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TUBE TRANSPORTATION

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11-Advanced Systems

PREFACE

TUBE TRANSPORTATION

Both the Clinton-Gore Administration and the Intermodal Surface Transportation Act of 1991[1] (ISTEA) emphasize infrastructure revitalization and innovation to insure future productivity growth and resultant economic growth for the Nation. The Declaration of Policy in ISTEA states in part:

> *The National Intermodal Transportation System shall be adapted to "intelligent vehicles", "magnetic levitation systems" and other new technologies wherever feasible and economical with benefit cost estimates given special emphasis concerning safety considerations and techniques for cost allocation".*

The Clinton-Gore Administration believes that:[2]

> *"Leadership in the use and deployment of technology is also essential for the achievement of other national goals, including sustainable development, energy efficiency, an industrial base capable of meeting our national security requirements, and a government that works better and costs less."*

The Federal Department of Transportation, Federal Highway Administration, recognizing the policies noted above and concerned about providing for growth of future general merchandise freight traffic has begun to examine alternatives beyond the traditional approach of building more highways to accommodate more trucks. Tube Transportation systems are currently being actively promoted by some as one alternative approach to increasing the nation's general merchandise freight movement capacity.

The Volpe National Transportation Systems Center of the Department of Transportation"s Research and Special Programs Administration was requested by the Federal Highway Administration (FHWA) to perform a preliminary review and evaluation of Tube Transportation systems in support of the FHWA 's "new" systems evaluations. The resulting report which follows was prepared by Dr. Lawrence Vance and Mr. Philip Mattson of the Volpe Center. The work was performed for FHWA's Office of Advanced Research, Thomas J. Pasco, Director. We acknowledge the aid and support of Milton Mills of the Office of Advanced Research who provided immediate oversight of this project.

L. Vance
2273

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[1] Public Law 102-240. Note that section 6020 requires a study of Pneumatic Capsule Pipelines, a topic that falls under Tube Transportation.

[2] February 22, 1993 statement on technology policy.

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EXECUTIVE SUMMARY

TUBE FREIGHT TRANSPORTATION

The U.S. Department of Transportation, 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 powered and 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 and Russia 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

In the early 1980's the concept of propelling the capsules in a tube system by linear induction motors (or other external power) was conceived and patented in the United States. All indications are that such systems are technically feasible and within the state-of-the art. This approach appears to have the promise of providing much higher throughput than earlier pneumatically powered systems. In fact, estimates indicate railroad magnitude capacity with a 6 foot diameter tube (assuming full utilization). The large estimated capacity obviously also makes the economics of tube transportation more attractive. Proponents of both linear induction and pneumatically powered, general merchandise systems are currently active in the United States.

TECHNICAL FEASIBILITY

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 foot 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 as a major part of the capital requirement is for tunneling costs which are highly variable and site specific. Port or urban core access corridor lines would appear likely study candidates 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. Postoffice are candidate users of such a system.

SECTION 2

DEFINITIONS

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.

For the purposes of this study the future tube transportation systems to be examined will have the following characteristics. First, all will be exclusively freight carriers. Second, they will be totally automated (except cargo loading and unloading at terminals). No personnel will ride on the vehicles. Third, they will be primarily long-haul, intercity carriers. Local distribution will be briefly discussed in the context of terminals and in the historical section. The historical section will also include passenger references since they have some elements in common with freight operations.

> *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[1]. 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 definitions above 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 the following study are hydro capsule pipelines which have been proposed. These pipelines would use water or another fluid to propel the capsules through the pipe.

1.The International Freight Pipeline Society refers to these systems as Pneumatic Capsule Pipelines.

SECTION 3

CURRENT TUBE TRANSPORTATION PROPOSALS

By 2015, surface transportation is expected to grow beyond current traffic levels with significant constraints on construction of new capacity. Figure 3-1 shows truck traffic growth from 1960 through 1990 with projected traffic through 2020[1]. By the year 2020 intercity trucking is projected to increase by 50% over 1990 levels. New transportation routes are likely to be difficult to obtain to accomodate 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:

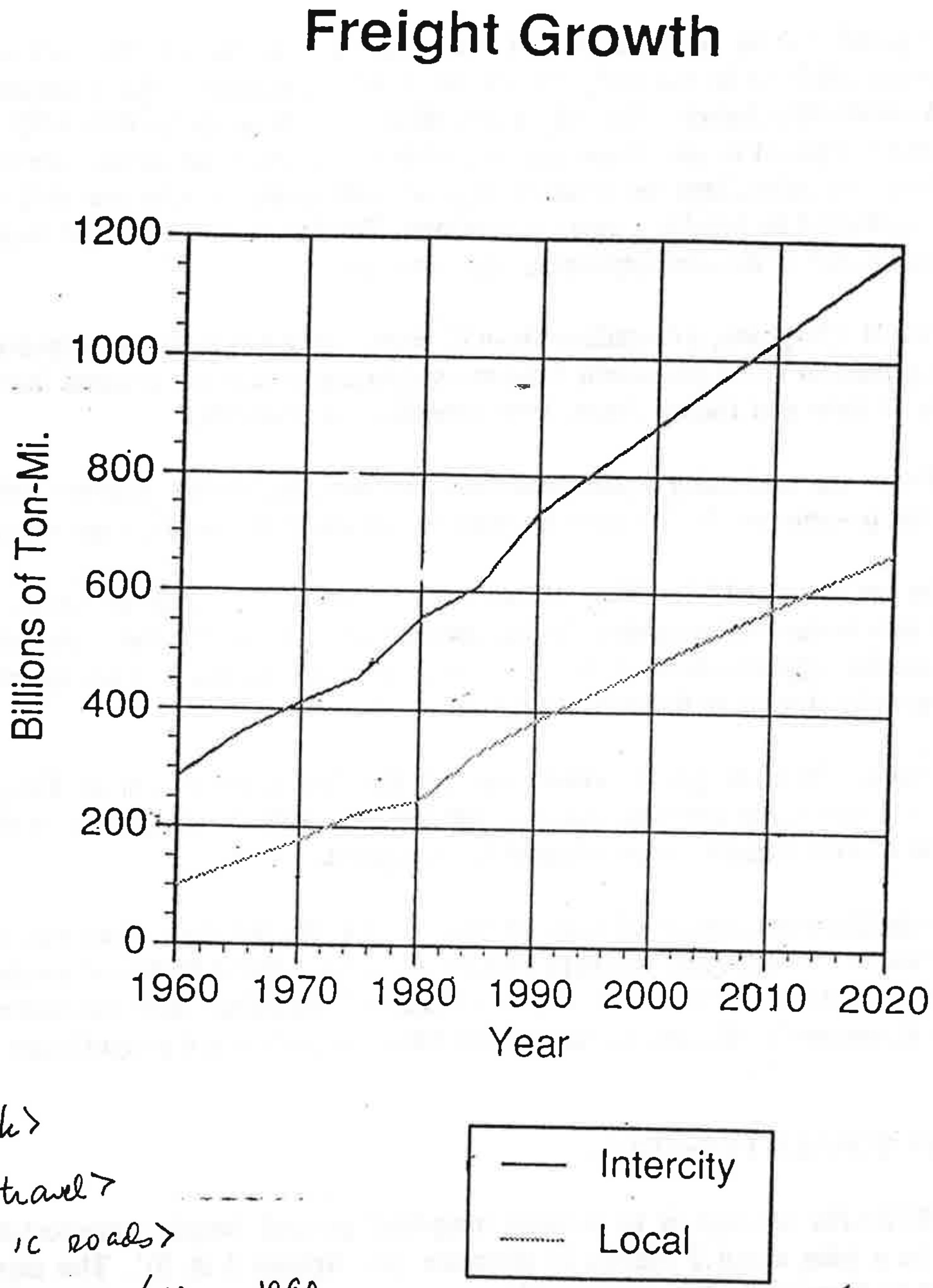
1. Freight facilities using highway or other rights-of-way (primarily underground).
2. Completely automated operation . No personnel on board vehicles.
3. Electric power.
4. Complete grade separation.
5. Very high reliability service.

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 operating cost savings due to automation.
5. Higher reliability than existing alternatives.
6. Very high productivity.
7. Lower energy costs.
8. Increased control over delivery schedules.

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. Mr Vandersteel currently owns 50% of the TUBEXPRESS Corporation.



IF

<35 tons/truck>

<100 miles/travel>

<10,000 miles IC roads>

20 B TRUCK MILES/YR 1990 60 M TRUCK MILES/DAY

200 M TRUCKS/YR

Figure 3-1
Trucking Freight Growth, 1960-2020

- 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, highspeed, 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 hypervelocity component would acheive approximately 1 hour travel times 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.

A through literature search of U.S. periodicals for the last five years has located no other common carrier tube transportation proposals. As is noted in the historical section, however, the Japanese and the Russians are also players in materials handling, tube transportation. All can be expected to become active in common carrier tube transportation if a significant market appears.

THE PROPOSALS IN DETAIL

The SUBTRANS concept is to provide long-haul general freight transportation in capsules running in a tube about 2 meters in diameter (see figures 2 & 3)[2]. The capsules would be propelled by linear induction motors. Non pneumatic propulsion of the system is the subject of a U.S. patent granted to Mr. Vandersteel in 1984 (patent number 4458602). The system would be totally automated. The system is intended to operate at a constant speed of about 60 MPH. Capsules to be removed from the main routes to enter terminals or other routes will be switched out of the main route at speed. The capsules are unconnected, pneumatic pressure providing buffering between capsules. Insertion of capsules into the moving stream takes place by a reverse process. This operating concept is similar in many respects to those proposed for operating

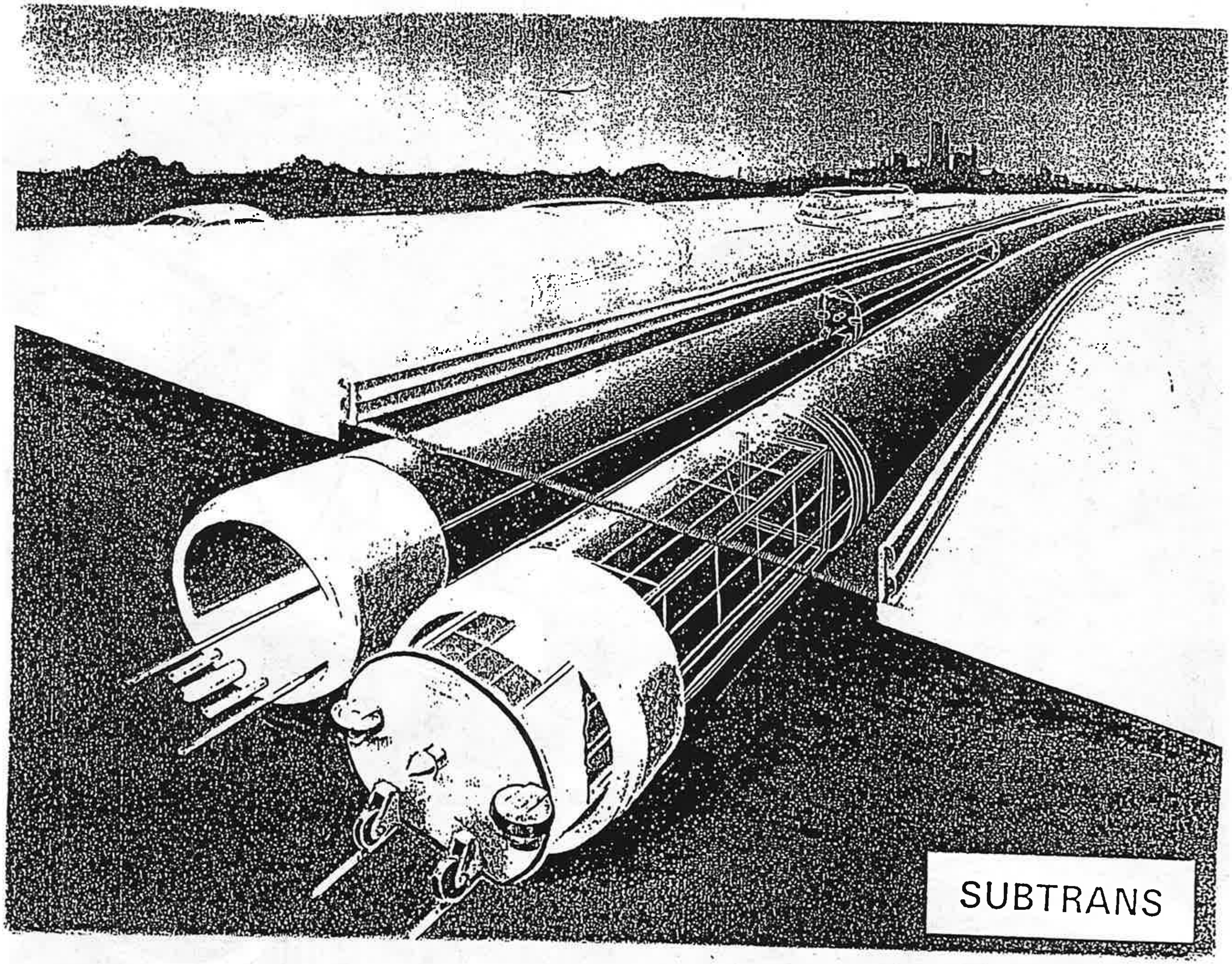


Figure 3-2
SUBTRANS Concept in Freeway Median

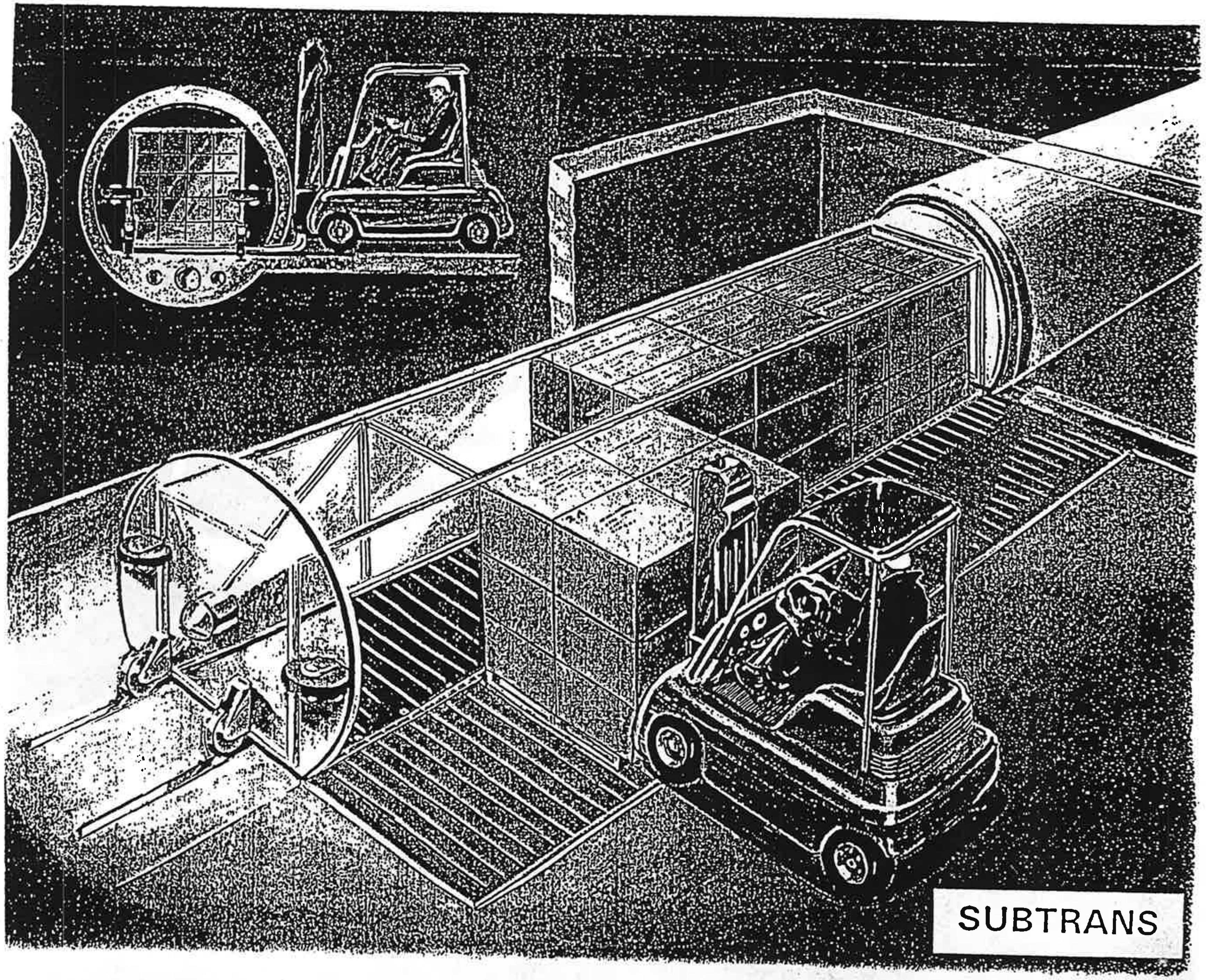


Figure 3-3
Loading Concept for SUBTRANS Capsules

platoons of automobiles on fully automated highways under the Automated Vehicle Control Systems (AVCS) portion of the Intelligent Vehicle Highway Systems (IVHS) program.

The SUBTRANS capsules are designed to accept pallets to facilitate rapid loading and offloading. Automated warehousing is an option in this concept with the capsules being used for temporary warehouse storage. The developer claims a maximum throughput of 1875 capsules pre hour which is roughly 15,000 tons/hr at average cargo densities. At this time SUBTRANS is a undeveloped concept.

