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Oil Pipeline Energy Consumption and Efficiency

J. N. Hooker

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OIL PIPELINE ENERGY CONSUMPTION AND EFFICIENCY

J. N. Hooker

Research Assistant
R. B. Hofstra

Regional and Urban Studies Section

Energy Division

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
Operated by
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ABSTRACT

This report describes an investigation of energy consumption and efficiency of oil pipelines in the U.S. in 1978. It is based on a simulation of the actual movement of oil on a very detailed representation of the pipeline network, and it uses engineering equations to calculate the energy that pipeline pumps must have exerted on the oil to move it in this manner. The efficiencies of pumps and drivers are estimated so as to arrive at the amount of energy consumed at pumping stations. The throughput in each pipeline segment is estimated by distributing each pipeline company's reported oil movements over its segments in proportions predicted by regression equations that show typical throughput and throughput capacity as functions of pipe diameter. The form of the equations is justified by a generalized cost-engineering study of pipelining, and their parameters are estimated using new techniques developed for the purpose. A simplified model of flow scheduling is chosen on the basis of actual energy use data obtained from a few companies. The study yields energy consumption and intensiveness estimates for crude oil trunk lines, crude oil gathering lines and oil products lines, for the nation as well as by state and by pipe diameter. It characterizes the efficiency of typical pipelines of various diameters operating at capacity. Ancillary results include estimates of oil movements by state and by diameter and approximate pipeline capacity utilization nationwide.

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SUMMARY

Purpose

The objective of this study is to learn how much energy oil pipelines used in the United States in 1978 and how efficiently they used it. The study was undertaken because existing estimates of these quantities differ by as much as a factor of 10 (Chap. 3).* It was hoped that by conducting an investigation more thoroughgoing than its predecessors, more reliable estimates could be had. The year 1978 was chosen because it is the most recent year for which all the relevant data are available.

The difficulty of the problem does not stem from any mystery about how oil pipelines use energy. Given the diameter, flow rate, and other relevant parameters, an engineer can calculate the energy consumption of a specific pipeline with ample accuracy. The difficulty lies in the fact that these parameters vary along the 250,000 km (150,000 miles) of trunk pipeline in the United States. To make matters worse, energy efficiency is highly sensitive to some of them. In particular it is very sensitive to the rates of flow, which are not made public by pipeline operators and are difficult to ascertain. If pipeline companies reported their energy use to the government or to some other organization, there would be no problem. But they do not.

The pipelines covered in this study include essentially all U. S. oil products pipelines, all crude oil trunk lines, and all crude oil gathering lines, both regulated and unregulated. Separate energy use estimates are developed for these classes of pipelines. The products lines covered included not only carriers of such traditional pipeline liquids as gasoline, jet fuel and fuel oil but carriers of liquefied petroleum gases (LPG) and liquefied ammonia as well.

It was anticipated that several sorts of information that had not been forthcoming from earlier studies could be developed. They are as follows.

1. Approximate oil pipeline energy use and efficiency <u>in each state</u> in 1978.

2. Approximate pipeline energy use and efficiency <u>for each pipe diameter</u>. It is well known that large-diameter pipelines operate much more efficiently than smaller pipelines. The rate at which efficiency improves with increasing diameter is easily calculable when the rates of flow for each diameter are specified. The difficulty, of course, is

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*Chapter and section references indicate where in the body of this report one can find more detailed discussion.

knowing how the rate of flow depends on diameter. An aim of this study has been to calculate the average efficiency for each diameter in 1978, based in part on estimated rates of flow that actually obtained across the pipeline network in 1978.

3. The connection between throughput capacity and diameter for existing pipelines. The aim here has been to perform a regression analysis that would yield a simple formula predicting the typical throughput capacity for a pipeline of a given diameter, based on actual capacity data. Such a formula would tell one roughly how much oil he could expect a pipeline of a given diameter to be able to transport.

4. The rate at which efficiency improves as diameter increases for typical pipelines operating at capacity. This would be based on the typical throughput capacities resulting from the regression analysis just mentioned. It would permit one to estimate roughly the minimum efficiency at which a pipeline of a given diameter would operate. (A pipeline is less efficient when running at a capacity than when running under capacity.)

5. A machine-readable data set showing for nearly every trunk pipeline in the United States those aspects relevant for energy calculations. The preparation of this and other data sets consumed the bulk of the labor devoted to the project, but now they are available for other studies as well.

6. Sundry technical results and statistical methods developed in the course of estimating energy use.

Method

There are basically three ways to ascertain how much energy oil pipelines use.

1. Ask the pipeline companies (there are about 220 of them).*
2. Use reported fuel expenditures as a basis for estimating the amount of fuel purchased.
3. Try to determine the manner in which oil actually flowed through the network and use engineering principles to estimate energy consumption on that basis.

The first method was rejected for three reasons. First, it was thought best to carry out this project in a way that adds as little as possible to the governmental burden imposed on the pipeline business. Second, the

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*Some companies do not know how much energy they use for pumping oil.

method adopted should be able to produce annual updates with only a little extra effort. Obtaining energy data from 220 companies, some of whom would be reluctant to cooperate, would be laborious and time-consuming. Third, if energy data were obtained directly from the companies, the system that consumed that energy would remain a black box. No understanding would be gained about what is happening in the system and how it affects energy use.

A variation on the first method is to contact a few "representative" pipeline companies, and this has been tried (Sect. 3.1). But companies differ so greatly in their energy characteristics that it is impossible to know which are representative without in effect carrying out the third method.

The second method has also been tried (Sect. 3.3). It is severely limited by the lack of reliable estimates of the average price paid for pipeline fuel, and it was rejected for that reason.

That leaves the third method, the one adopted here. It is a combination of statistics and engineering. It involves (1) simulating the active movement of oil over the network, as nearly as data and statistical techniques permit, and (2) using engineering equations to calculate the energy that pipeline pumps must have exerted on the oil to move it in this manner. The efficiencies of pumps and drivers can then be estimated so as to arrive at the amount of energy consumed by pumping stations.

The method for estimating the energy use of crude and products trunk lines is depicted schematically n Fig. S.1. It consists of the following four stages (Chap. 5).

I. Estimate throughput in each pipe (Boxes 1 and 2 in Fig. S.1)

Divide each company's pipeline network into homogenous segments, or lengths of pipe over which there are no diameter changes or connections, and estimate the annual throughput in each of these segments (Sect. 7.4). Do this by allocating each company's reported oil movements (in m^3-km or bbl-mile) to its segments in a way that takes into account the diameter and throughput capacity of each segment. Specifically, the ratios by which oil flow is distributed among the segments should be those predicted by a regression formula that expresses throughput as a function of diameter and reported or estimated capacity. The functional form should be justified independently by a generalized cost-engineering study (Sect. 6.1–6.2). The estimation of its coefficients will require that unorthodox statistical procedures be developed for the purpose (Sects. 6.3 through 6.5).

II. Model flow scheduling (Box 4)

Note that even once the annual throughput in a pipeline segment is known, it cannot be assumed that the oil flows at the same rate all year.

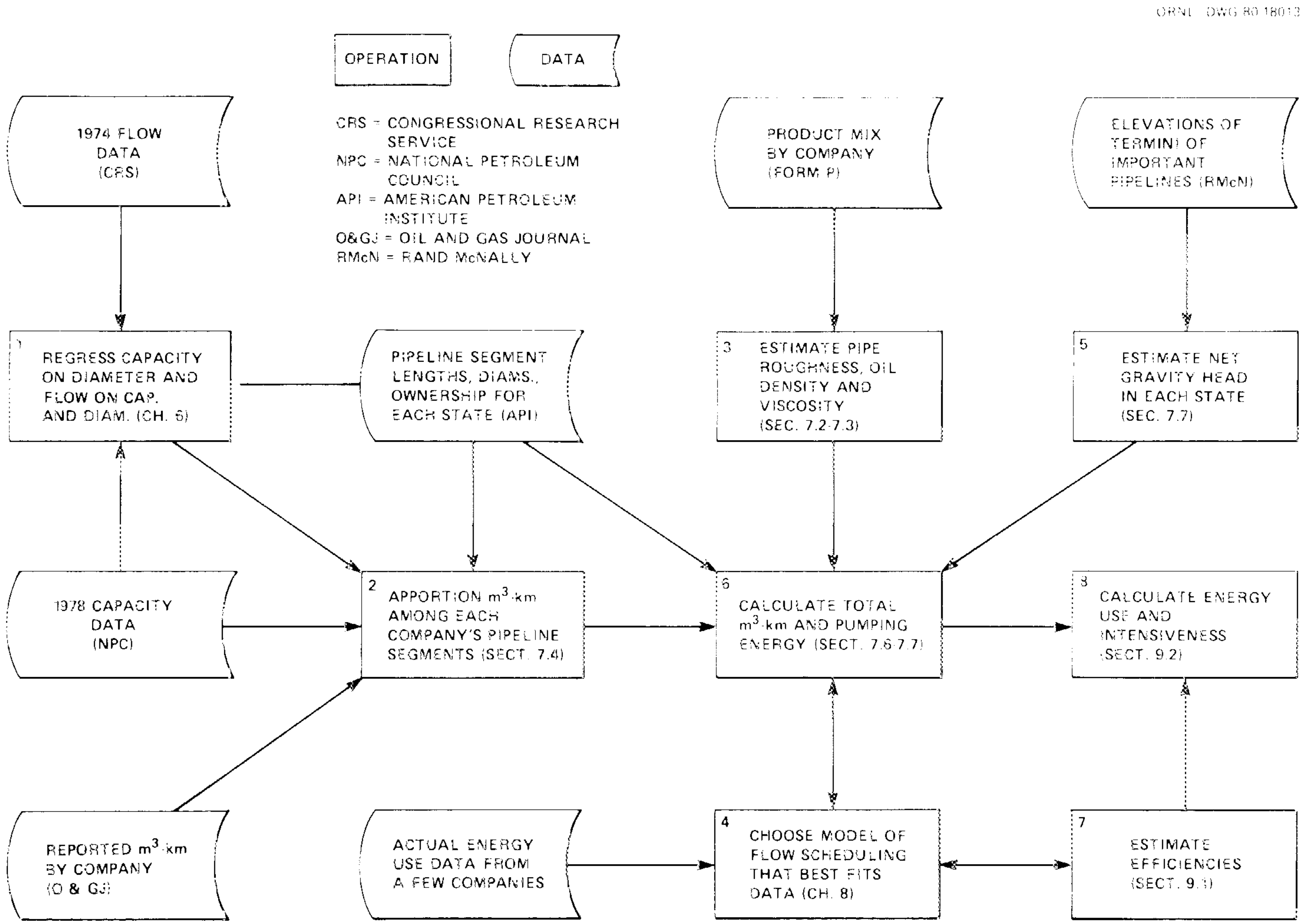

Fig. S.1. Flow chart for estimation of oil trunk line energy consumption.

Contact about a dozen pipeline companies so as to obain actual energy consumption data, and use these data to choose the most realistic of several simplified models of flow scheduling (Chap. 8).

III. Calculate pumping energy (Boxes 3, 5, and 6)

Use the flow rate in each segment, along with its diameter and length (Sect. 7.1) and the density and viscosity of the oil (Sec. 7.3), to calculate the pumping energy required to overcome friction generated by the flowing oil (Chap. 2; Sects. 7.6 and 7.8). Pumping energy is defined here to be the mechanical energy actually delivered to the oil by the pumps. Adjust the resulting energy figure by taking into account how much oil must be pumped uphill and how much downhill (Sect. 7.7).

IV. Estimate efficiencies (Boxes 7 and 8)

Estimate the efficiency with which electric power plants, pump station engines, electric motors, and pumps convert primary energy to pumping energy (sect. 9.1). Use the company data obtained for Stage III to help calibrate this efficiency. Divide the calculated pumping energy by this efficiency to arrive at pipeline energy consumption (Sect. 9.2).

It remains to estimate the energy consumption of crude oil gathering lines. Since oil movements (m^3-km or bbl-mile) in gathering lines are not reported and are extremely difficult to infer, only rough estimates of energy use are possible. The method is as follows (Sect. 7.9). Let the throughput for each size line be 80% of the predicted capacity of a line of that diameter, as given by a regression formula. Compute the resulting average length of haul, in each state, which sometimes is unreasonably long due to the presence of idle lines. To compensate, reduce any state's average length of haul that is over the national average to the national average. Compute energy consumption on the basis of the resulting movements.

Results

Table S.1 provides an overall picture of oil pipeline energy use, as it is estimated by this study. Note that rather than showing energy efficiency, the table shows its inverse, energy intensiveness. A pipeline that is more energy intensive than another uses more energy per unit of transportation and is therefore less efficient (see Sect. 1.2). The results of this study are compared with those of earlier studies in Table 3.1 of Chap. 3.

All results of this study assume, unless stated otherwise, that the efficiency of electrical generation and transmission is 32.3%. This figure is higher than the more customary 30% (sometimes 22%) because it correctly counts hydroelectric generation as 100% efficient, whereas the other figures seem to ignore hydroelectricity (Sect. 9.1). It is

Table S.1. Oil pipeline energy consumption and intensiveness in 1978[a]

	Assuming 32.3% efficiency of electric generation and transmission			Assuming 30% efficiency of electric generation and transmission		
	Energy consumption	Energy intensiveness		Energy consumption	Energy intensiveness	
		By mass	By volume		By mass	By volume
Crude oil trunk lines	86×10^{15} J (0.082 quad)	180 J/kg-km (250 Btu/ton-mile)	150 J/m^4 (37 Btu/bbl-mile)	91×10^{15} J (0.087 quad)	190 J/kg-km (270 Btu/ton-mile)	160 J/m^4 (40 Btu/bbl-mile)
Crude oil[b] gathering lines	10×10^{15} J (0.0096 quad)	350 J/kg-km (490 Btu/ton-mile)	300 J/m^4 (73 Btu/bbl-mile)	11×10^{15} J (0.010 quad)	380 J/kg-km (520 Btu/ton-mile)	320 J/m^4 (78 Btu/bbl-mile)
Oil products pipelines	64×10^{15} J (0.061 quad)	220 J/kg-km (300 Btu/ton-mile)	160 J/m^4 (40 Btu/bbl-mile)	68×10^{15} J (0.064 quad)	230 J/kg-km (320 Btu/ton-mile)	180 J/m^4 (42 Btu/bbl-mile)
Total	160×10^{15} J (0.15 quad)	200 J/kg-km (280 Btu/ton mile)	160 J/m^4 (40 Btu/bbl-mile)	170×10^{15} J (0.16 quad)	210 J/kg-km (290 Btu/ton-mile)	170 J/m^4 (42 Btu/ton-mile)

[a]All estimates rounded to two significant digits.

[b]Gathering lines figures are less reliable than the others.

important to be aware of which efficiency is assumed, since roughly 80% of oil pipeline pumping power is supplied by electric motors, and estimates of energy consumption must account for the energy that is consumed to generate the electricity. Table S.1 shows energy figures predicated on both the 32.5% and 30% efficiencies, to permit comparison with figures derived elsewhere that assume the more popular 30% efficiency. But all subsequent tables presuppose 32.3% efficiency. Sect. 9.1 tells how to convert from one efficiency to another.

Table S.2 shows estimates of the total oil movements both in pipelines regulated by the federal government and those not regulated. The table is discussed in more detail in Sects. 7.4 and 9.3. The Conclusions section explains its significance.

Table S.3 compares the energy consumption and intensiveness of oil pipelines with those of other modes of energy transport.

Other tables and graphs in this report provide the additional sorts of information sought as part of this study and enumerated 1 through 6 in the Purpose. Most of these tables and graphs need interpretation, and it is provided as part of the Conclusions section.

1. 1978 energy use and intensiveness by state appears in Tables 9.3 and 9.4 in Chap. 9. Tables 7.5 and 7.6 of Chap. 7 show more detail concerning gravity head and gathering lines in each state, respectively. Appendix B provides energy and throughput estimates broken down by pipe diameter in each state.

2. 1978 energy use and intensiveness by pipe diameter appear in Tables 9.5 and 9.6. The little circles in Figs. S.2 and S.3 plot 1978 energy intensiveness against diameter.

3. The general connection between throughput capacity and diameter is evinced by Tables 9.7 through 9.9. Chapter 6 presents in detail the results of the regression study that investigated this relationship.

4. Tables 9.7 through 9.9 and the lines plotted on Figs. S.2 and S.3 show the way that energy intensiveness varies with diameter for pipelines operating at capacity flow rates typical for their size. Figure S.4 shows what happens to energy intensiveness when the rate of flow is made to vary about the typical capacity rate for each diameter. Table 9.10 shows how fully U.S. pipelines appear to be utilized and what would happen if they were all to run at capacity. This table requires careful interpretation, which is provided in the Conclusions section.

5. The pipeline network and other data sets are described in appendices to this report. The network representation, as well as the list of capacity versus diameter observations, appear to be the most complete that are publicly available.

6. A few of the results of the project that were garnered along the way are interesting in their own right. Among them are

Table S.2. Estimated oil pipeline movements by type of carrier, 1978

Type of carrier	Movements					
	Crude oil pipelines			Oil products pipelines		
	10^9 m^3-km	10^9 bbl-mile	Percent	10^9 m^3-km	10^9 bbl-mile	Percent
All carriers accounted for in this study	347.2	2184	100	241.2	1517	100
Regulated carriers for which movements were reported	311.4	1959	90	224.6	1413	93
Regulated carriers for which movements were estimated	3.7	23	1	1.1	7	0
Unregulated carriers[c]	32.1	202	9	12.1	76	5
Pipelines of unknown ownership	0.0	0	0	3.3	21	1
Sum of excess of reported movements over estimated carrier capacity for carriers showing an excess[a]	8.7	55	3[b]	2.5	16	1[b]
Regulated carriers not accounted for in this sutdy[a]	10.3	65	3[b]	2.7	17	1[b]

[a] Explained in Sect. 7.4.

[b] Percent of total movements of carriers accounted for in this study.

[c] Coverage may be incomplete; see Sect. 7.4, 9.3 and the Conclusions section of the Summary.

Table S.3. Comparison of energy intensiveness for several modes of energy transport[a]

Mode	Energy intensiveness			
	By mass		Percent of the energy transported	
	J/kg-km	Btu/ton-mile	Per 1000 km	Per 1000 miles
Oil by pipeline:[c]				
Crude oil	190	270	0.4	0.7
Oil products	230	320	0.5	0.8
Natural gas by pipeline[d]	1440	2000	2.5	4
Oil by water:				
Coastal tanker or barge[e]	350	480	0.8	1.2
Lakewise tanker[f]	470	650	1.0	1.7
Lakewise barge[f]	220	300	0.5	0.8
River barge[f,g]	350	480	0.8	1.2
Coal by water:				
Lakewise freighter[f]	390	540	1.3	2.1
Lakewise barge[f]	220	300		
River barge[f,g]	350	480	1.1	1.8
Oil by rail[f]	470	650	1.0	1.7
Coal by rail[f]	250	340	0.8	1.3
Oil by truck[f]	1430	1980	3.2	5.1
Coal by truck[f]	1630	2260	5.4	8.7

[a]The energy intensiveness of a mode of transport is highly sensitive to the route, speed, size of vehicle, etc. These figures are rough averages, in some cases very rough.

[b]Assumes 45.3×10^6 J/kg (39×10^6 Btu/ton) for all oils, 30.2×10^6 J/kg (26×10^6 Btu/ton) for coal, 54.6×10^6 J/kg (47×10^6 Btu/ton) for natural gas.

[c]As estimated by this study.

[d]As estimated by Banks (1977, p. 2-2).

[e]As estimated by Rose in Hooker et al. (1980, p. 11).

[f]As estimated by Rose (1979).

[g]Ignores circuity of 1.9.

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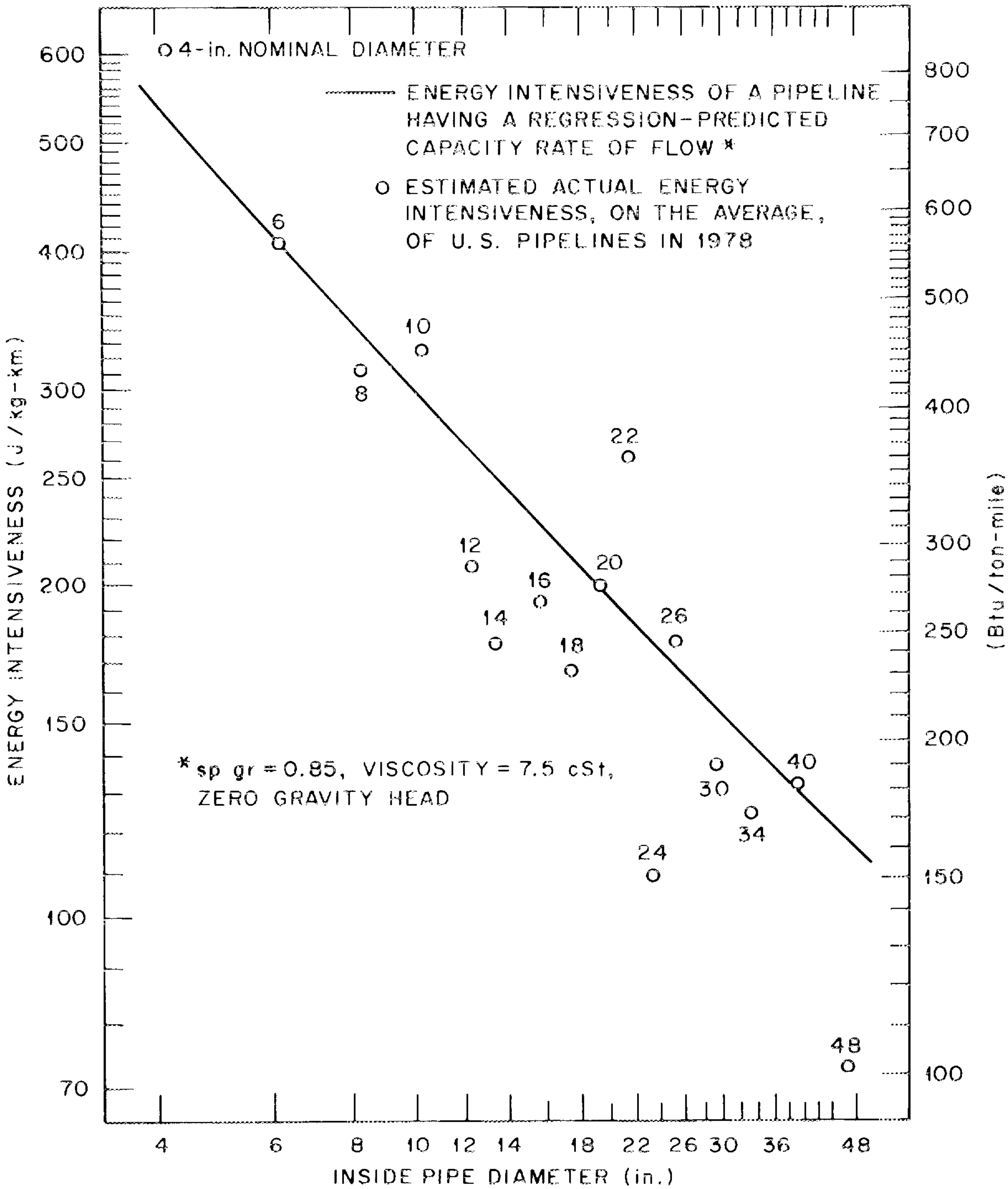

Fig. S. 2. Energy intensiveness vs. diameter of U. S. crude oil pipelines in 1978.

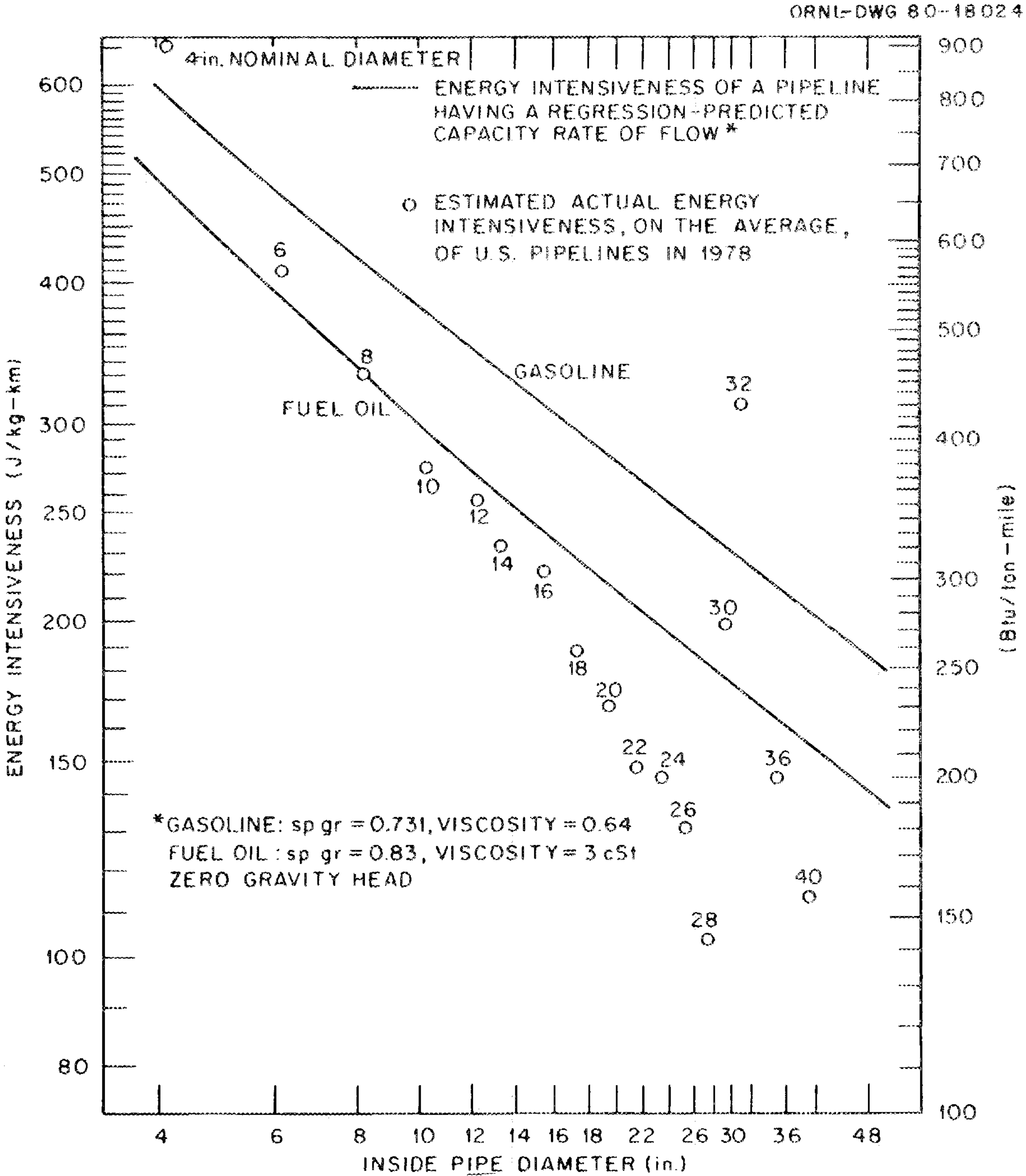

Fig. S.3. Energy intensiveness vs. diameter of U.S. oil products pipelines in 1978.

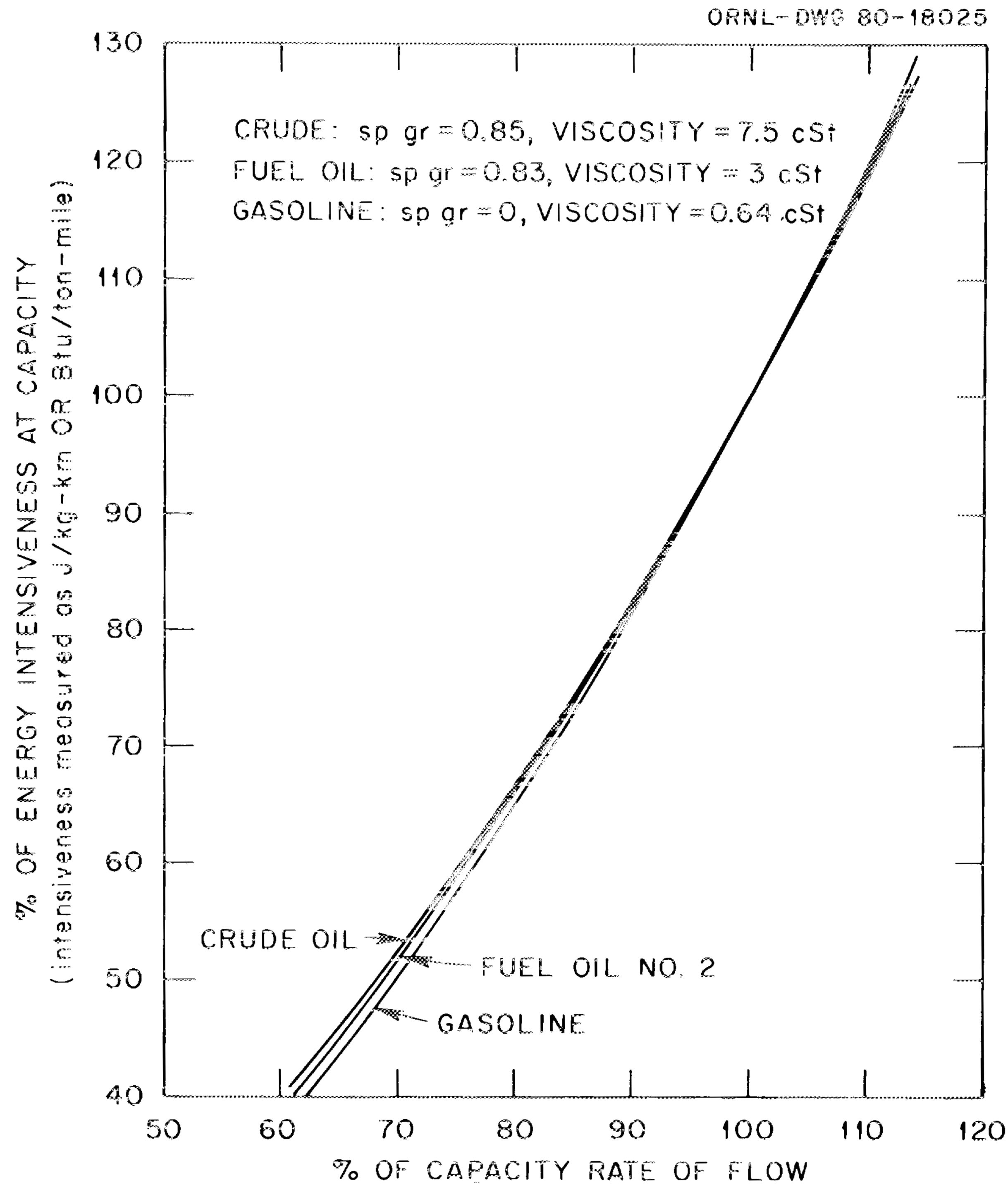

Fig. S.4. Energy intensiveness vs. instantaneous flow rate of any given pipeline carrying crude oil, gasoline or fuel oil.

1. The method and conclusion of the engineering-economic analysis of pipeline dimensions vs. capacity that is carried out in Sect. 6.1.
2. The statistical methods developed in Sects. 6.3 and 6.4.
3. The review of past work in Chap. 3.

Energy consumption data obtained from a few pipeline companies suggest that the national energy consumption estimates are probably accurate to within ±10% for crude lines and ±15% for products lines (Sect. 8.3). The crude gathering lines estimate is much less reliable. The numbers provided for individual states and pipe diameters are less reliable than the national figures. Since a 95% confidence interval for any given pipeline company's energy estimate is ±35 to 40% (Sect. 8.3), estimates for states in which only one or a few companies operate could show errors of ±20 to 40%. Other states can be expected to receive more accurate estimates. The estimates for these other states and the nation as a whole are accorded more credence because a certain amount of independence among the errors that occur in company estimates is assumed. If the errors are more systematic than expected, the national confidence intervals should be widened. The Conclusions section and Sect. 9.3 discuss the vulnerability of the estimates to misreporting of data.

Conclusions

1. Oil trunk pipelines are the most efficient carriers of energy materials, in two ways. They use the smallest fraction of the energy content of the material carried, and they move more of this material per unit of energy consumed (Table S.3). To be sure, other modes of transport can in certain instances operate more efficiently than oil pipelines, but oil pipelines excel when one entire transport system is compared with another.

