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SYSTEMS, SCIENCE AND SOFTWARE

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Revision 0

PROSPECTS FOR ENERGY CONSERVATION
IN THE
PIPELINE INDUSTRY

by

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Technical Report - Tasks 4 and 5
Contract EY-76-C-03-1171

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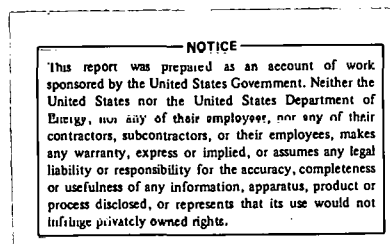
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Abstract

A qualitative projection (the "baseline scenario")
is made of the pipeline industry growth to the year
2000. This projection is based on the conventional
wisdom of the industry. It is concluded that, to
achieve significant growth, the industry must develop
the capability, called freight pipeline, to move
other commodities than oil and gas, i.e., bulk and
packaged goods. Technical and economic performance
criteria are identified which, if met by the freight
pipeline capability, could induce modal shifts result-
ing in a reduction of total transportation energy
consumption, and would offer other benefits, including
compatibility with high-speed rail passenger service.

1.0 INTRODUCTION

1.1 Objectives

1.1.1 Purpose of the Project

The work reported here is a part of a project which is being conducted by the team of Systems, Science and Software (S^3) and Pipe Line Technologists, Inc. (Pipetech) of Houston, under DoE contract EY-76-C-03-1171, "Energy Study of Pipeline Transportation Systems." The basic purpose of the project is to assess the susceptibility of the oil, gas, and other pipeline industries to energy-conservative technological innovations, and to identify the necessary research, development, and demonstrations (R,D,&D) to exploit those opportunities.

The project final report is being published as S^3 report SSS-R-77-3020, "An Energy Study of Pipeline Transportation Systems." That final report will be a summary, combining the results from the seven task reports listed in Table 1.1-1. As will be noted from the table, this present report is one of those task reports.

1.1.2 Purpose of this Report

This report presents the results of Task 4, an assessment of the future of the industry, and of Task 5, a brief review of the technology of freight pipelines.

1.2 Method of Approach

The discussion begins with a qualitative projection of industry growth based on the conventional wisdom of the industry, and is termed the "baseline scenario." This projection shows that the pipeline industry, if it follows present trends, will not be a growth industry. To achieve significant growth, the industry must expand into new markets. That is, pipelines must be developed, built, and operated to transport other commodities than oil and gas. Such systems are hereafter referred to as freight pipelines.

TABLE 1.1-1

Project Reports

SSS-R-77-	Title	Associated Tasks
3020	An Energy Study of Pipeline Transportation Systems - Executive Summary	All
302	An Economic Model of Pipeline Transportation Systems	1 (partial)
3022	Energy Consumption in the Pipeline Industry	1
3023	Slurry Pipelines - Economic and Political Issues - A Review	2.1
3024	Federal Regulation of the Pipeline Industry	2.2
3025	Efficiency Improvements in Pipeline Transportation Systems	3
3027	Prospects for Energy Conservation in the Pipeline Industry	4,5
3069	S^3 Financial Projection Model - Preliminary User's Manual and System Overview	1 (partial)

Three basic questions then arise, all of which may be phrased in terms of feasibility. Are freight pipelines, on any significant scale,

- economically feasible?
- technically feasible?
- politically feasible?

These questions are addressed in this order because, until the possibility of an affirmative answer to the question of economic feasibility is seen, there is little point in pursuing the others in any depth.

The approach just described is somewhat unconventional. The more customary approach is to postulate a business-as-usual scenario as the baseline, then examine perturbations on that scenario, i.e., to explore the indicated effects of scenarios which embody more or less governmental action than the baseline. The present approach is preferred in this case, however, because it is believed to be both simpler and more realistic.

The conventional wisdom perceives quite well what the government is attempting to accomplish, and reflects a realistic composite assessment of how successful those efforts will be. The only way to outsmart the conventional wisdom is to introduce a totally unconventional factor, as will be done in Section 5.0 below. This of course is exactly the proper role for the DoE, i.e., to support the research, development, and demonstration which is necessary to enable the industry to grow in new directions which serve the national interest, but which would be very unlikely without such support.

2.0 Summary

The consensus of industry opinion is that, over the
rest of the 21st Century, the amounts of oil and gas produced in
the United States will decline, while demand continues to increase.
In both cases, some of the shortfall will be offset by imports and
a small amount of synthetics, so that the total amount of oil and
gas delivered to customers will not decline and will probably in-
crease somewhat.

The consequence of this scenario for the pipeline industry
is that total ton-miles of traffic will increase only slightly,
but total miles of operating system will continue to increase
more strongly because for a while at least, old lines will be re-
tired from service at a slower rate than new lines are brought
into service. Later, as fewer new discoveries are made and old
sources deplete, retirements will exceed new additions, and the
trend will reverse. Thus, for a number of years yet, moderate
growth will continue, but at a declining rate of increase. There
is no booming expansion in the future of the pipeline industry,
unless some completely new applications can be found, i.e., unless
ways can be found to move other commodities than oil and gas.

When one reflects on the strong and attractive advantages of
pipeline transport, it is easy to become wistful. Pipelines
generally are much the cheapest, quietest, least obtrusive, safest,
and most reliable mode of freight transport. The compensating
offsets are that they are also the slowest, and they can only,
within the limits of today's applications, move fluids and a few
powdered solids. If a way could be found to enable them to move
other commodities and packaged freight, at moderately faster speeds,
then the advantages enumerated above would seem to portend a large
expansion of the pipeline industry.

It is concluded that such pipelines, referred to here as
freight pipelines, are most likely to materialize in two forms:

slurry pipelines and capsule pipelines. As is discussed in depth
in Report R-3023 of this series (see Table 1.1-1 above) the pres-
sures for slurry pipelines are developing and the battle lines
are drawn; hence they are not treated in this report. Capsule
pipelines, on the other hand, may possess even more promising
potential, but there is little likelihood that comparable pres-
sures for them will develop without a DoE-sponsored program of
research, development and demonstration. Further study of the
concept is strongly recommended.

3.0 RECOMMENDATIONS

In this brief analysis, it was not possible to perform quantitative performance comparisons or systems studies of the various concepts for freight pipelines and accordingly, such analysis was not attempted. Instead, an attempt was made, by an examination of all modes of freight transport and of the effects of modal shifts between them, to identify the general performance envelope into which they must fall if they are to be economically competitive. This analysis indicated that system technical performance objectives should include:

1 - Capability to accommodate both packaged freight of medium size and bulk commodities;

2 - An average speed of 20 mph or more;

3 - Capability to ascend and descend steep grades;

4 - Capability of high throughput.

Requirement 1 calls for a capsule system. Requirements 2 and 3 determine capsule separation. Requirement 4 is determined by the economic analysis.

These requirements are in some ways contradictory. For example, requirement 3 calls for wide capsule spacing and limited speed, in contradiction to requirements 1, 3 and 4. Further study is required to examine these and other tradeoffs, and to identify a concept for analysis and possibly for an R,D,&D program.

In Report R-3025 of this series (see Table 1.1-1 above), the broad outlines were presented of the programs of research, development, and demonstration which are needed to realize the energy-conservative potential of the technological innovations that were discussed in that report. In each case, the recommended program consists of the six phases described below:

Phase 1 - Identification of the Opportunity

This phase has been in progress under the present study, and with the publication of this report is now complete.

Phase 2 - Concept Validation

In this phase the concept is validated analytically and a definitive program plan developed.

Phase 3 - Research and Development

The research and development identified under Phase 2 is performed in accordance with the approved R&D plan. The R&D program continues through the design phase (Phase 4) and possibly beyond.

Phase 4 - System Design

A preliminary design is prepared of the demonstrator system on the selected site.

Subphase 4.1 - Site Selection - Several candidate sites are identified and the one best meeting the criteria developed under Phase 2 is selected.

Subphase 4.2 - Preliminary Design - A preliminary design is prepared of the demonstrator system on the selected site.

Subphase 4.3 - Detailed Design - The detailed design of the demonstrator, consisting of drawings and specifications suitable for use in construction, is prepared and documented, along with supporting design analyses. This subphase is paced by the progress of the research and development under Phase 3 above, which will have been proceeding concurrently with Phase 4.

Phase 5 - Demonstrator Construction

The demonstrator system is constructed. Data regarding construction costs, design feedback, and technological difficulties are collected, analyzed, and published in accordance with the program plan which was developed under Phase 2.

Phase 6 - Demonstrator Operation

The demonstrator system is operated in accordance with the program plan. Data regarding the operation is collected, analyzed, and published in accordance with the program plan.

The generic schedule for phase 2 of this program is presented in Fig. 3.0-1. It is strongly recommended that this next phase be implemented. If available resources cannot support the entire Phase 2 immediately, then at the very least, Subphase 1, opportunity confirmation, and a preliminary Subphase 5, Program Definition, should be performed.

Months Subphases	1	2	3	4	5	6	7	8	9	10	11	12

1 - Opportunity Confirmation
  Update Phase 1 analyses △
  Laboratory experimentation △
  selection of development △ model/site
  Conceptual designs △
  Market identification △

2 - System Assessments
  Technical feasibility △
  Economics △
  Operational dependability △
  Environmental impact △
  Demographic impact △

3 - Supporting Studies and Assessments
  Existing studies review △
  Alternate A △
  Alternate B △
  Alternate C △

4 - Experimental Program Plan
  Update and modify Task 1 results △
  Prepare test program plan △

5 - Program Definition
  Program criteria △
  Total program plan △
  Final report △

Figure 3.0-1 Generic Phase 2 Schedule

## 4.0 THE CONVENTIONAL SCENARIO

In speculating about the future, it is useful to have
a reference (baseline) case against which to make comparisons.
For present purposes, it is convenient to take as the reference
case a projection of the pipeline and petroleum industry future
as the industry leaders would expect it to unfold. This pro-
jection may be inferred from the collection of papers contained
in the Oil and Gas Journal's special commemorative issue,
"Petroleum/2000" of August 1977. Virtually all of these
authors are experienced engineers in the pipeline industry and
now hold senior management positions. Their collective judge-
ment may therefore be regarded as the conventional wisdom.

The future of gas pipelines is discussed by Bowen [1977],
who predicts that "... natural gas will supply about the same
volume of energy in the year 2000 as it does today. Its per-
centage of the whole, however, will be considerably less (Fig.
1)." Figure 4.0-1, which is Bowen's Fig. 1, shows his projec-
tion of energy supply, while Fig. 4.0-2 shows his projection
of gaseous fuel consumption.