The British BHRA system[3] proposed 10 ton capsules operating in a 5 foot diameter tube. Speeds of 20 to 30 MPH were anticipated with traffic of 100 to 150 capsules per hour. Pneumatic pressures for propulsion are generated by jet pumps developed and patented by BHRA . Their systems were marketed by The British Technology Group.

The Swiss high-speed, maglev proposal would utilize a 4.5 meter diameter tube (figure 4)[4 5]. The tube would be buried 40 meters deep in most areas, deeper under mountains. Speeds in the range of 250 - 300 km/hr are projected. Linear induction motors are to be used. The purpose of the tube transportation approach, in this case, is to reduce tunneling costs by reducing the tunnel diameter. Air resistance is reduced through evacuation of the tunnel. The alternative would be the use of a very large cross section bore to minimize aerodynamic drag and undesirable pressure changes at tunnel entrances and exits. This proposed system is currently under serious evaluation by the Swiss government. The primary motivation for this system is to obtain the benefits of a high speed passenger system in a region where there are major environmental constraints and new right-of-way is unavailable.

The NASA "New Millennium Transportation System" proposes two national maglev systems[6]. The first, a surface system, is not tube transportation. The second, "hypervelocity" system, would be an underground system operating in evacuated tunnels at speeds up to 4000 MPH. Few other details are available at present.

Professor Masaki Koshi of the University of Tokyo has proposed an underground freight transportation system for the city of Tokyo (figures 5 & 6)[7]. The system is not a tube transportation system as defined here since it has standard subway clearances and modest speeds. It is of interest here, however because it is a totally underground, automated freight system intended to significantly reduce street truck traffic. This system, which proposes to use linear induction traction, is currently being evaluated and developed by the Ministry of Construction. Non ISO containers are designed to be moved through 5.5 meter diameter tubes. Automated loading and unloading of the containers at terminals is part of this concept. A 300 kilometer network is projected with automated terminals which move the containers to the first basement of major shipper/receivers or to street level for local distribution to small consignees. An experimental line a few kilometers long is expected to be initiated in 1993.

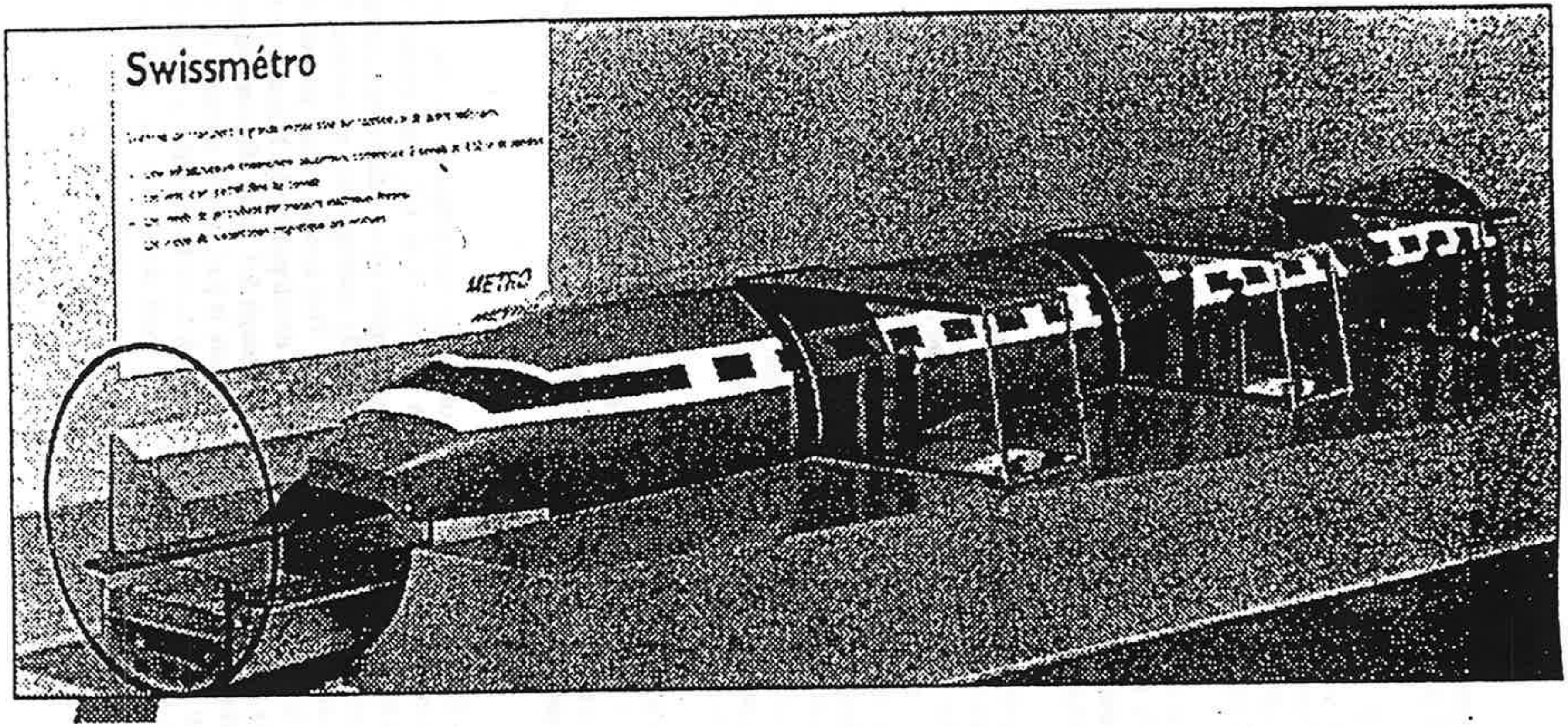


Figure 3-4
The Swissmetro Concept

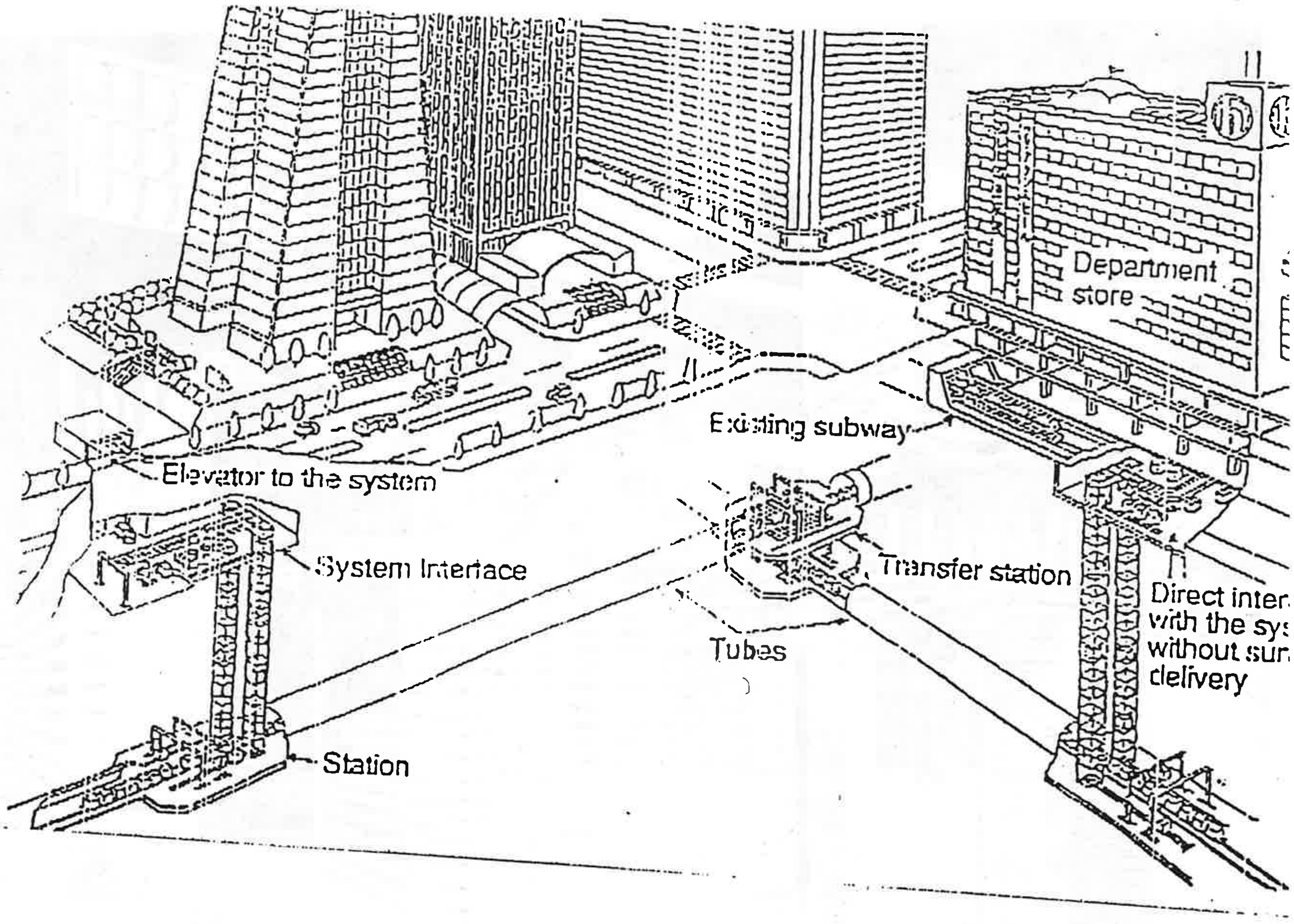

Department store
Existing subway
Elevator to the system
System Interface
Transfer station
Tubes
Direct inter
with the sys
without sur
delivery
Station

Figure 3.5

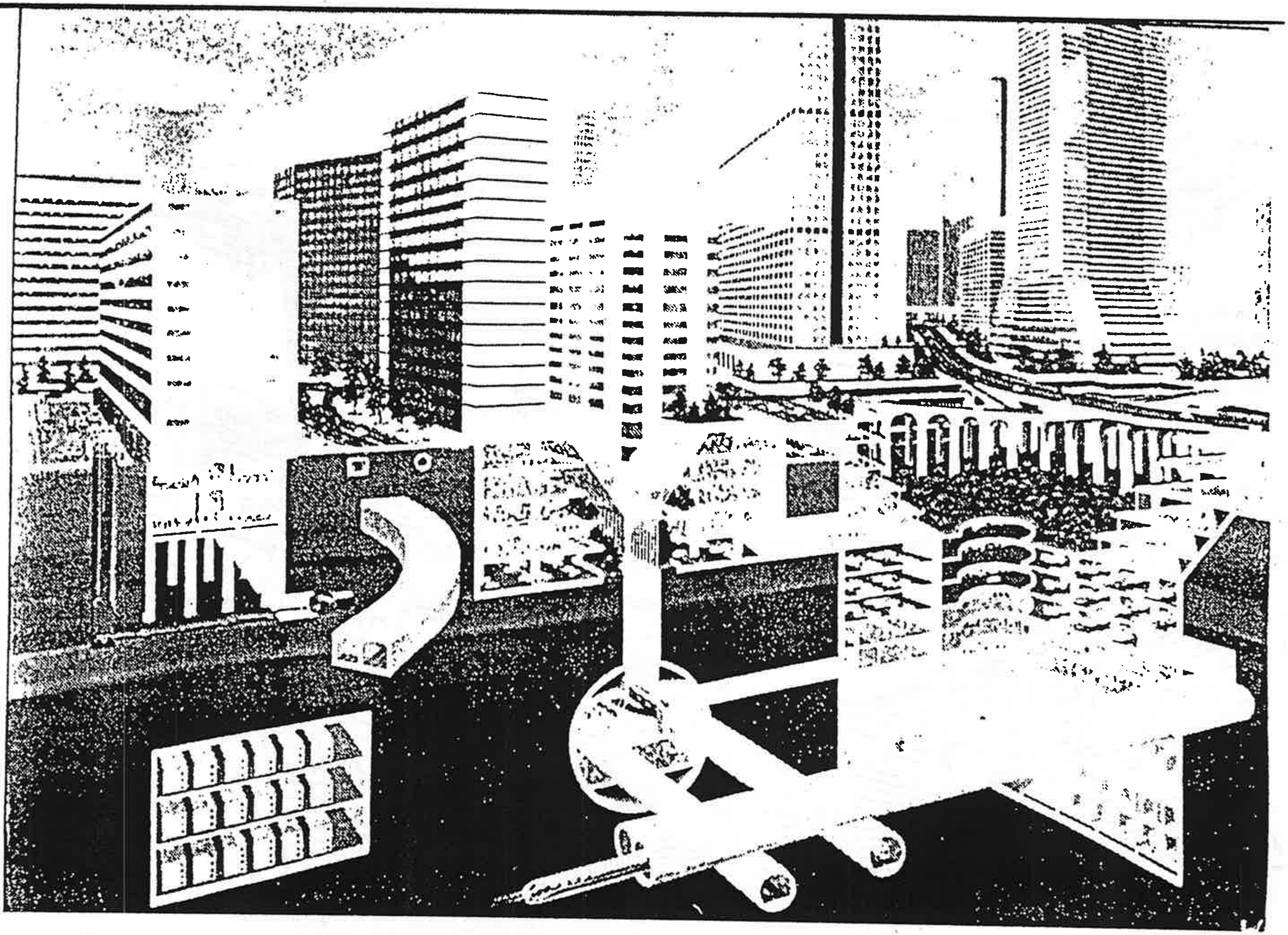


Figure 3-6
Geoblock Network Concept for Underground Development by the Takenaka Corp.

FUTURE VISIONS FOR TUBE TRANSPORTATION

The promoters of tube transportation generally have two separate visions for the future of their systems. First are proposals addressed to the broad, common carrier freight market. Second, are applications for niche markets. Common carrier applications, competitive with long-haul trucking and railroads and would be substantial replacements for them in the long run. For freight systems the niche markets fall within the category of materials handling systems or initial elements of common carrier systems.

SUBTRANS and similar approaches have as their key conceptual elements the following:

1. Provision of long-haul, common carrier freight services in partial competitio with long-haul trucks, railroads and air freight. Initial installations might be in shorter, high traffic corridors.

2. Complete automation of the system. The system would operate at constant speed (perhaps 60 mph) and capsules would be inserted or removed from the main line at speed. (An option would be to reduce speed at switches on more lightly traveled lines.)

3. Complete enclosure of the system in tubes except at some terminals. This insures that no crossings at grade exist. Complete enclosure prevents intruders from entering the automated system and assures freedom from weather effects. (Significant portions of the system may be at grade.)

4. It is assumed that the system is designed for very high reliability. The combination of high reliability and an information system which maintains real time data on location and status of each capsule (and its cargo) would make this system a highly effective element in just-in-time manufacturing.

5. Pneumatic or non pneumatic propulsion. Non pneumatic propulsion from linear induction motors or other electric motors.

6. Use of existing transportation or utility rights-of-way. The system is assumed to be underground in congested areas.

7. Direct access to large volume shippers/consignees.

8. Use of the systems low cost capsules as storage devices in automated warehouses

directly connected to the system.

Tube transportation systems are inherently high capacity, high capital cost systems. Because their infrastructure is immobile and long lived, routing decisions require careful planning. The systems are presumed to be more attractive economically in the future due to declining tunneling costs and increased right-of-way and environmental costs. These systems are a concept at this time. Few detailed engineering, market or economic studies have been performed to date.

1.U.S.Department of Transportation, Bureau of Transportation Statistics: *National Transportation Statistics*, Annual Report, September, 1993, Historical Compendium, 1960-1992. (Linear projection to 2020)

2.Vandersteel, William, *The Future of Our Transportation Infrastructure*, Ampower Corporation, North Bergen, N.J., 07047, 1993.

3.Livesey,R "BLOWN FREIGHT IS A LOVELY CHANGE FROM ROAD AND RAIL, A new underground transport system which could slash costs twenty five times and could take freight off the roads and railways - would keep Britain's environment clean and quiet", *The Engineer*, London, 28 October 1971.

4.Im nächsten Jahrtausend in 57 Minuten von Genf nach Zürich, *Der Bund*, Sonderbeilage, Bern, Switzerland, September 8, 1992.

5.Vacuum Technology Weighed for Swiss Maglev Proposal, *MAGLEV News*, Vol 1, No. 15, May 17, 1993.

6.'New Millennium Seeks Support From NMI Officials', *Maglev News*, March 22, 1993.

7.Koshi, Masaki, "An Automated Underground Tube Network For Urban Goods Transport", *Journal of International Association of Traffic and Safety Sciences*, Volume 16, No.2, 1992.

SECTION 4

TUBE TRANSPORTATION HISTORY

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. The extensive literature cited here can be consulted for more historical detail.

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 proposals 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!)[1]. 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.

Only four demonstration systems are known to have been built and operated in passenger carrying service[2]. In 1826-1827 John Vallance built in Brighton, England a 150 long, nearly 8 foot diameter tube in which he operated a 20 passenger vehicle. The 22 foot 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.