2. Oil pipelines consumed only about 5% of the 3.23×10^{18} J (3.06 quads) consumed in 1978 for freight transport (see Table S.1 and Kulp et al., 1980, p. 1-28). Their consumption was the equivalent of 12,000 m^3 (75,000 bbl) of crude oil per day, or about 0.2% of the national energy diet of the equivalent of 5.9 million m^3 (37 million bbl) of crude oil per day (Kulp et al. 1980, p. 1-8).

3. The energy intensiveness of oil pipelines is less than may have been expected (Table S.1), certainly less than most previous estimates (Table 3.1 in Chap. 3). The high efficiency owes mainly to the fact that many pipeline companies do not run their lines at capacity. This apparent slack in many pipelines results in lower energy intensiveness because it permits the oil to be pumped more slowly on the average. (A 10% reduction in the rate of flow in a given pipeline results in a 17% reduction in energy intensiveness; see Chap. 2.) Table 9.10 shows that energy intensiveness would rise about 28% for crude lines and 41% for product lines if all pipelines were run at capacity. It is explained below, however, that these estimates of energy use at capacity are upper bounds that very probably would never be achieved in practice.

4. The energy intensiveness of pipeline operations varies considerably from one state to another (Tables 9.3 and 9.4). It is mainly a function of which states contain the efficient large-diameter pipelines, and in a few mountainous states a function of the effect of gravity.

5. Figures S.2 and S.3 show that although efficiency generally increases with diameter, there is a good deal of scatter in the points (see also Tables 9.5 and 9.6). This scatter results from the fact that efficiencies are nearly as much affected by variations in flow rate as by diameter, even when national averages are taken.

The crude pipeline scatter in Fig. S.2 appears fairly random. Yet all but one of the points lie near or below the diagonal line, which is to be expected because this line depicts the energy intensiveness typical of lines running at capacity. The one exception is the value for 22-in. lines,* which is high because a certain 22-in. Texas Pipe Line Company line in Texas and Louisiana is reported to have a surprisingly high throughput capacity.

It shuld be understood that even if all pipelines operated at capacity, a fair amount of scatter would remain. This is because a pipeline generally begins operating with a capacity somewhat below the capacity that can ultimately be achieved by adding more pumping power. The fact that different pipelines are in different stages of this development of capacity would result in an uneven relationship between energy intensiveness and diameter even if all lines ran at capacity. For example, the 1978 capacity of the fully-utilized Trans-Alaska Pipeline (represented by the 48-in. value in Fig. S.2) was less than its ultimate design capacity, and the pipeline's energy intensiveness consequently falls below the line.

The products pipeline scatter in Fig. S.3 is less random. Pipeline sizes up to 28 in. show a fairly regular descent in energy intensiveness. This may reflect declining utilization as well as increasing diameter. The high intensiveness for 30 and 32-in. lines is due to the high capacities reported for the strategic Colonial lines in Virginia, Maryland, and New Jersey, a matter discussed in Sect. 9.3. The 32-in. Colonial line is currently being looped to relieve the bottleneck (Pipeline Industry 1980, p. 31).

It is clear that the pattern of points in Figs. S.2 and S.3 is as much a function of the logistics of pipeline movement in 1978 as the inherent efficiencies of the different diameters. This was fully expected, and it is precisely the reason the study of pipeline energy use is as difficult as it is.

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*This report uses those SI units of measurement recommended by the Oil Companies Materials Association for use in the petroleum industry (Hobson and Pohl, 1973, p. 961). This body recommends that inches be retained as the measure of pipeline diameter.

6. One who wants a measure of the "inherent" efficiencies of various pipe diameters can get it by expressing the capacity flow rate of a given diameter as an appropriate function of the diameter. The flow rate predicted by this function can then serve as a basis of calculating the energy intensiveness at capacity for each diameter. A cost-engineering study (Sect. 6.1) found that the function can reasonably be taken to have the form of a simple power function. The coefficients in this function which provide the best fit to observed capacities were estimated using a regression technique that had to be developed for the purpose (Sect. 6.2). The results are reflected in Tables 9.7 through 9.9 and by the diagonal lines plotted in Figs. S.2 and S.3. They imply that the tendency of efficiency to increase with diameter is somewhat tempered by the fact that oil usually flows more rapidly in larger pipes (see Fig. 3.1 in Chap. 3). It should be borne in mind, however, that the predicted velocity in large products lines would be less if the Colonial lines mentioned above had had capacities more typical of their diameters.

A planner who wants a rough indication of the energy intensiveness and oil throughput of a proposed pipeline operating at capacity can consult Tables 9.7 through 9.9 and Figs. S.2 and S.3. If the throughput is expected to be other than the predicted values shown in the tables, he can use Fig. S.4 to make adjustments. For instance, suppose a proposed 36-in. crude oil pipeline is to carry 80,000 m^3/d (500,000 bbl/d). The energy intensiveness of a 36-in. crude line carrying 112,000 m^3/d is estimated in Table 9.7 to be 139 J/kg-km (193 Btu/ton-mile). Since the proposed throughput is 71% of 112,000 m^3/d, Fig. S.4 indicates that the resulting energy intensiveness should be about 53% of 139 J/kg-km, or 74 J/kg-km (102 Btu/ton-mile).

7. Although the subject of this investigation is energy use and not pipeline utilization, the remarkably low utilization figures in Table 9.10 deserve attention. They put oil pipeline capacity utilization at 73% for crude lines and 57% for products lines. These figures clearly indicate that there is considerable slack in the U.S. pipeline system. Nonetheless they are highly misleading, because they induce one to overestimate the ease with which pipelines can meet demand for transport. This is true for two reasons. First, although parts of the system are slack, many of the principal links run at capacity. Notable examples are the Capline crude oil pipeline and the Colonial products system. There are also a number of strategically located lines, both large and small, that cannot satisfy demand, such as the Platte pipeline from Kansas to North Dakota. The existence of slack in the system, then, is compatible with capacity shortages in many areas.

Another reason the utilization factors in Table 9.10 are misleading is that they are ratios of actual to capacity movements (in m^3-km or bbl-mile), not actual to capacity throughputs (m^3 or bbl). To see what this means recall that a pipeline (particularly a products pipeline) may have several terminals or connections along it, one or more for receiving oil and several for delivering it. The throughput of such a pipeline is the total amount of oil that is turned out of the line at delivery terminals. The oil movement for each segment of pipe along the way is the product of the volume that passes through it and its length; the oil movement for the whole pipeline is the sum of the movements of its segments. Consequently a pipeline is running at 100% movement capacity only if every inch of it is carrying all the oil it can. A pipeline is at 100% throughput capacity if no more oil can be got to the delivery terminals. It is evident that if there were a bottleneck along the way -- such as a stretch of pipe having less capacity that the pipe on either side of it -- a pipeline could operate at 100% throughput capacity even while operating at less than 100% movement capacity.

Furthermore, a pipeline may be unable to meet demand even while running at less than throughput capacity. This happens when the capacity at various points along a pipeline does not match the demand at its terminals, so that some terminals cannot meet local demand while others have excess capacity.

To take an example, the large Colonial products pipeline system was, according to calculations of this study, operating at about 75% movement capacity in 1978. Yet the system was by all accounts taxed nearly to the limit. The data were double-checked without uncovering an error. The most likely explanation is that the system contains certain bottlenecks that result in a mismatch of capacity and demand and that prevent complete utilization of the entire network. More generally, the fact that the products pipeline utilization is lower than crude pipeline utilization may derive entirely from the fact that demand for oil products is logistically more complex and thus more difficult to match with pipeline capacity.

The utilization factors of Table 9.10 should be read with these thoughts in mind. Furthermore, the corresponding energy intensiveness figures should be regarded as absolute upper bounds. This is because it is highly unlikely, for reasons just explained, that the U.S. pipeline system could ever operate at 100% movement capacity.

8. The movements figures in Table S.2 indicate that 90% of crude oil and 93% of oil products movements occur in federally regulated pipelines. If this is the case, it is significant because the Department of Transportation (DOT) has traditionally assumed that regulated carriers are responsible for about 84% of oil movements, measured in ton-miles (see U.S. Department of Transportation 1978). DOT bases its extrapolation from known reported movements to otherwise unknown total movements on this 84% figure. Yet the unregulated companies covered by Table S.2 are only those represented on API maps (American Petroleum Institute 1977). Since this coverage may be incomplete, no conclusion should be drawn at this point. This matter is discussed further in Sect. 9.3.

9. It was stated earlier that the national pipeline energy use estimates offered here are probably correct to within ±10 to 15%. The same could reasonably be said of the estimates of energy intensiveness nationwide. Yet these estimates are highly sensitive to the oil movements in barrel-miles that pipeline companies report to the Federal

Energy Regulatory Commission. The fact that many company systems appear to be underutilized may lead one to suspect that the companies have underestimated oil movements. A 10% average underestimate would cause roughly a 10% underestimate of energy intensiveness and a 20% underestimate of energy use. There is in fact reason to believe that pipeline companies usually misestimate their oil movements (Sect. 9.3). Yet this is not to say that the misestimates are systematic. The energy use data obtained from a few companies (Sect. 8.3) are reasonable in relation to reported movements, and they provide no reason to believe the movements are understated. In general there is no evidence that systematic errors in reported movements invalidate the results of this study.

Another type of error that could prejudice the results, if it were systematic, is error in the reported capacity of particular lines. These capacity estimates were got from pipeline companies by the National Petroleum Council as part of a recent study (see Chap. 4). Although it has been suggested that companies have an incentive to underreport capacity, no evidence of such has been uncovered in this study. Some of the capacity figures are suspicious, but due to the wide range of design pressures under which a pipeline can operate, none are so extreme as to be clearly false. Nor does there seem to be anything systematic about the apparent errors. Errors in reported capacities for individual lines may bias the energy intensiveness estimates for particular states or pipe diameters (particularly the larger diameters), but it is unlikely that the national estimates are significantly affected.

1. INTRODUCTION

This report describes an investigation of oil pipeline energy consumption and efficiency in the United States in 1978. The investigation was carried out at Oak Ridge National Laboratory in 1979 and 1980. Its purpose and scope are set out in the preceding Summary.

1.1 Organization of the Report

The report is prefaced with a fairly comprehensive summary designed to familiarize the nontechnical reader with the purpose, method, results, and conclusions of the investigation. The Method section of the Summary is redundant of the body of the report, but the Purpose, Results, and Conclusions sections contain material that can be found only in the Summary.

The body of the report begins with a short discussion of the physical determinants of pipeline energy use and efficiency (Chap. 2). It then surveys previous work on the problem and singles out four studies for criticism (Chap. 3). After describing the sources of data that are available (Chap. 4), it provides an overview in Chap. 5 of the methods used to estimate energy consumption. The overview attempts to explain how the various stages of the method, described in Chaps. 6 through 9, fit together. Chapter 9 ends with a discussion of the results that supplements the conclusions drawn in the Summary.

The following section attempts to sort out the many ways in which the energy intensiveness of transportation can be measured. It should be helpful in interpreting the different kinds of energy intensiveness estimates that appear in this report.

1.2 The Notion of Energy Intensiveness

An energy intensive operation is one that consumes a relatively large amount of energy in exchange for a reduction in the consumption of other resources. The term "energy intensive" seems to derive from economics, which has long spoken of "labor intensive" agriculture, or agriculture that reduces land and capital requirements by employing a large labor force. Energy intensiveness (often termed "energy intensity") is measured by taking the ratio of the energy consumed to the quantity of goods produced as a result of its consumption.

In transportation, the "quantity of goods produced" must be interpreted as some measure of the amount of transportation provided. There are at least three ways to do this. The most prevalent is to measure transportation as the product of the mass of the cargo and the distance covered. The resulting unit of energy intensiveness is the joule per kilogram-meter (J/kg-m), or more commonly the joule per kilogram-kilometer (J/kg-km = kJ/t-km), or in the English system the Btu per ton-mile. Since the cargo is measured by its mass, this unit might be described as a unit of hylimetric energy intensiveness (from the Greek for "matter"), to distinguish it from the other units to be discussed shortly. The J/kg-km is equivalent to a unit of acceleration, mm/s^2, and it in fact represents the constant acceleration that would be delivered to the cargo if all the energy were devoted to its acceleration. (In reality, most energy consumed is lost in its conversion to mechanical energy or is used to overcome friction.) 1000 Btu/ton-mile is similarly equivalent to 2.37 ft/s^2.

Another way of reckoning the quantity of transportation has the advantage that it results in a dimensionless measure of energy intensiveness. It takes this quantity to be the product of cargo weight and distance rather than of cargo mass and distance. The resulting sort of energy intensiveness, measured as joules per newton-meter (J/N-m), or in the English system as Btu per ton-mile (weight tons rather than mass tons), might be called barimetric energy intensiveness. It is dimensionless because J/N-m = N-m/N-m. The barimetric intensiveness can be got by dividing the hylimetric intensiveness in J/kg-m by gravitational acceleration, 9.8067 m/s^2. The same result can be got by dividing Btu/ton-mile by 13.58.

Barimetric energy intensiveness also has the advantage that it permits more than one interpretation, depending on the transport mode in question. Since barimetric intensiveness can be expressed as N-m/N-m, the distance unit can be cancelled to obtain a ratio of a kind of generalized resistance to the weight of the cargo. In other words, if all the energy consumed were devoted to overcoming the force of resistance, then the ratio of this force to the cargo weight would be the barimetric energy intensiveness. This interpretation is especially appropriate to water transport, where overcoming gravity is of no concern and overcoming resistance is paramount, and somewhat appropriate to land vehicles. Another interpretation, very useful for pipelines, can be had by cancelling the force units in the fraction N-m/N-m to obtain a ratio representing the total head in meters or feet per unit distance (assuming all the energy consumed goes to maintaining head, and none is lost in drivers and pumps). The "head" in a pipeline is simply a way of measuring the pressure exerted to overcome friction and gravity. To say that the total head in a given oil pipeline is 3 m/km, for instance, is to say that a vertical column of oil 3 m high would provide the right pressure to move the oil at its present speed through 1 km of pipe. Since there are losses in the drivers and pumps, however, the overall energy intensiveness of the pipeline, expressed as head per km, would be greater than 3 m/km, perhaps about 10 m/km (10 m/km is of course equivalent to the dimensionless ratio of 0.01, which is a somewhat less convenient scaling for pipeline work).

Though dimensionless, barimetric energy intensiveness is hardly an absolute quantity, since it is inversely proportional to gravitational acceleration. Most forms of transport (except perhaps elevators) would test at a substantially higher intensiveness on Mars than on earth, simply because the cargo would be lighter on Mars. Yet since the sort of transportation of concern here is exclusively terrestrial, this dependence on gravitational acceleration is of no consequence.

A third and final way to measure the energy intensiveness of transport is to divide energy consumption by the product of cargo volume and distance covered. The corresponding unit is kilojoules per cubic meter-kilometer (kJ/m^3-km = J/m^4), or Btu per barrel-mile in the English system. It represents the force that would be applied to each unit of cargo volume if all the energy consumed were devoted to exerting a force on the cargo, and it can be expressed accordingly as N/m^3 or lb/bbl. This volumetric measure of energy intensiveness is highly useful in pipeline work for two reasons. One obvious reason is that pipeline movements are popularly measured in bbl-mi or m^3-km, so that it is convenient to express energy intensiveness in Btu/bbl-mile or kJ/m^3-km. A less obvious reason is that volumetric energy intensiveness can be interpreted as pressure drop per unit distance, assuming all the energy in question is devoted to maintaining pressure drop. One J/m^4 corresponds to a pressure drop of 0.1 N/cm^2 per km, and one Btu/bbl-mile to a pressure drop of 0.9618 psi/mile. This is useful for pipelining because expressions involving psi/mile are ubiquitous in pipeline calculations.

2. DETERMINANTS OF PIPELINE ENERGY USE

A liquid does not flow effortlessly through a pipe. Not only must pressure be applied to overcome any net increase in elevation, but additional pressure is required to overcome friction between the fluid and the walls of the pipe. Friction losses are in fact the dominant consumer of energy in most oil pipelines, and nearly all the effort described in the following pages is spent on the estimation of friction.

Friction losses occur because the pipe walls create a drag along the circumference of the moving column of liquid, and the viscosity of the fluid itself transmits part of this drag to the center of the column. Overcoming this drag requires that some, and in most cases nearly all of the mechanical energy provided by the pumps be converted to heat. The amount of energy lost to heat depends in part on the properties of the pipe wall and the viscosity of the liquid.

The relation betewen a pipeline's energy intensiveness and these and other of its determinants can best be seen in a mathematical formula. A handful of engineering formulas have been developed empirically for predicting friction losses in pipe, such as the Fanning formula (Gulf 1978, p. 132) and the Service Pipeline Co. formula (Hale 1975, p. 161). These formulas are all derived by evaluating experimentally the friction factor f in the theoretical D'-Arcy-Weisbach formula for the friction head h_f:

$$h_f = fLv^2/2Dg \ , \qquad (2.1)$$

where L = length of the pipe, (ft),
v = average velocity of flow, m/s (ft/s),
D = inside pipe diameter, in.,
g = gravitational acceleration, 9.8067 m/s^2 (32.17 ft/s^2).

The friction head h_f, measured in meters (feet), is conceived as the amount of work in newton-meters, i.e., joules, required to move a quantity of oil weighing one newton (or the amount of work in foot-pounds required to move a pound of oil) through a pipe of length L. The friction head is therefore a measure of the energy intensiveness of a pipeline, at least as far as friction losses are concerned.

It is instructive to replace the velocity of flow v in formula (2.1) with the volume rate of flow $V = \frac{1}{4}\pi v D^2$ in m^3/s (ft^3/s). This yields,

$$h_f = 8fLV^2/\pi^2 D^5 g \ . \qquad (2.2)$$

Formula (2.2) reveals the startling fact that, at a fixed throughput V, the energy intensiveness of a pipe varies inversely with the fifth power of the pipe diameter. If arteriosclerosis, for example, halves the diameter of a certain artery, then roughly 32 times as much energy is required to maintain the original rate of flow. Formula (2.2) also implies that, when the pipe diameter is fixed, the energy intensiveness varies with the square of the throughput. It is true that f also varies with the diameter and throughput in such a way as to alter these relationships, but it will be seen that the alteration is relatively slight. It can be concluded, then, that pipeline energy intensiveness is highly sensitive to both diameter and rate of flow.

The remaining determinants of pipeline energy intensiveness require an analysis of the friction factor f. The value of f increases with the turbulence and viscosity of the flowing liquid. High viscosity obviously increases friction because it serves better to transmit the drag against the pipe wall to the interior of the pipe. High turbulence also increases friction because the swirls and eddies characteristic of turbulent flow increase the coupling between the slower flow near the pipe wall and the faster flow near the center, thus dissipating the kinetic energy of the center more rapidly.

The viscosity of oil, measured in poises (= dyne-s/cm^2) or lb-s/ft^2, reflects the rate at which one layer of oil flows over another when a specific pressure is applied. Due to the design of viscosimeters, it is customary in the oil business to speak of kinematic viscosity, which is the ratio of a liquid's viscosity to its mass density. Kinematic viscosity is measured in stokes (= cm^2/s), ft^2/s, universal Saybolt seconds, Saybolt furol seconds, Engler degrees and SAE viscosity numbers. Crude oil can be quite viscous, while the viscosities of residual oil, diesel oil, kerosine and gasoline are progressively smaller. The viscosity also depends on temperature, quite critically so in the case of crude oil that is cooled to a temperature near its pour point.

The degree of turbulence depends on the roughness of the pipe wall and on a dimensionless quantity called the Reynolds number. The Reynolds number R is defined,

$$R = vD\rho/\mu \ , \qquad (2.3)$$

where ρ is the mass density of the liquid in kg/m^3 (lb$_m$/ft^3) and μ the viscosity in N-s/m^2 (lb-s/ft^2). R can also be written

$$R = vd/\nu \ , \qquad (2.4)$$

where ν is the kinematic viscosity in m^2/s (ft^2/s). The Reynolds number can be conceived as the ratio of inertial forces created by the swirling eddies, which are proportinal to the numerator of formula (2.3), to viscous forces in the liquid, proportional to the denominator. A high

Reynolds number, then, indicates that the liquid is moving fast enough, the diameter of the pipe large enough, and the density of the fluid great enough to sustain turbulence incited by irregularities in the pipe wall. A wall that is rougher relative to the pipe diameter tends to result in greater friction due to turbulence. The relative roughness of pipe is generally measured as the ratio of the average asperity height ϵ to the inside pipe diameter D.

The dependence of the friction factor f on the Reynolds number and relative roughness for Newtonian, homogenous liquids (such as water or pipeline oil) is well known and widely published in the form of graphs (e.g., Kreith 1973, p. 429; Merritt 1976, pp. 21–30; Gulf 1978, p. 131). An algebraic equation that closely approximates this dependence is presented in Sect. 7.2.

Although the equation in Sect. 7.2 is used throughout this study to calculate the friction factor, a better feeling for the nature of the dependence of f on diameter, throughput, length and viscosity can be had by examining the approximation on which the Standard Pipeline Co. formula (mentioned earlier) is based:

$$f = \text{constant} \cdot (\nu D/V)^{0.252} . \qquad (2.5)$$

Substitution of this into formula (2.2) yields that:

$$h_f = \text{constant} \cdot LV^{1.748}\nu^{0.252}/D^{4.748} . \qquad (2.6)$$

The head still varies roughly with the square of the throughput and roughly with the inverse fifth power of the diameter. Here it is also seen to vary roughly with the fourth root of the kinematic viscosity of the oil.

A summary of the determinants of pipeline energy consumption, in order of importance, might go as follows.

1. The inside pipe diameter is most important. At a fixed throughput, a pipeline's energy intensiveness varies inversely with its fifth power. Fortunately, nominal diameters of U.S. pipelines can be obtained and the inside diameters estimated accurately on that basis.
2. Next in importance is the volume rate of flow, whose square is proportional to the energy intensiveness. Note that it does not suffice to know a pipeline's average daily or average throughput, since its energy intensiveness is not directly proportional to the volume rate of flow. Rather, daily and even hourly fluctuations must somehow be taken into account. Regrettably it is difficult or impossible to ascertain even the average throughput of individual pipelines. The difficulty of estimating throughput and its fluctuations, to which

energy use is so sensitive, stands as the principal obstacle to estimating pipeline energy use. The bulk of this report is devoted to overcoming this obstacle.

3. A pipeline's energy consumption is of course directly proportional to its length, other things being equal. The length of practically any pipeline in the United States can be read with sufficient accuracy from maps, as described in Sect. 7.1.
4. Of less importance is the viscosity of the oil, which is affected by its temperature as well as its composition. Energy intensiveness is proportional to the fourth root of kinematic viscosity. Viscosities of crude oil, however, vary considerably, and this matter is taken up in Sect. 7.3.
5. When a pipeline loses or gains substantial elevation from one end to the other, gravity head is an important component of its energy intensiveness. It is estimated in Sect. 7.7.
6. The roughness of the pipe wall has some effect on the friction factor and hence on the energy intensiveness. A pipe's roughness depends on its degree of corrosion and the presence of any coatings that have been applied. The relatively slight importance of this parameter is established in Sect. 7.2.

3. PREVIOUS WORK

Estimates of typical or average oil pipeline energy intensiveness range in the literature from 217 to 1880 J/kg-km (300 to 2600 Btu/ton-mile) for products pipelines and from 149 to 1880 J/kg-km (207 to 2600 Btu/ton-mile) for crude oil pipelines. The estimates vary greatly in spite of the fact that one can calculate readily the energy intensiveness of a pipeline when the diameter, terrain, flow rate, and other parameters are specified. The difficulty, of course, is that these specifications vary enormously from one pipeline to another, and a profile of "the average pipeline" is not easy to construct. Reasonably accurate estimates of the total movement of oil through pipelines in t-km (ton-miles) are available, but a determination of energy intensiveness requires that this figure be divided into total pipeline energy use, which is unknown (see Chap. 4). Consequently most estimates of pipeline energy use are made on the basis of sample data from a few pipeline companies or on assumptions as to the physical properties of a typical or representative pipeline.

The situation is complicated by the fact that an energy intensiveness number of questionable derivation is sometimes copied from one publication to another until its ignoble origin is forgotten. The mere appearance of a number in so many references may itself be taken as a signal that it is authoritative. For instance, a Pace Company study of future pipeline transport (Fenton et al. 1976, p. 14) adopts an energy intensiveness figure of 300 Btu/ton-mile for crude oil pipelines, and cites as its source a report for the governor of Texas (Holden 1975, pp. 5, 26). The latter report in fact uses the figure 500 ton-mile/gal, which is about 260 Btu/ton-mile not 300 (assuming 130,000 Btu/gal). The Texas report credits a paper in Science magazine (Lincoln 1973, p. 157) as the source of the 500 ton-mile/gal figure. The Science article, in turn, cites an unpublished American Society of Mechanical Engineers paper (Rice 1970, p. 6). But the ASME paper puts pipeline efficiency not at 500 but at 300 ton-mile/gal (about 430 Btu/ton-mile). It mentions, as the source of its energy intensiveness figures, the Transportation Association of America's Transportation Facts and Figures (sic), which is presumably a reference to Transportation Facts and Trends (Transportation Association of America 1969). This last publication provides estimates of fuel consumption by aircraft, trains, automobiles, trucks and ships, but not by pipelines. (This is understandable in view of the fact that pipeline energy use was unknown.) It appears, then, that the energy intensiveness figure in question has not only undergone two alterations but is of untraceable origin.

A table prepared by Jack Faucett Associates (Jack Faucett 1978, p. 151) summarizes well some recent estimates of oil pipeline energy intensiveness. Parts of it are incorporated in Table 3.1, to which the estimates of this report are added at the bottom. To permit comparison of the different estimates, each is converted to a figure based on the assumption that electricity is generated and transmitted with an efficiency

Table 3.1. Recent estimates of oil pipeline energy intensiveness[a]

	Source	Method	Electrical efficiency[b] (%)	Estimate (Btu/ton-mile) Crude	Estimate (Btu/ton-mile) products	Estimate adjusted to 32.3% electrical efficiency (J/kg-km) Crude	(J/kg-km) products	(Btu/ton-mile) Crude	(Btu/ton-mile) products
1.	Rand Corporation (Mooz 1971)	Based on data for a small California residual oil pipeline and rough cross-checks against ICC data on transportation expenses.	30[c]	1200–2600[f]		817–1770[f]		1131–2451[f]	
2.	ORNL (Hirst 1973)	Reference to a 450 Btu/ton-mile estimate of R. A. Rice (1970, 1972) and comparison with sample calculations for different diameters and flow rates.	30	450	450	307	305	425	423
3.	Jack Faucett Associates (Federal Energy Administration 1974)	Data on actual fuel consumption of five large pipeline companies, adjusted to reflect the fact that larger companies are more efficient in general.	22	550	550	300	292	415	404
4.	Pace Company (Fenton et al. 1976)	Taken from a report from the Governor of Texas (Holden 1975).	30	300	300	205	204	284	282
5.	Aerospace Corporation, 1976 estimates (Aerospace 1976)	Based on installed horsepower data in <u>Stationary Internal Combustion Engines</u> (McGowin 1973) and estimated Btu's per hp-hr. Ton-miles from Jack Faucett report (FEA 1974).	31.8	1150	621	820	443	1136	613
6.	Aerospace Corporation, 1977 estimates (Aerospace 1977)	Based on calculation of energy required to move oil through a pipeline of "average" diameter at an "average" flow rate.	31.8	586[d] 782[e]	261[d] 349[e]	481[d] 558[e]	186[d] 249[e]	579[d] 773[e]	258[d] 344[e]
7.	Peat, Marwick & Mitchell (Leilich et al. 1977)	Engineering calculations based on pipeline stock by diameter and estimated flow rates for each diameter.	30	207	379	141	257	196	356
8.	Systems, Science & Software (Banks 1977)	Based on fuel expenditures of companies accounting for 88% of regulated bbl-mile and a rough estimate of fuel costs.	22	300	400	164	212	226	294
9.	ORNL (this report)	Calculation of energy required in each pipeline segment in the U.S., where flow rate is based on regression analysis and the resulting distribution of each company's reported bbl-mile to its segments. Gravity head is considered, and duty cycle is inferred by calibrating results against actual energy use of a few companies.	32.3	250	300	180	220	250	300

[a]Parts of this table are taken from a table prepared by Jack Faucett Associates (1978, p. 151).

[b]Efficiency of electrical generation and transmission.

[c]Efficienices were set by the reporting companies.

[d]100% duty cycle.

[e]85% duty cycle.

[f]Same range of estimates for both crude and products lines.

of 36.5%. (When the efficiency underlying an estimate is not specified by the source, it is assumed to be 30%, since this is the most popular figure.) The fourth estimate in the table, that of the Pace Company, is the 500 ton-mile/gal figure discussed above. Three of the more recent estimates are considered separately below.

3.1 Jack Faucett Estimates

As part of its report for Project Indepenence (Federal Energy Administration 1974), Jack Faucett Associates estimated oil pipeline energy intensiveness to be roughly 400 J/kg-km (550 Btu/ton-mile). This figure is based on energy use data obtained from five companies operating "relatively large diameter pipes" during the period 1970 through 1973. The average energy intensiveness of these companies, weighted by movements (m^3-km), is 313 J/kg-km (433 Btu/ton-mile), and this figure was adjusted upward to 400 J/kg-km to allow for the fact that larger pipes are more efficient.

It is disturbing that the Jack Faucett estimate is about 50% higher than the estimates offered in this report, especially since it is based directly on company data. It is easily possible, of course, that a random sampling of pipeline companies will have an energy intensiveness as high as 400 J/kg-km. The four products and five crude systems studied in Chap. 8, for example, showed 430 and 350 J/kg-km respectively (assuming an electric generation and transmission efficiency of 22%, as does the Faucett study). Yet once the characteristics of these nine systems and of the other systems in the nation are taken into account, crude and products estimates of 240 and 300 J/kg-km for the nation result (again assuming 22% efficiency).

A possible explanation for the discrepancy is that pipeline companies operate more efficiently now than in pre-embargo years. Chapter 8 explains how operating practice can substantially affect energy consumption. But it is difficult to believe that improvements in operating efficiency can account entirely for the discrepancy. Another possible explanation has to do with the fact that the Jack Faucett figure is "adjusted to exclude fuel used on non-trunk operations since ton-miles were available only for trunk line movements" (p. 153). The adjustment could have been incorrect. But in view of the relatively small energy consumption of gathering lines, this could account only for a small part of the discrepancy.

The most plausible explanation is that the companies reporting to Jack Faucett Associates not only operated less efficiently in those years but also happen to be companies that fully utilized their pipeline capacity. As pointed out in Sect. 9.3, there appear to be a fairly large number of companies whose pipelines run substantially under capacity, and these tend to improve the overall efficiency of the pipeline network. Tables 9.7-9.9 shows that fairly large-diameter lines, while running at capacity, could easily operate at an energy intensiveness near that ascribed to the five companies polled by JFA. Since the Faucett method cannot account for any underutilized pipelines that may exist, a poll of five companies running near capacity could be expected to result in a substantial overestimate of energy intensiveness nationwide. This represents a serious deficiency in the Faucett method, as well as the others discussed below, since energy intensiveness falls off drastically when the throughput falls somewhat below capacity.

3.2 Aerospace Estimates

The Aerospace Corporation, in a study for the Energy Research and Development Administration (Aerospace 1976), originally estimated crude and products pipeline energy intensiveness to be 830 and 448 J/kg-km, respectively (1150 and 621 Btu/ton-mile). However, these estimates have been superceded by those in a later version of the Aerospace report (Aerospace 1977), and the later estimates will be discussed here. They are 423 to 565 J/kg-km for crude lines (depending on the duty factor) and 188 to 252 J/kg-km for products lines (586 to 782 Btu/ton-mile and 261 to 349 Btu/ton-mile), respectively.

The estimates are obtained by calculating the energy required to move oil through a pipeline of average diameter at an average flow rate. The viscosities used are 30 cSt for crude oil (Sect. 7.3 estimates 7.5 cSt) and 1.7 cSt for products (a reasonable figure). The average diameter used is "D^2 averaged," given as 13.75 in. for crude pipes and 11.6 in. for products pipes. This average is presumably

$$D_{avg} = \sum_i L_i D_i^2 / \sum_i L_i D_i \ , \tag{3.1}$$

where L_i is the length of pipe having diameter D_i. No justification is given for using this average, but a justification would presumably go as follows. On the assumption that the flow velocity v is the same in pipes of all sizes, formula (2.2) in Chap. 2 implies that the energy intensiveness of a pipe of any diameter D_i can be written

$$EI_i = kfv/D_i \ , \tag{3.2}$$

where f is a friction factor and k an appropriate constant. The friction factor f actually varies somewhat with the diameter D, but it can be presumed constant for present purposes. Since the volume rate of flow V_i in a pipe of diameter D_i is given by

$$V_i = v(\pi/4)D_i^2 \ , \tag{3.3}$$

the average energy intensiveness, weighted by the oil movements L_iV_i in pipes of each diameter D_i, is

$$EI_{av} = \frac{\sum_i \left[(kf\nu/D_i) \cdot L_iV_i\right]}{\sum_i L_iV_i} = kf\nu \frac{\sum_i L_iD_i}{\sum_i L_iD_i^2} = kf\nu/D_{av} . \qquad (3.4)$$

This would justify the use of eq. (3.1) for D_{av} if the flow velocity v were in fact constant with respect to diameter.

