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TRANSPORTATION RESEARCH FORUM

TRANSPORT BY CAPSULES moving through a pipeline is a two-phase flow in which the fluid provides the thrust to push the load-carrying capsules through the pipeline. In order to develop the thrust on the capsule, the capsule should be unstreamlined and should present a low frictional resistance to movement. In a pneumatic system, these requirements are met by a wheeled vehicle which is nearly as large in cross section as the inside of the pipe resulting in a capsule that rolls through the conduit like a loose-fitting piston in a cylinder. Figure 1 is a photograph of one of

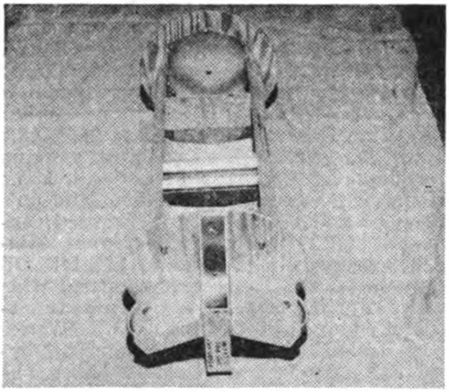

FIGURE 1

the test vehicles being studied in the 16-in-diameter, 1630-ft-long, steel pipeline loop at the Houston Test Facility of Tubexpress Systems, Inc. Because of the limited clearance between the vehicle and pipe wall a small flow of air will leak by the capsule with the result that the capsule velocity, U, will tend to be slightly less than the air velocity, V. Figure 2 is a sketch of the pressure line within the pipeline showing the pressure drop across each capsule. The total pressure decrease will be the sum of the pressure drops across the capsules in the line plus the pressure decrease required to push the air through the pipeline. Pumps can be end-of-the-line pumps located at either end or can be booster pumps located intermediate between the loading and unloading stations. Because standard pumping equipment is designed to pump only the air-phase of the two-phase flow, special pumps are required to handle the flow of both air and solid capsules.

Capsule pipelining through pneumatic tubes is an established technology. The inception is traced to Denis Papin, a French physicist, who presented a paper describing a vacuum capsule-transport system to the Royal Society of London in 1667 [3]. (*Numbers in [ ] correspond to the numbered entries in Appendix-References.) The earliest systems appeared in the first half of the 19th century. Split spherical capsules were used in the earliest systems to carry messages within the hollow balls with the sender providing the motivating thrust by means of a bellows. With the appearance of better pumping equipment in the latter half of the 19th century, the use of capsule pipelines for transporting documents became widespread and remains so today in sprawling complexes such as hospitals and air terminals. Aside from science fiction and Beach's aborted pneumatic underground railway completed in 1870 [2], the use of the pneumatic capsule pipeline has been limited to transportation of documents.

RECENT DEVELOPMENTS

About six years ago, the first writer began studying the pneumatic capsule pipeline as a potential alternative (with