The second system was built in London for the Crystal Palace Exposition and placed in operation in August, 1864 (figure 1). This 1800 foot 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 foot 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

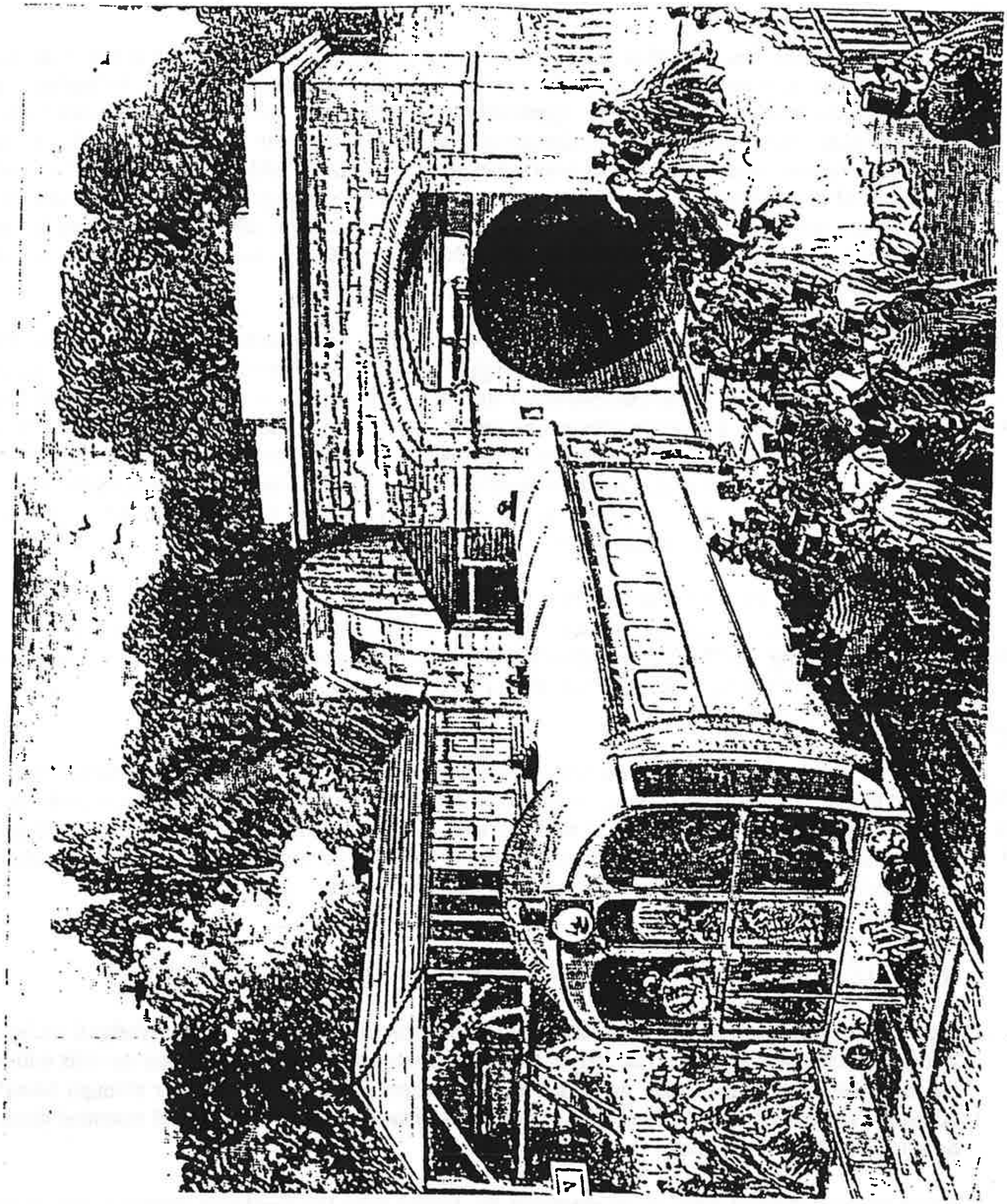


Figure 4-1
Crystal Palace Demonstration System, London, 1864

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 foot 9 inch inside diameter iron tubes sunk and covered in an excavated trench in the river bottom. Even though three of the 221 foot 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.

The last two demonstration systems were built by Alfred Ely Beach, editor of the *Scientific American.* He was an advocate of both passenger and freight systems and was also an advocate of the use of pneumatic tube transportation for water crossings. He first built a short, 6 foot diameter system using a wooden tube which was demonstrated at the American Institute Fair in September 1867. His better known system under New York City was built in 1869-70 (figure 2). An 18 passenger car operated in a 9 foot diameter tunnel 312 feet long. Like the Crystal Palace system Beach used a fan to power his system. This system shut down after a year of demonstration runs lacking legislative support for expansion.

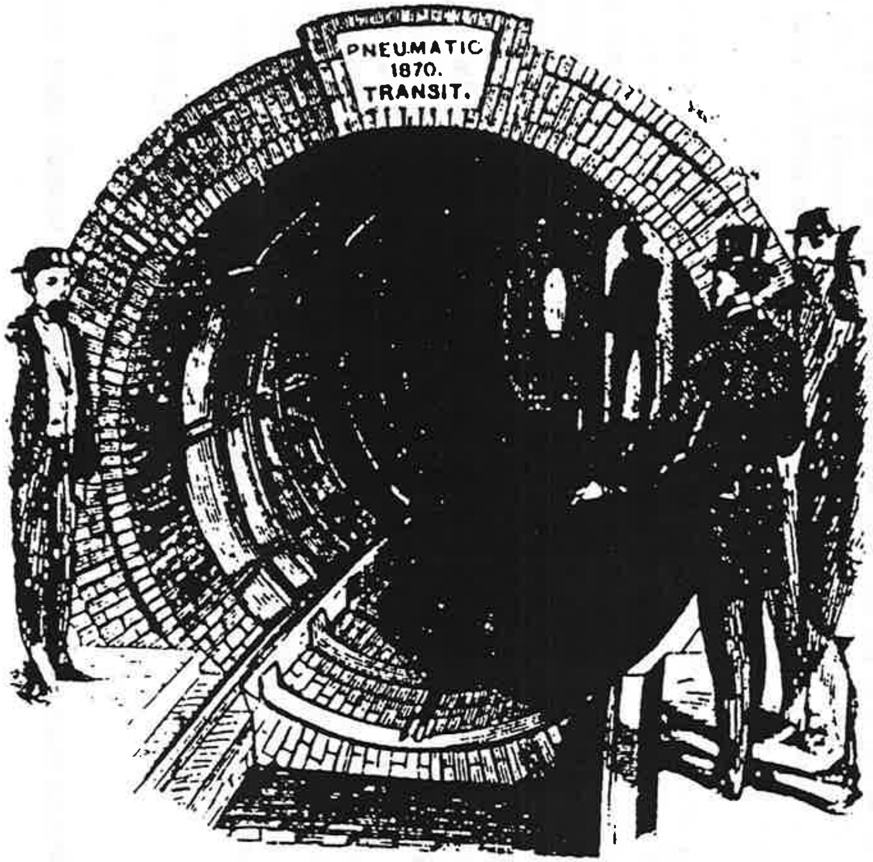
Various proposals for tube transportation have been made in the twentieth century (prior to the current proposals). The period between 1965 and 1975 was particularly active. Professor J. V. Foa was proposing jet propelled vehicles in tubes for high-speed transportation[3]. L. K. Edwards was promoting "Gravity Vacuum Transit" a gravity assisted pneumatic tube system for high-speed passenger transportation[4].

Despite four demonstration systems and innumerable proposals no large size tube transportation system has been introduced into common carrier service. The primary result of this activity was to lend support to the development of underground electric railway systems for urban passenger transportation. Unlike the large systems discussed above many of the smaller, freight systems discussed in the next section have been successfully introduced.

"SMALL" DIAMETER FREIGHT TUBE TRANSPORTATION SYSTEMS

George Medhurst proposed a pneumatic tube transportation system for goods (freight) using a 2 foot diameter tube in 1810. The freight was to be conveyed in "trucks" running on rails within the tube. He also, at this time, proposed to move letters at 100 miles per hour through tubes[5]. Although he was far ahead of his time, many such systems have been built and operated since. Some are in operation today.

There are two parallel lines of development for freight tube transportation systems. One type, pneumatic dispatch systems, are designed to serve the market for rapid movement of high priority documents, using tubes ranging from 1.5 to 8 inches in diameter. The second type, materials handling systems, are designed to move larger objects or bulk cargos and range from roughly 20


PNEUMATIC
1870.
TRANSIT.

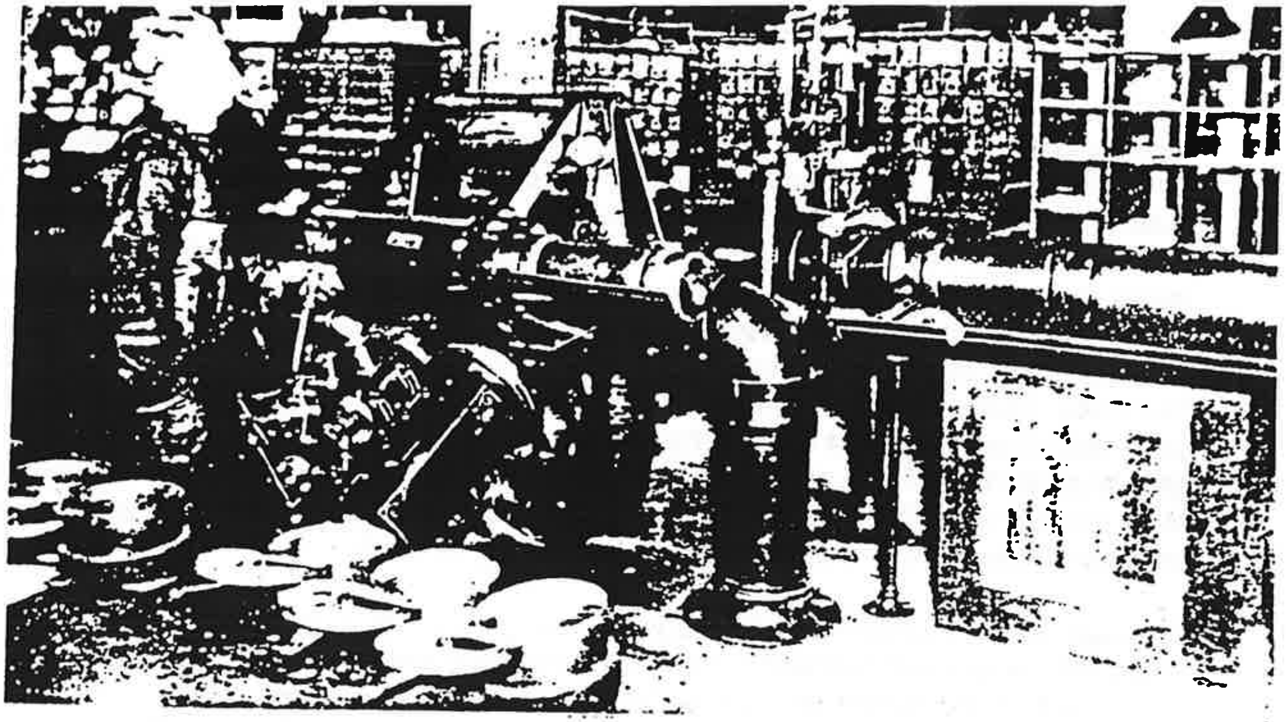
to 40 inches in diameter. The latter systems typically use wheeled capsules while the former use wheelless capsules.

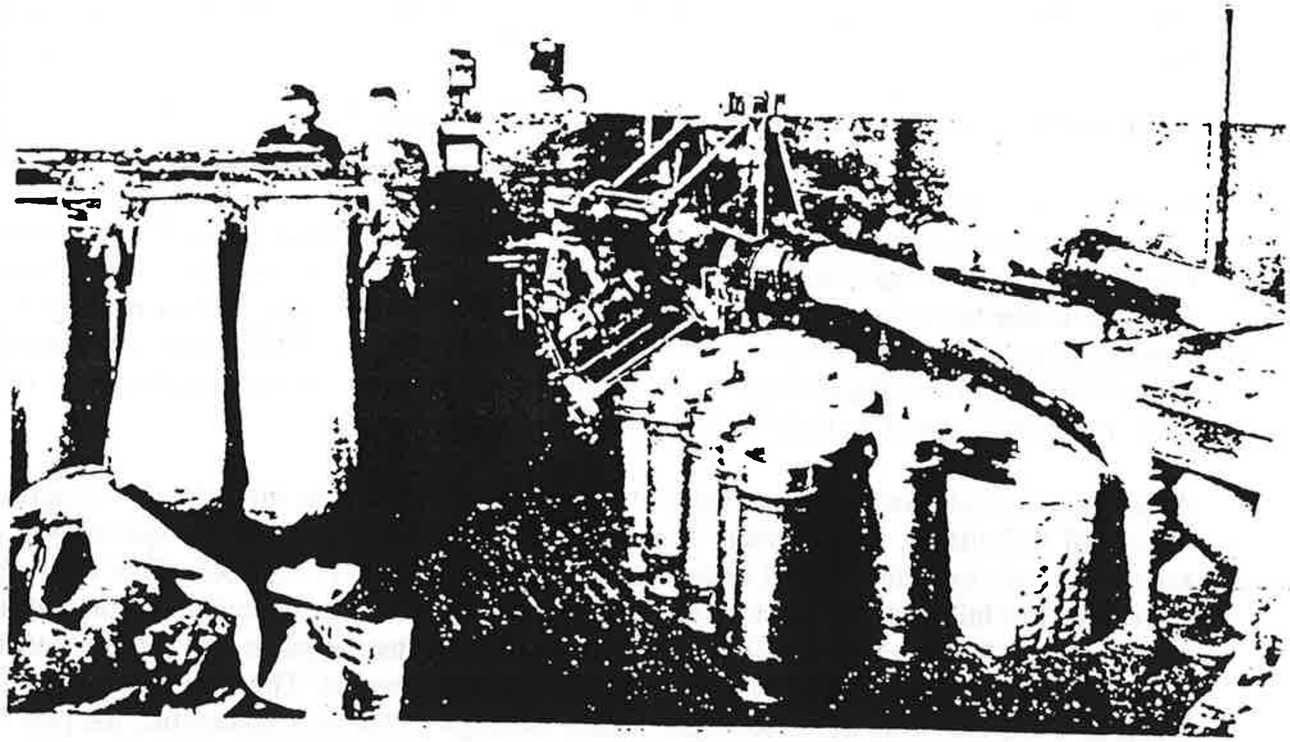
PNEUMATIC DISPATCH SYSTEMS

The systems for rapid movement of high priority documents are often referred to in the literature as pneumatic dispatch systems. Their original purpose was to move telegrams and messages from telegraph centers to local, high activity locations. Pneumatic dispatch was used since it was less expensive than telegraphic retransmission. The first such system built connected the offices of Electric and International Telegraph Co. with the London Stock Exchange. A 1 1/2 inch tube connected the locations which were 675 feet. apart. This system was operational in 1853. Most subsequent activity in England was undertaken by the telegraph service of the British Post Office. By 1875 London had 33 miles of tubes in operation with 7 other English cities having 7 miles between them[6]. The standard tube diameter for most of these systems was 2 1/4 inches. By 1909 London had 40 miles of tubes and 17 other English Cities had service as well[7]. Most of the major cities on the Continent had pneumatic dispatch systems as well. Berlin's system was started in 1865 using 3 1/2 inch tubes, for example. Paris has a major system which had 212 miles of pipes ranging from 6.5 cm (2.6 inches) to 30 cm (11.8 inches) diameter in its centennial year of 1966.

The first pneumatic dispatch system built in the United States was built in New York City by The Western Union Telegraph Company in 1876. Several lines using 3 inch tubes were installed. The first "large" (6 inch) system for transmitting mail in the United States was built with private funds in Philadelphia in 1892-93[8] (figure 3). It was designed to move mail between the main post office and a branch post office 3000 feet away. Although technically successful the company that built and operated the system encountered financial difficulties in part because of a national recession. The Post Office was sufficiently satisfied with the system that Congress was requested to fund additional lines. In 1897 Congress appropriated $150,000. to lease an additional line in Philadelphia, three lines in New York City and one line in Boston. The private building program resulted in a total of 7 1/2 miles of new double tube. All of the new lines were 8 inches in inside diameter and were completed by 1898. The lines were used to expedite mail movements between post offices and main train terminals, the railroads providing all long-haul mail service at that time (figure 4). (The Boston line, for example, connected the main post office with North Station.) Service was also provided between main post offices and major branches. In 1902 additional lines were built in New York City and Chicago. The maximum extent of Post Office lines was achieved after the addition of the St. Louis lines in 1906. At the peak, 63 miles of double pneumatic lines were in operation in the United States.[9] These systems operated into the early 1950's when large scale cutbacks in the Railway Postoffice system caused them to become surplus (the Philadelphia lines were shut down in 1918).

All of the pneumatic dispatch systems above are referred to as "street" systems since they are usually buried under streets. Other pneumatic dispatch systems are referred to as "house" systems because they are internal to a user's facility. Of all of the pneumatic tube systems the "house" systems used by large department stores to transmit cash to and from a centrally located cashers desk were the systems the public was most likely to encounter over the first 60 years of this





Figures 4-3, 4-4
United States Pneumatic Mail Distribution Systems, 1897
Boston Post Office Above, Pennsylvania RR Station, Philidelphia, Below

century. Similar systems have been used in many businesses to expedite movement of paper documents, small tools, laboratory samples, etc. It is of interest to note that the Federal Aviation Administration still has a few control towers in which flight strips are moved from airport controllers to enroute controllers by pneumatic dispatch. The Library of Congress also moves books through four 660 foot long elliptical tubes 8 by 14 inches between the library and an annex. Many document systems are likely to be replaced by all electronic systems in the future, although some may remain in use where paper documents or physical objects must continue to be moved. There are still a number of firms in the business of designing and installing "house" pneumatic dispatch systems today[10] (figures 5,6,7). The only application which is familiar to the general public today is the use of pneumatic capsules to move transactions between driveup bank lanes and the tellers in the associated branch bank. No industry statistics have been located but pneumatic dispatch was clearly a significant industry by 1900.