The average flow rate used is 9347 m^3/d for crude lines and 7074 m^3/d for products lines (58,000 and 44,500 bbl/d). There is no word of explanation as to the origin of this crucial number. One way it might be developed is to write, using eq. (3.3),

$$M = \sum_i L_iV_i = v(\pi/4)\sum_i L_iD_i^2 , \qquad (3.5)$$

where M is the total reported pipeline movement in m^3-km or bbl-mile. Solving eq. (3.5) for v,

$$v = (4/\pi)M/\sum_i L_iD_i^2 , \qquad (3.6)$$

and the average volume rate of flow is that resulting from oil moving at velocity v in a pipeline of average diameter:

$$V_{av} = v(\pi/4)D_{av}^2 = M \frac{\sum_i D_i^2L_i}{(\sum_i D_iL_i)^2} . \qquad (3.7)$$

The average velocity v would then presumably be given by

$$v = V_{av}/[(\pi/4)D_{av}^2] . \qquad (3.8)$$

This method suffers obviously from the false assumption that v is constant with respect to diameter. Oil velocity varies not only among pipes of different diameter, but varies among pipes of like diameter and varies over time in any given pipe. To smooth out these fluctuations by using a single average figure results in a substantial underestimate of energy use, due to the nonlinear relation between energy use and velocity. (The underestimate is even worse than that of Method 0, discussed in Sect. 8.2, since that method smooths out only the fluctuations over time.)

Curiously, the Aerospace estimates are high, not low. Unfortunately the study is too poorly documented to permit an explanation as to why the estimates are as high as they are.

3.3 Leilich Estimates

A study of freight transportation conducted by Peat, Marwick, Mitchell and Company (PMM) for the Department of Transportation (Leilich et al. 1977, pp. 2-33 to 2-39, Appendix E) estimates pipeline energy intensiveness to be 150 and 274 J/kg-km (280 and 379 Btu/ton-mile), respectively, for crude and products lines in 1972. This study alone among the five considered here approaches the problem from the same direction as the present study, that of calculating the energy required to move the oil that actually moved through the existing pipeline network. Unlike the present study, however, the PMM effort attempts neither to allocate flow regionally, to account for fluctuations over time, nor to calibrate the calculation against reported actual consumption of a few companies.

PMM's method is to convert reported movements in ton-miles to bbl-miles, using the reported mix of products moved and their densities, and to distribute these movements among the various diameters of existing pipe so as to result in an average flow rate appropriate to each diameter. The power use of pipelines of each diameter, at the assigned rate of flow, is computed using a standard engineering formula similar to formula (2.6) and assuming a pump efficiency of 0.75 for pipeline diameters less than 16 in. and 0.80 for larger diameters. The calculations take into account the properties of the different oil products by assigning to each pipeline diameter a mix of products having proportions equal to those of the overall ton-mile mix and by using a friction factor appropriate to each product (see Chap. 2).

The success of the PMM method depends on the validity of three assumptions:

1. the distribution of flow among pipes of different diameters is approximately what PMM takes it to be,
2. the flow is more or less evenly distributed among pipes of a given diameter, and
3. the flow in a given pipe of a given diameter is relatively constant.

Assumption (1) appears to be false at least in the case of crude oil lines. The way PMM determines a representative flow rate for each diameter is to draw a straight line on a graph of oil velocity vs. energy intensiveness. The graph is on linear paper and shows a curve for each pipe diameter. On the products pipeline graph the straight line is made to intersect the 2-in. curve at 1.5 mph and the 48-in. curve at 6.5 mph (on tips from people in the pipeline industry), and the velocity at which the connecting line intersects any curve in between is taken to be the velocity of oil in a pipe of corresponding diameter. On the crude pipeline graph the line intersects the 2-in. curve at 1 mph and the 48-in. curve at 5 mph. The curves on these graphs represent the relationship

$$EI = k_1 \, v^{1.852}/D^{1.166} \, , \qquad (3.9)$$

where EI = energy intensiveness (J/kg-km),
v = flow velocity (m/s),
D = inside pipe diameter (in.), and
k_1 = an appropriate constant.

The straight line expresses the assumption that energy intensiveness is in practice a linear function of flow velocity:

$$EI = k_2 v + k_3 \qquad (3.10)$$

for appropriate constants k_2, k_3. Equating the expressions for EI in (3.9) and (3.10) and solving for d:

$$d = \left(\frac{k_1 v^{1.852}}{k_2 v + k_3} \right)^{0.858} . \qquad (3.11)$$

For crude oil (specific gravity = 0.851) the PMM curve imply that k_1 = 2624 for lines less than 16 in. diameter and k_1 = 2460 for larger lines; also k_2 = −32 and k_3 = 195. For gasoline (specific gravity = 0.740) k_1 = 2013 for diameters less than 16 in. and k_1 = 1887 for larger diameters; k_2 = −110 and k_3 = 558.

The resulting relations between velocity and diameter are compared in Fig. 3.1 with those predicted by the regression equations derived in Chap. 6. The latter are based on a statistical treatment of several hundred observed capacities and throughouts. For purpose of distributing flow among pipe diameters only the slopes of the lines are important. Note that the PMM curves are significantly steeper than the lines derived from Chap. 6, except for the products capacity line. As a result, PMM's estimate of the relative efficiency of large-diameter lines is considerably less than that of this study. PMM estimates a 6-in. crude line to be, on the average, only 1.3 times more energy intensive than a

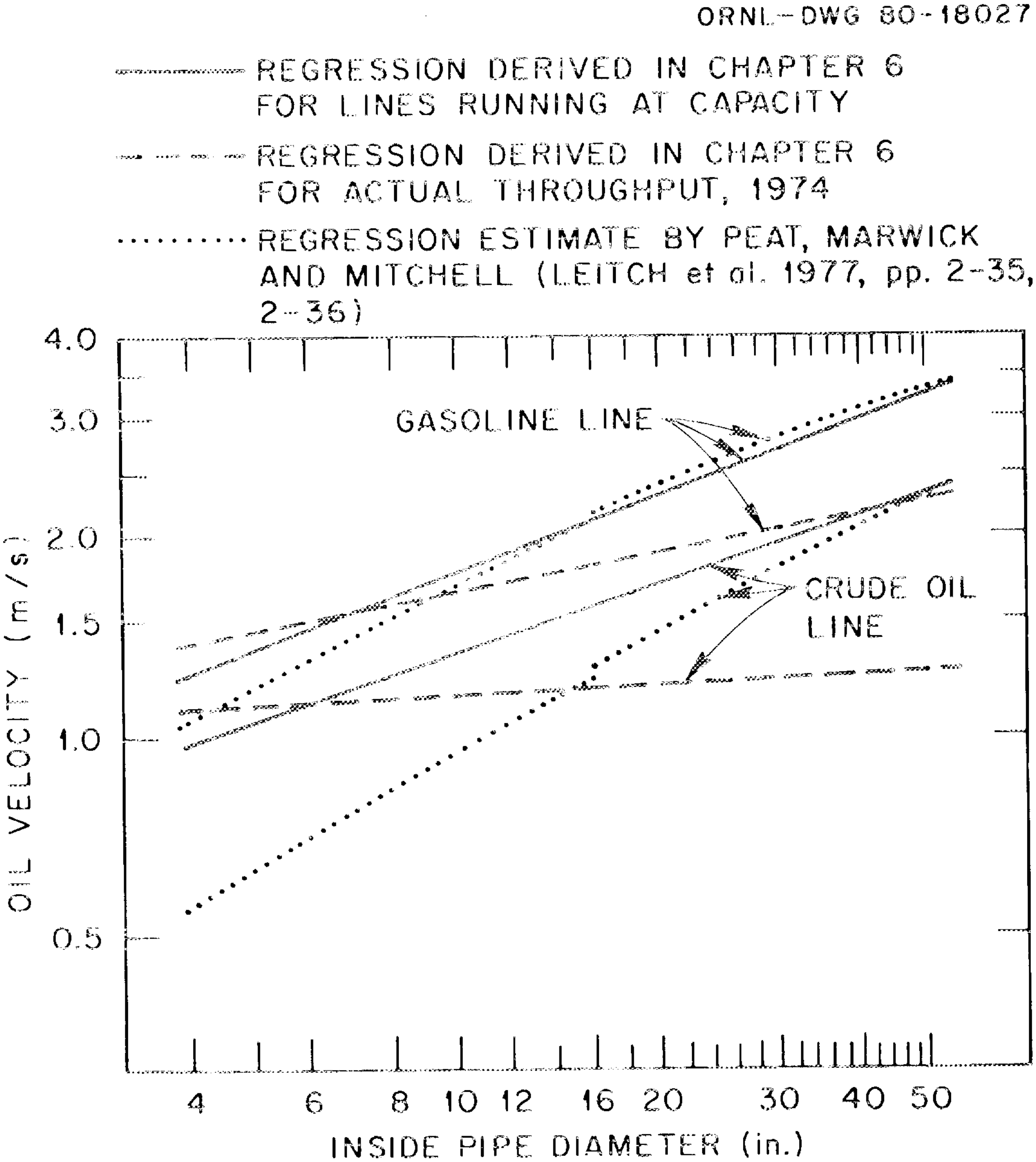

Fig. 3.1. Comparison of predicted oil velocities in crude oil and in oil products pipelines.

40-in. line (164 vs. 123 J/kg-km),* while this study puts the ratio at 3.1 (414 vs. 133 J/kg-km, Table 9.5). BMM says that the ratio is 1.9 for products lines (307 vs. 161 J/kg-km for gasoline, 428 vs. 225 J/kg-km for fuel oil), while this study says it is 3.7 (414 vs. 113 J/kg-km, Table 9.6). It should be noted that the results of this study are based not only on the regressions of Chap. 6 but also on the reported oil movements of individual pipeline companies, some of which own predominately small lines and others predominately large-diameter lines.

Assumption (2), that the flow is more or less evenly distributed among pipes of a given diameter, is significantly false. It is pointed out in Sect. 9.3 that, while some pipelines are pushed to capacity, others are underutilized. This would tend to make the BMM figures underestimates.

Assumption (3), that there are no significant fluctuations over time, is likewise false, and a considerable underestimate can result from a failure to recognize this. The discussion of Chap. 8 makes it clear that different assumptions regarding the nature of the duty cycle can result in very different estimates, all of them higher than the result of assuming a constant flow velocity.

The falsehood of assumption (1), no less than that of assumptions (2) and (3), would tend to make the BMM estimates lower than those of this study. This can be seen as follows. It is not hard to show, using elementary calculus, that the distribution of flow among different (level) pipes that minimizes total energy use is one which produces the same head in each pipe (Hooker, Rose, Bertram 1980, pp. 30–31). From this and eq. (2.6) it follows that, when energy use is minimized, the flow velocity varies with about the 0.57 power of the inside diameter. This is very close to the relationship posited by BMM (Fig. 3.1). It is also the relationship that actually obtains when pipes are looped, and this may partially explain the origin of BMM's assumptions. Since the relationship derived in this study departs significantly from the minimum-energy ideal, the resulting energy use should be greater than that resulting from BMM's assumptions.

As expected, BMM's energy intensiveness estimate for crude lines is lower, 22% lower, than that of this study (Table 3.1). The difference would be even greater if the relatively efficient Alaska Pipeline had not come into operation between 1972 and 1978. BMM's products estimate, however, is ome 19% higher than that of this study. This is due in part to BMM's assumption that pumps have an efficiency of 75–80%, which results in a consumption estimate about 12% higher than would result from the 86% efficiency assumed in this study. But the principal explanation is that when BMM's oil products movements estimate for 1972 (310×10^9 m^3-km) is

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*BMM figures are adjusted, as described in Sect. 9.1, to reflect an efficiency of electric generation and transmission of 32.5% rather than 30%.

applied to the 1972 products pipeline network, higher flow velocities result than when this study's estimate for 1978 (388 m^3-km) is applied to the 1978 network. For instance, BMM puts the average oil velocity in 8-in. pipes at 1.1 m/s, while this study puts it at 0.94 m/s. For 36-in. pipes, the corresponding figures are 2.2 and 1.9 m/s. Since energy intensiveness varies with about the 1.75 power of oil velocity, this alone would make BMM's energy estimate about 30% higher than it would be if the velocities derived in this study had been used. This is compounded by the fact that relatively less oil moved through (more efficient) large-diameter pipelines in 1972 than in 1978. It is to be expected that these factors would more than offset errors in the opposite direction that result from the falsehood of assumptions (1) through (3).

In summary, BMM's crude pipeline energy intensiveness estimate is lower than that of this study because of oversimplifying assumptions regarding the flow of oil. The products pipeline estimate is higher because BMM used oil movements data that imply a higher oil velocity and hence a higher utilization of products pipelines in 1972 than in 1978.

3.4 Banks Estimates

A study done by Systems, Science and Software (Banks 1977) for the Energy Department puts oil pipeline energy intensiveness at 220 J/kg-km (300 Btu/ton-mile) for crude oil pipelines and at 290 J/kg-km (400 Btu/ton-mile) for oil products pipelines. Banks, who uses English units, declines to provide more than one significant digit.

Bank's procedure is to estimate, on the basis of their reported fuel cost, the total pumping energy consumption of pipeline companies that move primarily crude oil or primarily oil products. To get energy intensiveness he divides total consumption by the total bbl-mile shipped by these companies. He chooses 21 crude and 14 products companies whose oil movements (bbl-mile) comprise 88% of the regulated crude and products pipeline shipments in the nation. Since these companies carry nearly all crude or nearly all products (usually 95% or more), they are representative of crude and products operations respectively. He divides the fuel cost of each company, reported on Form P (Federal Energy Regulatory Commission 1978), by a rough estimate of the average price paid by pipeline companies for electricity. He focuses on electricity because oil pipeline pumps are primarily driven by electric motors.

The obvious weakness in this method is the difficulty of arriving at an average price of electricity. Electric power rates depend not only on the level of consumption at each pump station but on a contracted peak power demand, which is not easily inferred from the average power demand. In fact, the ratio of peak to average power demand is lower for pipelines than for most industrial operations. Consequently neither an examination of electric rate schedules nor of a sampling of industrial power bills is very helpful (this matter is taken up again in Chap. 4). Banks asked several pipeline companies to divulge the average price paid for electricity in 1976, but managed to get the information from only two crude pipeline companies (2.25 and 2.3 ¢/kWh) and three products companies (1.25, 2.35, and 3.5 ¢/kWh). Well aware of the substantial regional variation in electric rates, Banks took into account the locations of these companies to arrive judgmentally at a national average of 2.8 ¢/kWh for crude lines and 2.925 ¢/kWh for products lines. The resulting energy intensiveness values are 207 J/kg-km (286 Btu/ton-mile) for crude lines and 280 J/kg-km (388 Btu/ton-mile) for products lines, which Banks rounds to 300 and 400 Btu/ton-mile, respectively.

It is possible to dispute at length about the accuracy of Banks' rate estimates. The Jack Faucett study mentioned earlier states that 1.75 to 2.00 ¢/kWh is a better guess of pipeline electric rates in 1976. The relevant question here, however, is whether Bank's estimate is accurate even in its one significant digit. Note that an average rate of 2.07 ¢/kWh, rather than 2.8, would have resulted in a calculated energy intensiveness of 386 Btu/ton-mile for crude lines, rather than 286. An average rate of 2.33 ¢/kWh, rather than 2.925, would have resulted in an energy intensiveness of 488 Btu/ton-mile for products lines rather than 388. Consequently it is difficult to have much confidence, on the basis of Banks' evidence, that his one-digit figures are accurate even in their one digit. In fairness to Banks, however, it should be noted that probably no greater degree of confidence could be obtained without either a nationwide solicitation of pipeline companies for data or a study requiring substantially more time and labor.

It can be seen in Table 3.1 that Banks' estimates are quite close to those of the present study. This suggests that either (1) Banks' electric rate estimates are right or (2) they are too small, but this error is offset by the fact that the five companies responding to Banks were less efficient than the average, perhaps because their capacity utilization was greater than average.

4. DATA SOURCES

It is impossible to learn pipeline energy consumption directly. Although most pipeline companies annually file a 54-page form, Form P, with the Federal Energy Regulatory Commission, the form contains mostly financial data and nowhere calls for an indication of fuel consumption. No other agency or organization collects fuel or energy use data from pipeline companies, and pipeline companies seldom publish such information in corporate annual reports or other brochures. Some companies have been found quite willing to turn over the information if contacted personally, but this has been the exception rather than the rule (Banks 1977). Indeed, some pipeline companies seem not even to keep accurate records of fuel consumption.

The most straightforward alternative is to infer each pipeline company's fuel consumption from its total fuel costs, a figure that is reported in Form P (line 4, item 320, p. 40). This strategy was followed by Banks (see Sect. 3.4). But the rates paid vary considerably from one company to another and from one year to the next, and it is as difficult to learn the average rate paid by a company as it is to learn its fuel consumption. Pipeline companies do not publish such information, and many companies have been found unwilling to divulge it. It is true that most oil pipeline pumps use electricity and that rate schedules for every U.S. utility are published in the National Electric Rate Book (1978). These rate schedules are complex, but it would seem that one could write computer programs for the calculation of power bills at a given level of consumption and find, with the help of a computer, the consumption level that results in each company's reported power bill. But this requires that one somehow divide a company's power bill among its individual pumping stations, since it is consumption at pump station meters that determines the rate. Also, the power bills of companies that patronize more than one utility must be divided among the several utilities. Worse, a major component of an industrial power bill is the power demand charge, which is pegged to a contracted peak power demand that cannot be reliably inferred from the average level of consumption. The author has dealt with these difficulties in order to estimate the energy consumption of two all-electric pipeline companies (Hooker, Rose, Bertram 1980), but on a national scale their resolution appears not to be possible within the resources of this study.

Since there are no direct reports of pipeline energy use, and since fuel cost data permit no more than an order-of-magnitude estimate, the available information sources must be surveyed to determine whether a less direct method of estimation can be devised. Such a survey comprises the rest of this section.

1. The American Petroleum Institute publishes biennially a series of six large-scale 3- × 9-ft maps depicting the U.S. crude oil and oil products pipeline network (American Petroleum Institute 1977 and 1979). These maps show each pipeline's nominal diameter and company ownership.

The length of each segment of pipe can be measured on the map within two or three miles. The crude and product lines are shown on separate maps, and lines dedicated to LPG are so designated. The information on these maps was reduced to machine-readable form for this study (see Appendix D).

2. Interstate common-carrier oil pipelines annually submit Form P to the Federal Energy Regulatory Commission (Federal Energy Regulatory Commission 1978), a form that as mentioned earlier shows total fuel expenses in Item 320. In addition Item 400 tabulates the quantity of crude oil and of oil products (itemized by product) received from connecting carriers, originated on gathering and on trunk lines, delivered to connecting carriers, and terminated on gathering and on trunk lines. The form asks for a breakdown by state. There is also a blank in which the respondent is asked to enter the total barrel-miles of trunk line movement for crude and for products. Unfortunately there is little consistency in the way different companies respond to this item, and nearly every response is incomplete in one way or another. It is seldom possible to infer the average throughput of any one segment of pipeline. The responses are useful, however, for learning the relative volumes of different products carried and thereby permitting an inference of their viscosities and densities. Responses to Form P are not published. Some tabulations are made by the Energy Information Administration (EIA), but most are not published, reportedly because EIA officials are unsure of their validity (Dawson 1979). Employees at the Federal Energy Regulatory Commission have been very cooperative in providing information from Form P, but due to the magnitude of the task the above information was obtained by sending someone to the appropriate office to photocopy the forms at his expense.

3. The National Petroleum Council has prepared an accounting of U. S. oil and gas transportation capacities (National Petroleum Council 1979), the first such accounting since 1967. Design capacities and actual operating capacities in barrels per day (as estimated by the pipeline companies) are shown for most trunk lines, although what is treated as a single pipeline may consist of several lines running parallel. Also a pipeline assigned a single capacity figure may consist of segments having several different diameters, probably indicating changes in capacity. Finally, a good many pipelines, some of them important, are not covered. Actual throughput is not indicated. The report was obtained on the day it was released by the printers, January 17, 1980.

4. The Congressional Research Service and U. S. Geological Survey prepared a series of maps to accompany Vol. I of the report National Energy Transportation, written for the Senate committees on Energy and Natural Resources and on Commerce, Science and Transportation (U. S. Congressional Research Service 1975). One of these maps show major oil product pipelines overlaid with colored bands whose width indicates 1974 throughput. The flow in individual lines is not shown; generally only the combined flow in two or three or perhaps two dozen roughly parallel lines is shown. It is often unclear which lines are represented by a given band. The magnitude of the flow can be inferred only by measuring

the band width against a scale in the legend. A similar map depicts crude oil pipelines and throughputs. These maps are not without errors; most noticeable is the appearance of what can only be the large Lakehead crude oil pipeline on the map of products pipelines. Yet these maps are the best available source of information on pipeline throughput. By prior agreement with the pipeline companies, the data on which the maps are based were destroyed once the maps were drawn. Pipeline companies regard release of such information as harmful to their competitive advantage or as an invitation to increased and excessive government regulation. Several companies supply detailed throughput information to the government, but with the stipulation that it be used only for the purpose of national defense (Ellerbrake 1979).

5. The Oil and Gas Journal annually publishes a list of pipeline companies and their reported deliveries in barrels and trunk line shipments in barrel-miles (Oil and Gas Journal 1979). These figures are compiled from Form P. It should be carefully noted that the figures for deliveries are far too large due to double counting. The deliveries reported on Form P by each pipeline company include deliveries to connecting carriers, and the Oil and Gas Journal does not take cognizance of this. (Also, the 1979 report, covering 1978 movements, overstates the Lake Charles Pipeline Company bbl-miles by a factor of 1000, resulting in a products bbl-mile figure that is 18% too large.)

6. The Energy Information Administration (EIA) has published triennially an inventory of U.S. pipeline mileage broken down into crude oil trunk lines, crude oil gathering lines, and oil product lines (EIA 1978). The mileages are also broken down by state and by pipe diameter. Unfortunately the 1978 edition, accurate as of January 1, 1977, is the last one that is to be published.

7. The EIA also tabulates movements of oil products between Petroleum Administration for Defense (PAD) districts in the Energy Data Reports publication "Crude Petroleum, Petroleum Products, and Natural Gas Liquids" (EIA 1979). The same bulletin shows boths intrastate and interstate pipeline deliveries of domestic crude oil to refineries, by state, as well as production of crude oil by state. From this information one can, with sufficient care, deduce the throughput of a good many pipelines or groups of pipelines, and the author had developed elsewhere a method for doing so systematically (Hooker 1980). Such a deduction was not attempted for this study because a good deal of labor is necessary to set up the problem for computer solution. Since there was no guarantee that enough throughputs would be deducible to make the effort worthwhile for present purposes, it was thought best to invest the limited time and resources available to this study in surer efforts. On another occasion, however, this approach to the problem of determining oil pipeline flows would be well worth trying for its own sake.

8. In 1980 the EIA administered a survey form, EIA-184, which requests fairly detailed historical information regarding pipeline throughputs in the years 1968-79. At present there are no plans to

extend the form's use beyond this one-time survey. The detailed data have not been published but have been recorded on computer tapes. These data would permit a much more accurate deduction of throughputs, according to the method mentioned in the previous paragraph, than would otherwise be possible. Unfortunately the data were not available early enough for use in this study.

9. The trade journal Pipeline (often called "Pipeline News") publishes annually an issue containing a directory of pipeline companies and their officers and managers (Pipeline 1979). Some of the companies offer statistics concerning pipeline mileage or installed horsepower or even throughput, but to no consistent extent. The directory is useful, however, for unraveling the ownership relations among pipeline companies, an essential part of matching the company names on pipeline maps with the often different names in the Oil and Gas Journal's tabulation of barrel-miles shipped.

10. Such industry magazines as Oil and Gas Journal, Pipeline, Pipeline and Gas Journal, and Pipeline Industry can be valuable sources of information on pipeline technology and operations.

11. The list of references at the end of this report cites numerous other helpful sources of information about pipelines (e.g. International Pipeline Contractors Association, 1979; Jones 1973; Lewis and Hangs 1963; Petroleum Extension Service 1973).

5. OVERVIEW OF THE METHOD

The data sources described in the previous chapter permit one to estimate the volume and velocity of oil moving through each segment of pipeline in the United States and to perform engineering calculations that result in an estimate of the energy required to pump the oil. This chapter contains a synopsis of how this is done. Chapters 6 through 9 provide a more detailed accounting.

Figure S.1 in the Summary depicts schematically how energy use by trunk lines is estimated. The process can be divided into four main stages, as follows.

1. Estimate the 1978 throughput (average flow rate) in each pipeline segment (boxes 1–2 in Fig. S.1).
2. Use actual energy consumption data from a few companies to determine how the flow rate in a given segment can be assumed to fluctuate (box 4).
3. Perform engineering calculations, based on pipe roughness, oil density and viscosity and flow in each segment, to estimate the "pumping energy" for that segment — i.e., the mechanical energy that must be delivered by the pumps to pump the oil (box 3, 5, and 6).
4. Estimate the fuel-to-oil efficiency, which is the efficiency with which energy released from the combustion of primary fuel is converted to pumping energy, and divided the result into the pumping energy to get actual energy consumption (boxes 7 and 8).

Each stage is discussed separately in the four sections of this chapter.

The above calculations omit the energy used by crude oil gathering lines. Its estimation is a thorny problem, insoluble with any kind of accuracy. Here, the energy required to run each state's gathering lines at their predicted capacity is computed. Since this often implies an unreasonably long average length of haul (due to idle lines), any average length of haul above the national average is shortened to the national average. Pipe mileages for each diameter in each state are published by the federal government (Energy Information Administration 1978).

5.1 Estimation of Throughputs

As remarked in Chap. 2, this first stage is the most difficult one, because energy use is highly sensitive to rate of flow and because throughputs are not reported. The strategy used here is to apportion each pipeline company's reported oil movements in m^3-km among the pipeline segments in its system. (A pipeline segment, as the term is used here, is a single length of pipe over which there are no diameter changes, no connections with other lines, and no state line crossings.) The apportionment is made by determining the normal throughput of a pipeline having a given diameter and throughput capacity, and by placing on the segments belonging to a given company those throughputs that have the same ratios as normal throughputs for those segments and that add up to the company's total movements. The normal throughput (average m^3/d) in a pipeline of given diameter and capacity is determined via a regression described in Chap. 6. If the throughput capacity of a segment is not reported, it is estimated on the basis of its diameter using another regression formula derived in Chap. 6. If the capacity of an individual segment is not reported but the total capacity of a group of parallel segments of which it is a member is reported, then that segment's capacity is assumed to bear the ratios to the capacities of the other segments that are predicted by the capacity regression formula just mentioned. Finally, if a company does not report its total movements at all, they are assumed to be those that would result from the throughputs predicted by the two regression formulas just mentioned. This is made more precise in Sect. 7.4.

The derivation of regression formulas in Chap. 6 begins with an independent justification of the functional forms used. A generalized cost-engineering study of pipeline construction is carried out, and it concludes that throughput capacity C is reasonably taken to be a power function of pipe diameter D, $C = xD^y$. Actual throughput V is represented as a product of capacity and a power function of diameter, $V = zCD^w$. Estimation of the parameters x, y, z, w proves difficult because of the nature of the data, which are provided by a study of pipeline capacities by the National Petroleum Council (1979) and by a map showing throughputs that was prepared by the Congressional Research Service (1975). The difficulty is that the capacity or throughput of an individual line is often not provided, but only the capacity or throughput of a group of parallel lines of which it is a member. Furthermore, the throughputs map indicates only ranges within which the throughput magnitudes lie, ranges that are often too broad to collapse to a single representative number. Sections 6.3 and 6.4 develop a method of estimating x, y, z, w simultaneously with the parameters of a heteroscedasticity function while overcoming these difficulties. The parameter values are obtained by numerical solution of a system of nonlinear equations.

It should be understood that the regression formulas are not generally used to predict directly the capacity or throughput of a given pipeline segment. They are used to prescribe the ratios by which the total capacity or throughput of a group of pipes is allocated to the individual pipes. (In other words, in most cases the values of the multipliers x and z do not matter; only the exponents y and w figure in the calculations.) Total movements are got for nearly all federally regulated companies by consulting the Oil and Gas Journal (1979), which tabulates figures submitted by the companies on Form P (Federal Energy Regulatory Commission 1979). Companies whose throughputs must be estimated solely by regression formulas are the unregulated ones. It is seen in Chap. 9 that they are responsible for less than 10% of pipeline oil movements nationwide. The capacities of most of the important pipelines, or groups of parallel pipelines, have been published by the National

Petroleum Council (1980). Quite a few pipelines are not covered, and their capacities must be estimated solely by the regression formula. But since capacity is used only as one term in the throughput regression formula, which is in most cases used only to allocate a company's reported total movements among its pipes, the resulting errors should be small.

5.2 Fluctuations in Rate of Flow

Unfortunately it is not enough to know the throughput (i.e., average flow rate) of a pipeline segment. Every pipeline shuts down for maintenance or repairs now and then, and the average velocity of oil while the pipeline is running depends on how long the line is inoperative. Since the energy intensiveness varies almost with the square of the velocity, longer shutdown periods result in a substantially higher total energy consumption, even if the total annual throughput is constant. Worse, pipeline companies which carry less than capacity must adopt some strategy for reducing throughput below the maximum. They do not reduce the speed of the motors, since most of their motors do not permit this. They might shut off some of the pumps, run all of them part of the time, throttle the flow by closing valves partway, or perform some combination of these actions. The procedure followed can make a big difference in the total energy consumption that results.

Chapter 8 attempts to determine which generalized strategy of reducing flow and providing for maintenance shutdown results in energy use estimates that best fit the actual energy use figures provided by a handful of pipeline companies. The calibration provided by these company data also serves to confirm the wire-to-oil efficiency adopted in Sect. 9.1. In addition it provides an opportunity to make rough estimates as to the potential errors that result from the method employed here.

5.3 Estimation of Pumping Energy

As noted earlier, "pumping energy" refers to the mechanical energy actually delivered to the oil by the pumps. It is the sum of the energy required to overcome friction and that required to overcome the net elevation change. The latter is of course negative if the downstream end of the pipe is lower than the upstream end.

Formulas (2.2), (2.4), and (7.1) are the basis for calculating the energy required to overcome friction, as explained in Chap. 2. The information required for the use of these formulas is developed as described below.

1. The length of each pipeline segment. This is taken directly from a computer data set coded from the American Petroleum Institute maps (API 1977).

2. The inside diameter of each segment. The nominal diameters are read from this same data set and converted, as detailed in Sect. 7.1, to inside diameters.
3. The pipe roughness. See Sect. 7.2.
4. The density of the oil. The density of oil products is based on the mix of products delivered by each pipeline company, got from Form P (Federal Energy Regulatory Commission 1978), and the density of crude oil is given a single average value. See Sect. 7.3.
5. The viscosity of the oil. Viscosity receives a treatment similar to that given density. Section 7.3 discusses the effect of temperature on the viscosity of pipeline oil.
6. The rate of flow. The estimation of this most important quantity is the task of stages 1 and 2, already discussed.

The effect of gravity on energy use, significant in some states, is estimated simply by computing the rate of elevation gain in m/km for the larger pipelines, and taking an average H of these rates for each state, weighted by the movements in m^3-km caried by each line (Sec. 7.7). If g is gravitational acceleration in N/kg, then gH represents the average energy required to pump one kg of oil one km against gravity. Consequently, if M is a state's total oil movements in kg-km, MgH is the total pumping energy (possibly negative) used in that state to overcome gravity.

5.4 Estimation of Fuel-to-Oil Efficiency

Pumping energy is converted to actual energy consumption by dividing it by fuel-to-oil efficiency, which is the efficiency with which energy in the primary fuel is delivered to the pipeline oil. If the pumps are driven by electric motors, the fuel-to-oil efficiency is the product of the efficiencies of electric generation and transmission, motors and pumps. If the pumps are driven directly by prime movers (diesel or gas engines, for instance), it is the product of the efficiency of the prime mover and that of the pumps. An average efficiency is then computed for crude and for products pipelines, weighted by the fractions of pumping power supplied by electric and other drivers. The difficulty of defining what one means by the efficiency of electric generation and transmission is discussed in Sect. 9.1.