PRESSURE DROP ACROSS A CAPSULE

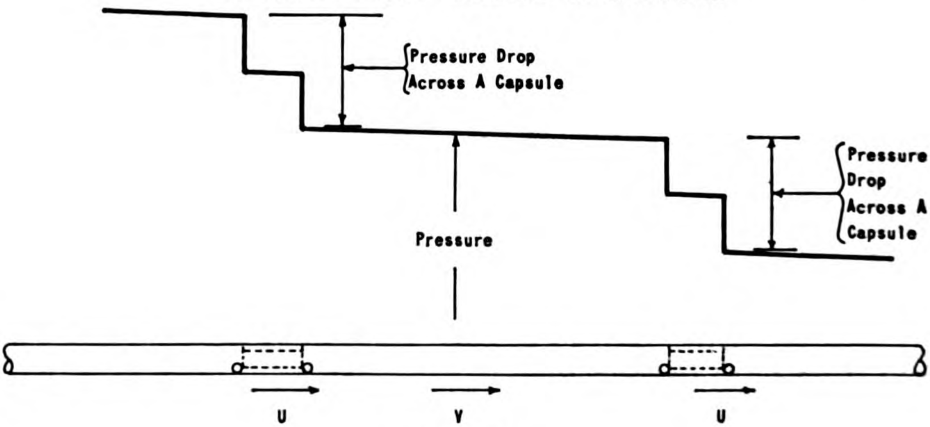

FIGURE 2

Pneumatic Capsule Pipeline

by M. R. Carstens and B. E. Freeze***

inherent ecological advantages) to existing modes of transport such as railway, truck, and conveyor belts. Aided by students and hindered by the lack of funds, progress in developing the pneumatic capsule pipeline was amazingly rapid. In 1970 responsibility for further development and marketing of the system was assumed by a well-known firm, a natural-gas transmission company, who formed a subsidiary company, Tubexpress Systems, Inc., to execute the responsibility.

The goal of the development program has been to decrease the energy intensiveness of the pneumatic capsule pipeline without sacrificing the ecological advantages associated with buried pipelines and stationary pumping stations. The main subdivision of the program is into analytical development and hardware development.

Development of mathematical models for pneumatic capsule pipelines is essential for design and efficient operation. Since pumps, moving air, and moving capsules all interact and since no two installations will be alike, physical modelling of systems is precluded. Rational mathematical models based upon Newton's second law and the first law of thermodynamics have been developed which are considered quite satisfactory for design and analysis. Two independent variables, the coefficient of rolling resistance and the coefficient of drag of the vehicle, must be determined experimentally. Both of these empirically determined coefficients can be measured at the Houston Test Facility.

Hardware development has been concentrated into development of specialized pumps and of lightweight capsules, Figure 1. Four different pumps have been developed, two types of booster pumps for use along the pipeline and two types of end-of-the-line pumps, each designed to pump both air and capsules without damaging the vehicles. The vehicle-development program is directed toward minimizing dead load, rolling resistance, and cost.

OPERATING CHARACTERISTICS

A study of the operating character-

PRESSURE DROP IN CAPSULE PIPELINE

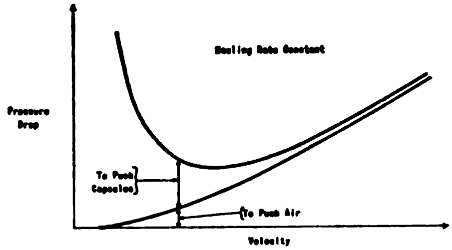

FIGURE 3

istics reveals that pneumatic capsule pipelines are similar to all other pipelines in that pipelines are best suited for slow-speed transport of large quantities at a steady sustained rate. Two products which appear to be best suited for transport by pneumatic capsule pipelines are compacted solid waste and ore.

Operating characteristics can be visualized by studying the pressure drop, Figure 3, and power input, Figure 4, as a function of velocity for a given hauling rate. The pressure drop along the pipeline, Figure 3, is the sum of the pressure drop to push air and of the pressure drop to push capsules. The pressure drop to push air is proportional to velocity squared. The pressure drop required to push capsules is inversely proportional to the velocity. In order to maintain a constant hauling rate the capsule-injection rate must also be constant. Hence the number of capsules in transit in the pipeline is inversely proportional to the velocity. The power input to the pipeline,

POWER INPUT

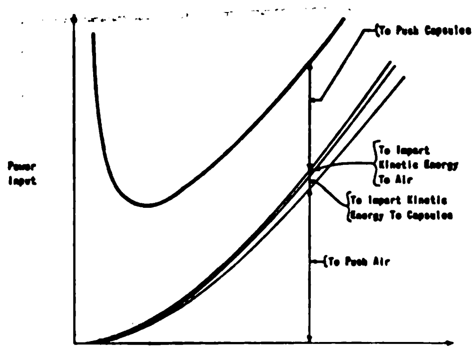

FIGURE 4

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Figure 4, is the sum of power to push the air, power to impart kinetic energy to the capsules, power to impart kinetic energy to the air, and power to push vehicles. The first three components of power input are proportional to the velocity cubed as shown in Figure 4. The power input to push capsules approaches a large value as the air velocity V is decreased to the relative velocity, V-U, between air and capsule and approaches a constant assymptote as the velocity is increased. The constant assymptote is proportional to the product of the length of pipeline, the capsule-injection rate, and the pressure drop across a capsule. The sum of the four parts or total power input has a minimum at a low velocity. Because only that part of the power to push capsules, Figure 4, is useful transport power the other three parts of the power input should be a small percentage of the total. Thus efficient operation of a pneumatic capsule pipeline is restricted to low velocities somewhere in the range from 15 to 35 feet per second.