Although many installations of pneumatic tube systems took place in the last half of the nineteenth century and first half of the twentieth century some were installed after world war II. As an example the West German Post Office installed new systems in Berlin and Hamburg in the early 1960's[11]. The systems use an internal tube diameter of 450 mm (17.7 in). Operating speeds are about 30 mph. Although these systems are generally an extension of the tube despatch systems discussed above they differ in one respect. The capsules in the German systems have wheels at both ends placing them in the second freight tube systems category to be discussed next.

PNEUMATIC TUBE FREIGHT SYSTEMS FOR MATERIALS HANDLING

Pneumatic tube freight systems having diameters between about 20 - 40 inches generally use capsules supported and guided by wheels at both ends. The systems are used for bulk materials handling and for package/mail delivery. The first system of this type was built by the Pneumatic Dispatch Company as a speculative venture to move mail bags from Euston railway station, London to a district post office about a third of a mile away in 1862[12]. The capsules ran on conventional railroad rails through an arched tunnel 30 inches wide by 33 inches high (figures 8,9). The system speed was about 20 mph.

Although technically successful, the post office was unwilling to enter into a long term agreement for use of the system. The problem appeared to be that the capacity of the system was much greater than the quantity of mail to be moved. Thus any charge to the post office which began to recover the full costs of construction and operation were much higher than other means of moving the mail which were available to the post office. After the panic of 1866 the Pneumatic Dispatch Company added 2 miles of new lines with private capital. The new lines were slightly larger at 4 1/2 feet wide by 4 feet high. Again, although technically successful, the post office was unwilling to enter into long term contracts for their use. As a result the lines were abandoned in 1874 after a total investment of 200,000. British Pounds. The failure of the Pneumatic Dispatch Company, the lack of similar systems in other major cities and the related demise of the atmospheric railways (see below) dampened enthusiasm for the larger tube transportation systems for many years.

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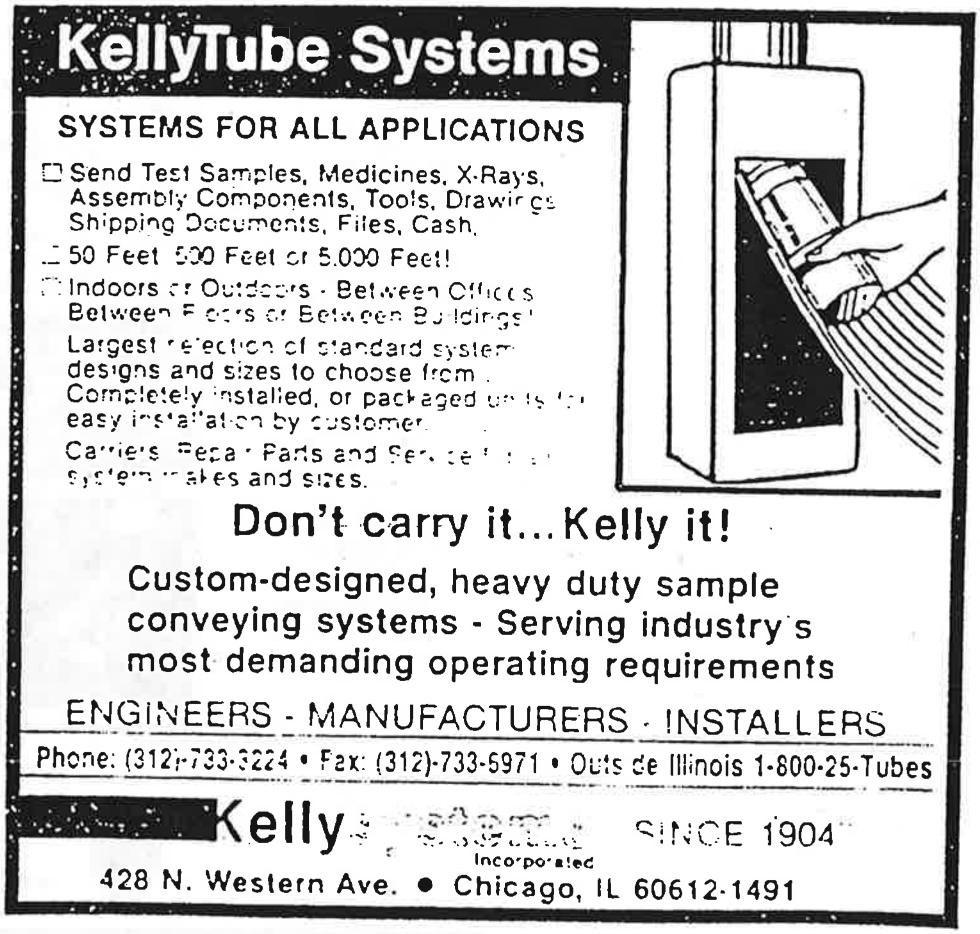

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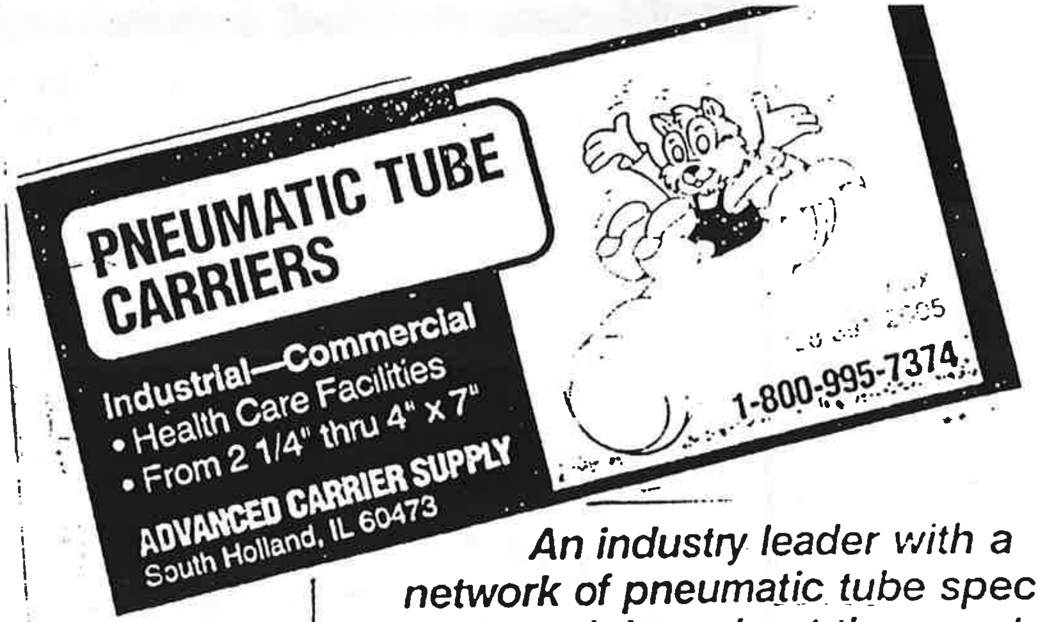
Figure 4-5



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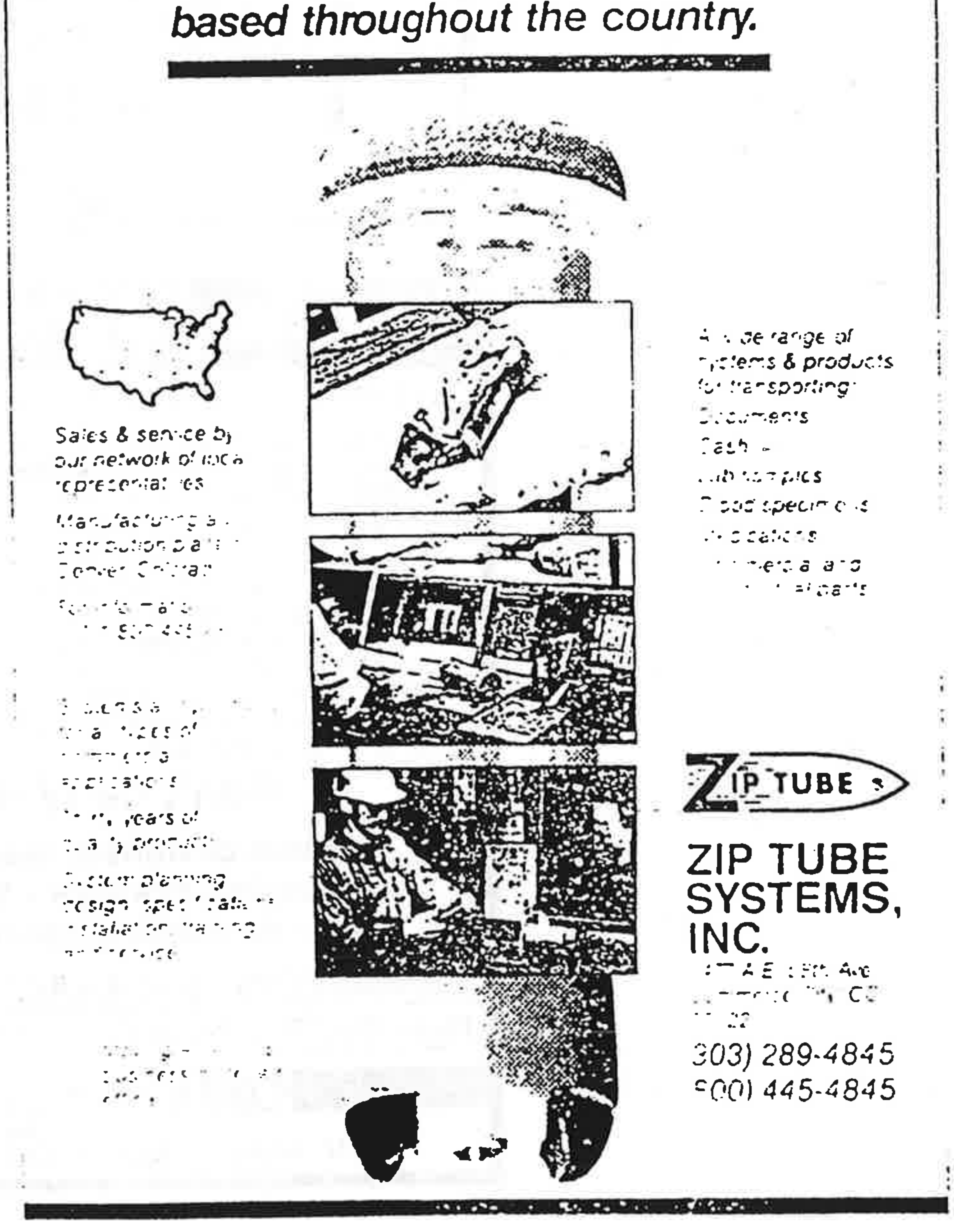

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Figure 4-6

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Figure 4-7

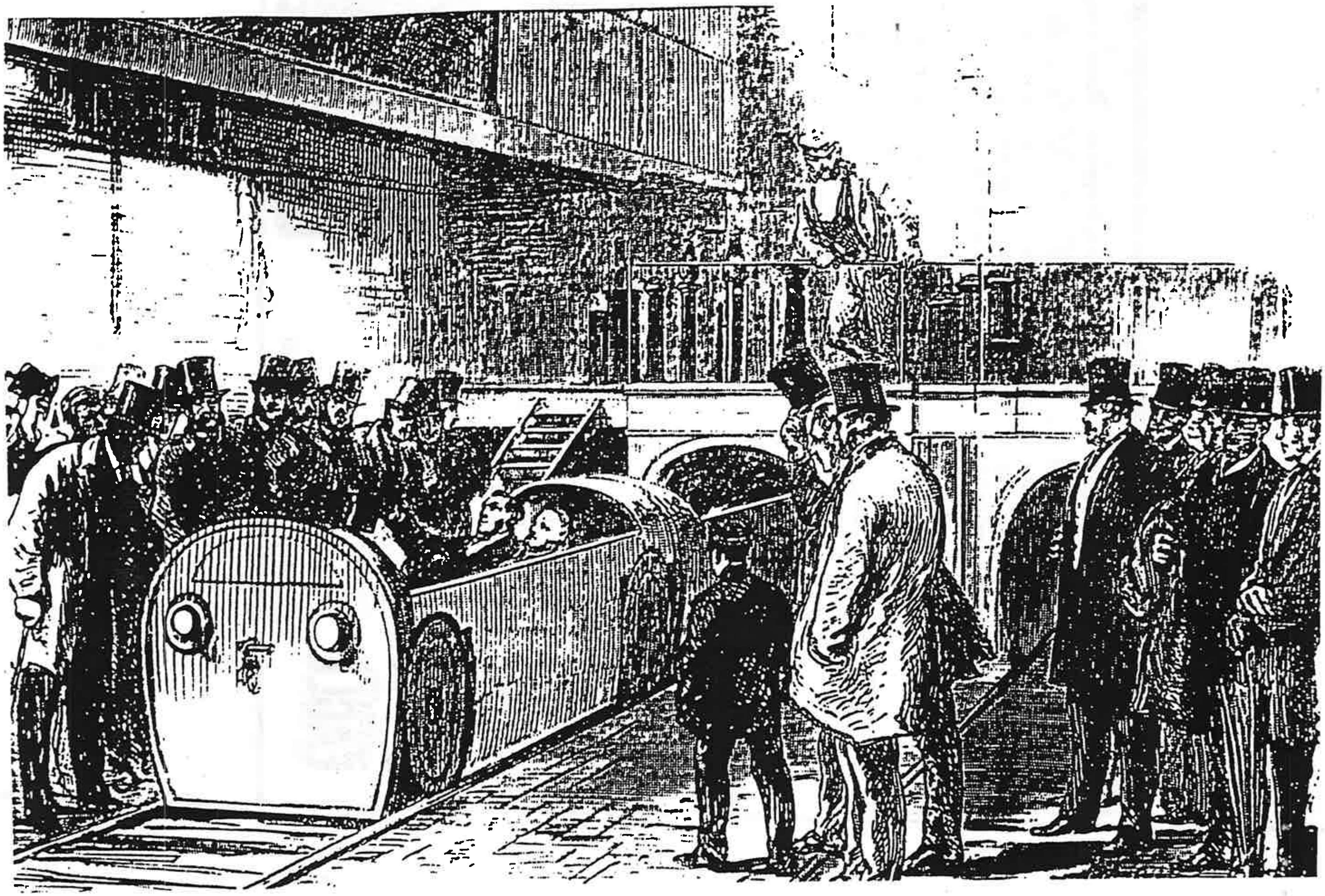

Figure 4-8
Pneumatic Despatch Company Directors Tour, November 7, 1865

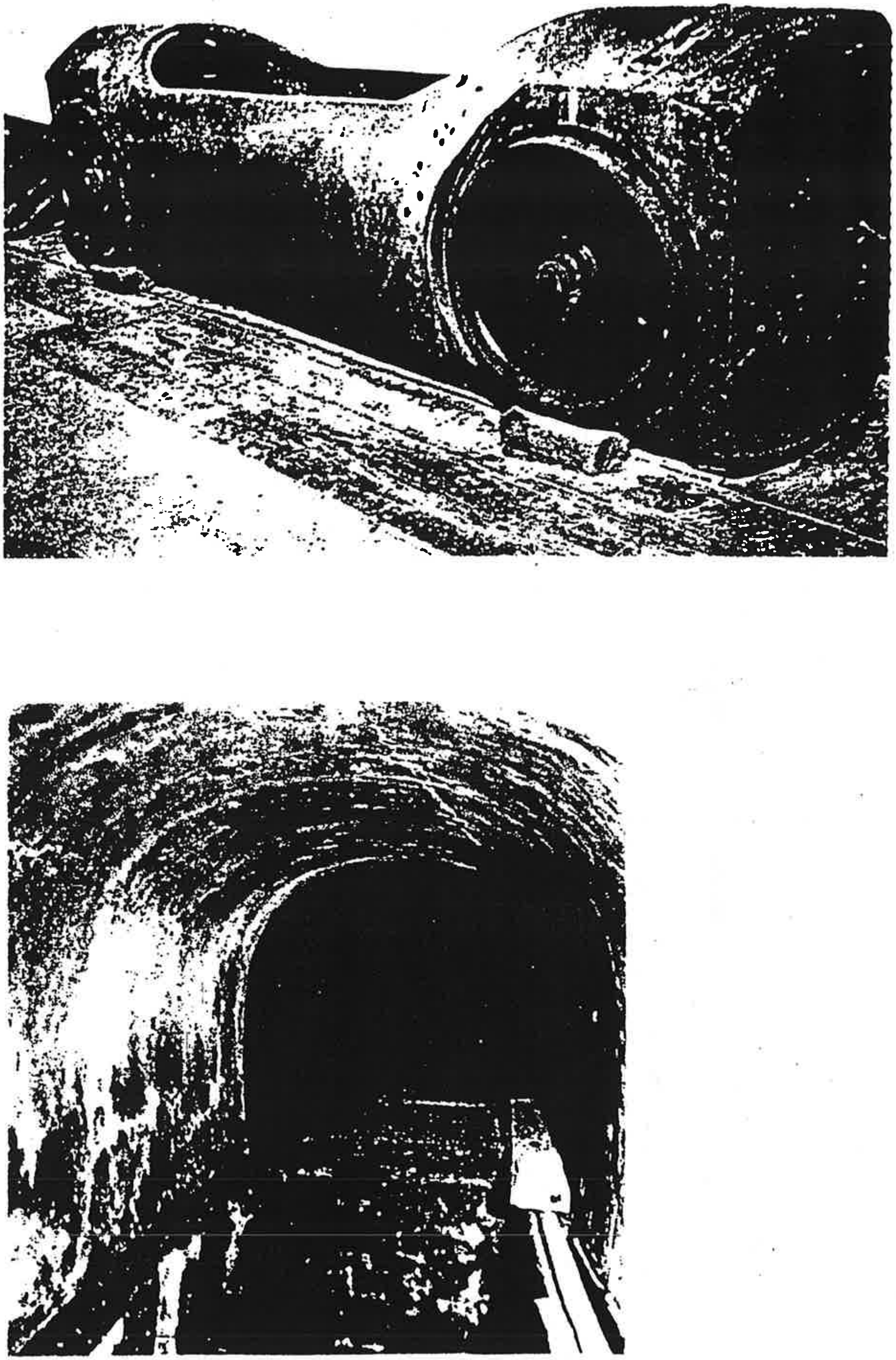

Figure 4-9
Car and Portion of the Tunnel of the Pneumatic Despatch Company

After World War II interest revived in the larger systems for bulk material handling. A.M. Alexandrov in the USSR and Dr. M. R. Carstens, of the Georgia Institute of Technology independently initiated new research in pneumatic capsule pipelines in the early post war period. The result of this work was a significant increase in the capacity of pneumatic capsule pipelines. This was acheived by increasing the number of capsules in transit at any given time. Prior systems generally operated with one or at most a few capsules in transit between pumping stations at one time.