Bowen's discussion relates only to natural gas. Privately,
many people in the gas pipeline industry refer to their industry
as a dying one. The American Gas Association (AGA) vocifer-
ously denies the validity of this characterization and adduces
evidence to support its position that "the gas industry is taking
action and is encouraging appropriate supporting government
action to assure that gaseous fuel will be available in signifi-
cant amounts well into the future" [Gibeaut 76]. The AGA pro-
jection is shown in Table 4.0-1 [Lawrence 77]. Of course, a
great deal more can be said about gas supply and consumption
in the future. The AGA's Gas Supply Committee maintains a
continuing overview of the subject and publishes a monthly Gas

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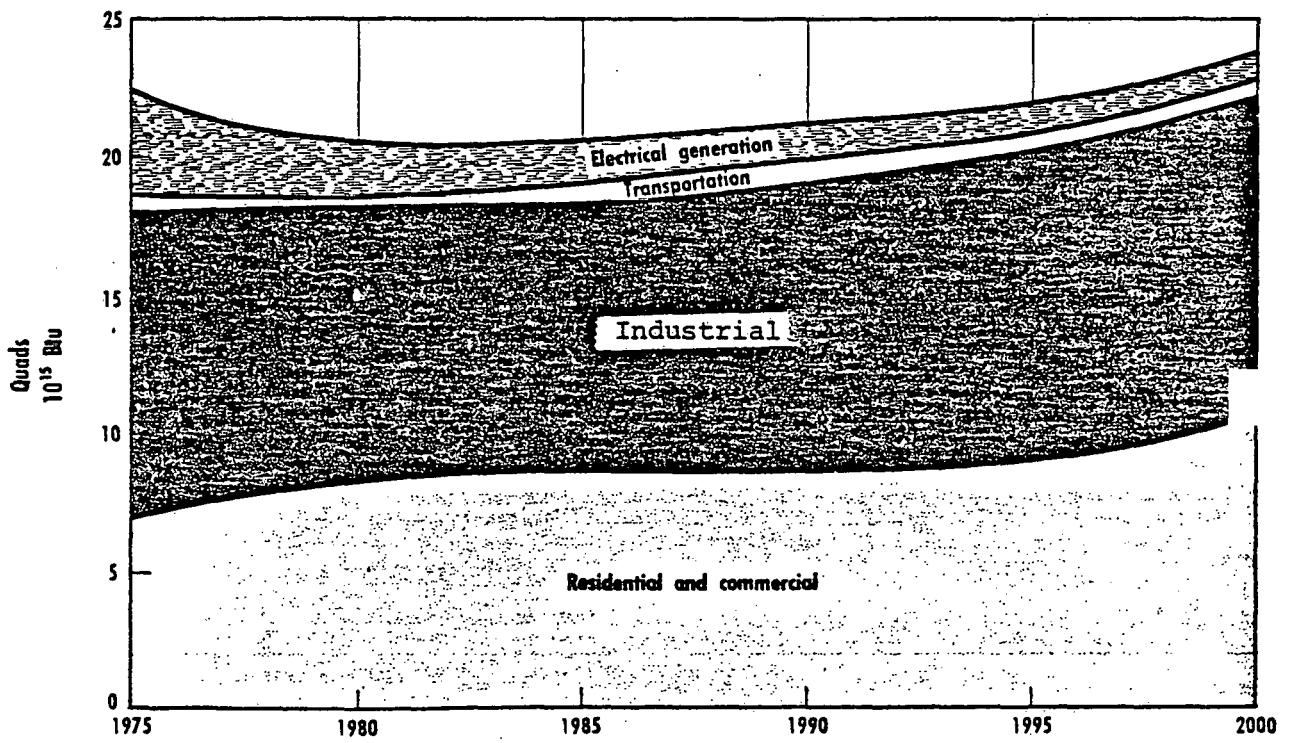
Source: Oil and Gas Journal (Bowen 77)

Fig. 4.0-2 - Energy consumption projection

TABLE 4.0

AGA Projection of gas production under full deregulation
(10^{12} Scf/hr)

|	1976	1980	1985	1990	1995	2000
Conventional supplies (lower 48)	19.5	19.6	20.0	20.1	19.0	18.0
Supplemental supplies	1.2	2.5	5.5	8.1	11.1	14.0
Total production	20.7	22.1	25.5	28.2	30.1	32.0

Source: Oil and Gas Journal (Lawrence 77)

Supply Review. It is important to note that, while the Association takes umbrage at the suggestion that its industry is dying, even the projection of Table 4.0-1, which is optimistic in that it assumes full and immediate deregulation, assumes only a very moderate (1.8%) annual growth.

From the foregoing and other available information, it is a conclusion of this study that the position of the Association is essentially sound. The American public will demand a continued supply of pipeline-quality gaseous fuel, and they will get it. The inevitable price increases to reflect the true economic cost of alternate gas supplies will occur and will result in an influx of synthetic gas. At the same time, however, there will be no significant overall industry growth in terms of total sales.

In the case of oil, a similar conclusion emerges. Figure 4.0-3 shows the projection of Granville [77] for U.S. crude production, and Fig. 4.0-4 shows his projection for supply and demand. The shortfall, beginning in 1985-1990, is also expected by Warner [77].

Now the fact that no significant growth in oil and gas production is projected does not mean that no pipelines will be built. All of these projections assume that new fields will be brought into production, and new pipelines will therefore be required. At the same time, however, traffic over many existing lines will diminish, as has in fact already occurred in many cases. Wacker [77] foresees that domestic crude pipeline construction will continue, but at a modest rate of about 1500-2000 miles/year. In discussing the future of products pipelines, Jones [77] projects a growth in refinery output of 2.6% per year. Thus it seems unlikely that large amounts of new products pipeline mileage will be built, certainly not if the nation is successful in limiting total consumption and oil imports.
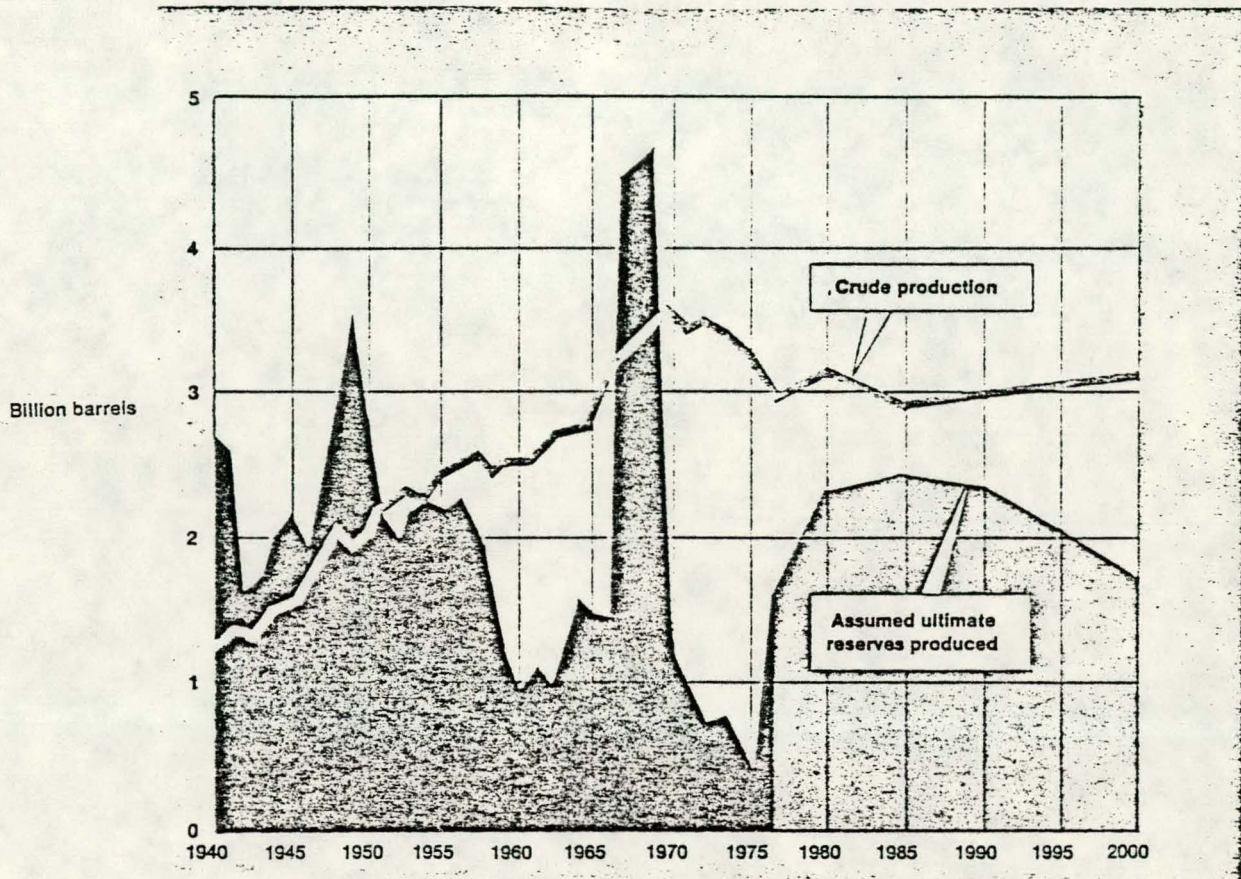
Source: Oil and Gas Journal (Granville 77)

Fig. 4.0-3 - U.S. Crude production
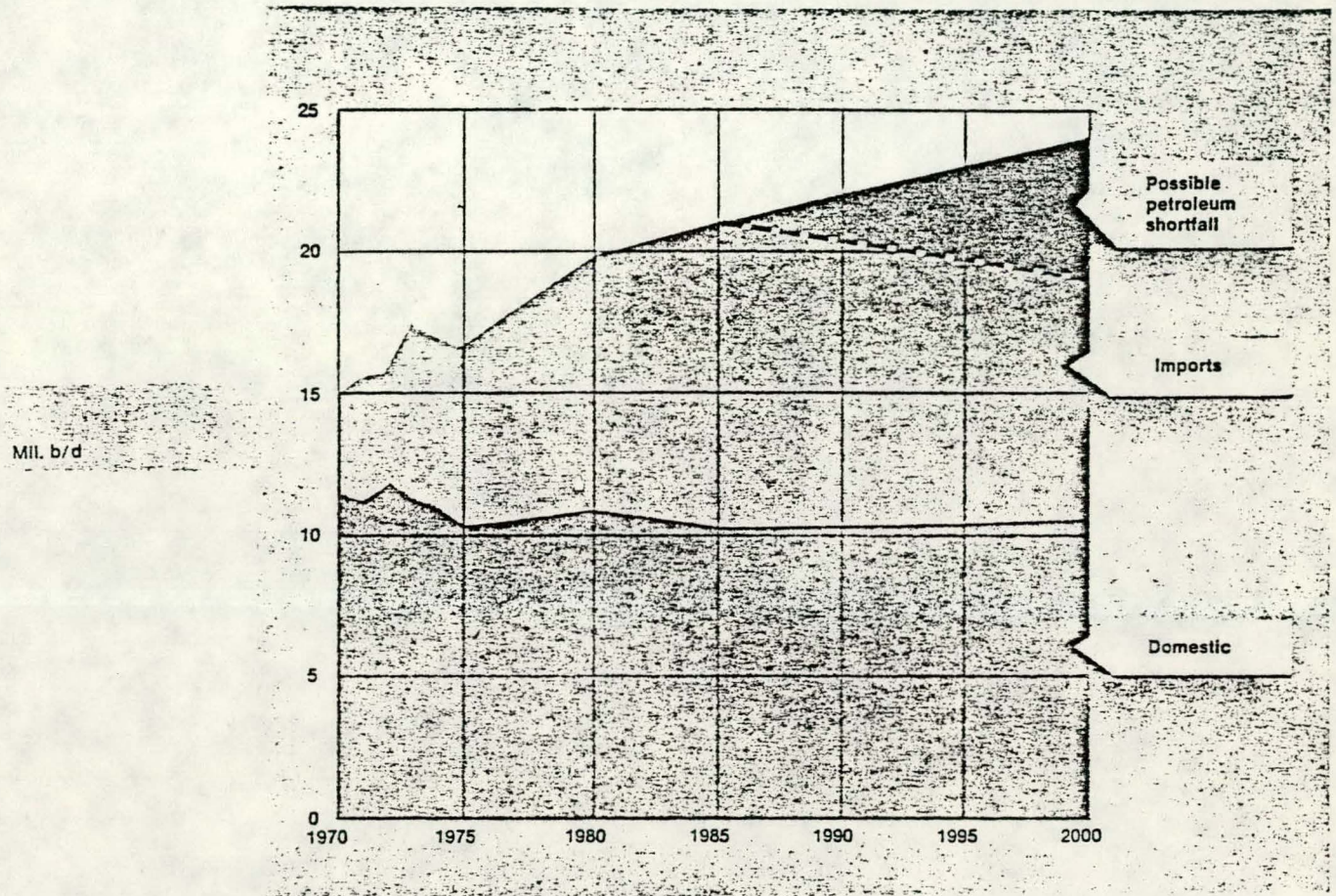
Source: Oil and Gas Journal (Granville 77)