Air columns between successive vehicles act as elastic connectors between vehicles thereby providing a mechanism for transferring potential energy from capsules rolling downhill to capsules which are rolling uphill. Because the thrust to push each capsule is by means of the pressure force and because pressure adjustments occur rapidly (a pressure wave travels at about 1100 feet per second in air at atmospheric pressure and temperature), pressure changes at any cross section in the pipeline are rapidly transmitted throughout the system. In a pneumatic capsule pipeline which crosses a mountain ridge, capsules descending from the summit may act as a piston pump to aid the system in pushing capsules up to the summit as shown in Figure 5. The descending capsule on the right of Figure 5 is rolling downhill slightly faster than the air velocity so that the air-drag force, pressure force, automatically reverses direction thereby braking the descending capsule from attaining excessive speed and giving the effect of a piston pump to aid the remainder of the system. The features of being able to utilize the stored potential energy is an inherent feature of pneumatic capsule pipelines, conveyor belts, and electrified railways with regenerative braking. On the other hand, stored potential energy is largely wasted in descent by mechanical braking with railroad trains powered by diesel-electric engines and with motor trucks.

The air-column separators, Figure 2 and Figure 5, between successive capsules are an inherent safety feature of pneumatic capsule pipelines which preclude damaging rear-end collisions. If a heavily loaded capsule is followed by an empty capsule, the empty capsule will gradually overtake the loaded capsule and gently form an uncoupled train with further movement proceeding as a train. Even the worst happening in a pneumatic capsule pipeline, the jamming of a capsule within the pipeline, does not result in damaging collisions because the jammed vehicle acts as a nearly closed valve thereby restricting the flow of air and stopping the remainder of the vehicles.

The same driving force, pressure force, which is used to propel the capsule along the pipeline can be utilized to decelerate the moving capsule to a stop at the terminal. By directing the moving capsule into a dead-end section of the pipe,

POTENTIAL-ENERGY INTERCHANGE

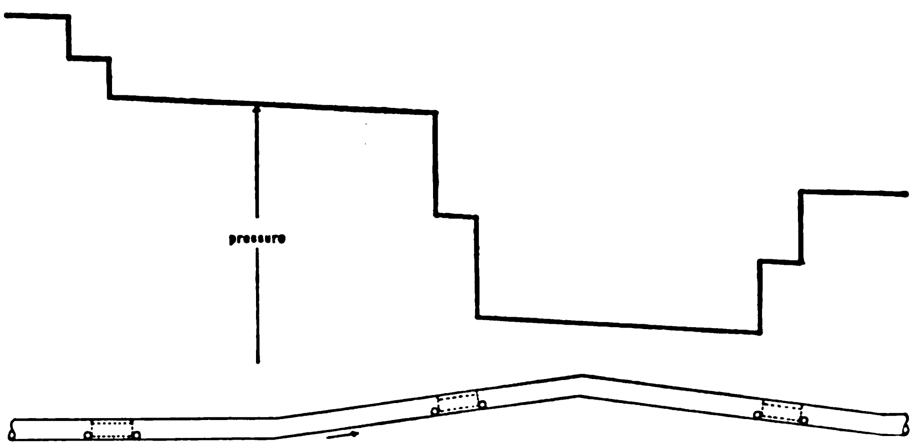

FIGURE 5

the pressure force against the loose-fitting piston moving into a closed cylinder acts as an external, non-mechanical braking system which is inexpensive, simple and reliable.

Because the thrust to push the vehicles is applied externally to the capsules by the pressure force, the slope of the pipeline can be as steep as desired. In contrast, slopes of railways and highways are limited by the thrust that can be developed between the drive wheels and road bed. Slopes of conveyor belts are limited to the angle at which the cargo will slide or roll. If intermediate bulkheads are incorporated into the capsules, spillage of cargo on steep slopes can be precluded.

