Motor and Drive at 60 Degree Phase Angle

Velocity in (m/s)	17	Efficiency (%)	58
Velocity out (m/s)	18	Power factor(%)	44
Time (s)	0.24	traction power (kW)	37
Acceleration (m/s^2)	4.2	input power (kW)	65
Thrust (N)	2,090	input power (HP)	88

When capsules are first introduced into the pipeline they need to be accelerated to their cruise velocity of 17.9 m/s. This requires ten modules in series. At lower speeds, for example, the initial stages of the accelerator section, the speed dependent trends illustrated by the two boost windings are more apparent. At the low speed end, the maximum thrust is limited by the available drive current and by heating in the windings.

The thrust that can be provided by the modules at a given speed is related to the cosine of the phase angle between the winding drive and the magnet poles on the capsule; it is maximum

when the angle is 90 degrees. If feedback control between the vehicle position and the drive phase is employed, angles approaching 90 degrees can be utilized. If the angle is reduced to 60 degrees, the system will operate stably without feedback control. The thrust at 60 degrees drops to 87 % of the maximum available, but is a reasonable tradeoff against the complexity of a feedback loop requiring continuous and accurate position sensing, and the need for on-board transducers.

ECONOMIC STUDIES

Economic studies have been made using a preliminary costing model. The model takes engineering and unit cost inputs and projects capital and operating costs for any prospective system. Major capital cost components include pipeline, vehicles, magnet assemblies, windings and load/unload stations. The elements of operating cost include power, material costs for maintenance (taken as a fixed percentage of capital cost) and labor costs for operating and maintaining the system.

The case studies show that pipeline diameters ranging from 457 to 559 mm (18 to 24 inches) and vehicle speeds of 9 to 18 m/s (20 to 40 MPH) are generally optimum for systems operating in the 4.8 to 48 km (3 to 30 mile), 1 to 10 Million tons/year (Mt/y) range. Slower speeds are more optimum at short distances where the load/unload station costs are a substantial fraction of the total cost. In nearly all cases, pipeline costs are the largest single component of capital cost, whereas the second-most expensive component depends on the distance and tonnage. The model minimizes total system cost, which is defined here as the sum of the annualized capital cost plus the operating cost. Calculation of the annualized capital cost requires a choice of a minimum attractive rate of return and a time over which the return will be realized. In our studies we have fixed these at 20% and 20 years as illustrative.

Figure 5 presents the total system cost projected by the model for a 30-mile, 10 Mt/y system as a function of the pipeline diameter, at vehicle velocities of 20, 30, 40 and 60 mph. The figure shows that a minimum cost occurs in the vicinity of pipeline diameters of 18 to 26 inches,
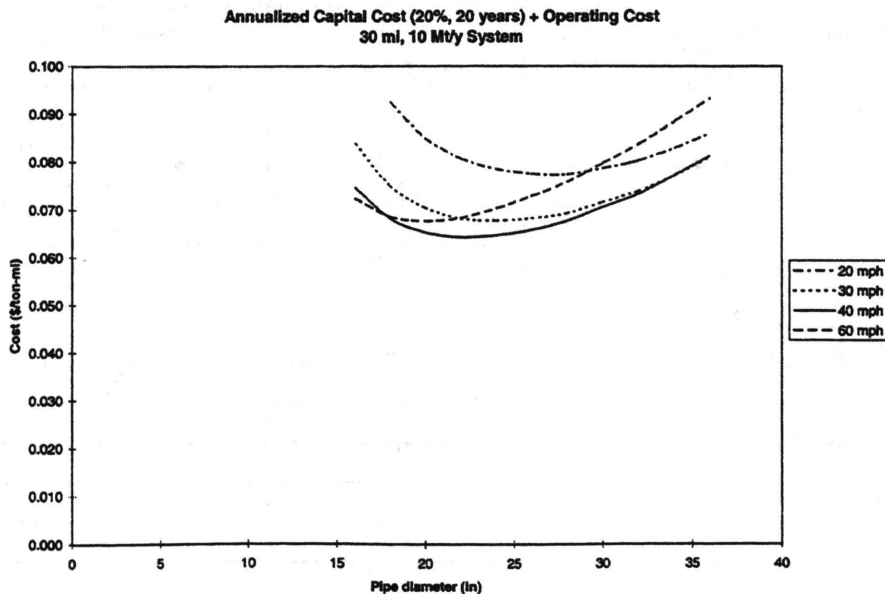
Figure 5: **Projected total system cost as function of pipe diameter and capsule velocity for a 30 mi., 10 Mt/yr. installation**

depending on velocity. Since pipeline costs are a strong function of the pipeline diameter, smaller diameters are desirable; to keep the throughput constant the smaller pipelines require higher speeds. All the constant velocity curves show a minimum point. Pipeline diameters below the minimum require such frequent launches of vehicles that the increasing number and cost of the required parallel load and unload stations and number of vehicles begins to increase the total cost. The system that minimizes total cost operates at 17.9 m/s (40 MPH), with a 559 mm (22-inch) pipeline. At higher speed, for example the 60 MPH curve shown, the increasing power penalty for moving air starts to add significant cost.

The 59 mm (22 inch,) 17.9 m/s (40 MPH) minimum cost case would require a total of 8652 vehicles (half outbound and half returning) and seven parallel load/unload-station branches at each end of the line to handle the 10 Mt/y throughput. The capsules are assumed to be coupled in sets of three. The cost elements at this minimum cost point are summarized in the table below.

Shorter haul distance case studies show higher total system costs per ton-mile, for example, rising to 0.10$/t-mile for a 10 Mt/y capacity at an 8 km (5 mile distance.) Shorter haul distances are increasingly dominated by the cost of the load and unload facilities, and minimum costs are achieved by minimizing those facilities, generally by increasing pipeline diameters and reducing speed. Lower capacity systems also have higher costs per ton-mile; for example, costs for a 5 Mt/y system at a distance of 48 km (30 miles) are 0.10$/t-mile.

Table 3.0: Capital and Operating Cost for 17.9 m/s, 559 mm Pipe Case

Capital Cost	$M	%
pipeline	18.8	30.7
vehicles	15.6	25.5
magnet assemblies	7.8	12.7
motor windings	7.7	12.6
load/unload stations	5.5	9.0
power units outbound	3.3	5.4
power units returning	1.6	2.6
central control	0.5	0.8
block control units	0.4	0.7
total	61.2	100.0
Capital recovery ($/t-mile)	*0.042*	
Operating cost	**$M/y**	**%**
Power	3.3	49.3
Maintenance	1.8	27.7
Labor	1.5	23.0
total	6.7	100.0
Operating cost $/ton-mile	*0.022*	
Total System Cost ($/t-mile)	*0.064*	

The economic model uses illustrative unit costs and scaling relationships to establish the sensitivity to variables and to determine what elements are likely to dominate the costs. The estimates for some of the elements, for example the pipeline itself and the power units, can be reasonably estimated from existing databases. Other elements such as the cost of vehicles, magnet assemblies and motor windings are much more speculative. For these elements, experience in fabrication of the prototype reduced by a factor for volume productions has been used. The reduction factor is only speculative as production engineering studies have not been done.

All examples above assumed a six percent winding coverage of the pipeline. For the 10 Mt/y, 30 mile case, if the coverage were to be increased to 12 percent, the capital cost would increase by 22 percent, increasing the total system cost by 14 percent, from $0.064/ton-mile to $0.073/ton-mile.

CONCLUSIONS

Preliminary economic studies have provided sufficient incentive for sponsorship of the demonstration project of a suitable scale to establish the feasibility of the technical approach. A follow-up project will likely be necessary before a viable product can be commercially available. Such a project might be to replace truck traffic between nearby processing plants and would serve to fully develop the technology, and establish the economics.

ACKNOWLEDGEMENT

REFERENCE

[1] Bulk Ore Transport by Linear Synchronous Motor Economic Model, Bradford A. Smith, MIT Plasma Fusion Center, 185 Albany Street, Cambridge, MA 02139; Internal Report, December 7, 1998.

Use of Linear Induction Motors for Pumping Capsules in Pneumatic Capsule Pipelines (PCP)

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ABSTRACT

The freight carrying capacity (throughput) of conventional pneumatic capsule pipelines (PCPs) can be greatly increased by using non-intrusive pumps such as electromagnetic pumps based on the principle of linear induction motor (LIM). LIMs can also be used for capsule acceleration at pipeline inlets, capsule deceleration or braking at pipeline outlets, and control at pipeline branching points. The purpose of this study is to optimize the design of LIMs used in PCP so that an efficient PCP system driven by LIMs can be built and used commercially. The study involves four phases: (1) deriving the fluid mechanics and electromagnetic equations that can be used to predict the behavior of LIM-PCPs, (2) using the derived equations to optimize the design of LIM-PCPs, (3) conducting small-scale laboratory experiments to check the validity and accuracy of the derived equations, (4) conducting a pilot plant study involving testing a large LIM in a large and long pipeline loop. This paper is a progress report of what has been accomplished so far, and a discussion of what remains to be done. From the preliminary analyses made, it is shown that using LIMs to improve PCP operation appears to be rather promising.

INTRODUCTION

Pneumatic capsule pipelines (PCPs), often referred to commercially and by the lay public as "tube transport," is the shipment of cargoes (solids) inside vessels or vehicles driven by air flow pumped or blown through a pipe or a pipeline network. Past and current use of PCPs have been mainly for post offices in major cities, drive-in banks, large hospitals, and large building complexes [1]. They are small and short systems, normally using less than 30 cm diameter pipes or tubes. However, in the last two decades, much larger and longer PCPs have been used in Japan for transporting limestone to a cement plant and certain other applications [2], and in the former Soviet Union for transporting rocks [3]. These newer systems use pipes of the order of 1 m diameter, and transportation distances are longer than 1 km. They are automatically controlled by computers.

Although the large new PCP systems have proven their reliability and practical values, they have not found a large market so far due to several reasons, such as industry reluctance to try new technology, and relatively high cost. The cost of transporting goods by a contemporary PCP system is usually not less than that of other conventional means such as trucks or conveyor belts. This is not attractive for new technologies. For a new technology to gain rapid acceptance, it must have a distinct economic advantage over the existing commercial systems that perform the same function. Therefore, to improve the commercial acceptability of large and long PCP systems, the economics of the current PCP systems must be improved.

The best way to improve the economics of current PCP systems is through a good understanding of the current systems and their shortcomings. The current systems have a common major shortcoming: it has very low linefill--less than 5%. This means less than 5% of the length of the pipeline is occupied by capsules moving in the pipeline; over 95% of the line is empty. Therefore, the most effective way to improve the economics of freight transport by PCPs is to increase the linefill rate. For instance, by a four times increase in the linefill, the freight carrying capacity (throughput) of the pipeline will be quadrupled, and the unit cost in terms of $/T (dollars per tonne of freight transported over the distance traversed by a pipeline) will be much reduced.

Contemporary PCP systems have low linefill rates for two reasons:
(1) They use blowers (fans) to drive the air which in turn drives the capsules. The blowers block the motion of capsules--the cargo-carrying vehicles. Capsules must be stopped before they reach any blower and then rerouted through another line in order to bypass the blower. The rerouting impedes the capsule traffic in the pipe and reduces the linefill.
(2) Loading and unloading of capsules are done in-line. The system comes to a halt or a snail's pace while loading/unloading takes place. To create a new PCP system of high linefill, loading and unloading cannot be done while the capsules are in-line. Off-line loading/unloading is a necessity.

Therefore, to improve the economics of contemporary PCP systems requires two measures: (1) The systems must use non-intrusive pumps that don't block the motion of the capsules. This can be done by using electromagnetic pumps such as the linear induction motors [4,5]. (2) An off-line loading/unloading system must be designed for use at each terminal. This has been studied but it does not belong to the scope of this paper [6].

The purpose of this research is to design and demonstrate an efficient and optimum PCP system based on LIMs. The research involves four steps or phases: (1) deriving the fluid mechanics and electromagnetic equations that can be used to predict the behavior of LIM-driven PCP systems; (2) using the derived equations to optimize the design of LIM-PCPs; (3) conducting small-scale laboratory experiments to check the validity and accuracy of the derived equations; and (4) conducting a pilot plant study involving testing a large LIM in a long pipeline loop. It is anticipated that after the completion of the four steps, the technology of LIM-PCP will be ready for commercial use to attain over 20% linefill on a continuous basis. Such a system will greatly enhance the economic competitiveness and the market acceptance of large and long PCPs.

LITERATURE ON PCP-LIMs

As early as 1976, Liu and Rathke proposed and investigated the use of electromagnetic pumps for powering capsule pipelines [4]. They investigated two types of electromagnetic capsule pumps--one using a LIM powered by alternating current, and the other using a set of solenoids powered by direct current. They tested both concepts by using bench-scale models. Both systems were found to work not only in a water-filled pipe (hydraulic capsule pipeline or HCP) but also in an air-filled pipeline (PCP). Subsequently, they applied for and obtained a U.S.

patent on a capsule pipeline system powered by electromagnetic pumps [7]. Later, a 4-inch (10 cm) diameter tubular linear induction motor (TLIM) connected to a pipe of the same diameter was tested in laboratory by Assadollahbaik using water as the fluid [5, 8]. Assodollahbaik and Liu also analyzed the efficiency of LIM for powering HCP [9]. They found that to get good efficiency, the LIM-capsule pump must have small "air gap" and small "slip." Note that "air gap" is the electrical engineer's term for the clearance between the capsule wall (the "rotor") and the LIM wall (the "stator"), whether the gap is actually occupied by air (for PCP) or water (for HCP). "Slip" will be defined later.

DERIVATION OF EQUATIONS

Both fluid mechanics equations and electromagnetic equations are needed to predict the behavior of PCP systems powered by LIMs. These two sets of equations must be solved simultaneously before the behavior of a PCP, such as the capsule velocity, pump pressure, power and efficiency, can be determined for any given case.

Fluid Mechanics Equations

The simplest fluid mechanics analysis of a PCP powered by LIMs assumes steady incompressible flow in which capsules with equal spacings travel through the pipe at a constant velocity. Figure 1 shows the general case where the diameter of the LIM, D', is slightly smaller than the diameter of the pipe, D. The smaller diameter for the LIM is needed to generate smaller air gap, larger thrust generated by the LIM, and better efficiency.
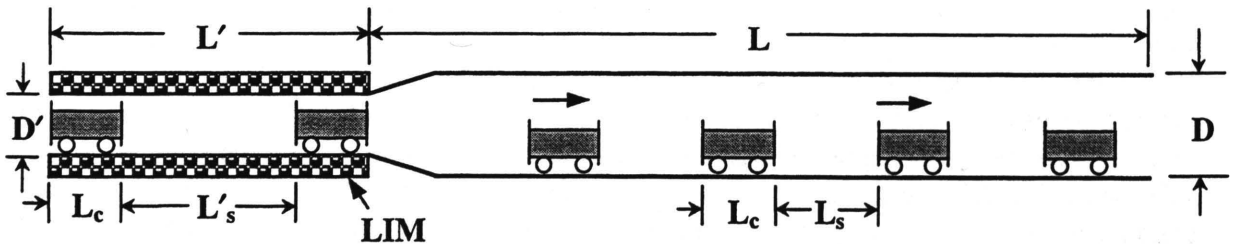
Fig. 1 Steady Flow of Capsules through a PCP Powered by a LIM

Assume that the lengths of the pipe and the LIM are respectively L and L'. In the pipe, the air velocity is V, the capsule velocity is V_c, the linefill is α, the cross-sectional area is A, and the number of capsules is n. The corresponding quantities in the LIM are V', V_c', α', A', and n'. Furthermore, assume that the capsule weight is W_c, capsule length is L_c, contact friction coefficient of capsule wheels is μ, and the electromagnetic force generated by the LIM on each capsule is F_e.

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For steady incompressible flow we have:

$$\alpha V_c = \alpha' V_c' \tag{1}$$

$$n L_c = \alpha L \quad \text{and} \quad n' L_c = \alpha' L' \tag{2}$$

$$V' = V_c' - \sqrt{\frac{2(F_e - \mu W_c)}{\rho C_D' A'}} \tag{3}$$

$$V = V' \frac{A'}{A} \tag{4}$$

$$V_c = V - \sqrt{\frac{2\mu W_c}{C_D A \rho}} \tag{5}$$

$$2\frac{\alpha' L'(F_e - \mu W_c)}{L_C A' \rho} - \frac{fL'}{D'}\left[V'_c - \sqrt{\frac{2(F_e - \mu W_c)}{A' C_D' \rho}}\right]^2 = \frac{2\mu n W_c}{A\rho} + f\frac{L}{D}\left(\frac{A'}{A}\right)^2\left[V'_c - \sqrt{\frac{2(F_e - \mu W_c)}{A' C'_D \rho}}\right] \tag{6}$$

The values C_D and C'_D can be calculated from the following equation proposed by Kosugi [10]:

$$C_D = \frac{4}{\left(\dfrac{1}{k_d^{\,2}} - 1\right)^2}, \qquad C'_D = \frac{4}{\left(\dfrac{1}{k'_d{}^{2}} - 1\right)^2} \tag{7}$$

where k_d is the diameter ratio of the end disk ($k_d = D_d/D$), and $k'_d = D_d/D'$.

Electromagnetic Equations

According to Assadollahbaik [5], the electromagnetic force exerted by a tubular LIM (TLIM) on a capsule is:

$$F_e = \frac{\phi^2 \, w L_C \, \rho_s K_w^2 N^2 I_1^2}{L_1^2 \, V_s \left(S + \dfrac{1}{SG^2}\right)} \tag{8}$$

in which the slip, S, and the goodness factor, G, are defined by

$$S = \frac{V_s - V_C}{V_s} \tag{9}$$

$$G = \frac{2\mu_0 \, f_e L_p^2}{\pi \rho_s b'} \tag{10}$$

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In the above three equations, ϕ is the number of phases, w and L_c are respectively the perimeter and length of the capsule, ρ_s is the surface resistivity of the capsule, V_s is the synchronous speed, K_w is the winding factor, N is the number of turns per phase, I_1 is the input current, L_1 is the stator length, V_c is the capsule velocity, μ_o is the magnetic permeability of air, f_e is the frequency of the electricity, L_p is the pole pitch, and b' is the effective air gap.

For a given LIM design and capsule design, and a given input current and frequency, Eqs. 8, 9, and 10 show that the electromagnetic force (thrust) on the capsule, F_e, is a function of the capsule velocity V_c. F_e is a maximum when $V_c = 0$, or $S = 1$, and it decreases to zero as V_c increases toward V_s. Details about how to determine the quantities in Eqs. 8, 9, and 10 are given in [5,9].

Using an approach similar to that described above, Plodpradista analyzed the performance of TLIMs of two different sizes under various conditions--different air gap, different aluminum wall thickness, different pole pitches, etc. [11]. One of the results obtained for a 1 m diameter TLIM is shown in Fig. 2, which shows that the air gap has a strong influence on both the thrust and the efficiency of TLIM. From Fig. 2, it is crucial to design commercial LIM-PCP systems with small air gaps, of the order of 1 cm. Any air gap much smaller than 1 cm will produce practical difficulties due to the small tolerance required in construction.

| (a) Efficiency Curves | (b) Thrust Curves |
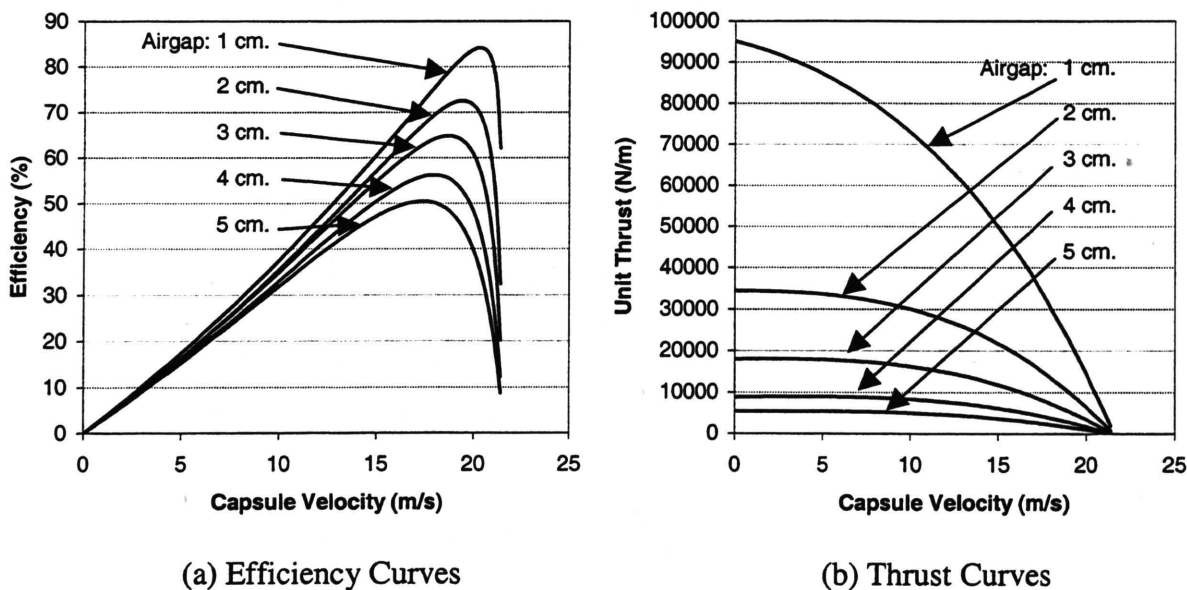
Fig. 2 Characteristics of a TLIM with 1-meter diameter bore (3-phase, 480 VAC, 60 Hz, 4 poles, 2 slots per pole per phase, 0.72-meter stator length, V_s = 21.6 m/s)

Solution of Equations

To analyze a given problem, the fluid mechanics equations (Eqs. 1-7) and the electromagnetic equations (Eqs. 8-10) must be solved together. This can be done as follows:

1. Design a particular LIM of large thrust and good efficiency for the system. Then, by using the electromagnetic equations, plot the thrust, F_e, and the efficiency, E, as functions of the capsule speed in the LIM, V'_c, as shown in Fig. 2.

2. From the graph in Fig. 2, find the capsule velocity V'_c and the thrust F_e that correspond to the peak efficiency, or near the peak.

3. Then, substitute the values of V'_c and F_e into Eq. 6.

4. Select a desired capsule length L_c (such as $L_c = 4D$), and a desired linefill (such as $\alpha = 0.20$). Then use Eq. 2 to determine the number of capsules in the pipe as a function of pipe length, namely $n = \alpha L/L_c$. Substitute the result into the first term on the right of Eq. 6.

5. Use Eq. 7 to calculate C_D and C'_D. Then substitute the value of C'_D into Eq. 6.

6. For simplicity, assume $f = 0.012$, $\rho = 1$ kg/m^3, and $\mu = 0.015$.

7. Use Eq. 3 to determine V'.

8. Use Eq. 4 to determine V.

9. Use Eq. 5 to determine V_c.

10. Use Eq. 1 to determine α'.

11. Use Eq. 2 to determine n and n'.

12. Assume a pipe length L, use Eq. 6 to solve for the LIM length L'.

Example: Consider a 1 m diameter TLIM that has 4 poles, using 3-phase, 60 Hz, 480 VAC and a synchronous velocity of 21.6 m/s as shown in Fig. 2. Assume that the air gap is 1 cm, and the capsule diameter is 0.98 m. From Fig. 2, at $V'_c = 19$ m/s, the TLIM has an efficiency of 80%, and a unit thrust of 23,000 N/m. For a capsule 4 m long, thrust on the capsule is $F_e = 92,000$ N.

Now that we have $V'_c = 19$ m/s and $F_e = 92,000$ N, Eqs. 3-5 can be used to determine the values of V', V, and V_c , Eqs. 1 and 2 can be used to determine α' and n', and Eq. 6 can be used to determine the length of the LIM, L', by using the following assumptions:

$\alpha = 0.2$, n = 500, L = 10 km = 10,000 m, A' = 0.7854 m^2, D = 1.04 m, A = 0.8495 m^2,
$\rho = 1.0$ kg/m^3, f = 0.012, $\mu = 0.015$, $D_c = 0.98$, $L_c = 4$ m, $A_c = 0.7543$ m^2,
$W_c = 2,000$ kg = 19,620 N, $D_d = 0.99$ m, $k_d = 9.99$, $C_D = 373$ and $C'_D = 9,703$.

Note that the values of C_D and C'_D are determined from Eq. 7.

The solution of Eq. 6 is:

V' = 14.1 m/s, V = 13.03 m/s, $V_c = 11.7$ m/s, $\alpha' = 0.123$, n = 500, n' = 1.57, and L' = 51 m.

The foregoing example shows that with a TLIM as short as 51 m, there is only about 1.57 capsules in the TLIM at any given time. However, the thrust generated is sufficient to drive 500 capsules in the pipe over a distance of 10 km approximately. This shows the effectiveness of a properly designed TLIM for pumping capsules in PCPs. The efficiency of 80% is also rather good.

PRESSURE CHANGE

Under steady-state or quasi-steady-state operation, the pressure rise across the LIM due to the capsule thrust on the air, $\Delta p'$, is equal to the pressure drop in the pipe between LIMs, Δp, namely

$$\Delta p' = \Delta p = \frac{n\mu W_c}{A} + f\frac{L}{D}\frac{\rho V^2}{2} \tag{11}$$

where the first term on the right of the equation is the pressure drop caused by contact friction between the capsules and the pipe, and the second term is the pressure drop due to air resistance caused by the pipe.

Using Eq. 11, the foregoing example yields a pressure change of $\Delta p = \Delta p' = 183$ kPa which is less than two atmospheres. Had the pressure been much higher, the assumption of incompressible flow would have been grossly violated, and a more complicated approach using compressible flow equations such as given by York [12] would be necessary.

OPTIMIZATION OF LIM

The foregoing description shows how the quantities F_e, V'_c, V_c, V', V, α', n, n', L' and Δp can be calculated for each case in a step by step manner. At a minimum, the number of capsules in the LIM at any given time must be greater than one (namely, $n' > 1$), or else, the operation of the LIM will be discontinuous. To increase the number of capsules in an LIM, one can either use a less powerful but longer LIM, or increase the distance L between neighboring LIMs so that L' will also be longer. The maximum distance L that can be used in a given case depends on practical considerations such as the maximum pressure that can be allowed in a PCP. Many other parameters, such as the efficiency of the LIM pump, must also be optimized in any future application. Such optimization will be part of our future research.

LABORATORY TEST

The purpose of the laboratory test is to check the corrections and accuracy of the predictions made from the derived equations. Once the laboratory test results compare favorably with the predicted values, then the derived equations can be used with confidence for analyzing and designing commercial PCP systems driven by LIMs.

The test system consists of a LIM of 190.5-mm inner diameter and a length of 1.44m, connected to a straight pipe having the same inner diameter as that of the LIM, and having a total length of 8 m, approximately. Most of the pipe is made of transparent Plexiglas so that the motion of the capsule in the pipe can be seen from outside. At the end of the pipe is a PVC

section with a sealed end to be used as a damper or trap to slow down and stop the capsule. The system is illustrated in Fig. 3.
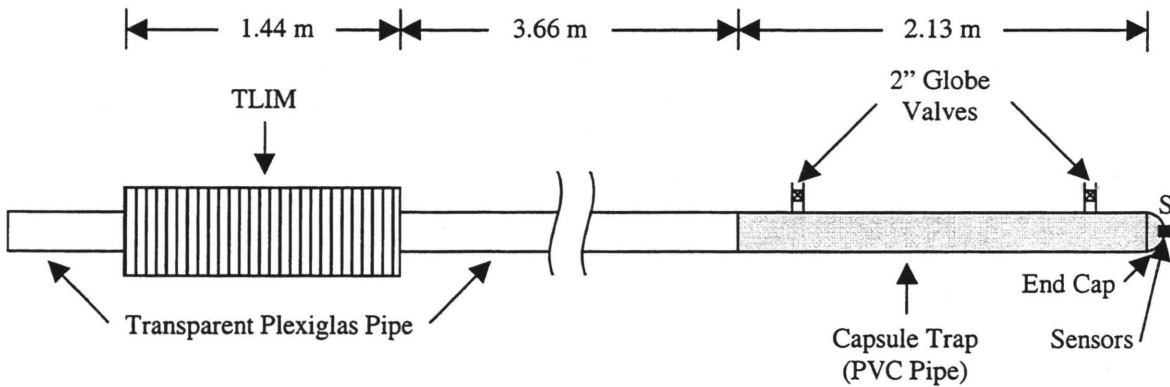
Fig. 3 Laboratory apparatus for testing a PCP-TLIM

The LIM is of tubular type--TLIM. It consists of four identical segments, each having a length of 360 mm which is approximately the same as the capsule length. Thus, the total length of the TLIM is about four times the capsule length. The TLIM is powered by 60 Hz, 3-phase, 220 VAC. Inverters will be used so that the frequency of the input power can be changed to cover a wide range of frequencies for the test. Current transducers will be used to record the current, and power transducers will be used to record the power consumed. The TLIM has been built by Force Engineering Limited in England, and is currently (September 1999) undergoing preliminary test by the company. Then, it will be shipped to Missouri for testing in this special PCP test system. A picture of the constructed LIMs is shown in Fig. 4.
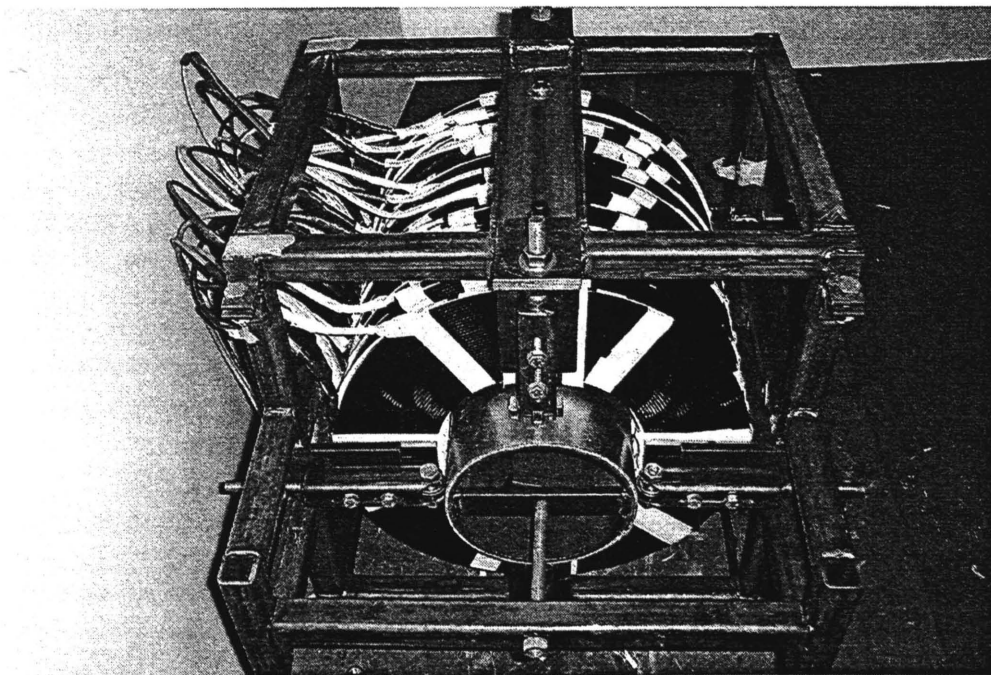
Fig. 4 TLIMs constructed by Force Engineering to be used for laboratory tests

The capsule is a cylindrical body with wheels mounted on both ends. The capsule body is made of a thin-wall steel pipe of 3.2-mm wall thickness. Both ends of the cylinder are sealed by a steel disk of a thickness of 6.4 mm and a diameter the same as that of the cylinder. They are welded to the cylinder or capsule ends. The cylinder wall also contains an aluminum outer layer where the electromagnetic eddy current and the thrust force are produced. To vary the air gap, three capsules of different diameters will be tested: 178, 181,and 184 mm. The weight of the capsules can be adjusted by filling sand into them. When empty, each capsule weighs about 10 kg; when filled with sand, it will weigh about 35 kg.

Special capsule sensors will be mounted both in the LIM and along the pipe to measure the capsule acceleration in the LIM, and deceleration in the pipe.

PILOT PLANT TEST

Before the LIM-based PCP system can be used reliably in costly commercial projects, it should be tested at a sufficiently large scale--a pilot plant. The pilot plant test will not only demonstrate the technical feasibility of LIM-based PCP, it will also provide needed data that can be used for the design of commercial systems, in order to insure the success of the first commercial demonstration project. Furthermore, construction of the pilot plant will also provide some cost data, such as the cost of large LIMs, and the cost of the capsules. Such cost data are needed for accurate determination of the cost of commercial systems, and for analyzing the economic feasibility of LIM-PCPs under various conditions.

Due to the large size of the LIMs and the pipelines used for the pilot plant test, construction of the pilot plant is expected to be costly. The cost can be reduced if existing pipeline system can be used. Two potential candidate facilities for the tests are under consideration. The first is the Flow Loop facility owned by the Gas Research Institute (GRI) and operated by the Battelle Company in Columbus, Ohio. This flow loop is made of a 600-mm steel pipe 1.4 km long. The facility is currently used for testing pipeline pigs (scrapers) used for inspecting pipe interior. With minor modifications, it can be used for testing PCP-LIMs. The second candidate is a 914-mm pipe approximately 1 km long, owned by the Willbros Engineers, Inc. in Tulsa, Oklahoma. The facility was used in the past for testing a commercial system of PCP, but is not used currently and is in disrepair. It can be renovated for the pilot plant test. Therefore, finding a test site for the pilot plant test is not difficult. What is more difficult is the acquisition of the funds needed for constructing the pilot plant and running the tests, estimated to exceed one million U.S. dollars.

With careful planning and adequate financing, the pilot plant test can be completed in two years. Then, the first commercial LIM-PCP system can be undertaken.

CONCLUSIONS

Based on the results obtained so far from analyses, tentative conclusions can be reached:

1. LIM is a practical means to provide the thrusts needed for powering or driving PCPs. The analytical results did not reveal any difficult problem associated with PCP-LIMs; the results look promising.

2. Efficient LIMs require small air gaps and a capsule speed slightly smaller than the synchronous speed of the LIM so that the slip can be kept a minimum.

3. For each PCP, the LIMs should provide the required thrust at or near peak efficiency. This involves optimum design of the LIMs.

4. By combining the fluid mechanics equations with the electromagnetic equations governing LIMs, the performance of LIM-based PCPs can be predicted.

5. For PCP at high linefill rates (say, 20%), the capsule-to-pipe contact friction is much higher than the fluid friction or resistance. In such a case, the thrust and power that must be provided by a LIM are almost linearly proportional to the contact friction coefficient μ and the capsule weight W_c. Decreasing μ and W_c will decrease the need for high thrust and large power. Therefore, capsules should be designed with low friction coefficient μ, and low deadload.

6. Much remains to be studied before an optimum commercial LIM-PCP system can be built and used reliably and efficiently. The required study involves an optimal design study, and testing both laboratory and pilot-plant scale systems.

ACKNOWLEDGEMENT

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Corridor Selection in Texas as Part of a Freight Pipeline Feasibility Study

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ABSTRACT

The purpose of this research is to describe the process that TTI is using to choose the appropriate corridor for analysis within the larger freight pipeline feasibility study. Three types of potential corridors are examined: intra-city, inter-city, and trans-Texas. The criteria for selecting potential corridors are chosen in an attempt to make the freight pipeline system economically viable. Economic viability means the defrayment of social costs, such as road construction and maintenance, and the ability to attract potential customers. The defrayment of social costs can be measured by the volume of trucks and miles traveled along different corridors. Other criteria, such as factors which affect modal shift, can be measured as the number of modal shift transfers per distance traveled. We find that the most probable corridors suited for a freight pipeline would be a trans-Texas system to capture both domestic and NAFTA traffic.

INTRODUCTION

The Texas Transportation Institute (TTI) received a federal earmark in the recent Transportation Efficiency Act for the 21st Century (TEA-21) legislation to research the feasibility of developing a freight pipeline system in Texas. The purpose of this paper is to describe the process TTI is using to choose the appropriate corridor for analysis within the larger freight pipeline feasibility study. A brief overview of the study provides the motivation for establishing the corridor selection criteria. Next, various types of corridors and examples of such corridors are provided. Lastly, a hypothesis is presented as to the types of corridors which are best suited for a freight pipeline. Data pertaining to existing and potential commodity flows (flows which could, under the proper circumstances, be shifted to a freight pipeline) are used to support the hypothesis.

TTI's freight pipeline study, sponsored by the Federal Highway Administration (FHWA) and the Texas Department of Transportation (TxDOT), stems from an appropriation in the TEA-21. It is being investigated as a possible means of alleviating some of the problems associated with growing traffic congestion on major highways and meeting the transportation capacity needs of the next century. A properly engineered and implemented freight pipeline system could alleviate some of the congestion attributed to truck traffic. Additionally, a freight pipeline could potentially serve to offset some of the construction, maintenance, pollution, and congestion costs associated with vehicular transportation.

Not only does Texas contend with intrastate truck traffic, the State also experiences more than 5,233,803 vehicle miles of NAFTA truck travel per day (TxDOT, 1996). The shift of freight from trucks to pipelines may alleviate some traffic congestion, but, in the final analysis, a system such as this will work only if the economics appeal to users. In fact, freight pipeline

viability has different connotations depending upon the perspective of the interested party. For the purposes of this paper, the interested parties are described as anyone having a financial stake in the development or operation of a freight pipeline system.

Viability from the State's perspective could mean realizing a lowering of the cost of the infrastructure required to move a ton-mile of freight in an added highway lane versus a freight pipeline system. Or viability could include the lowered cost of maintenance of state roads relative to the construction of a freight pipeline. Viability from the perspective of a private investor could mean finding that the operating cost of a freight pipeline system per ton-mile is less than that of truck transportation.

As a means to determine the economic viability of a freight pipeline system in Texas, TTI is conducting a four and a half year study (1999-2004), consisting of three major research areas: (1) Political issues, (2) Costs of differing technologies, and (3) Freight movement along corridors. Political issues are considered to be all issues outside of technological and economical issues which could affect the ultimate viability of a freight pipeline system during planning, construction, or operation. Political issues are driven by various groups. These groups may consist of competing transportation industries, political entities, environmental groups, land owners, or others. A degree of support for a freight pipeline system is necessary from these factions for the project to move forward smoothly. One particular political issue that will be evaluated relative to both the state or federal government is that of the right of eminent domain. Eminent domain may be necessary to facilitate right of passage through public and private lands. Some have contended that without some form of eminent domain, a freight pipeline system will be infeasible.

The next major research area is cost determination. Identification of available technologies is the first step in this process. Next, the fixed or capital costs associated with building the pipeline and the costs of operating the system (marginal costs) will be assessed. Capital costs are those costs which are independent of actual freight movement. Major capital costs are the pipe elements themselves, the guide way and propulsion systems, and the hardware required for command and control. The marginal costs, on the other hand, are directly impacted by the amount of freight moved since the greater the amount of freight moved, the greater the energy requirements (and hence energy costs) to move the freight. All of the operational costs, i.e. energy consumption, maintenance, management, technicians will be unitized by dollar per ton-mile accounting for several pipeline scenarios.

Further research activities will catalog freight size and freight movement between origins and destinations in Texas. The potential size of the system, along with terminal location decisions will depend upon the freight that is moving along candidate corridors as well as assessments as to the quantity that could potentially be shifted from trucks to pipelines. Lastly, a linear programming transportation model will minimize the cost subject to volume, weight, and quantity of freight moving within a given corridor.

The fixed and marginal costs will be determined for the optimal technical scenario and applied to three cases: (1) the case where the public sector is involved in the construction of the infrastructure, (2) the case where the freight pipeline system is privately owned and operated, and (3) the case where the public and private sectors join to construct and operate the system. The optimization model will determine for each case whether the quantity of freight moved, with assumptions about revenue, can offset the cost of construction and marginal costs of operation.

TTI's research begins by identifying potential corridors for the study. It is not feasible for all truck corridors to be studied, so criteria was developed to guide the selection of candidate corridors. Corridor selection is based on criteria which aids the State in achieving its transportation goals. TxDOT's goals address the improvement of public welfare, the reduction of congestion, and the improvement of safety on Texas' highways. Ultimately, these goals directly relate to the expenditure of tax dollars. To reduce congestion, the State is under pressure to build more highway infrastructure. To improve safety, the Department invests in a wide array of programs, design innovations, and roadside safety accoutrements. The criteria which supports these goals will also be the criteria which focuses, ultimately, on the economic viability of an alternative freight transportation system. By selecting an appropriate pipeline corridor, comparisons can be made between a functioning pipeline system and the cost of maintaining or building new highway infrastructure.

We define the primary criteria as current and future traffic levels. Related to this will be an assessment of the potential to induce freight traffic from other modes, i.e. modal shift. The corridors selected for study should have the real potential to slow the growth of highway congestion brought about by increased truck traffic. By extension, these corridors should be able to favorably impact air pollution production in Texas and allow for land use other than road construction. Other considerations for corridor selection will include an assessment of the potential to access other transportation modes and potential for expansion.

Choosing the correct corridors for initial study is a mandatory first step in finding viable corridors for freight pipeline. As mentioned earlier, the amount of freight which can potentially be shifted from highway to pipeline will help determine feasibility. The alternative corridor classes TTI will consider include intra-city, inter-city, and trans-Texas corridors.

Intra-city corridors can be defined to include certain metropolitan areas subsuming one or more major cities. Dallas-Fort Worth is an example of a Texas metroplex with the potential for freight transportation via freight pipeline. Houston and any other large city could also be considered as a candidate for assessment. Inter-city corridors, as contrasted to intra-city corridors, would link markets in cities separated geographically. Dallas to Houston, Dallas to San Antonio, Houston to San Antonio would all be examples of inter-city corridors with the potential for freight traffic. Lastly, a trans-Texas corridor has terminal ends near or outside of the border of the State. New Orleans to El Paso or Houston to El Paso would be examples of a trans-Texas corridor.

Corridor selection, whether intra, inter, or trans-Texas will depend on assessing traffic and market factors deemed critical to the economic success of an alternative mode of transportation. It may be that an additional consideration, one pertaining to geo-political issues,

will "tip the scales" toward selection of a corridor that maximizes the benefits to the citizens of Texas. These benefits, which are economic in nature, address the ability of a freight pipeline system to divert substantial volumes of truck traffic from Texas highways to something else. In the best case scenario, the diversion would focus on "foreign" trucks (either domestic, non-Texas based trucks, or Mexican and Canadian trucks) which use Texas roadways, but do not pay proportionately for the construction or maintenance of the state's highway system.