Fig. 4.0-4 - U.S. petroleum supply and demand

From these observations, two conclusions relative to the future of the pipeline industry that are significant for present purposes can be drawn. First, the total volume of gas and oil pipeline traffic will remain about level, or grow modestly through the rest of the 20th century. Second, on certain lines, traffic will decline and eventually some of these will be retired from service. If other uses for these systems than oil and gas transport could be found, the result would be a greater growth for the industry than the expectations discussed above.

These two general and nonquantitative conclusions constitute our reference case scenario for the future.

5.0 THE UNCONVENTIONAL SCENARIO

In the preceding section, it was seen that in all of the scenarios which were identified as reasonable postulations, a large number of pipelines are likely to be retired from service in the years ahead. With this conclusion, it is only natural to inquire into the possibilities for using these idle systems for other, i.e., unconventional, purposes. And if conversion of existing pipelines is feasible, the next obvious question is whether new facilities for such purposes can be economically justified.

Unconventional pipelines have been studied and built for many years. Coal slurry lines are the most visible example, because the first such system was placed in operation on a large commercial scale 20 years ago. There are numerous smaller slurry lines around the world which move various minerals [Gray 75]. It would also be possible to use pneumatic slurries.

Besides slurrying in a liquid or gas, it is also possible to move solid material through pipelines by means of capsules. Capsules may be propelled in a number of ways, e.g., pneumatically, hydraulically, or electrically, and they may or may not roll on wheels and/or tracks within the pipe. For the purposes of this discussion, all of these variations of slurries and capsules will be considered together under the general term of freight pipelines.

The history and technology of freight pipelines will be discussed later, in Section 6.0. The present discussion simply postulates technical and economic feasibility for pipelines which can transport both bulk and packaged goods over long distances, and then examines the energy consumption consequences of such services and their marketability. The point of departure for the discussion is a comparative examination of the energy intensity of freight transportation modes.

5.1 The Price of Speed

The energy intensity of a transportation vehicle is the energy that is consumed in moving unit mass of the vehicle over unit distance. In general, this energy consumption consists of acceleration and braking energy, changes in potential energy which result from elevation changes over the route, and the energy to overcome frictional resistance to motion. This latter element is generally by far the largest, and it is thus instructive to compare its magnitude for various transportation modes.

The earliest and apparently still the most comprehensive comparison of vehicular motion resistance appears to be that of Gabrielli and von Karman [1950], from which Fig. 5.1-1 is taken. They observed that the dashed straight line in the figure appears to constitute a limit upon vehicle performance. In Fig. 5.1-2, they have plotted the single-vehicle specific power, again noting the existence of the apparently limiting line.

Figures 5.1-3 and 5.1-4 present their corresponding curves of motion resistance and specific power for convoys. The limiting lines for single vehicles which were inferred from the previous two figures have also been plotted here. An order of magnitude performance improvement is seen to be realized as a result of convoying, particularly in the case of the railroad, a point which will be important in the discussion to follow.

Gabrielli and von Karman were interested in the possibility of expressing the performance limit, reflected by the limiting line in the figures, as a general law. They pointed to the dimensionless quantities, e.g., Reynolds number, Froude number,etc. which characterize the resistance laws of media through which the vehicles move. Recognizing that speed limitations upon vehicles arise through relationships between resistance of the medium and strength of the vehicle structure, they attempted to relate the rupture length (length of a vertically hanging rod which would break under its own weight) of the vehicle structural

Fig. 5.1-1 - Single-vehicle motion resistance
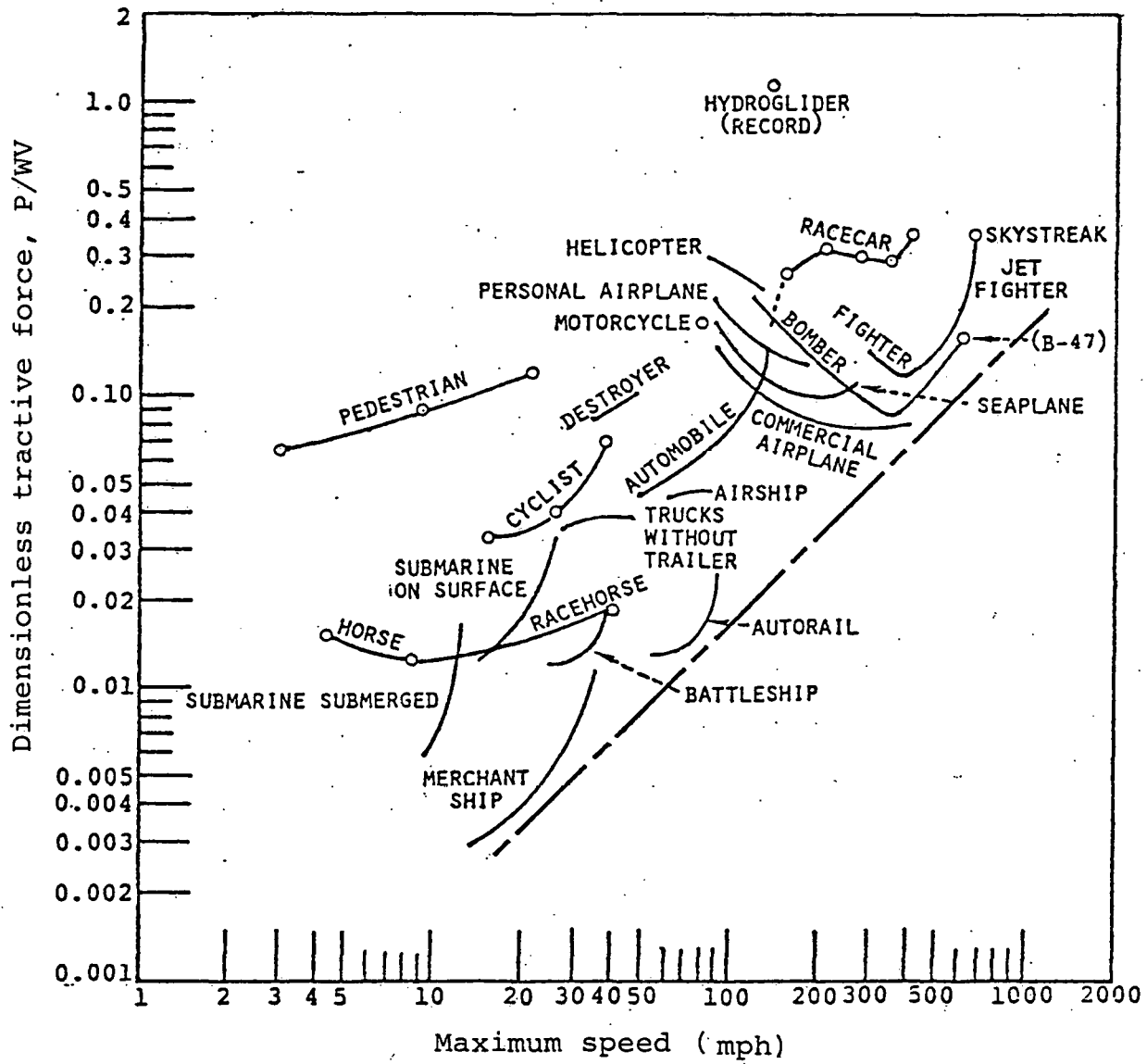
Notation: P $\triangleq$ power, ft-lb/sec

W $\triangleq$ vehicle gross weight, lb

V $\triangleq$ vehicle speed, ft/sec
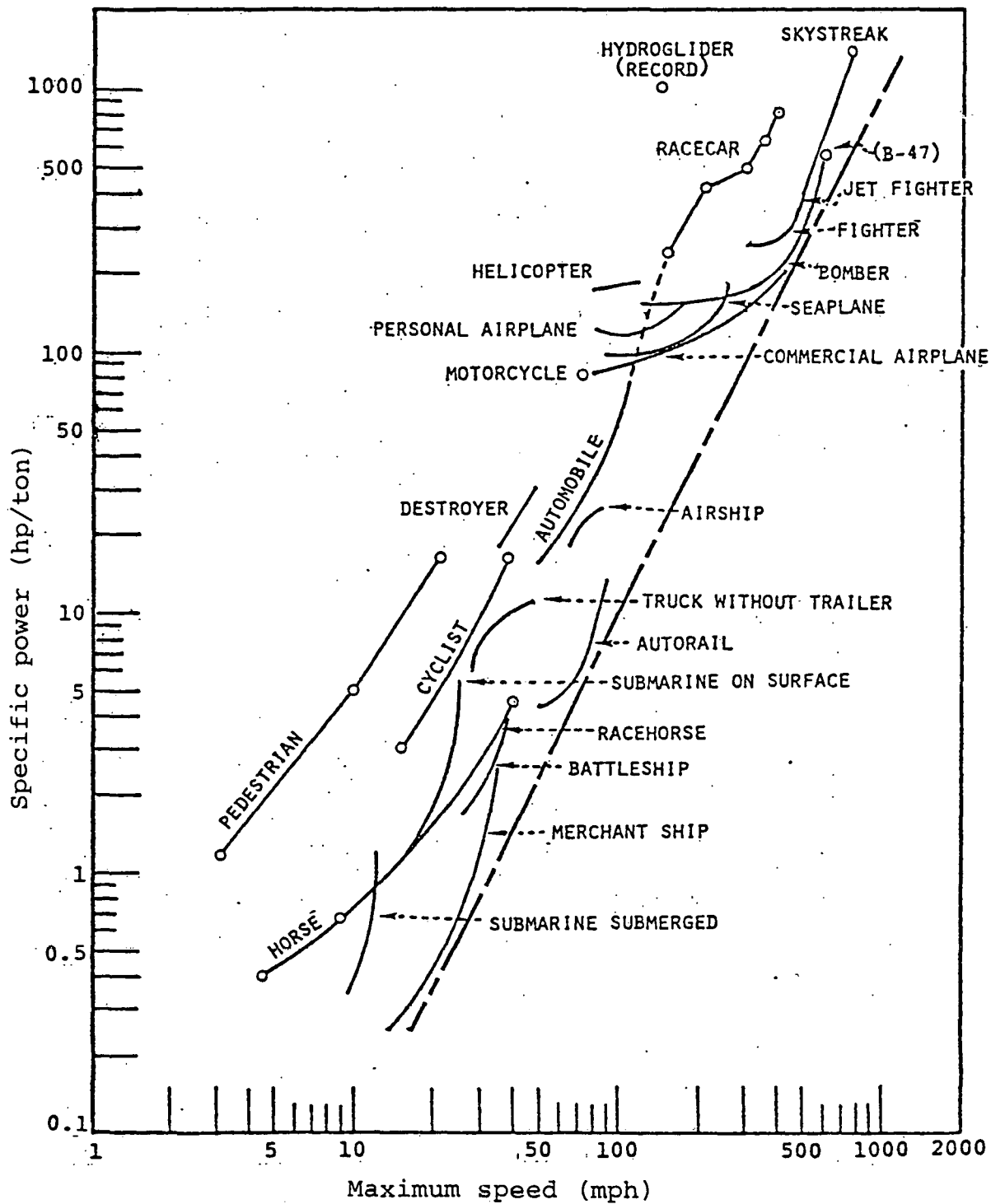
Source: Gabrielli and von Karman (1950)