EFFICIENCY

The relative efficiency between different modes of freight transport is measured by an inverse efficiency called energy intensiveness. A common unit of energy intensiveness is Btu/ton-mile in which the numerator is the rate of chemical energy input of the fossil fuel and the denominator is the live-load hauling rate. Except for the value listed for Tubexpress, the values of energy intensiveness tabulated below are those derived by Hirst [1].

Mode	Energy Intensiveness (Btu/ton-mile)
Pipeline	450
Waterway	540
Railroad	680
Tubexpress	1800
Truck	2300
Airplane	37000

The value of energy intensiveness for Tubexpress listed in the table was calculated for a 20-in.-diameter, 3.3-mile-long, ore-hauling system to transport 1 million tons of ore per year. The assumption was made that the compressors would be powered with electric motors and that 32 per cent of the chemical energy input to the electrical generating plant would be delivered as electrical energy to the pump stations of the pneumatic capsule pipeline. Power required to return the empty capsules from the unloading terminal to the loading terminal was included but the power required for the ancillary equipment to load and unload the capsules was not.

Excluding air transport and excluding changes in potential energy, the energy required to move cargo from origin to terminus is the product of the weight, a coefficient of friction, and the map length of travel. The weight is the total weight, that is, dead load of the vehicle plus the live load. Movement of the dead load of the carrier is a necessary but wasteful burden which must be borne by all transport modes except single-phase, fluid pipelines. The ratio of live load to total load of nearly 80 per cent for ore-carrying steel railroad cars as compared to 60 per cent for motor trucks accounts for part of the differences in the energy intensiveness of these two transport modes. However, the major advantage of railroads over trucks in a comparison of energy intensiveness is the superiority of the large steel wheel rolling on a steel rail which results in a very low value for the coefficient of friction. Even though steel-tired wheels can be used on capsules rolling through a steel pipeline, the coefficient of friction will be larger than for the railroad wheel because of the difference in wheel diameter but will be smaller than for pneumatic-tired wheels of trucks. The third element in the energy required is the length of travel. Obviously a straight line between origin and terminus is the shortest length but in mountainous terrain, the railroads and highways are limited as to grade. For example, if the terminus were 1000 feet higher in elevation than the origin, the map length at a 3 per cent slope would be 6.7 times the map length at a 20 per cent slope. The combination of potentially shorter travel lengths, the decreased necessity for extensive cut-and-fill or tunnels, and the inherent property of transferring the stored potential energy of descending capsules to the system is suggestive that pneumatic capsule pipelines could be the most economical mode of transport of ore in mountainous areas.

COST

As stated earlier in the paper, Tubexpress systems are custom designed as are most transportation systems for a specific application. Therefore, general system economics indicated below should be applied carefully. A computer program has been developed for use in preparing preliminary engineering cost estimates.

Output data from this program has been used to develop a series of average cost and horsepower curves. Figure 6 is the curve developed for material with a 50#/ft.^{3} density.

These curves can be used in the following manner. Enter the curve with a known hourly hauling rate and read vertically to the cost curve. Read to the right for the cost per ton-mile. Go back to the hauling rate and read vertically to the pipe size curve. The pipe size shown to the left of the point on the curve is the required size of pipe. Read to the left for the required horsepower per mile of pipeline. An example is shown in Figure 6.