These fuel-to-oil efficiencies cannot be calibrated entirely by reference to the companies from whom actual energy consumption figures are availiable (see Chap. 8). This is because the efficiency must be known at least to lie in a certain range before the company data can be used to choose the best model of the duty cycle. The method adopted here is to consult engineering handbooks and utility data (Sect. 91.) so as to place fuel-to-oil efficiency iin a range narrow enough to permit a choice of a flow scheduling model in Chap. 8. It turns out that under any reasonable choice of a scheduling model, the efficiency must be at the upper end of this range. As a result the fuel-to-oil efficiency is determined in part by the calibrating data and in part by engineering handbooks and utility statistics.

6. REGRESSION FORMULAS

The object of this chapter is to find a reasonable regression of pipeline capacity on diameter, and of average daily throughput on capacity and diameter. Functional forms for these regressions are chosen respectively in Sects. 6.1 and 6.2, and estimation procedures for their parameters are derived in Sects. 6.3 and 6.4. Section 6.5 describes the numerical results of these estimation procedures.

6.1 Functional Form of the Regression of Throughput Capacity on Diameter

Since the cross-sectional area of a pipeline varies with the square of its diameter, it may see a reasonable guess that its capacity likewise varies with the square of the diameter. But this presupposes that the velocity with which the pipeline is designed to move the oil does not vary with diameter, when as a matter of fact larger pipelines tend to be designed for faster movement. Another guess might be that the pressure drop per km in a pipeline varies little with diameter and that the throughput capacity would therefore exhibit the dependence on diameter implied by the D'Arcy-Weisbach equation, Eq. (2.2). That is, capacity would vary more or less with the 2.5 power of the diameter. But the pressure drop (and consequently the friction head) tends to be considerably less in larger pipelines. Rather, the correct exponent lies somewhere between 2 and 2.5.

The difficulty is that neither the typical design velocity of flow nor the resultant pressure drop bears any obvious relation to the pipe diameter. This is because their choice is influenced by a number of economic factors. Generally when one proposes the construction of a pipeline, he has in mind an estimated desired throughput and wishes to choose the optimal configuration of equipment to accommodate this throughput. This requires balancing the advantages of a large pipe against those of a small pipe. A large pipe costs more, but it is less energy intensive and so reduces power bills and the cost of installing pumping horsepower. A smaller pipe cuts materials and pipelaying costs but is more expensive to operate. Another variable is the strength of the pipe wall. A strong wall cost more but permits a higher pumping pressure to move the oil through a smaller-diameter pipe. A weaker pipe is less expensive per diameter inch, but it must have a large diameter to accommodate the desired throughput.

Figure 6.1 illustrates the relation between cost, throughput, and diameter. Examination of this figure reveals a seeming paradox in pipeline economics. Note that the optimal throughput for a 12-in. pipeline is about 8500 t/d, while the optimal choice of pipe diameter for an 8500 t/d throughput is not 12 but 16 in. In general, if D is the optimal diameter for a given throughput capacity C, then the optimal capacity for

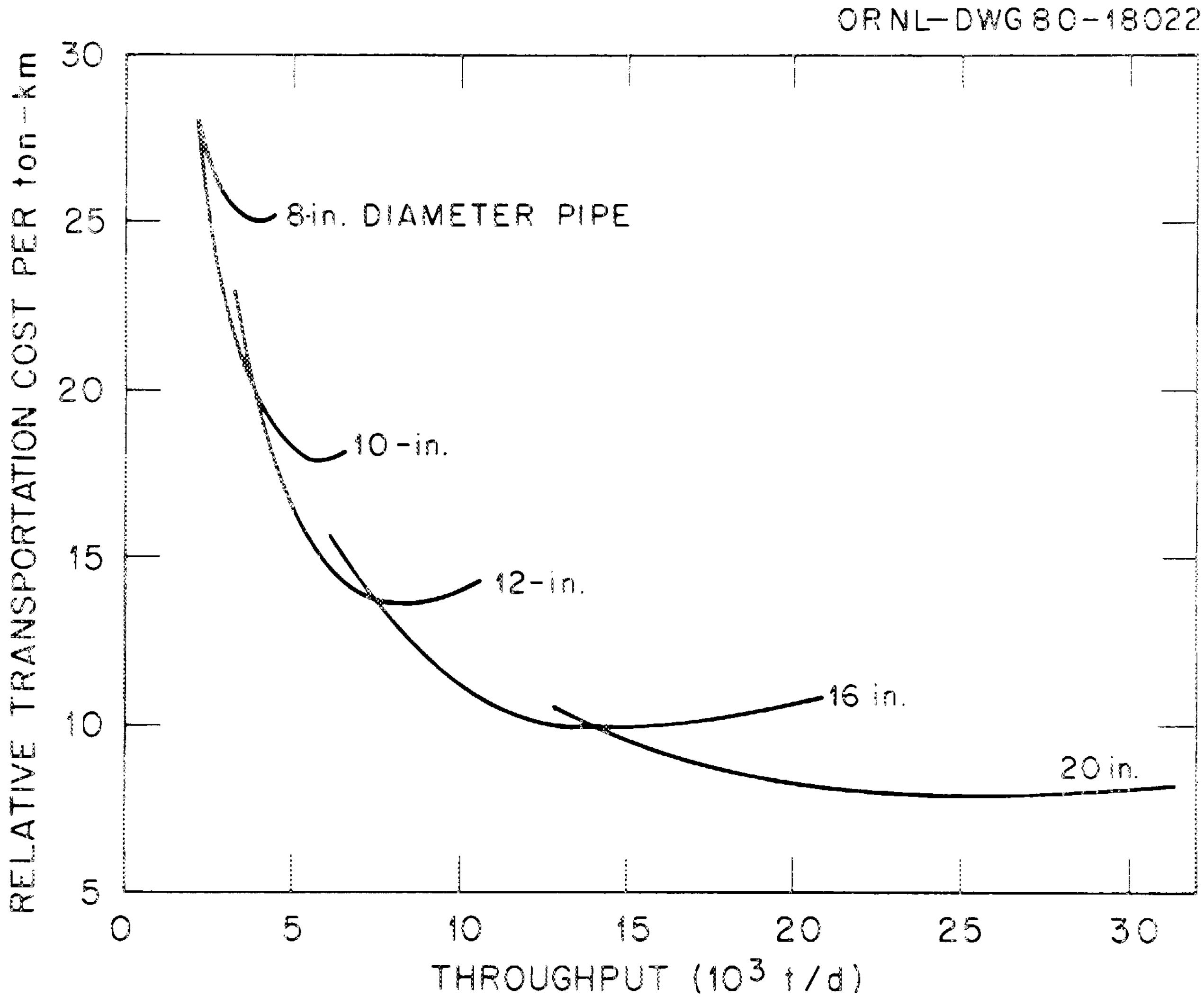

Fig. 6.1. Pipeline diameter and transportation cost related to throughput. Reproduced by permission from Jones (1973, p. 914).

diameter D is larger than C. Partly for this reason a pipeline is commonly built to withstand higher pressures than those initially used. This allows future installations of additional horsepower to respond to demands for increased throughput while lowering unit transportation costs.

It is difficult to say whether it is best to assume that diameter is typically optimal with respect to capacity or vice-versa. Although the initial design probably optimizes diameter with respect to a given desired capacity, older pipelines that have undergone increases in pumping power should tend more to optimize capacity with respect to a given diameter. It turns out, however, that either approach yields the same functional form for the regression of capacity on diameter. Some evidence for this can be gleaned from Fig. 6.1, which suggests on either assumption that the regression has the form of a power function. For, if D is the optimal diameter for capacity C, then Fig. 6.1 is compatible with the regression function

$$C = xD^y , \qquad (6.1)$$

where the exponent y is of the order of 2.8 and x is an appropriate constant of proportionality. The r^2 statistic for the regression is 0.98.* Likewise if C is the optimal capacity for diameter D, then the same function describes their relationship, where y is of the order of 2.1, and r^2 is 0.99. This suggests that a power function could be appropriate for regressing pipe capacity on diameter, albeit a fair amount of scatter of points about the regression line can be expected, since different pipelines of a given diameter are likely to be in different stages of development and hence to have different capacities. It also suggests that the resulting exponent would lie between 2.1 and 2.8.

It is unwise, however, to choose a functional form for a regression, such as Eq. (6.1), solely on the ground that it fits some available data fairly closely. It is preferable to be able to justify the choice of function by appealing to a model or theory that purports to explain the phenomenon in question. In fact, a simple cost model for pipelines, to be presented below, suggests that Eq. (6.1) probably does not mirror the actual relationship between C and D. Nonetheless this same model shows that Eq. (6.1) is correct if one makes some simplifying assumptions. These assumptions will be seen to be innocuous enough to justify the use of Eq. (6.1) for the purpose of this study.

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*The capacities for which the three diameters 10, 12, and 16 in. were taken to be optimal are the midpoints of the ranges of capacities for which these diameters, among those represented, are optimal: respectively, 1.00, 1.95, and 3.82×10^6 t/yr (metric tons per year). The exponent was estimated using a log-linear regression model.

A highly simplified analysis of pipeline costs would go

$$\begin{aligned} c(\text{total},D,C) &= c(\text{operation},D,C) + c(\text{pumps},D,C) \\ &\quad + c(\text{pipelaying},D,C), \end{aligned} \tag{6.2}$$

where

c(total,D,C) = total cost of building and operating a pipeline with diameter D and capacity C;

c(operation,D,C) = total operating costs over the lifetime of the equipment, appropriately discounted, when the diameter is D and the capacity C;

c(pumps,D,C) = labor and materials cost of installing the pumping equipment, when the diameter is D and the capacity C;

c(pipelaying,D,C) = labor and materials cost of installing the pipe, holding tanks and related facilities when the diameter is D and the capacity C.

The pipeliner's aim is to minimize the cost per unit transported, c(total,D,C)/C. This can be done by finding the optimal diameter D once the desired capacity is fixed, or by finding the optimal capacity C once the diameter is fixed. The remainder of this section wil attempt, through an analysis of the three terms in Eq. (6.2), to establish that in either case the resulting relationship between C and D is expressed accurately enough by the simple power function (6.1).

One assumption that must be made in the analysis to follow is that economy of scale generally behaves according to a power function. That is, if Q measures the quantity or size of an operation and c its cost, then

$$c = kQ^t$$

where the exponent t is less than one. ('k', here and elsewhere, is a dummy symbol that stands for whatever constant of proportionality is appropriate in a particular context. When two k's occur in the same formula, they need not be the same quantity.) This sort of relationship has been borne out by cost-engineering studies in many contexts, particularly in the transport of energy (Marchetti 1975, p. 3). Therefore, the use of a power function to describe economy of scale will be presumed to have, at least to some extent, the kind of independent justification endorsed above.

6.1.1 Operating expense

First to be considered is the operating expense c(operation,D,C). The dependence of a pipeline company's operating expense on the physical characteristics of the pipeline itself is of course very complex and sensitive to extraneous factors. Yet a relationship can be discerned, if somewhat dimly, between fuel expense and total operating expense, and fuel expense can be related to the dimensions of the pipeline itself. A log-linear regression of the total operating expense c(operation,D,C) of 78 crude oil pipelines on their fuel expense c(fuel,D,C), based on data from Form P (Federal Energy Regulatory Commission, item 320, lines 4 and 21), results in the formula

$$c(\text{operation},D,C) \doteq 171\ c(\text{fuel},D,C)^{0.759}\ .$$

The points are widely scattered, and the r^2 statistic is only 0.78. A similar treatment of 60 products pipelines gives

$$c(\text{operation},D,C) = 430\ c(\text{fuel},D,C)^{0.63}\ .$$

Here $r^2 = 0.71$. A working value for the exponent might in general be 0.7:

$$c(\text{operation},D,C) = k\ c(\text{fuel},D,C)^{t_1}\ ,\ \text{where } t_1 \doteq 0.7\ . \qquad (6.3)$$

Economy of scale (if any) in the purchase of fuel implies that

$$c(\text{fuel},D,C) = kF^{t_2}\ , \qquad (6.4)$$

where F is the fuel consumption and t_2 is less than one. Some 79% of oil-pumping horsepower is supplied by electricity (McGowin 1973, p. 32), so that the value of t_2 depends on the nature of electric rate schedules. A computer program developed for another study (Hooker 1979) was used to calculate the average power bill charged by 14 electric utilities serving the Colonial and Plantation pipelines along the Eastern Seaboard, at consumption levels typical of pumping stations belonging to these pipelines. The calculations were made using the actual rate schedules in effect on July 1, 1977. Based on the results of this prior study, the ratio of the average rate of consumption to the contracted peak power demand was taken to be 0.385, and the power demand charge was computed accordingly. A log-linear regression yielded that there is little economy of scale in these industrial electric rates; t_2 was found to be 0.94 ($r^2 = 0.998$).

Finally, a level pipeline's fuel consumpion F is its friction head h_f, estimated by formula (2.7), times the weight w of its throughput. Since the design throughput weight is proportional to the capacity C, the fuel consumption is

$$F = h_f w = kh_f C = k(LC^{t_3}/D^{t_4})C = kLC^{t_3+1}/D^{t_4} , \qquad (6.5)$$

where L is the length of the pipeline and where $t_3 = 2.75$ and $t_4 = 4.75$, as in formula (2.7). When (6.5) is substituted into (6.4), and (6.4) into (6.3), the result is

$$c(\text{operation},D,C) = k\left(L \frac{C^{t_3+1}}{D^{t_4}}\right)^{t_1 t_2} ,$$

where $t_1 t_2 \doteq (0.7)(0.94) = 0.66$. Since the length L is not a variable of interest here, it can be fixed and incorporated in the constant k

$$c(\text{operation},D,C) = k\left(\frac{C^{t_3+1}}{D^{t_4}}\right)^{t_1 t_2} . \qquad (6.6)$$

It should be noted that if the above regression of operating cost on total cost were performed on pipelines all having the same length L, the estimate $t_1 = 0.7$ might change.

6.1.2 Cost of pumping equipment

The cost c(pumps,D,C) of installing equipment should be roughly proportional to the cost of the equipment itself. A rule of thumb in the pipeline business is that the cost of pumping equipment varies roughly with the 0.7 power of the power rating P, so that

$$c(\text{pumps},D,C) = kP^{t_5} , \text{ where } t_5 = 0.7 . \qquad (6.7)$$

A regression based on Oil and Gas Journal cost data (1978, p. 67) puts t_5 at 0.69. The power requirement P is the product of the design friction head h_f, given approximately by formula (3.4), with the weight rate of flow in N/s. Since the weight rate of flow is proportional to the design volume rate of flow C,

$$P = kh_f C = kC^{t_3+1}/D^{t_4} \qquad (6.8)$$

where $t_3 = 1.75$ and $t_4 = 4.75$. Substitution of Eq. (6.8) into (6.7) yields

$$c(\text{pumps},D,C) = k\left(\frac{C^{t_3+1}}{D^{t_4}}\right)^{t_5} . \qquad (6.9)$$

6.1.3 Cost of pipelaying

The final term in the cost formula (6.2) is the cost of laying pipe, the most difficult cost element to characterize. A breakdown of the cost of pipeline construction (including pumping stations) based on reports submitted to the Federal Energy Regulatory Commission in 1978 goes as follows (Oil and Gas Journal 1978, p. 67):

Item	Percent of total cost	
	Crude Pipelines	Product Pipelines
Land	0.4	0.5
Right of way	2.5	2.8
Line pipe	31.0	25.5
Line pipe fittings	3.9	3.5
Pipeline construction	38.4	41.6
Buildings	2.8	2.2
Pumping equipment	5.5	3.6
Machine tools and machinery	0.0	0.0
Other station equipment	6.8	8.6
Oil tanks	5.5	7.0
Delivery facilities	1.5	3.0
Communications systems	1.0	0.1
Office furniture and equipment	0.1	0.6
Vehicles and other work equipment	0.6	0.6
Other	0.0	0.8

(These data are gathered from responses to item 320 of Form P.) These costs can be divided into three groups:

		Crude	Products
1.	c(pipe,D,C) = cost of line pipe and fittings	35%	29%
2.	c(pumps, D,C) = cost of pumping power (i.e., pumping equipment, buildings, other station equipment)	15%	14%
3.	c(other,D,C) = cost of everything else (mainly pipeline construction)	50%	57%

The pumping costs have already been considered. The remaining division is convenient because as will be seen shortly, the cost of line pipe is sensitive to both diameter and capacity, while the cost of installing the pipe can probably be represented as dependent on diameter only. Therefore, since c(pipe,D,C) is nearly all line pipe cost, it can reasonably be represented as a function of D and C, whereas c(other,D,C), which is dominated by the cost of laying the pipe, can be represented as a function of D alone. It should be understood, of course, that these costs can depend on a number of other factors as well, such as the difficulty of terrain, weather, ease of access, and so on. But it will be assumed that these factors are not correlated with pipeline diameter or capacity, so that they can be ignored in the present analysis.

The cost of line pipe depends on its diameter and its pressure rating, and the latter is a function of the wall thickness and the grade of steel used. A representative price schedule listing 557 varieties of line pipe (American Steel Pipe 1979) suggests the regression

$$c(\text{pipe},D,C) = kY^{t_6}D^{t_7} , \tag{6.10}$$

where Y is the pressure yield point in N/cm^2, D the inside diameter in inches, and where $k = 0.036$, $t_6 = 0.75$, $t_7 = 1.72$ (r^2 for the regression was 0.87. The pipe diameters ranged from 8 to 20 in., the wall thickness from 0.156 to 0.375 in. and the grades from B to X-65). The maximum expected working pressure can be considered proportional to the pressure yield point chosen; generally, maximum working pressure is about 60% of yield pressure. The margin of safety chosen depends on the circumstances, but these circumstances can be presumed independent of the pipe's diameter and capacity. Working pressure is the sum of pressure due to friction and that due to gravity. The maximum pressure Y_f due to friction is proportional to the friction head at the pump discharge, which is given by formula (2.6) where L is the distance to the next pumping station or to the end of the pipe. (Discharge pressure at the downstream end can be ignored.) So we have,

$$Y_f = kh_f = kLC^{t_3}/D^{t_4} .$$

Since the spacing of pumping stations depends on many factors unrelated to diameter and capacity (such as terrain and availability of land), L can be assumed dependent of D and C and incorporated into the constant k. As for the pressure due to gravity Y_g, it will for the sake of simplicity be assumed to comprise a fixed fraction of Y_f. This means that

$$Y = Y_f + Y_g = kY_f = KC^{t_3}/D^{t_4} . \tag{6.11}$$

Substituting Eq. (6.11) into (6.10),

$$c(\text{pipe},D,C) = k(C^{t_3}/D^{t_4})^{t_6}D^{t_7} = k(C^{t_3t_6}/D^{t_4t_6-t_7}) , \tag{6.12}$$

where it has been estimated that $t_3 = 1.75$, $t_4 = 4.75$, $t_6 = 0.75$ and $t_7 = 1.72$. Note that since $t_4t_6 - t_7 = 1.84$ is positive, the cost of buying pipe for a given capacity decreases monotonically as the diameter increases (within the range of values covered by the data). This suggests that if pipe cost were the only consideration, one ought to choose the largest pipe and smallest pressure rating that are jointly available and appropriate for the desired throughput.

The cost of burying the pipe changes the picture, however. General economy of scale suggests that

$$c(\text{other},D,C) = kD^{t_8} . \tag{6.13}$$

It is reasonable to make c(other,D,C) depend on diameter alone because the expense of burying a pipe depends primarily on the size of the pipe and not on its strength. The cost of holding tanks may depend on the pipe's capacity as well as its diameter, but their cost comprises only about 10% of c(other,D,C). Some years ago the Oil and Gas Journal (1958 and 1959) conducted surveys that provide construction cost data sufficiently broken down that the relation between diameter and c(other,D,C) can be discerned. Regressing the cost of stringing and burying pipe plus the cost of right of way against diameter, these data suggest that $t_8 = 0.90$ ($r^2 = 0.999$). Combining Eq. (6.13) with (6.12),

$$\begin{aligned} c(\text{pipelaying},D,C) &= c(\text{pipe},D,c) + c(\text{other},D,C) \\ &= k(C^{t_3t_6}/D^{t_4t_6-t_7}) + kD^{t_8} . \end{aligned} \tag{6.14}$$

Note that the cost no longer decreases monotonically, for a fixed capacity, as the diameter increases.

6.1.4 Relation between capacity and diameter at minimum cost

Substitution of Eqs. (6.6), (6.9), and (6.14) into the cost formula (6.2) yields the following expression for the cost per unit capacity:

$$\begin{aligned} c(\text{total},D,C)/C = {} & k\left(\frac{C^{(t_3+1)t_1t_2-1}}{D^{t_4t_1t_2}}\right) + k\left(\frac{C^{(t_3+1)t_5-1}}{D^{t_4t_5}}\right) \\ & + k\left(\frac{C^{t_3t_6-1}}{D^{t_4t_6-t_7}}\right) + k\left(\frac{D^{t_8}}{C}\right) , \end{aligned} \tag{6.15}$$

where the approximate values of the exponents are given by

$t_1 = 0.7,$
$t_2 = 0.94,$
$t_3 = 1.75,$
$t_4 = 4.75,$
$t_5 = 0.7,$
$t_6 = 0.75,$
$t_7 = 1.72,$
$t_8 = 0.90.$

No pretense is made that Eq. (6.15) is adequate to compute costs for any particular pipeline. Every situation has a unique set of circumstances that must be reflected in cost calculations. Yet Eq. (6.15) appears to capture the basic interrelations among the components of cost, those interrelations that can be expected to operate in any application. For this reason Eq. (6.15) should be adequate for the derivation of a general relationship between the capacity C and the diameter D when optimality is achieved. On the assumption that the choice of capacity an diameter is made in something approaching an optimal way, this relationship should be adequate to describe reality.

To find the optimal relationship between C and D, first fix the capacity C and find the diameter D that minimizes c(total,D,C)/C. To do this set,

$$\frac{\partial}{\partial D} c(\text{total},D,C)/C = 0 \ ,$$

which, rearranging terms, yields

$$1 = k\left(\frac{C^{(t_3+1)t_1 t_2}}{D^{t_4 t_1 t_2 + t_8}}\right) + k\left(\frac{C^{(t_3+1)t_5}}{D^{t_4 t_5 + t_8}}\right) + k\left(\frac{C^{t_3 t_6}}{D^{t_4 t_6 - t_7 + t_8}}\right) . \qquad (6.16)$$

Solution of Eq. (6.16) for D would give the optimal diameter in terms of the capacity C. Now find an optimal capacity C when the diameter D is fixed. Set

$$\frac{\partial}{\partial D} c(\text{total},D,C)/C = 0 \ ,$$

which, after rearranging terms, yields an equation identical to Eq. (6.16) except for the values of the constants. Solution for C in terms of D would give the optimal capacity. Unfortunately, Eq. (6.16) has a closed form solution neither for D in terms of C nor vice-versa. Solution can be achieved by numerical methods only. Strictly speaking, then, the dependence of C on D is not described by a power function having the form of Eq. (6.1), nor for that matter by any effable algebraic function.

Note, however, that if $t_1t_2 = t_5 = t_0$ the equation reduces to

$$1 = k\left(\frac{C^{(t_3+1)t_0}}{D^{t_4t_0+t_8}}\right) + k\left(\frac{C^{t_3t_6}}{D^{t_4t_6-t_7+t_8}}\right) . \qquad (6.17)$$

Previous estimates that $t_1t_2 = (0.7)\ (0.94) = 0.66$ and $t_5 = 0.7$ suggest that t_1t_2 and t_5 are in fact nearly equal. Equation (6.17) has no explicit solution, but an observation regarding the estimated values of the exponents reveals how a solution can be approximated. Note that the ratios

$$\frac{(t_3+1)t_0}{t_4t_0+t_8} \doteq 0.46 \text{ and } \frac{t_3t_6}{t_4t_6-t_7+t_8} \doteq 0.48 \qquad (6.18)$$

are nearly equal (setting $t_0 = 0.7$). This means that Eq. (6.17) can be approximated with the equation

$$1 = k\left(\frac{C^{0.47}}{D}\right)^a + k\left(\frac{C^{0.47}}{D}\right)^b , \qquad (6.19)$$

for appropriate exponents a and b. (In this instance $a \doteq 4.1$ and $b \doteq 2.8$.) Equation (6.19) can be solved (numerically) for the <u>ratio</u> $C^{0.47}/D$, where the solution value is a constant with respect to C and D:

$$\frac{C^{0.47}}{D} = k .$$

At optimally, then, C and D bear the approximate relationship

$$D = kC^{0.47}$$

or

$$C = kD^{2.13} .$$

The outcome is the same (up to a constant k) whether D is optimized for a fixed C or vice versa.

The above derivation indicates that if reasonable estimates of the parameters are made, and if the simplifying assumptions are made that $t_1t_2 = t_3$ and that the ratios in Eq. (6.18) are equal, then the dependence of C on D is described approximately by a power function. The resulting value 2.13 of the exponent serves as a check on the validity of the derivation. It implies that oil moves slightly faster in larger pipes, which is correct, and it is only a little smaller than the estimates got in Sect. 6.5 from capacity and diameter data: 2.339 for crude lines, and 2.383 for products lines.

A difficulty that arises in the estimation of the parameters x and y has already been mentioned in Sect. 5.1. It is that the National Petroleum Council's pipeline capacity data (described in Chap. 4) sometimes do not show capacities of individual pipelines, but only the total capacity of a group of parallel pipelines of different diameters. The estimation procedure must be designed to accommodate this fact, and this is done in Sect. 6.3.

6.2 Funtional Form of the Regression of Throughput on Capacity and Diameter

It would be very difficult to perform an analysis, economic or otherwise, from which one could infer the likely functional form of the dependence of a pipeline's throughput on its other properties. Certainly, pipelines with more capacity can be expected to have, on the average, greater throughput. But the fraction of its capacity a pipeline uses (i.e., its utilization) is not in any obvious way a function of its physical characteristics. Whether a pipeline runs at capacity depends on the market for oil movement along its route, the tariffs its owners charge, and on other factors difficult to assimilate into a generalized analysis.

Nonetheless it would be unwise to assume that utilization of a pipeline's capacity is independent of its diameter and other physical properties. It is possible, for instance, that larger-diameter pipelines tend to be more highly utilized that smaller ones, perhaps due to their superior efficiency. It is necessary to be aware of any such dependence, since the method used in this study requires that a pipeline company's oil movements be allocated among its pipeline segments in some fashion that reflects reality (see Sect. 5.1). If throughput is not generally proportional to capacity, the allocation must take this into account.

In the absence of any <u>a priori</u> analysis of the dependence in question, it seems best to represent it using a function that is as simple as possible while providing for one or more parameters that reflect the degree to which a pipeline's utilization depends on its capacity and diameter. The following functional form suffices:

$$V = aC(C^bD^c) \quad , \qquad (6.20)$$

where V is the given pipeline segment's throughput, C its capacity, and D its (inside) diameter. This function shows throughput to be proportional to the product of capacity and a correction factor C^bD^c that is proportional to utilization. Since it is desirable to minimize the number of parameters to be estimated, replace C with its regression formula estimate (6.1) to get

$$V = ax^{b}CD^{by+c} = uCD^{z} ; \tag{6.21}$$

z is the parameter of interest. If z is zero, throughput is precisely proportional to capacity. If z is positive, larger-diameter pipelines are more fully utilized than smaller ones, and vice-versa if z is negative. Since no heavy dependence of utilization on diameter is expected, the absolute value of z should be considerably closer to zero than to one. That is, a pipeline's capacity is expected to be the principal determinant of the throughput allotted it, although its diameter may have some influence.

Two problems in the estimation of u and z should be mentioned. One is the problem that arises in connection with the estimation of capacity regression parameters: throughputs of individual lines are often not reported, but only the total throughput of a group of parallel lines. This is a more serious problem for the throughput regression because the Congressional Research Service map, from which throughput observations are taken, often covers three, five, or even ten parallel lines with a single throughput figure. Also there are relatively few individual lines for which throughputs are given. (See Chap. 4 for a description of the data sources.) The estimation procedure described in Sect. 6.4 accommodates this weakness in the data.

Another problem that besets the estimation of u and z is that throughputs are given on the CRS map in multiples of 5×10^6 bbl/year. The result is that many if not most of the observed throughputs are 5×10^6 bbl/year, even though the (groups of) pipes having this throughput may differ in diameter. It would be a distortion to require that an estimation procedure try to fit a curve to data showing that so many pipes of different diameter have the same throughput. Since the data simply do not distinguish throughputs in this range, it seems better to design an estimation procedure that assumes only that the throughputs set at 5×10^6 bbl/year are somewhere between 2.5 and 7.5×10^6 bbl/year, and similarly for other throughputs. This substitution of ranges for single values has little effect when the throughput is, say, 100 million bbl/year, but it is important when the throughput is 10 million bbl/year or less. It permits the estimation procedure to take into account only so much knowledge about typical throughputs as actually exists, rather than forcing a fitted curve to accommodate a fictitious equation of throughputs of lines having different diameters. Such a procedure is presented in Sect. 6.4. The consequences of using single values rather than intervals are quantified in Sect. 6.5.

6.3 Estimation of Capacity Regression Parameters

We have seen that the average daily capacity C of a pipeline is likely to be a function of the diameter D having the form

$$C = xD^y \,. \tag{6.22}$$

In this section procedures for estimating the parameters x and y will be derived.

Recall that in many cases it is only the sum of several capacities, rather than individual capacities, that can be observed. Let us say that the i^{th} measured capacity C_i is known to be the sum of the capacities in a certain group of one or more pipes having diameters

$$D_{i1}, \ldots, D_{in_i} \,.$$

If C_{ij} is the unknown capacity of the j^{th} pipe in group i, then

$$C_i = \sum_{j=1}^{n_i} C_{ij} \,.$$

There are 391 capacity observations C_i for crude oil lines and 395 observations for products lines.

The parameters x and y cannot be estimated, on the basis of this or any other sort of data, unless some assumption is made about the manner in which observed capacities deviate from the values predicted by the regression formula. Generally one of two basic error processes is presumed to occur. One is an additive process, in which each deviation is regarded as a sum of many small independent deviations, each representing one of the many influences that perturb an observed value. Whatever be the distributions of these individual disturbances, their sum is likely to have a distribution that is nearly normal, since it is a mathematical property of a normal distribution that it is asymptotically the result of summing a large number of random variables having distributions that commonly occur in nature. The additive model results in the regression equation,

$$C_{ij} = xD_{ij}^{y} + \varepsilon_{ij} \;, \tag{6.23}$$

where the error term ε_{ij} is normally distributed.

The multiplicative error model presumes an observed deviation to be the product of many small, independent deviations. Each deviation is represented by a multiplier; a multiplier of one represents no deviation, and a multiplier greater than or less than one represents an increase or decrease, respectively. An instance would be a transcontinental telephone signal, which can be seen as passing through a number of wires and amplifiers that decrease or increase the signal strength according to certain multipliers. The alteration in the received signal would be represented by the product of these multipliers. This can be contrasted with the case in which the received signal is a mixing of several signals, identical except for strength, travelling over parallel lines from the same source. Alterations in the received signal would be the algebraic sum of alterations made by the several lines. An additive error model would fit the latter case, and a multiplicative model the former.

The multiplicative regression equation is

$$C_{ij} = xD_{ij}^{y} \varepsilon_{ij} . \tag{6.24}$$

It is usually convenient to suppose that the logarithms of the individual deviations that contribute to ε_{ij} are so distributed that their sum has a distribution that is asymptotically normal. This allows one to take the logarithm of both sides of Eq. (6.24),

$$\ln C_{ij} = \ln x + y \ln D_{ij} + \ln \varepsilon_{ij} , \tag{6.25}$$

to get a linear regression formula with normally distributed error term $\ln \varepsilon_{ij}$. Ordinary least-squares estimation will yield values for ln x and y in Eq. (6.25), but it of course cannot be used here, since the individual capacities C_{ij} are unknown.

An example illustrated in Fig. 6.1 suggests that a multiplicative error model better suits pipeline capacities. Here there are six pipes, and (for simplicity) individual capacities are known for each. Nonlinear least-squares estimation yields the regression formula

$$C = 767\ D^{1.397}$$

for the additive model (curve A), and log-linear least-squares estimation yields the substantially different formula

$$C = 114\ D^{1.880}$$

for the multiplicative model (curve B). The additive model appears to err in that it presumes there is no heteroscedasticity in the deviations about the regression curve. That is, it assumes that the range of observed capacities for small pipes is as great as that for large pipes, whereas small pipes are likely to show a smaller range of capacities. Since the multiplicative model gives equal percentage deviations equal weight, it correctly expects a smaller absolute range at the lower end of the curve. Curve B therefore lies closer to the three smaller capacity observations than curve A, since a given deviation at the lower end of the curve is presumed much less probable than an equal deviation at the upper end. It appears, then, that the multiplicative model ought to be used, since it weights deviations in a more reasonable fashion.