Fig. 5.1-2 - Single-vehicle specific power

The figure is a log-log plot of Specific power (hp/ton) on the vertical axis versus Maximum speed (mph) on the horizontal axis. Labeled curves and points include: HYDROGLIDER (RECORD), SKYSTREAK, RACECAR, (B-47), JET FIGHTER, FIGHTER, BOMBER, HELICOPTER, SEAPLANE, PERSONAL AIRPLANE, COMMERCIAL AIRPLANE, MOTORCYCLE, AUTOMOBILE, DESTROYER, AIRSHIP, TRUCK WITHOUT TRAILER, AUTORAIL, CYCLIST, SUBMARINE ON SURFACE, RACEHORSE, BATTLESHIP, PEDESTRIAN, MERCHANT SHIP, HORSE, SUBMARINE SUBMERGED.

Source: Gabrielli and von Karman (1950)

Source: Gabrielli and von Karman (1951)

Fig. 5.1-3 - Motion resistance of convoys
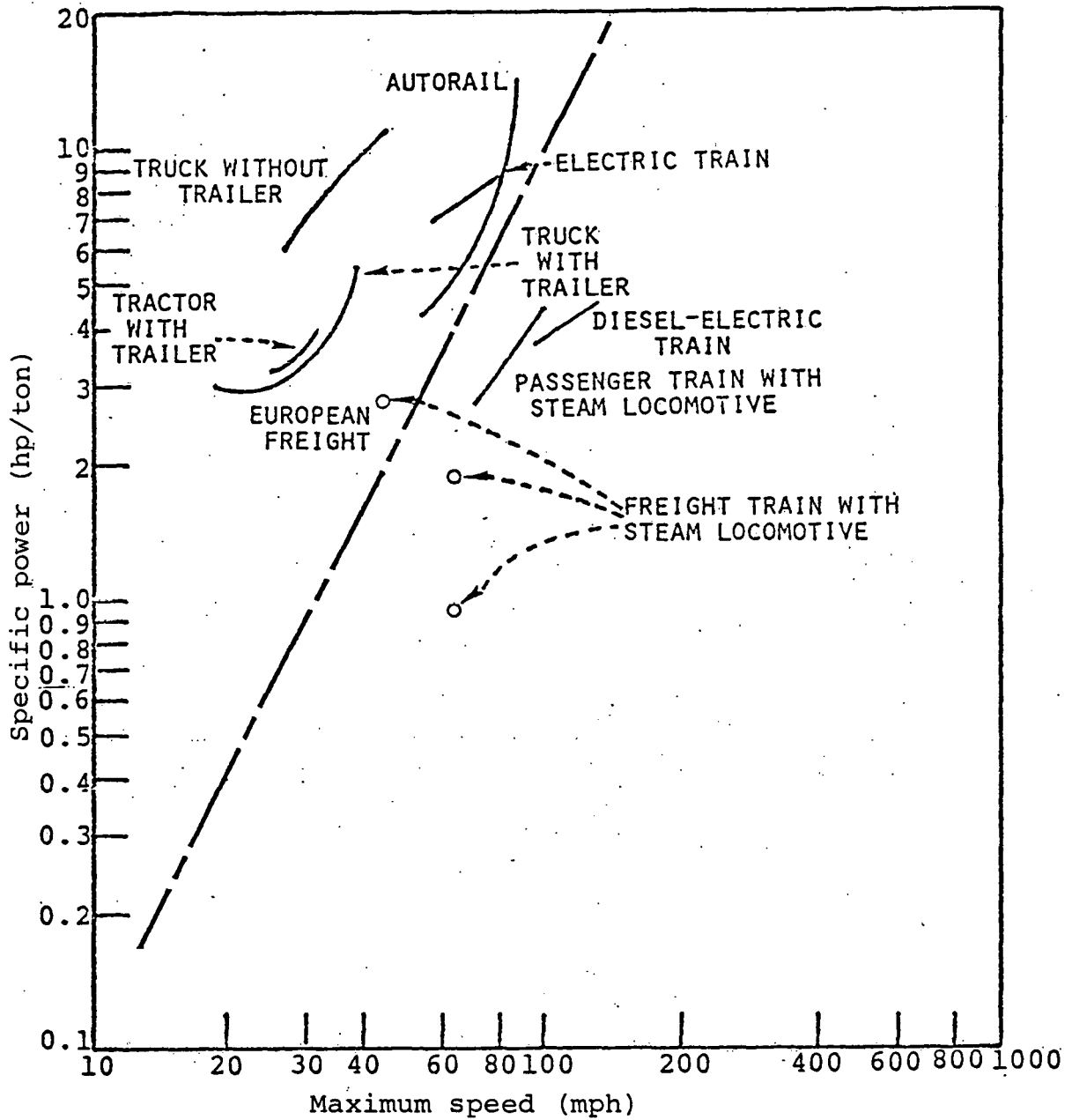
Source: Gabrielli and von Karman (1950)

Fig. 5.1-4 - Specific power of convoys

material to motion resistance parameters.

Denoting the rupture length as L, they defined the dimensionless structural characteristic of the vehicle as

$$N_{st} \triangleq \frac{\rho g L}{\sigma_u}$$

where

$\rho \triangleq$ density of the structural material

$g \triangleq$ acceleration of gravity

$\sigma_u \triangleq$ ultimate stress of the material.

This number characterizes the ratio of maximum vehicle length to rupture length of the material. Eliminating L between this parameter and the Froude number $V/\sqrt{gL}$, they obtained the new parameter

$$\frac{V}{\sqrt{\sigma_u/\rho}}$$

which represents the ratio of vehicle speed to a speed which is a characteristic of the material, being the circumferential linear speed at which a thin ring would centrifugally disintegrate.

Speculating further that the Young's modulus E of structural materials may dominate the performance of vehicles, Gabrielli and von Karman noted a surprisingly small variation in the two characteristic speeds, $\sqrt{\sigma_u/\rho}$ and $\sqrt{E/\rho}$, for the materials which they listed in Table 5.1-1. For comparison, some values presented in Table 5.1-2 were taken from engineering handbooks and other sources 25 or more years later.

This line of investigation appears not to be particularly fruitful, although its usefulness will be seen later in a

TABLE 5.1-1

Comparison, $\sqrt{\sigma_u/\rho}$ and $\sqrt{E/\rho}$, 1950

Material	σ_u 10^3 psi	$\sqrt{\sigma_u/\rho}$ fps	$\sqrt{E/\rho}$ fps
Structural steel	80	870	16,800
Stainless steel	80	875	16,600
Heat-treated steel	150	1190	16,800
Duval 24 S-T	65	1320	16,650
Titanium, 1950 production	120	1410	15,800
Titanium, projected	180	1725	15,800

Source: Gabrielli and von Karman (1950)

TABLE 5.1-2

Comparison, $\sqrt{\sigma_u/\rho}$ and $\sqrt{E/\rho}$, 1975-77

Material	σ_u 10^3 psi	$\sqrt{\sigma_u/\rho}$ fps	$\sqrt{E/\rho}$ fps
Steel, low carbon	60	750	16,500
Steel, stainless 316	90	910	16,100
Steel, API, 5LX-65 (pipeline)	90	920	16,400
Aluminum 5086,H34	47	1140	16,900
Magnesium, ZK60A	52	1453	16,200
Titanium (6A14V)	155	1610	16,200
Wood, fir	6.3	1110	16,900
Nylon 66	11.8	880	16,400
Epoxy, wound	80 - 250	2330	-

Sources: Liley (1976),Singer (1975), Mihelich (1977)

somewhat different context. The primary reason lies in the
fundamental differences in the physics of the different modes
of locomotion. For example, the Froude number is related to the
resistance encountered by a ship due to its generation of waves.
There is no obvious reason to suppose that a parameter which
relates a vehicle's structural strength to its Froude number in
the water would influence its speed on land or in the air. At
the same time it is intuitively clear that the primary price of
speed is always specific power, and that the power which can
be carried on board is limited by the strength-to-weight ratio
of the vehicle structure.

Bekker [1956] was also interested in the characterization of
speed limitations. However, he approached the subject differently,
beginning with analysis of the physics of the different locomotion
processes, as distinguished from the statistical correlation at-
tempted by Gabrielli and von Karman.

The equations developed by Bekker reveal interesting dif-
ferences in the price that is paid for speed by the various loco-
motive modes. The power law dependencies of modal specific power
upon speed are listed in Table 5.1-3. It is interesting to
observe that the animal modes power consumption rises only as
the first power. Figure 5.1-5 shows Bekker's plot of specific
power. In the flow regime, he only considered rivers, i.e.,
open channel flow, but the near-third-power dependence which
obtains for vehicles passing through fluid media at moderate
speeds gives his chart a broader significance. The third-power
dependency is, as indicated, only approximate since the actual
dependency is governed by coefficients which are nonlinear
functions of Reynolds number. It must be recognized that the
specific power of channel or pipe flow is for cargo only, whereas
for the other modes the horsepower per ton refers to the gross
vehicle weight. Payload specific power for those modes is
therefore much higher than the values indicated in the figures.