Tubexpress systems are comparable to other types of pipelines in that they are

HORSEPOWER AND TRANSPORTATION COST

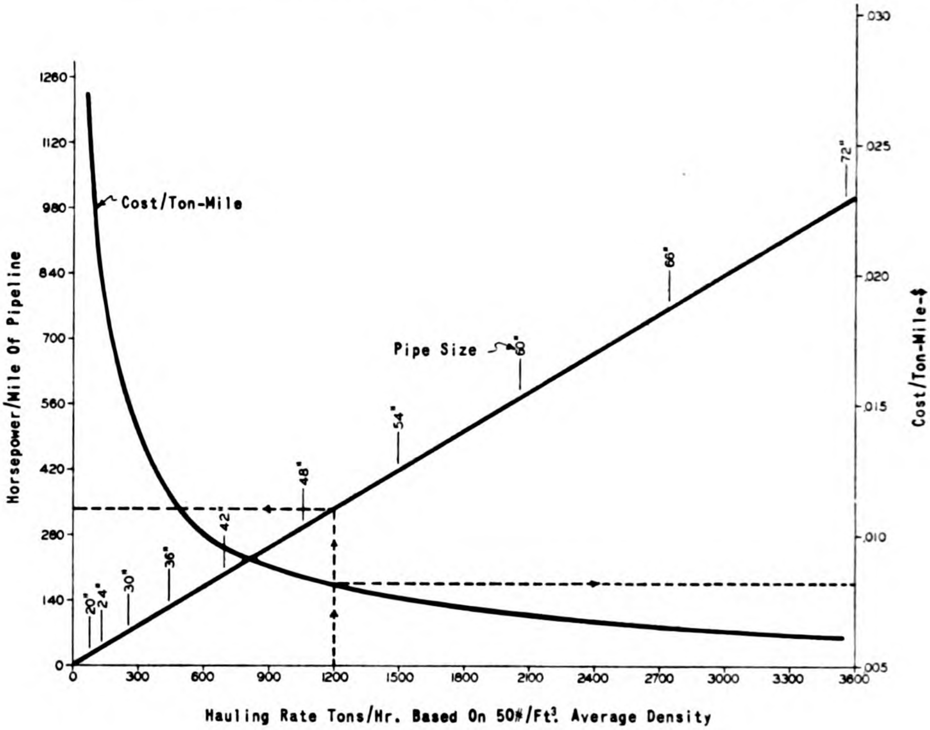

FIGURE 6

capital intense systems, but they also have the desirable pipeline characteristics of low operating and maintenance costs. The cost of the pipe including coating and installation accounts for approximately 65% of the capital cost of a Tubexpress system. But like other pipelines, this system too has a long service life and the capital costs can be amortized over a much longer period than other modes of transportation.

ADVANTAGES

Ecological—Buried pneumatic capsule pipelines with stationary compressor stations powered by electric motors would nearly eliminate noise, air, and visual pollution associated with other modes of transport. The ecological superiority of pipeline transport is demonstrated by the innocuousness of the water, natural gas, and liquid-waste pipeline systems which perform the transport function unnoticed in close proximity to people. Because of the unobtrusiveness of buried pipelines, pneumatic capsule pipelines could serve to transport compacted solid wastes from collection stations to recycling plants in metropolitan areas, thereby relieving some of the congestion on the streets.

Labor saving—Inasmuch as pneumatic capsule pipelines will probably be devoted to handling a single product, the operations of loading, unloading, switching, stopping, and release of capsules will be repetitive which can be automated and will be concentrated at the terminals. In addition, the operations can be sequenced by local feedback control without the necessity for centralized computer control. Figure 7 is a photograph of the automatic loading station for a 6-capsule train at the Houston Test Facility.