Yet it is possible to allow for heteroscedasticity independently of the choice of error model. One need only suppose that the standard deviation σ_{ij} of each error variable ε_{ij} is a specified function of capacity or some other variable, a function whose parameters can be estimated along with x and y. The essential difference between an additive and multiplicative model has to do with the shape of the error distribution, not with any dependence of its variance on other variables. In fact, were it not for a change in distribution shape, the results of a multiplicative estimation could be got by way of an additive estimation (and vice-versa). The multiplicative equation

$$C_{ij} = xD_{ij}^{y}\, \varepsilon_{ij}$$

can be written, after Greene and Barnbrock (1978), as an additive equation

$$C_{ij} = xD_{ij}^{y} + (\varepsilon_{ij} - 1)\, xD_{ij}^{y} ,$$

whose error term is $(\varepsilon_{ij} - 1)\, xD_{ij}^{y}$. It is true that the variance of this error term depends on other variables, but as just mentioned additive estimation can accommodate this. The only bar to estimation is the fact that the error term is not normally distributed. So, it is only because additive estimation ordinarily presupposes a normal distribution of errors that it cannot replace multiplicative estimation. Indeed one could in theory carry out an additive estimation using the distribution of $(\varepsilon_{ij} - 1)\, xD_{ij}^{y}$, although there is no visible intuitive justification for doing so. The distribution fails even to have a mean of zero, as can be seen as follows. The random variable ε_{ij} is e^{Z}, where Z is nor- normally distributed with mean zero and variance σ^2. The mean of ε_{ij} is $E(e^{Z})$. But $E(e^{tZ})$ is just the moment generating function of Z, given by

$$E(e^{tZ}) = \exp(t^2\sigma^2/2) .$$

Consequently the mean of $(\varepsilon_{ij} - 1)\, xD_{ij}^{y}$ is

$$[\exp(\sigma^2/2) - 1]\; xD_{ij}^{y} \neq 0 .$$

The choice between error models, then, is tantamount to a choice between two error distributions: Z and e^Z. It is difficult to adduce arguents *a priori* in favor of one or the other. Also it is not unlikely that the data would fail to favor one over the other, once heteroscedasticity is accommodated in both cases. Finally, the derivation of estimates under a multiplicative model is mathematically awkward. Since each observed capacity C_i is (potentially) a sum of capacities, the regression Eq. (6.24) must be written

$$C_i = \sum_{j=1}^{n_i} C_{ij} = x \sum_{j=1}^{n_i} D_{ij}^{y} \varepsilon_{ij} .$$

(Note that logarithms are no longer useful.) Ordinarily one would compute maximum likelihood estimates of the parameters x and y (i.e., values of x and y that maximize the probability of making the observations that were in fact made). But there is no closed-form expression for the probability density function of the random variable $\sum_{j=1}^{n_i} D_{ij}^{y} \varepsilon_{ij}$, which is a weighted sum of random variables e^Z. Derivation of maximizing values of x and y would require heavy use of numerical methods. Since there is no reason to choose a multiplicative model *a priori*, and since the data may well fail to favor either model definitively, the amount of computation required to implement it seems unjustified.

It remains, then, to derive maximum likelihood estimates of x and y under an additive model adjusted to allow for heteroscedasticity. The regression equation is

$$C_i = \sum_{j=1}^{n_i} C_{ij} = \sum_{j=1}^{n_i} D_{ij}^{y} + \varepsilon_i , \qquad (6.26)$$

where $\varepsilon_i = \sum_{j=1}^{n_i} \varepsilon_{ij}$. If the error variables ε_{ij} are presumed to be independent and normally distributed with mean zero and variance σ_{ij}^2, ε_i is normally distributed with variance $\sum_{j=1}^{n_i} \sigma_{ij}^2$. As discussed earlier it is necessary to suppose that the variance of observed capacities for pipes of a given diameter depends somehow on the typical capacity of pipes of that diameter, since smaller-diameter pipes are likely to show less variation in their capacities. The variance cannot be made a direct function of a pipe's capacity, however, since individual capacities are in general not known. Rather, it must be made a function of diameter. Although it is difficult to know in advance what functional form is appropriate, it is reasonable to impose two requirements: that it allow for the possibility that the standard deviation of ε_{ij} is constant for all diameters, and that it allow for the possibility that the standard deviation is proportional to the predicted capacity (as is assumed by the multiplicative error model). A simple power function

$$\sigma_{ij} = hD_{ij}^{k} \qquad (6.27)$$

satsifies these requirements. σ is constant when $k = 0$, and it is proportional to the predicted capacity when k's value is the maximum likelihood estimate of the exponent y in Eq. (6.26). Let us adopt Eq. (6.27), then, and observe that if the error terms ε_{ij} are independent, the variance of ε_i is

$$\sum_{j=1}^{n_i} \sigma_{ij}^2 = h^2 g_{ik} \text{ , where } g_{ik} = \sum_{j=1}^{n_i} (D_{ij})^2$$

Let $L(x,y,h,k)$ be the proability density function representing the probability that a set of observed capacities $C_1, \ldots, C_n$ will deviate from their regression formulas respectively by $\varepsilon_1, \ldots, \varepsilon_n$. Since the error terms ε_i are independent, $L(x,y,h,k)$ is the product of the density functions of n normal distributions having variance $h^2 g_{ik}$ and mean zero. That is,

$$L(x,y,h,k) = (h\sqrt{2\pi})^{-n}(\prod_i g_{ik})^{-1/2}\exp[-(1/2h^2)\sum_i(C_i - x\sum_j D_{ij}^{y})^2/g_{ik}] \text{ .}$$

For any given h and k the values of x and y that maximize $L(x,y,h,k)$ can be found. The resulting regression formula $C = xD^y$ describes the curve that best fits the data on the assumption that h and k correctly characterize the error variance. The aim is to choose h and k so that the resulting maximum-likelihood regression curve creates residuals whose distribution is most nearly normal. This will be made more precise shortly.

It turns out that the maximum likelihood estimates of x and y depend only on k and are independent of h. If the parameter k is fixed, the values of x and y that maximize $L(x,y,h,k)$, which we can denote x_k and y_k, can be found by setting the partial derivatives of $\ln L(x,y,h,k)$ with respect to x and y equal to zero and solving simultaneously for x and y.

$$\frac{\partial}{\partial x}\ln L(x,y,h,k) = \frac{1}{h^2}\sum_i[\sum_j D_{ij}^{y}][C_i - x\sum_j D_{ij}^{y}]/g_{ik} = 0 \text{ ;} \qquad (6.28)$$

$$\frac{\partial}{\partial y}\ln L(x,y,h,k) = \frac{x}{h^2}\sum_i[\sum_j D_{ij} \ln D_{ij}][C_i - x\sum_j D_{ij}^{y}]/g_{ik} = 0 \text{ .} \qquad (6.29)$$

Solving (6.28) for x,

$$x_k = \frac{\sum_i [\sum_j^y D_{ij}] C_i / g_{ik}}{\sum_i [\sum_j^y D_{ij}]^2 / g_{ik}} .$$

The solution value for y can be found by substituting the above expression for x_k into Eq. (6.29) and solving (6.29) numerically for y. Note that the outcome is indeed independent of the value of h.

Once x_k and y_k are found, it remains to test the normality of the resulting error distribution. Since the variance of the distribution is assumed to depend on the diameter, the size of each error ε_i must be divided by the predicted standard deviation $h\sqrt{g_{ik}}$ of ε_i and the distribution of the quotient tested to determine whether it is standard normal (i.e., normal with mean zero and variance 1). Since h is unknown, it must be estimated. This can be done by noting that h is the standard deviation of the variable $\varepsilon_i\sqrt{g_{ik}}$ [since $h\sqrt{g_{ik}}$ is the predicted standard deviation of ε_i] and by estimating this standard deviation. Since part of the hypothesis to be tested is that $\varepsilon_i/(h\sqrt{g_{ik}})$and hence $\varepsilon_i/\sqrt{g_{ik}}$ have a mean of zero, the estimate h_k of h is computed on this assumption.

$$h_k^2 = \frac{1}{n}\sum_i \varepsilon_i^2/g_{ik} = \frac{1}{n}\sum_i [C_i - x_k \sum_j^{y_k} D_{ij}]^2/g_{ik} . \qquad (6.30)$$

There are a number of methods for testing the normality of $\varepsilon_i/(h\sqrt{g_{ik}})$, a matter discussed in Sect. 6.5. The object here is to find the value of k that results in a random variable $\varepsilon_i/(h\sqrt{g_{ik}})$ that is most nearly standard normal, by whatever measure proves appropriate. The resulting x_k and y_k are the desired estimates of the regression parameters. The hypothesis that $\varepsilon_i/(h\sqrt{g_{ik}})$ in fact achieves standard normality can then be tested. If the hypothesis is not rejected, then the normality assumption on which the above derivation is grounded can be presumed true.

6.4 Estimation of Throughput Regression Parameters

Recall that the average daily flow V (i.e., throughput) in a pipeline is likely to be a function of its capacity C and diameter D having the form

$$V = uCD^z . \qquad (6.31)$$

In this section procedures for estimating the parameters u and z will be derived. There are 418 crude oil throughput observations and 542 products throughput observations on which to base the estimation.

This regression is doubly complicated by the fact that both flows and capacities are often not observable individually, but it is often only the total flow or capacity in a group of parallel pipes that is known. Furthermore, the groups whose total flows are known do not necessarily correspond to the groups whose total capacities are known. Let us say that the i^{th} measured flow V_i is actually the sum of flows $V_{i1}, \ldots, V_{in_i}$ in pipes having diameters $D_{i1}, \ldots, D_{in_i}$ respectively. Let us also say that the p^{th} mesured capacity C_p is the sum of capacities $C_{p1}, \ldots, C_{pm_p}$. Note that the capacity of the pipe with flow V_{ij} and diameter D_{ij} is not necessarily C_{ij}, since the C's are likely to be grouped differently and hence to be indexed differently.

A further complication is introduced by the fact that the observed flows are known only to lie in intervals, intervals that in the case of the smaller flows are too broad to collapse to a point. We can take each observed flow to be an interval $[V_i, W_i]$ within which the actual flow is known to lie. This additional uncertainty will eventually be taken into account, but it is convenient first to develop the regression on the assumption that the observed flow is known exactly; that is, on the assumption that $V_i = W_i$.

For reasons very similar to those adduced in the previous section, an additive rather than a multiplicative error model will be used. On this model each individual flow V_{ij} is written as a sum of the regression formula and an error term

$$V_{ij} = uC_{pq(ij)}D_{ij}^{z} + \varepsilon_{ij}$$

where $C_{pq(ij)}$ is the capacity of the pipe whose flow is V_{ij}. (The notation pq(ij) is merely meant to indicate that p and q are to take values such that C_{pq} is the capacity of the pipe whose flow is V_{ij}.) Now,

$$V_i = \sum_j V_{ij} = u\sum_j C_{pq(ij)}D_{ij}^{z} + \varepsilon_i \ , \qquad (6.32)$$

where $\varepsilon_i = \sum_j \varepsilon_{ij}$. We will again suppose that each ε_{ij} is normally distributed with mean zero and standard deviation $\sigma_{ij} = hD_{ij}^{k}$, where h and k are parameters to be estimated along with u and y. If the ε_{ij}'s are independent, ε_i is normally distributed with mean zero and variance

$$\sigma_i^2 = \sum_j \sigma_{ij}^2 = h^2\Sigma(D_{ij}^{k})^2 = h^2 g_{ik} \ .$$

An obvious difficulty with Eq. (6.32) is that the C_{pq}'s are not known individually. It is known only that $\sum_q C_{pq} = C_p$ for $p = 1, \ldots, m$. One resolution of this difficulty would be to use the regression formula (6.31) to predict the capacity $C_{pq(ij)}$ given the known diameter of the pipe D_{ij}. But to do this is to waste a valuable piece of information: that each C_{pq} lies in a particular group of pipes whose total capacity C_p is known. Once it is known that a group of C_{pq}'s sum to C_p, determining the values of the C_{pq}'s is equivalent to determining their ratios with each other. It is reasonable, then, to require their ratios to be those that would be predicted by the capacity regression formula (6.22). What we require, then, is that

$$\sum_q C_{pq} = C_p$$

$$\frac{C_{pq}}{C_{p1}} = \left(\frac{C_{pq}}{D_{p1}}\right)^y \quad \text{for } q = 1, \ldots, m_p ,$$

where y is the maximum likelihood estimate of the exponent derived in the previous section. Solution for each C_{pq} yields

$$C_{pq} = \frac{D_{pq}^y}{\sum_q D_{pq}^y} C_p . \tag{6.33}$$

Now that values for the individual capacities C_{pq} have been found, it is possible to find maximum likelihood estimates of the parameters u, z, and h for a given k. Let the density function $L(u,z,h,k)$ represent the probability that a set of observed flows $V_1, \ldots, V_n$ will deviate from their respective regression formula estimates to the extent they in fact did. $L(u,z,h,k)$ is again the product of the density functions of n normal distributions having variance $h^2 g_{ik}$. If we set

$$\frac{\partial}{\partial u} \ln L(u,z,h,k) = \frac{1}{h^2} \sum_i \left[\sum_j C_{pq(ij)} D_{ij}^z\right]\left[V_i - u \sum_j C_{pq(ij)} D_{ij}^z\right] / g_{ik} = 0 \tag{6.34}$$

and

$$\frac{\partial}{\partial z} \ln L(u,z,h,k) = \frac{u}{h^2} \sum_i \left[\sum_j C_{pq(ij)} D_{ij}^z \ln D_{ij}\right]\left[V_i - u \sum_j C_{pq(ij)} D_{ij}^z\right] / g_{ik} = 0 \tag{6.35}$$

we can solve simultaneously for maximum likelihood estimate u_k and z_k of u and z for a fixed value of k. Solution of (6.34) for u yields

$$u_k = \frac{\sum_i [\sum_j C_{pq(ij)} D_{ij}^{z}] V_i / g_{ik}}{\sum_i [\sum_j C_{pq(ij)} D_{ij}^{z}]^2 / g_{ik}} , \quad (6.36)$$

and subsitution of (6.36) into (6.35) permits numerical solution of (6.35) for z_k. The resulting values of u_k and z_k are again independent of h.

As in previous section, an estimate h_k of the parameter h can be equated with an estimate of the standard deviation of $\varepsilon_i/\sqrt{g_{ik}}$, so that

$$h_k^2 = \frac{1}{n}\sum_i \varepsilon_i^2/g_{ik} = \frac{1}{n}\sum_i [V_i - u_k \sum_j C_{pq(ij)} D_{ij}^{z_k}]^2/g_{ik} . \quad (6.37)$$

If the value of k that results in a most nearly standard normal error distribution is found, then u_k and z_k are the desired estimates of u and z.

Our next task is to replace the observed flows V_i with observed intervals $[V_i, W_i]$ within which the actual flows are known to lie. Since nothing is known about where in the internal $[V_i, W_i]$ the actual flow lies, a given observation should not be considered a deviation from the regression formula prediction

$$r_i = u \sum_j C_{pq(ij)} D_{ij}^{z} ,$$

unless r_i lies outside the interval $[V_i, W_i]$. The magnitude of a nonzero deviation ε_i can be taken to be the difference between r_i and the closest boundary of the interval. That is, the error term ε_i is given by

$$\varepsilon_i = \begin{cases} r_i - W_i & \text{if } r_i > W_i . \\ r_i - V_i & \text{if } r_i < V_i . \\ 0 & \text{otherwise} \end{cases}$$

The density function L(u,z,h,k) is

$$L(u,z,h,k) = (h\sqrt{2\pi})^{-n} (\prod_i g_{ik})^{-1/2} \exp[(-1/2h^2)\sum_i \varepsilon_i^2/g_{ik}] .$$

For fixed k, maximum likelihood estimates u_k and z_k can be found by solving simultaneously the equations

$$\frac{\partial}{\partial u}\ln L(u,z,h,k) = \frac{1}{h^2}\sum_i(\varepsilon_i/g_{ik})\frac{\partial}{\partial u}\varepsilon_i = 0 \qquad (6.38)$$

and

$$\frac{\partial}{\partial z}\ln L(u,z,h,k) = \frac{1}{h^2}\sum_i(\varepsilon_i/g_{ik})\frac{\partial}{\partial z}\varepsilon_i = 0\ . \qquad (6.39)$$

Since ε_i is only piecewise differentiable, the chain-rule differentiation in Eqs. (6.38) and (6.39) is not valid at all points. In particular, ε_i is not differentiable when $r_i = V_i$ or $r_i = W_i$, and Eqs. (6.38) and (6.39) are false when $r_i = V_i$ or $r_i = W_i$ for at least one i. If we stipulate, however, that

$$\partial\varepsilon_i/\partial u = 0 \quad \text{if } r_i = V_i \text{ or } r_i = W_i$$

and

$$\partial\varepsilon_i/\partial z = 0 \quad \text{if } r_i = V_i \text{ or } r_i = W_i\ ,$$

then Eqs. (6.38) and (6.39) hold without exception. It is not possible to solve explicitly for u_k in terms of z as before, but Eqs. (6.38) and (6.39) can be solved simultaneously for u_k and z_k using numerical methods, again independently of the value of h. (Newton's method or some similar method will usually extract a solution. It is true that the functions whose zeros are sought are only piecewise differentiable. But if they are chain-rule differentiated in the normal fashion, and if the terms $\partial\varepsilon_i/\partial u$ and $\partial\varepsilon_i/\partial z$ are evaluated as above, Newton's method will usually converge to a solution.)

Once u_k and z_k are found, h^2 can again be estimated as the variance of the distribution of deviations from the regression curve. Deviations ε_i from the nearest boundary of the observation intervals are inappropriate for this purpose, however, since they underestimate the true variance of deviations when the diameter is small. This is because, for small diameters, the observation intervals (V_i,W_i) are as wide as the spread of observations, so that the predicted values will lie completely outside of only a minority of the intervals, with the result that only a minority of the ε_i's will be nonzero. A better course is to measure deviations, for the purpose of estimating h^2, as the difference between predicted values and the midpoints of the observation intervals. So if we set

$$\tilde{\varepsilon}_i = r_i - 1/2(V_i + W_i)\ ,$$

then

$$h^2 = \frac{1}{n} (\Sigma\tilde{\varepsilon}_i^2/g_{ik}) .$$

The value of k that reults in a distribution of $\tilde{\varepsilon}_i/(h\sqrt{g_{ik}})$ that is most nearly standard normal is found, and the resulting u_k and z_k are the desired estimates of u and z.

It should be noted that if ε_i vanishes for each i when Eqs. (6.38) and (6.39) are solved simultaneously, the solution can be a region of points (u_k, z_k) rather than a single point. In other words, when a regression curve passes through all the observation intervals for some value of u and z, there may be a family of regression curves that pass through all the intervals. These regression curves would be equally good, since nothing is known about where in the observed intervals the actual values lie. The region of parameter values (u_k, z_k) that defines this family of curves is the solution of the system of nonlinear inequalities

$$r_i \leqslant W_i$$

$$r_i \geqslant V_i, \quad i = 1, \ldots, n .$$

When there exist values for u and z that make each $\varepsilon_i = 0$, it is unnecessary to estimate the heteroscedasticity parameters h and k. This is because the same family of solutions would result for any assumption regarding the values of h and k $(h > 0)$.

6.5 Numerical Results

This section describes the numerical procedures by which estimates of the capacity and throughput regression parameters were obtained and displays the results. The capacity regression is dealt with first, and the throughput regression afterwards.

6.5.1 Capacity regression

The capacity regression parameters x, y in Eq. (6.22) were estimated as follows. As in Sects. 6.3 and 6.4, let x_k, y_k be maximum likelihood estimates of x and y that result for a fixed value of k in the heteroscedasticity function (6.27), where h in (6.27) is given by Eq. (6.30). A bisection search of values of k was performed to determine which values makes the distribution of $\varepsilon_i/(h\sqrt{g_{ik}})$ most nearly standard normal. For each k, x_k and y_k were computed by solving Eqs. (6.28) and

(6.29) numerically. The solution technique was Newton's method, which provided rapid and sure convergence in every case.

For each value of k for which the estimation procedure was run, outliers (i.e., observed capacities deviating an unusual amount from predicted values) were noted. None of the observed capacities were altered or removed simply because they were outliers, but all outliers were checked against the data sources. Several transcription errors were discovered in this way. Once corrections were made, the remaining outliers were not extreme.

There was some difficulty in finding an acceptable measure of normality. The chi-square test was tried first. If $Z_k = \varepsilon_i/(h\sqrt{g_{ik}})$ is the random variable whose distribution is to be tested, let o_j be the number of observed values of Z_k for which $L_{j-1} \leq Z_k < L_j$ (for conveniently chosen points $L_0, \ldots, L_r$). Let n_j be the expected value of o_j on the assumption Z_k has the standard normal distribution. Then the random variable

$$X_k = \sum_{j=1}^{r} \frac{(o_j - n_j)^2}{n_j}$$

has a chi-square distribution with r − 2 degrees of freedom (since the scaling factor h is estimated from sample data). It can be reasonably supposed that smaller values of X_k indicate distributions that are nearer standard normality.

It was found that were it not for numerous small wiggles, X_k would be a unimodal function of k (or at worst bimodal), which would permit a simple bisection (or Fibonnaci) search for the minimum value of X_k. But as k increases, observed values of Z_k move in and out of the intervals $[L_{j-1},L_j]$ in such a way that X_k fluctuates up and down irregularly. The bottom part of X_k's convex curve was flat enough and the wiggles large enough that the minimum was difficult to find. And once found, the minimum was a chance dip in the curve some distance from what, due to the general shape of the curve, struck the eye as the "true" minimum. The size of these spurious wiggles could be diminished by increasing the number of intervals, but not significantly unless the intervals were so numerous as to destroy the power of the chi-square test (Kendall and Stuart 1979, p. 465).

The Shapiro-Wilk "W" test for normality (Shapiro and Wilk 1965) was then considered, because of its superior power (Shapiro, Wilk, and Chen 1968) and because it does not require the data be grouped as the chi-square test does. Yet this test was rejected as too difficult to implement because it requires the tabulation of a large number of normal order statistics.

The next best test seemed to be the classical Kolmogorov-Smirnov test, which is easy to implement and does not require the grouping of data. If $F(z)$ is the standard normal distribution function and $Z_{k1}, \ldots, Z_{kn}$ are the observations of Z_k, the Kolmogorov-Smirnov statistic is

$$K_k = \max_{1 \leq i \leq n} \left| i/n - F(Z_{ki}) \right| .$$

A smaller K_k indicates a more nearly normal distribution. K_k was found to be a well-behaved function of k, and the k that minimizes K_k was found without difficulty.

The results of the capacity regression appear in Table 6.1. The upper third of the table shows the results of the simultaneous estimation of the parameters x, y, h, k. Note that pipeline capacity C in m^3/day is predicted by the formula

$$C = \begin{cases} 26.95\ D^{2.339} & \text{for crude lines} \\ 26.48\ D^{2.383} & \text{for products lines} \end{cases} , \qquad (6.40)$$

where D is the inside diameter in inches. This represents capacity for No. 2 fuel oil; formula (7.6) in Sect. 7.4 provides a correction for oils having other viscosities. The standard deviation σ of the distribution of residuals is estimated to vary with D as described by the formula

$$\sigma = \begin{cases} 3.937\ D^{2.75} & \text{for crude lines} \\ 3.228\ D^{2.95} & \text{for products lines} \end{cases} . \qquad (6.41)$$

It is evident that as the diameter increases the spread of residuals increases somewhat more rapidly than the capacity. This suggests that percentage variations in capacity among pipes of a given diameter are somewhat greater when the diameter is large than when it is small. These results are illustrated in Figs. 6.2 and 6.3.

The two lower thirds of the table attest to the importance of estimating heteroscedasticity parameters. When the residual variance is presumed constant (k = 0),as is normally done in an additive error model, the resulting parameter estimates are significantly different. This is also true, if to a lesser extent, when the standard deviation of the residuals is presumed proportional to the dependent variable, as is usually the case in a multiplicative model. This proportionality is obtained here by choosing k so that it equals the resulting estimate of y.

Table 6.1. Results of capacity and throughput regression parameters (C = capacity in m^3/d, V = throughput in m^3/d, D = inside diameter in in.)

			Capacity regression $C = xD^y$		Throughput regression $V = uCD^z$	
			Crude pipelines	Products pipelines	Crude pipelines	Products pipelines
Residual variance σ^2 fitted to data	Heteroscedasticity parameters	exponent, k	2.750	2.95	0.496	1.31
	($\sigma = hD^k$)	multiplier, h	3.937	3.228	1564	209.2
	Regression parameters	exponent, y or z	2.339	2.383	−0.291	−0.185
		multiplier, x or u	26.95	26.48	1.69	1.280
	Kolmogorov statistic		0.03553	0.05517	0.09175	0.07766
	r^2 statistic		0.811	0.977	0.934	0.954
σ^2 constant	Heteroscedasticity parameters	k	0	0	0	0
		h	15595	7763	6371	5893
	Regression parameters	y or z	2.184	2.504	−0.2669	−0.156
		x or u	46.34	19.31	1.562	1.191
	Kolmogorov		0.20218	0.2189	0.12963	0.16446
	r^2		0.817	0.977	0.934	0.954
σ proportionate to dependent variable	Heteroscedasticity parameters	k	2.394	2.413		
		h	9.900	10.53		
	Regression parameters	y or z	2.394	2.413		
		x or h	23.30	24.69		
	Kolmogorov		0.04853	0.05675		
	r^2		0.808	0.977		

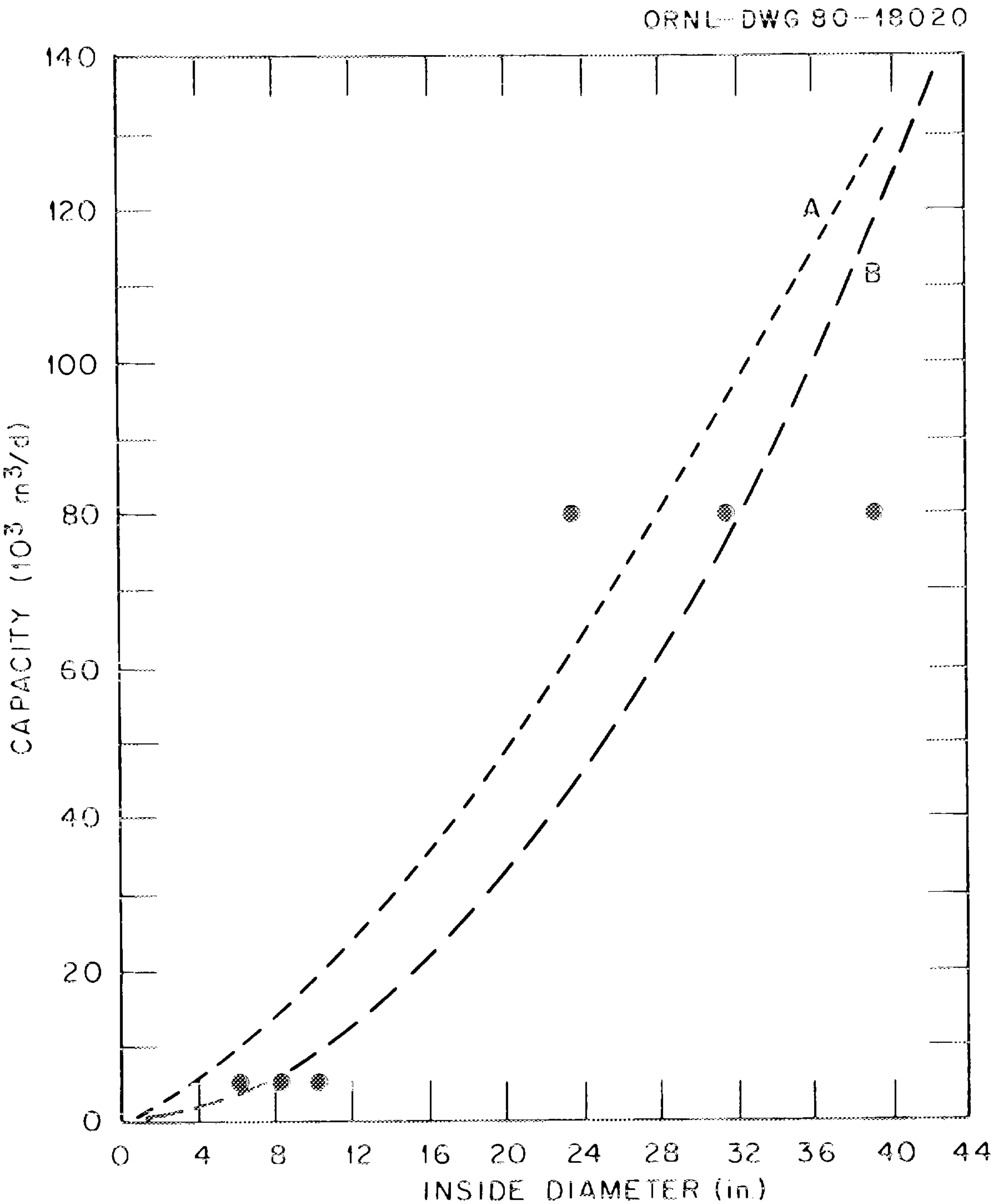

Fig. 6.2. Comparison of an additive model (A) and a multiplicative model (B) of the regression of pipeline capacity on diameter.

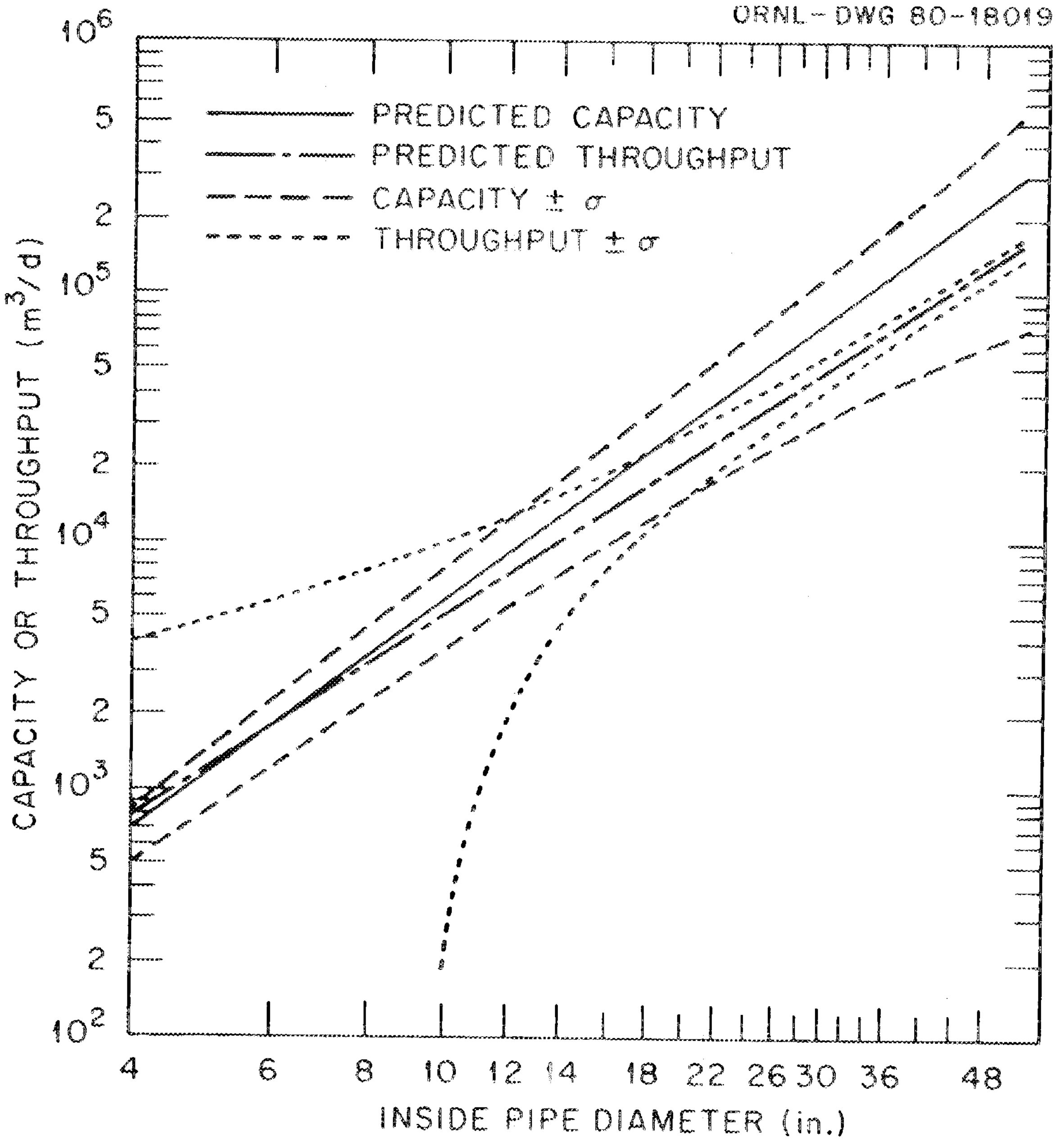

Fig. 6.3. Predicted throughput capacity and actual throughput vs. diameter for crude oil pipelines.