TABLE 5.1-3

Power-law dependence,
specific power vs. speed

Mode	Power law exponent of speed
Quadruped running	1
Crawler	1
Slider	1
Biped walking	1
Hard wheel on hard surface	1
Liquid flow	∿3
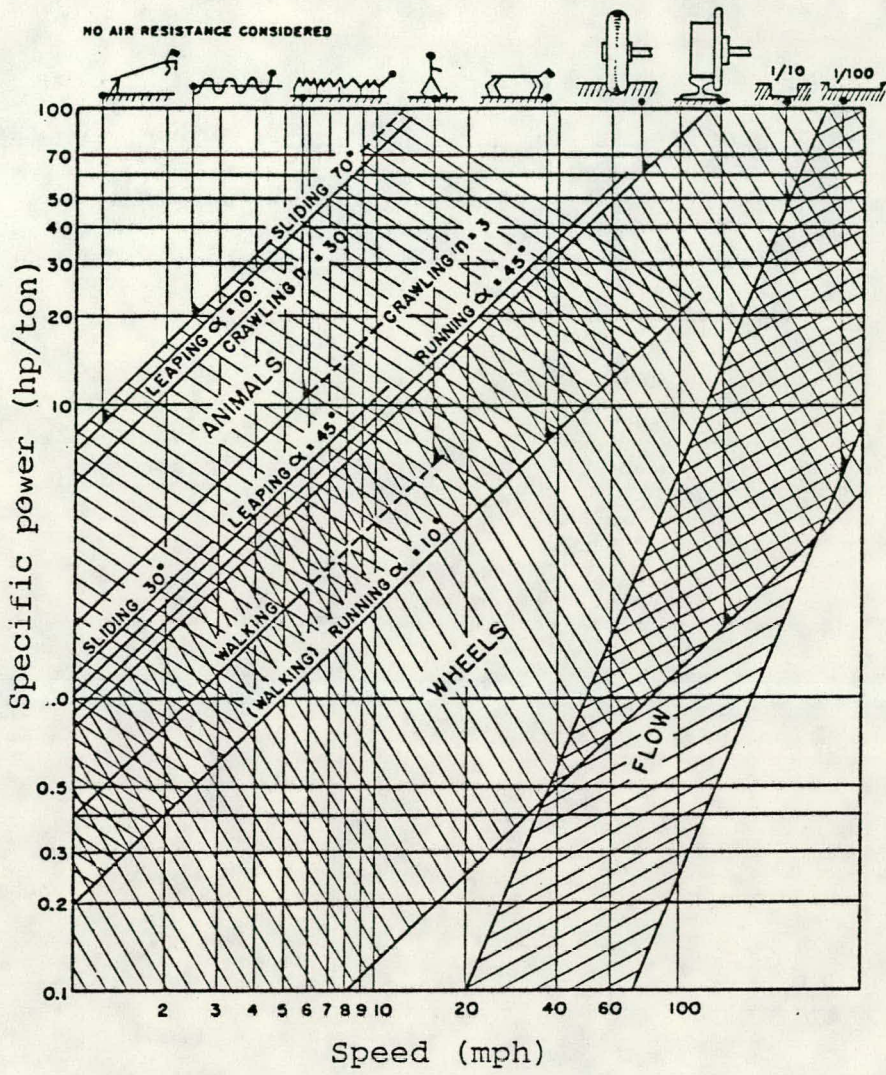
Source: Bekker (1956)

Fig. 5.1-5 - Specific powers of land on fluid medium
         transport modes

Now, while the attempts to identify a universal law of limitation of vehicle performance have not been successful, they have nevertheless served to illustrate some points of interest. First, even though there may be no universal law governing the price of speed in terms of energy, the Gabrielli-von Karman plots show that for single vehicles, whatever the nature of the limiting influences in the various regimes, they are quite consistent. The limiting line appears to exist, though in the absence of a rationale, that consistency across different regimes must be presumed coincidental. Second, the advantages of convoys were dramatically illustrated in Figs. 5.1-3 and 5.1-4. Taken together, these observations suggest an approach to optimization of the allocation of freight among the transport modes, a subject which will be developed in the next section.

5.2   Characterization of the Modal Mix

The primary interest of this study is energy conservation; hence a most important objective of the optimization process is minimizing energy consumption. In the preceding discussion, comparisons were drawn between the characteristic motion resistances of transport vehicles, with particular attention to the on-board specific power, i.e., hp/ton. However, for purposes of energy conservation, a preferred index is the energy intensity (EI or I_R). The approach here will be to estimate the EI for the five principal freight transport modes, characterize them as the price paid for speed in terms of energy, and attempt to identify modal shifts which might reduce overall energy consumption.

The EI may be defined as the dimensionless ratio of the foot-pounds of energy consumed in moving a pound of freight through a distance of one foot. That is, it is the ratio of transportation work used in overcoming resistance to the useful work of moving the goods. However, a more commonly used unit is the Btu/ton-mile.

Report R-3022 of this series (see Table 1.1-1 above) discusses the methodology of calculating the EI for pipelines and presents estimates of the EI for the various types of pipeline. Table 5.2-1 lists these estimates along with average speed and average tariff for the five principal freight transport modes. In Fig. 5.2-1 the energy economy (inverse of energy intensity) from the table is plotted against the average modal speed, along with the regression line. The next step in the optimization analysis is to define a criterion of merit.

5.3 A Criterion of Merit

The reader will already have reflected that, since the scales on both axes of Fig. 5.2-1 were so chosen that desirable increases are in the outward direction, improving performance is reflected on the chart by increasing distance from the origin. And if the scales should happen to reflect equal values, then downward sloping lines at 45 degrees would represent lines of equal performance. That is, suppose that the scales were such that one unit of energy economy were equal in value to one unit of speed. Then all systems on the 45 degree line would have the same energy-speed product, which could then be defined as the transportation figure of merit.

While further pursuit of this idea appears interesting, it is beyond the scope of this study. Its importance for present purposes derives from the fact that it allows us to generalize about the relative performance merits of the different modes. Some observations can now be made.

First, whatever value judgements one may place upon the two axes, the regression line represents average industry performance. Suppose, for example, that an entirely new transportation mode were introduced. If its speed-energy product fell anywhere on the regression line, it could be asserted that

TABLE 5.2-1

Estimated average parameters for transport modes

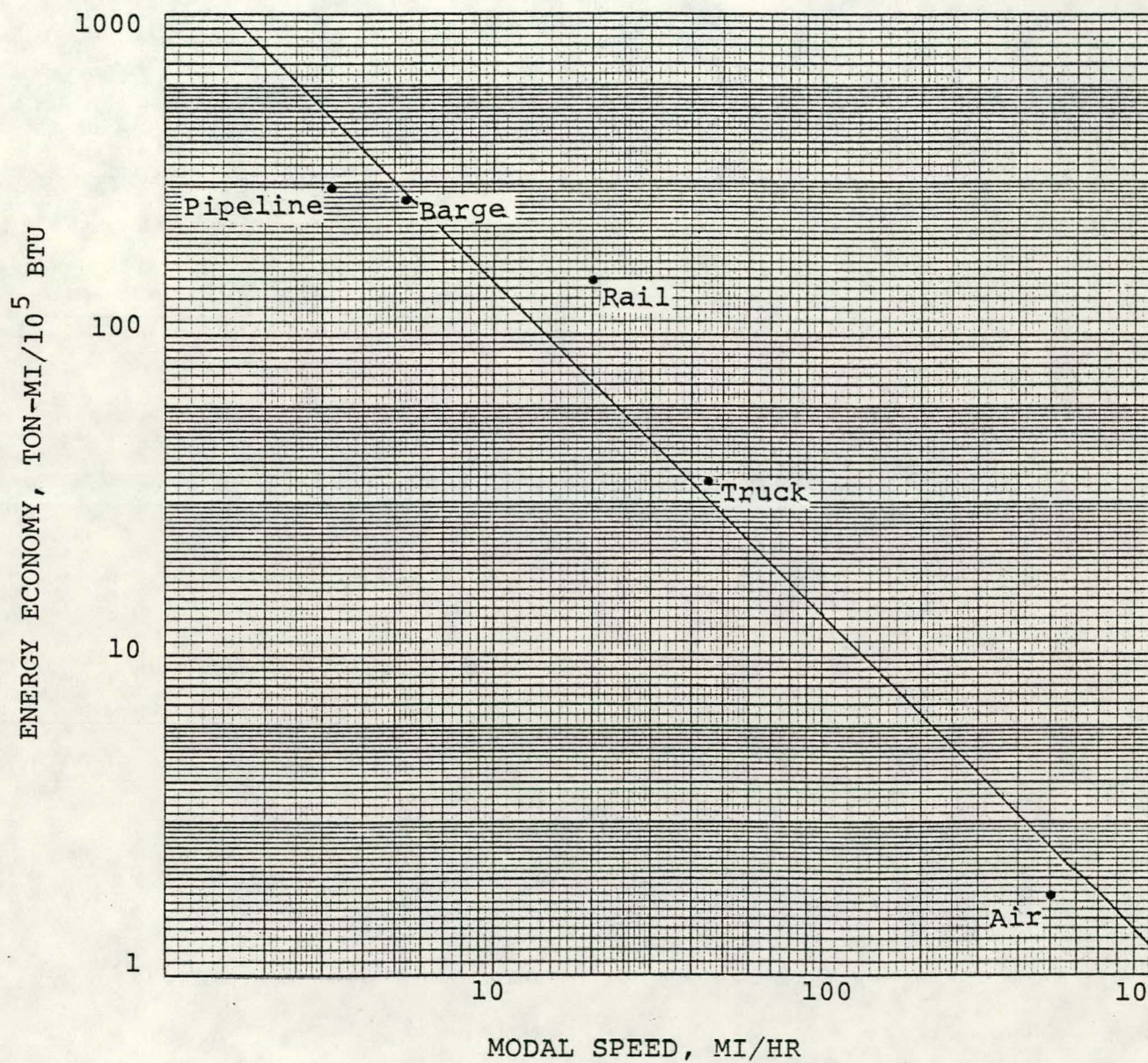|	Speed (mph)	EI [1] Btu / Ton-Mi				EE [2] (S3) Ton-Mi / 10^5 Btu
		P-M	ORNL	PI	S3	
Pipeline	3.2	158 (281)	565	550	350	286
Barge	5.4	272	1404	500	380	263
Rail	20	687	641	700	672	149
Truck	45	2343	8485	2311	2825	35.4
Air	500	39,949	56,965	29,600	56,700	1.764

(1) Energy Intensity

(2) Energy Economy

Figure 5.2-1   Energy Economy of Transportation Modes

the new mode offered performance equivalent to the industry average. This line of argument was advanced by Shure et al. [1973] in suggesting development of air cushion vehicles (ACV's) to serve the market between truck and air freight.

Second, in the sense discussed above, the railroad is the best performer. It lies farthest from the regression line, on the desirable side of the line, indicating that, on average, it offers a better speed-energy product than any other mode.

5.4 Optimization of the Modal Mix

This latter observation leads naturally to the question of how this performance superiority could be exploited to effect an overall reduction in energy consumption. A possible answer is illustrated in Fig. 5.4-1. This figure is the same as the preceding one, with the addition of postulated future points for the rail and pipeline modes. Two postulations have been made which are listed below and then discussed:

1) High-speed (130 mph in the figure), lightweight freight trains have been introduced. This innovation is indicated by the dashed line from the present rail performance, point (1) in the figure, to point (3). The intermediate point (2) will be explained later.

2) Freight pipelines, i.e., pipelines which transport solid freight, have been introduced. This innovation is indicated in the figure by the dashed line from the present pipeline performance, point (4), into the vicinity of present rail performance, point (1).