For practicality's sake, all three corridor types will not be studied extensively. However, an initial review applying two criteria, congestion and the potential for modal shift, will aid in revealing which corridors are most suitable for the freight pipeline study.

Intra-City

After an initial evaluation, the intra-city corridor type was first to be eliminated from the pool of eligible corridors to be studied. Three principal factors were considered. First, drilling is sometimes necessary to install pipelines in urban areas and the cost of drilling is substantially higher than the cost of trenching. Secondly, potential patrons would be less likely to use the system if the number of transfers (moving materials from one mode of transportation to another) increases. This is especially true for such a short distance between origin and destination. Also, intra-city freight movement would likely be more time sensitive than freight moving greater distances. Lastly, the criteria of 'access to alternative transportation modes', although possible, becomes discounted in importance when considering an intra-city system due to the excessive costs of drilling.

Inter-City

The elimination of the intra-city corridor leaves the inter-city and the trans-Texas alternatives. An inter-city corridor may be appropriate considering that 86% of the truck traffic in Texas has a Texas destination (TxDOT). However, other considerations besides traffic levels may influence potential freight pipeline customers. As mentioned earlier, one of the factors which influences modal shift potential is cost. It may be the case that the terminal locations for an inter city freight pipeline system would only be convenient for a select group of customers. Also, freight pipeline transportation could conceivably be slower than truck transportation. Consumer goods which travel shorter distances are typically time sensitive.

Trans-Texas

A trans-Texas corridor may be the most appropriate corridor since it could capture both NAFTA traffic and some inter-city traffic. One measure of corridor appropriateness could be truck movement through particular areas. Tables 1 and 2 show how truck traffic in selected border towns has changed since the inception of NAFTA. The three cities with the most tuck traffic in 1999 are represented in these tables; Laredo, Brownsville, and Pharr. As the data shows, the highest number of trucks moving in and out of Mexico are going through Laredo.

Over the past five years, 1995 through 1999, the overall percentage changes into and out of Laredo are approximately 153% and 61%, respectively. Pharr has a much greater percentage change in truck traffic going into and out of Mexico, approximately 2010% and 370%, but the overall number of trucks are much lower than Laredo and the major growth occurred in 1997 with a tapering off of growth since that time. Brownsville has the third highest truck traffic. This city has had an approximate growth in truck traffic of 53% over the last five years, but has seen roughly even levels of traffic out of Mexico.

Truck counts are necessary when measuring traffic relative to a stationary point. Other measures important to potential corridor selection are vehicle miles traveled (VMT) by corridor and the amount or volume that is moved on each corridor. Table 3 provides vehicle miles traveled on each major corridor for all truck traffic and provides the average volume of NAFTA trucks. The locations of the different corridors are pictured in Figure 1 which shows the volume of NAFTA truck traffic carried on major highways by depicting the level of volume with bandwidth. IH-35 is the most heavily traversed with all types of trucks, NAFTA trucks, as well as average volume of NAFTA trucks. The average *daily* volume of NAFTA trucks along the 589 mile IH-35 corridor was 2,809 trucks in 1996 and the average daily VMT for was 4,477,244 (Table 3). Given the percentage change increase in border truck counts in Tables 1 and 2, one may assume that the 1999 average daily VMT and average daily volume of trucks, has increased significantly over the 1996 levels on IH-35 and other corridors carrying NAFTA traffic, as well. The next highest VMT by all trucks is on the IH-10 corridor with 4,167,542. IH-10 also has the second highest daily NAFTA truck VMT, 903,511. IH-20, IH-30, IH-45, IH-40, and US-59 all have total daily VMT of over 1,000,000.

Table 1. Number of <u>January</u> Truck Shipments into Mexico Through Selected Texas Cities (1995-1999) and the Overall Percentage Change in Shipments for Those Years.

	1995	1996	1997	1998	1999	Percentage Change
Brownsville	14,580	16,286	17,680	23,060	22,381	53.5%
Laredo	3,664	37,962	48,194	91,388	92,872	153.3%
Pharr	715	3,411	6,810	13,317	15,092	2010%

*Source: Texas A&M International University

Table 2. Number of January Truck Shipments out of Mexico into Selected Texas Cities (1995-1999) and the Overall Percentage Change in Shipments for Those Years.

	1995	1996	1997	1998	1999	Percentage Change
Brownsville	9,751	8,695	9,757	8,430	9,450	-3.0%
Laredo	31,238	40,579	44,067	43,978	50,411	61.3%
Pharr	**	3,231	12,004	12,173	15,204	37.0%

*Source: Texas A&M International University
**Data not available for this year.

Table 3. Daily Truck VMT, NAFTA truck VMT, and Average Volume of NAFTA Trucks by Corridor for 1996.*

Corridor	All Trucks Daily VMT	NAFTA Trucks Daily VMT	Roadway Length (miles)	NAFTA Trucks Average Volume
IH-35	4,477,244	1,654,573	589	2,809
US-77	636,031	426,327	232	1,838
IH-37	439,753	215,511	129	1,671
US-281	339,015	247,687	164	1,510
IH-30	1,444,034	242,960	223	1,090
IH-10	4,167,542	903,511	875	1,033
US-75	576,102	78,414	86	912
IH-20	3,416,678	443,151	627	707
US-59	1,579,009	318,023	580	548
US-83	140,478	53,016	177	300
US-87/190	461,943	42,120	559	75
IH-40	1,041,379	7,072	181	39
IH-45	1,988,075	5,976	287	21
Other	10,964,419	595,462	20,156	30
Total	31,671,702	5,233,803	24,865	210

*Table reproduced from TxDOT's *Effect of NAFTA on the Texas Highway System*, p.20.
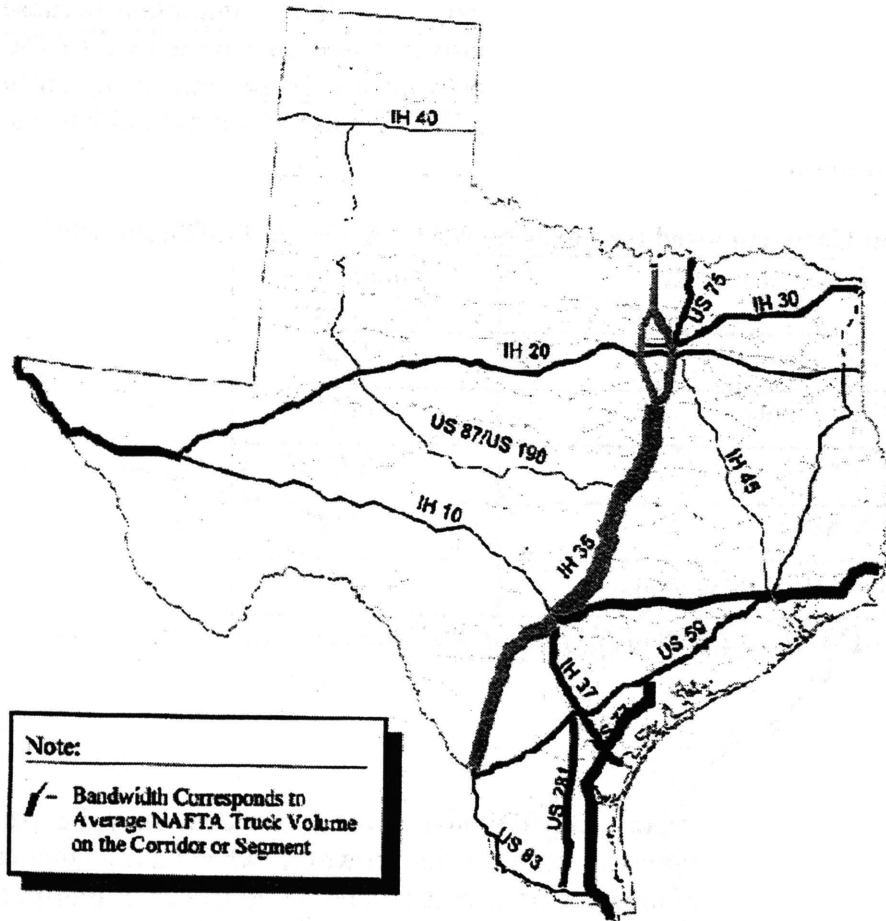
Figure 1. Volume of NAFTA TRUCK Traffic Carried on Major Highways

In "Effects of the North American Free Trade Agreement on the Texas Highway System," the concluding remarks state that NAFTA-related truck travel represented 16.4 percent of all truck travel in 1996. Also, thirteen highway corridors carried almost 90 percent of all NAFTA trucks. IH-35 carried 31.6 percent of all NAFTA-related truck traffic. Also, of the total truck traffic on US-281, 73 percent was due to NAFTA trucks.

While a freight pipeline system would not focus exclusively on NAFTA commerce, NAFTA commerce has a particular role in corridor consideration. Since much of the NAFTA traffic is moving to destinations outside of Texas, the marginal saving of using a freight pipeline system may be relatively greater for these trips than for shorter, intra-state trips. These savings occur because a transition cost is incurred when switching modes. On longer trips, the transition cost may be made up for by the potentially lower cost of operation. Additionally, time may actually be saved up with a pipeline that doesn't suffer service interruptions due to inclement weather or driver fatigue. Hence, the incentive to use a freight pipeline system would be greater for the long-haul patrons. Based on these considerations, the level of NAFTA traffic seems an important consideration.

The measures of volume of trucks and truck miles are doubly important because they translate into social costs. Table 4 shows the annual costs imposed on Texans by NAFTA truck traffic. Since NAFTA truck traffic accounts for approximately 14 percent of all traffic, the potential defrayment of annual costs due to truck traffic with the use of a freight pipeline system could be closer to $950 million.

Table 4. Annual Costs Imposed on Texas by NAFTA Truck Traffic for 1996

Types of Impact	Annual Cost (millions)
Congestion	$ 213.2
Accidents	158.7
Air Pollution	89.7
Noise	49.2
Total Annual Cost	$ 510.8

*Table reproduced from TxDOT's *Effect of NAFTA on the Texas Highway System*, p.20.

CONCLUSIONS

The data from the TxDOT report suggests that several corridors may be potential candidates for study due to the high volume of truck traffic. However, when taking other criteria into consideration, such as potential for modal shift, access to alternative modes of transportation and expansion capabilities, a few corridors stand out: the Laredo to Dallas corridor and the Houston to El Paso corridor (Figure 2), in particular. In examining the Laredo to Dallas corridor, strategically placed freight pipeline terminals north of Dallas and at Laredo, would provide convenient access to NAFTA commerce arriving from several northern states and Canada as well as from Mexico. These terminal locations would access interstate traffic moving north and east of Dallas, as well as being within close proximity to two rail lines north of Dallas.

The Houston to El Paso corridor has access to the Port of Houston and could also pick up NAFTA commerce moving west from Austin. These corridors would also encompass the major intercity traffic between Houston and Austin, Austin and Dallas, San Antonio and Austin, and Houston to Dallas via Austin. However, preliminary evaluation suggests that the greatest modal shift potential exists with traffic moving across Texas to Mexico because there would be relatively fewer transportation shifts, hence transaction costs, per mile traveled.

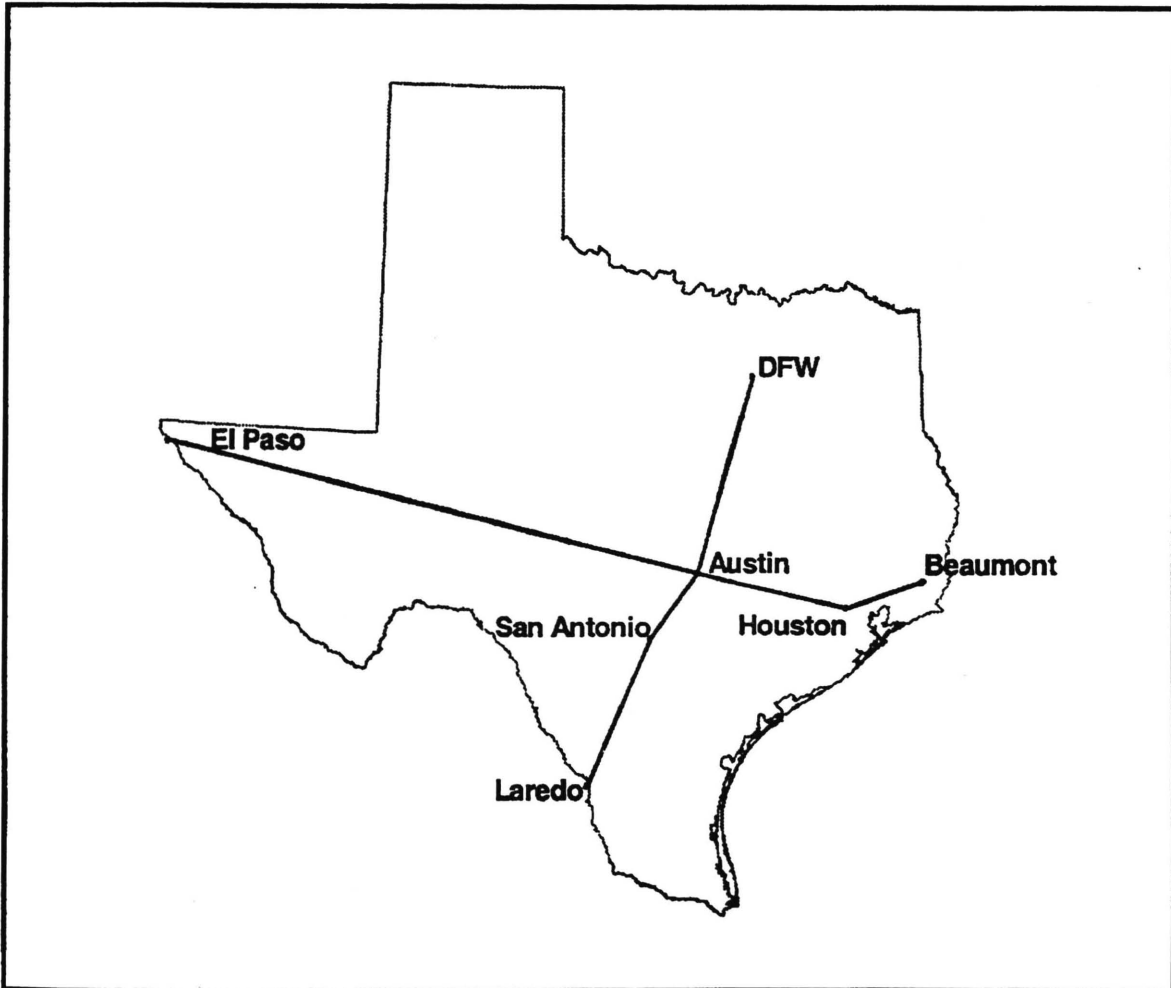**Figure 2. Suggested Corridors in Texas for the Freight Pipeline Feasibility Study.**

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1. *Effect of the North American Free Trade Agreement on the Texas Highway System*, Texas Department of Transportation, December 1998.

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Underground Freight Transport in Urban Areas

Future Transport Concepts for a Sustainable and Intermodal Urban Freight Transport

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ABSTRACT

During the past few years a number of governmental organisations in the Netherlands, together with the private sector and a few scientific research organisations, have focused attention on the innovative power of underground transportation systems for transport of general cargo. This new mode of transport is presented as an alternative to daily truck delivery. In 1997 the "Interdepartementale Projectorganisatie Ondergronds Transport" (IPOT) was formed to study underground transport. IPOT is an interdepartmental organization consisting of representatives from several ministries of the Dutch government, including the Ministry of Transport, Public Works and Water Management. The IPOT task force started with an exploratory study of the feasibility of underground freight transport (UFT). It is estimated in this study that about thirty percent of the domestic freight transport – this represents 245 million tonne per year – is suited for this new concept. Underground freight transport has some important social benefits, such as a decrease in nuisance, energy consumption, and air pollution, as well as a more economic use of space. Other benefits are fewer congestion problems, more reliable transport, and reduced operating costs. On the other hand, a new infrastructure has to be built, which is expensive and will take a long time to complete. The network that is needed will consist of about 4600 kilometres of tubes. The investments that are required will amount to between 25 and 50 billion dollars (US). This paper describes in more detail the approach and the results of the study.

INTRODUCTION

Underground transport of gases and liquids has for many years been a common occurrence in the world. This concerns not only the transportation of drinking water and sewage (and in some countries also natural gas) to households but also the transportation in large quantities of liquids and gases within and between chemical industrial complexes. The NATO tube network for fuel (kerosene) in Europe must also be mentioned. Since 1985 the Dutch national policy for pipeline transport has been covered by a Structure Plan for Tube Systems (Dutch acronym: SBUI). Although transport of bulk goods by pipelines plays an important role next to road, rail and waterborne transport, no attention is paid to it in the current national policy regarding freight transport, particularly in the modal shift-policy of the national government.

During the past few years a number of governmental organisations, with the private sector and a few scientific research organisations, have focused attention on the innovative power of underground systems for transportation of general cargo. This new mode of transport presents an alternative to daily truck delivery. It has some interesting social benefits, such as less nuisance,

lower energy consumption and resulting air pollution, and a more economic use of space. Other benefits are fewer congestion problems, more reliable transport and reduced costs. On the other hand, a new infrastructure has to be built that will be expensive and that will take a long time to complete. The social relevance, and the technical and economic aspects are described in several studies (Haccoû et al., 1996; Brouwer et al., 1997; CTT, 1997). These studies have drawn the attention of a number of politicians, including members of parliament. The Underground Logistic System Schiphol project in particular received a lot of public attention (see the contribution of Pielage). This attention can be explained by the following three important factors:

1. the existing national policies in the field of freight transport have failed to solve the current accessibility and environmental problems related to freight transport by provoking a modal shift
2. the need to achieve a sustainable economic growth, considering the expectation that freight transport in the Netherlands is likely to double over the next 25 years
3. the promising potential (social and economic) qualities of underground freight transport

It is for this reason that the national government wanted to know:
- what the role of the government can and should be in the development of traditional and new underground freight transport systems
- what the social and economic potential qualities of new concepts are
- what the role of these concepts will be in the future transport system and how they can be implemented

In order to find answers for these questions Interdepartementale Projectorganisatie Ondergronds Transport (IPOT), a government task force for the study of underground transport was formed, consisting of representatives from the following ministries:
- Transport, Public Works and Water Management
- Economic Affairs
- Housing, Spatial Planning and the Environment.

The IPOT task force started with an exploratory study of the feasibility of underground freight transport. The first phase of the study took place from September 1997 until March 1998. The progress report, published in April 1998 describes the results of this exploratory study. Phase two started at the end of 1998 and will continue until the end of 1999; this phase concentrates on feasibility studies of local applications of underground freight transport systems, for instance in the Airport Schiphol area, and in the city of Leiden (see the contribution of Visser).

THE OBJECTIVES OF THE EXPLORATORY STUDY

To identify the role of the government, the exploratory study focused on the contribution of new underground freight transport systems (UFT) to government objectives. Therefore the following potential qualities of UFT were to be made clear:
- the increase in efficiency, effectiveness and reliability of freight transport
- the reduction of the burden on the environment, the improvement of traffic (and transport) safety, and efficient use of space
- strengthening of the economic structure

There is little experience as yet with underground transportation of general cargo. It is therefore important to know all relevant aspects of this kind of transportation and to gain insight into the possible effects of its introduction. The following principal question was formulated for the exploratory study:

Is underground freight transport a desirable and viable mode of transport for the 21st century?

The research was carried out by scientists from the research organizations TRAIL Research School, NEA, TNO and Buck Consultants under the auspices of the IPOT task force. The members of the research group had already been involved in earlier studies in the field of underground freight transport. The exploratory study is mainly based on the results of these studies (Haccoû et al., 1996; Brouwer et al., 1997).

Background Studies

In 1994 the Dutch Governmental Program for Sustainable Technology Development (DTO) organized several round table discussions with experts and actors concerned on sustainable technologies for transport in the future (Grontmij, 1994). In these meetings underground freight transport was mentioned as one of the interesting and potentially sustainable technologies for freight transport. Within the framework of this research programme, a definition study (Haccoû et al., 1996) was carried out to determine in more detail the feasibility of underground transport and to define the field of application. This study demonstrated that underground freight transport within urban areas was potentially an interesting, but also a sustainable and competitive, application. The underground transportation system should make use of small diameter tunnels (at maximum approximately 2.4 metres), which means that the introduction of such a system needs radical changes in the way freight is distributed today. But, on the other hand, this concept fits within the current logistical trends of just in time service with smaller and more frequent delivery. The study also concluded that, in the field of urban freight transport, no alternative sustainable transport modes are available in the way that rail and waterborne are available for long distance transport.

The next step within the framework of DTO was to design a logistic concept for underground freight transport within urban areas and to define an implementation strategy. The work was carried out in 1996 and 1997 in a project called an 'Illustration process for tube transportation of freight within urban areas' (Brouwer et al., 1997). This new logistic concept was based on automated transport of commodities through networks of small tubes between shopping areas, residential areas, industrial estates as well as between regions. Automated freight transport through tubes deals with palletised or containerised consumer goods which are transported automatically through a network of underground tunnels or tubes. The load units are relatively small: approximately 1 cubic metre. This concept should provide a solution for the rise of economic and social costs due to traffic growth and the resulting congestion and environmental problems in the long term. The concept can also be placed in a broader perspective. Future transport concepts should provide a solution for the increasing demand for reliable, high frequency, fast transport of consumer goods in relatively small units (that means loads of about one cubic metre or dividable into units of this size), to, from and within urban areas in a sustainable way. The expectations at the moment are that road transport can only handle this demand by generating more freight traffic. This will result in higher economic and

environmental costs. Future transport concepts should provide the infrastructure for a more network based logistic approach. The network approach should lead to better transport performances (more reliable, more frequent and with lower transport costs), a more efficient use of the transport system due to consolidation and should also support the use of other transport modes, such as rail and inland navigation. In the Dutch situation this means that a national backbone network will connect regional networks. The regional networks do not necessarily have to be based on the same transport technology as the backbone network. Underground freight transport is only one of the technological solutions.

APPROACH AND RESULTS

The exploratory study contains a global design of relevant inter-modal or uni-modal concepts of underground freight transport, a goods flow analysis, a technical analysis and a cost-benefit analysis. The outline of the research is shown in Figure 1. The research started in September 1997 and finished at the end of January 1998. The results of the goods flow analysis, the specification of the concepts and the evaluation are presented in this paper.
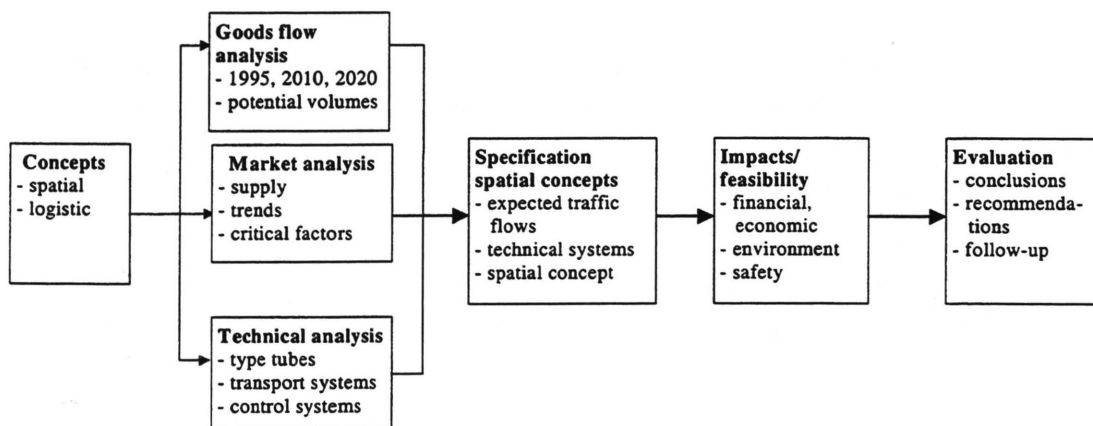
Figure 1. Outline of the Research Projects

Concepts for Underground Transport Systems

Two fundamental aspects of network design need to be analysed: the scale of the network and the inter-connectivity of the network (uni- or multimodality of the network). The scale of the network, the first aspect, can be local, regional or national. For the situation in the Netherlands, the following network concepts relative to scale are defined:
* an 'Urban' network: a system that is implemented in only one city or urban area
* a 'Randstad' network: a backbone network between and a regional network within four large urban areas in the western part of the Netherlands.
* a so-called 'Randstad-plus' network: a 'Randstad' network that also connects important industrial areas.
* a 'National-optimised' network: a national backbone network that connects the 14 most important urban origin and destination areas in domestic transport of consumer goods, in combination with regional networks within those urban areas.

These concepts are based on regional underground networks within the urban areas, and a backbone network that connects the regional networks. Four possible options for interregional transport are considered: road transport, automated freight transport lanes (Combi-road concept), short distance rail transport concept, and automated underground freight transport.
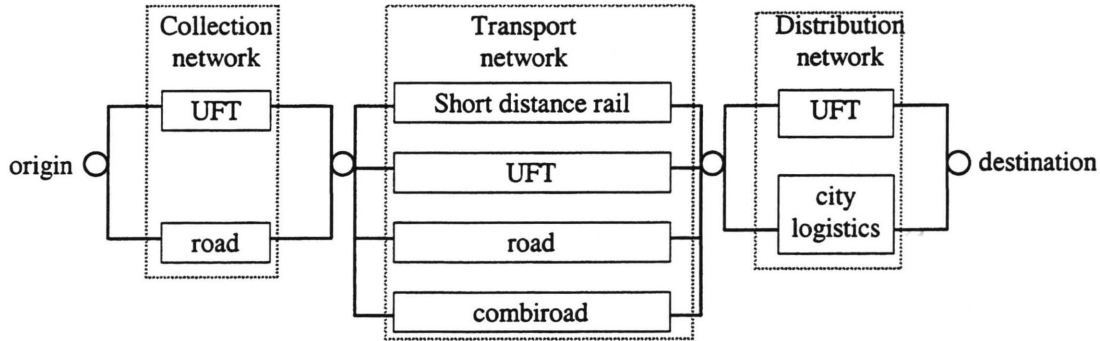
Figure 2. Uni- or Multi-modal Underground Transport Concepts

Goods Flow Analysis

The goods flow analysis was carried out by NEA/DHV (1998). The analysis is based on the long-term prognosis on the demand for freight transport within, to and from the Netherlands for the year 2020. The determination of the potential volumes was done by estimating the percentage of the goods, which answer to certain criteria. These requirements are based on mainly physical characteristics of goods:

- *Type of goods.* It concerns general cargo only. Bulk goods, like ore, chemical or petrochemical products, but also livestock are excluded. Consumer goods are the main focus.
- *Restrictions in size.* The goods must fit within a tunnel or tube with a diameter of about 2 metres. This means a volume of about one cubic metre or less.
- *Safety restrictions.* Dangerous goods, which need to be transported under certain safety conditions, are excluded.
- *Place in the logistic chain.* It concerns transport in the middle or at the end of the logistic chain.

Table 1. Transport Volumes per Transport Flow in the Year 2020

(in million tonnes per year)	1992	1995	2010	2020
Domestic freight	550.3	576.8	796.9	1,005.8
<50 kilometres	333.5	337.4	455.6	558.8
>50 kilometres	216.8	239.4	341.3	446.9
International	703.9	706.6	1,032.5	1,337.0
import/export	368.5	405.7	602.6	806.3
transit	335.4	300.9	429.9	530.7
Total	1,254.2	1,283.4	1,829.4	2,342.8

Source: NEA/DHV, 1998

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Other conditions, such as geographical condition (the origin and destination of transport flows needs to be connected to the new freight transport concept) and commercial conditions (the cost-performance ratio of a new freight transport concept should match with the market conditions of the goods) are not considered.

Two types of goods are selected: consumer goods and general cargo which can both be transported in standard load units, like pallets or mini-containers. In case of the 'Urban' network and the 'Randstad' network the new freight transport concept only delivers transport services between distribution centre and shops (that means at the end of the logistic chain). This means only consumer goods. In the situation of the National-optimised network the transport services are also delivered between production locations and distribution centres (this means in the middle of the logistic chain). Because the network-alternatives are different in that respect, both options have to be worked out. By using the Delphi-method among experts the percentages of the potential volume of goods are estimated for both options. The standard (NSTR-) classification of goods is used. With this information it is possible to estimate the potential transport volumes for each concept alternative of the new freight transport concept. The following table shows the estimated transport volumes. For each scenario tonne-kilometres are also estimated.

Table 2. Estimation of Potential Transport Volumes for New Freight Transport Concept

Scenario	Potential transport volume in 2020 (in million tonnes per year)	Share in modal split (in percentages)
'Urban' network – consumer goods		
- Amsterdam	4.4	14.4 %
- Utrecht	3.2	11.9 %
- Den Haag	1.9	14.3 %
- Rotterdam	5.9	15.0 %
Total	15.3	14.0 %
'Randstad' network – consumer goods		
- consumer goods	70.2	14.1 %
- standard load units	212.1	26.6 %
'National-optimised' network – standard load units		
- standard load units	245.9	30.6%

Source: NEA/DHV, 1998

Specification

The next step in the research process contained the specification of the concept alternatives. In each scenario the characteristics of the network are specified in terms of the number of terminals, infrastructure length and vehicles; the performance of the concept is determined. The results from the goods flow analysis are used as inputs for the specification. With the information from a technical analysis the capacity of the transport system is estimated. Transportation takes place by using load units with dimensions 120 cm (l) x 125 cm (w) x 125 cm (h). The transportation system for the regional network is based on an underground transportation system for freight. Automated guided vehicles carry out transport with the capacity of one load unit per vehicle with an average speed of about 20 kilometres per hour. The network is ring-shaped, with a tunnel or tube with a diameter of 2.0 to 2.4 meters.

The transportation system for the backbone network has been worked out in four alternative concepts: road transport, Combi-road, rail transport, and underground freight transport. Road transport contains articulated trucks with a capacity of about 20 load units per vehicle. The average speed is 45 kilometres per hour. Combi-road is a new concept of automated transport, developed for medium distance transport of ISO-containers. The loading capacity is also about 20 load units per vehicle. Combi-road uses a separate road-infrastructure. The average travel speed is 50 kilometres per hour. The rail transport concept is based on future rail concepts. Existing rail transport specialises in bulk transport and long distance container-transport, and therefore does not have the right requirements for this kind of transport. Based on information of NS Cargo (the Dutch Freight Railway Company) the characteristics of the new rail transport concept are formulated. A train contains 192 load units. The average travel speed is 60 kilometres per hour. Underground freight transport contains the same transportation system as on the regional network. The difference is that the vehicles will be linked up in combinations of about four vehicles. The average speed is increased to 40 kilometres per hour.

Table 3. Main Characteristics of the Transportation System

	Urban	*Backbone*			
	UFT	*road*	*Combi-road*	*rail transport*	*UFT*
Load weight (in tonnes/ vehicle)	0.3	5.6	5.6	53.8	1.2
Max. lane capacity (in vehicles/hour)	1500	1000	1000	40	1500
Max. transport volumes (in million tonnes per year)	2.1	15.7	15.7	9.1	6.9

Source: Visser et al., 1998

The number of terminals in each urban area is determined on geographic information about the size and location of existing industrial zones and shopping areas in urban areas. By using extrapolation, the number of terminals in the year 2020 is determined. The location of the terminals is used to determine the average distance between terminals in the network. The average distance between terminals is about 1.6 kilometre. This also includes remote terminals in satellite living areas. The average distance within city centres is much less: about one kilometre.

Table 4. Number of Terminals Within Each Network Scenario

Network scenario	*'Urban'*	*'Randstad'*	*'Randstad-plus'*	*'National-optimised'*
Urban areas	Utrecht	Amsterdam, Utrecht, Den Haag, Rotterdam	Amsterdam, Utrecht, Den Haag, Rotterdam	14 regions in the Netherlands
Regional transfer/ transhipment points	3	11	11	24
Local terminals	77	592	592	1,411

Source: Visser et al., 1998

The 'Urban' network has been applied to the urban area of the city of Utrecht, while the 'Randstad' and 'Randstad-plus' has been applied to the four main urban areas of the Randstad (Amsterdam, Utrecht, Den Haag and Rotterdam). The 'Randstad-plus' network also connects main industrial areas within the Randstad. Due to a lack of data it was not possible to make this operational in terms of number of extra terminals and network length. In the 'National-optimised' network concept the Netherlands are subdivided in 14 regions. In the study, subdivisions with four, six, and eight regions have also been worked out. The results are not described in this paper.

Network Assignment

Before using the results of the goods flow analysis, supplementary criteria were applied to meet the geographical restraints. In the 'Urban', the 'Randstad' and the 'Randstad-plus' network scenarios, the assumption is made that within the urban areas, stringent restriction measures are taken such that one hundred percent of the potential volume will use the regional UFT network. In the 'National-optimised' network, the percentage depends upon the manner in which the regions of origin and destination of the goods flows are connected to the network. This will be explained later on in this paper. The following table shows the assignment of the transport volumes to the backbone network in the different scenarios.

Table 5. Assignment of the Transport Volumes to the Networks in Each Scenario

Network Scenario	'Urban'	'Randstad'	'Randstad-plus'	'National-optimised'
Type of Goods	Consumer Goods	Consumer Goods	Consumer Goods	Standard Load Units
Regional network	100 %	100 %	100 %	assignment
Backbone network				
- intra-regional	N/A.	0 %	0 %	0 %
- between regions in the Randstad	N/A.	50 %	50 %	assignment
- to and from the rest of the Netherlands	N/A.	0 %	10 %	assignment
- international	N/A.	0 %	0 %	0 %

Source: Visser et al., 1998

In the 'National-optimised' network concept a special type of assignment has been applied. The Netherlands was subdivided into fifty-four zones (traffic zones). Each zone is dedicated to one of the fourteen regions. Each zone within the region is categorised as: local, regional or hinterland, depending on the location of the zone within that region. The assumption is that the distance to the backbone network determines the use of the network. Only the local zones have a (sub-)regional underground freight transportation network. The other regions only make use of the backbone network. For each type of zone, an estimation of the use of the network has been carried out. The percentages are shown in the following table.

Table 6. Assignment in the 'National-Optimised' Scenario

Sub-region	Destination		
Origin	Local(90%)	Regional (50%)	Hinterland (10%)
Local (90%)	81%	45%	9%
Regional (50%)	45%	25%	5%
Hinterland (10%)	9%	5%	1%
Shaded = will be assigned to the regional network			

Source: Visser et al., 1998

Only 45 percent of a transport flow with the origin in a regional sub-region and a destination in a local sub-region will be assigned to the backbone network if the origin and destination sub-regions do not belong to the same region. The network assignment also results in the transport-volume on each link of the backbone network. This information is used to determine the required capacity on each link. The following tables show the network-length and performance of each scenario. The network-length is the total length of the network expressed in single lane or tunnel kilometres.

Table 7. Specification of the Regional Network in Each Scenario

Regional network	'Urban'	'Randstad'	'Randstad -plus'	'National-optimised'
Network length (in km)	123	666	666	1,885
Vehicles	9,634	53,128	53,128	242,909
Transport volume (in million tonnes per year)	3.9	19.7	19.7	91.5
Transport volume (in million ton kilometers per year)	28	155	155	723
Traffic (in million vehicles per year per link km)	196	1,054	1,054	4,904

Source: Visser et al., 1998

Table 8. Specification of the Backbone Network in the 'National-Optimised' Scenario

Backbone Network in 'National-Optimised' Network	Road	Combi-road	Rail transport	UFT
Network length (in km)	2,144	2,144	2,349	2,712
Vehicles	4,360	3,936	393	24,644
Transport volume (in million tons per year)	58.8	58.8	58.8	58.8
Transport volume (in million ton kilometers per year)	5,943	5,943	5,943	5,943
Traffic (in million vehicles per year per link km)	2,123	2,123	221	10,613

Source: Visser et al., 1998

Evaluation

The evaluation step contains the determination of the feasibility of the new freight transport concept, as well as a cost-benefit analysis. One of the difficulties in this part of the research was to construct a consistent reference scenario. Between 1998 and 2020 measures, such as road pricing, will probably be implemented. The question was if these kind of policy measures, and the costs of it, should be included in the reference scenario. Another question was how to incorporate the congestion costs. The reference scenario is based on prognosis for the year 2020 under the assumption that large investments in road infrastructure will be spent on reducing congestion costs. Using the measures taken by the Ministry of Transport to reduce

congestion (not shown here), another scenario for the year 2020 was constructed. Both scenarios are used as references. The calculations for the evaluation were based on available information. This means that the results can only give a rough impression of the quantities. Only very rough information on costs and emission parameters of new transport systems is available. In addition, only rough indicators are used. For instance, the reduction of the congestion cost is used as an indicator for the reduction of the transport costs and the improvement of the quality of transport. Other savings like logistic trade-offs are not considered. The evaluation has been carried out on a limited number of scenarios. Only the concepts with underground freight transport within and between regions are considered.

Table 9. Evaluation of Financial Aspects

	Reference 2020	'Urban' Network	'Randstad'	'National-Optimised'
Performance (in billion ton kilometers per year)				
UFT	0	0.03	0.65	6.67
Road transport	55.3	-0.03	-0.65	-6.67
Share freight on roads	23.0 %	23.0 %	23.0 %	21.0 %
Investment costs (in billion guilders)				
UFT	0.0	1.9	14.9	55.5
Road	83.9	-0.1	-1.6	-15.5
Balance	83.9	1.8	13.3	40.0
Exploitation costs (in billion guilders per year)				
UFT	0.0	0.2	1.3	4.5
Road	42.2	-0.1	-0.7	-5.0
Balance	42.2	0.14	0.64	-0.47

Source: Dullemond and Dekker, 1998   *(One Guilder = 0.41 in American Currency as of 08/01/00)*

Table 10. Evaluation of Social Aspects

	Reference 2020	'Urban' Network	'Randstad'	'National-Optimised'
Congestion costs (in million guilders per year)				
Reduction	2,290.0	-6.0	-87.0	-339.0
Reduction emissions (in million kg per year)				
CO_2	18,600.0	-2.0	-200.0	-1,800.0
NO_x	202.0	-0.1	-2.4	-24.4
Particles	14.1	-0.01	-0.2	-1.7
C_xH_y	49.8	-0.03	-0.6	-6.0
Saving space use (in hectare)				
	p.m.	p.m.	-60	-600
Safety compared to 1995 (percentage, only severe casualties)				
Reduction injured persons	3,487	-0.1 %	-1.2 %	-12.1 %
Reduction deaths	727	-0.1 %	-1.2 %	-12.1 %
Reduction hindrance (in number of houses)				
Noise (> 55 dBa)	0	-1,000	-5,300	-27,000
Noise (< 55 dBa)	0	-4,000	-24,300	-140,000
Visual	0	-1,000	-2,600	-13,700

Source: Dullemond and Dekker, 1998

The reference scenario shows that an investment of about 84 billion guilders (approximately $34 billion in American currency) in road infrastructure is needed to facilitate urban freight transport within urban areas. The new freight transport system with underground freight transport needs an investment of about 55.5 billion guilders ($22.8 billion in American currency). The investment in underground freight transport also leads to lower exploitation costs, due to transport automation. The cost savings are less than was expected at the start of the study. The evaluation also shows that there is a reduction in emissions, an improvement in traffic safety and a reduction in hindrance. Particular the reductions of CO_2 and NO_x are interesting from an environmental point of view. The new freight transport concepts offers the opportunity to meet the policy objectives; this seemed not possible with current policy measures.

CONCLUSIONS

The project offered the opportunity to analyse new freight transport concepts in a rough way. The conclusions from the study must be considered as preliminary. At maximum, one third of the transport volume in the year 2020 can be transported by the new freight transport concepts. The scale of the network and market conditions will dictate the transport volume to be expected in the year 2020. New freight transport concepts need large investments but generate large economic and social benefits. Implementation on a national scale generates the highest economic and social benefits. Small scale implementation will probably face exploitation problems. From a policy point of view, the development of such a system on a national scale is the most interesting option. Although the new freight transport concepts based on rail, road and Combi-road are not evaluated, the expectation is that these concepts are also promising, particularly from a costs point of view, but that they still need to be worked out.

The results of the study look promising but there are still too many uncertainties that have to be studied. Innovations like underground freight transport need more research and development. Also a lot of effort needs to be put into developing rail or other concepts which can be used for transport of general cargo over short and medium distances. Implementation, especially of underground freight transport, requires a long-term strategy. This strategy contains the construction of the physical and organisational network, as well as a change of the spatial-economic structure of the distribution and trade of goods. Spatial concentration of distribution centres, depots and warehouses stimulates consolidation and makes it possible to connect these concentrations to the multi-modal network in a sufficient way.

The project team IPOT decided in 1998 to concentrate on feasibility studies of local applications of underground freight transport systems. The following studies were started: OLS Leiden, OLS Utrecht, OLS-DSM Geleen and OLS KAN (area Arnhem-Nijmegen). Also a laboratory for testing vehicles and control systems for underground freight transport will be build and operational before the end of the year 1999. Finally, two others study will be carried out; a more detailed goods flow analysis and a design study on a national backbone network.

ACKNOWLEDGEMENTS

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OLS-Schiphol, a Pilot Study for Automated Underground Freight Transport in the Netherlands

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ABSTRACT

Transportation by road is becoming a problem in the area of Schiphol Airport and the flower auction-mart at Aalsmeer in the Netherlands. The deteriorating accessibility, congestion of traffic and growing costs increasingly threaten the position of the airport and flower auction-mart. An underground logistic system (called OLS) will help solve the problems. The goal of the OLS is to transport flowers and time-critical aircargo through an unmanned underground system, thereby reducing the growing road traffic and creating an undisturbed connection between the airport, flower auction-mart and international railways.

The approach taken to the pre-design phase of the OLS is to generate plausible options for the method of transport, materials handling and terminal layout, within the constraints imposed by the logistical functions of the OLS. This will permit the assessment of the technical and financial feasibility of the OLS. The constraints and logistical functions have been formulated and several concepts for the method of transport, materials handling and terminal layout are being developed. This paper discusses the current state of the OLS project and will give an overview of the transport technological aspects.