In 1970, TRANSCO of Houston Texas began funding Dr Carstens work at Georgia Tech. They built an initial test facility at Stockbridge, Georgia in 1971 (figure 10). This facility had a 1400 foot long, 36 inch diameter tube. A second test facility was built at TRANSCO's Houston, Texas station in 1973 (figure 11). This facility had an 1688 foot loop of 16 inch pipe with both loading and unloading facilities. The second facility was designed to demonstrate the feasibility of handling dense bulk materials such as coal. After four years of development the test facility was shutdown as TRANSCO concluded that the system, now called TUBEXPRESS, was ready for specific applications[13]. Two systems have been built in Japan influenced by this and other development work.

Nippon Steel Corp. and Daifuku Machinery Works Ltd. using an early license from TRANSCO have built a 2 foot diameter, 1.5 km, double line in Nippon Steel's Muroran Number 2 steel plant to move burnt lime[14] (figure 12). This elevated line, built in the mid nineteen eighties, uses capsule trains (two cars per train) to move 20,000 tons per month. The Nippon/Daifuku system is called AIRAPID.

A similar system was built in 1983 by Sumitomo Cement Co. to move limestone 3200 meters between a mine and their cement plant[15]. The 1 meter diameter pipe carries three car capsule trains delivering 2 million tons per year. This system was originally based on a Russian license but considerably redesigned by the company. This company has proposed their system for other applications as well (figure 13).

An independent development effort in materials handling capsule pipelines was started in the USSR in 1968[16]. Their first operational system was a 1000 mm (3.2 ft.) diameter system for moving crushed rock. This system was built in 1971 near Tbilisi in Georgia. This system, called Lilo-1, used 12 capsule trains. In 1979 a second line for crushed rock was built in the Tula Province of the USSR. This 1200 mm (3.94 ft) diameter line extended 2.4 km and had a capacity of 2 million tons per year (figure 14). The success of these lines led to construction of the Lilo-2 line in Georgia in 1980, again for crushed rock. A 1200 mm diameter line of 17.5 km, Lilo-2 was extended to 44 km in 1984. These systems are referred to as TRANSPROGRESS systems by the Russians.

A 1200 mm line for garbage was built in 1983 from Leningrad 11 km to an outlying processing facility using the TRANSPROGRESS technology. This technology has also been applied to intra plant systems. Two plant systems of 600 mm (23.6 in) diameter have been designed as well as

Figure 4-10
TUBEXPRESS Stockbridge Georga Test Facility

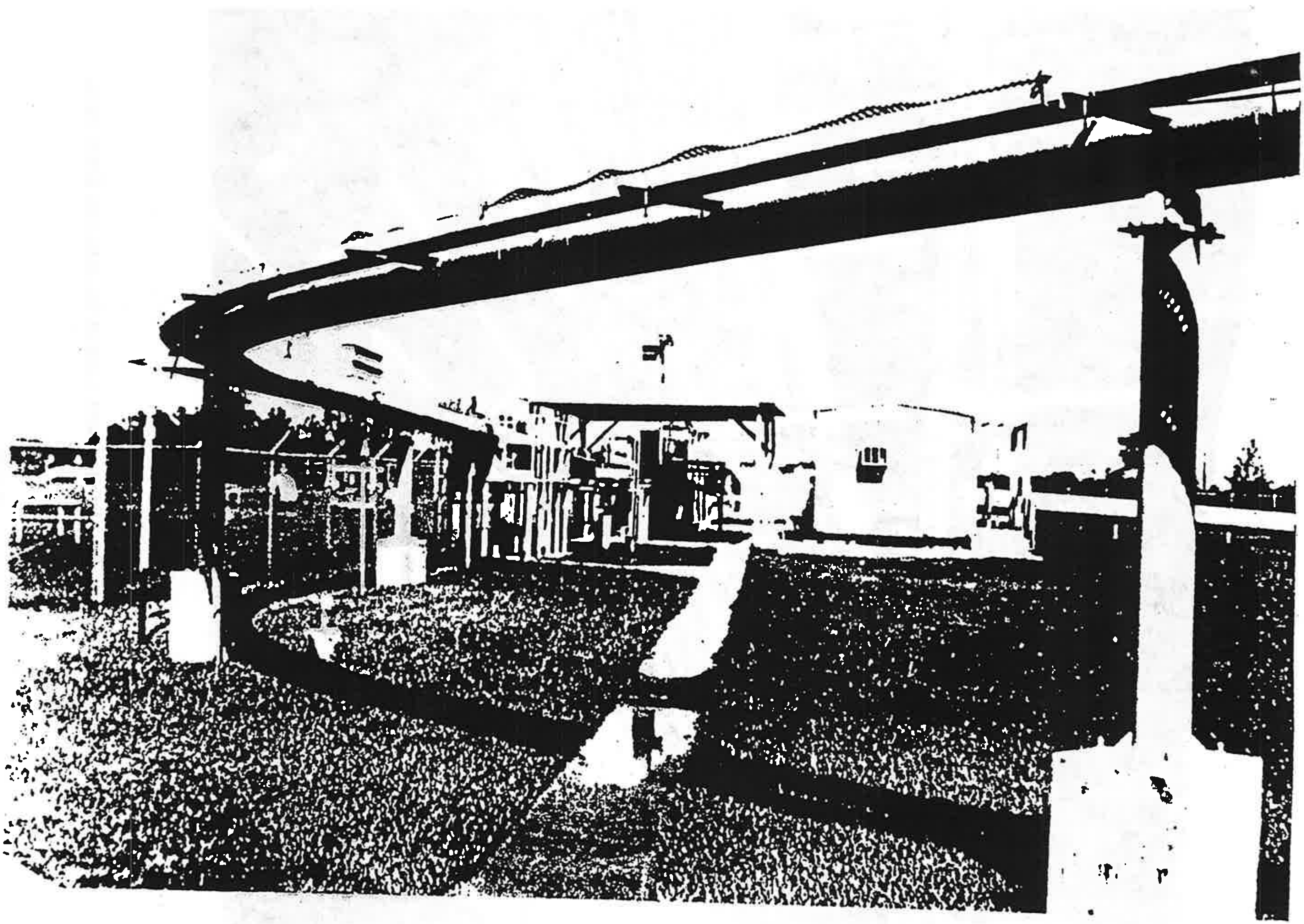

Figure 4-11
TUBEXPRESS Houston Texas Test Facility

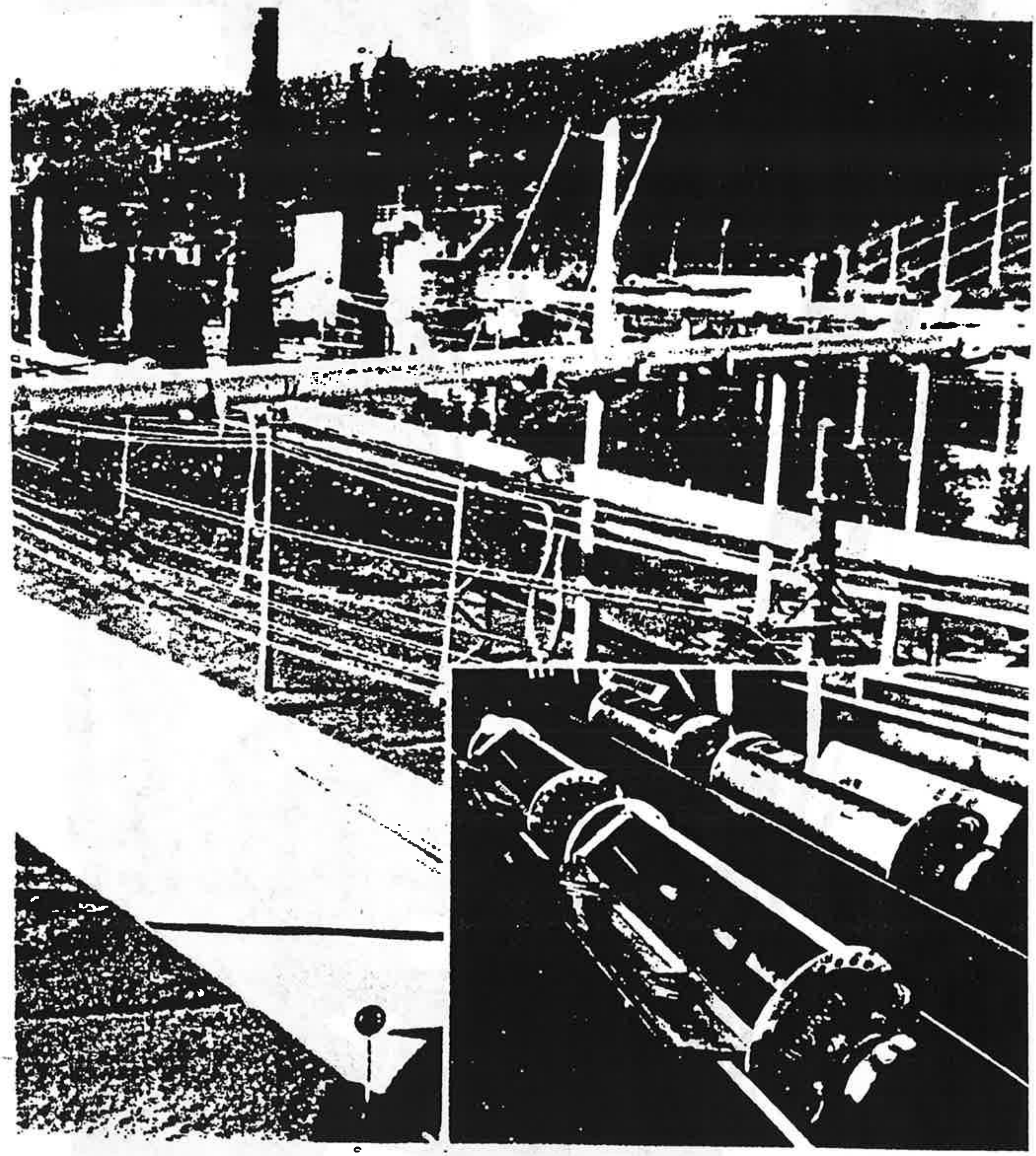

Figure 4-12
Nippon Steel Pneumatic System for Moving Burnt Lime at the Muroran Steel Plant.

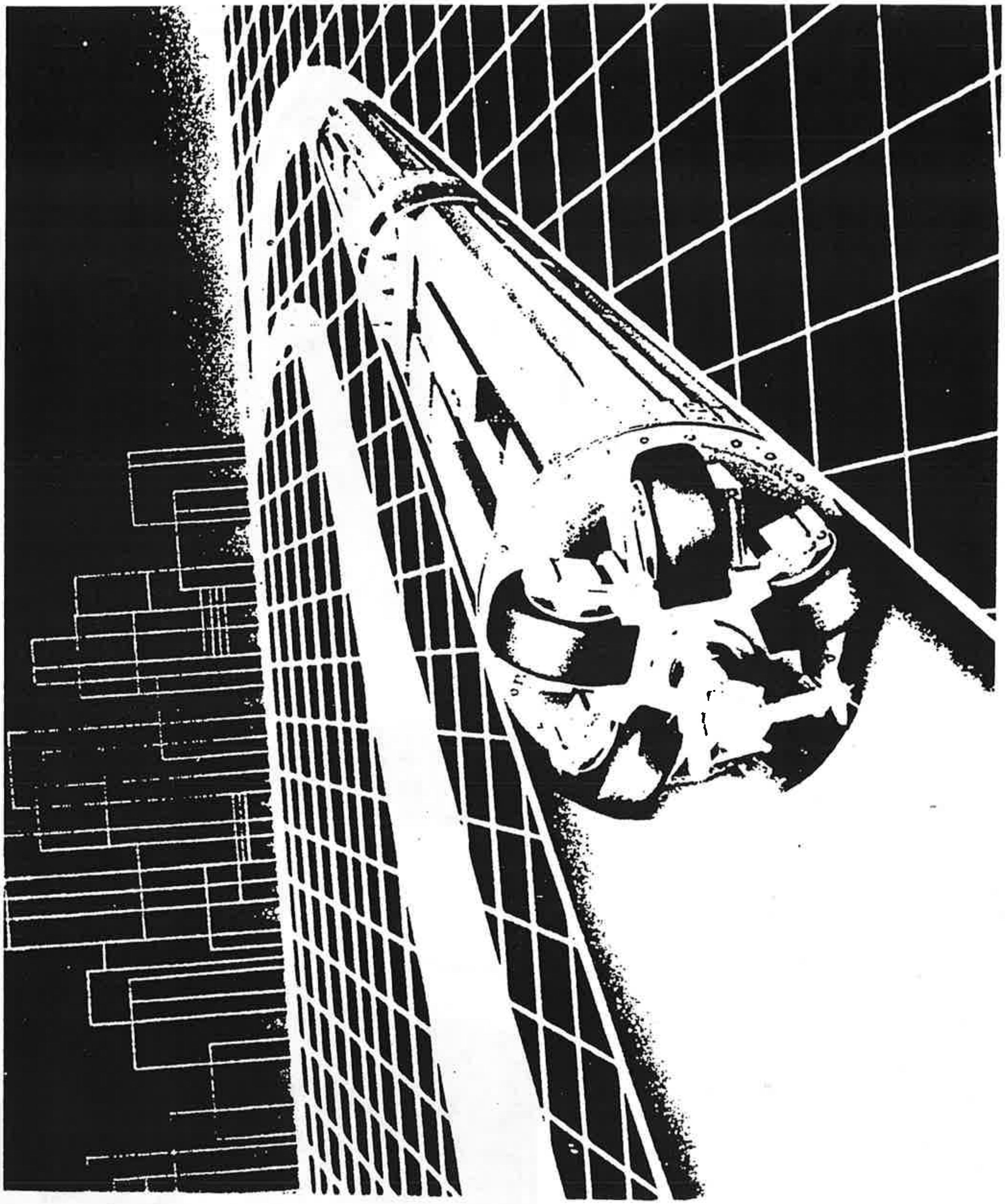

Figure 4-13
Sumitomo Concept for Pneumatic Transportation of General Commodity Goods

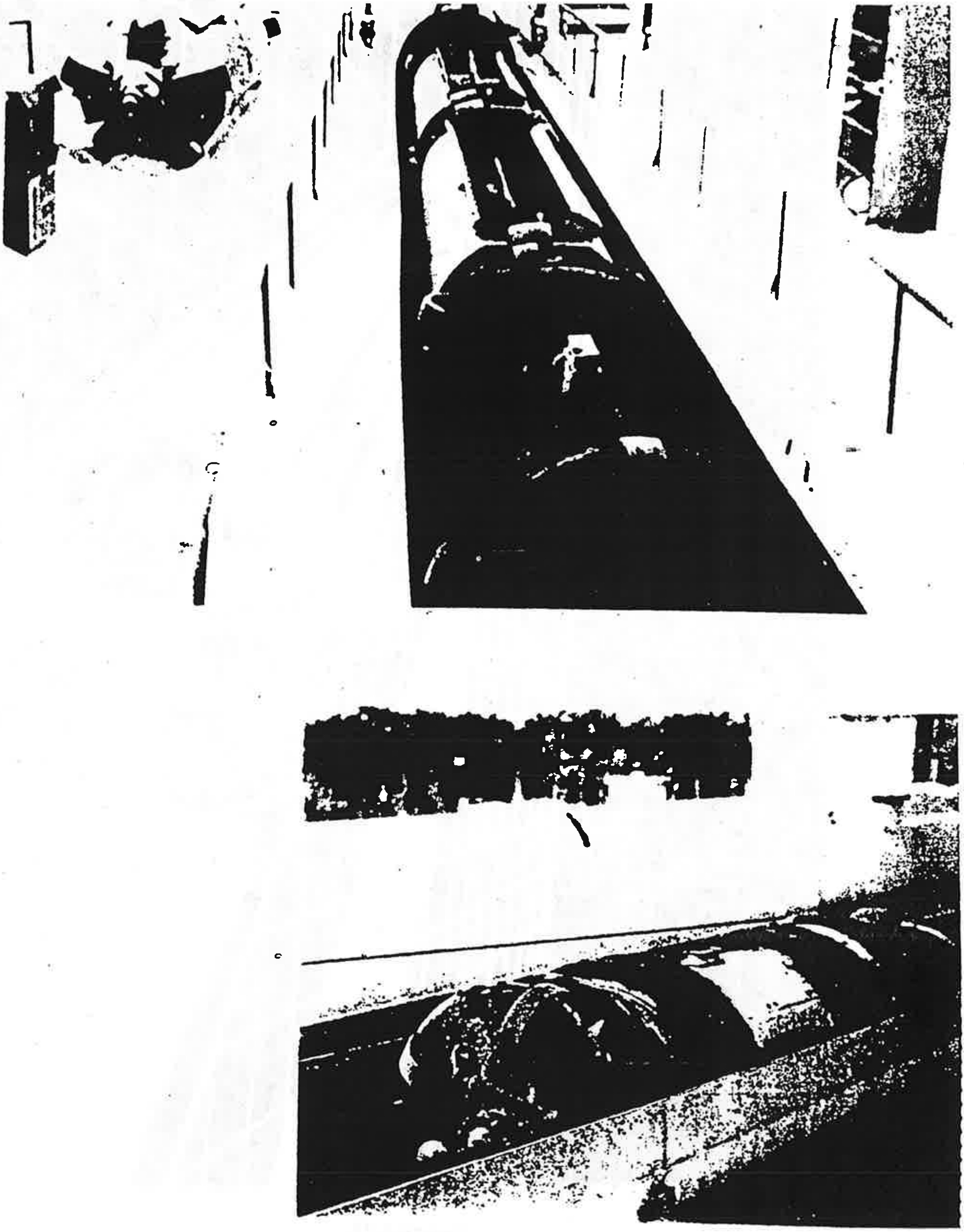

Figure 4-14
TRANSPROGRESS Pneumatic System for Transporting Crushed Rock in Tula Province

two library systems for the movement of books through a rectangular tube 200 mm by 400 mm (7.9 by 15.7 in).