Postulation (1) is seen as reasonable for two reasons. First, Hopkins [1975] has shown that some increase in train speed would result in an increase in fuel economy, rather than a decrease as might be expected. Figure 5.4-2 presents one of his results.
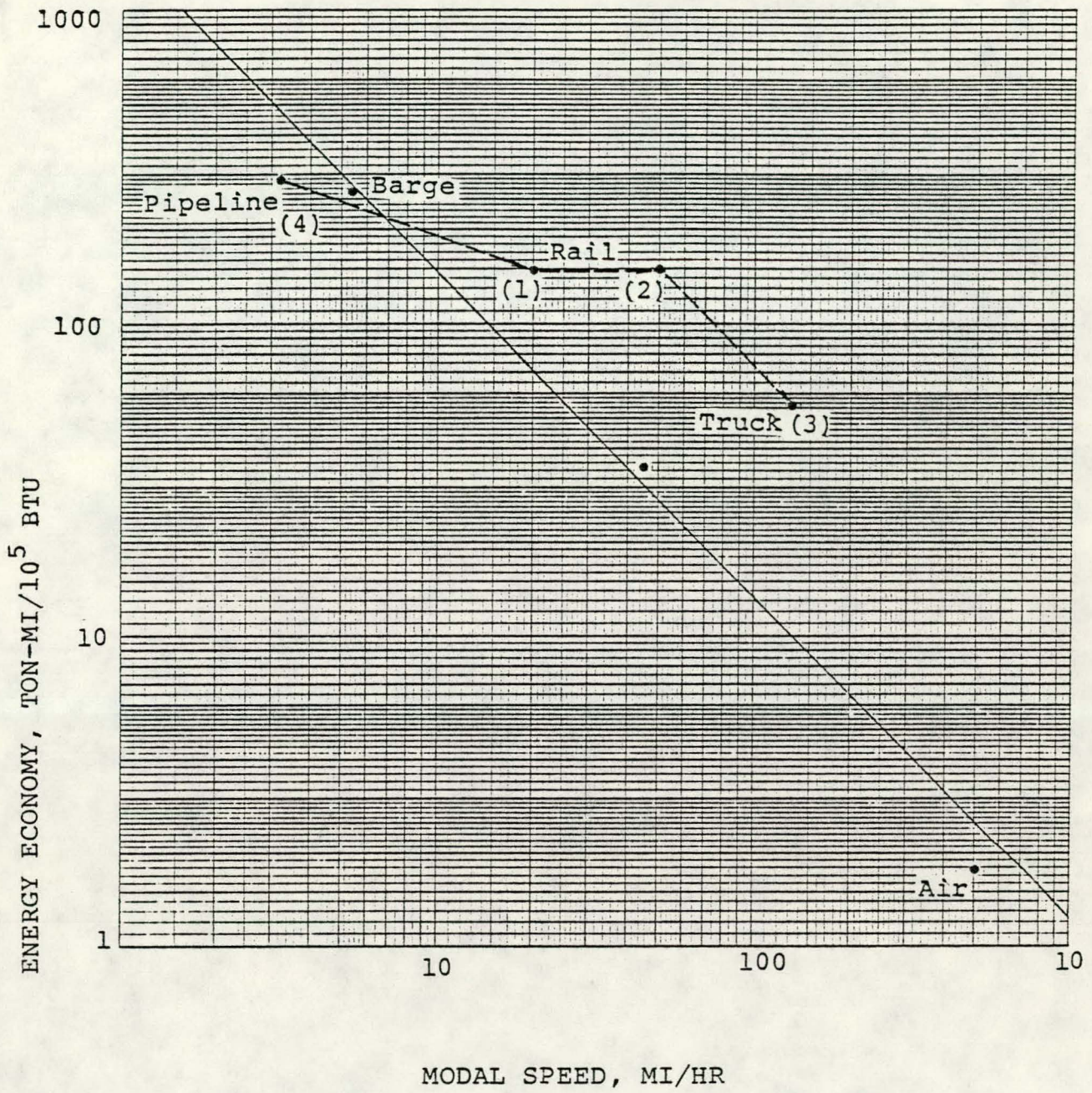
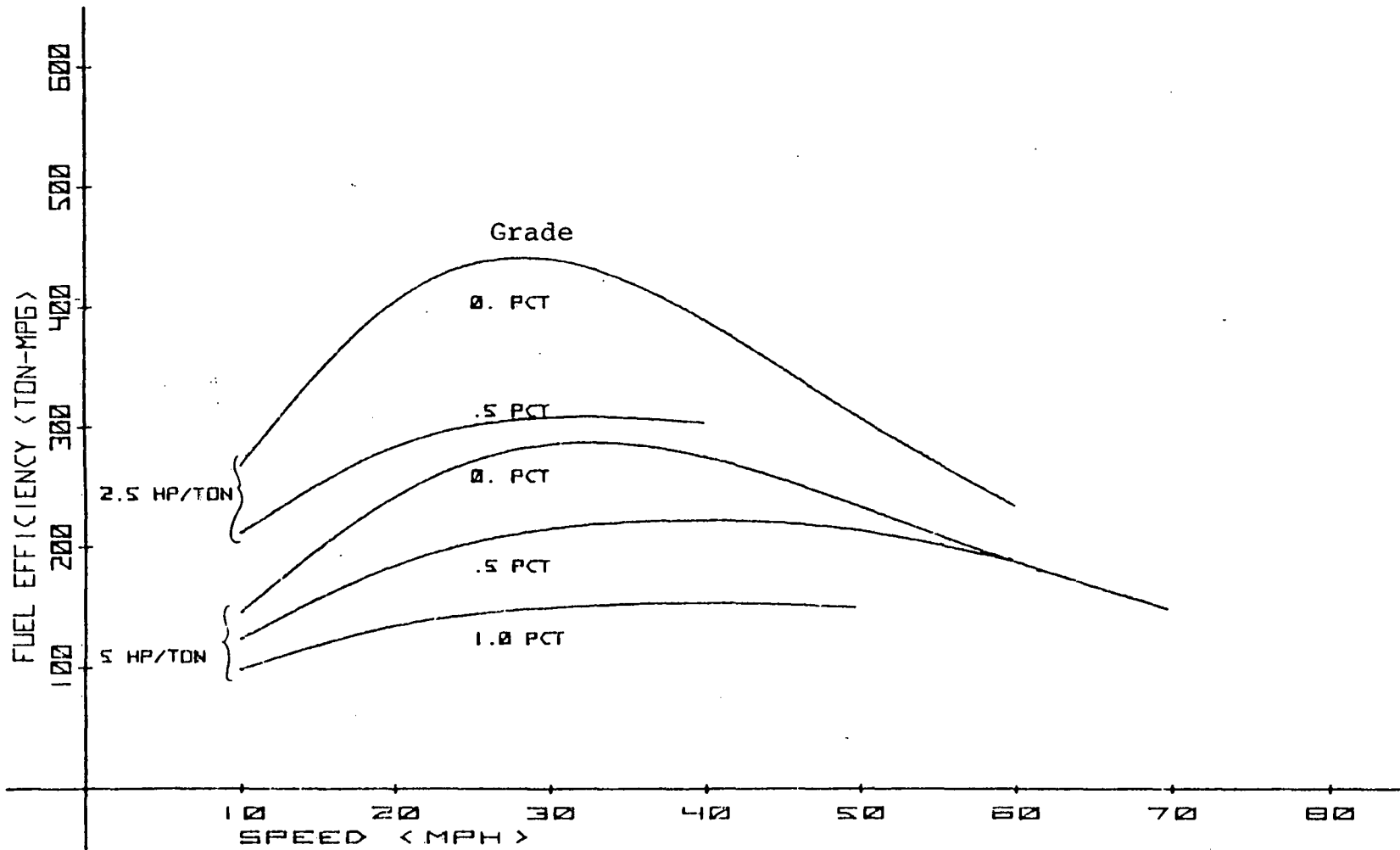Figure 5.4-1   Improvement of the Modal Mix

Fig. 5.4-2 - Rail fuel efficiency vs. speed [Hopkins 75]

Setting aside for the moment any reservations regarding the repre-
sentativeness of these results, one may observe that it is not
necessarily unreasonable to project a substantial increase in
average rail speed without energy penalty. Rail speeds in the
United States are generally restricted by the condition of the
track and seldom by the limitations of the equipment. Figure
5.4-2 indicates that the locomotive equipment operates more effec-
tively at 30 to 40 mph than it does at 20 mph, which is not sur-
prising. Thereafter, aerodynamic effects become important, and
efficiency decreases until at about 50 mph it is about equal to
what it was at 20 mph. With this observation in mind, point (2)
on Fig. 5.4-1 is seen to indicate generally what might be done
with rail transportation by enabling speeds in the neighborhood
of 50 mph. This improvement requires a great deal of upgraded,
and some new, roadbed but no new rolling stock or other equipment,
and hence no new technology.

Point (3) on Fig. 5.4-1 indicates the performance region to
which rail transport might be transformed by the introduction of
new equipment, along with further roadbed improvements, to enable
speeds in the range of 125-150 mph. Point (3) is at the inter-
section of the postulated 130-mph speed and a line parallel to
the regression line. This construction simply postulates that
speed can be increased above the 50 mph of point (2) in ways
that are as energy efficient as the present industry average
energy performance, which is represented by the regression line.
This innovation does not require development of new technology,
but does require introduction of existing technology from abroad,
since that is where all the existing high-speed trains are.

Postulation (2) represents the freight pipeline inno-
vation, which would absorb at least part of the heavy, slow-speed
rail traffic. As noted earlier, it is indicated on Fig. 5.4-1 by
the line from present pipeline performance over into the general
vicinity of persent rail performance. Unlike postulation (1),
which requires no new technology, though a very large capital in-
vestment, postulation (2) requires a large amount of both. It is

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therefore of interest to briefly examine the economics of the
two postulations before proceeding to consideration of the
technology development.

5.5 Modal Economies

In Fig. 5.5-1, the dollar economy of the modes is
presented, where the inverse tariffs from Table 5.5-1 have
been plotted against speed. As before, the desirable region
of the chart is outward, and the product of the x and y coor-
dinates of any point constitute a figure of merit for any sys-
tem represented by that point. The numbered points on the figure
correspond to the same two postulations which were described in
the preceding section. Under postulation (1), it seems rea-
sonable to further postulate a tariff increase (dollar economy
decrease) for the rail which goes parallel to the regression
line of average industry performance. The dashed line from
point (1), present rail performance, to point (3), projected
rail performance, represents this transition. The intermediate
point (2) which appeared on Fig. 5.4-1 needs no counterpart
here.

Similarly, it is postulated that the pipeline dollar econ-
omy moves from its present performance, point (4), to the vici-
nity of present rail performance, point (1). Both of these
changes involve substantial gains, i.e., factors of five or six,
in unit revenue.