INTRODUCTION

Transportation by road is becoming a problem in the area of Schiphol Airport and the flower auction-mart at Aalsmeer in the Netherlands. The deteriorating accessibility, congestion of traffic and growing costs increasingly threaten the position of the airport and flower auction-mart. An underground logistic system (called OLS) will help solve the problems. The goal of the OLS is to transport flowers and time-critical aircargo through an unmanned underground system, thereby reducing the growing road traffic and creating an undisturbed connection between the airport, flower auction-mart and international railways.

The project started with a feasibility scan, which was completed in January 1996. The general conclusion was that the OLS could make an important contribution to improve the accessibility of the Schiphol area and reduce the pressure on the environment. The next phase, the definition phase, was completed in January 1997. This introduced some financial and technical transparency. The findings of the feasibility scan were examined and first steps needed for the design phase were taken. Currently work on the pre-Design phase is in progress and this will be completed in December 1999. We plan to start the actual design phase in the year 2000 and the OLS at Schiphol should be operational in 2004.

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The project is an initiative of Schiphol Airport and the flower auction-mart in Aalsmeer. The research is funded partly by the government and partly by other participating companies. The OLS is a complex project, if only because of the many parties concerned. To structure the research, two main clusters have been distinguished: the transport technology aspects managed by the Center for Transport Technology (CTT) and the civil engineering aspects managed by the Center for Underground Building (COB). This paper focuses on the transport technology aspect of the OLS and draws heavily on the collections created within the CTT cluster [1]&[2].

The proposed route for the OLS is shown in figure 1. The figure shows one railterminal at Hoofddorp (left), three terminals at Schiphol (center) and one terminal at the flower auction-mart in Aalsmeer (bottom right). Underground tunnels will connect the terminals. A mixture of building methods will be used. Two single-track sections will be built by boring underground. The double-track section at Schiphol will be built by the cut and cover method. The distances Hoofddorp-Schiphol and Schiphol-Aalsmeer are approximately 5 kilometers each. The investment needed to construct the OLS is estimated at NLG 450 million (≈ USD 220 million).
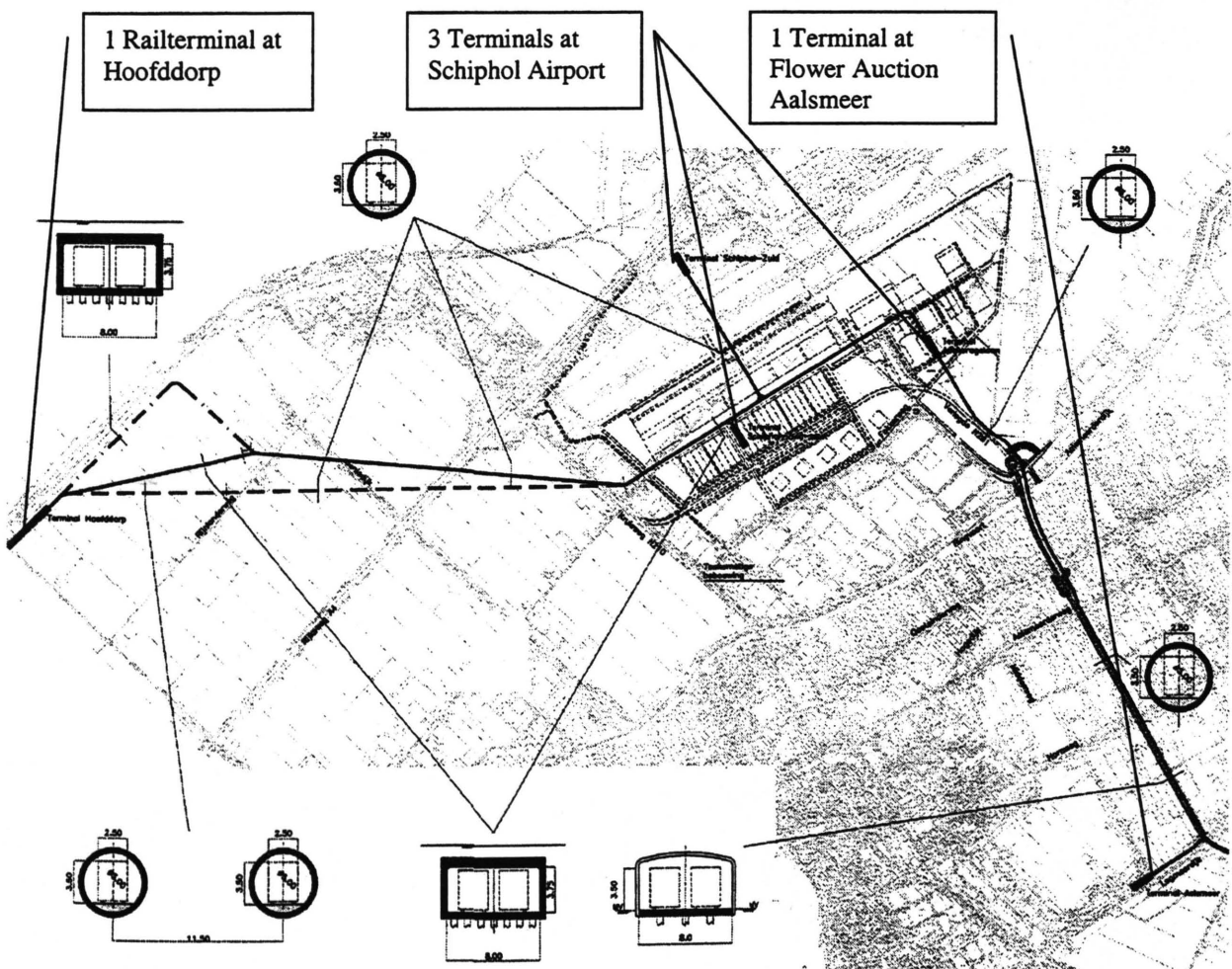
Figure 1. Proposed Route for the OLS.

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SYSTEM DEFINITION, TYPES OF CARGO AND TRANSPORT PROGNOSIS

The OLS system can be presented as shown in figure 2. The center represents the OLS system itself as a link between the flower auction-mart, airport and railway. At the interfaces cargo and information move from one system to the other.
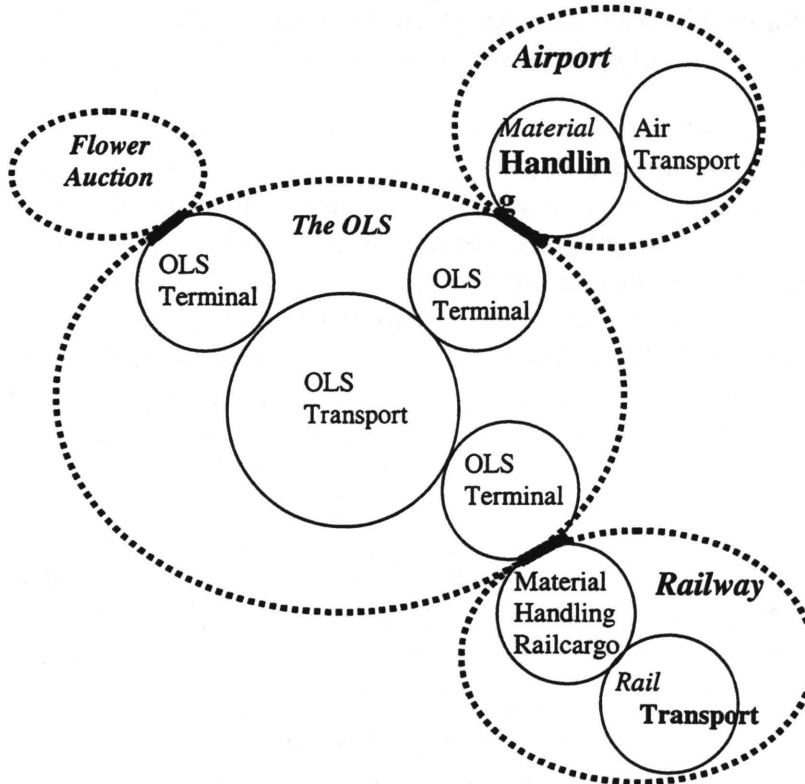
Figure 2. The OLS System

The OLS system can be divided into two subsystems; terminals and transport. The terminals take care of the interfaces with all the different clients on one hand and, on the other hand, attend to the transport system. The transport system focuses on the actual transport of cargo between terminals.

Several types of cargo must be transported by the OLS. Figure 3 gives an impression of the different types of cargo with their different dimensions.
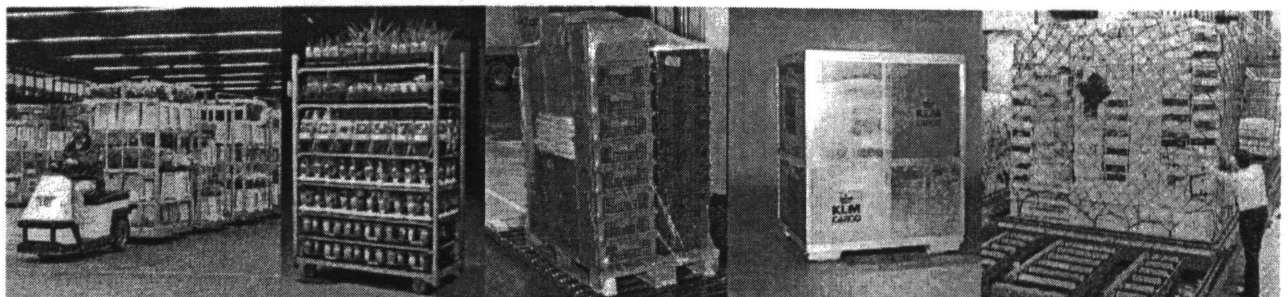
Auction cart	Danish cart	(euro/industry) pallet	Airmodule container	10 ft. pallet
lxwxh = 130x104x260 [cm]	lxwxh = 135x57x240 [cm]	lxwxh = 120x80/100x240 [cm]	lxwxh = 122x102x150 [cm]	lxwxh = 318 x 244 x max300 [cm]

Figure 3. Impression of Different Types of Cargo to be Transported by OLS.

Because of the many different types of cargo, a more standardized transport unit is needed. A better description of the amount of cargo to be transported is then possible. Figure 4 shows the defined transport unit (called TRE) which has a length and width equal to the 10-ft. main-deck aircraft pallet (3180x2440 mm). A TRE can exist of one 10-ft. aircraft pallet or six (euro/industry) pallets or eight danish carts or 4 auction carts.
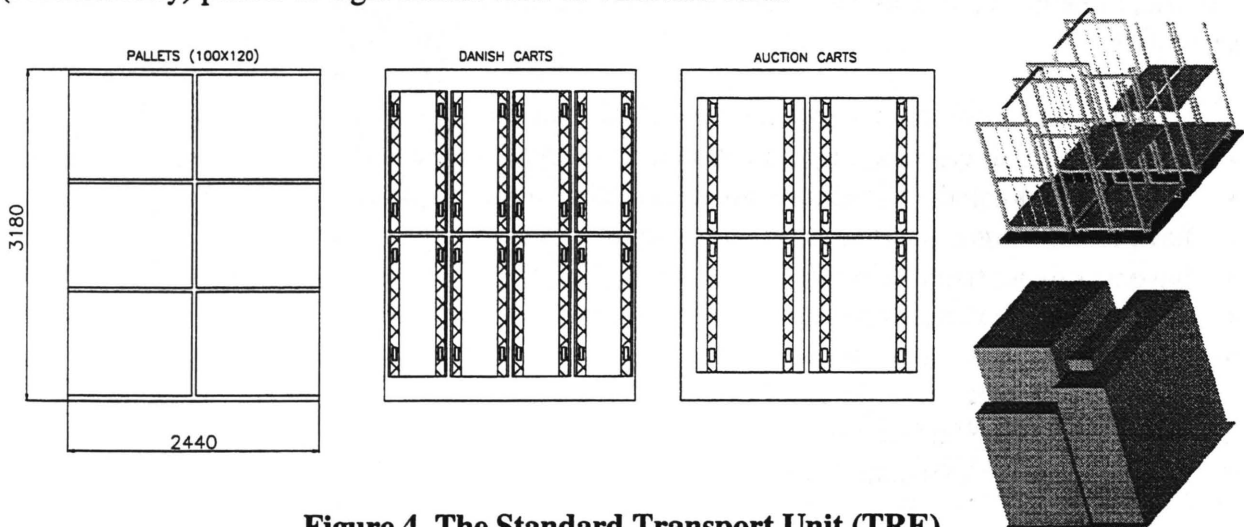
Figure 4. The Standard Transport Unit (TRE).

Predicted transport volumes for 2020 are presented in figure 5. With the transport unit (TRE) defined in the previous section, the Ton per Year can be expressed in TRE per Year.
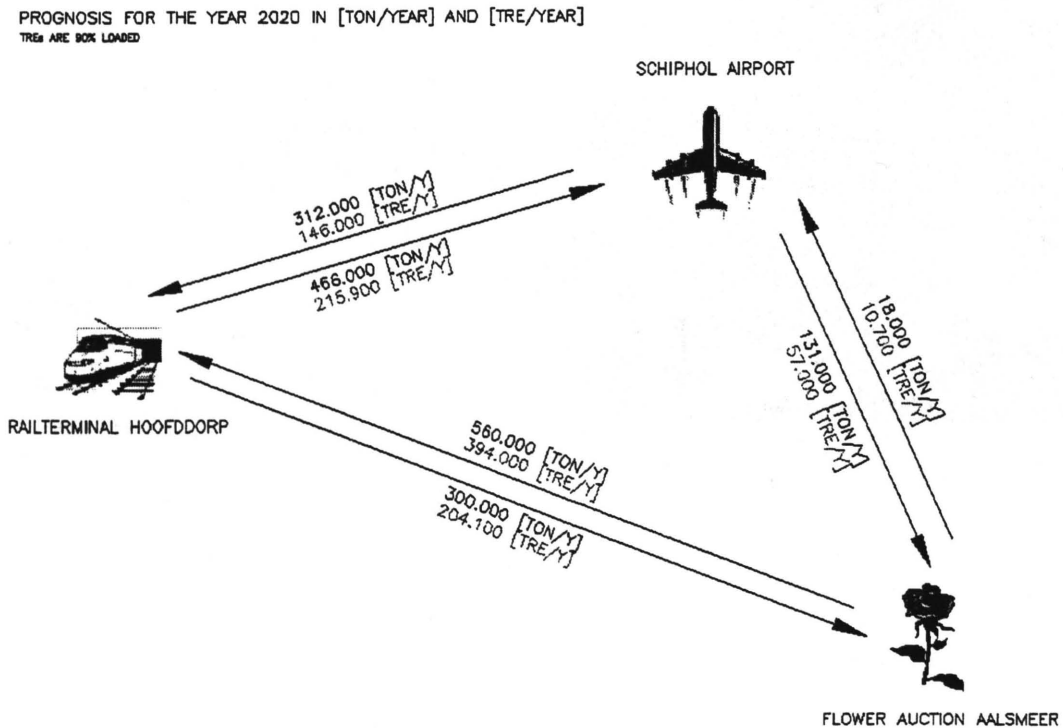
Figure 5. Prognosis Transport Volumes in 2020

METHOD OF TRANSPORTATION

The method of transportation is usually one of the first aspects to be considered in the whole system when designing a transport system. Several different concepts are available. Three different vehicles are being developed for the OLS project. This section describes the general specifications for all three vehicles and presents them and their different characteristics separately.

General specifications, for all three vehicles are that they:
- can transport all types of cargo mentioned in the previous section
- are fully automated. (all vehicles are Automated Guided Vehicles - AGV's)
- have electric drives (self-sustaining on terminals)
- have a cruising speed of 6 m/s (10 m/s optional)
- are capable of taking slopes up to 12% at a minimum speed of 3 m/s
- have a maximum acceleration of 1 m/s^2
- have a maximum deceleration of 2 m/s^2
- are "free ranging" on terminals
- have a speed on terminals of up to 2 m/s

A company called Spykstaal in the Netherlands is developing the first vehicle. An impression of this AGV is given in figure 6. The specific characteristics are:
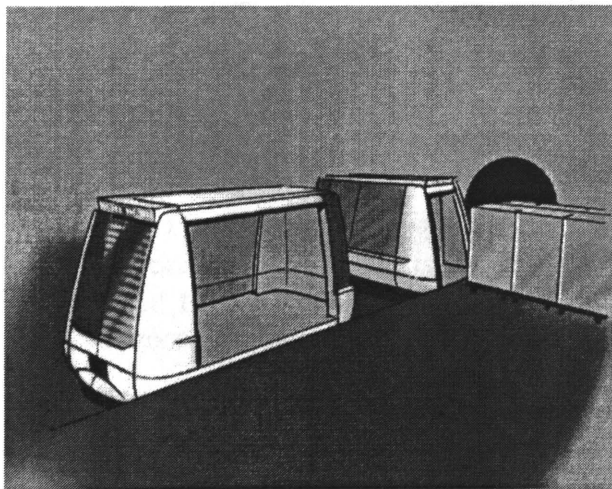
- rubber tired AGV
- full electronic guidance
- front wheel steering
- wheels under loading deck
- front and side loading
- DC electric drive
- battery powered

Figure 6. Impression of the Spykstaal AGV

A more conservative approach to vehicle design has been followed. Proven technologies are being applied to generate a solid and reliable vehicle. However, the loading and unloading of the vehicle is more innovative as carts are loaded and unloaded through the front of the AGV and pallets through the side. More information on the material handling can be found in the following section.

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The second AGV developed by Lödige in Germany is shown in figure 7. Its characteristics are:
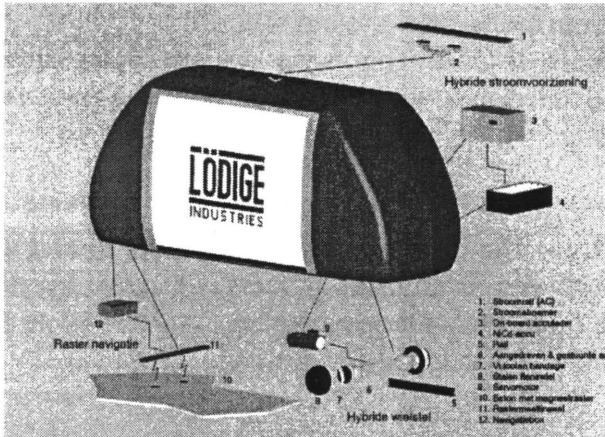
- rail mounted AGV in tunnel and rubber tired on terminal
- rail guided in tunnel and electronic guided on terminal
- four wheel steering
- loading deck between wheels
- side loading
- AC electric drive
- battery powered on terminal and powered by powerrail in tube

Figure 7. Impression of the Lödige AGV

Here a vehicle with a hybrid character is being developed. Both, power supply and wheel type are tailored to the desired function and physical properties of the surroundings. The vehicle is rail mounted in the tube and powered by a power-rail. On the terminal more flexibility is desired and the vehicle leaves the rails and continues on Vulcolan tires. The power supply on the terminals is delivered by battery, which is charged during the travel period in the tube.

The third AGV is called the DTM (Delft Tunnel Mover) and is being developed by a company in The Netherlands called "Machinefabriek Braband van Opstal". The specific characteristics of this vehicle, presented in figure 8, are:
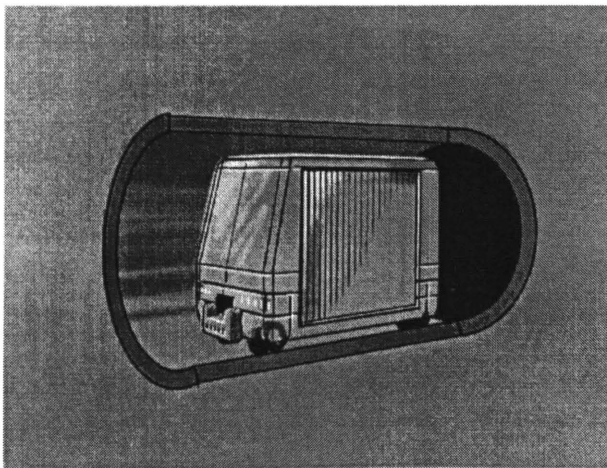
- rubber tired AGV
- self guidance in tube (wheels on tube surface) electronic guidance on terminal
- front wheel steering
- loading deck between wheels
- side loading
- AC electric drive
- battery powered

Figure 8. Impression of the DTM by "Machinefabriek Braband van Opstal"

This innovative vehicle will drive on the circular tunnel surface. The rubber-tired wheels have a self-centering mechanism, which guarantees a right angle between wheel and tunnel surface. The tube thus guides the vehicle, making guide-mechanisms in the tube unnecessary.

TERMINALS AND MATERIAL HANDLING

The terminal is one of the main subsystems in the OLS system. Terminals form the link between the OLS transport system and the clients of OLS. The cargo systems at the airport, railway or flower auction-mart must have good interfaces with the OLS-system. This section presents the terminal design and materials handling.

The free ranging vehicles described in the previous section will enter the terminal and drive to a certain dock to unload and/or load cargo. The cargo is then handed over to a certain client. Several aspects can be distinguished when performing this process. Different types of docking, material handling concepts and vehicle maneuvers are presented in figure 9, 10 and 11 respectively. These basic "buildingblocks" have been developed for designing terminals for the OLS.

Side Docking	Double Side Docking	Front/side Docking
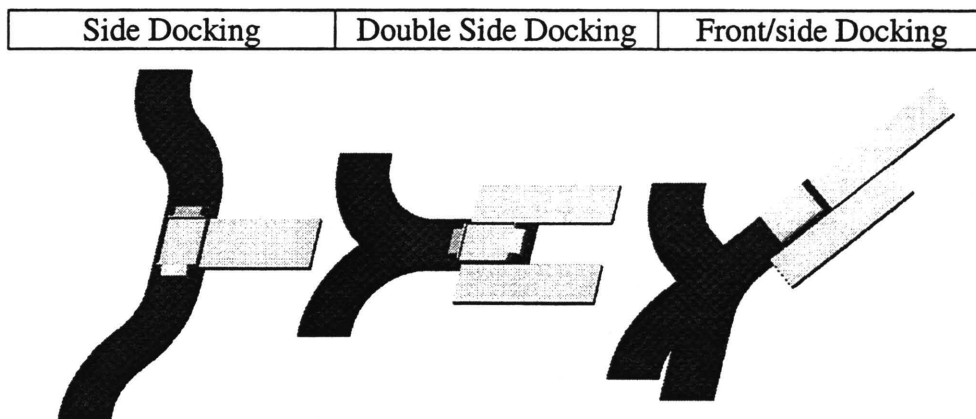
Figure 9. Docking Types

The docking types have different configurations for positioning the vehicle for loading and unloading. After the docking of the vehicle, cargo can be handled in many different ways. To promote uniform handling, the use of slave pallets can be considered. Another choice when handling materials is whether to lift or to roll the cargo in and out of the vehicles. Figure 10 shows just some of the many concepts that can be created.

Rolling cargo & use of slave pallets	Lifting cargo & use of slave pallet	Rolling cargo & separate cargo handling	Lifting cargo & separate cargo handling
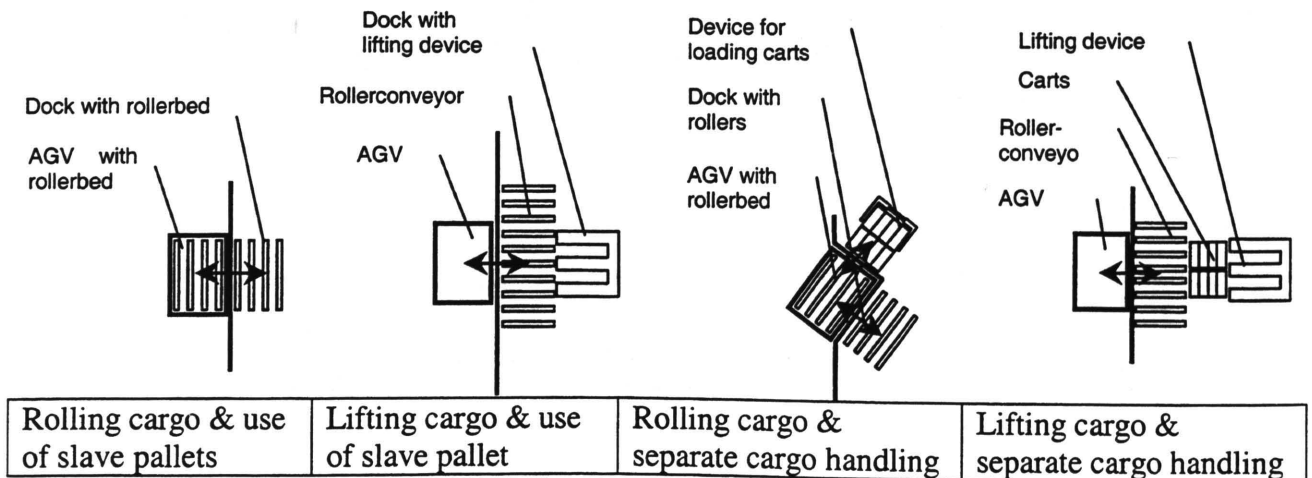
Figure 10. Material Handling Concepts

When developing terminal layouts, insight is needed in the vehicle maneuvers and the space needed to perform these maneuvers. Figure 11 shows some basic docking and turning maneuvers for the three vehicles presented in the previous section.

Side Docking DTM (front wheel stearing)	Side Docking Lödige (four wheel stearing)
Front/side Docking Spykstaal	U-turn DTM · U-turn Lödige
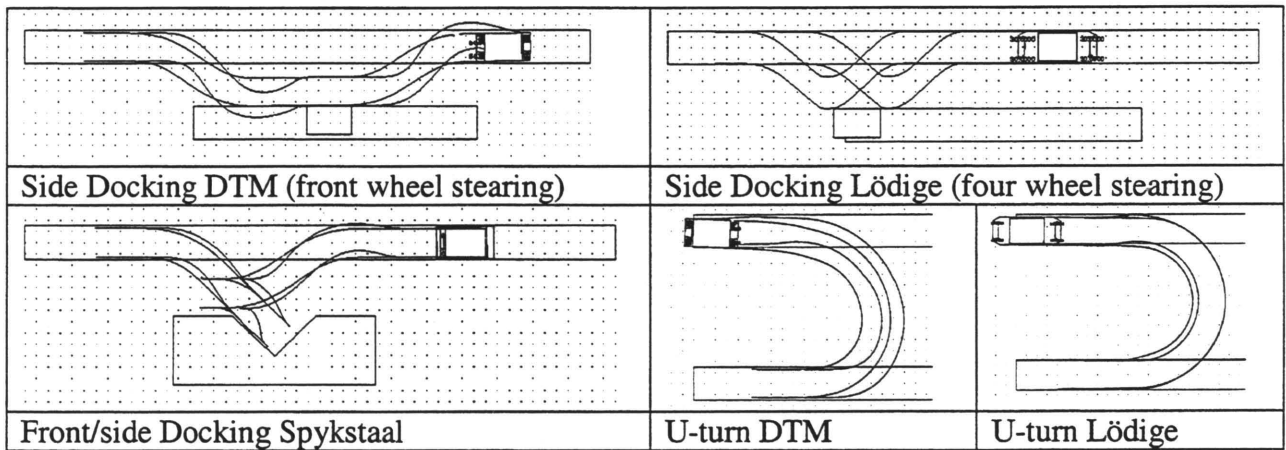
Figure 11. Typical Vehicle Maneuvers on the Terminal

A basic terminal design is presented in figure 12. This shows a terminal concept for the flower auction-mart, presenting the most important functions, using the "building blocks" described in this section. Different terminal concepts are being developed for various surroundings and specific client specifications.
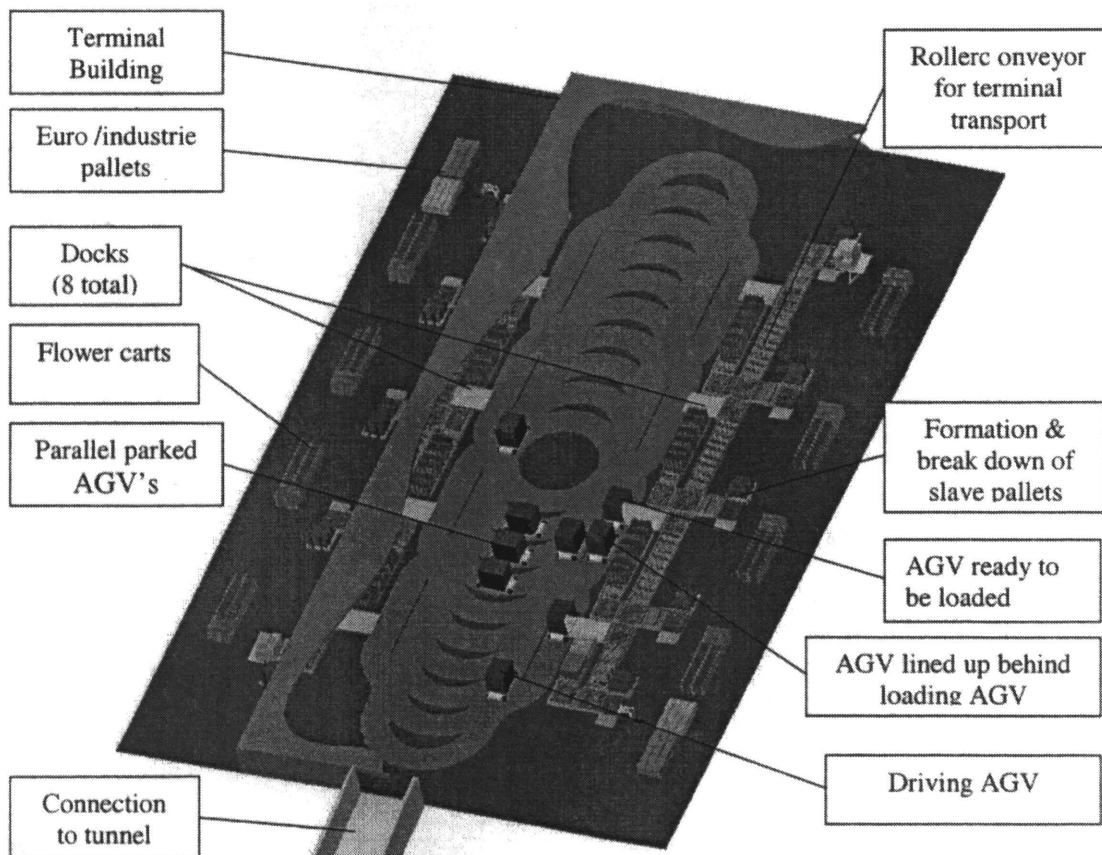
Figure 12. Terminal Concept for the Flower Auction-Mart

SYSTEM PERFORMANCE

To determine the performance of the system using a varying number of AGV's and docks, simulations are needed. Several terminal designs have already been simulated. The performance of the entire system has also been analyzed on a higher level. Both aspects are discussed briefly.

Many terminal simulations have been carried out to determine the performances of different concepts. Performance indicators like, the capacity of the terminals and turn-around time of AGV's are used to compare terminals. The most important parameters used for tuning the terminals are the loading and unloading time of the AGV and the combination of loading and unloading on the same dock. The terminal shown in figure 12, which is called Terminal Concept 1, proved one of the most promising concepts. Table 1 presents some of the simulation results. The general conclusion is that the terminal shown in figure 12 with eight docks and a loading or unloading time of one minute is capable of handling the predicted cargo for 2020 at the flower auction-mart.

Table 1. Simulation Results of Experiments on Terminal Concept 1 (See Figure 12)

Terminal-concept	AGV's per dock [per hour.]	Dockoperatio ns per dock [per hour.]	Terminal time [min.]	Driven distance [km]	Number of times accelerated	Average speed [m/s]
TC1 with 8 loading or unloading docks	28	44	6.8	0.34	15	1.1
TC1 with 8 combi docks	35	53	5.5	0.28	10	1.2
TC1 with 12 loading or unloading docks	27	42	5.7	0.34	13	1.4

The OLS system with a route as shown in figure 1, five terminals and two single track tubes between the different area's, is able to perform adequately with 360 AGV's. Figure 13 shows the system time distribution per track. The two single-track tubes create a batchprocess with batches up to 100 AGV's.
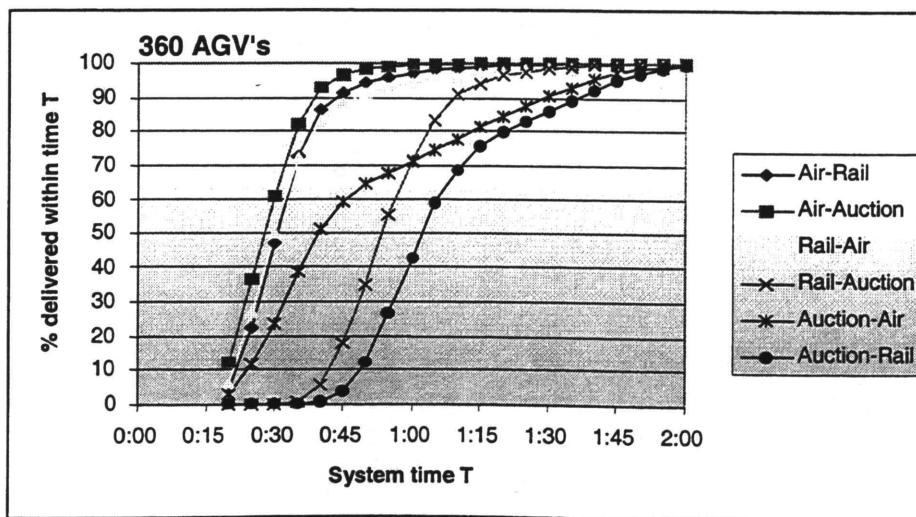
Figure 13. System Time Distribution Per Track with 360 AGV's

CONCLUSIONS

The OLS is to become one of the first fully automated underground transport systems of its kind in the Netherlands. The pre-design phase is coming to an end and promises to provide a feasible technological solution for underground freight transport. The system is thought to be a competitive, reliable and more environmental-friendly alternative to traditional road transportation, especially in densely populated areas.

The pre-design phase has resulted in the design of three prototype vehicles capable of transporting cargo between the flower auction-mart, Schiphol Airport and international railways. It is necessary to test the specific characteristics of these vehicles and prove their usefulness before selecting the most suitable method of transport for the OLS system. Several terminal concepts have been generated and simulated. A more systematic approach to material handling has resulted in several conceptual designs ready for prototyping and testing. The pre-design of the entire system has been analyzed to determine the performance and amount of equipment needed. This has established a solid basis for further design and engineering. The general view is that the OLS is a technologically feasible project.

Before a complete detailed design can be made, several transport and terminal technologies will have to be developed and tested further. The control and operation of the system is also one of the main aspects under development that will need further testing before a system of this magnitude can be realized. In order to facilitate these needs, a TestSite is being developed in the Netherlands. This TestSite will help innovative transport technological research in general and the further design of the OLS in particular.

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ACKNOWLEDGEMENT

The Continued Potential for Pneumatic Capsule Pipeline Systems in North America

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ABSTRACT

The origins of pneumatic capsule pipelines go back almost 200 years and although in the 19th Century there was marked interest in this form of transportation and many commercial systems were built, for a number of well-documented reasons they fell into disfavor. For almost another 70 years this form of transport was ignored until it was revived by the Federal German Postal Service for the bulk movement of mail in Hamburg. In the period 1960-1980 there was again increased activity with a number of commercial systems being built; these have also been well-documented.

There has been a hiatus of activity since the period 1960-1980 with little or no commercial interest shown in those countries which built commercial systems—although the economics of these systems are still very viable both from a capital and operating cost point of view when compared with other bulk transportation systems. In the meantime however, theoretical and experimental studies have continued.

In this paper the history and development of pneumatic capsule pipelines world-wide will be summarized with specific emphasis on studies made and systems built in the last twenty years.

Illustrations of application to large volume flow systems will be made by reference to two feasibility studies which are currently being made in Canada.

It is concluded that although there have been technological changes relating to fan improvements, and better and more precise and sophisticated control systems are now less expensive than ever before, nothing has changed during the last twenty years relating to overall economics. Operating costs are still lower when transporting large volumes by pneumatic capsule than by other systems for the appropriate operating envelopes. Capital costs are also usually less. Taking into consideration the increasing importance of environmental issues the feasibility of this method for material bulk transport is even more viable now than earlier.

INTRODUCTION

Historical

The beginnings of pneumatic capsule pipelines have their origins as long ago as the early 19th Century, when in 1810 George Medhurst proposed that a small diameter tube in which a hollow piston containing letters could be propelled by compressed air. At the Brighton Exhibition of 1827 in England, a 2 m diameter model of Medhurst's idea was demonstrated.

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Prior to this in 1824, John Vallance was granted a patent based on an 8-ft diameter pipeline 180-ft long containing a carriage running on a railway track. The carriage was propelled by air—the power for which was provided by steam engines.

In 1844, a short history of the first commercial pneumatically driven railway-employing an outside pneumatic tube was published [1]. The system was called "The Atmospheric Railway" and was built specifically for the transport of passengers between Kingstown and Dalkey, Ireland. The line operated from 1843 to 1855. The great 19th Century engineer Isambard Kingdom Brunel was sufficiently impressed with the performance of "The Atmospheric Railway" that he was instrumental in the construction of a 41-mile section of the Great Western Railway form Croydon to Devon using the same principles. Unfortunately, the valve controlling air flow was make of ox hide and performed poorly in adverse weather conditions causing the project to be abandoned 9 months after the start of operation. The idea was again revived in 1868 by Alfred Ely Beach who constructed a 9-ft diameter pneumatically driven subway in New York City. This particular system operated for two years. In the meantime, the idea of pneumatic transmission of letter and parcel mail was revived again. In 1853, Josiah Latimer Clark built a 1½-inch-diameter, 675-ft long telegram dispatch system in London. Five years later, a larger diameter, longer line was built.

In 1861, an historical account was published [2] of the first commercial large-scale pneumatic pipeline ¼-mile long, 2-ft 9-inch in diameter for the transport of letter and parcel mail in London. The pipeline was elliptical in shape, made of cast iron with fixed rails inside. The event was described as: "a solution to the congestion problem on London streets."

By the late 19th Century several pneumatic lines were in place for mail—the most well-known of these were those in Philadelphia, Boston and New York [3,4]. In the 1960's the Federal German Postal Service opened a pneumatic line in Hamburg; a detailed account of this pipeline, from the planning, design, construction to operation is given in a textbook by Vierling [5]. It is interesting to note that Sumitomo Metal Industries recently [6] conducted a feasibility study of moving mail through the Washington D.C.-New York City corridor. A cost analysis demonstrated that a pneumatic capsule pipeline was much more economic than truck.

At the same time that the Hamburg pneumatic mail line was operating, interest in high speed (supersonic) passenger transport in high population density corridors by pipeline was burgeoning in the United States. A series of papers in the High Speed Ground Transportation Journal and elsewhere appeared at this time [7,8]. These covered a wide range of subjects from propulsion energy requirements, telemetry and braking to the aerodynamics of the vehicles. The vehicles were to be internally propelled. However, it was not until the 1970's that the application of pneumatic capsule pipelines to the movement of bulk cargo began to be considered in earnest. The impetus for this work came from American (Carstens), British (BHRA) and Russian (TRANSPROGRESS) studies. Since 1983, Japan constructed and used successfully a 40-inch-diameter pneumatic capsule pipeline for hauling limestone to a cement manufacturing plant over a distance of 2 miles [9].

TECHNICAL ASPECTS

Present day pneumatic capsule pipelines appear in a variety of forms but their origin from the 19th Century is readily apparent. A system may be monotubular (single-line reversing), bitubular or a variant of the latter which is called 'cyclic.' Bitubular systems are by far the most common for large volume flow rates although some are used for in-plant systems. They vary in length from in-plant systems of a few tens of metres to large diameter lines tens of kilometres long. In each system loaded, wheeled containers or 'capsules' are propelled by low pressure air to their destination, unloaded and returned to their origin, empty, by the same pipe (monotubular) or by another pipe running parallel (bitubular).

The pipelines may be made of steel, plastic or ferro-concrete. There are advantages accruing to each depending on the service, the location and the type of material being transported. The pipe diameters are usually in the range 0.7 to 1.4 m—although there have been other pipes of smaller diameters. The capsules themselves have a wide variety of forms. They may be open or closed, their wheels may be fixed of be capable of being peripherally rotatable; the number of wheels on a capsule may also vary. Wheel materials range from rubber and polyurethane to steel. Fixed wheel capsules may run on internally mounted rails in the pipe of if guiding rails are not used, they will be designed in such a way as to be 'self-tracking.' Freely rotating wheels will be in contact with the inside surface of the pipe.
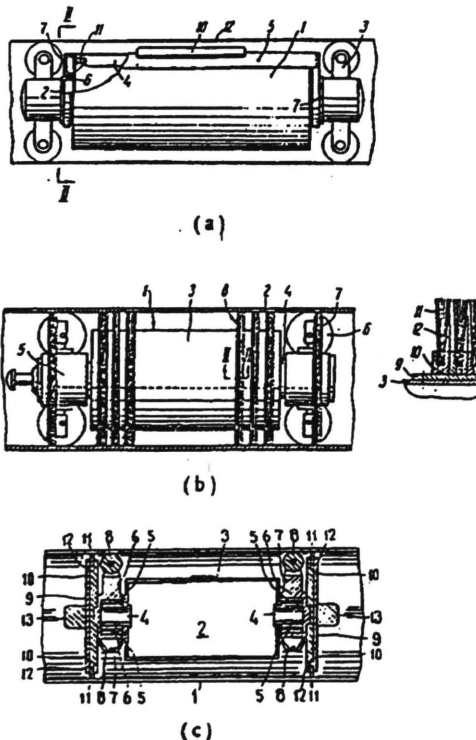
Figure 1. Some Patented Capsule Designs
a) **Alexandrov** *et al.* **(1970)**
b) **Alexandrov** *et al.* **(1971)**
c) **Eijiro Ueno (1978)**

Rolling friction which results from the wheel/inside pipe contact or alternatively the wheel/rail contact is an important component of energy absorption by the capsule. It is important that the coefficient of rolling friction be reduced as much as possible. Carstens [10] investigated the rolling coefficients of polyurethane wheels in contact with a steel pipe. The coefficients were found to vary from 0.32-0.37 for polyurethane wheels on steel and 0.018-0.021 for steel on steel. One of the possible advantages of a steel/steel contact would be an improvement with aging because of metallurgical micro structure changes-in effect, a 'smoothing' of the contact surfaces. On the other hand, steel is prone to oxidation, which would have the reverse effect on the coefficient of rolling friction. Rubber wheels on steel would be expected to have a much larger coefficient [11].