The British also developed some capability in capsule freight pipelines after world war II. BHRA Fluid Services in conjunction with the Warren Spring Laboratory of the Department of Industry developed a 2 foot diameter test loop 1790 feet long for concept demonstration which was operated from 1976 - 1980[17].

ATMOSPHERIC RAILWAYS

Atmospheric railways were briefly described above. Although they are not tube transportation systems as defined here they were the only historic example of pneumatic powered, common carriers to have operated. Four atmospheric railways were operated in England between 1844 and 1860 with an aggregate length of 30 miles[18]. They provided quiet, smoke-free, and relatively reliable service during this period (figure 15). They were justified for high traffic lines with numerous stops where their higher capital cost was offset by rapid acceleration capability. They were also used where severe grades made conventional adhesion locomotives less reliable. They were retired after a relatively short life because improvements in conventional steam locomotives made it increasingly difficult to justify the higher capital costs inherent in atmospheric railway design. Atmospheric railways also were inflexible in that switching was difficult to achieve smoothly. As railway networks became complex, involving large numbers of routing options, the switching limitations of the atmospheric concepts precluded their further adoption or expansion.

It is of interest to note that the atmospheric railway concept has reappeared as an automated people mover. The Aeromovel system developed by Mr. O. Coester has operated as a demonstration, 600 meter long system in Porto Alegre, Brazil since 1984[19]. The elevated system is atmospherically powered using the inside of the box beam it rides on as the vacuum chamber. Current plans are to extend the system to a total length of 2.3 km.

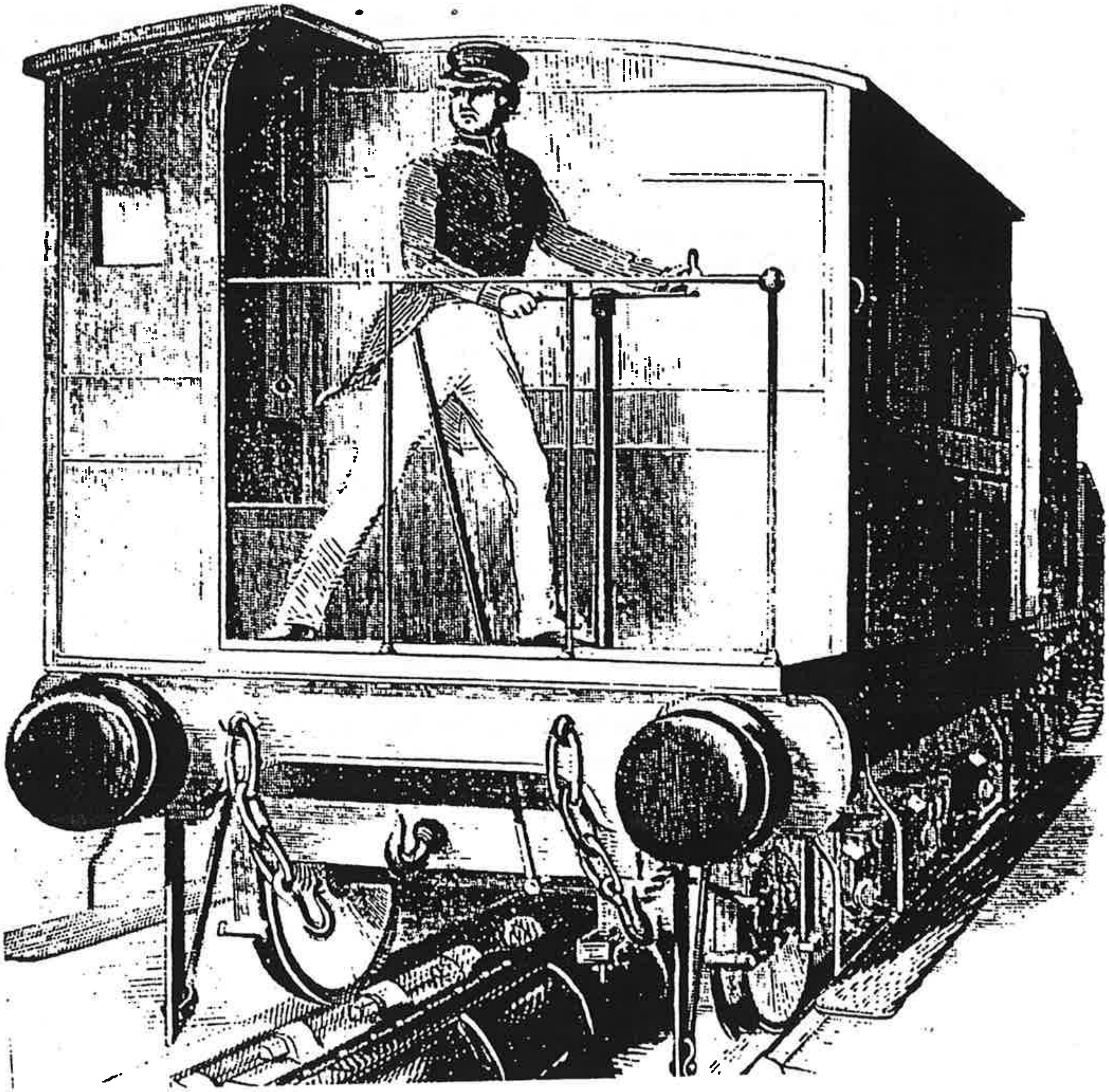

Figure 4-15
Piston Carrage on the Croyden Atmospheric Line

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Japan.

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SECTION 5

Technical Feasibility and System Considerations

Introduction

Tube transportation systems for common carriage exist primarily as concepts at this point in time. While there are no known technical barriers to attaining a large scale tube transportation system in the future, the design features for a number of necessary elements are presently undefined.

Freight Tube Technology

Freight materials transported through pipelines and tubes have historically been conveyed in an atmospheric or fluid medium by differential pressures. Freight has been transported freely intermixed in the media, as in slurry pipelines, or via separate "hydro-capsule" or "pneumo-capsule". Many types of materials are presently available for tube and pipeline use, including steel, reinforced concrete, fiberglass, plastics, etc.

Encapsulated freight may be conveyed through air tubes propelled by differential (pneumatic) pressure acting on the opposite faces of capsules closely fitted in the tubes. Other systems of propulsion could include conventional electric motors, linear induction motors, or mechanical/cable drives.

Pneumatic propulsion systems typically require pumping stations, control, maintenance, and communication facilities, and terminal valves and pressure relief facilities to maintain and direct air pressures. Similarly, electric motor or cable driven capsules would require power distribution systems as well as facilities for maintenance, control and communication. A major difference between pneumatic and non-pneumatic systems is that for close fitting capsules in non-pneumatic systems, special consideration still must be taken in the design for pneumatic effects.

Capsule fabrication, inspection, maintenance, control and monitoring are requirements of any capsule system. The simplicity in the design and operation of the capsule will bear directly on the costs associated with these requirements.

Feasibility of System Elements

Automatic Control

It is in the area of automatic control that tube transportation would seem to have advantages over competing modes of freight shipment. With a dedicated, weather-proof, and intrusion-proof capsule and guideway system, automatic controls available today could provide almost complete automation from point of freight origin through to destination.

Given the state of the art and development of existing control systems for passenger transportation, where safety and operational standards are much higher than they would be for freight, it can be assumed that automatic controls would be somewhat readily available and adaptable. This would apply regardless of the electric and/or pneumatic elements of the propulsion system.

Underground Tubes

It is assumed that substantial portions of any tube transportation system will be constructed underground, especially in urban areas. It is further assumed that those underground portions will represent a substantial part of the capital costs of such a system. Therefore a review of underground construction costs is presented in Appendix _.

It is because transportation tunneling costs are so high that tube system proponents scale their concepts down in size. There are substantial costs to be saved by utilizing capsules on the order of six feet (roughly two meters) in diameter. Tunnel excavations of a diameter of eight feet or less are then acceptable.

Even with scaled down tubes of about 6 foot inside diameter these systems have maximum throughput capacities comparable to railroads. For example; with 24 foot capsules, 16 feet between capsules and a speed of 60 MPH, a single one-way tube would have a maximum capacity of 33.9 thousand tons per hour (10 pounds per cubic foot cargo). This is roughly equivalent to 3 unit coal trains per hour (100 cars per train, 100 ton hopper cars). SUBTRANS is assumed to have a maximum capacity of 15.0 thousand tons per hour, one-way, by its promoter which results in an average capsule spacing of about 250 feet.

There are two traditional construction methods for installing six to eight foot diameter tubes below ground. These are:

- tunneling
- cut and cover, or trenching

1. Bored and Mined Tunnels

Tunnel construction of the type and scale required to accommodate tube transportation is entirely feasible. Tunnel construction can be accomplished by tunnel boring machines (TBM's), drill and blast, and hand-mining methods, depending on the geology and length of drive. Typically the supporting structural liner is installed at the face end as construction advances.

2. Open Excavation

"Cut and cover" is terminology associated with the tunneling industry, and is usually applied to excavation by open cut for relatively large size underground spaces. In practice, tubes of a diameter as small as six to eight feet would likely be installed in an open cut in the same manner as "trenching" of large size sewage pipes or other pipelines.

3. Pipe Jacking

One of an emerging field of "trenchless technology" methods gaining wider acceptance is known as "pipe jacking". Typically applied to utilities projects, it is known to have been used successfully for installing smooth-walled fiberglass pipes as large as six foot inside diameter. A german contractor is currently pipe jacking an 8.5 foot diameter concrete sewer line headed by a shield in Wuppertal Germany. The costs are reported to be greater than trenching, but with the advantage of significantly reducing adverse environmental impacts at the ground surface during construction.

As the name implies, sections of prefabricated pipe are hydraulically forced horizontally through the soil from jacking pits located intermittently along the pipeline route. Excavation can be accomplished manually from inside the pipe, or by a remotely controlled tunnel boring machine which can mix the cuttings with a slurry and pump out the muck for disposal.

4. Other Construction Issues

Tube construction tolerances for alinement and profile would likely require greater control for a transportation system than comparable gas, water, and sewer line construction. Tube manufacture would most logically be of steel or reinforced concrete. However, plastics or fiberglass are possibilities if deflections can be controlled. Steel liner thicknesses would preferably be on the order of one-half to three-quarter inch, any thicker requiring special handling and welding.

Special provisions to achieve watertightness would be required for concrete liners utilized in conjunction with a linear induction propulsion system (further discussion follows). Steel or other liner types could offer greater waterproofing characteristics. Site specific conditions of geology and the length, alinement and profile of the tube system will dictate construction details.

Some design optimization of tunnel and capsule size will be required to address the pneumatic effects on capsules operating at speeds up to 60 miles per hour. Appropriate venting of the tunnels, and also the provision of service access points, would be additional design considerations.

Offshore Tunnels

Offshore tunnels might appear as cost saving alternatives to expensive underground construction. The use of "suspended" tunnel tubes tethered to the ocean floor has been proposed. System construction, maintenance, operational and safety considerations would have to be fully evaluated to assess the feasibility of this concept.

Obvious risks are shipping and fishing activities, and the hazards associated with the adverse undersea environment (material corrosion accelerated by electrical fields, difficulty in conducting periodic visual inspections, etc.). An undersea tube failure would shut down significant segments of the transportation system. It is also likely that most freight commodities could be ocean-shipped in bulk at very competitive prices..

Track Concepts

Tube transportation systems of small diameter, up to one foot, have been built with wheel-less capsules that slide through smooth-walled tubes. For larger and heavier bulk freight capsules, wheels and appropriate running surface on the tube floor will be required. Capsules are generally considered to be cylindrical in shape, fabricated from steel, aluminum, fiberglass, or plastic. Some proposals feature guide wheels on the sides of capsules, providing lateral stability against the sidewalls of the tunnel liner.

Numerous steel and rubber-tired systems with running track of varying designs presently exist for industrial and passenger transit applications. It is reasonable to assume without detailed analysis that existing track configurations will meet tube transportation needs, regardless of propulsion system utilized.

Linear Induction and Pneumatic Propulsion Systems

The concept of linear induction propulsion applied to tube transportation represents one of the primary enhancements of one vendor from previous pneumatic propulsion concepts. The advantage claimed for linear induction propulsion is a presumed improvement in system capacity through simplicity of design and operation, coupled with a simple capsule configuration promising relatively easy and inexpensive fabrication and operation. While numerous studies and prototype pneumatic systems have been built in the past, there are no known examples of tube systems which have operated utilizing linear induction propulsion. Such a system is within the state-of-the-art but undemonstrated.

Typical of numerous technical difficulties associated with linear induction propulsion is the issue of maintaining critical tolerances in the air gap between the capsule-mounted stator and the induction windings installed in the tube invert. Capsule weights will vary considerably from the empty to the fully loaded condition. Suspension of the bulk of the capsule and payload will be necessary to prevent rapid deterioration of the track structure. The promoter of SUBTRANS proposes to provide the capsules with suspensions for the payload but leave the stator unsprung. This concept has not been demonstrated.

Similarly, it is likely that construction tolerances exceeding those for FRA Class 6 track would be required for the construction of the tube invert. Will it be necessary to incorporate profile and alinement adjustment mechanisms into the "track" surface and propulsion coils in the invert? Solutions to these problems are technically feasible, but will add to system capital costs.

Switching

The transfer of capsules at speed from one line to another, for example out of a mainline to a siding, remains somewhat problematic in tube transportation systems. As in the case with monorail or maglev guideways, the only proven switch mechanism is a cumbersome hinged guideway element capable of directing vehicles off one line onto another. Such a mechanism must be structurally robust and of considerable dimensions. It is unlikely that speeds anywhere near 60 miles per hour could be maintained during movement through such a switch. Even lower speeds would be required for "turntable" types of switches, which could, however, be well-suited to warehouse and terminal environments.

It is theoretically possible that a capsule propelled by linear synchronous motor may be directed from an alinement in one tube to a diverging alinement in a neighboring tube, by the excitation of windings in a guideway crossover. However, the concept remains to be demonstrated.

Yards and Terminals

Concepts for tube transportation yards and terminals are limited only by a vendor's imagination. The functions to be fulfilled are primarily freight capsule routing, presumably intermodal transfer for customers lacking direct system access, and short term storage capacity. Large volume customers could have their own "sidings" and handle their own commodities.

System Considerations

Size of Tube

There are two general tube sizes to consider. Tubes and capsules on the order of six to eight feet in diameter are small enough to achieve significant cost reduction in tunneling and guideway construction. They also represent a reasonable lower limit to capsule volume and carrying capacity, still probably large enough to efficiently transport break bulk commodities.

A larger tube size on the order of twelve to fifteen foot diameter offers advantages in terms of integration with the existing shipping container industry. Standard eight to eight and one half foot high by eight foot wide shipping containers could be accommodated on such a tube system, with obvious savings in reduced handling and packing of freight. However, infrastructure costs per unit length would increase dramatically, and one would essentially be recreating a conventional railroad, albeit with modifications in terms of access, propulsion, etc.

System Configuration

The use of capsules to deliver large volumes of cargo requires separate tubes for each direction unless the capsules are disposable at the receiving end, or the line is in a loop. For systems

operating at lower levels of utilization, routing and economic studies as applied to railroads could determine optimum distribution of single and double track lines.

SECTION 6

ECONOMICS OF TUBE FREIGHT TRANSPORTATION SYSTEMS

Introduction

Tube transportation systems are inherently high capital cost, low operating cost systems much in common with railroads. Introduction of tube transportation systems involves either technological substitution for existing systems or expansion of total transportation capacity (or a combination of both). Introduction of tube transportation of freight in the U.S. economy at this time would be to introduce additional capacity into the national system which currently has excess capacity. In the future this excess capacity will likely be reduced by increasing freight traffic. Thus, tube transportation of freight could supply future freight capacity when needed. It could also provide substitute capacity for existing freight systems if national policy requires increased safety, a more environmentally friendly infrastructure or significant increases in freight movement productivity.