The Kolmogorov-Smirnov statistics, also shown in Table 6.2, can be used to test whether Z_k in fact has a standard normal distribution. This is equivalent to testing ε_i for normality while taking the standard deviation of ε_i to be $h\sqrt{g_{ik}}$, a quantity estimated from the sample data. Consequently standard tables of the Kolmogorov-Smirnov statistic, which assume that the mean and variance are fixed in advance, cannot be used here. Lilliefors, however, has published a Kolmogorov-Smirnov table for testing normality (generated by a Monte Carlo method) that is based on the assumption that both the mean and variance are estimated from sample data (Lilliefors 1976). The Lilliefors table, then, is designed for cases in which there is one less degree of freedom than in the present case. Yet since the size of critical values increases with the number of degrees of freedom, a Kolmogorov-Smirnov statistic that does not permit rejection of normality using the Lilliefors table certainly would not permit rejection of normality using a table designed for the present case, in which only the variance is estimated from sample data. It would suffice to show, then, that the Kolmogrov statistics of Table 6.2 do not permit rejection of normality using the Lilliefors table.

The critical values that pertain to the present problem are shown in Table 6.2. Note that normality cannot be rejected in the case of crude oil capacities even at the 0.05 significance level. The products capacity Kolmogorov statistic, 0.05517, is slightly higher than the Lilliefors critical value at the 0.01 significance level, but normality almost certainly cannot be rejected at the 0.01 significance level when only the variance is estimated from sample data. The distribution of residuals, then, can be presumed normal for the capacity regression.

6.5.2 Throughput regression

The throughput regression parameters u, z in Eq. (6.31) were estimated by finding the value of the heteroscedasticity parameter k for which maximum likelihood estimates of u_k and z_k resulted in a distribution of $Z_k = \varepsilon_i/(h\sqrt{g_{ik}})$ that was most nearly standard normal. Outliers were again checked for errors, and normality was again guaged by the Kolmogorov-Smirnov statistic. Maximum likelihood estimates of u_k and z_k were got by way of a simultaneous solution of Eqs. (6.38) and (6.39). These equations were solved numerically using Newton's method, despite the fact that the functions whose zeros were sought were only piecewise differentiable with respect to u and z. The values of derivatives at nondifferentiable points were stipulated as described in Sect. 6.4. It was found that test problems involving only three or four observations occasionally required that the starting point be chosen very carefully before convergence could be achieved. But when applied to the actual pipeline problems, which had close to 500 observations, Newton's method was robust and rapidly convergent. It is in fact not hard to see that convergence should be more easily achieved in problems involving a large number of observations.

Table 6.2. Kolmogorov-Smirnov critical values

Parameters estimated from sample data	Significance level 0.05 Mean variance	0.05 None	0.01 Mean variance	0.01 None
Capacity regression				
Crude lines	0.045	0.069	0.052	0.082
Product lines	0.045	0.068	0.052	0.082
Throughput regression				
Crude lines	0.043	0.067	0.050	0.080
Products lines	0.038	0.058	0.044	0.070

The results of the throughput regressions appear in Table 6.2. Note that pipeline throughput V in m^3/d is predicted by the formula

$$V = \begin{cases} 1.69\ CD^{-0.291} & \text{for crude lines} \\ 1.280\ CD^{-0.185} & \text{for products lines} \end{cases}, \tag{6.42}$$

where C is the capacity in m^3/d and D the inside diameter in inches. The negative exponent implies that smaller-diameter lines generally are more fully utilized than larger lines. This is odd, in view of the fact that the largest lines are almost always run at capacity. Perhaps usage of the next-to-largest lines is sufficiently slack to result in a negative exponent. In any case, it is not clear how this phenomenon is to be explained. The standard deviation of the distribution of residuals is estimated to vary with D as described by the formula

$$\sigma = \begin{cases} 1564\ D^{0.496} & \text{for crude lines} \\ 209.2\ D^{1.31} & \text{for products lines} \end{cases}. \tag{6.43}$$

Note that as the diameter increases, the spread of residuals increases more slowly than the throughput increases, unlike the state of affairs in the capacity regression. This means that percentage variations in throughput among pipes of a given diameter are greater when the diameter is small than when it is large. This is especially so for crude lines, and it may be explained by the fact that the smaller crude lines often serve particular oil fields, some of which are new and use pipelines to capacity, and others of which are declining in production and no longer fill the pipelines. The larger crude lines would presumably serve several oil fields, whose aggregate production would perhaps show smaller percentage variations.

A prediction of throughput as a function of diameter alone can be had by substituting (6.40) into (6.42), resulting in the formula

$$V = \begin{cases} 45.6\ D^{2.048} & \text{for crude lines} \\ 33.9\ D^{2.198} & \text{for products lines} \end{cases} \quad . \qquad (6.44)$$

This formula is plotted on Figs. 6.2 and 6.3 along with the capacity regression curves.

The test for the normality of the distribution of residuals does not proceed as smoothly as in the capacity regression. Examination of Tables 6.1 and 6.2 reveals that normality can be rejected at the 0.01 significance level for crude lines, and at the 0.05 significance level (and probably at the 0.01 level) for products lines. These rejections are not entirely definitive, since in either case the Kolmogorov statistic is near the critical value, but they are rejections nonetheless. A regression that assumed a residual distribution that better fit the data could be expected to deliver more accurate estimates of u and z.

It is likely, however, that the errors generated by the normality assumption are not large. One reason is that the magnitude of the Kolmogorov statistics suggests that the residual distribution does not stray far from normality. Another is that the resulting estimates of u and z are only moderately sensitive to assumptions regarding the distribution of residuals. For instance, variations in k that result in substantially different assumptions as to the shape of the distribution of residuals have only a moderate effect on the parameter estimates:

k	Estimated	
	u	z
0	0.805	−0.267
0.496	0.820	−0.291
1	0.822	−0.293
2	0.793	−0.206

So, although the throughput regression problem should be regarded as less tractable than the capacity regression problem, the parameter estimates

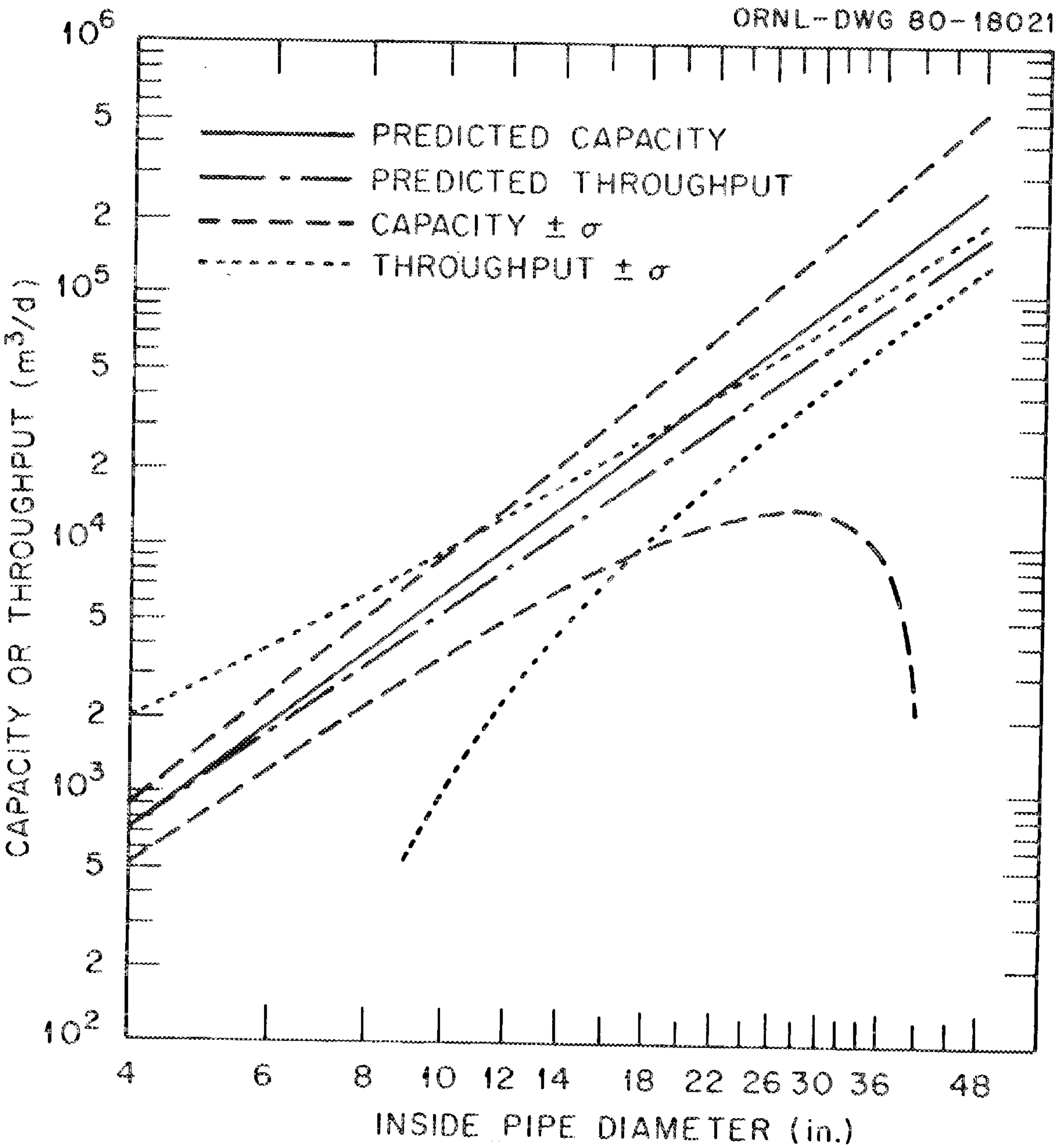

Fig. 6.4. Predicted throughput capacity and actual throughput vs. diameter for oil products pipelines.

probably do not suffer from large errors due to a false normality assumption. It is arguable, however, that the falsehood of this assumption makes it pointless to estimate the heteroscedasticity parameters h and k, since the errors introduced by using a constant k may be of the same magnitude as the errors caused by assuming normality. This argument applies only to the throughput regression, of course, since normality could not be rejected in the capacity regression.

It is interesting to note the parameter estimates that ensue when one regards observed throughputs as point values rather than as intervals within which the actual throughput lies. The regression formula that results from a point-value estimation is

$$V = \begin{cases} 0.798\ CD^{-0.254} & \text{for crude lines} \\ 0.767\ CD^{-0.313} & \text{for products lines} \end{cases} .$$

The resulting heteroscedasticity formula has the exponent $k = 0.963$ for crude lines and 2.49 for products lines. These results differ substantially from the interval-value estimation results in Eqs. (6.42) and (6.43), especially in the case of products lines. They suggest that a specious equation of throughput values that are really known only to lie within the same interval can significantly falsify the results of a regression study.

7. CALCULATION OF PUMPING ENERGY

This chapter details the method by which pumping energy is calculated, where pumping energy is the mechanical energy actually delivered to the oil by the pumps. It draws on the regression results of Chap. 6 and the flow schedule investigation of Chap. 8, which itself depends on parts of this chapter. Pumping energy is converted into total energy consumption in Chap. 9, which estimates fuel-to-oil efficiency. These interrelationships are described more fully in Chap. 5, of which Sect. 5.3 is a summary of the procedures documented in this chapter.

7.1 Pipe Diameters and Lengths

Nominal pipe diameters for nearly all U.S. trunk lines are available from the American Petroleum Institute maps, as noted in Chap. 4 (American Petroleum Institute 1979). Only inside diameters are relevant to energy calculations, however, and a pipe's inside diameter is seldom the same as its nominal diameter. If the outside diameter of a pipe is known, the probable inside diameter can be computed on the basis of the typical wall thicknesses listed in Table 7.1. Even when a pipe has a wall thickness other than the one listed, the discrepancy is likely to be small.

The outside diameter of standard pipe over 12 in. in diameter is the nominal diameter, but the outside diameter of smaller pipes is another matter. The standard outside diameters can be learned by consulting the Pipeline News Line Pipe Size Charts (Pipeline 1978). They are indicated in Table 7.1. The resulting inside diameters for all nominal sizes, 6 to 48 in., are also shown. These inside diameters are used throughout this study.

Table 7.1. Outside diameters and typical wall thicknesses for line pipe of various nominal diameters

Nominal diameter (in.)	Wall thickness (in.)	Outside diameter (in.)	Inside diameter (in.)
6, 8	0.25	6.625, 8.625	6.125, 8.125
10, 12	0.25	10.75, 12.75	10.25, 12.25
14–24	0.312	14–24	13.376–23.376
26–34	0.375	26–34	25.25–33.25
36–42	0.406	36–42	35.188–41.188
48	0.462	48	47.076

The pipeline lengths used in calculation are segment lengths. The pipeline network was represented as a collection of interconnected pipe segments for purposes of coding (see Appendix F). Each segment consists of a single pipe having no connections with other lines and no changes in diameter, ownership or state of location along its length. The lengths of the segments were measured directly by running a measuring wheel over the links on the API maps (American Petroleum Institute 1977). Since this sort of measurement can result in errors, each regulated company's total measured pipe mileage was compared with its reported pipe mileage (Oil and Gas Journal 1979). The reported figures were usually about 10–15% larger, as reflected in the national figures displayed in Table 7.2.

Table 7.2. Comparison of reported and measured pipe mileage nationwide

	Regulated carriers only		Discrepancy (%)
	Total measured length (km)	Total reported length (km)	
Crude pipelines	86,093	100,233	14
Products pipelines	88,504	101,093	12

The discrepancies are due partly to the tendency of map measurement to straighten out bends, and perhaps partly to the omission of some pipelines on the maps. To correct for such errors, each segment in each company was lengthened by a fixed proportion so as to make the total length match the reported total for that company. The segments belonging to unregulated companies, which do not report pipeline mileages, were not lengthened. This may result in a 10 to 15% underestimation of pipe mileage and hence oil movements and energy use among unregulated companies. But since unregulated companies account for only 9% (crude) or 5% (products) of oil movements, any resulting error is likely to be 1% or less (see Table S.2).

7.2 Pipe Roughness

As explained in Chap. 2 the friction factor f in the D'Arcy-Weisbach formula (2.2) for friction head depends not only on the Reynolds number but on the roughness of the pipe wall as well. This section presents a formula that closely approximates this dependence and briefly assesses the importance of pipe roughness to energy calculations.

Empirical work has shown that a film of laminar flow clings to the wall of a pipe even when the flow is very turbulent elsewhere in the pipe (Wolfe 1956). When the film thickness is greater than the height of the protuberances on the pipe wall, roughness has no effect on flow resistance, and the friction factor depends on the Reynolds number only. When the film thickness is less than the average asperity height, the friction factor depends only on roughness and is nearly independent of the Reynolds number. In typical pipeline flow regimes, however, the laminar film thickness is of the same magnitude as the asperity height, so that both the Reynolds number and roughness affect the friction factor.

The dependence of the friction factor on the Reynolds number R and the relative roughness (i.e., the ratio of average asperity height ε to inside pipe diameter D) was originally established by coating the interior of smooth pipes with sand grains of known size. Graphs depicting the dependence are well known and widely published (e.g., Merritt 1976, pp. 21–30; Gulf 1978, p. 131). For purposes of computer computation it is convenient to have an algebraic equation that approximates this regression. The following logarithmic-quintic equation provides an excellent least-squares fit in the range of values at issue in this study.

$$\log_{10} f = \sum_{i=o}^{5} \sum_{j=o}^{i} a_{ij} r^j e^{i-j} , \qquad (7.1)$$

where $r = \log_{10} R$, $e = \log_{10}(\varepsilon/D)$,

and $a_{00} = -1.29717905$,
$a_{10} = 0$,
$a_{11} = 0$,
$a_{20} = 0$,
$a_{21} = -0.17592600$,
$a_{22} = 0$,
$a_{30} = 0.13828152$,
$a_{31} = 0.27214050$,
$a_{32} = 0.27704850$,
$a_{33} = 0.03979336$,
$a_{40} = 0.02515647$,
$a_{41} = 0.02264316$,
$a_{42} = -0.01653602$,
$a_{43} = -0.03852152$,
$a_{44} = -0.00623620$,
$a_{50} = 0.00088359$,
$a_{51} = -0.00176603$,
$a_{52} = -0.00505742$,
$a_{53} = -0.00326456$,
$a_{54} = 0.00026943$,
$a_{55} = 0.00005803$.

This regression was based on 20 observed values, with R ranging from 10^4 to 10^7 and ε/D ranging from 10^{-3} to 10^{-6}. The resulting r^2 statistic was 0.999946, and the discrepancy between predicted and observed values of f ranged from 0.05% to 1.92%, well within the accuracy required by this study. The solution values of the parameters a_{ij} were calculated by the statistical program SAS (Barr et al. 1976). SAS found the matrix whose inversion is required for solving the normal equations to be singular, and the solutions are therefore based on the generalized inverse of the matrix.

On the recommendation of F. L. Moody, the average capacity asperity height ε is generally taken to be 0.0018 in. for oil pipeline calculations (Moody 1944), and that convention is followed here. Table 7.3 shows that only a rough approximation of ε is necessary. Even a consistent error of a factor of 3 or 5 in either direction results in friction head errors within the tolerances of this study.

Table 7.3. Effect of pipe roughness on friction head (friction head in m/km)

Average asperity height ε (in.)	Crude oil pipeline, Sp gravity = 0.85, Viscosity = 7.5 cS		Products pipeline, Sp gravity = 0.77, Viscosity = 1.5 cS	
	8 in. ($3,620\ m^3/d$)	36 in. ($111,590\ m^3/d$)	8 in. ($4,309\ m^3/d$)	36 in. ($141,690\ m^3/d$)
0.0005	8.73	3.59	8.63	4.39
0.001	8.83	3.61	8.96	4.52
0.0018	9.00	3.66	9.40	4.73
0.003	9.22	3.75	9.93	4.98
0.005	9.51	3.89	10.61	5.33
0.01	10.07	4.16	11.86	5.96

7.3 Densities and Viscosities

This section details the methods by which the density and viscosity of oil in each pipeline segment are calculated.

7.3.1 Densities of oil products

Since the pressure drop in a pipeline is directly proportional to the density of the oil, other variables held constant, it is important to estimate the density of the oil in each pipeline segment so far as is possible. This estimation is straightforward in the case of products pipelines if the mix of products delivered is known, since the density of a given product is relatively constant. Density variations resulting from variations in the refining process are slight. The dependence of density on temperature is likewise slight, relative to the tolerances of this study. In the range of specific gravities of concern (from 0.51 for liquefied propane to 0.84 for no. 2 fuel oil), specific gravity varies less than 0.2% per °C as temperature rises from 0 to 100°C (Gulf 1978, p. 174). An Oil and Gas Journal survey of crude oil temperatures in 28 pipeline segments found a range of temperatures from 8 to 41°C over the four seasons, with the majority between 10 and 27°C (Kennedy 1956, p. 43). Since oil products are likely to show less temperature variation than crude oil, which comes out of the ground hot, temperatures of a given oil product should lie in a range at most 25°C wide. The variation in specific gravity over this range is less than 5%.

The densities of the various oil products and ammonia were taken to be those given in Table 7.4. The mix of these products flowing in each pipeline link was taken to be the mix delivered by the operating pipeline company as a whole. These data are reported by regulated common carrier pipelines on Form P (Federal Energy Regulatory Commission 1978, item 400). The product density used in calculations is the average of the densities of the products shipped, weighted by the fraction of total deliveries each product comprises. Companies for which data are not available are assumed to pipe a product having specific gravity 0.80 (49.9 lb/ft^3).

Table 7.4. Densities and viscosities of petroleum products and ammonia

Product	SP gravity[a]	lb/ft^3	Kinematic viscosity[b] (cstokes)
Gasoline	0.73	45.6	0.64
Kerosene	0.81	50.5	2.2
Fuel oil	0.83	51.8	3.0
Jet fuel	0.78	48.7	1.2
LPG	0.54	33.7	0.3[c]
Ammonia	0.66[d]	40.9	1.0

[a]At 60°F relative to H_2O at 60°F. From Lewis and Hangs 1963, p. 1-8.

[b]At 70°F. From Lewis and Hangs 1963, p. 1-8.

[c]At 30°F.

[d]At 10°F relative to H_2O at 60°F. From Gulf 1978, p. 175.

7.3.2 Density of crude oil

The density of crude oil flowing in a particular link is difficult to ascertain, since pipeline companies do not report the characteristics of the crude oil they transport. It is true that oil from a given field has characteristic properties and that it is possible in principle to trace oil through the pipeline system to determine the density of oil flowing through each link. But it is not readily known how oil is routed, and to infer its routing would in itself require a sizeable research project. Fortunately, crude oil densities do not vary enormously. Specific gravities range from 0.73 to 1.02 at 100°F, and most crudes fall in the range from 0.80 to 0.95 (Hobson 1973, p. 6). For the purposes of this study it is permissible to use an average value, and that used by the Association of Oil Pipelines, 0.85 (35° API, or 53.04 lb/ft^3) at normal piping temperatures, is acceptable (Association of Oil Pipelines 1980).

7.3.3 Viscosity of oil products

The viscosity as well as the density of oil flowing in a given products pipeline link can be based on the product mix delivered by the operating company as a whole. The product viscosities used in this study are displayed in Table 7.4. The energy use of a pipeline is only mildly sensitive to viscosity, since the friction head varies only with the 0.252 power of the oil viscosity [see formula (2.6)]. Viscosity does vary with temperature, but the resulting variation in friction head for oil products is small enough that temperature can be neglected for present purposes (Fig. 7.1).

Since friction head is not proportinal to kinematic viscosity, the viscosity figure for a given link cannot be a simple weighted avearge of the viscosities of the products transported by the operating company. The viscosity used in energy calculations must be that which results in the average friction head h_f for that link. If w_i is the fraction of company deliveries comprised by product i, then formula (2.6) implies that the average friction head in a given link is

$$h_f = k\sum_i w_i \nu_i^{0.252}$$

for an appropriate constant k, where ν_i is the kinematic viscosity of product i. The single viscosity value ν_o that would result in a friction head h_f is therefore

$$\nu_o = (h_f/k)^{1/0.252} = \left(\sum_i w_i \nu_i^{0.252}\right)^{1/0.252} . \qquad (7.2)$$

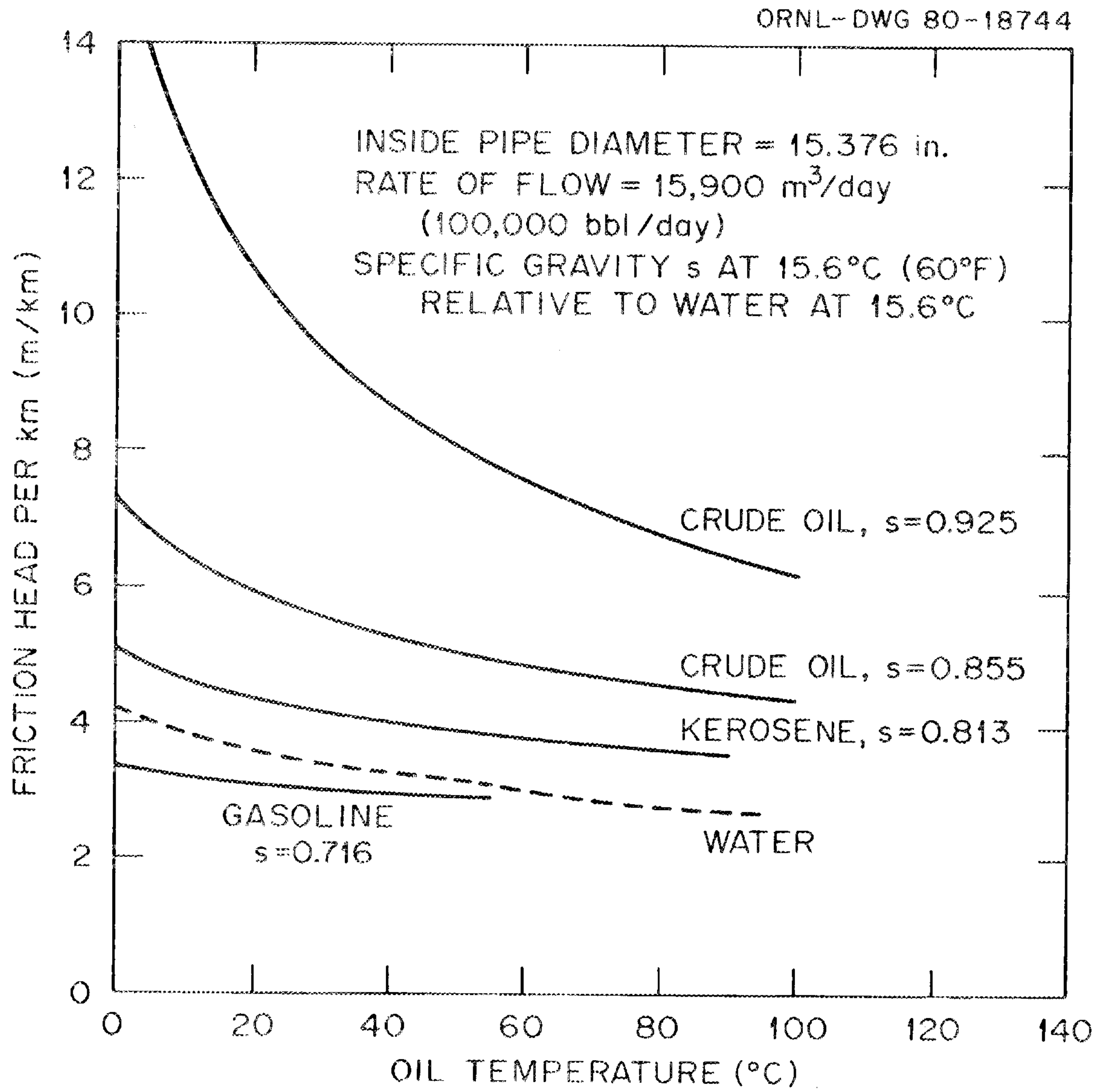

Fig. 7.1. Friction head vs. temperature for various pipeline oils.

Formula (7.2), then, is used for averaging the viscosities of products transported by the company operating a given link.

7.3.4 Viscosity of crude oil

Determining the viscosity of crude oil presents a difficult problem, since it can be very sensitive to temperature. Figure 7.1 illustrates the dependence of friction head on temperature in a pipeline for two representative crude oils. If crude oil pipeline temperatures range from 8 to 41°C, as stated earlier, then friction head at the lower end of the range is 27% higher than at the upper end for the lighter crude, and 50% higher for the heavier crude. Since it is possible to estimate the average pipeline viscosity directly, based on data to be discussed shortly, temperature variations could be ignored if they did not correlate with any other important variable. But they do, because oil is likely to be warmer, on the avearge, in large pipes than in small ones. Use of a single average viscosity figure, then, is likely to result in an overestimate of energy use by large-diameter pipelines, since warm oil is less viscous than cool oil. In the end it will be possible neither to compensate for this error nor to assess whether it is significant. Nonetheless a brief investigation of the problem will suggest that the error is almost certainly not large and may well be insignificant.

Oil in large-diameter pipelines is likely to be warmer because oil is pumped hot from the ground and because its temperature drops more slowly while flowing through large-diameter lines than through small-diameter lines. This can be seen as follows. Temperature drop due to heat dissipation over a length of pipeline is given by the equation (Myers 1971)

$$\log_{10} \frac{T_i - T_a}{T_L - T_a} = 0.0346 \frac{DkL}{Vsc} \qquad (7.3)$$

where T_i = oil temperature at upstream end of pipe;
T_L = oil temperature at downstream end;
T_a = air temperature;
D = outside pipe diameter, in.;
k = heat transfer coefficient for outside of pipe, kJ/h-m^2-°C;
L = length of pipe, km;
V = rate of flow, m^3/h;
s = specific gravity of oil
c = specific heat of oil, kJ/kg-°C.

The drop in temperature due to heat dissipation is counteracted to a small extent by friction heating of the oil. Since the friction heating depends on the oil viscosity, which in turn depends on the temperature, the change in temperature is best calculated by dividing the pipe into small segments having length ΔL. The temperature drop ΔT_{loss} due to heat dissipation in one segment of pipe (ignoring friction heating) is given by a rearrangement of Eq. (7.3):

$$\Delta T_{loss} = (T_i - T_a)(1 - 10^{-0.0346Dk\Delta L/Vsc}) ,$$

where T_i is the temperature at the upstream end of the segment. The temperature gain ΔT_{gain} due to friction heating (ignoring heat dissipation) is

$$\Delta T_{gain} = h_f g/c ,$$

where g is the gravitational acceleration (m/s^2) and h_f is given by formula (2.6). The resulting temperature at the downstream end of the segment is

$$T_{i+\Delta L} = T_i + \Delta T_{gain} - \Delta T_{loss} .$$

The calculation is repeated for each segment of pipe, letting the downstream end temperature of one segment serve as the initial temperature of the next segment, until the end of the pipe is reached.

The value of the heat transfer coefficient k depends on the medium through which the pipeline passes. One source lists the following values, determined empirically (Lewis and hangs 1963, p. 1-23):

Medium	kJ/m^2-h-°C
Sandy soil, dry, 24-in. cover	5.1–8.2
Sandy soil, moist, 24-in. cover	10–12
Sandy soil, soaked, 24-in. cover	23–27
River bed, 50-in. water, 60-in. cover	41–51
Sandy soil, dry, 8-in. cover	12–14
Sandy soil, moist to wet, 8-in. cover	25–29
Clay soil, dry, 24-in. cover	4.1–6.1
Clay soil, moist to wet, 24-in. cover	12–18
Open air	4.1

The results of a sample set of calculations, based on heat transfer coefficients of 5, 10, and 15 kJ/m^2-h-°C, appear in Fig. 7.2. The crude oil chosen for these calculations is the lighter crude whose viscosity properties are depicted in Fig. 7.1. The rate of flow is set at the capacity flow predicted by the regression equation (6.40) derived in Sect. 6.3.