In order to "seal" the capsule, gaskets make of a flexible material are attached to the ends of the capsule. The purpose of the seals is to contain the propulsion air and thus give the capsule as high a drag coefficient as possible while at the

same time keeping sliding friction between the seal and the pipe wall to a minimum. Figure 1 shows two Russian and one American designs for capsules showing the seals.

The other source of energy absorption is the frictional resistance of the air in the pipe. It would obviously be advantageous to use as smooth a pipe as possible. Thus to minimize energy consumption, four component effects must be minimized:

a) rolling friction due to the wheels
b) mechanical friction of the bearings and coupling surfaces
c) sliding friction of the seal and the inside surface of the pipe
d) air friction of the propelling air.

Propulsion for capsules is provided by large volume, low pressure, centrifugal fans, compressors, turbo-blowers or Roots-type blowers. Flow rates typically are in the range of 1-10 m^3/s with pressures less than one atmosphere.

The capital cost of any pneumatic capsule system, as with any system of this sort, is a function of the degree of sophistication. The basic components of any system are the same. The cost of each element in the system, however, will vary depending on the annual throughput and state of the material, i.e. the degree of automation which may be both necessary and desirable. Lynam [12] for example, carried out a cost study, based upon costs in the U.K. and estimated the following breakdown of costs as a percentage of the total:

pipe:--30-50%
capsules:--up to 20%

It was further estimated that the major proportion of operating costs would be for power, with maintenance and administration costs being small. These proportions will of course vary from country to country. It might well be that the energy proportion of operation costs in a country which has relatively abundant energy might be less than other costs.

Figure 2 illustrates a compilation of data for various systems for a flow rate of 3.5 million tonnes/year. The costs include capital depreciation and operating costs normalized to truck costs, i.e. relative cost/tonne-km for trucks equals one. The slurry curve in this particular example includes dewatering. Below 2 km the pneumatic curve rises very steeply and will become increasingly uneconomic as zero distance is approached vis-à-vis any other method of transport.

Figure 3 shows the relative costs for a pneumatic capsule pipeline normalized to a specific tonnage as a function of distance with annual throughput as parameter. It can be seen for a throughput of up to 10 million tonnes/year above 10 km the specific relative costs become constant. Below 5 km the curves rise increasingly steeply with decreasing flow rates. The indication here is that for low flow rates, i.e. less than 1 million tonnes/year and short distances 2-2.5 km, this technique is probably no longer competitive.

Fixed flow rate of 3.5 million tonnes/year

Costs normalized to truck costs
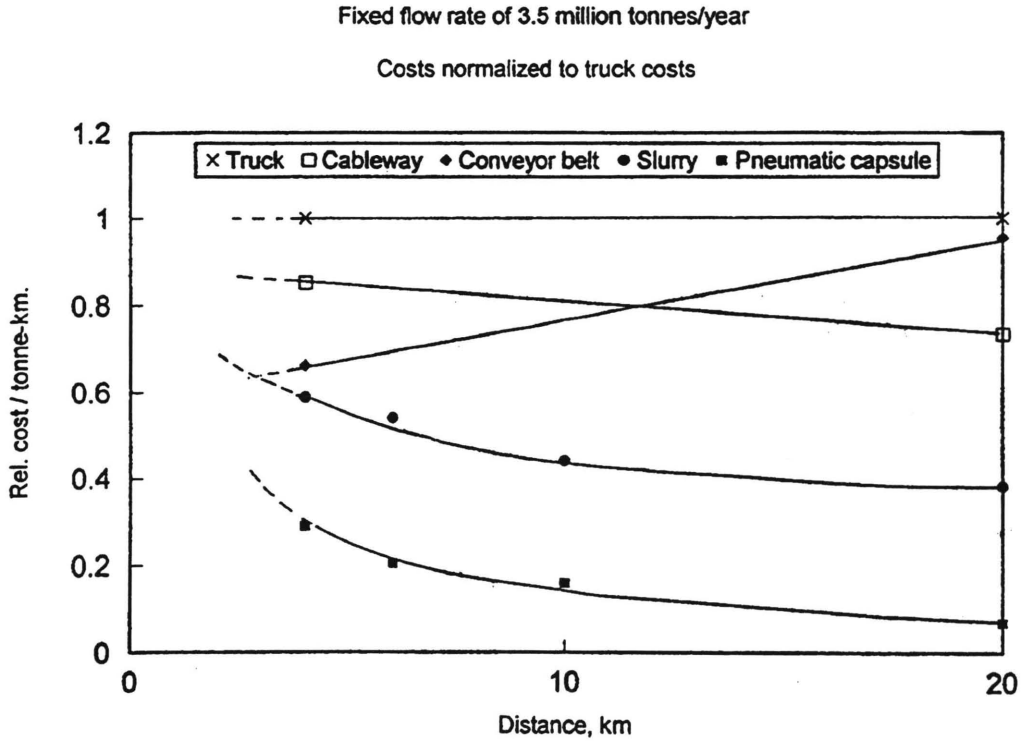
Figure 2 - Relative operating costs of different systems

Recovery of capital 5 years

Cost normalized at 2 km and 1.5 million tonnes/yr
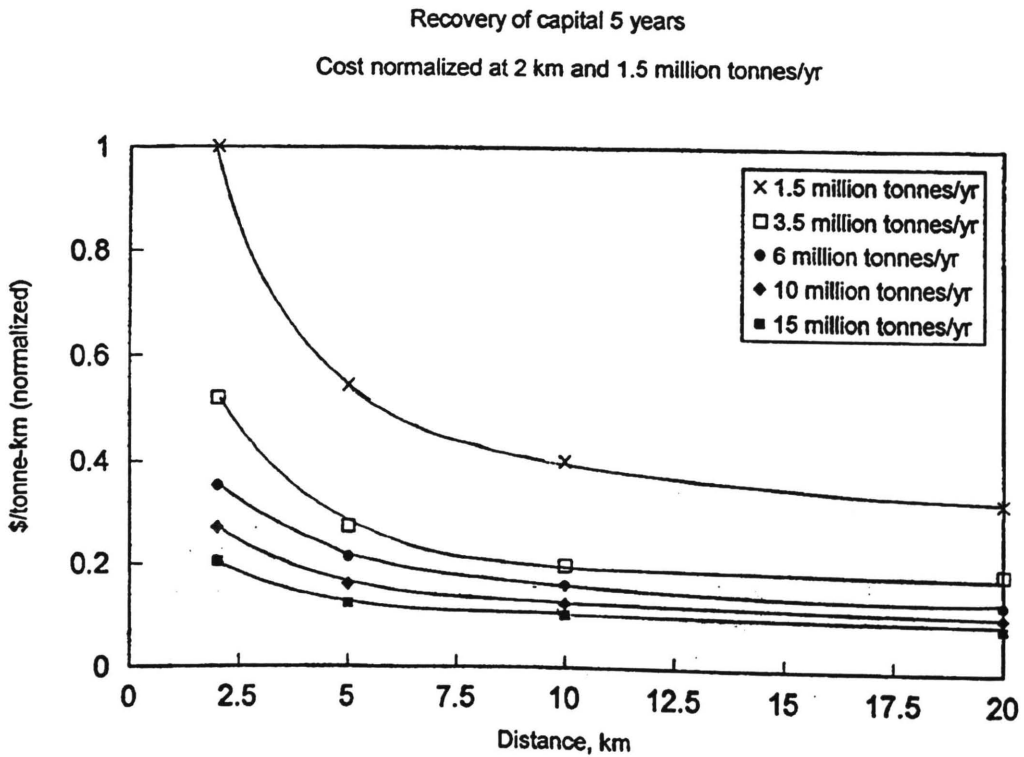
Figure 3 - Cost/tonne km for pneumatic capsule pipelines Theoret

Theoretical and Experimental Studies

Theoretical and experimental studies may be divided into:

        a)   aerodynamic—capsule drag and capsule interactions
        b)   capsule acceleration and braking

a) Aerodynamic-

There have been a number of studies both theoretically and experimentally on the drag associated with propelled capsules. The majority of this work has been carried out in Japan, North America and U.S.S.R. The flow around a capsule is a complex phenomenon. There have been a number of attempts to model this with varying degrees of success. The central theme of all these has been an effort to model the flow through the restricted gap between the capsule and the inner pipe wall.

Morikawa *et al.* [13] measured drag forces and pressure distributions around moving capsules and found that on the average the C_D for moving capsules was 20% greater than that for stationary ones. Tsuji [14] derived a fundamental equation for the drag coefficient in terms of capsule/pipe diameter ratio, capsule length/diameter ratio, capsule/air velocity ratio, annulus cross-sectional area and an annulus friction factor r. His results agreed very well with experiment. It is the Tsuji model which is used for predictions in the feasibility study which follows. In a later study Tsuji *et al.*, [15] studied experimentally the interactive effects of neighbouring capsules on the flow field and how it affected C_D. He found that at separation distances greater than two capsule diameters the effects were negligible.

b) Acceleration and braking-

Hisamitsu and Kosugi [16,17] set up mathematical models for the control of air pressure for braking. The results from the modeling agreed well with experimental tests. Tsuji *et al.*, [18] investigated the effects of closed end tube braking by changing the cross-sectional area of the end plate. Ohba *et al.*, [19] made an analytical study of the braking characteristics of a capsule in a closed end tube. It was found that the results based upon a polytropic gas law, with n=1.2 agreed best with experiment. Round [20] carried out a numerical study on the acceleration of capsules on injection into a line, the effects on capsule and air velocity for different blower characteristics and the interaction of pairs of capsules.

Elements of Design

1. Capsules

Capsules usually have bodies made of steel. There are numerous designs in terms of loading—some are top loaded and top unloaded by rotating them about their axes, others are top loaded and bottom unloaded. There have been some designs which have end flaps for unloading and guides in the pipe itself. Wheel and wheel systems are equally varied—see Fig. 1.

2. Loading/unloading stations

Alexandrov and his co-workers in the 1970's patented the largest number of station designs.

These covered:

 a) a means of charging capsules (1973)
 b) a loading/unloading station in which a pipe section acted simultaneously as a charging and discarding port (1974)
 c) a parallel pipe loading/unloading chamber (1975)
 d) a repair station with an arrangement of troughs and switches (1977).

3. Propulsion

Probably the most important choice in the matter of the propulsion units, whatever they may be, is that the propulsion unit's characteristic curves must be carefully matched to the system's requirements. This means in effect, that the system must operate at or close to the propulsion unit's maximum efficiency. Maximizing the system efficiency will be of no avail if the propulsion unit is inadequate or alternatively operates beyond its optimal operating point with consequent financial penalty.

4. Braking and flow control

Work in this area has concentrated on:

 a) control of flow in the line while the capsules are being transported by changing the launching frequency and compressor operation [21]

 b) decelerating a train in a uniform controlled way prior to unloading. The majority of work has been done on the latter.

Braking is usually done by changing the air flow, either by: bypassing the air, or by sealing the end of the tube and releasing compressed air in a controlled fashion. In some cases an hydraulic piston arrangement is used at the end to the line to bring the train to a full stop.

5. Economic considerations

There have been a number of economic studies on pneumatic capsule systems and comparison studies with other modes of transport. Vasil'ev *et al.*, [22] in 1975 assessed the economic applicability to the mining of coal. They concluded in the context of the U.S.S.R. that for shallow mines (80-100m), distances of 3-5 km and 10 million tons/year throughput the technique is economically viable. Koo [23] carried out an economic feasibility study by applying the TUBEXPRESS system to the shipment of grain in the Northern Plains of the U.S.A.

INSTALLATIONS

The majority of commercial pneumatic capsule installations around the world transport crushed rock, foundry sand, limestone or garbage. At present there are only three countries which have commercial installations, U.S.S.R., Japan and Romania, although there have been other countries which have had pilot plants.

While none of these installations are in wilderness or Arctic locations, pneumatic capsule pipelines are particularly useful in such areas, where adverse weather conditions **may** preclude or severely limit other methods of bulk transport.

FEASIBILITY STUDY

Introduction

As an illustration of application of the design technique, two mines were considered for different companies for application of pneumatic capsule pipelines: the first in North America is 88 km from mine to unloading, shipping lead/zinc ore at 2-2.5 million tonnes/year and the second in South America shipping another metal ore 20 km at 12 million tonnes/year. In each case commercial centrifugal fans were considered; the only proviso was that the zero flow pressure for a fan would not exceed 100 kPa and that the H-Q characteristics of the fans obeyed a third-order polynomial equation. The Tsuji equation [14] was used to predict the drag coefficient of the capsule train.

The following comments need to be made about obtaining a solution to the problem in terms of the pressures, flow rates and energy requirements.

- The equations which describe the compressible isothermal flow behaviour of air propelling a capsule train together with the coupled equation of motion of the train are complex and each parameter is interdependent.

- Therefore, to obtain solutions recourse must be made to numerical methods.

- Operation points depend on the fan/system characteristics. A constant pressure fan will give an operation point quite different from a centrifugal fan with the same zero flow pressure. The choice will depend on the system. In the cases considered here a centrifugal fan which had a characteristic H-Q curve which could be represented by a 3rd order polynomial and which had a zero flow pressure of 100 kPa was used.

The problem was resolved by solving numerically, using an explicit forward marching method, for the equation of motion of the capsule together the coupled equation for isothermal compressible flow of the air. The method has been reported elsewhere [24] and will not be repeated here. Suffice to say that for all the computations the method was convergent and stable for time increments of 0.5 seconds or less. Figures 4 and 5 summarize the computed results. In each case 2000 m long sections were considered. The bulk density of the material is 1500 m^3/kg.

Pipe L = 2000m: Pipe d variable: Bulk density: 1500 kg/cu.m., fan const. = 0.9

25 capsules in train; power absorbed approx. 140 kW for each diameter
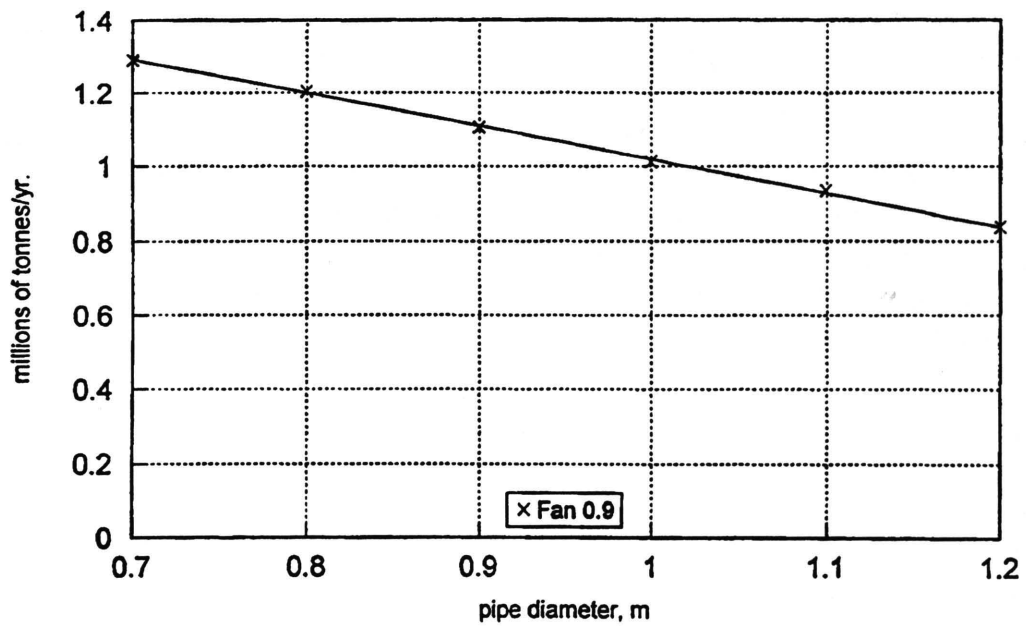
Figure 4 - Variation of throughput as a function of pipe diameter

Pipe L = 2000m: Pipe d = 1m: Bulk density: 1500 kg/cu.m.

Values of fan constants indicate pressure at zero flow
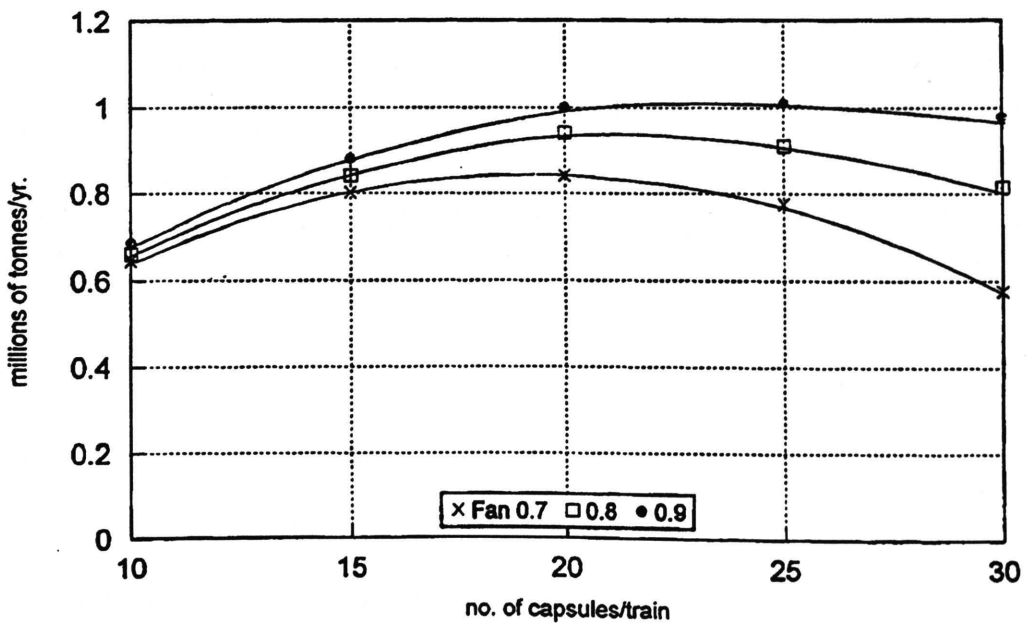
Figure 5 - Variation of throughput as a function of train length

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The fan constants shown indicate the value of pressure at zero flow, i.e. a fan constant = 0.9 means the zero flow pressure is 90 kPa.

Table 1. Power Requirements-To be Used in Conjunction with Figure 5.

Power Requirements (kW) for 1 m diam. line			
No. of 2 m capsules/train	Fan = 0.7	Fan = 0.8	Fan = 0.9
10	68	69	71
15	93	96	99
20	111	116	122
25	123	133	140
30	128	145	156

Discussion of Results

Figure 4 shows the variation of throughput with pipe diameter for one fan constant. Over the range shown the throughput is virtually a linear function of pipe diameter. At some point less than 0.7 m pipe diameter a maximum value must be reached; then the curve must fall rapidly to zero. Figure 5 shows throughput as a function of train length for different fans. It can be seen that each fan has a different optimum train length.

Conclusion from the Results

- For a throughput of minimally of 1 million tonnes/year the power required using a high performance centrifugal fan for a 1 m diameter pipe is approximately 140 kW per 2 km of line.

- Thus for a 10 km line requiring 1 million tonnes/year to be transported the power required would be 700 kW.

- Over the pipe diameter range 0.7-1.2 m the power requirements for the same tonnages are approximately the same.

- The optimum number of capsules in a train for any pipe diameter is between 20 and 25.

For comparison purposes calculation runs were made for constant pressure fans. As an example, a constant pressure fan (59 kPa) for a 1 m diameter line gave a throughput of 3.36 million tonnes per year. But, the power absorbed at 2 km was 635 kW and the train velocity was unacceptably high—of the order 19.5 m/s. Thus the type of fan chosen is critical. For a throughput of around one million tonnes per year, a centrifugal fan would be the best compromise. For higher flow rates, a larger pipe would be required with consequent higher capital cost and high power cost.

GENERAL CONCLUSIONS

The development of pneumatic pipeline transport has been slow to develop considering that the concept has been known since the early 19th Century. In fact, the development of all

pipeline systems other than those for single phase fluids has been slow. There are a number of reasons for this; perhaps the primary one is that pipelines are dedicated to the movement of one commodity. This in turn implies that the lifetime of the system must be guaranteed in terms of the market for the commodity both in terms of the amount and the period over which the commodity is transported. Other transport systems, e.g. rail and truck, are more easily switched to transporting other things. However, there is no doubt that the cost/tonne-km envelope for pneumatic pipeline transport is better than other systems in terms of its economics. The envelope is restricted in terms of distance, that is 2-3 to 100 km, and throughput, that is greater than a few hundred thousand tons/year at the shortest distance. Individual circumstances will dictate which transport system will be best.

The factors which must be considered for the choice of any system are:

a) annual throughput
b) distance
c) topography and nature of the ground surface
d) climate
e) condition of the material to be transported and end use of the material
f) capital inflation rate
g) energy costs
h) safety

Additional advantages of pneumatic capsule pipelines are:

- Pneumatic capsule pipelines are environmentally benign; air is the carrier fluid, the fans are usually electrically driven and dust is contained.

- A pipe break or capsule jam is not nearly as serious a problem as a similar misfortune with a slurry or hydraulic pipeline.

- Total cost of a pneumatic capsule pipeline operating within its optimal envelope will be less than a slurry pipeline requiring dewatering because capital investment for dewatering, especially for large flow rates, can often greatly exceed the capital investment in the line.

Thus the primary reasons for the choice of a pneumatic transportation system over another system must be based on economics and environmental considerations. It is unwise to choose any particular system if the conditions do not allow the system to operate in its optimal operating envelope.

There is often a political input into the choice. In third-world countries in particular, this may be the overriding consideration. Additionally, quite apart from the above there is a psychological factor with old and established industries. This manifests itself as reluctance for change—the problem which we face here is one of acceptance.

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Transportation of Goods Through Pipelines
- A Comprehensive Study –

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ABSTRACT

An efficient transportation and traffic system formed by a capable transportation infrastructure—streets, railways, waterways and airfields—is essential to economic development. A non-capable transportation infrastructure characterized by obstructions and delays inevitably leads to a restriction of the economic development of an area. While a further increase of transportation needs for North-Rhine-Westphalia—and the Ruhr area in particular— is to be expected, the existing transportation infrastructure has already reached limiting capacity. An alternative for transportation is urgently needed.

The Ruhr-University Bochum has conducted a feasibility study shifting the transport of high-quality goods to underground pipelines based on economical, legal and technical aspects for the market of Ruhr area.

INTRODUCTION

The transportation of goods on streets is critical to the economic development of Germany, especially in congested areas with high density of population and buildings. The cities are threatened by traffic collapse as the number of motor vehicles increases much faster than the capacity of the street network, and timely delivery of goods from producers to processors is becoming more and more important.

The consequences of this development are:
- limitation of economic development caused by inadequacies of infrastructure, especially within cities
- increasing air pollution in proportion to fuel consumption
- intensified wear on road surfaces resulting in increased and expensive maintenance costs.

The available transportation infrastructures— streets, railways, waterways and airfields— have failed to create a trouble-free, safe and non-polluting environment compatible with increased traffic. It becomes necessary to seek new ways to create fast, flexible and timely handling of traffic processes as well as non-polluting solutions. This requires solutions that fulfill the needs of the present without restricting the possibilities of future generations.

According to the partners of this project, a possible solution is freight transportation via underground pipelines. The pipeline serves either as the structural cover or the route of

transportation, depending on whether the system is based on linear motor technique or pneumatically or electrically driven self-propelled transporting units.

The advantages of such an underground transportation system for shipping goods through pipelines are:

- small surface areas are needed, and there are few restrictions to route selection
- flexible distribution of goods combined with reliable delivery times due to lack of interference from above ground traffic jams and restrictions
- assurance of a certain quality and safety of transportation due to independence from weather and protection from interference by a third party
- applicability of emission-free and thus non-polluting propulsion concepts
- high degree automation resulting in a highly efficient, safe and low-cost transportation for great amounts of mass and volume.

The Ruhr-University of Bochum conducted a feasibility study on freight transport through pipelines with respect to economy, law, mechanical engineering, control techniques and pipeline construction (as specified in the following) under the research project "Underground Transportation and Supply Systems."

ECONOMIC ASPECTS

The economic structural change and the changing demands for production have led to increasing demands on the transportation system. Possible explanations include:

- merchants' reduction of stock-keeping (ordering ahead to anticipate demand) resulting in greater reliance on trucks for short-term delivery of small individual orders and a decrease of bulk commodity transports
- splitting up of the added-value chain with increasing transports of intermediate goods
- manufacturers' increased production for anticipated demand creating a need for faster and more reliable transportation
- short product life cycles resulting in a demand for rapid turnover (sales) and greater transportation flexibility.

This generally means transportation of high-quality goods generates strong demand for speed and reliability in transportation while the importance of transportation costs fades.

Due to their frequent use and in spite of various efforts to ease the traffic burdens (traffic guidance, road pricing etc.), the existing traffic systems in congested areas can no longer satisfy the needs of freight transport. For this reason, alternative solutions must be found to avoid the loss of trade from this area, which results in negative regional impacts (e.g. unemployment and long journeys for commuters). The transportation of goods through pipelines promises to meet these demands as it will be constructed exclusively for freight transportation without depending on other vehicles or changes of weather. Pipeline transport will easily adapt to the needs of its users.

Prof. Dr. Paul Klemmer, a business studies faculty member and chair for National Economics at the Ruhr-University Bochum, made the initial step toward assessing transportation demands, with a study focusing on shipment speed, capacity and routing. This led to a need for new data about the smaller transports which are especially important for congested areas. There were no complete statistics to draw from. However, the material available established an approximate number of relevant shipments.

The second step is to get information from potential users of the transportation pipeline concerning volume and speed of delivery demands. Additional information is needed about the necessary procedures and subsequent services (stock-keeping, commissioning, bundling) to complete the transportation system.

The results from this study should set standards for transportation speed, capacity and volume delivery. The choice of the routes is preliminary as a traffic infrastructure only develops its full efficiency as the traffic network develops to meet demand. On the basis of the constructional demands resulting from this development, the next step is to determine the investment costs for several routes considering compatibility with above ground structures (buildings, municipal streets, highways and railways). Expenses can be then calculated to form the basis of a utilization fee. Moreover the advantages for the national economy should be assessed including reduced wear on streets, reduced air pollution and noise.

Furthermore, the small government budget will probably not allow coverage of expected high investments costs. Therefore, financing must come from private investors mainly. Government participation will address political concerns about the economic structure and provide the necessary support on the legal aspects of planning.

Future plans might include the extension of the transportation network within a region (completing the network) and to adjacent regions (expanding the network) thereby increasing the efficiency and attractiveness of the transportation system.

LEGAL ASPECTS

The implementation of freight transportation by pipelines comes with comprehensive legal problems which were examined by Prof. Dr. Thomas von Danwitz from the Institute for Mining and Energy Law at the Ruhr-University Bochum. The initial problem to be solved is the legal classification of such an innovative transportation system—determining whether it is a supply or transportation system. This determination is difficult because each supply system includes transportation functions. Other legal issues which must be resolved pertain to street and railroad right-of-ways and building codes. Special legal consequences are linked to classifying freight transportation pipeline. Currently, the system is classified as transportation system but in the course of the project, and pending changes of the general conditions, freight transportation by pipelines may be classified as a supply system.

After this classification, the general conditions for the installation of the pipeline must be clarified. Here, possibilities of public traffic network utilization were of primary importance. A major concern was what city and government permits would be needed and if contractual regulations were possible. The freight pipelines' main layout as to contents also had to be assessed and evaluated.

Apart from public street network, the usage of private property will be inevitable. Thus the possibilities of utilization of private properties had to be discussed. Besides design options as to law of contract and material, the predictions of legally authorized usage of private property against the will of the respective proprietor had to be checked to enable reply to possible opposition.

The legal position concerning contact with other infrastructure systems, e.g. subways and railroads, was quite complicated which is mainly due to technical reasons. As for public waterways, no important problems with the utilization of public waterways are expected. However, a contract of permission is needed and possibly additional permission to use electricity and water guard will be required.

Implementation of a freight pipeline transportation system introduces legal questions concerning environment, building planning (construction permits) and law of building regulations (building codes) as well. The environmental demands refer to vibrations and noise as well as air, ground and water endangerment. The law of building planning differentiates between routing in areas with specific development plans and areas without plans. Established building codes do not raise any particular problems.

Standards for contract negotiations with possible users must be established. In addition, the organizational structure, liability, participation of the government and the required insurance coverage need to be debated. In conclusion, these findings should help to determine the executive and legislative demands which will enable and facilitate the implementation of such a system for the future.

MECHANICAL ENGINEERING ASPECTS

As already mentioned above the aim of this interdisciplinary research project is the conception of a new efficient transportation system for goods via underground pipelines. To accomplish this, the system will rely on mechanical engineering for the construction of a number of components. As a completely new technology, a comprehensive analysis of the tasks and their respective components is needed—including the interrelated demands—must be made prior to construction. This analysis and the concrete conversion of the components are the tasks of the chair of Machine Parts and Material Handling conducted by Prof. Dr.-Ing. Gerhard Wagner.

To get an initial survey about the tasks an analysis concerning the functions has been made. This leads to the sub-functions as shown in Figure 1.
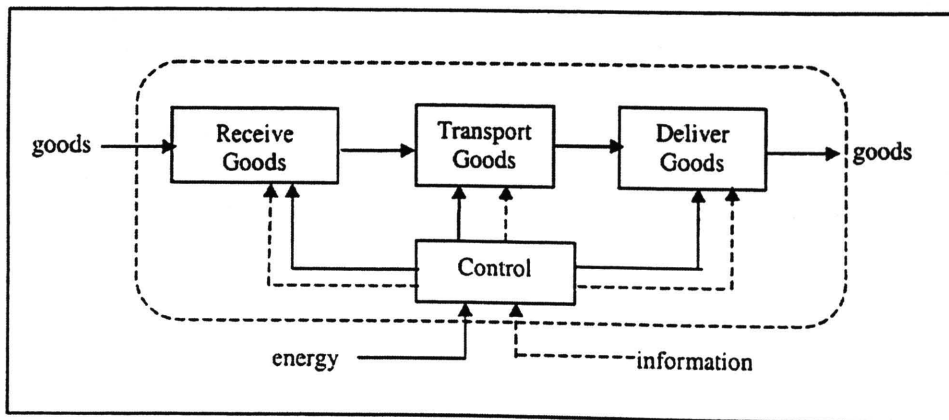
Fig. 1: Analysis of the Process "Transporting Goods"

The realization of the two sub-functions "receive goods" and "deliver goods" depends to a high degree on the concrete individual case of the transportation system and will therefore only be dealt with in the further course of the project. The sub function "steering" is worked on in co-operation with other partners of the project. The sub-function "transporting goods" however has to be worked out independent from concrete circumstances in the first place and takes a key position among the realization of the complete system. Therefore this function has been edited as per Figure 2.
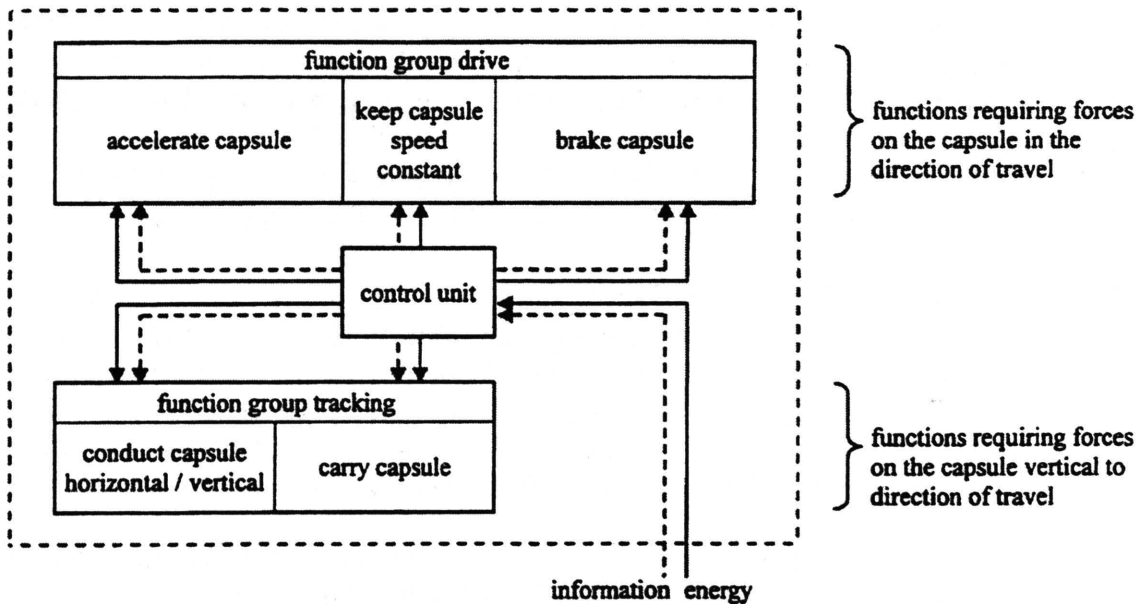
Fig. 2: Precision of the Sub-Function "Transporting Goods"

In the first phase of the project the research work concentrates on the realization of the sub-functions "drive" and "tracking". Here the special attention is drawn on the components to be developed concerning this functions e.g. the transportation unit, additionally needed constructional elements within the pipe etc.

On analyzing the existing transportation systems in pipelines it turned out that up to now mainly pneumatic dispatch systems have been realized. The means of transportation is conducted through a pipeline without additional construction elements and driven pneumatically with the help of compressed air. This type of freight transportation through pipelines proved worthwhile for small items at small distances, accepted because of relatively quiet operation and little maintenance. However tests have shown that the size of goods in question and the planned transportation capacity and distance does not allow application of the system of pneumatic dispatch. Problems arise due to the distances (loss of compressed air in the pipe), the big diameter of the pipe (high stream of volume) as well as the considerably branched network (difficult conduction of the air, one compressor needed for each branch) and the difficult steering of the individual capsules (all capsules have to be steered equally per each compressor).

Therefore the development of alternative driving and tracking concepts have been worked out. The use of modern electrical drives provides the main alternative. The application of a

frequency controlled three-phase motor in connection with a wheel-rail-system promises — due to its technical perfection — to be a robust drive and tracking unit with small need for maintenance and easy steering. Another alternative that has been considered is the use of a linear motor, because of its ability to track without touching (by magnetic hovering) which allows a nearly total elimination of moving, i.e., abrading, elements both within the pipe and at the transporting vehicle.

At the same time detailed solutions for tracking the vehicle are being developed. To this end fundamental examinations are executed on the construction of switches and other essential functions for the track (loading and unloading area) depending on various carrying and conducting systems, e.g., conduction by castors or magnetic hovering. The transport vehicle is being built to meet demands for increased life span and reliability as well as maneuverability of vehicle in pipe, protection of the goods to be transported and easy handling. In this field, special attention is drawn on the ability to integrate into already existing logistic chains.

ASPECTS OF STEERING TECHNIQUE

Examination standards for the development of innovative pipeline transportation systems (which are executed by the engineer's office of B.I.T., Prof. Dr.-Ing. Wolfgang Weller) set demanding goals—to establish a high standard of security concerning collision avoidance, flexibility of traffic performance, management in high traffic situations, and quality service especially by restriction of delays, expansion of the network and smooth traffic steering.

To this end research has focused on problems of transportation networks concentrating on determination of steering objects and processes. Essential objectives are examination of permissible and advantageous network topologies, development of typical structures of nodal points as well as elaboration of suitable methods for network analyses. This forms the basis for development of steering conceptions which are most important for realization of the system's standards and goals. The main emphasis is put on development of typical steering methods for nodal points. These steering methods must provide efficient and provide timely regulation of the pipe switches to couple, uncouple and conduct the containers within the network which requires a high degree of precision. The performance of the steering unit is determined by making decisions which require man-like cognitive features. Therefore the steering units could be characterized as "intelligent".

The examinations are very comprehensive. Again, the most stringent requirements relate to container-management and the observation of individual container performance in traffic. The essential result from these tasks is the data processing. To this end suitable solutions have to be found and conceptions developed. Another emphasis is put on the elaboration of principles and algorithms for the individual steering modules. This includes steering of the various pipe switches and peripheral units, steering and regulation of the drives, traffic and unit monitoring, and so on. Further examinations refer to the extension of traffic steering into steering hierarchies and the use of suitable methods for error-free data transfer and trouble-free steering techniques. Other objectives are useful implementation and instrumentation of traffic steering as well as the employment of tools for software development.

Aspects of Pipeline Construction and Maintenance

On acquisition of data and experience for construction and operation of pipe-conducted transportation systems, e.g. the large pneumatic dispatch system in Hamburg, the Russian "Transprogress" and the Japanese "Capsule Liner," little literature is available. The research on pipeline construction and maintenance led by Prof. Dr.-Ing. Dietrich Stein analyzes information about existing systems. The main emphasis of this research is put on the pipeline which conducts the transportation units and carries all inner and outer loads. The operation demands as to transfer of net weight and effective centrifugal force of the moving transportation unit on the pipeline and the implementation into the surrounding ground are formulated in close co-operation with the faculties of Mechanical Engineering and Steering Technique.

Pipeline criteria examines layering methods in pipeline construction. Pipe materials and pipe connections are examined for technical suitability. Special attention has focused on the development of trenchless construction in the past 13 years which has the potential to make possible an underground freight pipeline which is technically faultless and cost-effective. Apart from the open trench construction method, research concentrates on two controllable methods of trenchless construction—shield jacking and horizontal directional drilling. The most economically suitable pipe diameter for future freight delivery is within DN 1200–1500.

In case of horizontal directional drilling a drilling rig executes the pilot drilling by means of a controllable drill head. According to the type of soil a hydraulic jetbit or a mechanical rollerconebit is used. Subsequently the pilot drilling will be enlarged by so called barrelreamer until the diameter required is achieved. Finally the pipe will be pulled or pushed into the drilling. This principle in depicted in Figure 3.
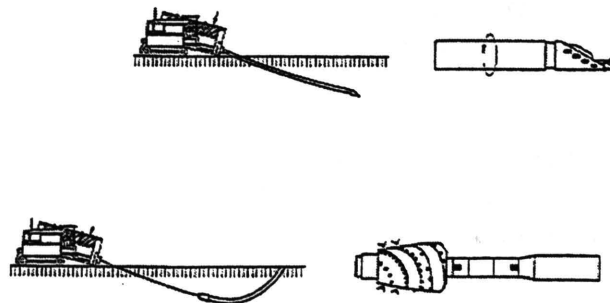
Figure 3. Horizontal Directional Drilling

Shield jacking methods are characterized by driving of pipes by the cutter head with simultaneous complete removal of soil at the mechanical fluid supported face. The continuous removal of soil is effected hydraulically from the suspension chamber which is located behind the cutter head.

Shield jacking method

Driving a casing pipe or product pipe, with mechanical removal of the soil by means of a cutter head with fluid supported face and hydraulic removal, of the bored soil. The drive for the cutter head is located in the shield machine.
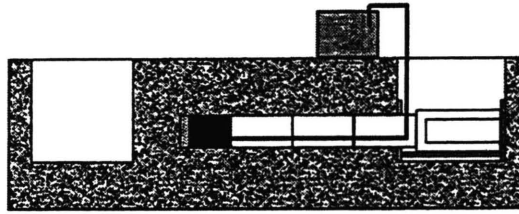
Figure 4. Shield Jacking Method

Closely connected with the choice of the laying method is the examination of suitable pipe materials and connections. These are analyzed with consideration for fabrication requirements, construction and operation conditions. The restrictions for underground capsule transportation require very little variations of diameter and ovality to secure a constant nominal inside diameter on the complete length. Preferably, there should be no transitions at the pipe connections. Pipe should be wear-resistant against castors and protected against corrosion in pneumatic operation. There needs to be insulation against inner excess and low pressure and outer water pressure. The pipeline must be vibration-free, durable and immovable. Apart from straight pipe elements, pipe arcs, arms and transfer stations must be designed and realized.

Furthermore, suitable methods for maintenance of pipelines as to servicing, inspection and renovation are investigated. Servicing comprises all measures to keep the demanded readiness—to secure steady availability of the system. Measures of inspection serve to assess and value the actual condition as data is gathered about the state and the wear of the unit in question. Renovation measures can be prepared on the basis of the results from inspection. Renovation methods restore the demanded condition of the plant or improve it by means of repair, renovation and renewal.

The freight transportation pipeline's total construction and maintenance goals are to provide an economical and durable transportation system, which is not only expandable but safe and requires low maintenance.

SUMMARY

Under a feasibility study on the economic, legal and technical possibilities of an underground capsule transportation system via a pipeline network DN 1200-1500, researchers determined its ability to serve as an alternative for the current delivery system of the economic area, the "Ruhr area". The economic investigations concentrated on analysis of the branches of industry in the congested "Ruhr area," the locations of distribution centers, definition of potential users and the dimensions of goods to be transported. The research results established an economic diameter for the pipeline and explored the possibility of integrated tracking in the Ruhr area. The legal possibilities for realization of an underground pipe-conducted transportation plant were also determined and legislative actions recommended. The driving types—pneumatic, linear-motor technique, electrical drive—were discussed as to their application for pipelines. Furthermore, conceptions for tracking and junctions (so called stations) were developed.

Efficiency and restrictions from the point of view of steering technique were worked out and fundamental conditions formulated. For realization of the pipeline network, practical and economic construction methods were evaluated as well as pipe materials, pipe connections and measures for maintenance.

The final result of these investigations proved the feasibility of a developing an efficient, reliable, safe, non-polluting, emission-free and economic alternative to the conventional transportation by trucks. That alternative is the underground freight pipeline system.