Economic Objectives

The SUBTRANS proposal by Vandersteel has as its primary objective substitution of tube freight transportation for long haul trucking. He envisions break bulk cargo typical of many trucking loads as the market for his system. Outsize loads and merchandise which could not be conveniently stacked in capsules within a 2 meter diameter load limit would be excluded. In the long run he envisions a national network system linking major urban areas with direct service to major shippers and consignees. The national network would clearly be competitive with both motor carriers and railroads.

The BHRA proposed application in 1971 was similar to the SUBTRANS proposal, in economic terms except that it was advanced as a substitute investment for English motorways which were projected but not constructed at that time. Both proposals projected economic benefits from increased productivity and safety and decreased environmental impact.

Competitiveness of Tube Freight Transportation

Both SUBTRANS and BHRA have computed <u>average</u> costs for tube freight transportation which indicate lower costs than long haul motor carriage and competitive costs for some rail transportation. Vandersteel, for example, estimates capital recovery for high volume operation of his system in 8 years with a 25% profit. He assumes a $0.10 per ton mile charge for this service. He also assumes operation at an annual volume of 20.7 million tons in each direction.

The major cost assumptions used in Vandersteel's analysis are included at the end of this section. Others have obtained roughly similar results.

The most complete study of tube freight economics located by the authors was sponsored by the University Research Program of the U.S. Department of Transportation in 1975 - 1978[1] [2]. This study, performed by the University of Pennsylvania, examined a variety of pipeline technologies in real corridors based on actual and projected commodity flows. Both bulk solid and break bulk dry cargoes were considered in this study.

In all of the studies cited above the tube transportation systems were assumed to be 2 meters (6.56 feet) in diameter or less. A system of this crossection clearly is not fully competitive with motor carriage or railroad since both can carry larger loads. This aspect is discussed further in the section on intermodalism below.

Another crucial aspect of the prior analyses is their comparison of competing systems on an "average" cost basis. Most commonly, current average costs for rail and highway (historic investment and right-of-way costs excluded) are compared to the full average costs including capital investment for pipeline (e.g., Pennsylvania study). While useful for assessing the comparative advantage of pipeline when introduced into an existing competitive environment, this approach understates the costs of rail and highway when considering construction of totally new freight capacity.

Why Haven't We Built Tube Freight Transportation Systems ?

Since general commodity tube freight transportation systems appear to be both technologically feasible and competitive on at least an average cost basis why haven't they been built? The answer in a word is; history. Imagine for a minute we are in a world without railroads. Only road and air systems are available for passenger and freight transportation. As a mater of national policy we decide to build a dedicated 'surface" freight system for the nation. Both railroads and tube systems would be candidates for such a national system. If sufficient weight is given to productivity, safety and environmental considerations tube transportation would likely be the preferred alternative.

Unfortunately we already have a existing, mature railroad network with excess capacity. If tube freight systems are introduced into direct competition with the railroads today the railroads reaction to the loss of existing and future traffic would be very vigorous price competition. Since the marginal cost of rail transportation is significantly lower than the average cost, the railroads with their current pricing freedom, can lower their prices to marginal costs as necessary to under price competition. (Marginal cost in this case is the direct cost of adding a few cars to a train or adding a train to a well maintained and utilized track.)

Some tube freight transportation promoters have suggested that their system would only compete with long haul trucking, not railroads. Railroads, however, do compete for this traffic which they now primarily carry as trailer-on-flat-car (tofc) or container-on-flat-car (cofc) loads. Recent studies document the growth of this traffic on the railroads and the substantial diversion of long haul (greater than 1500 miles) trucking to rail TOFC/COFC operations[3].

Tube transportation systems have been implemented in new niche markets where they carry bulk cargo in dedicated service. These systems, which can be considered materials handling systems as much as tube transportation systems, are described in the historical section. No general cargo tube transportation systems have been introduced into niche markets although this is possible in the future. Because of the long term capital financing required for such applications finding dedicated cargo requirements where the participants are willing to enter into 15 to 30 year contracts for service is difficult. Niche markets are also discussed below in the section on introduction of tube transportation systems.

How Could Tube Freight Be Introduced?

It is evident that a comprehensive national tube freight system cannot be financially and physically implemented overnight even if this were a national objective. Several types of transition to a national system can be envisioned. In one; isolated, financially viable segments would be built and then expanded into a national system. This is the historical development path the railroads took with periodic government subsidies and other incentives. This approach has the obvious disadvantage of requiring standardization after initial segments are built and operating.

A second approach is to develop a national plan, with appropriate standards in advance. This was the general approach taken to implement the Interstate Highway system. This approach would appear more appropriate for introduction of a national system of tube freight transportation. It has the disadvantage, however, of requiring an extensive period for planning, consensus building and enactment.

A third approach is to assume tube freight transportation would only provide niche, general commodity services and allow totally private planning and development with limited enabling legislation and perhaps, access to federal rights-of-way.

Intermodal Issues

Any tube freight transportation system operating as a common carrier will be required to transfer freight to other carriers for final delivery except for those large consignees located on the system with private, direct access (like railroad sidings). Likewise freight tendered to the tube system will be delivered by another carrier except for freight originating on the system. In most cases trucks are likely to provide offline service.

Currently intermodal transfers between trucks, railroads and ships are facilitated by the use of standard intermodal containers[4]. In addition truck trailers act as containers, being hauled in intermodal service both by truck tractors and on railroad flat cars. Intermodal shipments are increasing as noted above. To be successful it is likely that any tube freight transportation system acting as a common carrier would find it necessary to have some means of efficient intermodal transfer like standard containers.

For tube freight transportation systems in common carrier service intermodal terminals will be a critical element from both a capital and operating cost perspective. For efficient cargo transfer and rapid integration into existing transportation infrastructure it would be desirable for tube systems to handle standard intermodal containers. Tube diameters of about 10 to 12 feet are necessary to accommodate these containers. Such tubes would have approximately four times the capital cost of the 6 foot diameter tubes advocated by most promoters and would, thus, be much less economically attractive. (Rectangular tubes might be one means of slightly reducing the cost of tube systems designed to move conventional containers.)

Tube promoters suggest that pallet loads would be suitable loading modules for 6 foot diameter tubes. This approach is suitable for shipments both originating and terminating at online plants as most such facilities move materials and products in pallet loads. For shipments originating and/or terminating offline intermodal transfer in pallet loads is more efficient than manual operations but certainly less efficient than existing container transfer unless pallet transfer is highly automated. An option which has not been explored would be the development of a special container for tube systems of approximately 6 foot diameter. Could a 4 foot by 4 foot crossection container be developed to be compatible with current 8X8 foot standards? Clearly much more cost and design analysis needs to be addressed to tube terminals.

Environmental Benefits

Although difficult to quantify there are clearly environmental benefits from implementation of tube transportation as a replacement for trucks. Air pollution from truck engines will be reduced in proportion to the number of trucks removed from the road. All current tube transportation system proposals envision the use of electrical power. Even if the electrical power is generated from fossil fuels a net reduction of air pollution can be expected from a proposal like SUBTRANS since its steel wheel on steel rail technology is more energy efficient than trucks.

The second major environmental benefit of tube transportation is its below ground location which reduces intrusion in environmentally sensitive locations. This is one of the major factors in the Swiss high-speed maglev proposal. Underground location is beneficial where surface land values are high, where surface conditions are already congested, or surface routes are unavailable. These are not new issues but are becoming more important with national growth[5].

Historically, there is precident for underground freight operations. The most notable underground freight system was the 50 mile electric railway system built under the City of Chicago for collection and distribution of general cargo and coal. The Chicago system operated from 1904 through 1958[6] interfacing with the main line railroads. The Tokyo proposal described under current tube freight proposals would perform the same function as the Chicago system except that the Tokyo system would be automated and would interface primarily with trucks.

Energy Benefits

As noted above tube freight transportation systems are likely to be quite energy efficient, particularly if they use steel wheel on steel rail technology (as proposed by SUBTRANS) when substituted for truck transportation. Tube transportation has no significant advantage over railroads from an energy viewpoint. If all highway combination trucks were removed from the nations roads highway fuel use would be reduced by about 13%. If all combinations and large single unit trucks were removed the saving would rise to 19% (based on 1990 data). High energy efficiency for tube systems requires the use of noncontact seals on the capsules (like existing materials handling systems in the larger diameters) and minor aerodynamic losses.

Safety Benefits

A major benefit of tube transportation is likely to be safety. Large trucks in mixed traffic with much lighter passenger cars have been a safety concern for many years. By the 1920's The Hoover Commission was already recommending separate roadways for trucks in congested areas[7]. Currently several national interest groups are lobbying for reduction in heavy truck traffic[8]. Tube freight transportation systems, since they are automated (without on board personnel) and operate in isolation, are likely to be far safer than trucks in mixed traffic. Tube transportation is also safer than railroad transportation since its design (no crossings at grade and complete enclosure) will eliminate highway-grade crossing and unauthorized intruder accidents. Highway accidents involving heavy vehicles result in about 4000 fatalities per year inn the U.S. while grade crossing, intruder and employee railroad accidents result in about 1000 fatalities per year.

Historically, pneumatic freight pipeline systems, the antecedents of current tube transportation proposals, have had high operational reliability and, thus freedom from accidents. This has resulted in an extremely low rate of cargo damage in these systems, an additional safety related benefit which is likely to also be the case with common carrier tube transportation systems.

Productivity Benefits

Substitution of an automated system for a non-automated or semi-automated system will clearly increase system productivity. Tube freight transportation systems are inherently automated in their line-haul portions (except for supervisory personnel) and may have automated terminals. Terminal automation is not a technical problem as such terminals exist today: for example, the new automated container terminal built by Sea-Land in Rotterdam[9]. Automation of tube transportation terminals is primarily a economic decision dependent on cargo mix, specific capsule design, characteristics of the trucks discharging and receiving the cargo, etc.

Tube freight transportation has an additional productivity advantage over railroads. Tube capsules are dispatched individually from terminals or warehouses like trucks. There are no delays while sufficient cars are loaded and assembled into a train as in standard railroad practice.

Other Benefits

Tube freight transportation systems have the potential to provide reliable, predictable, rapid, safe and secure service. Because each capsule can be dispatched when loading is complete, delay in the system is minimized. Since the system is very predictable when operating; complete, real time information on the location of each capsule can be maintained very inexpensively. These attributes can be summarized as a high level of service. This service should be particularly attractive to just-in-time manufacturers.

Reduced highway maintenance costs are a benefit of removing truck traffic from the nations highways.

SUBTRANS Cost Analysis

Summarized below is the SUBTRANS cost analysis presented by William Vandersteel[10]. We have made two changes to simplify the presentation. First, we have presented the costs on a one-way mile basis rather than the 50 mile two-way segment used in the SUBTRANS example. Second, we have amortized the capital investment over 30 years at 10% interest rather than present the cash flow analysis as performed for SUBTRANS. Neither change has a significant effect on the conclusions.

Capital Costs (Assumed by Vandersteel)

Tube and liner installed in ground	2,900	K$/one-way mile
Linear propulsion and control	1,000	"
Terminal construction (One terminal assumed per two-way, 50 mile segment)	250	"
Capsules (six per mile)	72	"
TOTAL	4,222	"

Thus the annual capital cost at 30 years and 10% interest is roughly 422 K$/one-way mile.

Annual Operating Costs (Assumed by Vandersteel)

Energy	750 K$/one-way mile	
Maintenance, Staff and Insurance	<u>113</u>	"
TOTAL	836	"

Annual Revenue (As calculated by Vandersteel)

At 60 miles per hour 360 capsules pass per hour. They generate 360 x $.10 per ton mile x 8 tons per capsule = $288 of revenue per hour per mile. Assuming 24 hour operation, 300 days per year, this is 2,074 K$ per mile per year.

Annual Net Revenue

Annual net revenue is total revenue - total cost = 2,074 - 836 - 422 = 816 K$/one-way mile. A graph of net revenue as a function of throughput using the assumptions above is shown in figure 6-1. From this figure it can be seen that breakeven is achieved at a traffic level of about 12.5 million tons per year.

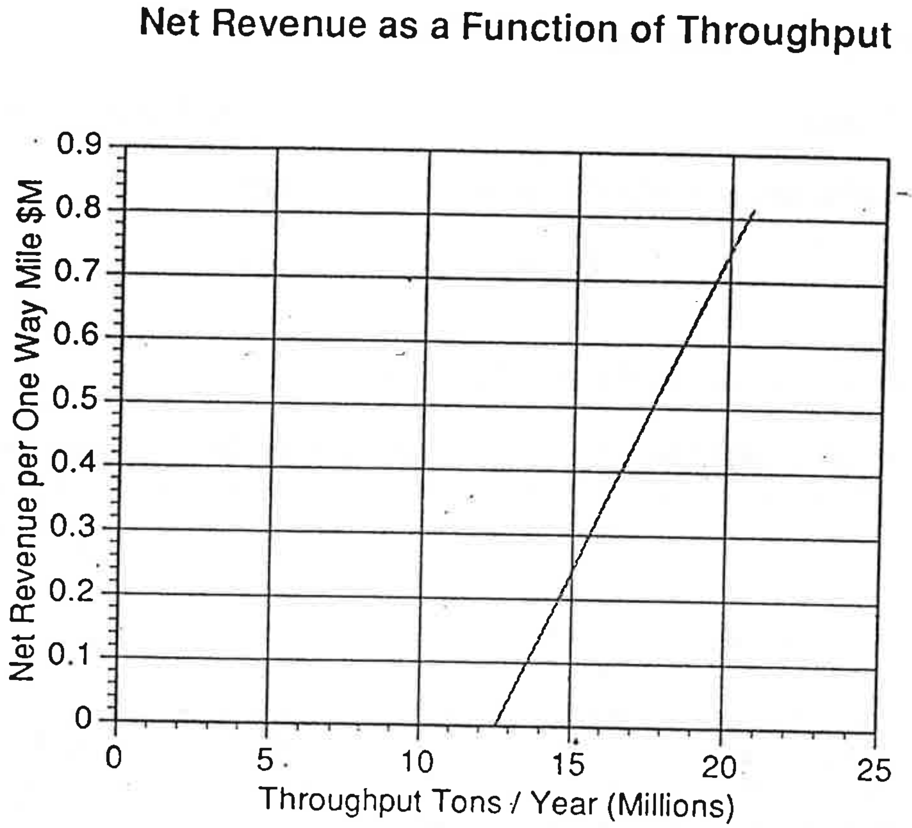
Comments:

1. K = thousands.

2. The largest capital cost element for this system is tunneling. Vandersteel's figure of $ 2.9 million per mile is reasonable for average conditions but costs can increase dramatically under difficult conditions. See table A-1 in the appendix for recent tunneling costs.

3. The cost of linear induction motor, power conditioning equipment, controls and installation were not estimated directly. These costs were inferred from the current cost of rotary motors of equivalent horsepower.

4. No costs for delivery of goods to this system and distribution of goods from the system are included in this calculation. Note that the University of Pennsylvania study previously



Vandersteel Costs Except Amortization of Capital at a 30yr 10% rate.

Freight rate = $0.10 / ton-mi.

Figure 6-1
Net Revenue vs Throughput for SUBTRANS

cited assumed local truck collection and distribution and they included this cost.

5. There is no variable element in either the capital or operating costs of terminals.

6. Two-way balanced traffic is assumed.

7. Right-of-way is assumed to be free.

8. No general overhead expenses are considered.

9. Net revenue is before taxes. It is assumed this system would operate in the private sector.

10. No tunnel operating costs are included. Tunnel drainage could be a problem for example.

11. A traffic volume of 20 million ton miles per year is slightly less than 1% of the total U.S. intercity ton miles produced by trucks in 1990.

12. The number of capsules in the analysis above is only sufficient for cargo in transit. The number of capsules should be increased by something like a factor of two to account for capsules being loaded and unloaded and for out of service vehicles.

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    Vol 1- *Cost and Level of Service Comparison*
    Vol 2- *Freight Pipeline Technology*
    Vol 3- *Cost Estimating Methodology*
    Vol 4- *Demand Analysis Methodology*
    Vol 5- *Impact Assessment*

U.S. Department of Transportation report numbers DOT-TST-76T-35 through DOT-TST-76T-39.

2.Zandi,I.; Warner,J.; Allen,B.; Kerrigan,J.; Younkin,C.; and Thomas,K: *Transport of Solid Commodities via Freight Pipeline;* Department of Civil and Urban Engineering, University of Pennsylvania, Philadelphia, Pennsylvania, 19174, December, 1978. (Two vols, /Two Task reports)

Vol 1- *Cost Comparison Among Various Modes of Freight Transport.*
Vol 2- *The Demand For Solid Freight Pipeline*

Task Report 1- *Noise Impact Assessment*
Task Report 2- *Intercity Transportation of Manufactured Products in Unit Trains.*

U.S. Department of Transportation Report Numbers: DOT/RSPA/DPB-50/78/35 Through dOT/RSPA/DPB-50/78/36.

3.*INTERMODAL FREIGHT TRANSPORTATION Combined Rail-Truck Service Offers Public Benefits, but Challenges Remain,* United States General Accounting Office, Report to the Committee on Public Works and Transportation, House of Representatives, Washington, D.C., December 1992. (GAO/RCED-93-16)

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APPENDIX A.

OVERVIEW OF UNDERGROUND TUBE CONSTRUCTION COSTS

CONSTRUCTION

It is assumed that substantial portions of any tube transportation system will be constructed underground. It is further assumed that those underground portions will represent a considerable part of the capital costs of such a system. Therefore a review of underground tube construction costs is presented for two general sizes of tubes, those defined as medium (six to eight feet) and large (twelve to fifteen feet) in diameter.