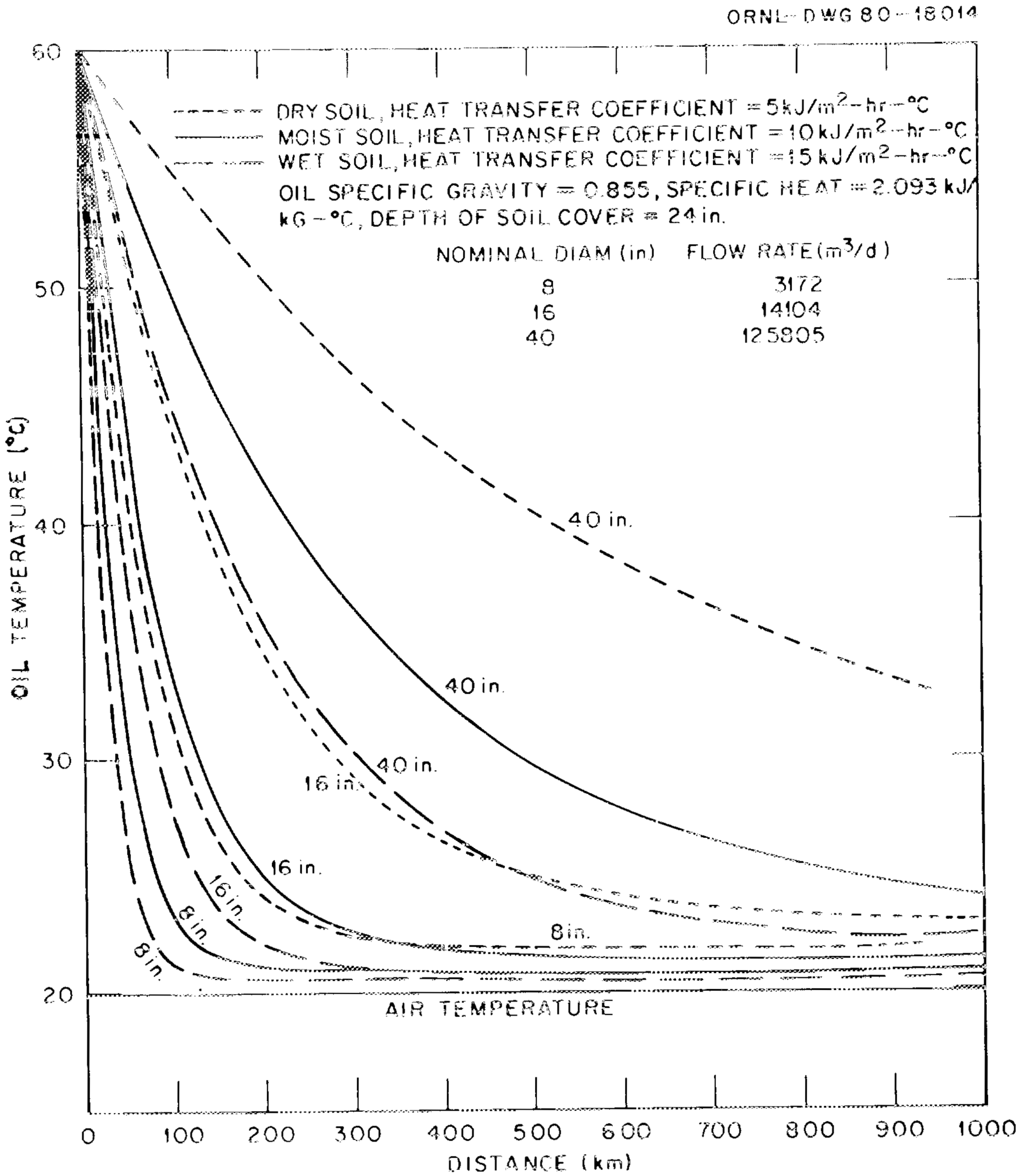

Fig. 7.2. Temperature drop in crude oil pipelines.

Figure 7.2, although it reflects the high sensitivity of the rate of heat loss to soil conditions, nonetheless permits the generalization that whereas oil in smaller pipes quickly cools to an equilibrium temperature near that of the surroundings, oil in large pipes can require hundreds of km to cool. If a significant temperature difference is taken to be one that results in at least a 10% difference in friction head, then comparison with Fig. 7.2 reveals that, for this particular crude oil and for an initial temperature of 60°C, the temperature difference between 8- and 40-in. pipes is significant at distances between 20 and 160 km downstream in wet soil, between 40 and 260 km in moist soil and between 100 and 510 km in dry soil. If oil enters pipelines at near 60°C, then, it is likely that temperature differences between 8- and 40-in. pipes are significant over an appreciable portion of the network.

The choice of a 60°C initial temperature is largely arbitrary, however, because it is unclear what the initial temperature generally is. Although it is known that oil leaves the well at tempertures on the order of 80 to 100°C (Tevepaugh 1979), an undetermined amount of heat dissipates from gathering lines and holding tanks before the oil enters trunk lines. The fact that the Oil and Gas Journal survey, mentioned earlier, sampled no temperature higher than 41°C may suggest that the initial temperature is generally less than 50°C. But to make this inference would be rash, since all of the lines surveyed were 24 in. or less in diameter (except for one 31-in. line), and the temperature in lines of this size would be expected to approach ambient temperatures rather rapidly even if the initial temperature were near 60°C. In any case, it is instructive to compute the temperature differences between lines of different diameters that would result from an initial temperature of, say, 40 or 50°C. These differences can be read from Fig. 7.2 simply by taking an appropriate fraction of the plotted differences (1/2 for 40°C and 3/4 for 50°C), since temperature differences down the line vary almost proportionately with the difference between the initial temperature and 20°C. (This proportionality fails to hold as the equilibrium temperature is approached, but by this time temperature differences are clearly insignificant anyway.) The temperature difference between 8- and 40-in. lines, it turns out, are significant at no point along the line when the initial temperature is 40°C, and only over a 30- to 70-km stretch (depending on soil conditions) near the upstream end of the line when the initial temperature is 50°C.

It is clear that if initial temperatures are in the 40 to 50°C range, temperature differences between lines of different diameters should in general be insignificant. To be sure, initial tempertures are higher than 50°C in at lest some lines. There are evidently no heated trunk lines in the United States, but some heavier crudes are turned into lines at elevated temperatures. North Slope crude oil enters the 48-in. Alyeska Pipeline at 63°C. It has also been reported that fast-moving crude in very large-diameter pipelines can rise in temperature, due to friction heating, over long distances (Petroleum Extension Service 1973 p. 13). Yet this should not occur at flow rates and for viscosities found in this study to be typical.

The upshot is that the use of a single viscosity figure for pipelines of all sizes should result in no significant error if initial temperatures typically are not much higher than 50°C, which may well be the case. But there is no reason to be sure that initial tempertures are not often 60°C or higher, and this could result in something on the order of a 10% overestimate of energy intensiveness for the largest pipelines and a 10% underestimate for the smallest pipelines. Currently available data do not permit a resolution of this difficulty, but in either case the errors are not large.

It remains to estimate an average pipeline crude oil viscosity. The Oil and Gas Journal survey (Kennedy 1956, p. 42) obtained 42 viscosity readings from 28 crude oil pipeline segments in the United States and Canada (except for one line in Saudi Arabia). Diameters ranged from 12 to 31 in., and the pipes carried crude in fields from Wyoming, California, the mid-continent, west and south Texas as well as the panhandle, Canada and Arabia. (Viscosities must be deduced from tabulated flow rates and Reynolds numbers for each segment.) The average reading, weighted by volume of flow, is 8.59 cSt. But since friction head varies with the 0.252 power of viscosity, it is preferable to compute an average according to formula (7.2). The result is 7.55 cSt. Consequently the figure 7.5 cSt can be taken as an average viscosity for pipeline crude.

A nagging worry is that crude oil piped in 1978 may have tended to be more viscous than the average crude of the 1950s, when the above survey was made. But in the absence of data to the contrary, the 7.5 cSt estimate is the best to be had.

7.4 Throughputs

The average daily throughput in each pipeline segment is estimated as described generally in Sect. 5.1. This section presents a more precise description of how the estimation works. It ends with a discussion of some of the difficulties encountered in using the company reports of total oil movement.

Let

- p, q = arbitrary pipeline segments;
- V_p = the estimated throughput of segment p (m^3/d);
- C_p = the estimated capacity of segment p (m^3/d);
- L_p = the length of segment p (km);
- D_p = the inside diameter of segment p (in.);
- $co(p)$ = the collection of segments belonging to the company to which p belongs;
- $M(p)$ = the total oil movements (m^3-km) reported by the company to which segment p belongs, if that company is federally regulated;

cap(p) = the collection of segments containing p whose total capacity is reported. If the capacity of p in particular is reported, cap(p) contains just p. If p belongs to no such group of segments, let cap(p) = ϕ (i.e., cap(p) be empty);

C(p) = the reported total capacity of segments in cap(p) (m^3/d);

ν_p = the kinematic viscosity of the oil in segment p, computed as described in Sect. 7.3 (cSt);

x, y = capacity regression parameters in Eq. (6.22), given by Eq. (6.40);

u, z = throughput regression parameters in Eq. (6.31), given by Eq. (6.41).

An initial estimate C'_p of the capacity C_p of segment p is got by making the ratio of C'_p to C(p) the same as the ratio of the predicted capacity of p, xD_p^y, to the total predicted capacity of the segments in cap(p). The predictions are those made by the regression formulas (6.40). More precisely,

$$C'_p = \begin{cases} \dfrac{C(p)xD_p^y}{\sum_{q\varepsilon cap(p)} xD_q^y} & \text{if } cap(p) \neq \phi \\ xD_p^y & \text{if } cap(p) = \phi \end{cases} . \qquad (7.4)$$

C'_p is only an initial estimate because it does not take into account the viscosity of the oil carried by segment p. All crude oil is assumed to have a kinematic viscosity of 7.5 cSt (sect. 7.3), but the viscosity of oil in a products pipeline depends on the reported mix of products it carries. The reported capacity data (National Petroleum Council 1979) show products line capacities for no. 2 fuel oil, which has a viscosity of about 3 cSt. To approximate p's capacity for carrying oil having viscosity ν_p, first arrange Eq. (2.6):

$$V = \text{constant} \cdot h_f^{0.572} D^{2.716} / L^{0.572} \nu^{0.144} . \qquad (7.5)$$

This shows that if the friction head h_f is held constant, a line's throughput is inversely proportional to the 0.144 power of the oil viscosity. So, the capacity C_p of p for carrying oil of viscosity ν_p is about

$$C_p = \begin{cases} C'_p & \text{if p carries crude oil} \\ C'_p(3/\nu_p)^{0.144} & \text{if p carries oil products} \end{cases} , \qquad (7.6)$$

where C'_p is given by Eq. (7.4).

An initial estimate V_p' of the throughput V_p of segment p is got by allocating the total movements of p's company among that company's segments in ratios prescribed by the regression formula (6.41). That is, the ratio of V_p' to the total throughput of the segments in co(p) is made to be the same as the ratio of the predicted throughput of p, $uC_pD_p^z$, to the total predicted throughput of co(p). Since the companies report total movements ($m^3 \cdot km$), rather than total throughput, the throughput of V_q of each segment in co(p) must be multiplied by its length L_q before ratios are taken. Then the desired equation of ratios is

$$\frac{L_pV_p'}{M(p)} = \frac{L_puC_pD_p^z}{\sum_{q \varepsilon co(p)} L_quC_qD_q^z}.$$

This yields,

$$V_p' = \begin{cases} \dfrac{M(p)uC_pD_p^z}{\sum_{q \varepsilon co(p)} L_quC_qD_q^z} & \text{if p belongs to a regulated company} \\ uC_pD_p^z & \text{otherwise} \end{cases}, \quad (7.7)$$

where C_p is given by Eq. (7.6). Note that if p's company is unregulated, V_p is estimated simply by the regression formula (6.41). This is because unregulated companies do not report total movements M(p).

Occasionally V_p, so computed, turns out larger than p's capacity C_p. This happens when a company's reported movements is simply too large for its system (a matter to be discussed shortly). To avoid placing a ridiculously high throughput on a line, the throughput V_p is not permitted to be more than 10% above capacity when the capacity is based on reported data, or more than 20% above capacity when the capacity is based on the regression formula alone. The 10 and 20% margins allow for misestimation or misreporting of capacities. So,

$$V_p = \begin{cases} \max(V_p', 1.1\ C_p) & \text{if } cap(p) \neq \phi \\ \max(V_p', 1.2\ C_p) & \text{if } cap(p) = \phi \end{cases}, \quad (7.8)$$

where V_p' is given by Eq. (7.7).

It is clear that the accuracy of reported movements is crucial to the estimation of energy use and intensiveness. Yet with one exception there is no practical way to criticize or verify these data. This exception, however, is an important one. It arises from the fact that two important crude oil pipelines, Capline and the Trans-Alaska (Alyeska) Pipeline, do not report movements under these two names. For instance, Capline movements are not reported as Capline movements, nor are they reported (entirely) as movements of Shell Pipeline Company, which operates Capline. Rather, they are reported by the seven joint owners of Capline in proportion to the fraction of Capline's throughput allotted to each owner. Since each company's maximum allotted usage is pro-rated according to its fraction of ownership, and since Capline is used at capacity, each company reports a fraction of Capline movements very close to its fraction of ownership. It is on this basis that the seven owners of Capline have been allotted Capline movements in this study. The difference between each company's reported movements and its Capline allotment is then placed on the remainder of that company's network. The eight owners of the Alyeska Pipeline have been accorded similar treatment (see discussion in Appendix B).

The ownership fractions used in this study are as follows:

Capline	Fraction	Alyeska	Fraction
Ashland	20.26%	Sohio	33.34%
Marathon	10.39	British Petroleum	15.84
Shell	13.4	Atlantic Richfield	21
Amoco	6.2	Exxon Pipeline	20
Mid-Valley	10.0	Mobil Alaska	5
Southcap	18.7	Union Alaska	1.66
Exxon, Inc.	21.05	Phillips Alaska	1.66
		Amerada Hess	1.5

The sources include Standard and Poor's (1979), Moody's Transportation Manual (1979), and direct contacts with company officials. Since Exxon's share of Capline is, according to these sources, held by Exxon, Inc., rather than by Exxon Pipeline Company, this share is not subtracted from Exxon Pipeline's reported movements. Also, when this study had been completed an Energy Department accounting of pipeline ownership (U.S. Department of Energy 1980) was obtained, and it differed somewhat on the ownership of Capline; in particular, Exxon was not listed as a part owner. Yet the differences are not large enough to result in significant errors.

In no other instances were company figures adjusted in this way, since aside from a few apparent and unimportant exceptions, every other pipeline system's movements is reported under the name of that pipeline system.

A few apparent exceptions are indicated by the fact that occasionally, a company's reported movements exceeded the capacity of its system, where capacity is gauged as described above. The crude pipeline companies reporting excess movements were Pure Transportation Company, Texas Pipeline Company, and Williams Pipeline Company. The total excess of crude movements over capacity, where excess is defined as in (7.8), is shown in Table S.2 of the Summary to be 3% of crude movements nationwide. These excess movements are entirely omitted from energy calculations, but presumably they result from the fact that these three companies reported movements in pipelines that are marked on maps as belonging to other companies. If so, at least part of the overage may be recovered in the movements assigned companies for which reported movements were not available. The excessive reported products movements were those of Cities Service Pipeline Company and Hydrocarbon Transportation Company. The total overage was 1% of products movements nationwide. In the cases of both crude and products pipeline the overages were too small to result in significant errors.

Another problem encountered in the movements data is that a few regulated companies who reported movements were found on none of the pipeline maps and consequently were omitted from calculations. The omitted crude pipeline companies wre Acorn, Cook Inlet, Osage, Owensboro-Ashland, Seway, Tamahawk, Wascana, and White Shoal Pipeline Companies. These are small companies whose total reported movements add to 3% of crude movements nationwide (Table S.2). Products companies omitted were Air Force, Crown Central, Kanch, Okan, and Pinto Pipeline Companies. Their movements add to 1% of total products movements. Omission of these small companies causes the estimates of energy use to be slightly small (1 to 3%), but it has no discernible effect on calculated energy intensiveness.

7.5 Rates of Flow

The rate of flow (m^3/d) in a pipeline segment is determined according to flow schedule 4, described in Sect. 8.2. This schedule results in the following formulas for rate of flow. First, let

V = average daily throughput in the segment of interest (m^3/d), determined as described in Sect. 7.4;

$\dot{V}$ = instantaneous rate of flow (m^3/d);

V_2 = flow rate (m^3/d) when the segment is operating at capacity, determined as described in Sect. 7.4. This is the flow rate produced by two pumps, in the simplified model of pump station operation presented in Sect. 8.2;

V_1 = flow rate (m^3/d) when the segment is using half the pumping power required to produce capacity flow, where pumping power is calculated as described in Sect. 7.6. This is the flow rate produced by one pump, in the simplified model.

Then, if $V > V_1$,

$$\dot{V} = \begin{cases} V_2 \text{ during } \dfrac{V - V_1}{V_2 - V_1} \text{ of the time} \\ V_1 \text{ during the rest of the time} \end{cases}, \tag{7.9}$$

or, if $V \leq V_1$,

$$\dot{V} = \begin{cases} V_1 \text{ during } \dfrac{V}{V_1} \text{ of the time} \\ 0 \text{ during the rest of the time} \end{cases}. \tag{7.10}$$

7.6 Friction Head

Friction head in a pipeline segment is calculated according to the D'Arcy-Weisbach formula, already stated in Chap. 2,

$$h_f = 8fLV^2/\pi^2D^5g \ , \tag{2.2}$$

where h_f = friction head (m);
f = friction factor (dimensionless), given by Eq. (7.1) in Sect. 7.2;
L = segment length (m), determined as described in Sect. 7.1;
V = instantaneous rate of flow (m^3/d), given by Eqs. (7.9) and (7.10) in Sect. 7.5;
D = inside diameter (converted to m), determined as described in Sect. 7.1;
g = gravitational acceleration, 9.8067 m/s^2.

7.7 Gravity Head

No attempt is made to estimate the gravity head in each pipeline segment. As Tables S.3 and S.4 in the Summary shows, gravity head accounts for only a small portion of pipeline energy use in the nation and in most states. Its calculation for each segment, which is a laborious and time-consuing task, is therefore not worth the effort.

A better course is to estimate the average capacity head per km of pipeline in each state, based on a sampling of the state's more important pipelines. This average can later be used to derive an estimate of the energy used to overcome gravity in that state (Sect. 7.8). The average gravity head per km was got by computing, for each state, a flow-weighted average gravity head per km among the pipelines represented in the NPC study of pipeline capacities (National Petroleum Council 1980). For each state s this average is

$$r_s = \left(\sum_{p \varepsilon s} C_p H_p \right) / \left(\sum_{p \varepsilon s} C_p L_p \right) \quad , \tag{7.11}$$

where r_s = average graivty head per km in state s (m/km);
C_p = capacity of pipeline segment (or group of parallel segments) p (m^3/d), as given on NPC maps;
H_p = elevation change over segment p (m);
L_p = length of segment p (km), determined as described in Sect. 7.1;
$p \varepsilon s$ indicates that pipeline segment p lies in state s.

Note that the pipeline capacities are here taken as surrogates for flow rates. Also the pipeline segments used here are not those used elsewhere in this study. Rather, they are simply lengths of pipe (or parallel pipes) that do not cross state lines and over which there are no capacity changes. The elevation change over a segment is got by looking up the elevations of towns at its termini in a large atlas (Rand McNally 1980).

The calculation of r_s is carried out separately for crude and for products pipelines. The results appear in Table 7.5.

7.8 Pumping Energy

Pumping energy, defined in Chap. 5 to be the mechanical energy actually delivered to the oil by the pumps, is the sum of two components: energy PE_f used to overcome friction and energy PE_g used to overcome gravity. PE_f is calculated for each pipeline segment, while PE_g is calculated for a state as a whole.

The pumping energy used to overcome friction is proportional to the product of friction head, flow rate and oil density. Since, as Sect. 7.5 explains, pipeline segments were assumed to operate on a split rate schedule, energy calculations must be carried out for two different flow rates in each segment. But Sect. 8.2 explains that calculations can be simplified by assuming that if the total throughput is greater than that provided by half the capacity pumping energy, then the pumping energy required to overcome friction can be approximated by that required to provide an even and continuous flow that results in the correct throughput. This leads to the formula,

Table 7.5. Pumping energy consumed to overcome gravity, by state

	Crude oil lines			Oil products lines			
	Gravity head (m/km)	Movements (10^6 m^3-km)	Energy (10^{12} J)	Gravity head (m/km)	Specific gravity	Movements (10^6 m^3-km)	Energy (10^{12} J)
United States	−0.152	558,750	−706.72	0.02	0.7497	389,844	49.82
Alabama	0.14	863	1.01	1.23	0.751	29,547	267.65
Alaska	0.00	68,450	0.00			0	
Arizona	−0.21	452	−0.79	−0.50	0.753	2,386	−88.09
Arkansas	0.09	3,191	2.39	0.05	0.783	5,863	2.25
California	0.21	10,068	17.62	0.13	0.763	6,805	6.62
Colorado	−1.22	3,060	−31.12	0.60	0.774	2,336	10.64
Connecticut		0		0.48	0.802	201	0.76
Delaware		0				0	
Florida	−0.06	433	−0.22	0.12	0.791	532	0.50
Georgia				−0.67	0.755	27,268	−135.26
Hawaii		0				0	
Idaho		0		−1.10	0.771	1,218	−10.13
Illinois	−0.02	47,512	−7.92	0.16	0.741	16,274	18.92
Indiana	0.36	8,218	24.66	0.19	0.759	8,972	12.69
Iowa	1.27	483	5.11	−0.15	0.729	8,920	−9.56
Kansas	−0.20	19,701	−32.84	−0.07	0.725	17,843	−8.88
Kentucky	−0.02	12,722	−2.12	1.23	0.791	261	2.49
Louisiana	0.17	42,490	60.21	0.28	0.756	35,162	72.99
Maine	1.29	1,126	12.11	−0.01	0.791	160	−0.01
Maryland		0		−0.75	0.762	6,346	−35.67
Massachusetts		0		0.78	0.773	190	1.12
Michigan	−0.12	31,082	−31.09	−0.22	0.749	5,234	−8.46
Minnesota	−0.16	34,127	−45.51	−0.76	0.708	2,462	−12.99
Mississippi	0.05	31,048	12.94	−0.17	0.739	40,235	−49.57
Missouri	0.23	22,764	43.64	−0.13	0.739	12,660	−11.93
Montana	−0.09	2,541	−1.91	−0.07	0.762	2,690	−1.41
Nebraska	−1.43	4,485	−53.46	−0.19	0.753	3,267	−4.58
Nevada		0		−1.69	0.770	319	−4.07
New Hampshire	0.45	555	2.08			0	
New Jersey		0		0.07	0.766	6,832	3.59
New Mexico	0.00	3,139	0.00	0.75	0.771	2,579	14.62
New York	0.10	234	0.20	−0.58	0.758	2,716	−11.71
North Carolina		0		−0.08	0.761	20,297	−12.12
North Dakota	−0.35	4,068	−11.87	−0.65	0.739	958	−4.51
Ohio	0.15	6,567	8.21	0.05	0.762	7,973	2.98
Oklahoma	−0.15	30,220	−37.78	0.20	0.731	11,945	17.13
Oregon		0		−0.83	0.761	569	−3.69
Pennsylvania	−1.02	87	−0.74	0.25	0.757	11,372	21.10
Rhode Island		0	0	2.44	0.791	50	0.95
South Carolina		0	0	−0.32	0.757	18,111	−43.02
South Dakota		0	0	0.51	0.735	760	2.79
Tennessee	0.03	29,512	7.38	0.09	0.762	1,475	0.99
Texas	−0.70	112,379	−655.70	0.14	0.739	41,177	41.78
Utah	−2.04	2,197	−37.36	−2.27	0.770	686	−11.76
Vermont	−0.60	991	−4.96			0	
Virginia		0		0.00	0.762	16,808	0.00
Washington	−1.42	228	−2.70	0.15	0.757	3,889	4.33
West Virginia	0.24	1,816	3.63	−0.02	0.791	54	−0.01
Wisconsin	0.22	19,185	35.18	−0.14	0.755	1,992	−2.06
Wyoming	0.17	10,583	15.00	0.68	0.765	2,437	12.43

$$PE_f(p) = \begin{cases} h_f(p,V) \cdot V(p) \cdot \rho g T & \text{if } V > V_1 \\ \frac{V}{V_1} h_f(p,V_1) \cdot V_1(p) \cdot \rho g T & \text{if } V \leq V_1 \end{cases} , \qquad (7.12)$$

where $PE_f(p)$ = pumping energy used to overcome friction in pipeline segment p (J);
$h_f(p,V)$ = friction head in segment p at flow rate V(p) (m), given by Eq. (2.2) in Sect. 7.6;
$V(p)$ = average throughput in segment p (m^3/s), determined as described in Sect. 7.4;
$V_1(p)$ = flow rate (m^3/s) resulting from half the pumping power required to produce capacity flow in segment p (see Sect. 7.5);
ρ = average mass density of oil carried by the company owning segment p (kg/m^3), determined as described in Sect. 7.3;
g = gravitational acceleration, 9.8067 m/s^2;
T = period of operation (s).

The total pumping energy consumed in state s is given by

$$PE(s) = \sum_{p \varepsilon s} PE_f(p) + M_s r_s \rho g , \qquad (7.13)$$

where PE(s) = pumping energy consumed in state s (J);
M_s = total (crude or products) pipeline movements in state s (m^3-km);
r_s = average gravity head per km in state s (m/km), given by Eq. (7.9) in Sect. 7.7;
$p \varepsilon s$ indicates that pipeline segment p is in state s.

Calculation of the second term in Eq. (7.13) is documented in Table 7.5.

7.9 Crude Oil Gathering Lines

Crude oil gathering lines must be treated separately because there are no available barrel-mile statistics for gathering lines as there are for trunk lines. In fact, the lack of this piece of information thwarts any attempt to estimate gathering line energy use accurately, and only very rough estimates can be had within the resources of this study.

The mileage of crude oil gathering lines by diameter in each state, as of January 1, 1977, is known (Energy Information Administration 1978). Likewise the production of crude oil by state is known (Energy Information Administration 1979), so that one can ascertain with fair accuracy how much oil is pumped through gathering lines in each state. The difficulty is that the average length of haul, and therefore the total movements in m^3-km, is unknown and unknowable within the resources of this project. It could be approximated reasonably well by measuring the distance from well to terminal along each gathering line in the nation. But no complete map or accounting of gathering lines exists, and if it did the task of reducing the information to usable form would be a sizeable one.

The following method of roughly approximating gathering line energy use was adopted for this study. First, calculate annual capacity throughput (m^3) for each size gathering line, using the regression formula (6.42) in Sect. 6.5. Then multiply the throughput in each size line by the number of km of that size line in each state, to get annual movements in m^3-km. Take 80% of this figure to reflect an assumption that gathering lines operate at capacity 80% of the time. The results appear in column 2 of Table 7.6. Now divide each state's movements by its 1976 crude oil production to get the average length of haul in 1976, shown in column 5. To estimate movements in 1978, multiply the 1976 average length of haul by the 1978 crude oil production. The results are in column 6. It is assumed that the average length of haul does not change between 1976 and 1978.

These figures sorely need adjustment because the estimated average length of haul is ridiculously long in some states. It is 627 km in Pennsylvania, for instance, despite the fact Pennsylvania is only 480 km long. Generally the states in which oil has been produced longest show the longest average length of haul, which suggests that a goodly amount of unused gathering pipe remains in the ground and on the books. Efforts to design a simple accounting model that would predict what fraction of gathering lines are unused failed, for two reasons. One is that it is unclear in what manner pipeline companies maintain and report statistics for unused line. Conversations with three or four oil men on this point were unhelpful. The other reason is that although data on the amount of gathering line laid (new and used) and taken up has recently been available triennially (Energy Information Administration 1978), such data could not be obtained for the long historical period over which much of the presently unused pipe may have been laid.

This insuperable difficulty was skirted simply by reducing any average length of haul exceeding the national average of 96 km to the national average, resulting in a new national average of 67 km. The adjusted lengths of haul were multiplied by the 1978 production to arrive at the adjusted movements in column 7. The energy consumption, shown in the last column, was then computed as follows. The pumping energy required for the 80% capacity movements in column 2 was computed for each pipe diameter according to Eq. (2.2) in Sect. 7.6, on the assumption that oil moves at its capacity flow rate 80% of the time and not at all the rest of the time. Gravity head was ignored. The result was multiplied by the ratio of the 1978 adjusted movements (column 7) to the 1976 80% capacity movements (column 2) to get the adjusted pumping energy in the last column.

Table 7.6. Calculation of pumping energy consumption by crude oil gathering lines, 1978

	Pipeline inventory Jan. 1, 1977[a] (km)	80% capacity movements 1976[b] (10^6 m^3-km)	Crude oil production[c] (10^3 m^3)		Av length of haul 1976–78[b] (km)	80% capacity movements 1978[b] (10^6 m^3-km)	Adjusted movements 1978[b] (10^6 m^3-km)	Pumping energy consumption 1978 (10^{12} J)
			1976	1978				
United States	109,110	45,290	473,123	505,241	96	48,365	33,646	2,622
Alabama	64	25	2,338	3,152	11	34	34	3
Alaska	37	29	10,078	71,317	4	275	275	2
Arkansas	1,754	293	2,877	3,323	102	329	310	33
California	4,331	2,456	51,828	55,191	47	2,615	2,615	203
Colorado	789	387	6,199	5,580	62	365	365	33
Florida	31	41	7,068	7,557	6	44	44	2
Illinois	4,664	1,299	4,176	3,714	311	1,155	357	33
Indiana	871	147	736	745	200	149	72	7
Kansas	10,300	3,896	9,334	8,995	417	3,755	864	81
Kentucky	2,723	683	1,190	910	574	522	87	9
Louisiana	4,468	5,232	96,415	84,690	54	4,596	4,596	279
Michigan	1,701	712	4,836	5,240	147	771	503	40
Mississippi	678	336	7,324	6,681	46	307	307	22
Montana	1,362	660	5,216	4,843	127	613	465	36
Nebraska	563	376	983	932	383	356	89	6
New Mexico	5,818	1,921	14,646	13,253	131	1,738	1,272	137
New York	531	30	136	135	221	30	13	2
North Dakota	816	230	3,454	3,944	67	263	263	24
Ohio	2,432	565	1,589	1,773	356	630	170	14
Oklahoma	14,848	4,954	25,662	23,918	193	4,617	2,296	226
Pennsylvania	4,130	301	480	459	627	288	44	7
Texas	38,664	18,240	189,098	170,742	96	16,469	16,469	1,282
Utah	222	193	5,453	4,987	35	177	177	12
West Virginia	4,318	396	400	379	990	375	36	5
Wyoming	2,998	1,878	21,326	21,840	88	1,923	1,923	124

[a]From Energy Information Administration (1978).

[b]As calculated by this study (Sect. 7.8).

[c]From Energy Information Administration (1979).

It should be noted that, since the gathering line inventory figures are for the end of 1976, Alaska's 1978 gathering line energy consumption is doubtless underestimated. Inquiries with Federal and Alaskan authorities failed to result in any more accurate figure for the 1978 gathering line inventory.

8. FLOW SCHEDULES

The purpose of this chapter is calibration. It uses energy consumption data obtained directly from a few pipeline companies to choose the best general model of flow rate fluctuations in a pipeline. It is noted in Sect. 5.2 that the choice of flow schedule can have a considerable effect on energy consumption. The first section of this chapter describes several schedules that might occur, and the second section picks the one that seems best to reflect reality. A third section uses the data developed in the second section to arrive at a reckoning of potential error in the energy use estimates.

8.1 Possible Flow Schedules

This section describes a few simplified flow scheduling policies under which pipelines might be assumed to operate. In the next section an attempt is made to pick the scheduling policy most reflective of reality.

Some pipelines run at or near capacity and some do not. Those that do can be expected to operate almost continuously at a constant flow rate, except when the pipeline is shut down for repair, cleaning, or other maintenance. In fact, estimates of pipeline capacity generally take into account the necessity of maintenance shutdowns. From Eq. (2.6) we have that if p is the fraction of the time a pipeline is inoperative, its energy use is increased by a factor of

$$\left(\frac{1}{1 - p}\right)^{1.748} .$$

When p is 5, 10, and 15%, this factor is 1.09, 1.20, and 1.33 — clearly a significant increase.

Pipelines that run under capacity present a further complication. It is wrong to assume that a pipeline simply reduces its pump speed to accommodate reduced throughput, since most pump drivers do not permit speed adjustment. Rather, only the three following methods of reducing throughput are generally available:

1. throttle the flow using a valve at the pump nozzle,
2. run the pumps only part of the time, and
3. turn off part of the pumps so as to reduce pressure.

These methods may of course be used in combination.

The least efficient method of reducing flow is of course simply to throttle it, since the pump continues to consume nearly as much energy as when the valve is open. A better method is to run all the pumps (with valve open) long enough to move the desired quantity of oil and to shut them down the rest of the time. But when there are two or more pumps in a pumping station, as is the rule, the best method is to shut down part of the pumps. This reduces the discharge pressure and thereby the flow rate.

Figure 8.1 illustrates the situation in a pumping station having two pump-driver combinations connected in series. When both pumps are running they operate at maximum efficiency and pump about 50,000 m^3/d. When one pump is shut off the flow drops to about 38,000 m^3/d, or about two-thirds of the maximum flow rate (this is typical). The remaining pump operates somewhat under its peak efficiency, but not much under it. When two pumps are connected in parallel, as in Fig. 8.2, the strategy of cutting off one pump is less workable because the other must operate at an efficiency considerably below its maximum — at least when the pipeline is level, as assumed for Fig. 8.2. However, parallel hookups are less common than series hookups, and when they occur it is usually in mountainous country where the gravity head is likely to be high relative to the friction head. Under such conditions the remaining pump operates against a higher pressure and hence more efficiently.