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ACKNOWLEDGEMENT

Megaships, Megaports, and Landside Access Problems in the U.S. Port Industry—An Opportunity for Freight Pipelines

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ABSTRACT

Improvements in containership technology, increases in containership size, and the consolidation and reorganization of U.S. ports into a "hub-and-spoke" system will require changes in port terminal facilities. The number of ships calling on U.S. ports is likely to decrease, but the larger and more automated "megaships" already being put into use and expected to proliferate by the early 21st century will greatly increase the amount of cargo handled per ship. The result will be greater cargo tonnages handled by a few large ports, called "megaports." The added tonnage will exacerbate congestion problems for existing landside transportation modes and on land used for cargo storage in the immediate port vicinity. Such congestion will slow the loading and discharge of cargo and increase the time at berth of vessels at the ports. This will increase port and demurrage charges and increase transportation costs of goods sold to consumers unless methods of increasing cargo turnaround speed are developed. For a port to stay competitive, it must increase cargo-handling capacity by acquiring increasingly expensive long-reach, heavy-lift cranes and automated cargo handling equipment, and it must find ways to solve its landside access problems. Container pipeline technology is a logical solution to a number of these problems. This paper presents the basic background of the problems facing ports in the next century, and examines the Ports of Houston and Galveston as potential candidates for using freight pipeline technology to increase their competitive position.

INTRODUCTION

Containerization has revolutionized the way we look at the process of freight transportation. The old system of independent incremental movements of breakbulk cargoes—an olio of methods that was the "standard" only forty years ago—has been replaced with today's globally streamlined and standardized transportation network. The typical shipment today is one of containers of cargo moving via a single integrated or "seamless" shipping contract from origin to destination. This change in the way cargo is transported has simultaneously transformed both the land and ocean sides of the exchange. Containerships appeared, followed by unit and, later, "stack" and "double stack" trains, and by containers on truck chassis. The increase in containerization became widely used when shippers and cargo owners discovered that reducing the number of times that cargo is handled between its origin and destination results in safety and security improvements and also provides efficiencies in cargo delivery speed. Further growth in containerization innovations has come as a result of increased international trade and the development of free trade areas such as the European Community.

Ships with capacities of more than 6000 twenty-foot equivalent units (TEUs) are already serving a few of the world's ports, and 7000- to 8000-TEU vessels are expected to be sailing international waters within the next five years. The main concern is whether any port will be able to handle them. There are currently no U.S. ports that have the proper combination of long-reach and heavy-lift cranes, big marine terminals, deep-water channels, and berths necessary for

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accommodating such megaships. Moreover, designers have yet to solve the problem of how to retool the inland infrastructure to handle the surge of new containers, "double-stack" trains, and truck traffic that lading and discharging cargo from a megaship would entail given current transportation technologies [1].

Several trends are emerging that will affect the way ports must plan in order to maintain efficiency and competitiveness in the next century. The most important of these are:

- Container trade increases — Worldwide container trade has grown 9.5% per year this decade and will continue to do so at an 8% growth rate for the foreseeable future. U.S. container trade has averaged 6.5% annually this decade and is projected to continue to grow at a rate of at least 6% per year well into the next century.

- Containership size and fleet capacity increases — Fleet capacity is increasing at a rate of 9.9% per year, with the highest percent of increase in the largest class of containerships.

- Infrastructure development — As ships' economies of scale lead to fewer port calls and a smaller number of larger vessels, ports will consolidate into a hub-and-spoke system of load center and feeder ports. They will also need to automate their cargo handling processes in order to make cargo movements more efficient and faster, given the larger numbers of containers they will see.

This paper concentrates on some of the landside infrastructure problems caused by the recent and continuing growth in the containerized freight system. First, the paper provides a little background as to how ship size is changing, and then it looks at some of the landside problems that this capacity change is causing. As an example, the paper describes some of the opportunities containerization has provided and some of the problems it has caused at the Ports of Houston and Galveston, Texas. Finally, the paper examines the potential for using freight pipeline technology to remedy some of the problems the ports are beginning to face and that are likely to become much more severe by the first years of the twenty-first century.

Container Trade

The rate of flow and origin/destination of container traffic volumes are two of the most important factors influencing the container market. Containerized trade will have grown at a rate of about 6.5% per annum between the years 1995 and 2000 [2]. Between 1991 and 1995, world container trade grew by about 9.5% per year, reaching a volume of more than 134 million TEUs in 1995. Growth in the U.S. trades has been somewhat slower, at only about 6% per year, reaching a volume of more than 21 million TEUs in 1995.

Perhaps more significant change is the world containerization of the general cargo trades, whose volume has nearly doubled over the last 10 years. Over 60% of all general cargo is now shipped in containers, compared with only 23% in 1980. Different regions of the U.S. will, of course, grow at different rates. The highest compound annual growth rate is forecast for the Gulf ports from Miami to El Paso (13.1%) and the southeast ports (7.6%). Northwest ports (Oregon to Alaska) are forecast to grow at 7.2%, while southwest ports (Oakland to San Diego) are expected to see 6.3% annual growth [1].

Containership Fleet

We can categorize the world containership fleet by vessel size and capacity. Table 1 divides containerships into three classes:

- **Feeder**—under 1000-TEU capacity;
- **Panamax** and **Sub-Panamax**—between 1000 and 4000-TEU capacity, capable of transiting the Panama Canal;
- **Post-Panamax**—4000-TEU+ capacity, which exceeds Panama Canal dimensions.

The physical and operational characteristics of ships change as their capacities increase, placing increasing demands on navigation channels, port infrastructure, and landside access capabilities. "Panamax" vessels (the largest that can transit the Panama Canal) average 273 meters (896 ft) in length and not more than 32.3 meters (106 ft) across the beam, with a draft just over 12 meters (39 ft). The typical "post-Panamax" ship in today's fleet averages around 282 meters (925 ft) in length and 38 meters (125 ft) across the beam, with a draft of over 13 meters (43 ft) [1].

In 1997, the feeder group accounted for 40% of the fleet in number and 13% of TEU capacity. Panamax and sub-Panamax ships accounted for 57% of the fleet and 78.6% of the TEU capacity. Post-Panamax vessels accounted for only about 3% of the fleet but handled about 8% of the TEUs.

During the period 1980-1995, the containership fleet grew an average of 9.9%. During the 1990-1994 period, the fastest growing vessel class, measured by TEU capacity, was the post-Panamax class, which grew 41%. Ships capable of handling over 1000 TEUs and capable of transiting the Panama Canal accounted for the second largest growth—slightly less than 35% [3].

Since the data in Table 1 were compiled, however, several vessels have been built that have length and beam sizes roughly 15 percent greater than the largest Panamax vessel and require a draft of between 14 and 15.25 meters (46 and 50 ft). Their container capacities are upwards of 50 percent greater than the largest Panamax vessel; that is, 6000 TEUs or greater. These ships warrant a new classification—"Beyond Post-Panamax," or "megaship."

Table 1. Classes of Containerships by Size and Capacity
(Source: *AAPA Advisory*, April 22, 1997 [4])

Class	TEU Range	Length (Feet)	Beam (Feet)	Draft (Feet)	Speed (Knots)	In Fleet (%)	TEU (%)
Feeder	100-999	354.3 -488.9	56.8-73.8	20.7-27.9	13.9-16.5	40	13
Sub-Panamax, Panamax	1000-3999	610.3-895.7	89.9-105.0	33.1-39.4	18.5-22.3	57	78.6
Post-Panamax	4000 +	928.5 +	124.7 +	43.3 +	24.1 +	<3	8

The definition of "megaship" varies. Some suggest that any ship with a capacity over 4500 TEUs is a megaship, while others argue for a 6000 TEU minimum for the class. The first of the megaships over 6000 TEUs, *Regina Maersk*, was delivered to the international carrier company Maersk in January 1996. Since that time, Maersk has placed five additional 6000-TEU vessels and eight 6600-TEU vessels into service. P&O Nedlloyd, another major carrier, has ordered six containerships with capacities of 6674 TEUs and one, the *P&O Nedlloyd Kobe,* with 6690-TEU capacity—the largest in the world. These new vessels will, for now, serve high volume, long distance trades—primarily from the Far East to the U.S. Pacific coast and from the Far East to Europe.

Eastern and Gulfcoast U.S. ports, however, must prepare for the changes in ship size that seem imminent. As vessel size increases, hub ports that allow the transfer of cargo to and from containerships for inland and coastal markets by use of feeder and barge services are becoming increasingly larger, fewer, more sophisticated, and more important to the overall transportation system. This past year Maersk and another carrier, Sea-Land Services, sent an ultimatum to Eastcoast U.S. ports that any port that wants to be a hub port for their companies must commit itself to building the necessary infrastructure to handle their vessels efficiently. In 1990, less than 6% of U.S. containerized cargo was handled on ships of 4000 TEUs or more. By the year 2010 almost 30% will be handled on ships in the 4000+ TEU class, with more than 9% on ships in the 6000- to 8000-TEU class [1]. The landside capacity problems, therefore, are unlikely to go away.

Infrastructure

Provided that these megaships can be filled with revenue cargo, increasing vessel size while maintaining or increasing speed can reduce the cost per TEU. The major hurdle for some ports, with regard to accommodating the megaships, will be dredging. Currently, only half of the top ten U.S. containerports, which together handle nearly 80% of the container traffic, have existing channel depths that can accommodate these vessels.

Second only to the channel depth and width problem is the need to provide better landside truck and rail access, larger berths, more efficient terminals, larger cranes, and greater storage yard capacity, or to look to alternative and innovative technologies to reduce capacity problems. Landside access to and from the major U.S. containerports has been one of the most critical bottlenecks in the international system of container movements. Whether this bottleneck occurs due to inefficient cranes, poor terminal operations, or problems at gates, bridges, tunnels, or at the carrier's entry, it must be addressed in order to keep the trade and economic development flowing. In 1993, the Transportation Research Board reported several causes of the problem of landside access, showing the percentage of twenty-five containerports in the U.S. that experience each of these problems, at least to some degree. The problem occurring at the largest number of ports (84%) is competition among uses for available land. Second in frequency is congestion along truck routes (64%), and the third most common impediment to landside access involves truck and rail due to at-grade crossings (56%) [5].

The increased carriage of cargo in containers on megaships puts greater pressure on the port terminal to process the containers off the ship, through the marshaling yard, and on their way to a further destination with dramatically increased efficiency. But a port is only as efficient as its smallest bottleneck. The port's interstate highway connection or railhead connection is often the point where the port's container flow is choked off [6]. According to port consultant

John Vickerman, the average time a container rests at a U.S. marine terminal—its dwell time—is 6 to 8 days. Compare this statistic to that of U.S. intermodal rail terminals, where the average container dwell time is 1.5 to 2 days. One way already suggested to reduce dwell time is to change the traditional berth structure at ports by creating slips for these ships so that they could be worked simultaneously from both sides. This solution also has the advantage or reducing the reach of cranes necessary for cargo discharge from these wider vessels. Further, shippers would be able to reduce the advance time needed to get containers to port in order to make ship cutoff times for export. The supply chain can be shortened in time and efficiencies can be realized if containers being discharged and those being laded onto vessels are able to move in like numbers in each direction directly through the port without extra steps of stacking and handling.

One last point should be made regarding the need for bigger and faster cranes. The estimated time needed in a port to work a 5000-TEU vessel carrying 85 percent capacity, a task that encompasses the handling a total number of 8500 TEUs on and off, is about 189 crane hours. That means the ship would spend a minimum of 47 hours in port with four cranes operating. The ship would spend 38 hours in port with five such cranes working, and 32 hours in port with six comparable cranes. This is considerably longer than the current time spent by a containership at a single port call, though it is comparable for a current vessel calling at two ports.

Presently, Panamax ships are calling at approximately three U.S. ports, with an average use of two to three cranes in each; so, the total time spent in each port is 24 to 30 hours with all aspects of the infrastructure working according to schedule. This means that these ships spend about three days of "unproductive" time in port before sailing foreign. When transshipments are added into the picture, they increase the time, pressure, and number of lifts required to load or unload a ship. As the number of ports called by a vessel decreases, the number of transshipments and the number of liftings per crane increases. There are at least four handlings for a transshipped container, as opposed to only two for a container going straight through the port.

Normally, containers must be discharged from the ship onto a chassis, then placed either in a stack or on wheels by a second type of crane, while those to be loaded are removed from one of these areas and placed by crane onto the ship. Then, when the inbound truck or train arrives, the containers headed inland are moved from the stack onto truck or train. Those on wheels are hooked to a tractor and pulled out. Those being transshipped are moved shipside and reloaded outbound. Improved efficiency of container handling and, therefore, lower dwell time results if the containers move directly from a ship onto the awaiting truck, train, or feeder vessel rather than going into storage in the port's container yard [7].

If containers are to be moved by rail, the location of dockside tracks is important, but varies among ports from tracks located immediately alongside ship to distances of more than 2000 feet away. Even if the track is not very close to the vessel, having the dockside rail in the container yard is far preferable from a throughput standpoint to having to rehandle and dray containers across town to a train. One solution to the problem of how to decrease dwell time lies in how the carriers and the port's administrators preplan and communicate efficiently to and from the rails in order for the containers to pass along the entire chain more quickly. Proper planning of rail facilities allows trains to run on a stricter schedule and allows the docks to be cleared of cargo and trains more quickly after each cargo move.

Concentrations of inventoried stock in fewer locations and the need for fewer distribution centers result from shortening logistics chains. These large concentrations of cargo in one place lead to corridors that open through main hub ports. It is along these routes, both domestic and international, that the concentrations of stocks in containers and trailers are being distributed. What arrives in concentrated unitized form is then redistributed by "second-line" hubs that, in turn, ship goods back along the same routes.

Access to these corridors from dockside is a critically weak link, or bottleneck [4]. The Transportation Research Board of the National Research Council found in 1993 that two-thirds of the U.S. containerports face growing traffic congestion on the major truck routes leading to the ports. Half of the ports have numerous at-grade crossings on rails serving them. One third of the ports do not have adequate bridge and tunnel clearances for efficient double-stack container trains [4].

Megaport Terminal Requirements

A container terminal that has the minimum physical requirements needed to entice megaships to call at its docks should have the capability, depending on hours of operation, ancillary equipment, and other related factors, of a throughput of 450,000 to 900,000 TEUs per year, a range equivalent to 3000 to 6000 TEUs per year per acre [1]. In addition, of course, to the terminal's own physical requirements, there must be adequate landside transportation connections to move the cargo to and from the terminal. Assuming that dockside rail moves 40 percent of these containers, moving the containers in and out of the port's gate via truck and rail (that is, assuming no transshipment) would require between 1730 and 3460 "standard" truck trips per day in a typical 5-day week, and between two and four unit trains calling per day in a 7-day week! Without dockside rail, the number of truck trips required would increase to between 2880 and 5770 per day per 5-day week [1]. Such heavy truck traffic would create congestion at all but the most efficient terminals and place an additional burden on most any highway system near the port. But as striking as these numbers are, it is more important to recognize that, while these minimum physical standards may be sufficient for efficient operation of a single megaship container terminal, a port that is to be a competitive "load center" port should have more than one such terminal—perhaps even several—each with its accompanying landside connections. Last year, the Port of Houston—the Gulf of Mexico's largest containerport—handled about 970,000 TEUs, including transshipments.

The Role of Pipelines in the Infrastructural Mix

By this point, it should be relatively obvious to anyone who has an interest in freight pipeline technology that the introduction of container pipelines into this infrastructural mix might solve, or at least reduce, a considerable proportion of the capacity problems that ports face. First, given the projected growth in containerized freight, most ports do not have cranes that are capable of loading and discharging cargo at a speed that is sufficient for existing containerships, much less the megaships that will operate in the near future. The inadequate cranes keep vessels in port longer than necessary. Second, even if cranes could move cargo faster, inadequate dockside rail facilities create bottlenecks at most ports. Even if rail facilities within the port are adequate, highway and rail bridges and crossings outside the port may create problems for double-stack trains and for long unitized trains. Third, truck traffic congestion is a problem around many large ports. Loading containers onto chassis takes too much time to be efficient, especially if a transshipment is involved, where cargo is often discharged from the vessel onto a

drayage vehicle, stored at the terminal, and then handled again when reloaded onto another vessel for final movement.

A container pipeline system at the port might eliminate all of the above problems, though not without some careful design considerations. A new containership with container loading and offloading facilities similar to a roll-on, roll-off (RORO) vessel could move cargo via a built-in feeder system directly into an on-dock (or under-dock) pipeline. Such a mechanism could eliminate the need for some, if not all, of the cranes currently used to move cargo. If the pipeline facility is under the dock it could move cargo to and from the vessel without using any dockside space at all for even temporary container storage. There would be less need for dockside rail, less need for long-haul trucks at the dock, and virtually no need at all for drayage vehicles to move cargo to a marshaling yard. Containers that need to be moved by truck or rail could be separated from those that could be moved by pipeline, thereby eliminating lines of rail flatcars or truckers waiting to pick up or discharge their cargoes. Pipelines could also bring about a significant reduction in heavy truck traffic on the highways around the port.

The rail and truck corridors that exist at some ports—rarely without bottlenecks—could be replaced with an underground pipeline corridor. Such a corridor would significantly reduce the need for using valuable acreage near the container facility for storage. The storage facilities could be located at remote facilities miles away from the port if automated pipelines could deliver containers to and from vessels at a few minutes notice from these yards.

Of course, containers as they currently exist are too large to move by current container pipeline technology. Further, because much container trade is international, no single port, nor a single country, can unilaterally design and build a container pipeline system and expect its technology to be embraced worldwide. Many other countries and many international water carriers have a stake in a worldwide network of container pipelines. New ship and container design will not be accomplished overnight, but nevertheless must be considered as a viable solution to the myriad landside problems that most ports face.

The Galveston-Houston Example

The container traffic situation at the Port of Galveston warrants special attention. In 1995, the port was among the largest containerports on the Gulf, handling about 350,000 short tons of containerized freight (about 50,000 TEUs). Those numbers fell precipitously by 1997 as the port lost several carriers to other Gulf ports. But last year the port agreed to lease its East End container terminal to the Port of Houston for the next twenty (or more) years, and is now considering an agreement to consolidate its legal authority with that of the Houston Port Authority. This agreement should revive somewhat the port activity at Galveston, a port that was once Texas' largest port but which has suffered major losses of customers over the last several years. There are some limitations to Galveston's resurgence as a containerport. First, only two berths are dedicated to containers, depth at berth (and the main channel's depth) is only 12.2 meters (40 ft), and the channel is not wide enough to handle a megaship. But parts of the port not currently dedicated to containers, including some berths on nearby Pelican Island, could be made to accommodate several more container vessels.

Galveston's landside access limitations pose the greatest obstacle to the port' competitiveness. The port is located on an island about 80 kilometers (50 miles) seaward of the

main Port of Houston container port, Barbours Cut. The island has only a single rail bridge to the mainland, and only one highway, Interstate 45, that is suitable for truck traffic.

The Port of Houston is the largest containerport on the Gulf of Mexico. In 1998, it handled about 8,100,000 short tons of containerized cargo (about 970,000 TEUs). Houston's main container facility at Barbours Cut has six berths, with acreage for a small seventh berth available for future occupancy. Houston also handles containers at its Turning Basin, Woodhouse, and Care terminal facilities. The port's main channel depth is 12.2 meters (40 ft), but is now being dredged to both widen and deepen the ship channel. The facility has suffered major bottlenecks in recent years because of the inadequacy of Highways 225 and 146 that service the facility, and with less-than-adequate rail connections. Though improvements have been made over these access routes, they are barely adequate for the cargo being handled and cannot support a large increase in container traffic. Because the Barbours Cut facility is operating at near capacity, the Port is planning a new terminal down the ship channel at Bayport. However, outcry by Bayport-area residents regarding expected traffic congestion and environmental impact of the new facility has caused public hearings to be held regarding the project. The outcome is not yet known regarding the future of the facility.

At the Barbours Cut facility—arguably the most modern and best-equipped container terminal now in operation on the Gulf—there are twelve wharf cranes available for the six working berths. This means that (assuming all of the cranes have adequate capacities and reaches) the facility is at least six cranes short of its optimum number. Only four of the existing cranes can actually be considered to be of BPP (Beyond Post-Panamax) capacity, so at least some of the eight other existing cranes at Barbours Cut will need to be modified or replaced if the terminal expects to handle megaships using current cargo handling methods. A pipeline might alleviate this problem. If the necessary dredging takes place and other facilities and landside intermodal linkages are upgraded, Barbours Cut would at best be able to provide half of the fourteen megaship berths that are projected as needed on the Gulf coast by sometime next century, except that berth length is not sufficient to accommodate seven megaships at the same time even if all other infrastructural limitations are overcome. So, the port needs the Bayport facility but is being held back by problems that a freight pipeline system could easily overcome.

CONCLUSIONS

Efficiency is the underlying basis for any terminal's physical layout and design. The longer that a vessel is forced to remain at berth to load or discharge cargo, the greater will be the unproductive time for the carrier. The bottlenecks caused by inefficient cargo-handling operations raise the costs of transportation to carriers, the landed costs to shippers and, ultimately, the prices of goods to consumers. Therefore, a terminal that does not provide facilities that allow for high productivity of both labor and capital equipment used to load and discharge cargo will see fewer carriers calling at the port.

Landside linkages to rail, truck, and air transportation are important problems for U.S. ports because only some of those problems are under the direct control of the port itself. Most ports suffer from some traffic congestion in at least one landside mode, and often in all modes. Highways may be inadequate, highway bridge heights may impede double-stack rail service, rail service itself may be inadequate, crossings between the two modes may create impediments to

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movements of traffic via one or both modes, or some other problem may exist that slows the movement of cargo to and from the port. Ports that are striving for greater efficiency in turnaround of all of the vessels that call at the port recognize the need for making improvements in linkages to these modes or for finding alternative technologies by which to move their cargoes. Containerized freight pipelines warrant consideration as a possible solution to these landside problems. But the port's ability to correct these problems depends particularly on public understanding of and support for infrastructural improvements. Given the current taxpayer sentiments toward lower taxes and smaller government, realization of these external, publicly funded infrastructure improvements may be a difficult task for ports over the next several years.

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TUBE FREIGHT SYSTEM RISK ASSESSMENT

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INTRODUCTION

This paper is a risk assessment of the tubular freight system using linear electric induction motor for capsulated freight transshipment in pipelines. Its engineering and economic feasibility has been studied in detail by different researchers in both academia and government. However, the concept of hauling freight in capsules through pipelines is still too new to be judged as a reliable alternative to congesting highways. This paper will center on the human safety, environmental and economic risks associated with this highly innovative alternative mode of transportation.

RISK ASSESSMENT ANALYSIS OUTLINE

Risk is defined as the combination of the frequency for occurrence of an event and the hazardous consequences of the event. Although in popular usage risk and hazard are used synonymously, the term risk expresses not only the potential for a hazardous consequence, but also probability that such a consequence will occur. The term hazard expresses the potential for producing an undesired consequence without determining the likelihood of the consequence. Risk is calculated by the magnitude of hazardous consequences of an event and by the magnitude of the probable frequency of the event occurring. This principle is used to construct a model of well-defined categories for both event frequency and hazardous consequences. This is the risk matrix approach. The risk assessment analysis refers to a process of deciding the acceptability of risk of an activity based on the probability of events whose occurrence can lead to undesired consequences.

The approach to the risk assessment of tube freight transport concept involves the following phases:
1. Safety, environmental, and economic issues identification
2. Scenario construction
3. Event tree and fault tree risk analysis
4. Risk estimation
5. Risk acceptability

These principles are applied in constructing the risk model by defining categories for both event frequency and consequences in a risk matrix approach. This approach breaks down issues related to the tube freight system into:

- safety issues,
- environmental issues, and
- tube freight system issues.

Hazard identification is the primary phase of the analysis. Hazard severity includes the general scope or range of the effects and the particular damage, injury, and degradation. The hazards are identified and the consequences and frequencies are characterized in this phase.

The second phase is scenario construction and sequencing of the events. For this study, the risks associated with linear electric motor propulsion subsurface tube freight transportation system are developed by "what-if" scenario sequences. These scenarios start out with the failure of a component and the possible consequences are conjectured.

The third phase is risk analysis. Building on the "what-if" scenarios, event and fault trees are constructed. Probability theory is used in fault tree analysis to establish the probability of hazardous conditions. This is accomplished by determining the probabilities of intermediate events and basic events as well as the particular adverse event, which is the *top event* in a fault tree analysis. The *initiating events* are the bottom events and the *intermediate events* are the middle events. Probabilities are associated with both the occurrence and nonoccurrence of events. The nonoccurrence of an event is expressed as *reliability*. Fault trees combine two or more events based on Boolean logic. Once all the primary event probabilities are assigned, Boolean algebra determines the probability of the top event.

The fourth phase is the risk score estimation for the preliminary evaluation. The hazards are assigned a risk index number based on the frequency of occurrence and the severity of the consequences. These risks affect people, ecological, and economic issues. People issues involve *injury* to public health and safety, environmental issues include *degradation* of the ecology, and economic issues relate to *damage* to the tube freight system. The severity of the consequences that are associated with the top event of the fault tree are calculated by combining the probabilities of the basic events. The risk matrix is then used to calculate the risk index number.

The final phase is the risk acceptability determination. The estimated risk is compared with the risk referent. If the estimated risk is within an order of magnitude of the risk referent, then the risk is considered acceptable. The risk referent is described in detail in the risk acceptability analysis section.

PRELIMINARY HAZARDS BREAKDOWN

There are several general safety, health, environmental, and economic issues that are related to the construction, operation, and maintenance of the tube freight system. In a study of linear induction motor guide-way systems for passenger travel, six safety issues were identified:

- Physical infringement of vehicles or structures
- Electromagnetic field (EMF) effects
- Dynamic interference
- Infringement of operating envelope involving common trackage
- Contact with hazardous materials
- Accessibility of vehicles or guide-ways for inspection, emergency assess, evacuation, and trespassers

Unlike the guided ground and elevated transportation system for passengers, the subsurface tube transportation systems do not include intersections or crossings, overpasses or underpasses, departures from and returns to the shared right-of-ways that are usually associated with shared right-of-way situations. Safety issues of infringement of vehicles or structures, electromagnetic field effects, dynamic interference, and infringement involving common trackage is eliminated by the construction design of a subsurface operating envelope and containment within a concrete shell. The tube design of the subsurface tube transportation system is contained in a concrete shell below ground. This design shields the tube transportation system from electromagnetic fields generated by both the system and other users such as transmission lines and elevated electric train transportation. Highways, railroads, transmission lines, elevated rail and magnetic levitation trains are located above the operating envelope of the subsurface tube transportation system. This eliminated physical infringement between these transportation modes and the subsurface tube transportation mode.

The hazards associated with the tube freight system are considered the same as other subsurface pipelines and linear electric motor guided systems. Safety, environmental, and economic issues that are relevant to the tube freight system are:
- Adjacent pipeline infringement,
- Earth movement,
- Third-party intrusion, and
- Groundwater infiltration.

Pipelines and tube transportation inherently share approximately the same operating envelope (subsurface within the same right-of-way). However, the metal and concrete pipe walls physically separate them. The hazard would be for the adjacent pipeline to rupture, the fluid contents of the adjacent pipeline to migrate to the tube freight system, and the contents intrude into the concrete shell.

Earth movement pose hazards to the structural integrity of the tube freight pipeline and the alignment of the guide-way. However, the design of the tube freight system enables the pipeline to adjust to earth movement. The tube system is grounded in a fill of gravel that shifts with earth movement within the system envelope.

Third party and water intrusions are hazards inherent with subsurface pipeline systems that share the right-of-way with other transportation systems. The subsurface design inhibits third-party intrusion, but promotes the potential for water intrusion. However, the durable steel and concrete construction of the pipeline protects the tube freight system from water intrusion. The protection of the system enhances the reliability and reduces the need for mitigative maintenance. For a system employing a guide-way, reliability is a prime requisite. Since most guide-ways do not permit one vehicle to overtake and pass another one, the breakdown of a vehicle can paralyze a major section of the system.

IDENTIFICATION OF HAZARDS

Currently there are no commercial tube freight systems in operation. The identification of hazards was derived from data for current freight transportation systems. This process was

inherently subjective. Available historical data from analogous hazardous incident occurrences and severity were important resources for identifying risk for the tube freight system.

The approach used was to search available literature. A study of the reference literature was conducted to identify the potential and real economic, environmental, and safety hazards associated with tube freight transportation. Pipeline construction, maintenance and operation, rail systems statistics, linear induction motor technology, and historical and experimental tube freight system information was used to identify hazards and potential exposure groups.

TABLE 1: Identification of Hazards

IDENTIFIED HAZARDS	TUBE FREIGHT SYSTEM	ENVIRONMENTALLY SENSITIVE AREAS	HUMAN POPULATION
TUBE CONSTRUCTION		X	X
TUBE RUPTURE	X	X	X
EARTH MOVEMENT	X		
MISALIGNED GUIDE-WAY	X		
GUIDE-WAY SHORT-CIRCUIT	X		
THIRD-PARY INTRUSION	X		
ADJACENT PIPELINE LEAK	X	X	X
INSPECTION AND SERVICE	X	X	X
SENSOR MALFUNCTION	X		
GUIDE-WAY TRACK DEFECT	X		
OPERATOR ERROR	X		
MECHANICAL/ELECTRICAL FAILURE	X		
CAPSULE DERAILMENT	X		
CAPSULE COLLISION	X		
HAZARDOUS MATERIAL	X		
FREIGHT DAMAGE	X		
HAZARDOUS MATERAL SPILL	X	X	X
FLASH FIRE	X	X	X
ELECTROMAGNETIC FIELD EFFECTS	X	X	X
TUBE HAZARDOUS MATERIAL LEAK		X	X

HAZARDS EVALUATION

Estimates of the probability of an incident such as a component failure or deviation in operation for the proposed tube freight system were developed for each hazard. The estimates are rates for each mile per year or rate per incident.

TABLE 2: Estimated Frequency of Hazards

HAZARD	CATEGORY	FAILURE/FAULT RATE	RELIABILITY	FAILURE/FAULT PROBABILITY
CONSTRUCTION ACTIVITIES	ROUTINE ACTION	1.6E-5	0.999984	1.6E-5
INSPECTION AND SERVICE	ROUTINE ACTION	1E-5	0.99999	1E-5
THIRD-PARTY INTRUSION	NON-ROUTINE ACTION	4.5E-4	0.9995501	4.5E-4
INTRUDER DAMAGES GUIDE-WAY SYSTEM	NON-ROUTINE ACTION	0.5	0.61	0.39
OPERATOR ERROR	NON-ROUTINE ACTION	1E-5	0.99999	1E-5
CONTIGUOUS WATER WITH TUBE SYSTEM	CONDITION	0.1	0.905	0.095
HAZMAT IN TUBE FREIGHT SYSTEM	CONDITION	0.25	0.78	0.22
HAZMAT IN ADJACENT PIPELINE	CONDITION	0.5	0.61	0.39
IGNITION OF FLAMMABLE MATERIAL	CONDITION	0.5	0.61	0.39
ELECTROMAGNETIC FIELD	CONDITION	1E-09	0.999999999	1E-09
TUBE SYSTEM ADJACENT TO ENVIRONMENTALLY SENSITIVE AREA	CONDITION	0.1	0.905	0.095
TUBE SYSTEM ADJACENT TO POPULATION AREA	CONDITION	0.01	0.99	0.01
WORKER EXPOSURE (CONSTRCTION, MAINTENANCE, AND SERVICE)	CONDITION	0.1	0.905	0.095
GUIDE-WAY MISALIGNMENT	COMPONENT	2.3E-4	0.99977	2.3E-4
GUIDE-WAY SHORT-CIRCUIT	COMPONENT	0.5	0.61	0.39
GUIDE-WAY TRACK DEFECT	COMPONENT	1.8E-4	0.99982	1.8E-4
ADJACENT PIPELINE LEAK	COMPONENT	4.5E-4	0.99955	4.5E-4
SENSOR FAILURE	COMPONENT	0.0086	0.9914	0.0086
MECHANICAL-ELECTRICAL FAILURE	COMPONENT	1E-4	0.9999	1E-4
GUIDE-WAY DAMAGED AND DISABLED	COMPONENT	0.007	0.993	0.007
FREIGHT CAPSULE DERAILMENT	COMPONENT	2.5E-6	0.9999975	2.5E-6
FREIGHT CAPSULE COLLISION	COMPONENT	0.01	0.99	0.01
HAZMAT CONTAINER DAMAGED	COMPONENT	0.1	0.905	0.095
HAZMAT SPILLS FROM CONTAINER INTO CAPSULE	COMPONENT	0.5	0.61	0.39
HAZMAT LEAKS FROM CAPSULE INTO TUBE FREIGHT SYSTEM PIPELINE	COMPONENT	0.5	0.61	0.39
RUPTURE OF THE TUBE FREIGHT SYSTEM PIPELINE	COMPONENT	9.1E-5	0.999909	9.1E-5

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SCENARIOS AND EVENT TREES

The scenario definition process is the guiding phase in the risk assessment process. The scenario description associates the possible causes to the frequency and consequences of potential hazardous incidents. From the literally thousands of possible scenarios, a manageable number of real and potential scenarios were developed to represent typical hazardous occurrences and consequences. The scenarios were developed to concatenate the disparate hazards into a sequence of actions and events that adversely affect the tube freight system, environmentally sensitive areas, or the human population. A particular natural event *(force majeure)* or human action initiates the scenario. Defining the sequence of events and describing the consequences constructs the event scenarios. The scenario is then mapped onto the event tree. Following from the initial event or action are alternative sequences that branch off. This is a step-wise and branch-wise progression. The events of the scenario are subsequently mapped onto the event tree framework of parallel and sequential nodes and branches.

The event tree model is an inductive approach that structures the event scenarios. A "grade-and-clade" tree represents the event sequences with each grade (G) identifying a particular sequential step and each clade (C) identifying a particular parallel branch of the cause-and-effect train of events. The following diagram demonstrates the event tree concept:
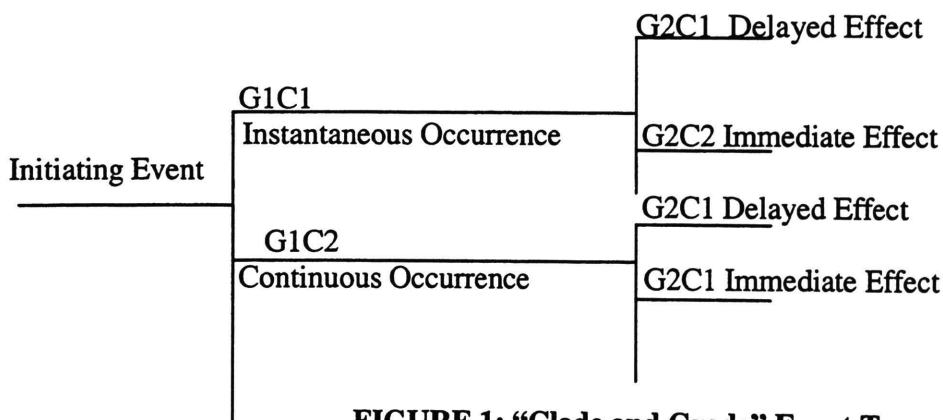
FIGURE 1: "Clade and Grade" Event Tree

In the simplified event tree diagram, consequences of the initial event in each grade are parallel to each other and the grades follow in sequence. At each node alternative sequences branch-off. The diagram represents the schematic of the event tree model and its structure is similar to a tree with nodes and branches. Each grade is a step in the sequence and each clade is a branch in the sequence. At the first node of the diagram, the initiating event branches into the instantaneous and continuous occurrences. At the second node instantaneous and continuous occurrence branches into immediate and delayed effects. The branch nodes diverge into different sequences that inductively result from the initiating event.

FAULT TREE

The logic used in the fault tree analysis is the reverse of the event tree analysis. The fault tree starts with an adverse effect and the cause is reasoned back to determine how it could have happened. The following figure is a representation of the fault trees used to determine the probability of a hazardous event occurring.

FIGURE 2:

Hazardous Material

Fault Tree

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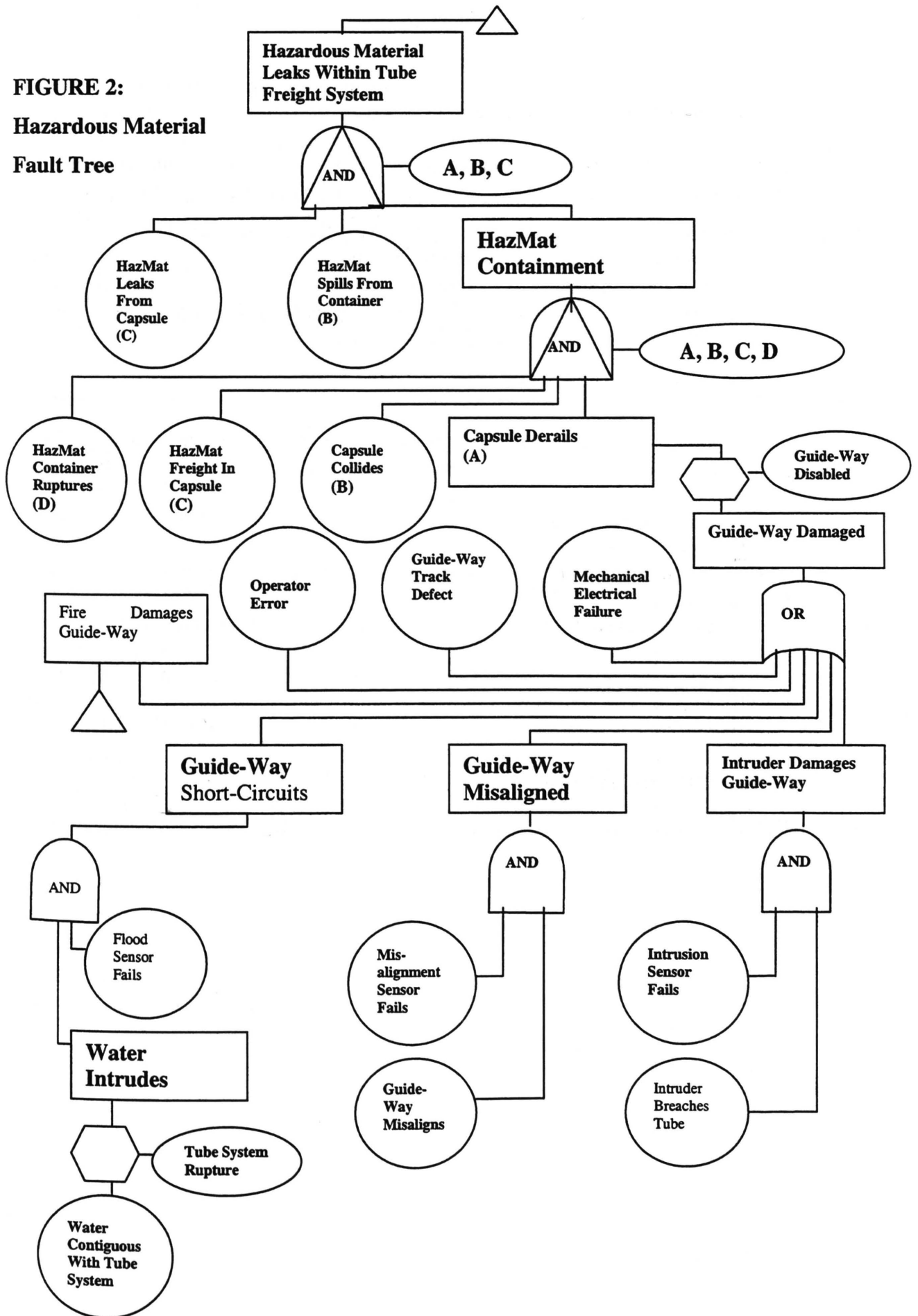
FAILURE/FAULT PROBABILITY MODEL

The failure/fault probability model used in the risk assessment analysis is an accumulative distribution function. The failure rate, μ, is in failure/fault occurrences per year or per incident. The reliability R, is equal to $e^{-\mu t}$ where t is the time in years or to $e^{-\mu n}$ where n is the number of cycles of operation or incidents. For our calculation of rate of occurrence per year or per incident t and n are equal to 1. Reliability is used to describe the probability that the system functions without failure or fault. The failure probability F, is equal to $1 - R$. The probability for each fault was determined using this model.

RISK REFERENT MODEL

The second tier in risk acceptability analysis uses the risk referent model. The risk referent model builds on the data of the risk matrix model. The risk referent approach includes four phases:
- Devise an appropriate risk classification scheme.
- Determine an absolute risk reference for each class in the scheme.
- Using risk references as a base, calculate risk referents that act as the acceptability limits for specific situations.
- Compare the estimated risk from fault tree analysis with appropriate risk referent.

The risk referent is an index of the risk that incorporates different considerations that affect the acceptability of risk. The approach in this study is to compare the estimated risk with a risk referent. The risk referent is determined from the following equation:

Risk referent = risk reference X F1 X F2 X F3.

The risk referent combines factors that account for the characteristics of the risk. These characteristics include:

- Voluntary vs. involuntary.
- Controllability.
- Ordinary vs. catastrophic.
- Natural vs. man-originated.

Using the Revealed Preference Concept, these characteristics are factored into the risk referent model and modify the acceptability of risk. Certain risk are *preferred* over other risks. Stakeholders and policy makers are more *tolerant* of voluntary risk than involuntary risk. The public *accepts* higher risks when they control the hazard. A large number of fatalities are more *acceptable* when they are distributed over many accidents than the same number of fatalities from a single accident. Natural risks are more *acceptable* than man-made risks.

The risk reference reflects the basic attributes inherent in the risk. This is based on the origin and the nature of the risk. The first two factors, F1 and F2, represent the inherent bias to accept or reject risk based on indirect benefit/cost ratio.