Medium Diameter Tubes

There are two traditional construction methods for installing six to eight foot diameter tubes below ground. These are:

- tunneling
- cut and cover, or trenching

"Cut and cover" is terminology associated with the tunneling industry, and is usually applied to excavation by open cut for relatively large size underground spaces. In practice, tubes of a diameter as small as six to eight feet would likely be installed in an open cut in the same manner as "trenching" of large size sewage pipes. Site specific conditions of geology and the length, alinement and profile of the tube system will dictate the more economical method.

Tunneling

To develop cost estimates of putting the tube underground by tunneling, a brief historical review of completed projects was undertaken. The primary reference for this effort was a massive case history study completed in 1984 by the National Academy of Sciences' U.S. National Committee on Tunneling Technology. The study "Geotechnical Site Investigations for Underground Projects" was conducted by developing a data base on 100 tunnel projects in the U.S. and Canada. It was conducted through the U.S.D.O.T. Transportation Systems Center (now the Volpe Center), and funded and technically supported by the following federal agencies:

Defense Nuclear Agency
Department of Energy
Nuclear Regulatory Commission
Urban Mass Transportation Administration

COMPARATIVE DATA FOR REPRESENTATIVE MEDIUM TUNNELS

TUNNEL PROJECT	TECHNICAL						COST			
	Purpose	Method	Dia. of excav., ft.	Length feet	Geology	Adv. Rate LF/day	Act. $ (M) Year	Act. $/L.F.	'93 $/LF (1)	Size Adj. $/LF (2)
O.M.E. YORK-DURHAM CONTRACT 85 (Toronto)	Sewage	TBM	8	8700	soft grnd.	68	3.7 1980 Can. $	$425	$805	$805 593/m^3
MMSD N.E. RELIEF CONTRACT 288 (Milwauk. Cty)	Sewage	TBM	8.8	12900	soft grnd.	35	11.9 1983	$922	$1,158	$957 705/m^3
NYDEP RED HOOK INTERCEPTOR (Brooklyn)	Sewage	Shield Comp. Air	10.5	8600	snd-grav. boulders	25	53.1 1979	$6,174	$10,498	$6,094
BUREC STILLWATER PHASE II (Utah)	Water	TBM	10.5	28600	soft rock	30 103 min/max	29.9 1983	$1,045	$1,313	$762
BUREC HADES / RHODES TUNNELS (Utah)	Water	TBM	10.7	26300	soft rock	86	27.6 1981	$1,049	$1,516	$847
WSSC BI-COUNTY TUNNEL, EAST (Maryland)	Water	TBM	12.5	18100	rock	50	20.3 1981	$1,122	$1,620	$864

PROPOSED "SUBTRANS" ESTIMATE	Freight	unknown	7.5	264000	unknown	n.a.	145 1993	$549	$549	$825

(1) Costs are adjusted for inflation using ENR Construction Cost Index

(2) For the purposes of comparison, tunnel costs ($/lf) are normalized to 8 ft. dia. by the ratios of the face areas.

Army Corps of Engineers
Bureau of Mines
Bureau of Reclamation
Geological Survey

Table 1 contains technical and cost summaries of selected case histories. The criteria for selection were:

- o The diameter should be close to six to eight feet (this eliminated most of the case history population).
- o The longest tunnels were sought, in order that the costs would most closely approximate the economies of scale of an extensive system network.
- o A variety of geologic conditions should be represented.

As indicated in the footnotes, the costs were adjusted for inflation to March, 1993, using the Engineering News-Record Construction Cost Index. This escalator reflects labor and material cost increases only. For the purposes of developing preliminary information for this study, no review has been made of the tunneling industry itself, including any productivity or efficiency gains which may have been realized in recent years. It should be noted that cost data in the tunneling industry is notoriously difficult to collect and assimilate for the purposes of comparison. Competitive pressures, proprietary information, and widely varying geologic conditions combine to frustrate quick and easy analyses.

The data presented in Table A-1 reflect as nearly as possible only those costs associated with tunnel excavation, muck removal, and concrete liner placement. Costs associated with construction of ancillary structures and facilities have been filtered out. Tunnel dimensions shown are representative of the amount of excavation for which payment was received.

As a rough approximation to establish a basis for comparison, adjustment has been made for the cost impacts of varying tunnel diameters by considering the volume of excavation and muck removal per linear foot of tunnel advance. A larger tunnel face area obviously requires a larger amount of muck excavation and removal. In fact, the ratios of the squares of the radii or diameters can be used to adjust the cost/linear foot, within a reasonable band of tunnel sizes. This has been done in Table A-1, with the assumed nominal excavation diameter of 8 feet established as a standard for comparison.

The following observations are made regarding the data:

- o With the exception of the Red Hook Interceptor Tunnel, which was relatively short and in particularly difficult geology, the projects' order-of-magnitude cost for excavation and liner installation is approximately $800 per linear foot, in 1993 dollars (based on a nominal diameter of 8 feet).

o Tunnel boring machines, or TBM's, are used in all the projects except Red Hook. This helps to explain why the costs/linear foot fall within an atypically narrow range for tunnel construction. The greater the project length, and the more uniform the geology, the more likely will TBM be the economical tunneling method.

o Although the Red Hook data appear anomalous in this presentation, in fact it is very common for tunnel costs to vary widely in the real world. The given data set reflects the fact that favorable geology is a major determinant in lower project costs.

Trenching

For the purposes of comparison and scoping of costs which might be reasonably expected in the installation of an underground tube delivery system, an analysis was made of installing relatively large diameter (8 feet) concrete sewage pipes. In reality, a tube delivery system of comparable size could be expected to be more expensive, for the following reasons:

o The tolerances and fabrication requirements for a freight tube liner would be somewhat more demanding than those for sewage pipe. Segment joints would be particularly critical for watertightness.

o The installation of a freight tube liner would require greater control of profile and alinement than is customarily the case for sewage pipe. In general, the higher the proposed speeds in the tube system, the more critical the construction tolerances become. This would require better foundation preparation in the trench to control any settlement or buoyant uplift, as well as tighter surveying controls.

Figure A-1 represents the cost of installing subsurface pipe, including trench excavation, concrete sewage pipe, placement and compaction of backfill, and removal of spoil material. The cost data were developed from the "Means Assemblies Cost Data" and "Means Heavy Construction Cost Data", and escalated to 1993 using ENR's Construction Cost Index.

All data reflect relatively favorable soil conditions amenable to the use of track mounted hydraulic backhoe at standard production rates. Depending on soil stiffness and standup time, the trench cuts vary from vertical face to a slope of 3 to 2. Also shown as a vertical line below depth of 20 feet (two and one half diameters) is the previously discussed value of $800/linear foot for comparable tunneling cost.

It can be generally stated that installing 8 foot precast concrete pipe by trenching will run on the

Cost of Subsurface Tube

8 Ft. Dia.,Trench and Tunnel

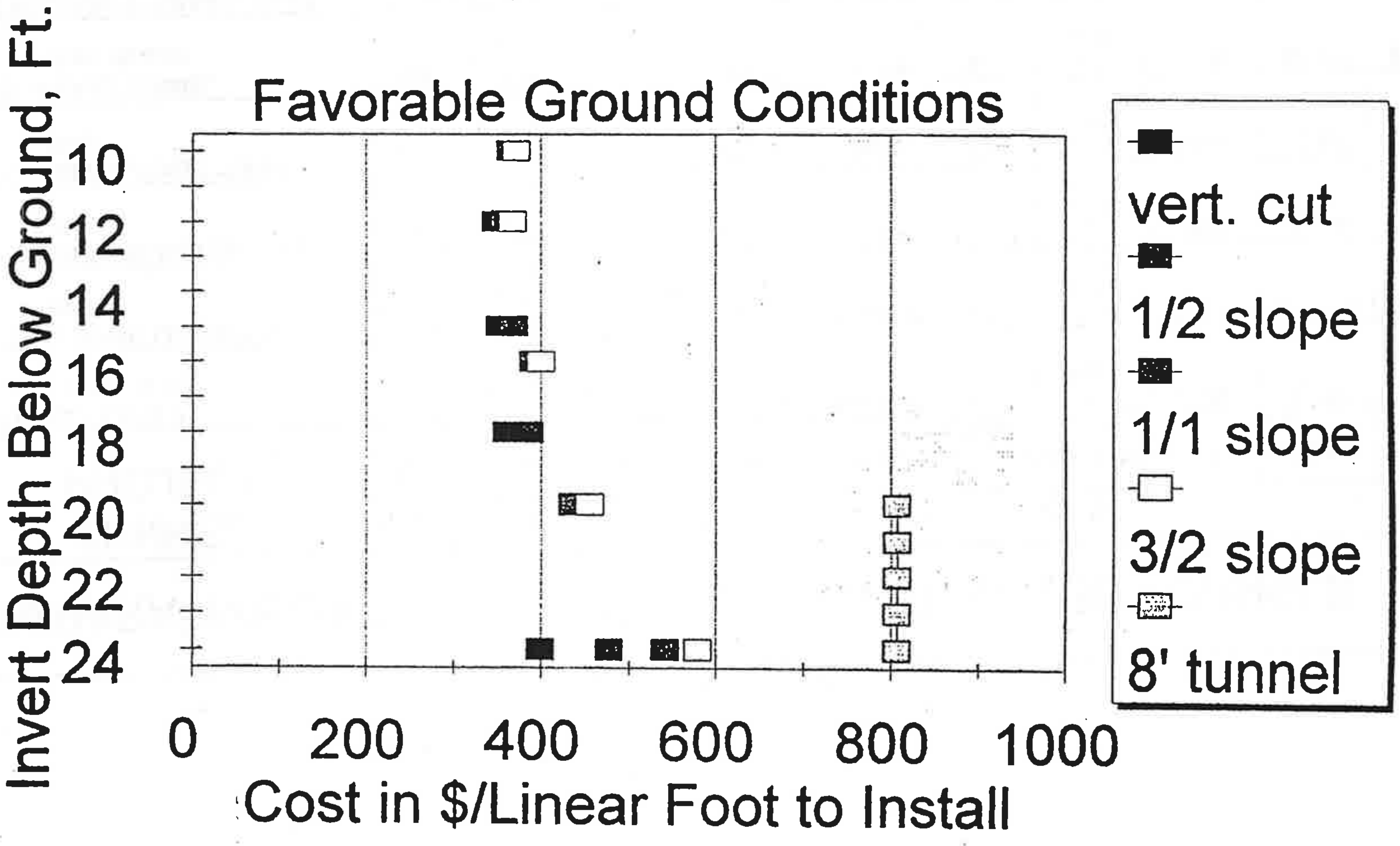

Figure A-1

$\$/m^3$ <637>

COMPARATIVE DATA FOR REPRESENTATIVE LARGE TUNNELS

TUNNEL PROJECT	TECHNICAL						COST 15' DIA			
	Purpose	Method	Dia. of excav., ft.	Length feet	Geology	Adv. Rate LF/day	Act. $ (M) Year	Act. $/L.F	'93 $/LF (1)	Size Adj. $/LF (2)
WMATA SECTION G-2 (Wash., D.C.)	Transit	Shield	20.9	13700	soft grnd.	18	23.1 1978	$1,686	$3,753	$1,933
BALT. LEXINGTON MARKET TUNNEL (MD)	Transit	Shield w/ comp air	19.1	3100	soft grnd.	24	11.8 1979	$3,806	$11,112	$6,854
COE NORTH FORK OUTLET TUNNEL (Texas)	Water	DRILL & BLAST	14	1200	rock	n.a.	1.1 1975	$917	$3,700	$4,247
CWR SAN BERNARDINO TUNNEL (CA)	Water	DRILL & BLAST	16.5	20100	rock	23	15.4 1970	$766	$2,833	$2,341
BUREC NAVAJO TUNNEL (New Mexico)	Water	TBM	13	7437	soft rock	85	3.7 1976	$498	$1,039	$1,383
WSSC BI-COUNTY TUNNEL, EAST (Maryland)	Water	TBM	12.5	18100	rock	50	20.3 1981	$1,122	$1,620	$2,333

(1) Costs are adjusted for inflation using ENR Construction Cost Index

(2) For the purposes of comparison, tunnel costs ($/lf) are normalized to 15 ft. dia. by the ratios of the face areas.

TABLE A-2

order of $400 to as much as $600 per linear foot, depending on the stiffness of generally favorable soil. As in the case of tunneling, unfavorable geology will rapidly escalate the costs.

Pipe-jacking

One of an emerging field of "trenchless technology" methods gaining wider acceptance is known as "pipe jacking". Typically applied to utilities projects, it is known to have been used successfully for installing smooth-walled fiberglass pipes of six foot inside diameter. It is primarily a "soft ground" methodology, not well-suited to dealing with boulders and rock conditions

As the name implies, sections of prefabricated pipe are hydraulically forced horizontally through the soil from jacking pits located intermittently along the pipeline route. Excavation can be accomplished manually from inside the pipe, or by remotely controlled tunnel boring machines of a wide variety, some of which mix the cuttings with a slurry and pump out the muck for disposal.

Due to the highly competitive and proprietary nature of the industry, reliable cost data are not readily available for pipe-jacking construction. The costs are reported to be greater than those for trenching, but with the advantage of significantly reducing adverse environmental impacts at the ground surface during construction.

Large Diameter Tubes

Table A-2 contains a second data set from the previously cited National Acedemy of Sciences study. It represents a broader range of geologic conditions. The costs per linear foot of tunnel, normalized to 15 foot diameter, exhibits wide scatter. From a minimum of just under $1400, to almost $7,000 per linear foot, the average cost is about $3,200, or approximately fourfold greater than the 8 foot diameter tunnels. This ratio is consistent with the "squares of the diameters" used to normalize the data. This non-rigorous analysis demonstrates the attraction of reduced capital costs associated with smaller diameter tubes.

Because cut and cover construction methods for large tunnels vary enormously with site specific conditions, no analysis of costs will be undertaken. Suffice it to say that cut and cover costs will be equal to, or less than, those for tunneling in most situations where the methodology is applicable.

INDIRECT COSTS

Up to this point, the discussion of cost data reflects only direct construction expenses. However, added to this must be the subsurface exploration, site-specific design and project management costs. Assuming that a tube technology system is eventually defined in detail, it is reasonable to estimate that an additional 15 to 20 percent of construction costs would be required, depending on the scale of the installation. A discussion of these issues follows.

Subsurface Exploration

Based on the judgement of the author, a reasonable estimate of geologic site investigation costs (soil borings and rock corings, geophysical methods of evaluation, laboratory analysis and interpretation, etc.) is approximately 2 percent of construction cost. This is on the high side of "normal" subsurface construction, but in the installation of an extensive underground tube transportation system, significant savings can be achieved by optimizing route location and construction methodology.

For example, in favorable geologic conditions, an open excavation can easily be less than one half of the cost of a bored or mined tunnel. Therefore a route constructed by open excavation theoretically can be twice as long and still be cheaper than tunneling. The only way to evaluate the most cost effective combination of route and construction method in the design process is with adequate subsurface data.

Design

Subsurface Construction

While at first glance it may appear that the design of underground tubes would be straightforward and somewhat repetitive in nature, the geologic conditions will largely define the process. Due to the extremely high cost of underground construction in unfavorable geology, the optimization of route selection and construction methodology will drive the design.

To the extent possible, problems and claims are to be anticipated and avoided through thorough and complete engineering design. In the large case history study cited earlier, "Problems and claims reported for mined tunnels" were summarized as follows:

1. "Blocky/slabby rock, overbreak, cave-ins"	38 percent
2. "Groundwater inflow"	33 percent
3. "Running ground"	27 percent

The likelihood of occurrence of these problems is quite high. Their costs in expanded scope of work and completion delays can likewise be quite high. Adequate design funding, therefore, can be viewed as a form of insurance against catastrophic setback..

System Elements

The design features for a number of necessary elements of a tube transportation system are not known to exist. For example, to optimize the system, there should be a means to remove capsules from the "mainline" for unloading, while leaving the line available for through traffic. Therefore some type of routing and switching mechanism is required. Like railroads with mainlines, secondary lines, and sidings, tube systems will need a transition device, such as a turnout, to direct capsules to distribution center "spurs" to load and offload freight. These devices will have to provide continuous operation at reasonable capsule speeds with high reliability, and presumably be largely automated.

Similarly, the operating requirements for freight terminals to support a tube freight system have yet to be defined. Vehicle/capsule costs will be greatly influenced by the mode of propulsion and suspension. The proposal to limit capsule cost by utilizing linear induction propulsion and fixed axles/wheels (i.e., no suspension) requires careful review. The propulsion system requires complete design. Capsules without suspension would be seriously damaging to the track/tube infrastructure if design speeds as high as 60 mph were contemplated.

Groundwater Effects

There will be locations where the groundwater table will be above the tunnel invert. In some cases, it may be well above the tunnel crown. This not only creates problems during construction, but also leads to water intrusion in the finished tunnel, and the subsequent need for collection and disposal. Electrical subsystems in the tunnel, such as power catenary or linear induction coils, must be protected. Shallow tunnels below high groundwater tables must also be designed to resist buoyant uplift forces.

Construction Management

As indicated above, there are numerous "unknowns" in the proposed tube technologies. Research and development is required to define a tube transportation system adequately in order that it can be designed and constructed. Assuming that such efforts are undertaken successfully, the construction management of a tube transportation system would be similar to many transportation and pipeline projects.

FUTURE TUNNELING COSTS

It is expected that tunneling costs will marginally decline in the future due to improvements in tunnel boring machines, pipe-jacking techniques and other productivity enhancements. We have not located any quantitative forecasts of tunneling costs in the recent, open literature. We do not foresee any breakthrough tunneling technologies in the immediate future which would cause a dramatic reduction in tunneling costs.