To generalize further would require a great deal of addi-
tional analysis, which would be much beyond the scope of the
present study. At this point, the somewhat surprising conclu-
sion has tentatively emerged that with available technology,
it may be economically feasible to run the freight trains five
or six times faster than at present, and that if they did so,
a tariff five or six times greater would be as close to average
industry dollar-speed economy as at present. Also, if freight
pipelines can be developed to assume the slower and heavier
traffic thus vacated by the rails, the average freight pipeline
tariff could possibly be five or six times greater than the
present liquid pipeline tariffs. With these notions in mind, the

Figure 5.5-1 Apparent* Dollar Economy of Transportation Modes
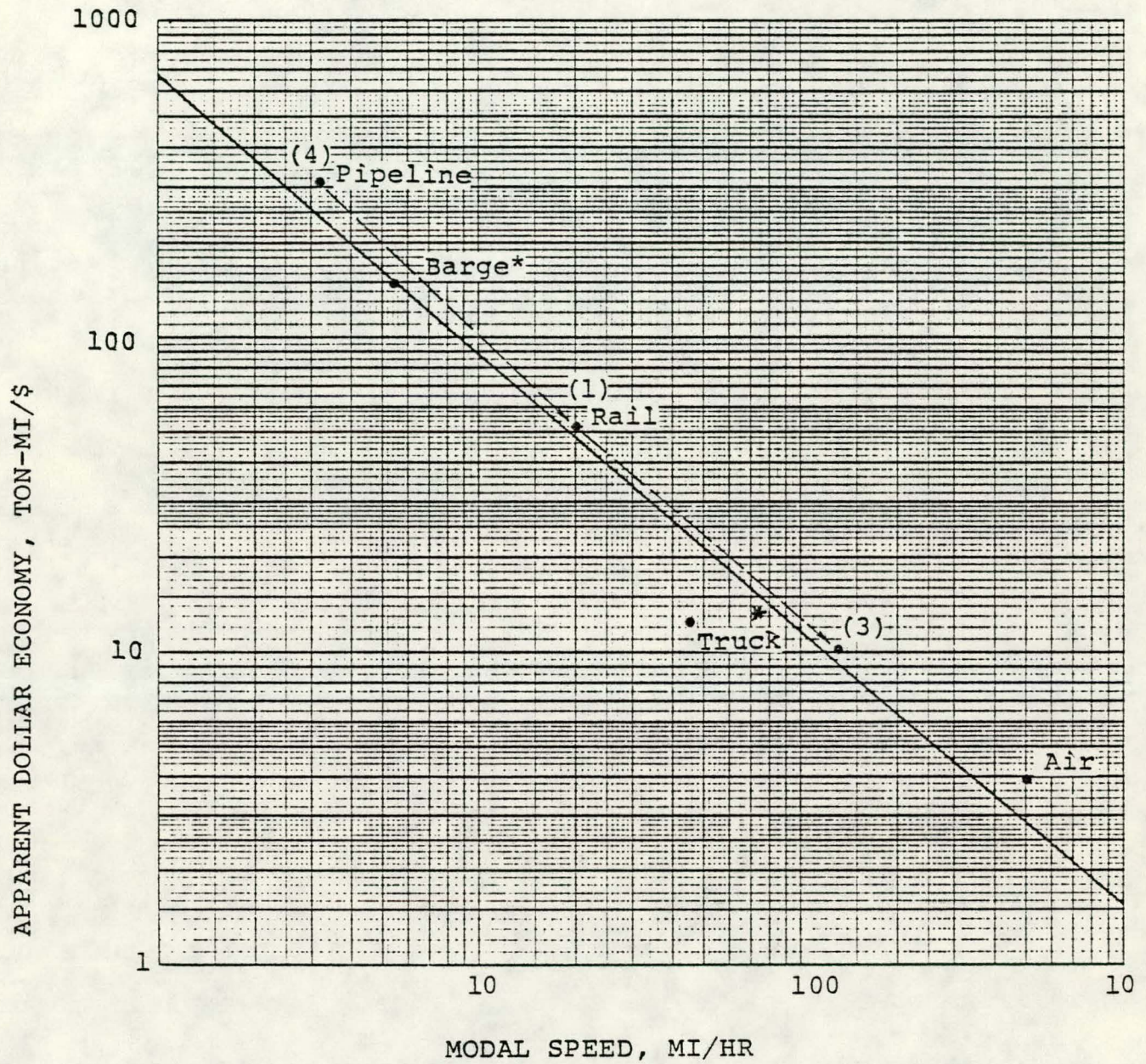
*Cost of Subsidy Not Included

TABLE 5.5-1

Inverse tariffs of transportation modes

	Oil Shipments				All Shipments	Avg. 4&5
	1974 Tariffs, ¢/100 B-Mi		1974 Tariff, $/T-Mi		Inverse Tariffs Ton-Mi/$	
	Range	Geometric Mean				
	(1)	(2)	(3)	(4)	(5)	(6)
Pipelines	2-10	4.47	0.00320	312	298	305
Water						
Coastal, long haul	5-10	7.07	0.00505	197	265	217
River	5-20	10.0	0.00715	140		
Rail	8-50	20.0	0.01429	70	62	66
Truck	40-80	56.7	0.0404	25	11	18
Air					10.5*	10.5

*Machinery, NYC to LA

economics of freight pipelines will be addressed in Section 6.0
below.   First, however, there are two additional aspects of
the scenario to be discussed.

5.6   Freight-Passenger Interaction

The foregoing discussion has treated only freight trans-
portation modes because the subject of the present study is pipe-
lines.   And while it is clearly reasonable to postulate the future
existence of freight pipelines and to examine their economics,
energetics, and technology, passenger pipelines appear to be
too far in the future to merit present study.   However, the
earlier discussion of other modes makes mandatory some comment
on passenger transportation.

A most significant and attractive aspect of the scenario
described earlier is the fact that the type of freight trains
which were postulated, i.e., small and fast, are compatible with
a true high-speed passenger service.   Thus, a part of the
scenario is the capture of significant portions of the short-
haul air passenger market.   While it seems unlikely that the
trunk airlines would lose much business on the longer trips,
say 500 miles and greater, there is every reason to believe
that large portions of the short-haul passenger business could
be assumed by the rails.   And that is precisely the portion of
the air transport market that is energy-inefficient, uneconomic,
and generally subsidized.   As noted earlier, while the details of
how the many classes of cargo might fare under the scenario are
beyond the present study, it seems clear that the economics of
fast trains would receive very considerable support from their
compatibility with fast passenger service.

5.7   Compatibility with Projected Trends

While it has been stated earlier that detailed con-
sideration will not be given to types of freight in this study,

an observation can be made regarding trends as between the two
major categories: bulk commodities and manufactures. Morton
[1974] points out that "the economic consumption of bulk commodi-
ties has not kept pace with the growth of GNP." He also dis-
cusses traffic in manufactures, i.e., manufactured goods:

"The other major category of freight traffic - manufactures -
consists primarily of finished goods or parts moving from fac-
tory to assembly plant, warehouse, or retail outlet. Manufac-
tures typically move in packages or discrete units; shipments
tend to be of lower volume than bulk commodity flows, smaller,
and less regular. The goods themselves tend to be of lower
density (i.e., lighter) and of higher value per unit of weight.
They are frequently fragile or perishable and subject to loss
of market value as a function of time. Traffic in manufactures
constitutes the bulk of truck cargo. Although the railroads
have already lost much traffic in manufactures to trucking, this
traffic still accounts for 25-40% of railroad ton-miles (depend-
ing on definition) and a still larger proportion, it is thought,
or revenues and profits. It is important, therefore, to under-
stand how the demand for the transport of manufactures has been
changing.

"Whereas the weight of manufactured goods must bear some
reasonably constant relation to the weight of raw material inputs,
it is apparent that traffic in manufactures is also growing
more slowly when measured in weight units than in real GNP.
Aggregate intercity freight tonnage in bulk commodities and
manufactures combined has been growing only about 60% as fast
as real GNP during the postwar period, Traffic in manufactures
is growing faster than bulk commodity traffic, however, partic-
ularly when measured in terms of freight revenues. The primary
causes of this relatively faster growth of traffic in manufactures
are an increase in number of shipments and in the quality of
freight service demanded. As per capita incomes rise, there is

a shift in consumer expenditures toward more highly fabricated products. To produce these, commodities must often pass through more stages of fabrication. Increasing specialization or "division of labor" in manufacturing industry also contributes to a rising number of interplant shipments. Hence, the total tonnage of manufactured goods shipped tends to rise more rapidly than bulk-commodity tonnage. The proliferation of distinct brands, models, and styles of manufactures tends to reduce the size of individual shipments and to require a more elaborate system of distribution. All these effects tend to increase the number of shipments of manufactured goods.

"Another fundamental change in the freight market is the higher standards of freight service that shippers of manufactures are demanding. The shift toward higher standards of freight service parallels a shift in most markets toward higher quality products and services. As the economy evolves toward production of more highly fabricated goods and more expensive brands, models, and styles, the value of manufactures per unit of weight tends to rise because of the relatively greater inputs of labor and capital. As the amount and cost of working capital tied up in goods rise, there is a tendency to opt for speedier, more reliable deliveries as a way of controlling this carrying cost. Growing sophistication among shippers concerning the tradeoffs between transport and other components of the total distribution bill (e.g., inventory) is also partially responsible for the gradual shift to higher-quality freight service.

"Highly fabricated and expensive goods are inclined to be fragile, perishable, or otherwise damage-prone, prompting the use of premium transport service. The reliability, speed, and convenience of deliveries is part of the product quality or service that the buyer looks for. This has been a powerful force in causing shippers to shift toward higher standards of freight service, so that freight demand has become more service-elastic and less price-elastic. The monetary value to shippers of swift,

reliable delivery may be rather surprising. In Great Britain, for example, trucking firms have begun to specialize in offering guaranteed delivery. Freight rates for guaranteed second-day delivery are roughly 40% greater than for seventh-day delivery, and rates for overnight delivery are about twice as high as for second-day delivery."

The general picture, then, is of a stagnating market in bulk commodity transport, and a growing market in transport of manufactures, a large part of which are highly fabricated and expensive goods, for which the value of time, i.e., speed, tends to be high. This is precisely the kind of market situation that the unconventional scenario described above would best capitalize upon. Thus, while quantitative analysis has not been adduced to confirm the validity of the scenario, it can be said that qualitative analysis of trends shows it to be consistent with observed patterns of market evolution.

6.0 FREIGHT PIPELINES

This section includes a report and analysis of the papers presented and discussions held during the International Symposium on Freight Pipelines, held December 5-8, 1976, in Washington, D.C. There was excellent coverage of the subject. Unfortunately, proceedings were not published, so that the present discussion is largely a reconstruction from the recollections and notes of the author.

6.1 History of Freight Pipelines

A recapitulation of freight pipeline history generally begins by taking note of pneumatic mail tubes. Such systems began operation in England in 1940 [Baker 76], in Germany in 1965 [Brauer 76], in France in 1967 [Zandi 74], and in the United States in 1892 [Zandi 74]. However, these tubes were not true freight systems, but communication systems. They do not qualify as freight systems in the sense of carrying significant amounts of payload at reasonable ratios of cargo-to vehicle weight.

The only true freight pipelines now operating on a commercial scale are slurry lines. Such systems have been extensively studied in many countries [Gandhi 76], and numerous ones have been built. Of the papers presented during the symposium mentioned above, almost a dozen reported on projects ranging from conceptual studies and experimental facilities through pilot plants to operating commercial systems. Table 6.1-1 lists the systems known to have been in operation by 1975 [Gray 75].