The third factor, F3, is the aggregate discounting factor reflecting four considerations associated with the controllability of the risk. The values are based on cardinal rating. For simplicity, the factors are multiplied together. The four factors are:

1. C1 - control approach
2. C2 - degree of control
3. C3 - state of implementation
4. C4 - control effectiveness

The following table is a matrix of the identified risks:

TABLE 3: Risk Referent Matrix

RISK	PROBABILITY AND COST	SEVERITY MIL-STD-882B	REFERENCE	FACTOR 1	FACTOR 2	FACTOR 3	REFERENT
TUBE FREIGHT SYSTEM							
DISTRUCTION OF THE TUBE FREIGHT SYSTEM	- ($ -)	CATASTROPHIC	$400,000	1	0.1	0.0225	$900
EXPLOSION WITHIN THE TUBE FREIGHT SYSTEM	5.00E-08 ($0.56)	CRITICAL	$400,000	1	0.1	0.0225	$900
DERAILMENT OF THE FREIGHT CAPSULE	0.002 ($2440)	MARGINAL	$200,000,000	1	0.1	0.0225	$450,000
DAMAGE TO THE GUIDE-WAY	0.28 ($31,360)	NEGLIGIBLE	$200,000,000	1	0.1	0.5	$10,000,000
ENVIRONMENTAL IMPACTS							
RELEASE OF HAZMAT WITHOUT CLEANUP IN AN ENVIRONMENTALLY SENSTIVE AREA	8.60E-15 ($9.6E-7)	CATASTROPHIC	$400,000	0.01	0.001	0.0001	$4E-4
RELEASE OF HAZMAT WITH CLEANUP IN AN ENVIRONMENTALLY SENSTIVE AREA	1.00E-12 ($1.1E-5)	CRITICAL	$400,000	0.01	0.001	0.0001	$4E-4
RELEASE OF HAZMAT IN A NON-ENVIRONMENTALLY SENSITIVE AREA	1.00E-11 ($1.1E-5)	MARGINAL	$400,000	0.01	0.001	0.0001	$4E-4
CONSTRUCTION AND MAINTENANCE ACTIVITIES OF THE TUBE FREIGHT SYSTEM	0.0026 ($292)	NEGLIGIBLE	$200,000,000	0.01	0.001	0.5	$1000
PUBLIC HEALTH AND SAFETY EFFECTS							
FATALITY FROM DRINKING WATER CONTAMINATED BY HAZMAT FROM TUBE SYSTEM	8.60E-26	CATASTROPHIC	1E-7	0.01	0.001	0.0001	1E-16
ADVERSE HEALTH EFFECTS FROM DRINKING WATER CONTAMINATED BY HAZMAT FROM TUBE SYSTEM	8.60E-24	CRITICAL	5E-7	0.01	0.001	0.0001	5E-16
TUBE FREIGHT SYSTEM WORKER FATALITY	1.00E-05	MARGINAL	1E-3	1	1	0.5	5E-4
TUBE FRIEIGHT SYSTEM WORKER IMMOBILITY	0.005	NEGLIGIBLE	0.3	1	1	0.5	0.15

CONCLUSION

The approach used in this study was to breakdown the subject into two part. In the first part of this study an account of the current freight transportation system and a description of the tube freight system were present. The tube freight system was presented as a feasible alternative to the current freight transportation system. This first part provided the background for the second part. The second part was the tube freight system risk assessment. The hazards connected with the tube freight system were identified and described. The frequency of occurrence of each hazard was estimated from analogous systems statistics. These hazards were incorporated into "what-if" scenarios and these scenarios were mapped onto event trees. The event trees were built using a "grade-and-clade" tree model where nodes were grades and branches were clades. Each branch of the event tree was assigned a probability. The event trees were used in constructing fault trees and Boolean logic was used to calculate the probabilities of the faults. The severity of the consequences and the frequency of occurrence of each fault were determined and a risk index was assigned each fault. The risks associated with the tube freight system were evaluated by using the risk assessment model that was developed for the analysis. The risk assessment model is a hierarchy of sub-models that incorporated:

- the risk scenario model,
- the event tree model,
- the fault tree model,
- the failure/fault probability model,
- the risk matrix model, and
- the risk referent model.

In summary, the risks associated with the tube freight system presented in this study were found to be acceptable. Using the Revealed Preference Concept, the risk acceptability for different concerns of the public is assessed. The final comparative analysis indicates an overwhelming advantage in terms of all different risk concerns for the tubular freight systems versus all other modes of freight transportation. From the evidence of this study, the tube freight system should significantly reduce injury to the public and environmental degradation compared to the current freight transportation system.

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Underground Goods Distribution in the City of Leiden: The Results of a Feasibility Study

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ABSTRACT

In the beginning of 1999 a feasibility study was conducted on an underground logistic system for the transport of consumer goods in the city of Leiden in the Netherlands. An underground logistic system (Dutch acronym: OLS) consists of the following components:

- one or more Logistic Parks: these are transshipment points at the edge of a city
- an underground transport system
- one or more Local Terminals where the goods emerge from the tube and are delivered (directly or via further transport) to the customer

A comparison was made between three types of systems: a Colli system (with a tube diameter of 1.5 m), a Pallet system (between 2 and 3 m diameter), and a Citybox system (5 m diameter). From the point of view of utilization of capacity, and because of logistic considerations, the Pallet system seems to be most suited to the city of Leiden. The Pallet system requires an investment of 100 million guilders[*] (for the infrastructure, and 14 million guilders for the transport system. The annual cost will be around 10 million guilders. The calculation of expenses indicates that the system will break even if more than 50 to 75% of all goods are transported by the OLS. Below that the OLS will be cost-covering if the government subsidizes the infrastructure–arguments in favor of this subsidy concern the social benefits of the system, such as reduced hindrance and energy use.

INTRODUCTION

Background

The Dutch Governmental Program for Sustainable Technology Development decided in 1997 that the introduction of underground freight transport to and inside cities in the Netherlands can lead to a sustainable development in the long term. The introduction of underground freight transport can offer a solution to problems that occur in cities as a result of road traffic, such as noise hindrance, air pollution, physical hindrance, and traffic un-safety. In addition, it may offer a possible solution for the problem of worsening accessibility of the Dutch inner cities due to congestion and traffic-restricting measures. In the Netherlands, in contrast to other countries, most important shopping areas are found in the inner cities. From the viewpoints of economy and control of mobility, great importance is attached to maintaining the economic viability of the inner city. It is also possible that underground freight transport is more energy-efficient than traditional transport and can therefore be significant in fighting the greenhouse effect (global warming).

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[*] One Dutch guilder is equal to 0.41 U.S. dollar, hence, 100 million guilders would be 41 million dollars.

Given the potential of underground transport, the social problems surrounding freight transport in cities, and the long amount of time it takes to develop such a system, the national government required a study of the feasibility of this concept. The concerns were not only about the technical and financial feasibility, but also specifically about support in the community. The "Interdepartementale Projectorganisatie Ondergronds Transport" (IPOT), an intergovernmental workforce commissioned a study in 1997 and 1998 into underground freight transport suitable for the Dutch context. It was a study of technical and financial feasibility of a nation-wide underground transport system. The results of this study are contained in the progress report "Transport onder ons" (IPOT, 1998). Some of the conclusions were that the results of a general study, although in general positively, had to be tested by means of case studies, and that the support for underground freight transport needs to be determined on the local level. The case studies may also form good "step-ups" to pilot projects–the first applications of underground freight transport. These underground freight transport systems in cities are identified as OLS (Ondergronds Logistiek Systeem), named after the underground transport system that is currently under development at Schiphol airport near Amsterdam (OLS Schiphol).

One of these case studies was performed in the municipality of Leiden, a city of 120 000 inhabitants in the Western part of the Netherlands. The city of Leiden has an old inner city with an important economic function. The city has experienced problems already for some time with freight traffic in the inner core. On the one hand, people want to limit freight traffic in the inner city by means of restrictive measures. On the other hand, it is recognized that the inner city is not easily accessible for freight traffic, partly because of these restrictive measures, but also because of congestion on access roads. The municipal distribution center that was created in 1995 offers insufficient solutions. In addition, the municipality is currently preparing a plan to re-develop a specific part of the inner city (the area around the Aalmarkt). This will create a large amount of space for new stores, catering establishments, and cultural activities. An underground logistic system (OLS) may provide a solution here; it is for this reason that the city of Leiden indicated interest in a pilot project.

Setup of the Study

The researchers were asked to determine the chances and conditions for success for an OLS in the city of Leiden. The study must determine if an OLS would be feasible on financial, spatial, technical, transport-economical, organizational, and commercial-strategic grounds. The study consists of two parts. The first part deals with working out an underground logistic system for the city and the calculation of the investment expenses attached to it. The second part consists of a series of interviews with industry (the potential users) to determine the support for an OLS. This paper focuses on working out a logistic system for the city of Leiden. To be able to determine the feasibility of an OLS in Leiden, the OLS needs to be dimensioned. After that the calculation of the investment cost can be made. The chosen research layout is shown in Figure 1.
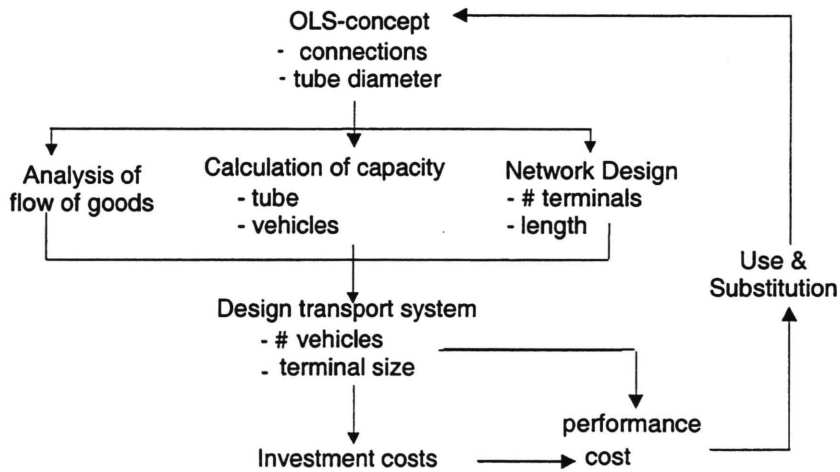
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Figure 1. Setup of the Study for OLS Leiden

The first step is to work out the concept of the OLS. This OLS concept is, as far as possible, attuned to earlier and parallel-running OLS projects. The concept is set up in as general a manner as possible, so that it can also be applied to other cities. On the basis of this concept a calculation of capacity is made, both for the tubes of an underground network and for the vehicles of the OLS. The next step is an analysis of the flow of goods. This analysis determines the amount of goods, expressed in cubic meters, that is transported to the inner city and to the rest of the city, using estimates on the basis of the number of businesses and typical values regarding their provisioning. The locations of the terminals are determined on the basis of the spatial structure of the city. The information on the spatial structure is also used to determine the network, specifically the length and tracing of the network. The next step concerns the determination of the number of vehicles needed in the OLS, as well as the size of the terminals. Finally, a calculation of investments needed is made on the basis of these data. Several investigations had already been done in the municipality of Leiden to determine the scope of freight traffic in the region and in the city of Leiden itself. As there was not much time available in the second phase of IPOT to perform case studies, it was decided only to use this information.

THE OLS CONCEPT FOR URBAN AREAS

The essence of an underground logistic system (OLS) is that goods that have to enter the city are delivered at a so-called Logistic Park, where they, after eventual storage or handling, are transferred into the OLS transport system. From there the goods are moved by automatic vehicles through an underground network and delivered in the city, either directly at the destination address, or at a Local Terminal. In the latter case, they are distributed further by (electric) vehicles on the road to their final destination. The system has provisions that make temporary storage, transshipment, and additional activities possible, so that we can speak of a "logistic system".

The OLS concept may look like an underground form of urban freight distribution, but there are significant differences. There are great expenses and loss of time that occur in urban distribution due to transshipment and the making of roundtrips with a great number of stops. These are avoided in an OLS by the automation of transport and transshipment, while the shipments are directly delivered at the destination without stops in between. Because the whole

process takes place in a closed and controlled environment, the system can be completely managed. This provides opportunities for all kinds of Just-In-Time services.

An urban OLS will after a while become part of a national (distribution) network, possibly of an underground network in the long run. In the short term, the stand-alone underground systems need to be connected to existing road, rail, and inland navigation systems or to new initiatives such as automatic freight vehicles, automatic (short) trains, and possibly national underground systems. The expectation is that the introduction of nationally functioning OLS systems will lead to great changes in the logistic chains (see Visser et al., 1998). This might even be a condition for an OLS: the chances for an OLS system in the city improve if it is connected to a national network. The starting point for a national system is that transport flows be bundled as much as possible to create advantages of scale (both economic and social). The national network looks after the connections between the Logistic Parks.

A Logistic Park is a terminal on a logistic industrial area. It provides access to the OLS and must therefore also be an important point of connection to the main road system, the railway system, and, if possible, to the Dutch system of waterways. The Logistic Parks form the focal points of transshipment, storage and distribution. From the Logistic Parks, collection and distribution takes place to and from the remaining businesses. The following services can be performed from the Logistic Parks:

- urban distribution by road
- underground urban distribution via the OLS
- regional collection and distribution
- inter-regional transport

Attracting regional distribution centers stimulates the use of the OLS. The Logistic Park functions as a transshipment terminal to the OLS for road, rail, and inland navigation, but in this way also concentrates distribution centers and transport-intensive activities.

A transport system is chosen where self-steering electric vehicles, by means of some type of guidance, move pallet-size load units at a speed of approximately 4.5 m/s through an underground network to a Local Terminal where the load unit (a pallet, for instance) is automatically unloaded and then delivered, by end-haulage, to the destination. The destination may also be a Lot Access, where the destination (a large supermarket, for instance) has its own connection. The advantage of a Lot Access is that no end-haulage is needed.
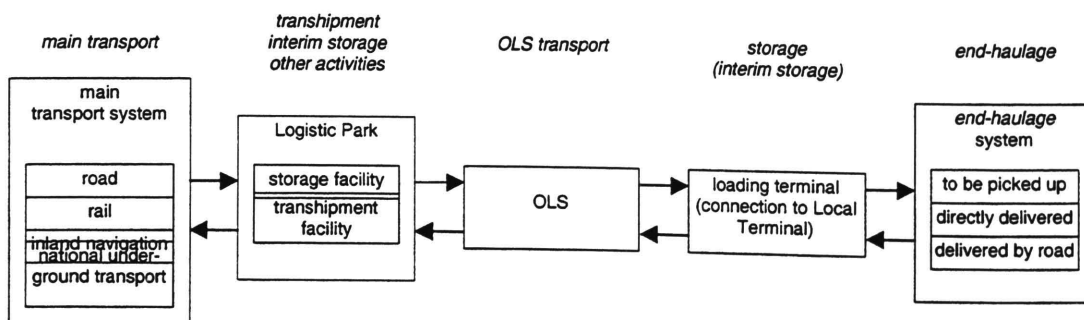

Figure 2. Transport Process

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Three types of OLS systems can be distinguished in principle:

- Colli system. A small tube with a diameter of approximately 1.5-meter, used for transport of small load units of 60 (l) x 40 (b) x 60 (h) cm named "Colli". This system is suitable for transport of boxes and parcels.
- Pallet system. A medium tube with a diameter of between 2- and 3-meter, used for transport of pallets of up to 125 (l) x 125 (b) x 180 (h) cm. This system is suitable for transport of pallets, roll-containers, and pallet-boxes.
- Citybox system. A large tube with a diameter of about 5-meter, used for transport of large units such as the Citybox.

The Local Terminals contain an underground section for loading and unloading of the OLS vehicles, and a surface section for aboveground dispatch. A Local Terminal functions as a "window" for the OLS on its assigned service area. Different kinds of terminals can be distinguished on the basis of the type of network and, to a certain extent also, the type of vehicle. These types of terminals are listed here in order of increasing size:

- lot-accessing terminals
  - individual lot: small store, catering establishment, office
  - dual access (two adjoining lots)
  - large store, catering establishment, office
  - shopping center, multipurpose business building
- street (section)-accessing terminal
- district terminal
- city-section terminal

If the Local Terminal is directly connected to a shopping complex, the terminal is identified as a "Lot Access". The characteristic feature of a "Lot Access" terminal is that it provides access to either a store, catering establishment or office (so that no after-transport needs to take place) or to a closed complex. In the latter case, there is still end-haulage, but this occurs in a protected environment (for example, indoors, it can be closed off to the public during certain hours). This is indicated as internal transport. The other types of terminals all require some sort of end-haulage, probably by road. A Local Terminal consists of the following parts:

- an underground platform for loading and unloading of the tube vehicles
- a vertical transport system (an elevator, for instance)
- take in and take out areas (aboveground and partly underground)
- storage facility
- an surface loading and unloading facility for after-transport vehicles

For internal and after-transport it will be necessary to provide (depending on the type of load units used):

- an (electric) cart or trolley (Colli system)
- a pallet-truck (Pallet system)
- a small road vehicle (Citybox system)

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The load capacity (the amount of load that fits in a vehicle) and the traffic capacity (the number of vehicles that fits in a tube) can be determined using the information provided below (Table 1).

Table 1. Vehicle Data for Determining of the Capacity

	Colli system	Pallet system	Citybox system
Data used for load capacity			
Vehicle length, net [m] (internal)	0,59	1,20	4,22
Width [m]	0,39	1,00	2,47
Height [m]	0,39	1,20	2,77
Volume [m³]	0,090	1,44	28,9
Load factor	0,71	0,53	0,5
Average loading [m³/load unit]	0,064	0,76	14,44
Specific gravity [kg/m³]	300	300	300
Total weight [kg]	19	229	4.331
Data used for traffic capacity			
Vehicle length, gross [m] (external)	1	2	5,1
Minimum distance between vehicles [m] (l_{margin})	0,5	1	2,55
Maximum reaction time [s] ($t_{reaction}$)	0,5	0,7	1
Maximum braking deceleration [m/s²] (l_{vtg})	-4	-3	-2

The capacity of a network is determined by the capacities of the tube system, the feeder lanes, and the terminals. The capacity of the tube system and the feeder lanes can be derived from the capacity of a single link. This is determined by the distance between vehicles and the speed of the vehicles (V_0). The so-called 'brick wall' method is a safe way of calculating the minimum time gap between vehicles. The formula is as follows:

$$H_{crit} = (l_{vtg} + l_{margin})/V_o + t_{reaction} + (1/2 \ V_o/a_o + \frac{1}{2} * (V_1)^2 / (V_o * a_1))$$

H_{crit} stands for "critical hiatus", which is the minimum time gap of vehicles (the time gap is the time that elapses between the passing of the fronts of succeeding vehicles). The number of vehicles per hour (and with that the capacity) can be determined by dividing H_{crit} into the number of seconds in one hour (3600). Speed influences the capacity in two ways: in principle, at a higher speed more vehicles will pass per hour through a cross-section; however, a higher speed also requires a greater distance or time-hiatus between vehicles. It follows from the theory that these effects oppose each other; this will lead eventually to an optimum situation, as is indicated in the graphs shown on the next page.
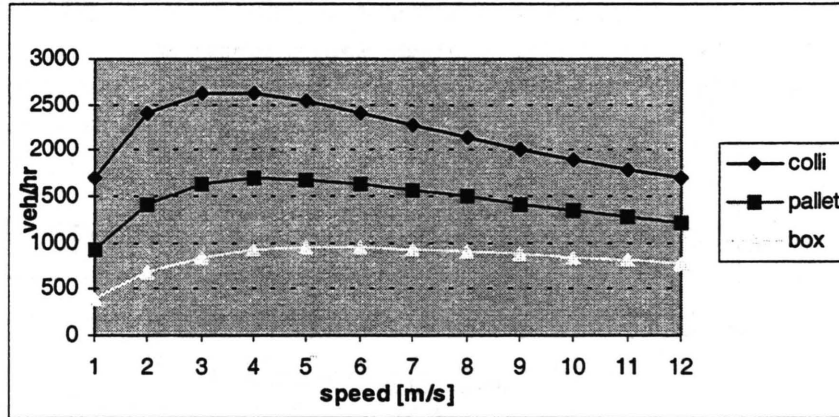
Figure 3. Tube Capacity for Vehicles

It can be seen from the graphs that the optimal speed for the Colli system lies around 3.5 m/s, for the Pallet system around 4.5 m/s, and for the Citybox system around 6.1 m/s. It also follows that the hourly capacity (expressed in number of vehicles) is much higher for the Colli system than for the Citybox system. The following table provides the exact values.

Table 2. Values for the 'Brick Wall' Follow-up Strategy

	Colli system	Pallet system	Box system
Expected braking deceleration leading vehicle [m/s^2] (a_0 and a_1)	-4	-3	-2
Speed V0 [km/u] (follower)	12,6	15,5	22
Speed V_1 [km/u] (leader)	0	0	0
Speed V_0 [m/s] (follower)	3.5	4.3	6.1
Speed V_1 [m/s] (leader)	0.0	0.0	0.0
H_{crit} [sec/vehicle]	*1.4*	*2.1*	*3.8*
Capacity [vehicles/hour]	*2635*	*1703*	*953*

The different systems are able to carry different transport volumes per vehicle. In practice vehicles may not be fully loaded, or the tube may sometimes be out of commission because of maintenance or problems. These factors taken determine the effective capacity, expressed in transport volume. It is also possible to draw graphs for the transport capacity. The optimal speed is of course the same as for the tube capacity for vehicles, as speed has no influence on the load.
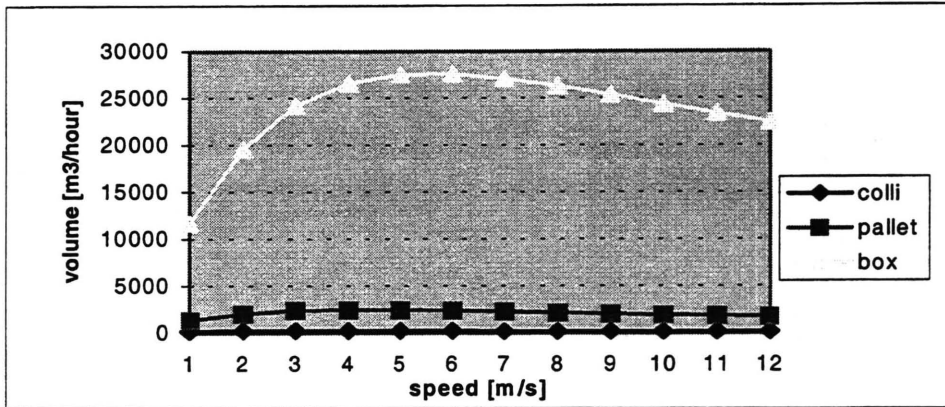
Figure 4. Tube Capacity Expressed in Volume

The following table shows the transport capacities, expressed in volumes, for the alternative tube transport systems.

Table 3. Transport Capacities in Different Tube Transport Systems

Tube connection	Colli system	Pallet system	Citybox system
Tube capacity per hour			
Tube capacity [vehicles/hr]	2635	1703	953
Units per vehicle	1	1	1
Average load [m³/load unit]	0,064	0,76	14,44
Availability of tube per year [percent]	85	85	85
Operational per day [hours]	18	18	18
Operational per year [days]	312	312	312
Tube capacity in volume [m³/hr]	*168*	*1299*	*13752*
Tube capacity per day			
in units [x 1000 units per day]	47,4	30,6	17,1
in volume [x1000 m³/day]	3,0	23,4	247,5
Tube capacity per year			
in units [millions of units per year]	12,6	8,1	4,5
in volume [millions of m³ per year]	0,7	5,3	55,8

ANALYSIS OF THE FLOW OF GOODS

The OLS is, in the first place, intended to provide the final distribution of consumer goods that are transported in load units with the maximum outside measurements of 125 (l) x 125 (b) x 150 (h) cm. The final destination is the retail trade, the catering establishments, offices, other businesses in the city, or the consumer itself. In the study of the city of Leiden no attention was paid to direct deliveries to the consumer, although it is an interesting option that will certainly be stimulated by the development of logistic systems.

The scope of the flow of goods is determined on the basis of information about numbers or size (expressed in business area) of stores, catering establishments, offices, and other businesses in Leiden and of typical values that refer to the provisioning of these types of business. An intermediate step was made where the provisioning, expressed in number of pallets, roll-containers, racks and boxes was converted into cubic meters of delivered goods per week.

Table 4. Typical Values for the Provisioning of Businesses

Business	Unit	Value
Retail trade - Daily - Not daily	Volume per establishment [m³/week]	12,23 3,76
Catering establishments	Volume per establishment [m³/week]	10,8
Offices	Volume per office area [m³/week/m²]	0,004
Industrial parks - Inner city - Outside inner city	Volume per industrial park area [m³/week/m²]	0,005 0,002

The following step was to determine the peak day (busiest day), with the volume on this day, and the peak hour (the busiest hour), with the volume during this hour. For the city of Leiden this resulted in the volumes (in cubic meters per week) listed in the table below. The values are estimates of the average volume of goods that are currently transported to and within the city of Leiden. This does not mean that all these goods would be transported by an OLS.

Table 5. Volume of goods for the inner city and the whole city of Leiden (in m³/week)

	Inner city	Leiden (total)
Retail trade	3348	6839
Offices	301	2238
Catering establishments	2441	3856
Other businesses	0	10065
Total	*6090*	*22998*

Prognoses have been made for the year 2020 on demographic developments, consumption, and the competitive position of Leiden as a shopping area. This led to the scenarios listed in the table below.

Table 6. OLS Transport Prognoses for the Retail Trade in the Inner City of Leiden in 2020

Scenario	Current	No growth	Moderate growth	Strong growth
Growth index	100	67	134	236
Yearly volume [x1000 m³/year]	318	213	427	751
Weekly volume [m³/week]	*6.121*	*4.101*	*8.203*	*14.447*

The next step is to use the estimated transport volumes to determine the transport intensities in the OLS system. No definite choice has been made with regard to the tube diameter, and the load unit that goes with it. This means that we must compare the possibilities. A number of the possibilities are worked out below in a qualitative fashion:

- In a Colli system, only units of the size of a box can be transported. This means that the system either can only transport boxes (and none of the other freight), or that other load units have to be stripped to box size (boxes / boxes + stripped other).
- In a Pallet system, pallets, roll-containers and racks that are offered for shipment, are transported as such. For boxes that are offered for transport there are the following possibilities:
    - to transport each box individually (this leads to a maximum of transport motions)
    - to transport boxes together if they are offered together and if they also have a common destination (the average shipment of boxes consists of four boxes), the "Boxes individually" alternative.
    - to build up boxes onto pallets (this leads to a minimum of transport motions) the "Boxes stacked on pallet" alternative.
- In a Citybox system, it is only Cityboxes that are transported. In the quantitative example it is assumed that no matter how the goods are offered, they will always be built up to (full) Cityboxes.

All this leads to "transport motions"–the transportation of a box or pallet from the Logistic Park to the Local Terminal or Lot Access. What this means for the situation in the city of Leiden is shown in the following tables. A distinction is made here between the retail trade and other businesses (catering establishments, offices, etc.). The number of load units to be delivered is considered for the inner city and for the whole city. The transport intensity is expressed in units per week. The following step is now to determine the transport intensity on the peak day and on the peak hour. This is done for the inner city and for the whole city. It shows that the Colli system, if all goods are stripped to boxes, leads to the most transport motions. The Citybox system has the least transport motions. The Pallet system is a good compromise system.

Table 7. Transport Motions in Different Systems - Inner City Leiden

	Week			Peak day		Peak hour	
	Retail trade	Other business	Total	Total	among retail trade	Total	among retail trade
Colli system							
Only for boxes*	5582	4571	10153	2031	1116	226	124
Boxes + stripped other	38014	31884	69898	13980	7603	1553	845
Pallet system							
4 boxes per truck**	5565	4557	10122	2024	1113	225	124
Boxes stacked on pallet	4418	3617	8035	1607	884	179	98
Boxes individually	9752	7985	17737	3547	1950	394	217
Citybox system**							
Cityboxes	116	95	211	42	23	5	3

*   pallets, roll-containers and racks are *not* transported in the system
**   pallets, roll-containers and racks are transported unmodified

The utilization of the tube will not be uniform due to peaks in the transport demand. The transport system must, to a certain extent, be able to deal with these peaks. In the following calculation it is assumed that a peak day constitutes one-fifth (1/5) of an average week (at a normal pattern of delivery for shipment spread over six days), and that a peak hour constitutes one-ninth (1/9) of the peak day (where the average is spread over 18 operational hours). The peak hour load is therefore 1/45 of the intensity per week. As the average intensity per hour amounts to 1/108 of the average intensity per week, the effective peak factor is therefore equal to 2.4.
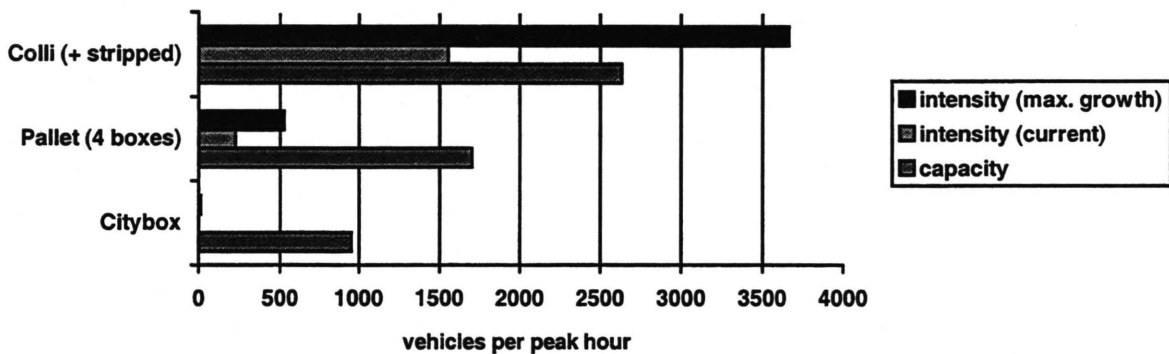
Figure 5. Capacity and Utilization of a Single Tube (Inner City)

Figure 5 shows that the capacity of the system is not exceeded if all transport for the inner city would take place through one tube. The Colli system has the most unfavorable ratio of intensity to capacity of 0.59 (this means that during the calculated peak hour the load amounts to 59%, and that there is therefore a reserve of 41%). The methodology used accounts for a relatively limited peak and takes the current transport values as its point of departure. In a high scenario (factor 2.36, see Table 6), the peak intensity in the Colli system would be more than 3600 vehicles, which would then exceed the capacity (2635 vehicles). A single tube with the Colli system would therefore not be adequate in the future. With the other two transport systems, the most unfavorable intensity-to-capacity ratio is much lower: 0.23 for the Pallet system, and 0.005 for the Citybox system. Even with the highest transport prognosis, one tube remains sufficient for these systems: this follows from the i/c ratio of at most 0.55 for the Pallet system, and 0.01 for the Citybox system. The Pallet system is therefore a safe choice, while the Citybox system would be considerably over-dimensioned. If all transport for the city of Leiden would have to take place through one tube, the following figure would apply:
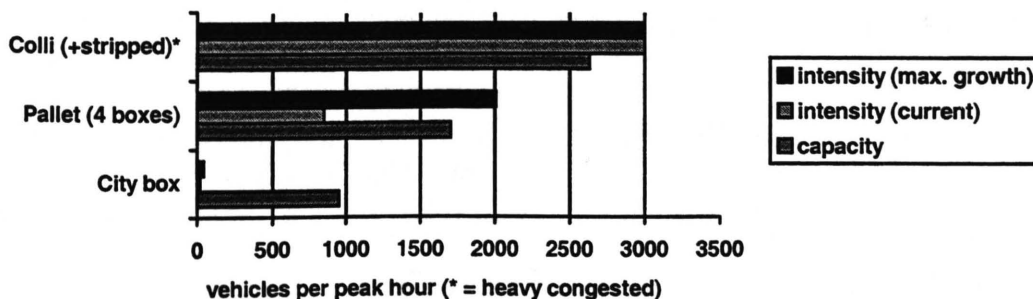

Figure 6. Capacity and Utilization of a Single Tube (the Whole City of Leiden)

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If all transport for the whole city of Leiden would have to go through one tube, the Colli system would become heavily overloaded. With that system parallel tubes would therefore be required. Using the Pallet system, with the "Boxes stacked on pallet" alternative, the intensity-to-capacity ratio is 0.4, which could be just sufficient for a development with large growth. There is therefore a reasonable amount of capacity in reserve. The other Pallet system alternatives are adequate in the current situation, but would not allow extreme growth (this applies especially to the "Boxes individually" alternative).

The Colli system has the advantage of a small tube diameter, so that the tubes are cheaper to put in place and a network with a finer mesh can be established. In addition, it is possible to set up a semi-continuous transport system with very short reaction times. It would be, in other words, a courier service for consumer goods. On the other hand, it must be noted that only part of the goods can physically go through the tube, that the logistics have to be adapted, that the tube is not directly accessible for repairs, and that the capacity is too small. In comparison, the Citybox system is actually capable to have small trucks drive through the tubes. The advantage is that it has a large capacity, and that transshipment is not necessary. On the other hand, the construction cost is much higher, while only a few connections can be realized. The Pallet system is a good compromise: it has a decent capacity with relatively low construction cost, while almost no adaptations are necessary to the logistics. The OLS system, when a Pallet system is used, can utilize existing load units, such as roll-containers and pallets with a maximum footprint of about 125 by 125 cm. It is, in principle, possible to go to a maximum height of 185 cm; however, we assume a maximum height of 150 cm. It is likely that the introduction of the OLS (or of other systems) will lead to new standards. It is essential that no (or as few as possible) extra actions need to be performed in order to get the load unit into the OLS. Extra actions create loss of time and increase of cost. As a result, it was decided that the underground network will consist of a drilled tube system with a tube diameter of between 2.5 and 3 meter.

NETWORK DESIGN

The number and location of the Logistic Parks depends on the orientation of the flow of goods towards Leiden. The A4 highway is the most important road connection along which goods to Leiden are transported. The distribution centers are mostly located along the A4 highway. The flows of goods are not sufficiently large to warrant several Logistic Parks. A selection was made of possible existing and new locations. On the basis of a multi-criteria analysis two Logistic Parks were selected: A4-Roomburg and Haagwegterrein. The Logistic Park Haagwegterrein is intended as a rail connection. A combined road/rail connection with one Logistic Park is not very feasible; it was for this reason that two Logistic Parks were chosen.

In the OLS concept, a distinction is made between a Lot Access (a terminal specifically for one user) and a Local Terminal (a terminal for several users). It was necessary to determine how many of these terminals were required (and realizable), and also where these were to be located.

With regard to the connection of the terminals, it was first determined which locations were to be connected (choosing the "situation"), and then it was decided where (choosing the site) and how many at each location. Because the study has a "explorative" character, it was not

decided where exactly the terminals were to be located. A few possible options were indicated for areas of exploration: for instance, empty public spaces, storage spaces that could be re-developed, and store fronts. A very interesting option is to integrate the terminals into new or existing underground parking garages. A number of phases can be distinguished in the development of an OLS in the city of Leiden. In the first phase, the inner city is connected to the OLS. Two Lot Accesses were selected: one for the LUMC (University Hospital Leiden), and one for the Aalmarkt complex. Three Local Terminals are at this point sufficient for the provisioning of the inner city. At a later date the OLS plan can of course be extended. The most obvious options are:

Phase two: an extension to the shopping centers elsewhere in the city.

Phase three: an extension to the large regional production and distribution centers. The size of these centers warrants that each gets its own Local Terminal.

The tracing of the network was done by looking for the "simplest" connection between the locations of the terminals. This means: as short as possible, and as free of obstacles as possible. A search was done for corridors, where a corridor is an underground trajectory that is probably obstacle-free, and of sufficient width to contain a single or double tube. A corridor is characterized by a minimal presence of buildings on the surface, even though mainly underground construction methods (such as drilling and pressing) will be used. This also means a reduced presence of piles, basements (cellars), and other underground obstacles. Possible corridors were canals or four-lane main roads leading to the inner city. The most promising corridors were checked to see if they were indeed obstacle-free (or at least "obstacle-poor"). Two designs were worked out—a phase one design for the connection of the inner city, and a phase two design for the connection of the whole city of Leiden. A phase three design connecting the important regional production and distribution centers has not been worked out yet.

INVESTMENTS

On the basis of estimates for the investment and exploitation costs, a first impression is gained of the yearly exploitation expenses of OLS in Leiden. The following table shows an initial provisional estimate of the total investment costs of the first phase of an OLS in Leiden.

Table 8. Investment Costs OLS Leiden (Phase One)

Component	Number/length	Costs (in guilders) Subtotal	Total
Logistic Park	1		10 million
Tube conduit	6 km	Open trench 5,000/m	30 million
Tube conduit	5.5 km	Drilled tunnel 8,000/m	44 million
Local Terminal	5	1 million each	5 million
Logistic Park NS-CS	1		10 million
Total investments into infrastructure			100 *million*
Transshipment equipment			5 million
OLS vehicles	180	20.000 / vehicle	3.6 million
After-transport vehicles	5	50.000 / vehicle	0.3 million
Management system			5 million
Total Investments into transport structure			14 *million*

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Besides the investment cost there are the annual expenses for maintenance, servicing and operation. These costs are shown in the following table.

Table 9. Exploitation Costs OLS Leiden (Phase One)

Description	Number	Costs (in guilders)
Energy		p.m.
Maintenance transport & management system		1 million/year
Manning the operating system	10 man-year	1.5 million/year
Manning the Logistic Parks and after-transport	18 man-year	1.8 million/year

A partial shift of activities from shippers and transporters to the Logistic Parks is calculated into the cost of manning the operating system. As a result only a limited number of extra jobs are projected for the Logistic Parks. It will be clear that a new manpower analysis will have to be performed before it will be possible to redesign the logistic chains. With regard to the after-transport, it is estimated that 6 man-years are needed for the final distribution in the inner city.

The investment cost is translated into annual expenses by converting into depreciation and interest costs. This was done both for the civil technical part as well as for the transport technical part. As shown below, the calculation results in a first estimate of 10 million guilders in yearly expenses. This amount is for the most part (>75%) not sensitive to the size of the flows of goods.

Table 10. Annual Expenses

Description	Expense per year (in guilders)
Depreciation civil infrastructure	2 million
Interest civil infrastructure	2.5 million
Depreciation transport facilities	1.5 million
Interest transport facilities	0.2 million
Exploitation costs	4.3 million
Total annual expenses	Approximately 10 million

On the basis of the current flow of goods, the current cost of the distribution of goods into and out of the inner city of Leiden amount to about 12 million guilders per year (7000 m^3/week at an average price of 35 guilders per m^3). These costs will likely increase in the coming years because of growth in both the size and the expense of distribution transport on the road. If these developments are taken into account in the calculations, and if we assume a substitution of the flows in the order of 50 to 75%, a situation arises where the size of the profits of the system are of the same order as the estimated cost. In a scenario where 50 to 75% of the transport flows shift to the OLS, it is estimated that 50 to 75% of the cost of the OLS can be paid from the direct transport revenue. At full subsidization by the government of the cost of the infrastructure, and without compensation for the concession and depreciation, the annual exploitation cost is estimated at 5.5 million guilders. Under normal commercial conditions, it is then possible to achieve a sufficient return on the exploitation at a modal shift to the OLS system of about 50%. Arguments to convince the government to carry the cost of the infrastructure, while only a part of the expense incurred this way will be recovered by means of a concession, generally center around the following:

- the reduction of the cost connected to the road infrastructure due to smaller growth of freight traffic
- the importance of a structural reduction in the environmental burden
- a contribution to the economic structure of the (inner) city

As the national network and the alternative to rail distribution begin to develop, the flows of goods will grow and make even more use of the OLS. The extra cost of extending the tube system to the production and distribution centers (phase three) will be balanced by the relatively large amounts of goods that will enter the system this way.

The feasibility of a national network with transport in a tube system is depends primarily on market support. Besides the importance for market parties, a national transport network ("Landelijk Transport Netwerk") can also supply valuable social contribution. Innovative transport solutions used in the OLS promise to decrease costs associated with congestion and air pollution; provide better space utilization of roads, and improve traffic safety. In addition, important economic effects will occur in the area of job creation: temporary jobs in the planning and construction phases, permanent jobs (direct and indirect) in the exploitation phase. Cost reductions will also include regional savings on infrastructure.

CONCLUSIONS

The study showed that there are possibilities for an underground freight transport system in an urban area, such as the city of Leiden. It is, however, not possible to formulate a definitive answer to the question if an underground logistic system in Leiden would be justified on financial, spatial, technical, industrial economic, organizational, and commercial-strategic grounds. The results of the study are reasonably positive. There are, however, many uncertainties that require further study. Besides that, the flow of goods is limited in size. The possible contribution on the basis of price and performance has not been estimated in this study. The study did, however, provide new knowledge: more insight was obtained in the size of the flows of goods. It also became clear that corridors could be found in Leiden (and therefore possibly also in other cities) that can be used for the construction of underground tubes.

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Analysis of Pneumatic Capsule Pipeline Systems with Bends

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ABSTRACT

The motion of capsule in a pilot pipeline is predicted with high precision by using an established numerical method. The length and the inside diameter of the pipeline are 664m and 30mm. The pipeline consists of several horizontal, vertically upward and downward sections connected with 47 pieces of 675mm-radius 90 degree bends of different configurations. The maximum height of the pipeline from the inlet is 11.9m. The capsule is cylindrical. The outside diameter, length and mass of the capsule are 28.3mm, 70mm and 34g, respectively. A blower generates the airflow of negative pressure in the pipeline. There is a requirement that the local capsule velocity should be larger than 12 m/s. The pipeline must first be closed to allow the pressure at the capsule front to reach a specified value; then the pipeline inlet is opened to the atmosphere, the capsule being released. The gas flow is assumed to be isothermal and one-dimensional. The numerical simulation is compared with the measurement taken in the pilot pipeline in terms of the capsule velocity at various points in the pipeline. The capsule is sharply decelerated at the bends but quickly recovers the previous velocity after the bends.

INTRODUCTION

Progress in technological development in recent years has caused design requirements for pneumatic capsule pipelines to become more stringent. This paper shows that by using an established method of numerical simulation, the motion of capsule in a complex pipeline is precisely predicted. Thus, the numerical simulation qualitatively and quantitatively becomes a useful and strong tool for practical design.

Capsule motion was calculated using a pilot pipeline which models transport of a sampling material from a production site to a test station in a steelworks. Pilot plant results were compared with the measurement taken in the industrial pipeline. The sampling material is contained in a cylindrical capsule without wheels. To cope with possible various situations in the works we constructed a complex pilot plant, which contains many bends that are necessary to connect pipeline sections of different configurations.

At the bend the centrifugal force acts on the capsule normal to the direction of travel and forces the capsule on the pipe wall, which affects the retarding force on the capsule. Thus, the capsule is decelerated in a horizontal bend. Since there was a requirement that the capsule velocity should be larger than 12 m/s, the airflow needed to satisfy this condition had to be determined. Then, it was necessary to trace the capsule motion in the pipeline, using numerical simulation for this purpose.