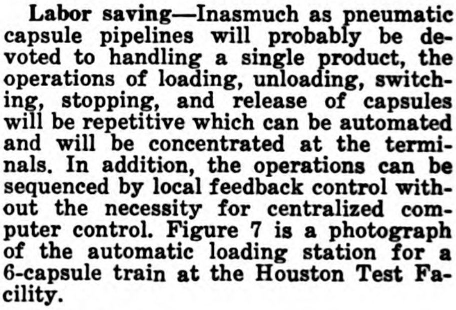

FIGURE 7

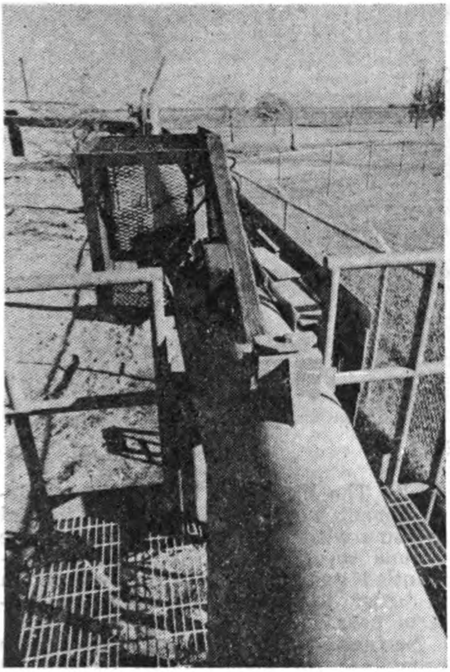

FIGURE 8

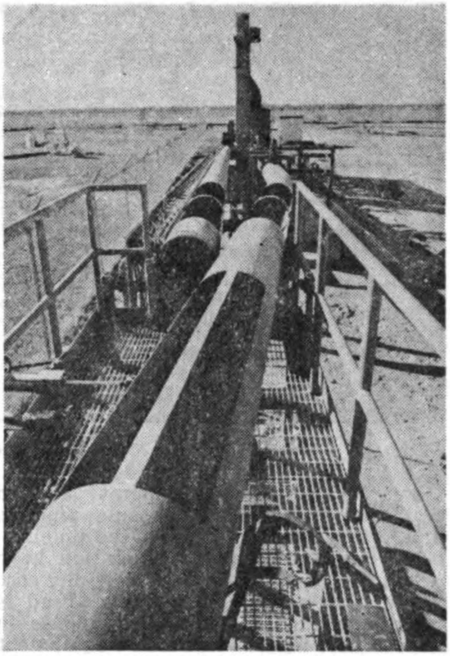

FIGURE 9

Safe.—The buried pneumatic capsule pipeline avoids the possibility of external accidents. All safety measures will be concentrated at the terminals and pump stations which will be directly supervised by the transportation company. Rupture of the pipeline by a careless excavation contractor will be frustrating but not hazardous since the fluid is air. These inherent safety features and the inherent internal safety features described above in Operating Characteristics make pneumatic capsule pipelines the safest of the transport modes to carry solid cargo.

Weatherproof.—Operation of a pneumatic capsule pipeline is independent of the weather except for storm conditions which result in a power outage to the pump stations.

Energy intensive.—In mountainous terrain, pneumatic capsule pipelines appear to require a lesser energy input than railroads and trucks because the absence of slope limitation in a pneumatic capsule pipeline can result in a significant decrease in length and because the potential energy of descending capsules is automatically transferred throughout the system. Even over a level route, the energy intensiveness is better than truck transport. Considering that the use of pneumatic capsule pipelines for freight movement is a developing technology, further decreases in the energy intensiveness can be expected.