The experience with slurry lines has not been universally encouraging. Table 6.1-2 lists a dozen Canadian projects that were never built [Jensen 76]. All except number 12 were to have been slurry lines.

The development of other types of freight pipelines than slurry lines has been much slower. The only one reported to be in commercial operation is in Russia [New Scientist 75,

TABLE 6.1-1

Slurry pipelines in operation by 1975

Slurry material	Location	Length (mi)	Diam. (in)	Annual Thruput (millions tons/yr)	Init. Op'n
Coal	Consolidation	108	10	1.3	1957
	Black Mesa	273	18		
Limestone	Calaveras	17	7	1.5	1971
	Rugby	57	10	1.7	1964
	Trinidad	6	8	0.6	1959
	Colombia	17	7	0.4	1944
Copper concentrate	Bougainville	17	6	1.0	1972
	West Irian	69	4	0.3	1972
	KBI Turkey	38	5	1.0	–
	Pinto Valley	11	4	0.4	1974
Magnetite concentrate	Tasmania	53	9	2.3	1967
	Waipipi (land)	4	8	1.0	1971
	Waipipi (offshore)	1.8	12	1.0	1971
Magnetite and hematite	Pena Colorado	30	8	1.8	1974
Gilsonite	American gilsonite	72	6	0.4	1957
Tails	Japan	44	12	0.6	1968
Nickel refinery tailings	Western mining	4.3	4	0.1	1970
Phosphate pulp	Florida	5	14	1.0	1949
Kaolin	Georgia	10	–	–	1950

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Sources: Gray 75, Zandi 74

TABLE 6.1-2

CANADIAN LONG DISTANCE SOLID PIPELINES PROPOSED BUT NEVER BUILT

No.	Company and Location	Commodity and Carrier	Length Miles	Diameter Inches	Capacity 10⁶ tons/yr.	Status
1	Pembina Pipe Line Ltd. Alberta to Thunder Bay	Sulfur in water or natural gas liquids	1600	-	-	Proposed 1958. Investigated at Colorado School of Mines 1958-59. Abandoned.
2	Pembina Pipe Line Ltd.	Woodchips in water	34	10	0.7	Feasibility investigated in t, 8 and 10 inch test lines at Marathon. Abandoned.
3	Prairie Commodities Pipe Line Ltd., Regina & Saskatchewan via Esterhazy to Chicago	Potash in potash brine or potash capsules in crude oil	377 / 915	8 / 10	2	Permit applied for 1964. Rejected and project abandoned.
4	Commercial Solids Pipe Line Co. Ltd., Calgary to Vancouver	Sulfur in oil / Sulfur in water	750 / 750	12 / 18 - 24	1.5 / 3 - 5.5	Proposed 1967 to operate 1970 Abandoned. Investigated and reported by ShelPac, 1973. Abandoned.
5	General Commodities Pipeline Ltd., Calgary to Vancouver	Coal, sulfur, gypsum in water	600	-	6	Proposed and abandoned.
6	General Commodities Pipeline Ltd., Saskatoon-Edmonton-Vancouver	Potash in water	1100	-	2	Proposed and abandoned.
7	Cascade Pipeline Ltd., Crowsnest area, B. C. to Roberts Bank near Vancouver	Coking coal in water	490	24	8 - 15	Proposed, 1969. Projected start up, 1972. Dormant.
8	Anaconda Iron Ore (Ontario) Ltd., Nakina - Kama Bay, Ontario	Iron ore concentrates in water	140	-	2.3	Test line operated. Pipeline feasible but project abandoned.
9	Canadian Javelin Ltd., Quebec and Labrador to Point Marmite on the St. Lawrence River near Sept Isles	Iron ore in water	153 / 80 / 50	18 / 16 / 8	12	Investigated by ShelPac 1970. Abandoned 1975.
10	Interprovincial Pipe Line Co. Limited, Alberta to Thunder Bay or Toronto	Coal in oil	1500	34	15	Proposed 1973. Feasibility study by ShelPac Abandoned 1975.
11	Alberta Research Council Mackenzie Delta to Fort McMurray	Frozen crude oil capsules in LNG	1350	48	oil: 22 natural gas 1 trillion ft.^{3}	Concept advanced 1973. Slurry proposal by System Sciences Inc.
12	Alberta Research Council Alberta - West Coast	Encapsulated grain in water	560	18	5	Concept disclosed 1975

Jvarsheistivili 76], and is said to be 2.2 km long, 1 m in diameter, and to carry sand and gravel. The Soviets are also reported to be testing a line 80 km long, north of Moscow, which carries ore in trains of six capsules, by pneumatic propulsion. Other projects are in progress.

In the United States, Tubexpress Systems, Inc., of Houston is offering pneumatic capsule pipeline systems to the commercial market [Carstens 76a, Tubexpress 76, Carstens 76b], although at this writing (October 1977) firm orders have not been received. Tubexpress has a large test facility in Houston which includes a complete, full-size test loop.

6.2 System Development Requirements

In describing the unconventional scenario of the preceding section, it was noted that the rail projection which was postulated did not appear to involve any significant development of new technology. On the other hand, the projection of freight pipelines other than slurries postulates a significant amount of development. At the same time, however, it is recognized that the technologies of the largest and most expensive portions of the freight pipeline system already exist. Laying pipe up to five feet in diameter and building associated compression or pumping stations, even in extremely difficult environments, are established commercial technology. And those are the most expensive and time-consuming parts of the system. On the other hand, numerous functions and techniques never before demonstrated must be perfected before the freight pipelines postulated in the scenario can become reality. Before discussing these development areas, it is well to first identify some performance requirements for the system. Having identified these requirements, it will then be possible to define the research, development and demonstration necessary to bring the concepts to fruition.

6.2.1 Types of freight and freight pipelines

In Section 5.7 above, the distinction in types of freight between bulk commodities and manufactures was recognized. The unconventional scenario developed in the preceding section envisioned that a substantial amount of normally slow moving, bulk commodity traffic, e.g., coal, ore, etc., would be absorbed by freight pipelines, leaving the railroads free to upgrade their facilities, increase speed of service, and generally to serve the higher speed market. It is therefore necessary to first examine freight pipelines which haul bulk commodities.

This is precisely what the slurry pipelines do. However, liquid slurrying is only practical where:
1) there is adequate supply of water available,
2) separation of the water from the commodity is easy, or a market for the water exists, and
3) the commodity is unaffected by wetting and drying.

Moving certain bulk commodities in pneumatic slurries does not require the special conditions enumerated above. However, gas compression is a very energy-consuming process, which is one of the reasons that led Duckworth [76] to conclude that pneumatic pipelines are "essentially inhouse systems," i.e., not suitable for long distance. There may be exceptions, e.g., the pneumatic slurrying of coal in its own gas [Nichols 76]. Nevertheless, if common-carrier pipelining of freight is ever to capture a significant portion of the market, it most likely will utilize capsule pipelines. Only capsules can provide the flexibility to make the special conditions identified above unnecessary. Any one of these conditions would severely restrict market penetration of the freight pipeline.

Several types of capsule pipelines can be envisioned. The Tubexpress system discussed earlier is known as a pneumatic capsule system, i.e., the capsules are propelled through the

pipe by compressed air, which is also reported to be the propulsion means for the Russian systems. The capsules are supported on wheels. In principle, they could be supported on an air cushion but at a greater consumption of energy and the practical difficulties of obtaining initial levitation.

The capsules would also be propelled and/or supported by a liquid, in which case they are referred to as hydraulic capsule systems. A hydraulic capsule concept which would be powered by electromagnetic action upon the capsule body, similar to that of a linear induction motor, has been studied by Liu and his colleagues at the University of Missouri at Columbia [Liu 76a, 76b, 77a, 77b]. The pump concept appears attractive and deserving of further study and experiment. However, need for the water is not clear since it only serves to levitate the capsule and lubricate its passage through the pipe, functions which wheels or rollers such as those used in the pneumatic capsule systems could also perform.

In principle, capsule pipelines could be constructed to operate without fluid action if the capsules were supported on wheels, rollers or magnetic fields and were continuously powered by electric rails, for example, so that accelerative and decelerative power were continuously available.

From this brief discussion, the reader can readily visualize some of the problems, such as propulsion, braking, and switching, facing the designer of a capsule pipeline. From a review of the references mentioned above, and of other available literature, it is the tentative conclusion of this study that the most immediately realizable system is the pneumatic capsule pipeline.

6.2.2 <u>Economic Feasibility of Freight Pipelines</u>

Thus far, the inferences have been that if the railroads could be induced to expand into the high-speed, high-value cargo field, an over-all transportation energy saving

could be realized. At the same time, an opportunity would be created for freight pipelines to assume some of the heavy, slow bulk commodity transportation. It was also concluded that to serve this role most effectively, the pipeline should be a capsule system, as opposed to a slurry system, so that it would possess wide cargo flexibility. For an order of magnitude examination of the economics of such a system, a cost model was developed.

Natural gas pipelines were selected as the prototype because they more nearly resemble the pneumatic capsule system than do the oil lines. Construction costs reported by the FPC for the 10-year period 1968-77 (government fiscal years) were reviewed and a regression analysis was performed on the larger sizes, i.e., 20-inch nominal diameter and greater, to obtain the functional relationship of cost to line diameter.

This model still requires an adjustment to incorporate the cost of the second pipe. That is, the freight pipeline system of the type that has been discussed above would be moving freight in both directions, and thus would require two pipes instead of the usual one. To include this feature in the cost model, the breakdowns of investment among system components, i.e., RoW cost, pipe and fittings, pumping equipment, etc., for ten pipeline companies were analyzed. Those cost elements which are doubled or otherwise increased by the construction of the second line were segregated, and that portion of the cost was increased according to the seven-tenths power law which is commonly used for estimating the effect of scale on plant construction.

Next, the actual cost of a large gas pipeline, i.e., 42-in-diameter and greater than 1000-mile length, which was completed in 1975, was reviewed. That cost was first escalated to 1977, using the Oil and Gas Journal pipeline construction cost index. Then, using that baseline estimate and the cost model described above, the cost of a two-way, 48-in freight pipeline was estimated. The result was an estimate of $2.08 million per mile.

Independent of the effort just described, discussions were held with Tubexpress Systems, Inc.,of Houston, a subsidiary of Transco. Tubexpress agreed to cooperate, and accordingly conducted a number of computer runs on their cost model for the Tubexpress system. This is the same model which they use in preparing their commercial quotations, and is naturally much more detailed and specific than the cost model developed under this study and described above. For the 48-in line, their construction cost estimate was $1.85 million/mile for a 500-mile length. Interestingly, the cost was found not to be highly sensitive to length.

These results were then applied to the pipeline economic model (PEM) developed earlier in this project and described in Reports R-3021 and R-3069, to determine what throughput would be required to achieve economic viability if the average tariffs projected in Section 5.4 above could be realized. It was concluded that the system would require a throughput exceeding 10 million tons/year. At what appear to be reasonable capsule speeds and separations, as indicated by Marstens, this throughput is consistent with utilization factors as low as 30%.

While this analysis is much too preliminary to justify any broad conclusions, it does seem clear that the concept merits further study. Such study is therefore strongly recommended.

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