PIPELINE CONFIGURATION

Figure 1 shows the schematic diagram of the pilot plant pipeline. The total length and the inside diameter of the pipeline are 663m and 30mm, respectively. The pipeline consists of several horizontal, vertically upward and downward sections connected with 47 bends, each of which is a 90-degree bend. The radius of the bends is 675mm. The capsule is collected in a box as a dead end for the gas flow after T-branch near the end of pipeline from where the gas is sucked to the blower. The maximum height of the line is 11.9m from the starting point for the capsule. To measure the capsule velocity, a number of photocells were installed along the pipeline as shown below.
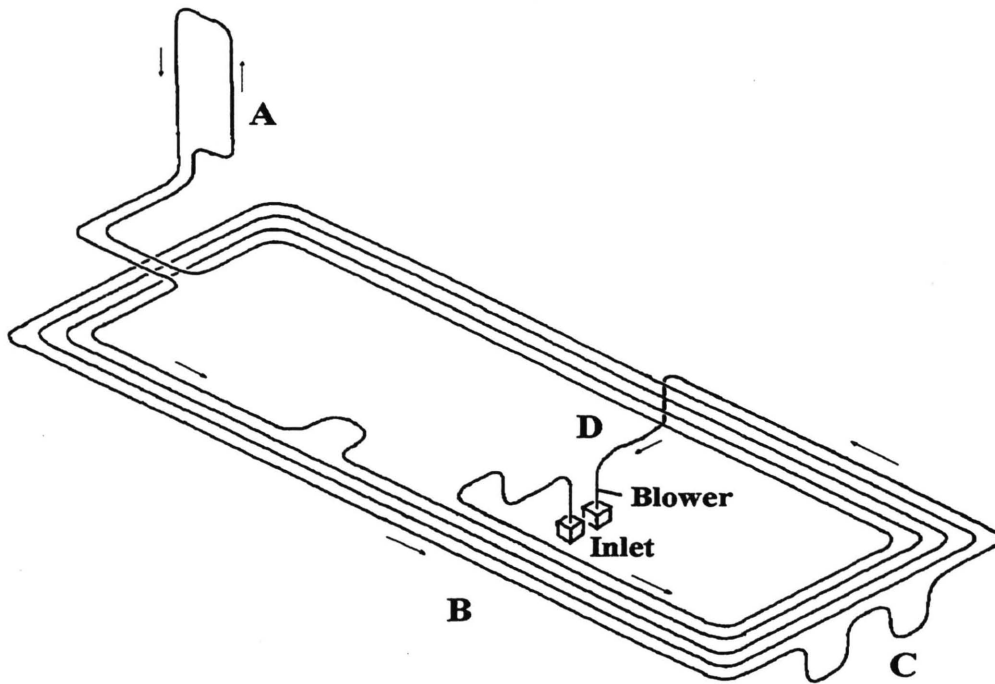
Figure 1. Schematic Diagram of Pilot Plant Pipeline

The capsule is cylindrical, the outside diameter and the length are 28.3mm and 70mm, respectively, and the mass is 34g.

A blower generates the airflow of negative pressure in the pipeline. The inlet of pipeline is open to the atmosphere after the vacuum pressure at the capsule front reaches a specified value, and then the capsule is released. When the capsule arrives at the pipe end, the exit valve to the blower is closed.

METHOD OF NUMERICAL SIMULATION

Researchers operated on the premise that the capsule is driven by the pressure difference between the rear and front sides of the capsule, and the shear force acting on the capsule side surface is ignored. Thus, equation of motion for the capsule in the horizontal bend is given by

$$m\frac{d^2V_c}{dt^2} = A_c(p_R - p_F) - fm\sqrt{g^2 + \left(\frac{Z^Y}{R_c}\right)^2} \tag{1}$$

In this equation, m represents the mass of capsule, V_c the capsule velocity, t the time, A_c the capsule cross-sectional area, p_R and p_F the pressures at the capsule rear and front sides, f the sliding friction factor of the capsule against the pipe wall, g the gravitational acceleration, and R_c the bend radius. In the horizontal to vertical upward bend, the equation motion for the capsule becomes

$$m\frac{dV_c}{dt} = A_c(p_R - p_F) - mg\sin\theta - fm\left(g\cos\theta + \frac{V_c^2}{R_c}\right) \tag{2}$$

where θ represents the angle between the direction of capsule velocity and the vertical line. There are three other cases for the equation of motion in the vertical bend.

As to the equations of gas flow, if we assume that the gas flow is one-dimensional, the conservation of mass is

$$\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0 \tag{3}$$

the conservation of momentum is

$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial x}(\rho u^2) = -\frac{\partial p}{\partial x} - \lambda\frac{\rho u^2}{2D} \tag{4}$$

and the equation of state is

$$p = \rho RT \tag{5}$$

where u represents the gas velocity, x the axial coordinate, ρ density of gas, p the pressure, λ the pipe friction factor for gas, D the pipe inside diameter, T the temperature and R the gas constant. Assuming that gas flow is isothermal, that is,

$$T = const. \tag{6}$$

Furthermore, we omit the second term of the left-hand side of equation (4) since the gas velocity is small as compared with the propagation velocity of isothermal pressure wave.

To solve the above equations, boundary conditions and the initial conditions for the gas flow must be known. After the vacuum pressure at the capsule front reaches a specified value, the pressure at the pipe inlet is set to the atmospheric pressure through an inlet valve. At the pipe exit we give the blower performance curve (or characteristic curve) which gives a relation between the output pressure and the flow rate at the suction side of the blower. At the capsule we use an orifice flow model to relate the gas flow at the capsule rear and front sides, that is,

$$A\rho_R(u_R - V_c) = (A - A_c)\rho_c u_c \tag{7}$$

$$A\rho_F(u_F - V_c) = (A - A_c)\rho_c u_c \tag{8}$$

$$\rho_c u_c = \text{sign} \; p_R - p_F \; C \; \sqrt{p_R + p_F)|p_R - p_F|} \tag{9}$$

where C represents the orifice discharge coefficient.

We apply the method of characteristics to calculate the gas flow. The method is described in reference [1]. As to calculation method at such fittings in pipe as valve and branch, the conventional method is utilized [2].

RESULTS AND DISCUSSION

Figure 2 shows the calculated results of capsule velocity and arrival time from the blower start against the distance from the pipe inlet. The inlet valve was opened when the gauge pressure at the capsule front reaches -16.66kPa. The many spikes in the capsule velocity show the decrease due to the bend. It was found that the capsule velocity was gradually increased and was always larger than 12m/s in this condition. The capsule sharply decelerated at the bends but quickly recovered to the previous velocity after the bends.
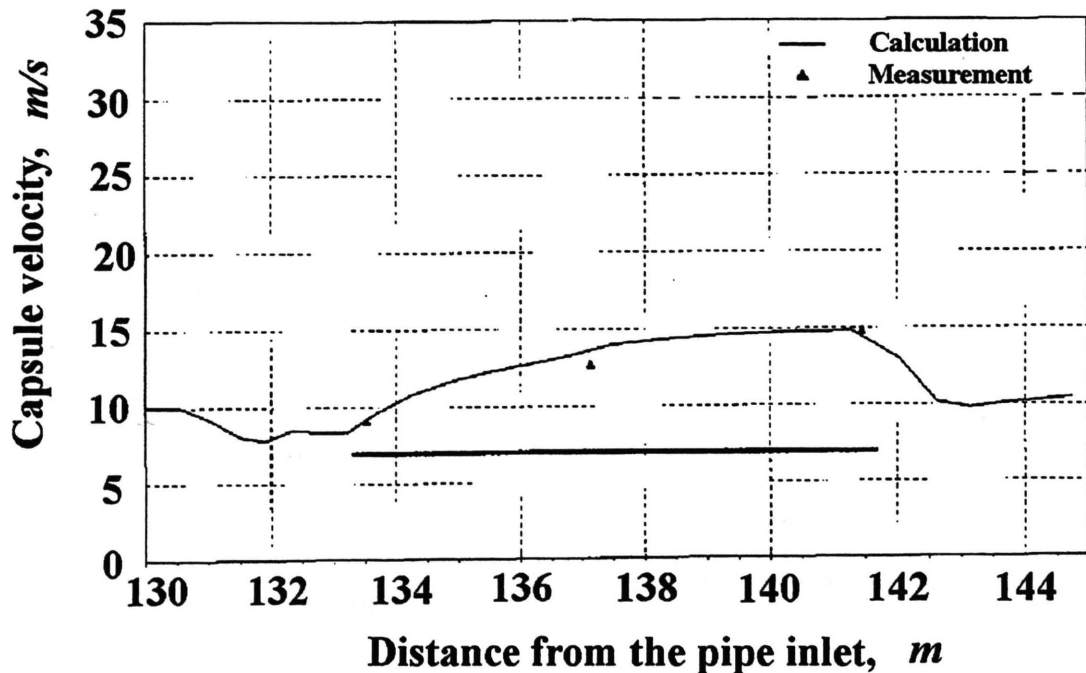
Figure 2. Capsule Velocity and Arrival Time

Figures 3 to 6 show the comparison of capsule velocity with measurement in different sections. Figure 3 shows that the capsule velocity is increased when it passes through a vertically downward section A. The agreement of calculation with the measurement is satisfactory.

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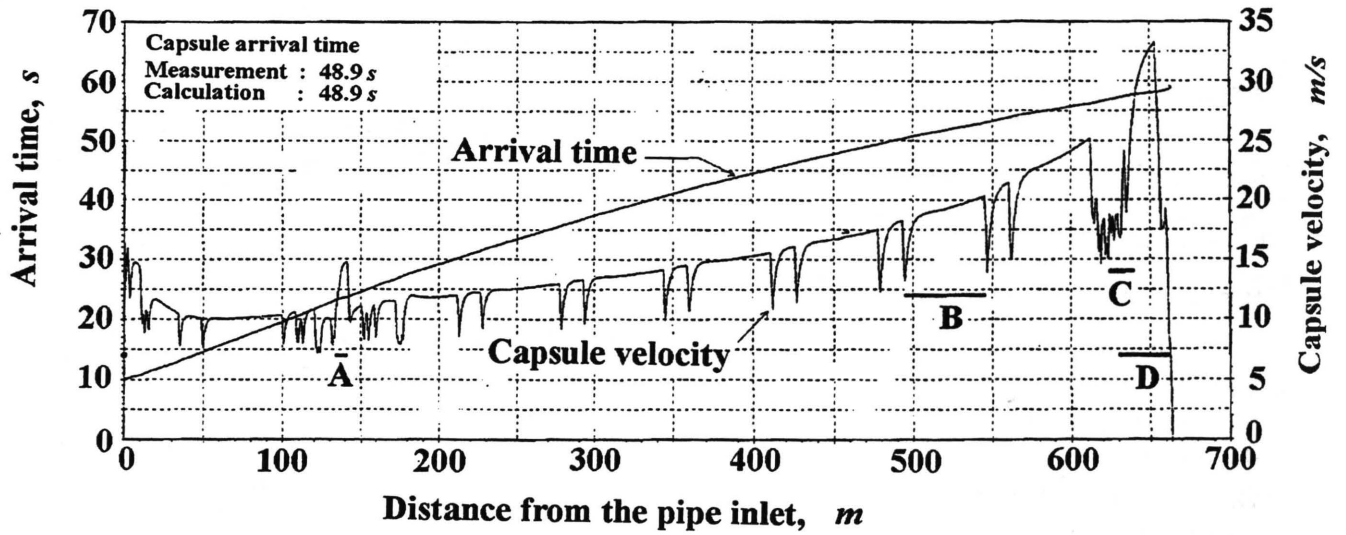
Figure 3. Capsule Velocity in the Vertically Downward Section A.
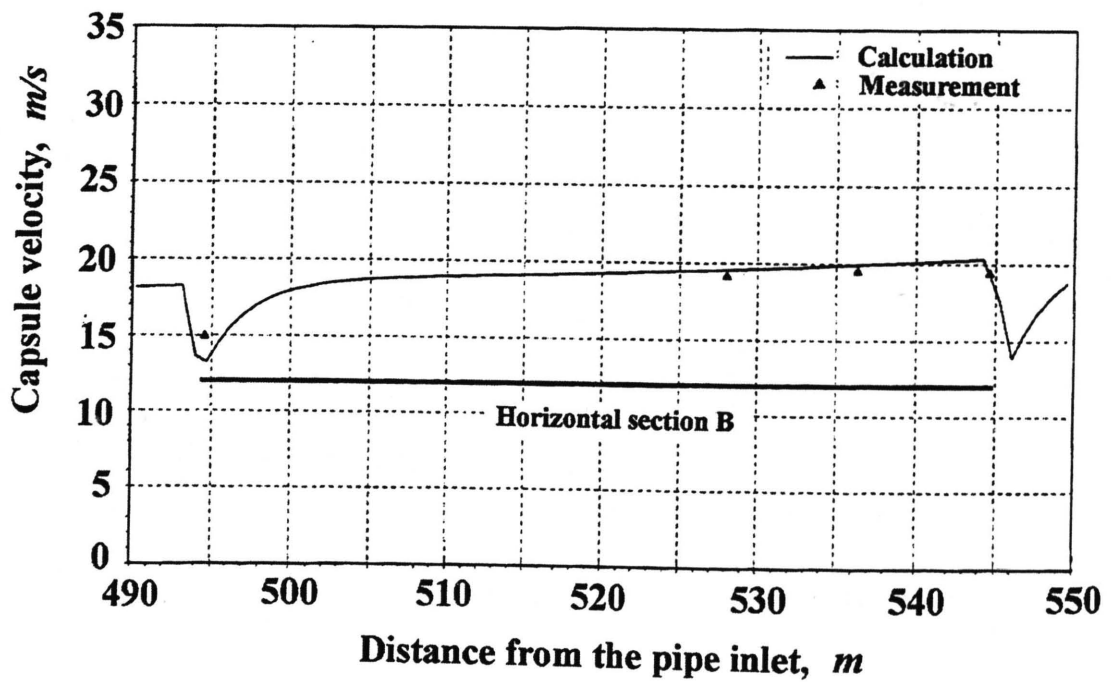
Figure 4. Capsule Velocity in the Horizontal Section B.
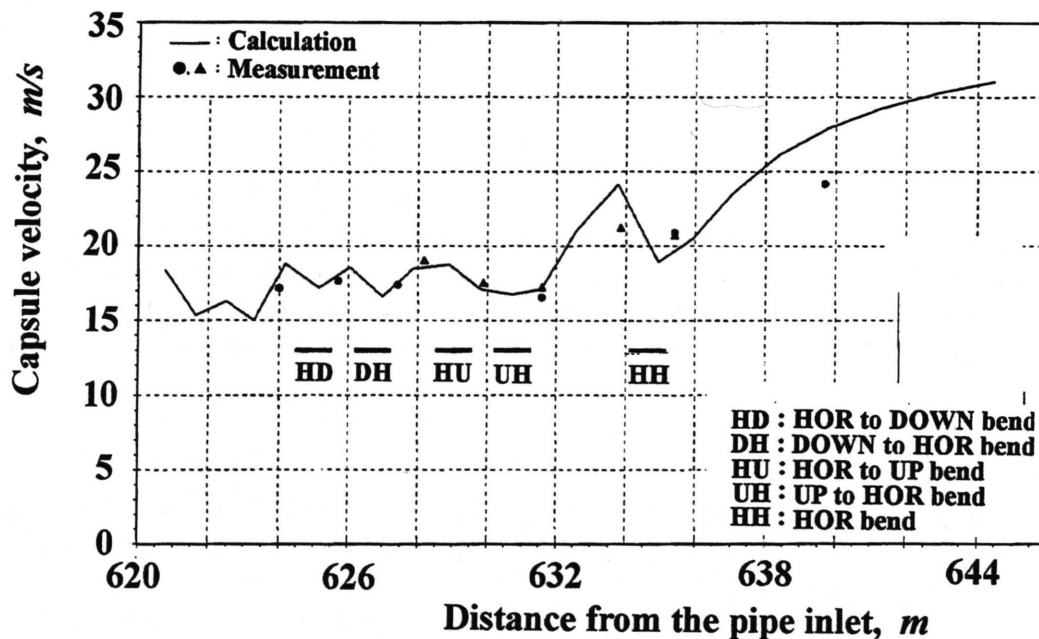
Figure 5. Capsule Velocity in the Bend Section C.

Figure 4 shows the result in the horizontal section B. Figure 5 shows the result in the section C that includes many types of bend configurations. Figure 6 shows the result in the section D near the end of pipeline. It is said that the agreement of calculation with the measurement is satisfactory.
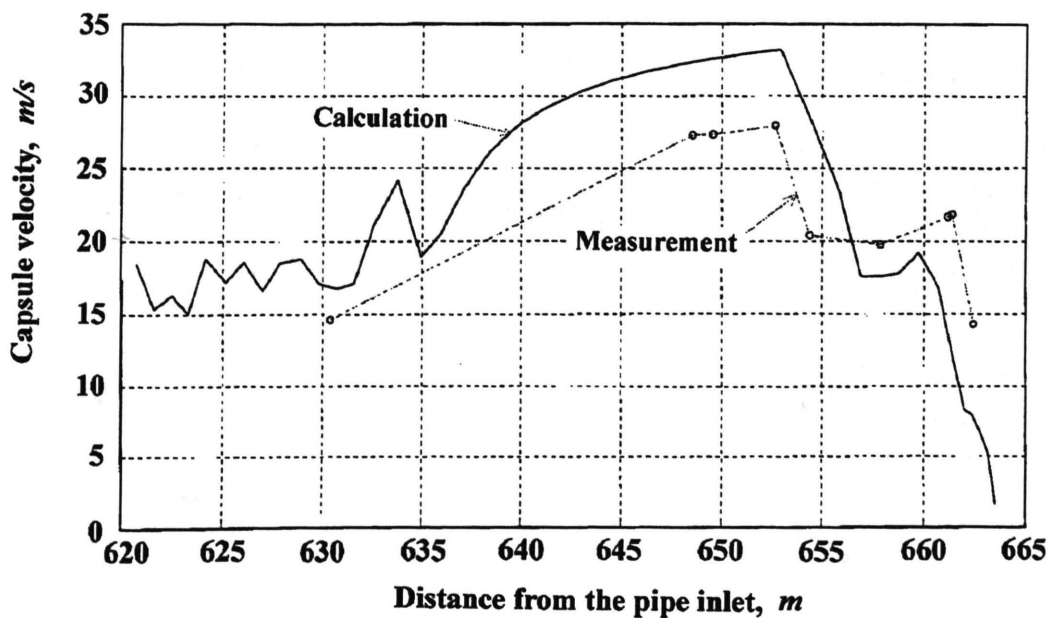
Figure 6. Capsule Velocity in Section D.

As to the result of gas flow, the agreement of calculation with the measurement was satisfactory as well. The present calculation method is easy and is flexible to include additional operating conditions of pipeline.

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CONCLUSIONS

In this paper we have shown that the capsule motion in a complex pipeline can be easily and precisely traced by the established method of calculation. Furthermore, it was easy to find out the operating conditions to satisfy the design specifications. Although in this calculation the size of capsule is small, this method is directly applicable to a large-scale pneumatic capsule pipeline.

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ACKNOWLEDGMENT

NOMENCLATURE

<u>English</u>
A = cross-sectional area of the pipe;
A_c = cross-sectional area of the capsule;
C = orifice discharge coefficient for the clearance flow at the capsule;
D = inner diameter of pipe;
f = sliding friction factor of the capsule against the pipe wall;
g = gravitational acceleration;
m = mass of capsule;
p = pressure;
R = gas constant;
R_c = bend radius;
u = gas velocity;
T = absolute temperature of gas;
V_c = capsule velocity

<u>Greek</u>
λ = pipe friction factor for the gas flow;
θ = current angle in the bend;
ρ = gas density;

<u>Suffix</u>
c = clearance between the pipe and the capsule;
F = front side of the capsule;
R = rear side of the capsule.

The Pneumatic Mail Tubes: New York's
Hidden Highway and Its Development

By Robert A. Cohen, Postal Inspector, U.S. Postal Inspection Service

INTRODUCTION

In 1971 The Postal Department became a quasi-private federal agency with the new name of The United States Postal Service. It no longer looks toward Congress to appropriate money; it must sustain itself. At the very beginning of my career with the postal service in 1972, I met people who were employed by the original Postal Department and knew of the Pneumatic Tube System. They would talk of a system of underground tubes around New York City that transported mail from one station to another. I wish I had listened more closely at that time. I was quite young and I had other interests on my mind. All I can now recall is them pointing to a section of the building where the tubes came up through the floor. I heard a few stories about its normal operation that always fascinated me. There were cylinders into which mail could be placed and sent through the tubes. I guess I had the same reaction that I get today when I tell people about it. It is usually disbelief. The whole idea was an anachronism to me. It was something you might see on the old TV series the "Wild Wild West." The old time postal workers also had colorful stories of the extraordinary use of the tubes. Supposedly, there was a cat sent through the system from one station to another just to see the reaction. I was sure that an order of a corned beef on rye with a knish and a pickle had been transported through the tube system from the post office nearest the Second Avenue Deli.

Over one hundred years ago Postmaster General (PMG) Charles Emory Smith predicted Pneumatic Tube Service delivering mail to every home in the upcoming Twentieth Century. He was partially correct. In 1910 The US Postal Department initiated the policy of home delivery of mail to every home in the nation. That service to every home is still in effect in spite of its annual cost. The Pneumatic Tube Service did not last as long, as a direct result of its annual cost.

In October 1997 the 100th anniversary of the Pneumatic Tubes passed without any official recognition. My interest was taken just before that time, when the curator of the postal museum in New York City told me about that upcoming event. I began researching and looking for any remnants of the tubes. My imagination went wild with images of my predecessor postal employees working the system and the heavy equipment used to transport and receive the carriers. I had recollections of the stories I had heard earlier in my career. I was amazed and fascinated when I learned of the tubes traversing the Brooklyn Bridge. The fast action of the system caused it to be described as "Mail shot from Guns". Its travel routes caused it to be described as "Subterranean Mail"

How could the one hundredth anniversary of the Pneumatic Tube system pass without recognition? How could such a marvel be forgotten? I have not forgotten it. Here is what I have learned.

Inception

The beginning of the system was not a "Pipe Dream." The creators had a plan and each step in the evolution of the system led to an improvement on the last.

In 1867 Alfred Ely Beach, who some of you may recognize as the editor of the Scientific American in the middle 1800s, wanted to build a subway in New York City. Past experience from experiments of others in Europe steered him away from steam locomotion within an underground tunnel. The steam and smoke caused severe problems to the eyes and noses of the passengers. Beach felt that air power, as the means of locomotion was the best method to employ successfully in a closed underground environment. Beach studied the early nineteenth century Danish theory: *"the creation of a vacuum in front of an object could produce tremendous atmospheric thrust behind it."* Mr. Beach applied to the city for authorization to build this subway car and track. The New York City council membership was in the control of the disreputable, and notorious, Boss Tweed. Nothing could get through his "Legislature-for-Hire", without Tweed's authorization. As Tweed and Beach had contempt for each other, Tweed was completely against Beach's plan to build this subway.

Beach also had theories about an underground Pneumatic Tube System for mail that would have pick up and drop off points at lampposts throughout the city. The clever Mr. Beach, as a ruse applied for authorization for construction of a pneumatic tube to carry mail around the city. He was successful in his lobbying efforts and the Pneumatic Tube System Bill passed through the city legislature. Beach secretly started the construction below a store on Warren Street in old downtown New York City. However, the construction he began was not for the pneumatic tube for mail. Instead Beach began construction of the Pneumatic Subway (Figure 1) He played the politics games well and asked the Legislature for an amendment to make the tube larger. Using this new authorization for the large tube he was able to complete his actual goal of the time, The Pneumatic Subway.
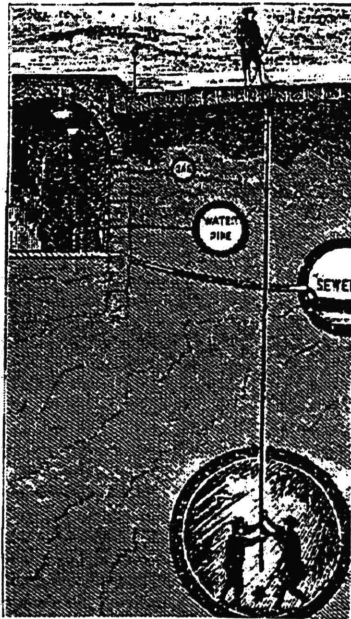
Figure 1. Workers check direction of digging during tunnel construction.

It was a very ornate project. The subway station was adorned with frescoes and easy chairs. Zircon lamps revealed the luxurious interiors of the stations. The subway car was also surprisingly ornate, luxurious and comfortable. This was very a pleasant and unexpected surprise for the first paying viewers (Figure 2).
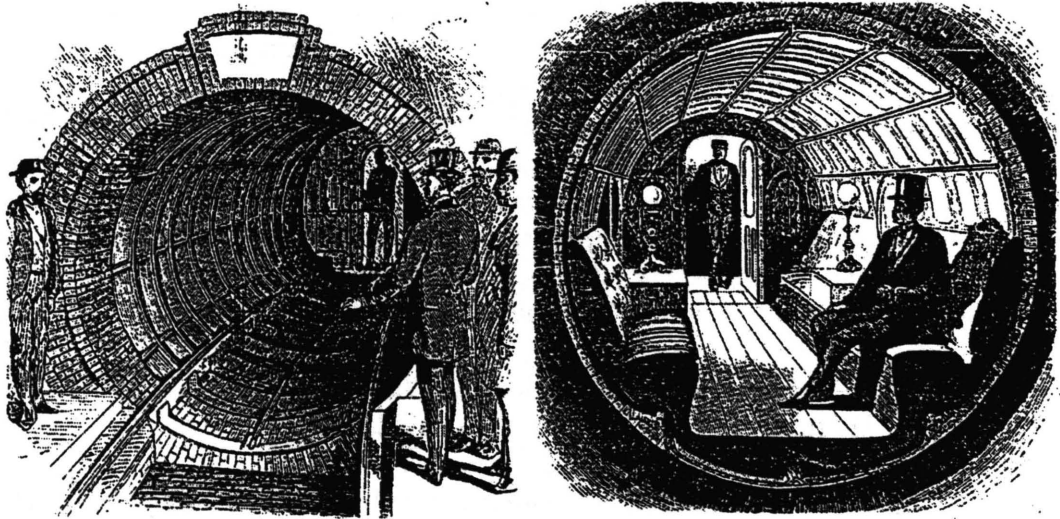
Figure 2. New York Socialites prepare to enjoy the ride in the Pneumatic Subway.

In order to stay within the law and his city contract, Beach built a pneumatic tube system for the mails. It was on a very small scale—1,008 ft of 8" inch pipe. It carried letters and papers at a speed of 60 mph. The system was connected to a hollow lamppost-drop on the street above. Beach's small prototype subway never really developed into anything, but his pneumatic tube system has the distinction of being the first mail tube in the USA. Eventually he had the tunnel sealed.

Forty-two years later New York City subway construction workers fortuitously came across Beach's Subway tunnel. It is unnecessary to say they were shocked at their archeological find. It was incorporated into the subway system. Supposedly, there is a plaque in the Brooklyn-Manhattan Rapid Transit (BMT) City Hall Station marking the site of Beach's vision.

Pneumatic tubes to carry mail were being developed in London, Germany and Paris. These systems lasted longer than the American systems, but they were only two inches in diameter. Therefore, they could not carry much mail. In Paris The Carte Pneumatique also known as "The Pneu", remained in operation until 1987 with 269 miles of tube. It was mainly used for telegrams and special delivery.

The Beginning of the US Post Office Department's System

Credit for the original pneumatic tube system idea must be given to Dennis Papin, an engineer whose paper on the "Double Pneumatic Pump" was presented to the Royal Society of London in 1667. Almost two centuries later it was put into operation in London by Latimer Clark. The first operational internal-facility Pneumatic Tube System in the USA was installed in 1887 at Lynn, Massachusetts. Western Union had a small external Pneumatic Tube System between two of its offices in New York City in 1888. Investigation at the time showed that pneumatic tube service used for commercial purposes was not a success. A system used commercially in Boston was eventually leased to the Post Office Department.

From 1889 through 1891 there was a series of annual reports to Congress by the PMG. These reported on investigations into the feasibility of implementing a pneumatic tube system for movement of the mail. In the Act of July 13, 1892 Congress authorized an investigation into the "Rapid Dispatch of Mail by means of Pneumatic Tube". They appropriated only $10,000.

Immediately thereafter Postmaster General Wanamaker solicited bids for contractors to build the system. He received eight bids, but if the bidder did not already have a pneumatic tube system in existence, it would have to build one at its own expense to conduct a test for the government. The successful bidder was the Pneumatic Transit Company of New Jersey.

The original agreement was to build and install all tubes, power, receiving and sending stations at each facility without any cost to the government. The Pneumatic Transit Company of New Jersey would incur this total cost. After the trial run period there was an agreement made to lease the system at a cost based on a rate per tube mile. The tubes were 6½" inches in diameter.

The initial test location was Philadelphia. The very first test was conducted on March 1, 1893 between The Philadelphia General Post Office and the East Chester Street Post Office. It was a distance of .58 miles. The test was successful and tube service officially began in Philadelphia. On October 15, 1897 the service in New York City began. Eventually, Pneumatic Tube Service was put into operation in Boston, Chicago and St. Louis.

On August 1, 1898 tube service began over the Brooklyn Bridge to the Brooklyn General Post Office from all Post Offices in Manhattan, New York (Figure 3). In New York there was a contract between The US Post Office Department and the "New York Mail and Newspaper Transportation Company." New York City's system was constructed in stages with additions over the years based on need. There were two service points in Brooklyn and eventually one at the Bronx General Post Office. They were connected with 23 post offices in Manhattan.

The first cylindrical carrier to travel through the New York City system was one that contained a bible, a flag and a copy of the Constitution. The second contained an imitation peach in honor of Senator Chauncy Depew, a driving force in this project. He was fondly known as "The Peach". A third carrier had a black cat in it, for reasons unknown to this author.
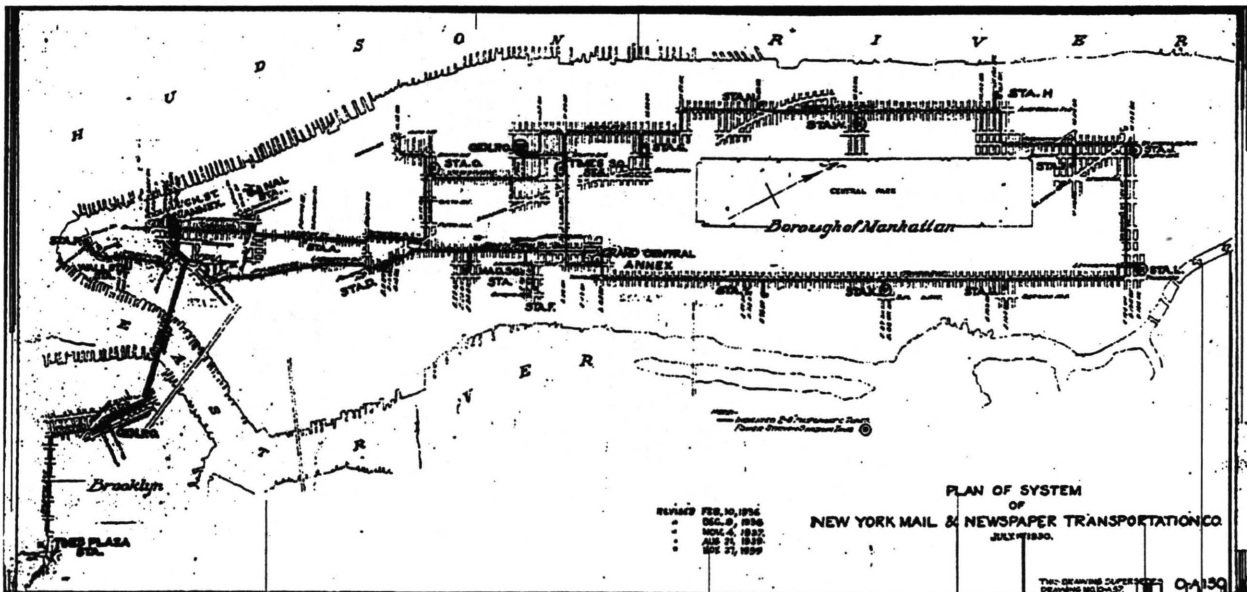
Figure 3. Map of Pneumatic Tube System in New York City.

The initial Congressional authorization in 1898 was for sixteen and two tenth miles in all cities. In 1916 the authorization was increased to 113 miles. The following is a breakdown of the tube distance authorization for the cities and the operating companies. New York City had 55.5582 total miles of tube, operated by The New York Mail and Newspaper Transportation Company. Boston had 13.6378 total miles of tube operated by The Boston Pneumatic Transit Company. St. Louis had 3.9760 total miles of tube operated by The St. Louis Pneumatic Tube Company. Philadelphia had 19.9998 total miles of tube operated by Pneumatic Transit of Philadelphia. Finally, Chicago had 19.814 total miles of tube operated by The Chicago Postal Pneumatic Tube Company.

The operation of the Pneumatic Tube System involved air forced cylinders known as "carriers," traveling in a spinning motion, through a well-greased tube at 30 miles an hour. At its peak productivity six million pieces of mail would whisk through the system daily at a rate of 5 carriers a minute with each carriers maximum load containing approximately 500 letters.

Pipe Design, Materials and Specifications

The tubes were made of cast iron with a bored inside diameter of $8\frac{1}{8}$". This tube size in a double-tube configuration had the capacity to transport 200,000 letters an hour. Postal officials had always specified eight-inch tubes. A committee of Postal experts estimated that eight-inch tubes were sufficient for present and future requirements. Eight-inch tube was the maximum size that could fit on the postal work floor. Each tube had a 9/16" inch thick wall and a special finished spigot and socket for correct alignment when the tube sections were joined together. Lead joints maintained the air seal needed. Direction changes were made by gentle tube bends

and a larger bored diameter that allowed the carrier to negotiate the turn. The tubes were fastened together by bolted flange. They were buried four to six feet below the busy streets.

New York City has a series of complex structures and rocks underground. This constrained the tubes, requiring them to be installed in the most practical rather than the most direct routes. There are ten north and south thoroughfares that handle New York City's underground utility traffic. Six of them are occupied by subway systems, the balance being used by public utility companies. Therefore sometimes the tubes were installed along the top of the existing subway tunnels. Another amazing feat was the traversing of the Brooklyn Bridge. The flexibility of that structure required various special devices to keep the tubes in alignment.

Carrier Design, Materials and Specifications

There were 95,000 steel cylindrical carriers that were said to resemble artillery shells or torpedoes (Figure 4). They were 24 inches long, 8 inches wide and they weighed 21 pounds. There were doors on each end that locked by cam. The carrier could not be placed into the sending unit for entry into the tube unless the end doors were locked. This was to ensure they would not open en-route and cause the mail to get damaged. Inside, the cylinders were 22 inches long and 7 inches wide. They were capable of holding five hundred letters. These dimensions were just under the size of the pipe and resulted in a snug fit. A felt strap on each end of the cylinder maintained an air seal.
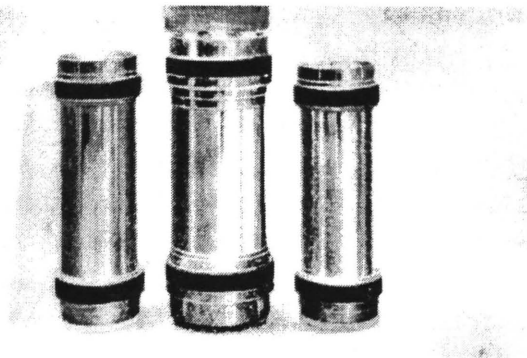
Figure 4. According to information printed with this picture of the capsules   (carriers), "Government Experts estimate that every day 20,000 letters are advanced by the "Pneumatic Tube Service." Twenty-eight hundred Carriers are constantly in motion traveling from one Post Office Station to another through the Pnuematic Tube Systems."

Power Stations

Power Stations, consisting of positive rotary blowers and reciprocating air compressors driven by electric motors provided air pressure ranging from three to eight pounds per inch (Figure 5). The carriers had the potential to travel up to 100 miles an hour but because of the many turns, carrier travel speed was kept at 30 mph.
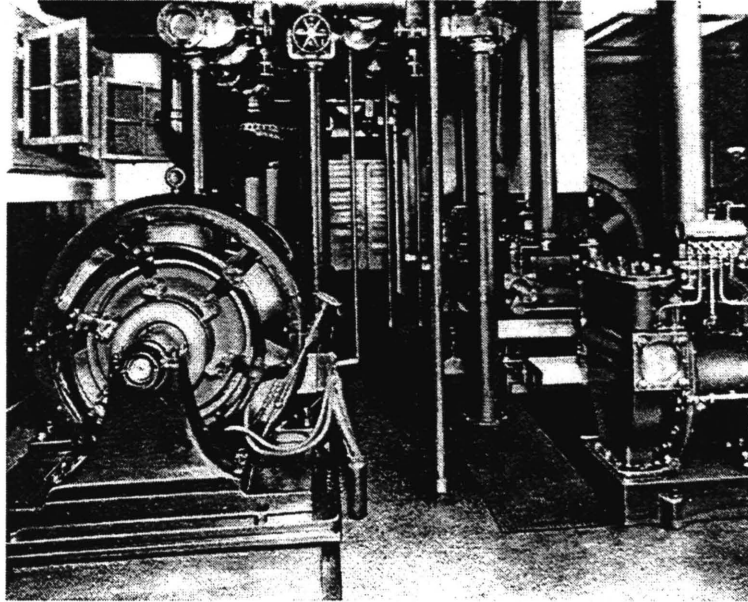
Figure 5. Power Station Generator

Sending & Receiving Units

Skillfully controlled air pressure allowed the carriers to gently reach their destination and land on an apron device-receiving tray (Figure 6).
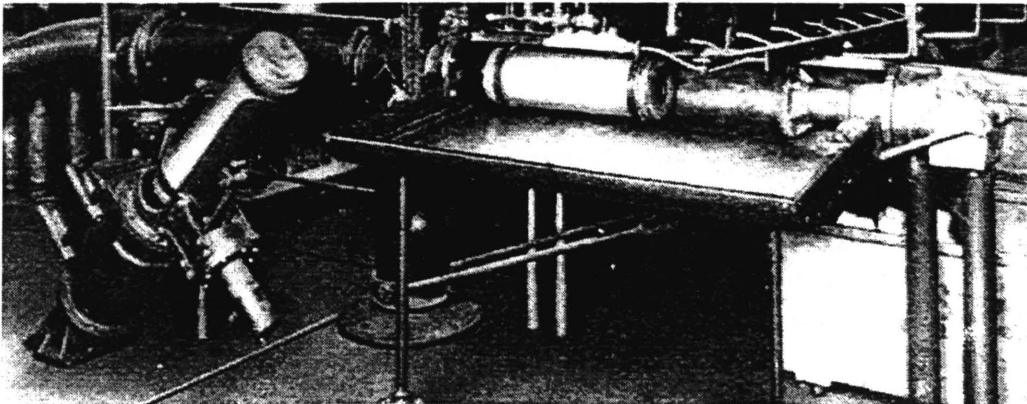
Figure 6. Transmitters and Receivers in Postal Station A, New York.

Operation and Maintenance

Maintenance was the responsibility of the system's owners in each of the cities where leases existed. The responsibility of the operation of the entire pneumatic tube system was in the hands of The Post Office Department.

The person responsible for the sending and receiving of the carriers was known as the Operator or Rocketeer. There were 136 Rocketeers in New York City (Figure 7). Dispatchers manned a telephone intercommunication system and ensured operations were not interrupted. They were also trained in the system's technical details. The telephone number of the tube room at the General Post Office was Pennsylvania 6-7000. In the 1940s, the "Swing" bandleader and music composer Glenn Miller put a similar telephone number (Pennsylvania 6-5000) to music. That telephone number was located right across Eighth Avenue from The General Post Office in Pennsylvania Station.
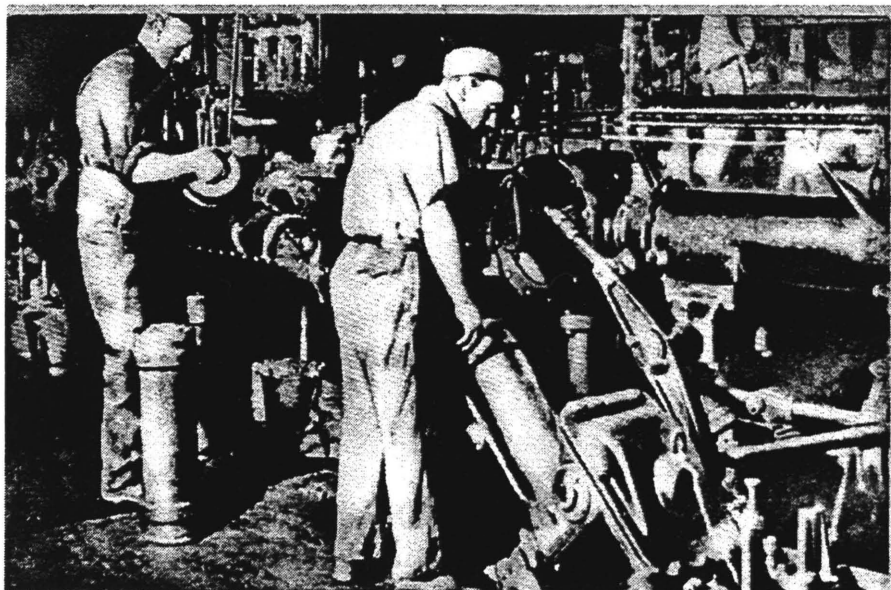
Figure 7. New York Postal Workers, also known as the "Rocketeers" are shown sending the mail on its way.

To keep the system well lubricated a perforated carrier containing oil would be sent out periodically through the entire system.

Each of the regular carriers had an outside label and it was not opened until it reached its final destination. They traveled through the tube to the next post office where the label was read and the carrier was then placed back in the tube to be sent onward, until it reached its marked destination.

Carriers could be dispatched at a rate of five a minute, that is about one every twelve seconds. In the 1950s during their regularly scheduled operation time period, 55% of all New York City mail traveled through the system. The hours of operation were 5:00 a.m.-10:00 p.m. Monday-Friday; 5:00 a.m.-10:00 a.m. Saturday and no service on Sundays and legal holidays. A snow emergency could prompt the system to run 24 hours a day. This system enabled mail to travel under the snow covered and clogged streets thus avoiding traffic congestion for the mail truck drivers and unnecessary mail delays. The blizzard of 1947 in New York City did not prevent the Post Office from living up to it's motto "Neither Snow nor Rain nor Heat nor Gloom

of Night Stay these Couriers from the Swift Completion of their Appointed Rounds." The mail flow continued underground and without interruption throughout the crisis.