Identifiable costs.—Because the cost of

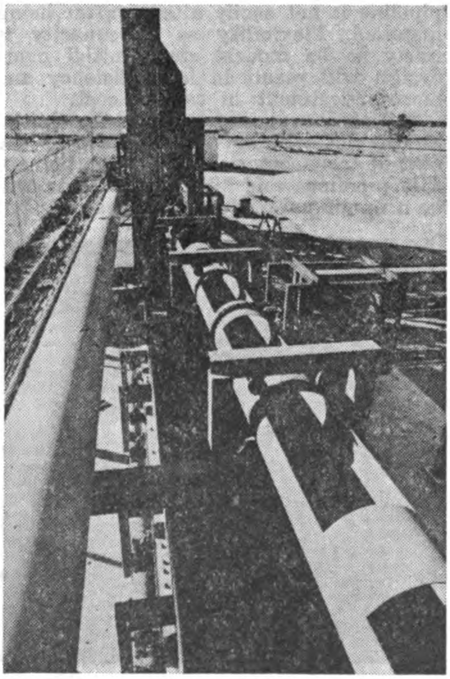

FIGURE 10

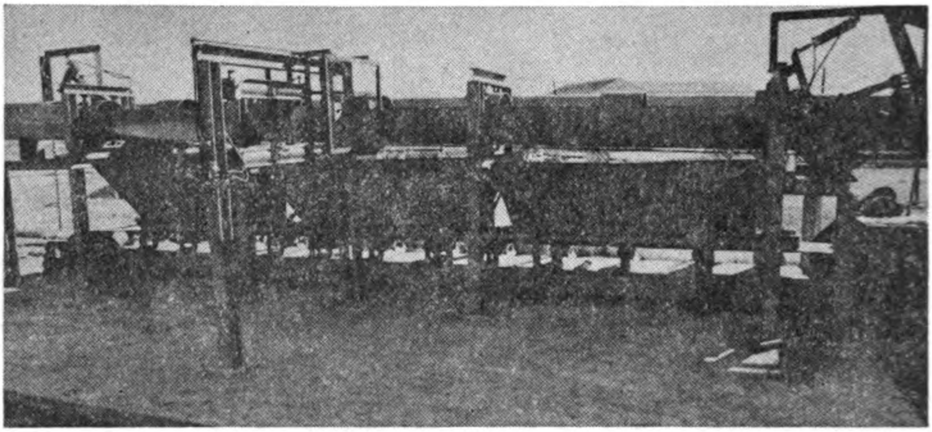

FIGURE 11

labor will be small to operate and to maintain a pneumatic capsule pipeline and because the major cost, the pipeline, is an initial investment which will have a long service life, projection of the cost of transportation in the years ahead is more accurate than for other modes in which the major items of equipment have a shorter service life and in which labor costs are a significant portion of the total cost.

DISADVANTAGES

Flexibility. — A pneumatic capsule pipeline is not easily altered after being installed. Flexibility as to capacity is likely to be modest since initial over-design will result in less efficiency and more investment in capital cost.

Initial investment.—Since the initial investment will be a large part of the cost of transportation by pneumatic capsule pipelines and since labor costs will be a minor part, short-term usage is unlikely. The likelihood is that future development work will be directed toward systems with the pipeline placed on the ground so that the system can be dismantled and rebuilt at a new location in order to accommodate the limited-term user.

Newness.—There is an understandable reluctance for managers to recommend investment in a transport system without a history of commercial usage. For this reason Tubexpress Systems, Inc. constructed the Houston Test Facility using 16-in.-diameter steel pipe whereas a test facility using 6-in.-diameter steel pipe would have served for testing at a considerably lower cost. The 16-in.-diameter pipeline is at the lower limit in size of the pneumatic capsule pipelines for ore or solid-waste movement but is large enough to demonstrate all of the components in operation. Figures 8-13 are a series of photographs showing the section of the test facility from just up-

FIGURE 12

stream of the first switch tube to just downstream of the automatic loading area. No photographs are included of the pump unit due to the proprietary nature of this component. The authors invite you to visit the Houston Test Facility. Arrangement for a visit and demonstration can be made by contacting the second author.

APPENDIX-REFERENCES

[1] Hirst, Eric, "Energy Intensiveness of Transportation," *Proc. Am. Soc. of Civil Engineers*, TE 1, Paper 9558, Feb. 1973, p. 111.

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[3] Vivian, C. H., "Early Pneumatic Tubes," *Compressed Air*, Vol. 77, No. 1, Jan. 1972, p. 8.

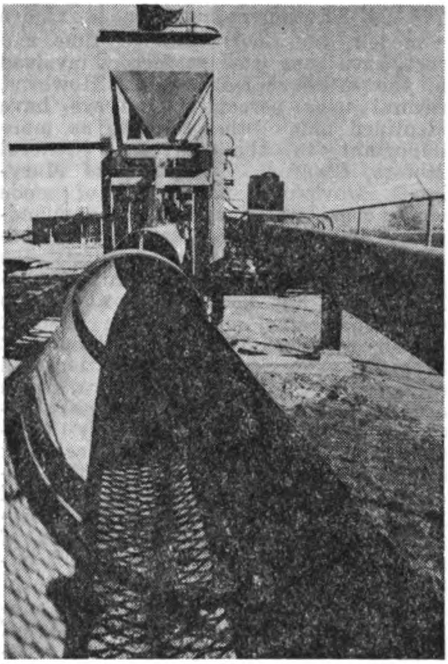

FIGURE 13