The occasional carrier that stalled in a tube could be easily detected. Each receiving machine was equipped with a "tell-tale" fan. If a carrier failed to arrive on time the air pressure would fall to level that would cause the fan to stop revolving. The operator at the affected station would call the switchboard at the telephone number PE 6-7000. On a control board there, the blocking carrier could be located through colored lights designating each station. In 90% of the cases the arrested carrier could be made mobile again by increasing the air pressure behind the blockage and decreasing air pressure in front of it. This would in effect cause a vacuum. In the 1% of the time that these methods did not work a maintenance crew had to go out and dig up the streets.

Cost of the Lease

In the very first year of the Pneumatic Tube System existence, the Post Office Department did not pay for the service. However the next year they began paying at a rate of $4000.00 per year for those .56 of a mile tubes. In 1917, $17,000.00 per mile per year was the lease rate for all cities. That was more than the cost it required to carry mail on the railroad. In a proposal of April 21, 1932, The New York Mail and Newspaper Transportation Company offered to lease the system to the New York Post Office for $515,946.60 from July 1, 1932 through June 30, 1934 at a rate of $19,500.00 per mile. In January 1951 a ten-year contract was signed with The New York Mail and Newspaper Transportation Company at a cost of $1,226,000.00. That contract was never completed.

Congressional Reviews

In 1907 US Postal Inspectors issued a report covering the Pneumatic Tube Service in which it was stated, "This is the most expensive method of mail transportation in use at the present time, and the Inspectors very much doubt whether the advantages obtained are commensurate with the heavy expense."

As stated earlier the whole Pneumatic Tube System was leased to the Postal Department and the contract was renewed periodically. Due to this method The Congress had to authorize the appropriation. Congress reviewed annual reports in order to determine if the service should be continued. The Postal Appropriations Bill of June 30, 1899 prohibited any new contracts for Pneumatic Tube Service. This prohibition continued until June 30, 1901. Therefore, suspension of service occurred in all cities in from July 1, 1901 through June 30, 1902.

Some early Congressional limitations placed on the Pneumatic Tube System were: contracts were written for 4 years or less; there must be a favorable annual report by the PMG; no contract could be for more than 4% of the gross postal revenue. After June 30, 1904 renewals had to be provided for in the annual appropriations bill. By imposing these restrictions Congress placed a ceiling on the cost.

In 1906 the pneumatic tube contract expired. The government was unable to secure bids in several cities. Their recommendation was for the service to be discontinued in Chicago, Philadelphia, Boston and St. Louis. However, Congress recommended service be continued in

New York City. At the insistence of the Pneumatic Tube companies and because of the political strings that may have been pulled, the contracts were extended by the Postmaster General until June 30, 1916 and later extended by Congress until March 3, 1917. The final extension ended June 30, 1918.

A committee report to the PMG October 13,1916 found the following in relation to the Pneumatic Tube System:

Advantages:

1. High rate of speed between stations for limited quantities of mail.
2. Freedom from surface congestion.

Limitations and Disadvantages:

1. Only five pounds of mail could be carried in each container; and all classes of mail could not be carried.
2. The minimum time between dispatches is 15 seconds allowing only 20 pounds of letter mail each minute. Therefore, vehicle service would be required to carry mail during heavy volume times.
3. The inability to carry special delivery parcels due to the size of the carriers.
4. The relays at station are built in delays but they are unavoidable requiring all stations to be manned and open during operation.
5. The inability to dispatch between intermediate stations during continuous transmission between any two points.
6. Inability to dispatch to railroad companies without additional handling.
7. Complaints resulting from careless locking and accidental opening of container in transit causing damaged mail.
8. Dampness and oil damage to mail.
9. Service interruptions block an entire line.
10. Congestion from heavy mail volumes.
11. Equipment takes up rented building space.
12. Excessive costs

By 1918 there was a growing debate about cost versus benefits of what had been essentially developed as an inner city business district service. After World War I, Congress hesitated at the price tag to continue the service. At this time Congress also reviewed the facts regarding the Post Office Department's decision just a few years prior, to begin Parcel Post service. This class of mail was too large to utilize the Pneumatic Tube Service. Suspension of service occurred in all cities in 1919, 1920, 1921 and 1922. In 1922 the system was resurrected in New York City and 4 years later in Boston

The End of an Era

Recently I met an old friend who told me her father was once a rocketeer. In conversation with him I learned that he had spent some time working on the Pneumatic Tube System at The Bronx General Post Office. I had an old map showing the proposed tube run from Manhattan to the Bronx. He assured me that the extension to the Bronx was completed. A

"swish and a thump" were his description of the sounds of the arrival and departure of a pneumatic carrier. The torpedo loading similar to that seen in a World War II, movie is how he described the Bronx tube room. He remembers that the carriers were very dirty and oily. Sometimes the bosses gave out aprons to the workers but most of the time you were told to wear dirty clothes. He told me something off the record. Since there was a renowned sandwich shop in the vicinity of The Bronx General Post Office, they often got orders from the downtown postal stations. The sandwiches were delivered through the system. Now that's what I call a real submarine sandwich!

The original concepts and design of the Pneumatic Tube Service were conceived with tunnel vision. Larger tubes would have meant more flexibility and room for change with time, but a larger tube would have required more expensive and larger equipment. The larger carriers would have been more expensive and heavier. Congressional restrictions and reviews were a deterrent to private companies. They did not want to bid on a negative cash flow business. From the very beginning the system had to justify its cost.

Eventually, because service was being hampered by systematic delays and because of the introduction of the automobile, The Postal Department began leaning toward abandoning the tubes. While all other means of transportation had improved the tube system did not. The frequency of carrier dispatch and their capacity did not change. Both of these factors controlled efficiency of the system. The system remained stagnant. As mail volume increased over the years the volume of mail transported by pneumatic tube became minuscule in comparison to the entire volume of mail. A comparison of the Pneumatic Tube System to a funnel would give an understanding of why it became antiquated. It takes a certain amount of time for a gallon of liquid to travel through a funnel. Two gallons take twice as long to pass through. The value of the Pneumatic Tube Service decreased as mail volume increased.

Another negative position can be viewed through the following situation. When mail was sent to railroad stations it was handled twice. The mail was first sorted at the post office then transported by tube to the railroad. There it was sorted a second time according to railroad schedule and destinations. If the original sort at the post office, was the final sort needed for the railroad, that same sorted mail could be transported in less time by truck to the railroad station. That second unnecessary and time-consuming sort would have been eliminated. Using the tubes in this situation did not effectively save any time. The travel time saved by using the tubes was lost in the time working the second sortation.

In 1953 the new President, Dwight Eisenhower, appointed Arthur Summerfield, as the Postmaster General. The controversy over the future of the pneumatic tubes finally came to a head. Even though in January 1951 a ten-year contract was signed with The New York Mail and Newspaper Transportation Company, Mr. Summerfield decided that the contract would be cancelled and the tubes were to be dismantled. The mail would be carried in the newly purchased fleet of trucks. It was felt that two additional trucks at a cost of $25,000.00 a year would sufficiently replace the Pneumatic Tube System. This saved the one million-dollar outlay for the lease of the system. On December 12, 1953 service was suspended in all cities. The approximately 130 regular postal employees formerly assigned to tube service were reassigned to other positions in the postal establishment. Some of these workers are pictured in Figure 8.

Figure 8. A few of the 130 postal tube service employees reassigned to other positions when service was suspended December 12, 1953.

Destruction of the System

The Pneumatic tube systems were built, maintained and owned by private business concerns outside of the Postal Department. The original contract, written and agreed upon at the time when the Postal Department first tested the system, stated "it was the responsibility of tube system owners to dismantle and remove the tube system from all stations at their expense". Since the Post Office department no longer had a need for the system and it was privately owned, Postmaster General Summerfield ordered The New York Mail and Newspaper Transportation Company to remove the tube systems from all government owned or government leased premises. This was necessary to allow space for the new age of mail processing equipment. In the late 1950s The New York Mail and Newspaper Transportation Company sued the Post Office for breach of the 1951 contract and won a settlement. They received $216,110 for services rendered before the cancellation of the ten-year contract. In a 3-2 opinion, it was determined by The United States Court of Claims, that the contract was invalid. The opinion was rendered because the contract came about through negotiation with the only bidder, The New York Mail and Transportation Company, and the contract differed materially to the requirement set out in the advertisement for bids.

In the Present

Periodically in New York City construction crews come across old pipe marked US Post Office Department. They usually report it to the New York Postal Museum and they are told not to be concerned.

Through my research I have located remnants of the system in three post offices in New York City. In two of them I found the actual pipe flanges coming out of the wall from beneath the city streets (Figure 9). The red brick surrounding them showed no sign of wear. At Madison Square Post Office I recovered a page of old New York Daily News. This newspaper must have been used to fill the gaps between the tubes as they traveled between floors of the post office. The tubes were gone but the round molded impression in the leftover hanging concrete still had a full page of the events of September 21, 1937. In the movie section Spencer Tracy was starring in the motion picture "Big City."

Just think of some of the other events that occurred in 1937. There was a newspaper strike in New York City and Mayor Fiorello Laguardia read the comics over the radio, to all New Yorkers. Amelia Earhart disappeared while flying, and The Hindenberg crashed.
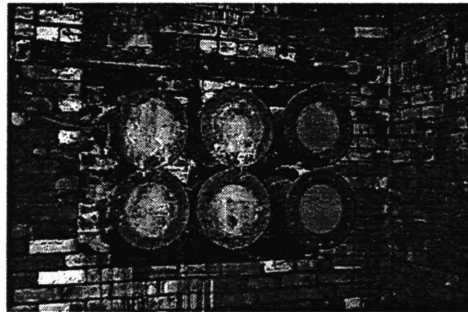
Figure 9. Flanges that are remnant tubes at Old Chelsea Street Post Office

The Pneumatic Tube System was very a controversial system. If it had not been dismantled and it was resurrected today, I think the tube system would be able to provide a remarkably quick, city wide Express Mail service, that no private concern would be able to compete with effectively.

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Joseph Cohen, Founding Curator, New York Postal Museum.

Paul Konigsberg, Curator New York Postal Museum.

Mr. Jack Steinglass, Retired Postal Clerk, U.S. Postal Service.

Megaera Ausman, US Postal Service Historian.

James H. Bruns, Director, National Postal Museum Smithsonian Institution.

Panel Discussion

"Need for Freight Pipelines"

Participants:

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Arthur P. James, Associate Research Scientist
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This panel includes a diverse group of people. Each has a very different perspective coming from a different background representing a different organization. Some see freight pipelines from the user's standpoint, some from the government official's standpoint, and some from the researcher's standpoint.

I would like to thank all the panelists for agreeing to be on the panel and to contribute opinions. I want to start with Larry Vance who is with the Volpe Transportation System Center and is the one who wrote the important report, "Tube Transport," for the Federal Highway Administration. This is the report on pneumatic capsule pipeline (PCP) that allowed the Department of Transportation Secretary to report back to the Congress as required by the ISTEA legislation. So, without further comment, I will start with Larry Vance.

Larry Vance, Transportation Planner, U.S. Department of Transportation, Volpe National Transportation System Center, Cambridge, Massachusetts

As most of you know, I have been involved since about 1993. Tube transportation was new to me at least in terms of current events at that time. As Henry Liu indicated yesterday, progress in a major field like this takes time. It seems excruciatingly slow to some of you, but my impression here from yesterday's meeting and this morning's session is that, in fact, very real progress is being made. I think there's a growing awareness at least within the technical community of the potential of underground freight transportation or tube freight transportation. I certainly see a lot of progress. I remember my first international e-mail on this came from the Netherlands. I watched with interest their progress and certainly there is excellent progress there. Certainly, the Japanese have been making excellent progress, and I think it's rewarding to see German representation here. So this is truly an international activity. I just say let's keep going full speed ahead. I think the U.S. Department of Transportation (DOT) certainly will watch with interest and will provide support. I had one thought this morning as I was listening to Johan Visser talking about the proposed Leiden UFT (Underground Freight Transport) system. I don't know how many of you are aware of it, but there is an existing system similar to what he described except it was never automated and it is no longer in operation under the streets of Chicago. It was a distribution system tunneled under the buildings of the central business district of Chicago around the turn of the century—mostly tunneled through clay. A lot of the tunnels were unlined and operated with small electric locomotives—designed to service the large stores and businesses in downtown Chicago. One of the major commodities transported was coal for heating--coal in and ash out. The system also distributed mail and parcels and was connected to the conventional rail system. So for those of you that are interested in history and precedence and perhaps a little understanding of why projects succeed or fail, it's a very good object lesson.

I would say one other thing that I am seeing here which characterizes where we are. I also worked with other major transportation programs and have been heavily involved in the early days of what we're now calling the intelligent transportation system initiative. They are, of course, further along on the development cycle than tube transportation is. Just to characterize, tube freight transportation has certainly entered an intensive development stage, but as you get into the later part of the development stage and much more into implementation, I can say that

from a governmental perspective the topic that becomes Number One is *Standards*. I haven't heard the word *Standards* yet today or yesterday, but it will come to, because at some point I expect that we will see short systems develop first. Just like the history of the railroads, and the gauge question with the railroads—eventually someone's going to want to connect one system to the other. Suddenly, standards will become a major issue. That one hasn't come up yet, but we will be seeing it one of these days. That is what I have at the top of my mind at the moment.

Arthur James, Associate Research Scientist, Center for Ports & Waterways, Texas Transportation Institute, Texas A&M University, Galveston, Texas

There are a couple of things that I would like to finish from yesterday's discussion with regard to underground pipeline transportation of freight at the ports. I impressed upon you yesterday the fact that a lot of ports are running out of room and that you're going to see more and more congestion problems with trucking if the carriers have their way, and they seem to be having their way. For example, the port of Houston, by the tonnage measure, is the second largest port in the country. At the Port of Houston, the Barbours Cut facility, which was built in the late '70s, is the most modern container port on the Gulf of Mexico. This facility handled 980,000 TEUs of containers last year, and it is at capacity. The Port of Houston has in the planning stages to build a second container facility down the ship channel a little ways (about 5 miles), toward the Gulf from the current facility. It will be called the Bayport facility. Bayport is supposed to be a 720-acre facility with intelligent systems. They've been studying gates and so forth worldwide to try to make this port as close to optimal as possible, but there's a big political brouhaha. People in the Bayport area have started protesting because of the congestion that's going to be caused on the landside—access problems, congestion, and noise and air pollution, etc. So, there are public hearings going on as we speak regarding whether the Port of Houston should be allowed to open this new facility. So, we don't know yet whether they are going to build this thing or not. If they can't build it, they've got a real problem, and the Gulf of Mexico has a real problem with regard to getting containerized freight into the Gulf. Houston is about twice as large as New Orleans, which is the second largest container port on the Gulf. If Bayport doesn't work, there are really no storage facilities near Houston. Houston will be stuck with a situation sort of like Los Angeles and Long Beach. Most of you are probably familiar with the Alameda Corridor that was built in Los Angeles. It's a 20-mile consolidated rail corridor that was built to prevent at-grade auto/rail crossing problems when moving cargo from the ports of Los Angeles and Long Beach up to a storage yard north of Los Angeles because they were having terrible landside storage problems and bad traffic congestion around the ports. This was all a rail facility. Had the technology been available to do what we've discussed at this meeting, LA-Long Beach would have been the perfect place for an underground pipeline. That kind of thing could happen in Houston and vicinity, too; they could build a storage yard on the other side of town somewhere. There's plenty of land in Texas, obviously, but not in Houston. The problem is how to get there, and rail and truck just don't get there. Well, rail doesn't carry many containers right now, and trucks are so expensive and cause so many problems. So, there are vast opportunities once the underground technology becomes standardized and available to be able to push cargo to and from the Port of Houston. Of course, Houston's still going to have to build another facility, whether it's at Bayport or somewhere else. Otherwise, they just are not going to have the room to get more ships in. But the idea is, they wouldn't need as much acreage for storage and so forth at the port or near the port if they could get that cargo out to remote

storage facilities or if we had longer range pipelines, whatever they look like in the future, out of town.

Now, I want to talk about Galveston. My office looks out on Galveston Bay and onto the Galveston ship channel. Before 1900, the Port of Galveston, which is 50 miles seaward of the Port of Houston (by land—only about 25 miles by sea!), was the largest seaport on the Gulf Coast. In 1900, some of you may recall from reading your history, a hurricane hit Galveston, and it's to this day the largest disaster that ever occurred in the United States. It killed at least 6,000 people and basically wiped the island out. To be honest with you, 99 years later there are still signs of that hurricane. They had to build a seawall, they jacked up the island by 8 feet--they came in and brought in dirt and refurbished the island, and basically rebuilt a new island on top of the old island. The Port of Galveston, of course, has not been nearly the same port as it once was relative to other ports in the Gulf now. But, the advantage of the Galveston Port is that it hangs out on an island where there's 25 or so miles less dredging that needs to be done to get a big ship into there, and there's a lot of unused land on Pelican Island out near Texas A&M. Pelican Island is right next to Galveston Island. One end—the seaward end--of that island is virtually deserted. There could be a container port built to handle some large ships, and there would be a lot less dredging for a 50-foot deep channel to get to Galveston Island than to the Bayport facility, for example. But, the problem with Galveston is that it's an island. On the north side of the island I-45 gets you off the island towards Houston. On the east side of the island to get to the bottom of the peninsula just east across the Bay--to get back to the mainland-- there's a state-run car ferry, not very suitable for trucks carrying containers. That's the only transportation. On the southwest side of the island, there's a two-lane toll bridge. There's one rail bridge to get trains off the island. So, the problem is clearly landside access. Nobody—no shipper--wants to come to Galveston because it costs more money to move the freight off the island once it gets on the island or to get the freight to the island. How to fix that? It seems like the perfect opportunity for an underwater freight pipeline. So, the setup is wonderful if the technology were available—a wonderful 30-mile or 20-mile tunnel. It's only 5 miles or so across the channel, depending on where you ran the pipeline. Engineers once again could do the cost estimates. We need a new bridge. How much would a pipeline cost compared to a new highway? To doubling the highway capacity, say? It seems like a good study could be done to try to determine the cost of an underwater pipeline. But once again, some standards have to be set before you can start figuring cost on these things.

And also, I want to make one more comment real quickly that I don't think I expressed strongly enough yesterday. One thing that we all must consider, of course, is that if we're going to have a pipeline facility that transports international freight—if it works at one end, it's got to be connected at the other end. So the standards can't just be U.S. standards or Netherlands standards, or those of any single country! We're all going to have to agree on some single standard, because if we're going to have ships delivering containers to a pipeline, then a pipeline that allows hookup and container entry at the Port of Houston or the Port of Galveston from a ship has got to hook up the same basic way at the other end of the voyage at, say, the Port of Rotterdam, for example. Now, Bill Vandersteel mentioned that 50 or 75 years from now we might not need some of these container ships. We may be able to run a pipeline underwater across the Atlantic or across the Pacific. So that will solve some of those standards problems. But those are going to have to be decided a long time before then. Thank you.

Tom Canter, Executive Director, Western Coal Transportation Association, Littleton, Colorado

I'm Tom Canter. I'm the Executive Director of the Western Coal Transportation Association, and with some trepidation, talking to so many folks with doctorates in here. I have to say though, listening to Dr. Marshal Lih yesterday, that I am a product of cooperative education. I went to General Motors Institute and worked six weeks in a manufacturing facility, and then went six weeks to college, and did that for about five years. Then I had a cooperative education opportunity with Admiral Hyman G. Rick over in the nuclear program in the U.S. Navy. Toward semi-retirement I became the Executive Director of the Western Coal Transportation Association which consists mainly of electric utilities in the United States. When you say Western, people using western U.S. coal are as far away as Europe, certainly Japan, Taiwan and South Korea. Florida Power & Light, American Electric Power, etc., people like that are also members of the Western Coal Transportation Association. I was pleased to see that Associated Electric, Ameren, Peabody Holding, Kansas City Power and Light have all been sponsors of Henry Liu's coal log pipeline project.

Let me also do a little evangelization work. Coal is now providing 56% of the fuel for producing electricity in the United States. It is not an inconsequential product in this country. Sulfur dioxide emissions are down since 1970 even though utilities are burning twice as much coal. I don't have an answer for entropy and the CO_2 emissions, but I would ask you, as most of you are scientists of sorts to take a real science when it comes to things such as global warming, and not take a political theory and try to expound it into public action before the results are actually in. Well, it looks like the good Lord put coal a long ways away from most of the urban areas in this country Today we're producing about 300 million tons of coal in Wyoming each year, and yet most of the market is at least 800 to 1500 miles or 1200 to 2400 kilometers away from the production area. The economics of train sets what we use today. Normally, we're running 110-120 car train sets, almost all going to aluminum cars. Depending on the car manufacturer and the type of car--whether it's a bottom dump or rotary, and most are going to rotary--you're looking at 110 and its almost up to 120 short tons per rail car hopper. The utilities for the most part are investing in these car sets, and that's $7 million just for a train of cars. The railroad has about $5 million up front in locomotives. For locomotives, we're going to the AC locomotive today, about 4,000 horsepower per locomotive. We're seeing the capability to replace some of the older locomotives and the DC motors because they have smaller horsepower. Rail rates today, their quoting rates, and we realize that these are incremental, into the 8 to 10 mills per ton mile, are less than one cent U.S. per ton mile. Frankly, it's not a bad rate these days. On the other hand, for most mines around the country except in the Powder River Basin, when you go to load a train and look up at the locomotive, it has the same name on it. In other words, you're subject to some monopoly power from the railroad. One of the things we probably don't want to do unless we have some control over it, is to exchange one monopoly conveyance system for another monopoly conveyance system. On the other hand, we're excited about the idea of the coal log pipeline because it has some great potential in looking at the congestion that we have today. We think it has some real niche market possibilities—I don't know where that length of pipeline is going to come out to be economical. I'm kind of interested in the possible demonstration project you talked about at Southwestern Public Service, another member of ours,

and looking at a 90-mile pipeline. Some of these things are quite exciting. Environmentally, it's the best answer in transportation that we're looking at-- and from a safety standpoint as well.

John Whitley, Mechanical Engineer, IMC-AGRICO, Mulberry, Florida

I'm John Whitley. I'm a mechanical engineer with IMC-AGRICO. I'm working down in central Florida right now with Bruce Montgomery from Magplane Technologies on a linear synchronous motor project that we're trying to build. This is a 700-foot prototype—full scale prototype practically as far as the ID of the pipe and the vehicle size. It's the first time that I've been involved in something like this, heavily involved in the last six months. I see a lot of promise, a lot of still different philosophies on how we're going to handle even the propulsion system, and that's going to be dependent on the commodities being transferred through the system. Some of my concerns, specifically, even though I'm working on a prototype design with Bruce, are still oriented toward the end user side of the systems. I don't see much addressed as far as loading and unloading which is something I'm even having trouble with just the small system that I'm working on now. When you're dealing with a bulk commodity such as a rock— which is basically what we're moving—about 20 million tons of rock a year. When I say rock it's phosphate rock anywhere from a very small size up to 1/4" or 1/2" size pebbles You don't want to put that on a pallet and try to forklift it obviously. So, you want to be able to rotary dump the vehicle properly on move because if you've got that many vehicles coming back and forth, it can get kind of ugly if you're trying to do this 100 tons at a time. That's a big vehicle you're trying to transport through a small tube. So if you've got a smaller vehicle with smaller loads, it just keeps compounding on you. That's basically all I have right now. We still need to look at the concept of loading and unloading.

Marvin Phillips, Liaison Engineer, Missouri Dept. of Transportation, Design Division, Jefferson City, Missouri

Good morning. I'm Marvin Phillips. I'm liaison engineer for the Missouri Department of Transportation. One of my duties involves dealing with utilities on the highway right-of-way. My concern is that there's so many trucks on the roadway. Trucking has grown significantly in Missouri. Being in the center of the United States, we are sort of a hub—we have two large metropolitan areas—St. Louis and Kansas City. We do receive a lot of truck traffic from all parts of the country. Our concern is three fold: congestion of trucks, safety, and the fact that our highways are wearing out with these heavy trucks hauling various commodities. I can see the need for the underground freight pipeline for that reason alone. My concern though from MoDOT, which is our acronym for Missouri Department of Transportation, is that we have linear types of right-of-way. Right-of-way is normally just minimal to build and maintain a roadway system. We have 32,000 miles of highways in Missouri. We do have a utility policy where we allow utilities to use public right-of-way. My concern here is, of course, we primarily purchase right-of-way for the roadway system but with the good neighbor policy of sharing that right-of-way. We do have a lot of utilities on the right-of-ways. We were approached by Henry Liu a couple of years ago asking whether pipeline can be on Missouri Department of Transportation right-of-way. My answer at that time, and probably still remains today, is that all utilities or pipelines can cross any of our right-of-ways. We have written guidelines. The pipelines can be either encased or they can be uncased. If they're uncased they have to be

cathodical protected. They are generally required to be a minimum of 30 inches below our low points in the cross sections of the roadway where you cross or in metric terms about 760 millimeters minimum. So we do have some flexibility on crossings. Where we see concern at this point is we have a lot of what we call utilities. They are privately, publicly, or cooperative owned lines that produce, transmit, or distribute communications, cable TV, power, electricity, light, heat, gas, oil, water, steam, waste, etc. We're not sure at this point whether capsule pipeline would be considered a utility or not. And the reason it's a big concern is because we do allow pipelines to cross the right-of-way. However, we are very specific in who we allow to be longitudinally on our right-of-way. The six-foot zones become used up pretty quickly with underground utilities, so size of a pipeline would be a great concern. We don't want to put a six-foot diameter pipe on the right-of-way because it would take up space that someone else might use. However, we do have generally the policy of first-come-first-served. Again, there's a lot of concerns here. We hope that we can accommodate the pipelines, but we can't guarantee it at this point. I think I speak for the Department, our Director and staff. We will certainly work with the pipeline companies whenever this technology becomes real and we start getting on-line business. I think you will find that to be common with other state DOTs too. We all generally design highways singularly according to ASHDOT standards in a lot of cases. So, there's not necessarily a real wide strip of right-of-way. The other constraints are that our right-of-way is not just a parallel strip of land. For example, a lot of utility easements are say a 100-foot wide linear strips. Ours are in and out and vary so there are a lot of breaks in the right-of-way line--transitions in and out so it makes it very difficult in some cases to build an underground line on our roadways. We also have in our 32,000-mile roadway system, we break the utility policy down depending on the functional classification of the roadway. For example, our interstate roadways here in Columbia (Interstate 70) goes east and west. It is considered a freeway with very restricted use longitudinally. We only allow utilities where there is an outer road, or a frontage road, or a service road. The reason for it is we don't want the utilities to have to come off the main thoroughfare out to the edge of the right-of-way with their equipment and cause disruption of traffic. And then on the other types of road that we have like here in Columbia--Route 63--it is an expressway. It does not have fully controlled access right-of-way. It has at grade intersections so in that case we do allow some parallel utilities pretty well up and down the line. However, on the other side of the coin is, we do have a lot of expressways in Missouri that we are converting to freeways. That means we are going to be taking out some of the grade intersections and putting in interchanges so that the utilities that are there now will probably be grandfathered to be allowed to stay in place. However, in the future when that does become a freeway, we may not allow other type of utilities to install. So, we have a dynamic change in our highway system occurring right now and in the future. We don't generally allow utilities through an interchange. There are some exceptions. And on our structures such as bridge on interstates, we don't allow anything to be attached to a bridge On other types of roadways, we have different rules. We do allow some pipelines to be on bridges, but it' s all case by case based on loading, and so forth. We do have a policy. I think it's very flexible, but there are some concerns. There may be some hindrance to any proposed constructions of new pipeline using highway right-of-way.

Henry Liu: Thank you very much every panelist. As you can see, we have a very diverse group of people representing different agencies talking about different things--that's what's intended. Keep in mind that freight pipeline is not just a single type, single diameter, or single

application. There are many types of different sizes transporting different commodities. We have two sessions of panel discussion. This session is on the United States. As soon as we finish, we will invite the international participants to talk about their country's needs and anticipated problems. Why do we discuss needs and problems? Because without clearly identifying the need, you will never be able to get the support needed to build a pipeline. You have to first identify the need--to solve traffic jam problem, to reduce air pollution, etc. Then you also must be realistic. We are not going to replace truck or train entirely. Only when we have a lot of traffic congestion in a particular place, there will be a stronger need for a freight pipeline. If there is no traffic problem--very few trucks on the highway--there isn't any need. The existing highway should take care of it. We are realistic. We are not suggesting that freight pipeline suddenly will be all over the place. It will be first built in those places that need it the most, and that's why we are talking about need. Also, besides knowing need, we also need to know limitations. If we don't know the limitations, then we are talking about something totally unreasonable, and we will lose the audience, and you will lose those people supporting you. For instance, if we are proposing to have highway department help us in order to solve right-of-way problems, they have their limitations, and we have to understand them. That is why we have invited these panelists, not to just come here to talk about need, but also to talk about problems that we must consider--that the promoters and researchers need to understand. Highways are not the only way that freight pipelines can go--in fact most pipelines don't use highway right-of-way--95% don't use highway right-of-way. It is just that--wouldn't it be nice if we could use some of the highway right-of-way? Sure, that would be very nice, even if we can use it on certain parts of a highway. It would solve a lot of problems. Without further comment, I would like to ask the audience if anyone has any comment.

Bruce Montgomery, Vice President, Magplane Technology, Framingham, Massachusetts

The thing I find most encouraging about this conference is the group of people that you have assembled. The broad makeup stems from your suggestion that we need to identify needs, and therefore to have a good representation of transportation planners. Pipeline transport is typical of a field which has been left to the developers and the technologists for too long. They are often more interested by the pipeline technology than its end uses, and that is a major reason the field has made little progress. It is my experience that a new application only get really rolling when you attract planners who identify needs, look at specific cases and make the economic case. The technologists can generally fill these needs in a variety of ways as we see in the Dutch airport study presentation. In that example, there are a number of ways in which one can solve the problem technically, but someone has to do the goods flow analysis and make the case at the political level before there is any action. We can also use the Texas ship unloading presentation as a further example. Someone in the decision making loop of infrastructure planning first has to do a needs analysis and to develop the arguments to support an underground system to serve a megaport. The technologists can be most useful in a support function, developing a design to the point where capacity and cost can be estimated. If left only to the technologists, nothing will likely happen.

Steve Roop, Director, Rail Research Center, Texas Transportation Center, Texas A&M University, College Station, Texas

As has been said several times here today, needs identification oftentimes flows directly from real problems that are occurring in the transportation arena. The state of Texas through

their DOT will make those problems known to an institution like Texas Transportation Institute, and contract with researchers to develop a solution to the problem. So, in Texas, and I think this holds true for most states, that is the way work is usually initiated—a specific problem generates the need for research and then answers are sought. It's rare that the solution is anticipated before the problem becomes acute enough to be a monetary or economic drain on resources. I think it's been identified, as Arthur James indicated, that congestion in and around the port of Houston is a problem and it's going to be a continuing problem. There's going to be pressure for transportation planners and analysts to come up with solutions and countermeasures--mitigating measures. The freight pipeline concept is one of the newer innovations that can be brought to the attention of policy makers. I think that's how we're going to get on the charts in Texas--either at the port or through the NAFTA trade that I spoke about yesterday, which is another similar area of difficulty, and it's costing the public money. It's costing a significant amount now, and it's going to cost more in the future. This is the source of pressure for innovation and this is when researchers and transportation planners get asked to come up with solutions.

Arthur James: Steve Roop and I work for the same institution, more or less. The Center for Ports and Waterways on the Galveston campus of A&M is a part of TTI, which is headquartered on our College Station campus. Steve is in College Station and I am in Galveston, but we share some responsibilities--not primary responsibilities. I'm a transportation economist and professor in maritime administration. What I need to do as a researcher is sit down with the folks at the Port of Houston and the Port of Galveston, and that's in the works. I consider the director of the Port of Houston, Tom Kornegay, to be a friend of mine, and I need to sit down with him and see if we can convince the port authority people that they need to look at this. We are going to have to do some selling, and then maybe the Port of Houston will give us some money to do a study. The Port of Galveston probably does not have enough money to do a study, but the idea is there. The Ports of Houston and Galveston are looking to consolidate and become one port authority. If that happens, it's going to be a lot easier to deal with the question of how do we move cargo from one of those ports to the other one, at least for storage. That's going to make a difference. In a year or two it's going to be easier for us to work with both of those ports to get something done.

Larry Vance: A point needs to be made about the regional planning studies. There is in fact a fairly organized national system of regional transportation study commissions or urban planning commissions which were years ago an outgrowth of federal highway funding. They were intended originally to focus on upgrades in the regional urban highway systems. They have been considerably expanded in their charter by federal legislation. So, they are required now to consider all modes of transportation. And the important thing about bringing these issues to their level is that they are not only interested in the commercial issues that are inherent in moving port traffic, but also interested in the overall urban or regional problem of moving both freight and passengers. They are very sensitive to community needs and expectations, and really are very capable of bringing together coalitions to support something well beyond the immediate interests of the freight shippers and freight transportation companies. So, the transportation needs should be brought to the consciousness of the people at the regional planning level.

John Whitley, Mechanical Engineer, IMC-AGRICO, Mulberry, Florida

Many times throughout this thing we've talked about the needs, and all the needs we keep hitting on is from the technical side and social side. However, the only way we (and I say we

because I'm on your side--take me on that) are going to sell this is to tell companies that they are going to make money by using this system. You can't tell them that we're going to take this many trucks off the road because they don't care about that. What it takes is money. That is what powers everything in this world right now.

Right now, my company is dependent on rails and trucks to transport the 25 million tons of goods (a year) that we transfer between our chemical plants, our mining facilities, and to the ports of Tampa and other places to get it distributed. I can't go to my boss---the divisional president and say it's going to cost us $30 million to put in this tube system that's going to transport this material back and forth to get to the port. That's a lot of capital investment that my company has to put in that they're not going to do unless I can guarantee so many savings or some major reduction in operating cost. As Dr. Marshall Lih said yesterday, it takes evangelism to make it work. I'm not minimizing the social impact but that's not what it's going to take to make it happen. In private enterprise, we just need to build something feasible, make it work, have the finances there to prove that it will work. Until we get that point across, and it will take entrepreneurial people to do it. I've talked to a couple of people here already about talking to some people in our company about this. Somebody can come in and say, okay, "You're paying 10 cents a ton per mile for a railroad to do it. I can do it for you for 7 cents a mile." That's when somebody's going to put some real capital money into this or get something going on it.

Henry Liu: Thank you. If you want to build a pipe, you better identify the need and also the cost and the economics of it. If it's not economical, people will say, "Why don't you use something else which is more economical to satisfy the same need." I think that's what you have made very clear. If you want to identify a project, it is important to have a feasibility investigation. Technical feasibility study is not needed when using an existing technology. But, economically, is it feasible to do a given project using a given technology. Once you have proven that, you have the possibility to get some industry or bank to back you up to develop it. We are doing coal log pipeline a lot in our Center to address the needs of Tom Canter's constituents. His members are electric utility companies. We worked with many of them in the past. We sent out a form to more than a 100 electric utilities and coal companies asking them whether they have any potential coal log pipeline project. If there's the possibility that a pipeline can transport coal, let us know and we will do a free feasibility study. We send a five-page form for them to fill it out. When it comes back, we do a free study using our computer model. It's not very difficult, and we also have Williams Technologies helping us to do that. And, then we tell them that based on the information supplied to us, how much will it cost them to transport coal from mine to their plant The study is crude, but we do consider some topographical effect, and so forth. It's not entirely a generic study; it's somewhat site specific. We ask them how many rivers you cross, and what are the terrain conditions and so forth. We give them approximate figures. We did that two years ago. We evaluated more than ten projects, came up with a few promising ones and one of those you mentioned, and we are doing that again now. Just for your information, Tom Canter, you may like to encourage your members to respond to that. When we send to the company executives, it may never get to the person who is really interested in the coal transportation. If you can bring it to their attention, we will be happy to respond. We can even put the survey form on our website so electric utilities can go ahead and do it themselves.

Tom Canter: You can put it on my website and send it in to us.

Henry Liu: So, we are talking about identifying--that is the specific need--can a company justify a coal log pipeline or a particular project. That takes a little more effort than just talking about getting rid of trucks, easing congestion, and so on.

Gerard Arends, Associate Professor in Subsurface Construction, Delft University of Technology, Delft, the Netherlands

My name is Arends from Delft University in the Netherlands. The situation in my country is very different from the situation in the States. We are a small country. Every five years, we make transport infrastructure plans for the future. Some 10 years ago private companies and engineering offices came up with the idea of underground transport tubes for non-bulk goods. At the same time, new governmental plans for future transport in the Netherlands were being made. It was a big surprise that when the first draft came out of these plans, that underground transport of goods was not considered at all. So, it was a strange thing that there were engineering offices who had it already worked out, but the planners did not have it in their plans. Now, luckily at that stage someone in the parliament jumped up and called its bluff--made it known to the politicians that there was an underground plan, and from that stage it started moving. So, going back to one of the speeches of yesterday, an important point is that in the end it's an economic matter. If it's more expensive, it will not come. But as there's another element in this round, it should have a fair chance. And what we see in Holland still today, is that plans are there without giving it a fair chance. And when the plans are already too far ahead, you cannot jump in anymore. You are already too late. I think it's the same here in America. Big infrastructure takes 10 to 15 years to develop. When the process is already five years ahead, and then you complete your plan of an underground transport system, you are simply too late. It is not the same when a company has a problem or a mine has a problem. Of course a mitigated system can always be considered. But even then, you may have the right-of-way problem. If there is no awareness in a country, you will never change the right-of-way situation. So, planners must be aware of the UFT option. We still need to have a lot of people who believe that this third dimension is an option.

Henry Liu: Thank you very much. I think you are very right about awareness--public awareness and planners awareness.

Andrew Fowell, Associate Director for Construction & Building, National Institute of Standards & Technology, Gaithersburg, Maryland

This is Andrew Fowell from NIST (National Institute of Standards and Technology). First, I'd like to reiterate the remark about the need for international standards. That will be very important. The other thing that occurred to me when I hear these people talking about large loads, many freight trains, and big ships is that roads and rails have been designed to take heavy loads. Even now, the roads can't take it; there's a lot of expensive repair needed on roads. We must be very careful not to say, "Oh, we can cut a hole in the ground, we can put a tube in at a certain cost. It appears quite cheaply according to the figures cited this morning. Yet, when you design something that will take the loads, the 6,000 containers that will be traveling on it on a regular basis, you're not going to do it with a fiberglass pipe. You're going to need structural building, and this is going to be expensive. We ought to consider that load factor when we're

designing underground systems--both the load and the wear. They should come into the cost calculation. Be very careful not to just scale up from a tube.

Chia "Rocky" Shih, Professor, Department of Civil & Environmental Engineering, University of Texas at San Antonio

I just like to share my frustrating experience related to freight pipeline when I worked as an Associate Administrator for Research & Technology in the RSPA of U.S. Department of Transportation. All the things that need to be done in the US Government to harvest the benefit of freight pipelines are not existing, including the technology development, systems planning, cost-benefit analysis, and the issues concerning the feasibility of its real-world application. So, why has it not been done? Because there has been no program authorization and budget appropriation for the freight pipeline R & D at all. Look at high speed rail--the same thing; urban transit--the same thing. There are two basic problems right here. First, there is not enough political visibility. Bill Vandersteel keeps expressing concern about eminent domain. If we, as a group of promoters, had enough political visibility, eminent domain would get considered and approved easily. The freight pipeline alternative must be sold to our political leaders so that they can put it on the national agenda. The second problem is associated with our teaching and implementation process related to transportation planning. When transportation engineers and planners think about transportation system alternatives in project planning stage, freight pipeline has never been part of the consideration. We even routinely think about freight designated highway and special lane design between urban cities, but we, as transportation planners, never considered freight pipelines.

Hank Brolick, President, Black Mesa Pipeline and Williams Technologies, Inc., Tulsa, Oklahoma

The old railroad blew up; it's gone. It's not there for some reason. So, you go to the bank and say the Power Plant's going to guarantee me that he's going to pay so much a ton for this coal for ten years. So I want to borrow the money. Looks like a no brainer. The banker says, *"Well, how stable is the power plant company? Are they going to be in business for the next 10 years?* Well Yeah. They've been in business for the last twenty years. *How do I know they're going to be in business for the next 10 years?* Well, let's see, you got to look at their financial statement. *What's their environmental issues? Are they going to have to put in scrubbers? What's going to happen with deregulation? Are they going to be competitive? Will their paying for your railroad make them not competitive?* So there, you've got another problem. *The coal reserves is there, but is that coal miner going to be in business? Plus the earthquakes—will ruin your railroad? Or, are you gonna have a flood that will wipe it out? The fact is,* your banker's going to worry about everything. That shouldn't frustrate any of us because it is normal. Now, when you add a technology risk, it orders the magnitude. Nobody should get frustrated. Matter of fact, that makes life interesting. These are just the hurdle that any project looks forward to.

Henry Liu: Let me try to put Mr. Brolick's remarks succinctly in a sentence. "As long as it's economically demonstrated, it will go." Is that what you're are saying?

Hank Brolick: Somebody has to make money.

Henry Liu: Has to be economical.

Wolfgang Weller, Consulting Engineer, Berlin, and Research Partner of Ruhr-University-Bochum, Germany

I think in principle I agree with what Hank Brolick is saying. But I think he missed a point. We are talking about a solution to a problem. But the benefits and the costs are not in the same hand. It is quite clear that this system, if you take a capital investment approach, tube transport is more expensive than ordinary freight transport systems. But, we have all said here in the last few days that there are environmental and safety advantages to society. The problem in all is that we know there are advantages, and we know there are costs. How do you match the benefits and the costs? How do you get them in the same hand? That is the problem we have to solve. The costs and the benefits are not falling into the same pocket.

Henry Liu: I did a lot of hydraulic studies in the past—traditional hydraulic such as reservoirs, dams, and so forth. To finance those projects, even government agencies such as the Corps of Engineers, must justify by determining benefits-to-cost ratio. In calculating the benefits, all tangible benefits are included. Intangible benefits, such as increased recreation values of reservoirs and the lives saved due to improved traffic safety, are also included in the consideration. There is a difference though between private projects, and government projects. Government projects consider intangibles and social benefits. Private project is often solely focused on making money. This seems to lead to an important question: Should large future pipeline systems for inter-city freight transport be government owned as in the case of most highway systems?

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