When a flow rate between that provided by two pumps and that provided by one pump is desired, method 3 above may be combined with method 1 or 2 or both. Clearly the better course is to combine methods 2 and 3 so as to result in a split-rate schedule. That is, it is better to run two pumps part of the time and one pump part of the time (without wasteful throttling) in such a way as to deliver the desired quantity of oil. If a single pump running full time already provides too much throughput, the best method is to run just one pump part of the time, and no pumps the rest of the time. Figure 8.3 shows that the energy use for a split-rate schedule is only slightly higher than the ideal level of energy consumption that would result from adjusting the driver to precisely the right speed to deliver the desired throughput in an even flow. The results of using method 1 alone and method 2 alone are also shown. Figure 8.4 illustrates the same things for parallel pumps (assuming level pipe). Here split-rate scheduling, though less efficient than for series pumps, is still the best option. The pump characteristics on which Figs. 8.3 and 8.4 are based are those depicted in Figs. 8.1 and 8.2 (Kerassik et al. 1976).

It stands to reason that pipeline companies would employ split-rate scheduling whenever possible, due to its superior efficiency. Yet it is possible that constraints on dispatching force a significant departure from optimal scheduling, and this possibility must be measured against actual data. Also, a typical duty factor (fraction of time during which a pipeline is operational) remains to be estimated. These matters were resolved by identifying ten generalized scheduling strategies and comparing the results of assuming each in energy calculations against the actual energy consumption of nine pipeline systems. It is true that different pumping stations operate according to different scheduling

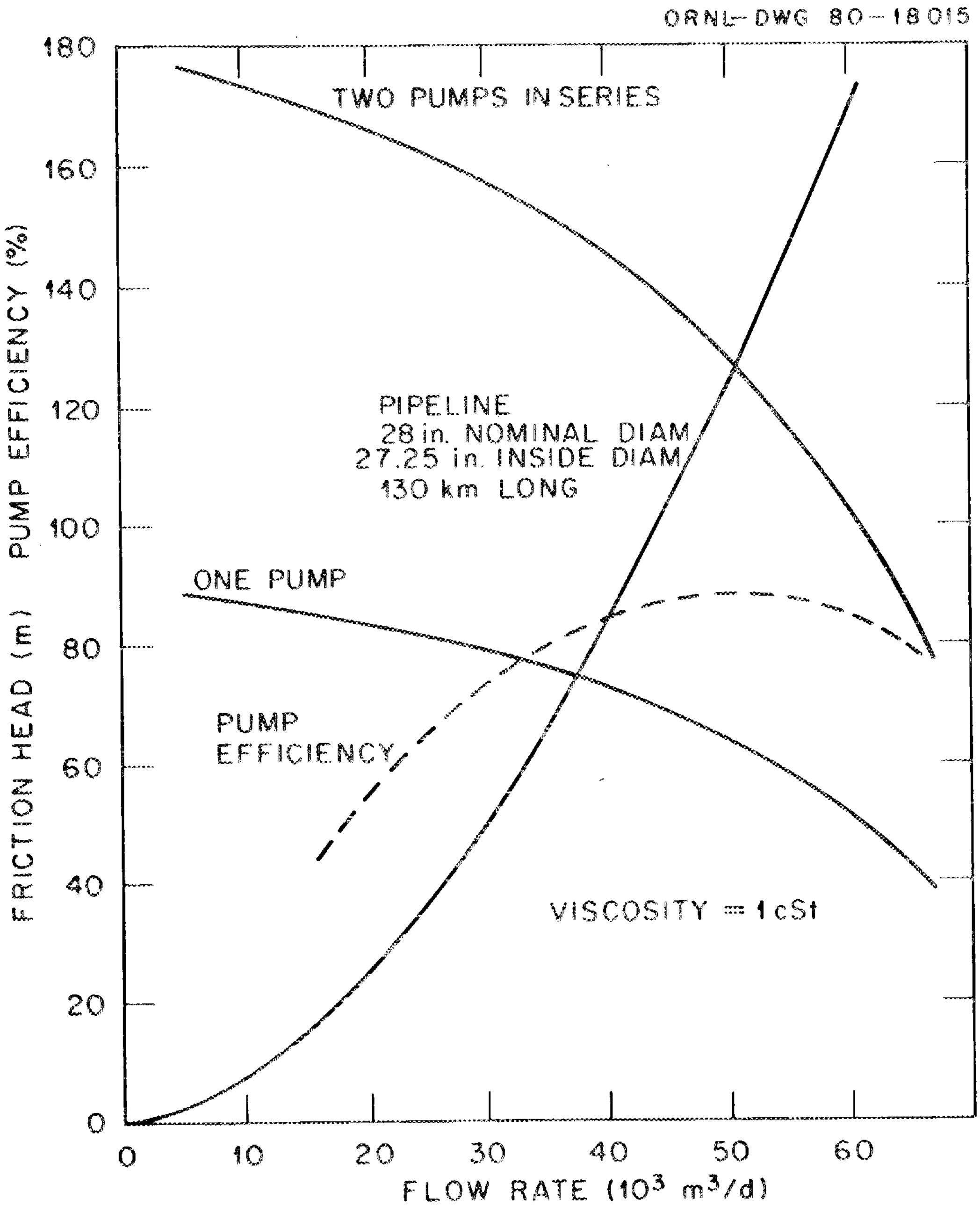

Fig. 8.1. Typical pipeline and pump characteristics for two pumps in series.

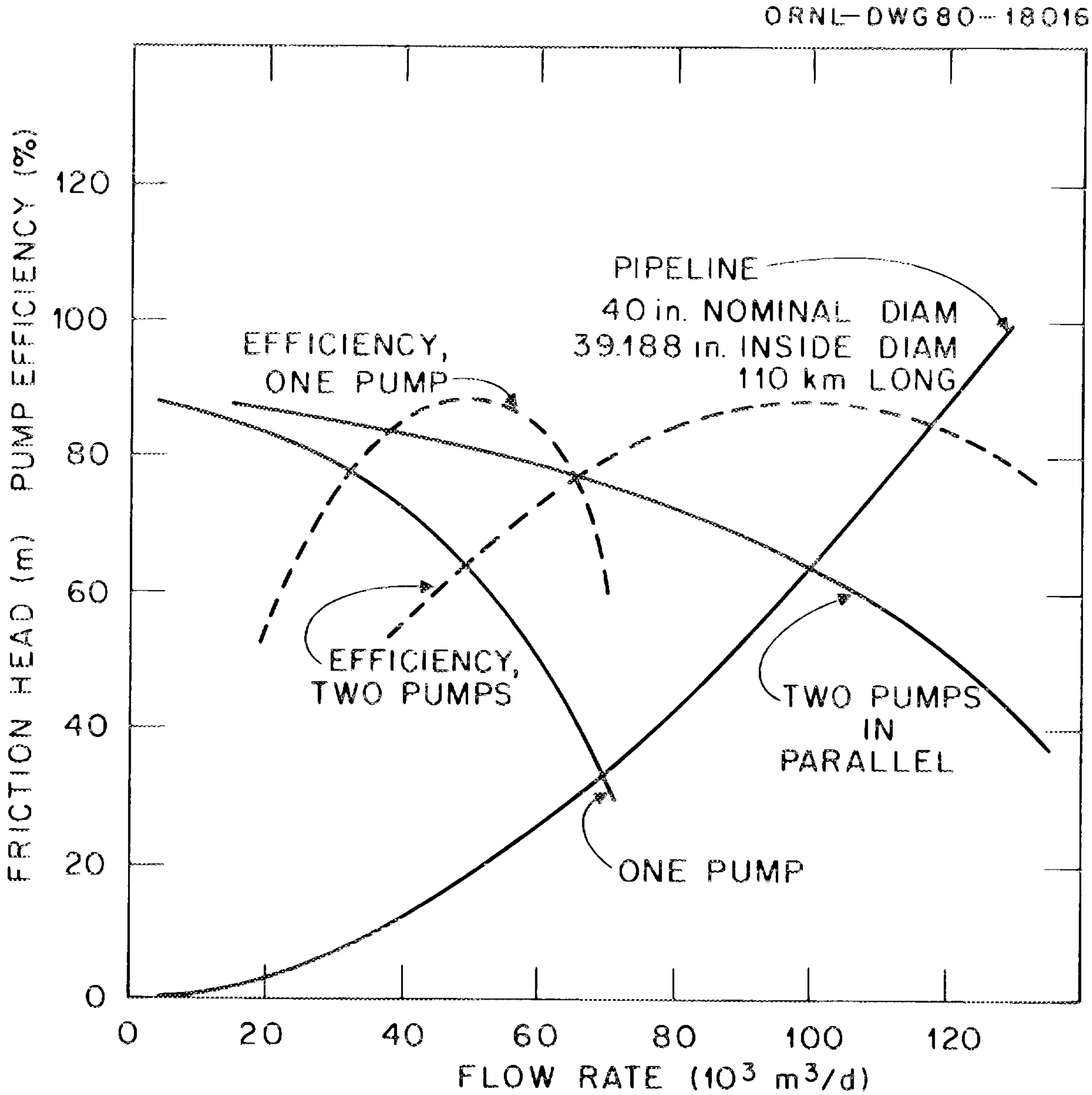

Fig. 8.2. Typical pipeline and pump characteristics for two pumps in parallel.

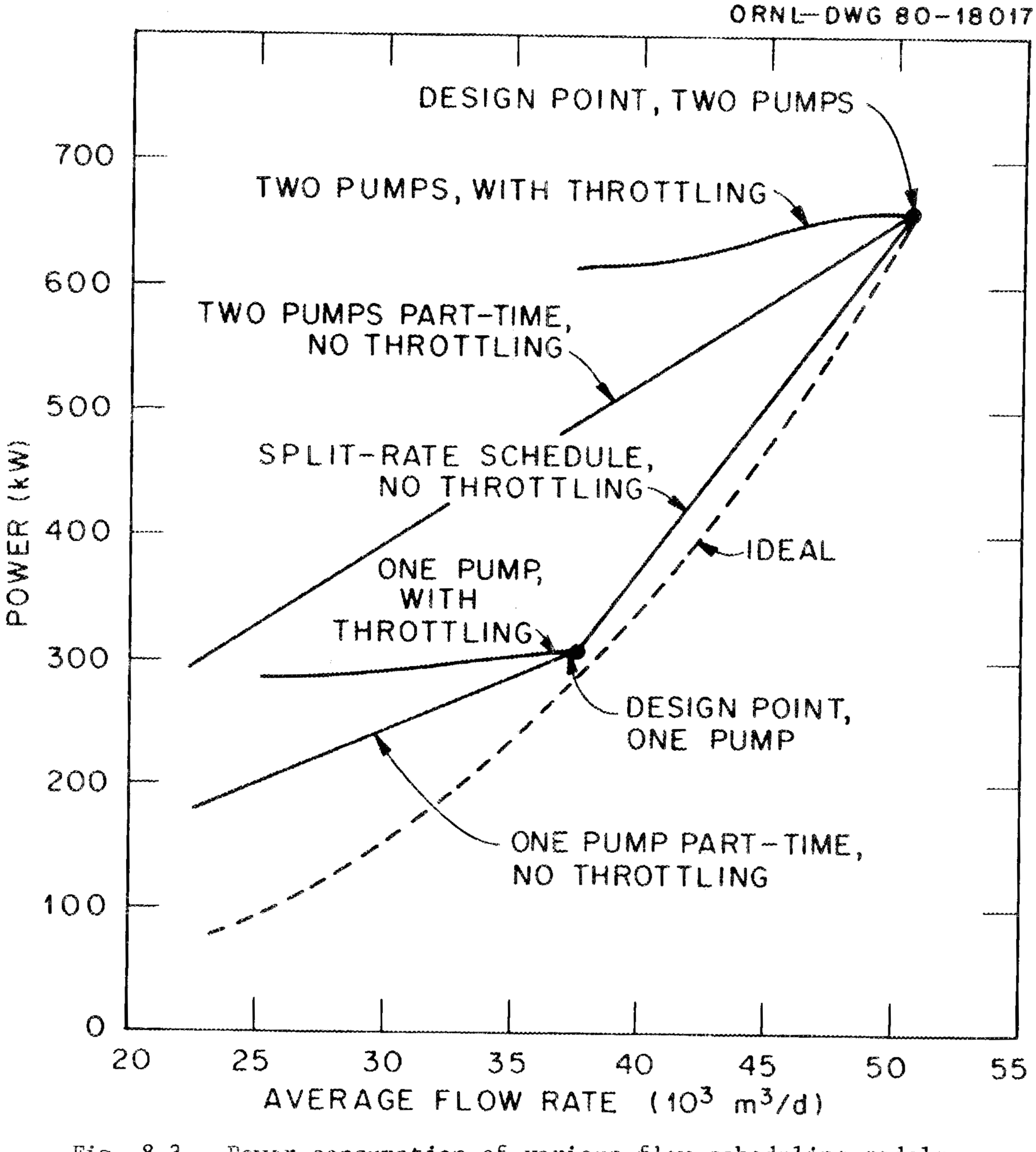

Fig. 8.3. Power consumption of various flow scheduling models for two pumps in series.

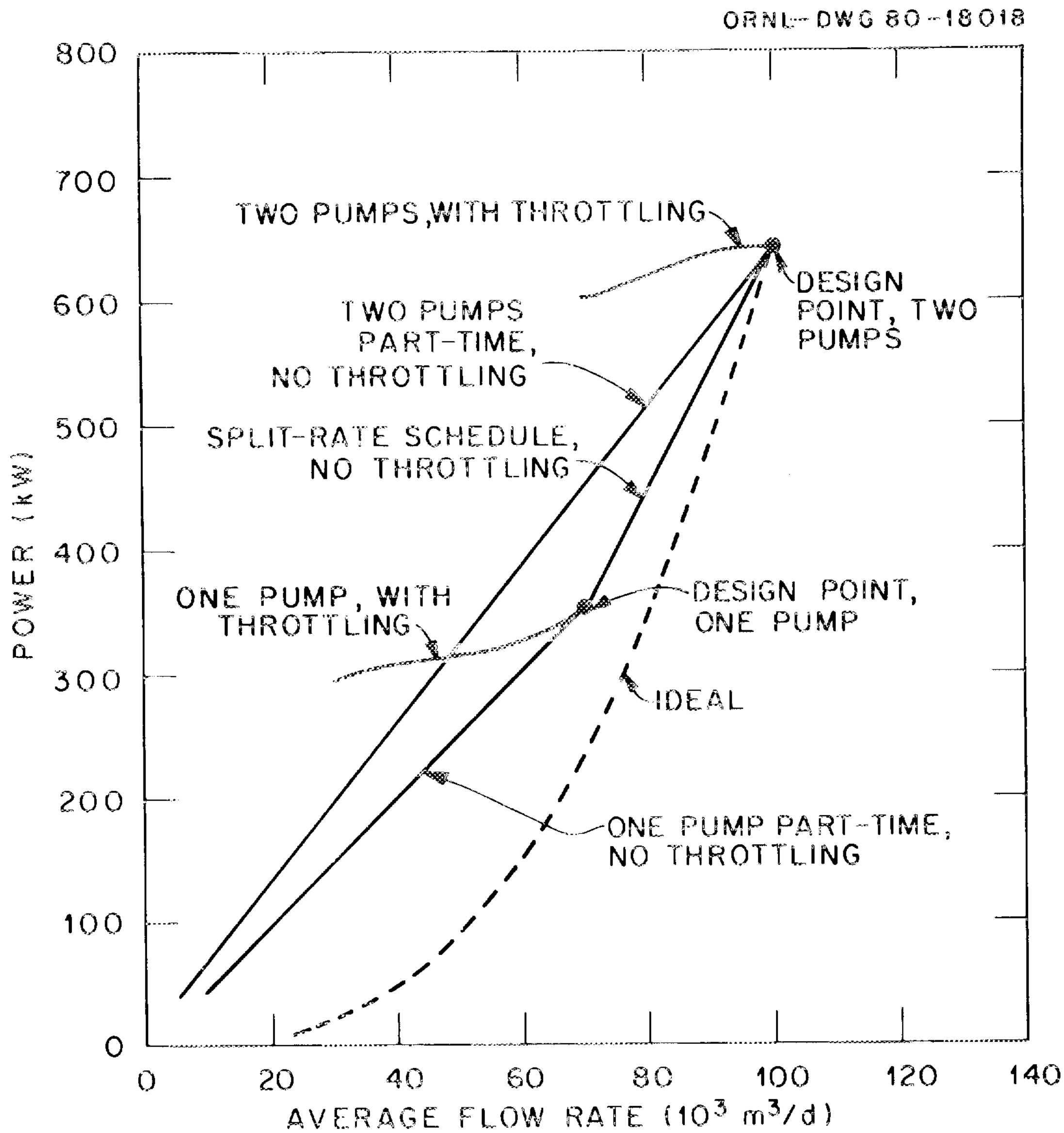

Fig. 8.4. Power consumption of various flow scheduling models for two pumps in parallel.

policies and that no one policy can reflect conditions everywhere. But a single generalized scheduling policy can be taken as representative of all pumping stations in the sense that it leads to reasonably accurate energy calculations, more accurate than those resulting from other generalized policies. The 10 scheduling policies considered are as follows.

Schedule 0. Let the flow be uninterrupted and even at exactly the flow rate required to provide the desired throughput. This schedule is not generally an option, due to the lack of a speed control on most motors, but it is entered into the calculations for purposes of comparison.

Schedule 1. Let the oil flow at the capacity rate for the fraction of time necessary to provide the desired throughput.

Schedule 2. Let the flow be uninterrupted and throttle it to result in the desired throughput. Assume that there are two series pumps in each station but that only one runs if it is enough to provide the desired throughput.

Schedule 3. Same as schedule 2, except that there are three series pumps per station. The number of pumps remaining is the minimum necessary to provide the desired throughput.

Schedule 4. Let the oil be pumped according to a split-rate sched-dule that results in the desired throughput. Assume two series pumps per station. Use only one pump part-time if it suffices, and otherwise use two pumps part of the time and one pump part of the time.

Schedule 5. Same as schedule 4, except that there are three series pumps per station. Use only one pump part-time, or a split between one pump and two pumps, or between two pumps and three pumps.

Schedule 6. Use a split-rate schedule, except with a 90% duty factor. That is, for 10% of the time during which one or more pumps would operate under schedule 4, all pumps are shut down, and the flow rate is increased accordingly in the remaining 90% of the time. Assume two series pumps per station.

Schedule 7. Same as schedule 6, except that there are three series pumps per station.

Schedule 8. Split-rate schedule with 95% duty factor; two series pumps.

Schedule 9. Same as schedule 8, but with three series pumps.

These do not represent all available options. Many pump stations, for instance, have a pump rated at half the power of the others so as to provide more flexibility. Nonetheless these 10 schedules represent the options in broad strokes, and in view of the fact that policies differ among pumping stations it seems pointless to differentiate policies any more finely.

Two simplifications are made in the calculation of energy use under these schedules. One is that closing the valve partially at the pump discharge is assumed not to affect the energy consumption of the pump. The effect is in fact small, as shown in Fig. 8.3. The other simplification is that the energy use for a split-rate schedule, when more than one pump is used at least part of the time, is asumed to be the same as the ideal energy usage that would result from adjusting the driver to optimal speed. Figure 8.3 shows, as remarked earlier, that the discrepancy is small. This simplification is made because it obviates calculating the throughput provided by one pump (or that provided by two pumps, when three pumps are used part of the time). This latter calculation is time-consuming because the throughput provided by a pump of a given power rating cannot be calculated directly. Rather, various flow rates must be tried (as part of a computer bisection search) until one is found that requires the quantity of power produced by one pump. (The power produced by one pump is known because it is 1/2 or 1/3 the power required for capacity flow, depending on whether there are two or three pumps.) If the desired throughput is so low that all pumps are shut down part of the time, then it is necessary to compute the throughput supplied by one pump, despite the inconvenience of doing so.

8.2 Case Studies

Requests for 1978 energy consumption data were addressed to twelve pipeline companies. The number of companies contacted was deliberately kept small so as to minimize the inconvenience imposed on the pipeline business. A study basing its energy estimates entirely on company energy use data would doubtless need a much larger sample. But since this study derives energy estimates primarily from reported oil movements and the physical characteristics of the oil, pipeline network and pumping equipment, a small sample is acceptable. It is not to be denied, however, that a larger sample would permit a more reliable choice of a flow scheduling model, and it will be seen that this choice has a significant effect on the resulting energy use estimates.

The companies were chosen according to six criteria:

1. Both crude and products pipeline companies should be included.
2. Each should operate exclusively crude lines or exclusively products lines, so that the two can be studied separately.
3. They should represent a cross section of sizes and geographical locations.
4. An LPG line should be included.
5. They should operate no crude gathering lines, so that no problem of separating gathering and trunk line energy use arises.

6. They should be federally regulated companies, in case bbl-mi figures are not obtained from the company and must be obtained from Form P.

The companies were promised that neither their identities nor their locations would be revealed in this report.

Seven companies eventually responded with usable data, one refused to cooperate, and one confessed ignorance of its energy consumption, and three did not respond at all. The statistics concerning these companies appear in Table 8.1. One crude pipeline company, company G, offered detailed throughput and energy consumption data for three separate portions of its system, bringing the number of observed data to nine.

The companies reported energy consumption data in terms of kwh of electricity and gallons of diesel fuel or propane. Since nearly all the energy accounted for was electrical, the energy content of the reported fuel was converted to an electrical equivalent by multiplying it by an estimated 30% efficiency of electrical generation and transmission. The energy content of diesel fuel was taken to be 38.7×10^6 J/L, and that of propane to be 23.8×10^6 J/L (company G performed the conversion itself). The electrical equivalent of each company's energy consumption appears in Table 8.1. The specific gravity was estimated as described in Sect. 7.3, and the gravity head as described in Sect. 7.7.

Table 8.1 also shows the total pumping energy that should be consumed by each company under each of the ten flow schedules outlined in the previous section, as calculated by the method described in this report. The object is to pick the schedule that results in a calculated pumping energy closest to the actual in the case of these nine systems. Since the reported energy use figures reflect losses in the pumps and electric motors, the calculated pumping energy must be divided by an estimated wire-to-oil efficiency before the comparison is made. Section 9.1 estimates this efficiency to be in the range of 0.74 to 0.80.

It is important to make the comparison in a way that makes the best use of the reported information. Simply to compare the total calculated with the total actual electrical consumption would be to overlook possible discrepancies that offset each other in the total. A better course is to attempt to minimize the root mean square (rms) relative discrepancy, defined as follows. If the observed electrical consumption figures are denoted E_i and the calculated pumping energies P_i, then

$$\text{rms relative error} = \sum_i \left(\frac{E_i - P_i/e}{E_i}\right)^2 , \qquad (8.1)$$

where e is the efficiency of the pump and motor. Relative errors, rather than absolute errors, are of interest here because the relative (or percent) error best reveals the reliability of the calculation method in question.

Table 8.1. Comparison of actual and calculated energy consumption for certain pipeline companies

Company	Type	Specific gravity	Gravity head (m/km)	Movements (10^6 m^3-km)	Actual electrical consumption (10^{12} J)	Calculated pumping energy (10^{12} J)										
						Schedule	0	1	2	3	4	5	6	7	8	9
A	Products	0.752	−0.078	5,012	440.9		341.4	647.6	517.4	574.6	412.7	374.7	506.1	459.1	455.8	413.7
B	Products	0.540	0.100	2,977	225.2		160.0	296.9	220.8	268.0	189.6	166.3	203.7	203.7	209.4	183.5
C	Crude	0.85	−0.383	2,292	282.1		132.3	413.2	302.4	197.7	259.8	197.4	317.5	241.7	286.5	217.9
D	Products	0.736	0.102	1,448	310.8		131.0	250.9	178.1	228.1	159.9	131.0	195.2	159.6	176.2	144.2
E	Crude	0.85	−0.750	4,593	287.6		32.3	272.2	308.1	190.0	157.6	110.9	200.5	143.9	177.5	126.1
F	Products	0.760	0.189	17,742	1,628.3		461.4	1564.2	1563.3	055.6	1015.2	797.5	1233.5	954.6	1115.9	864.6
G1	Crude	0.85	0.125	2,763	350.8		275.5	451.2	298.0	298.0	298.6	275.5	351.5	333.2	318.7	302.1
G2	Crude	0.85	0.138	9,197	1,194.6		946.3	982.7	973.1	973.1	946.3	946.3	1176.9	1176.9	1067.3	1067.3
G3	Crude	0.85	0.366	3,820	722.0		602.2	573.0	580.5	580.5	602.2	602.2	700.7	700.7	635.8	635.8
Totals	Crude			22,665	2,837.1	national	17,654		28,906		23,061	20,933	27,950	25,436	25,323	23,048
	Products			27,179	2,605.2	totals	16,691	23,937	23,208	17,972	16,121	13,610	19,725	16,646	17,784	15,011
					Crude	efficiency,	0.670	1.286	1.047	1.125	0.822	0.725	0.964	0.887	0.907	0.797
						rms error	(0.379)	(0.622)	(0.321)	(0.472)	(0.163)	(0.236)	(0.263)	(0.244)	(0.210)	(0.217)
					Products	efficiency,	0.726	1.130	0.939	0.773	0.810	0.737	0.977	0.891	0.883	0.807
						rms error	(0.427)	(0.468)	(0.217)	(0.100)	(0.160)	(0.240)	(0.263)	(0.236)	(0.183)	(0.217)
					All	efficiency,	0.705	1.194	0.982	0.932	0.815	0.733	0.972	0.890	0.892	0.603
						rms error	(0.410)	(0.531)	(0.260)	(0.300)	(0.161)	(0.237)	(0.263)	(0.240)	(0.183)	(0.217)

For reasons to be explained shortly, it is most instructive to minimize the rms relative error in the following way. Write the actual electrical consumption E as the calculated pumping energy P divided by the efficiency e

$$E = \frac{1}{e} P$$

and regard E as a dependent variable to be regressed on the independent variable P. Then find the 1/e that minimizes the rms relative discrepancy between E_i and P_i/e. Finally, choose as the best schedule the one for which the rms relative error is smallest among those schedules for which the resulting efficiency e has a reasonable value, viz. 0.74 to 0.80.

This procedure seems superior to that of simply fixing the value of e at some reasonable value and picking the schedule that minimizes the resulting rms error. For, at this point all that one can say about e is that it lies within a range of reasonable values; it is difficult to justify choosing one value in this range over another. This is important because it is possible that for one value of e in this range, schedule X is best, but for another reasonable value of e schedule Y is best and moreover results in a much lower rms error. This would suggest that Y is the best choice of a schedule and that the second value of e is nearer the truth. If e had been fixed at the first value, the better value of e would have been overlooked and the schedule wrongly chosen. On the other hand, if the error-minimizing value of e for each schedule had been computed, as proposed above, then the fact that schedule Y provides a better fit to the data for a reasonable value of e would have been discovered.

It is easy to derive that the value of 1/e that minimizes the rms relative error is

$$1/e = \sum_i P_i / \Sigma(P_i^2/E_i) \ . \qquad (8.2)$$

Calculated values of e and the resulting rms relative error are displayed at the bottom of Table 8.1 for crude lines, for products lines, and for all the lines together. The small number of observations suggests that the individual results for crude and products lines should not be given much credence, but they are nonetheless provided for comparison. The figures that matter are those at the bottom, which encompass both crude and products lines.

It is evident that company E presents a problem, in that the calculated pumping energy runs substantially low even under some schedules that overestimate the energy use of other companies. Conversation with officials of company E revealed that a single very long 8-in. trunk line was being pushed to the limit to relieve an acute regional shortage of crude oil, while the remainder of the company's lines were operating with relative slack. Since the energy penalty for such heavy use of a single line is high, it probably explains most of the discrepancy between the actual and predicted energy use. Due to the exceptional nature of this company's operations it was thought best to omit it from the regression described above, since otherwise the calibration of e could be biased downwards. Yet company E is not omitted in the estimation of potential error in the next section, since it is better to overestimate potential error than to underestimate it.

Returning to Table 8.1, it is evident that all schedules except 0, 4, 5, and 9 can be eliminated at once because e is too large, meaning that these schedules calculate a pumping energy that is too large. This is to be expected with schedules 1, 2, and 3, since they represent very inefficient ways of running a pipeline. The large e's resulting from schedules 6 and 7 show that an assumed 90% duty factor is too small. Schedule 8 overestimates energy use presumably because a 95% duty factor is too small in conjunction with the assumption that there are two pumps per station. This matter of duty factor will be taken up again shortly.

Of the remaining four schedules only schedule 0 results in a pumping energy estimate that is clearly too low. That schedule 0 results in an underestimate is to be expected, since it assumes an impossibly even and continuous flow of oil. Schedules 4, 5, and 9 all result in reasonable efficiencies, if slightly high in the case of schedules 4 and 9.

If the value of e were the only criterion of choice, schedule 5 would seem to be the best, since schedules 4 and 9 require pump and motor efficiencies very near optimal textbook values. But note that schedule 4 better fits the data, in that its rms relative error is less. That is, it better accounts for the factors that make one company more efficient than another. In fact, schedule 4 provides the best fit of all the schedules, not just those that result in reasonable efficiencies. In view of this it seems best to adopt schedule 4 as closest to reality and to accept that equipment efficiencies are higher than might be expected. Since 0.815 is a bit too high, it can be reduced to 0.80, the upper end of the range of 0.74 to 0.80. When e = 0.80, the rms relative error for schedule 4 is 0.172 — still the best.

As noted in Sect. 9.1, a wire-to-oil efficiency of 0.80 is consistent with a pump efficiency of 0.86 and a motor efficiency of 0.93. The latter figure is entirely reasonable. If the former seems too high for actual practice, one can consider that company G, the only company to remark upon such matters as pump efficiencies, reported that its pumps were operating at efficiencies "better than 86%." Also if one is concerned that an 80% wire-to-oil efficiency will result in an underestimate of national oil pipeline energy use, he should consider that schedule 5, which corresponds to the lower 0.73 efficiency, results in a national energy estimate that is lower than schedule 4's estimate for products lines and only 1% higher for crude lines.

A final matter that should be considered is the fact that schedule 4 calls for a 100% duty factor. It is counterintuitive that a model of pipeline operation can neglect the necessity of shutting down occasionally for maintenance and repairs. But recall that duty factor is defined in the description of these schedules so as to refer to how much shutdown time occurs during the period in which at least one pump would be operating under schedule 4. Since it is common under schedule 4 for all pumps to shut down for a short period (so as to result in the desired throughput), schedule 4 is compatible with a pipeline's undergoing maintenance and repair while shut down. It is even more common for only one of two pumps to be operating under schedule 4, allowing time for maintenance of the other pump. The rejection of schedules 6 through 9 signifies only that one need not provide for any shutdown time beyond this to account for energy use.

8.3 Error Estimation

The actual and the estimated energy consumption, in terms of their electrical equivalents, appear in Table 8.2 for each of the nine pipeline systems for which energy consumption data were obtained. Clearly the estimates, although close in some instances, are in other instances subject to considerable error. In view of this it is important that the error in these nine cases be used as a basis for estimating roughly what may be the errors in the national energy estimates. To do so is the aim of this section. The estimates can only be rough because nine observations are too few for a statistically reliable estimate of errors.

Let ε_i be a random variable representing the error in an estimate $E_i + \varepsilon_i$ of the energy E_i used by company i. The variance σ_i^2 of the distribution of ε_i may be the same for all i or may depend on certain characteristics of company i.

The total energy consumption of n companies nationwide is $E = \sum_{i=1}^{n} E_i$ and its estimate is

$$E + \varepsilon = E + \sum_{i=1}^{n} \varepsilon_i \, .$$

If the variables ε_i are assumed to be independently distributed with like variance σ^2, then the variance $\bar{\sigma}^2$ of ε's distribution is simply

$$\bar{\sigma}^2 = n\sigma^2 \, . \qquad (8.3)$$

Since to estimate energy use with the method in question, without correcting for bias, is to suppose that each ε_i has a mean of zero, this

Table 8.2. Analysis of errors in estimated energy use of certain pipeline companies

Company	Type	Movements (10^6 m^3-km)	Number of segments	Estimated electrical consumption (10^{12} J)	Actual electrical consumption (10^{12} J)	Relative error (%)
A	Products	5,012	51	516	441	17.0
B	Products	2,977	19	237	225	5.3
C	Crude	2,292	1	325	282	15.2
D	Products	1,448	19	200	311	−35.7
E	Crude	4,593	20	197	288	−31.6
F	Products	17,742	60	1,320	1,628	−18.9
G1	Crude	2,763	1	373	351	6.3
G2	Crude	9,197	1	1,216	1,195	1.8
G3	Crude	3,820	3	726	722	0.6
Total		49,844	175	5,110	5,442	−6.1
				Average absolute error		14.7%
				rms absolute error		117.4×10^{12} J
				rms relative error		18.9%

supposition must be maintained when the errors resulting from the method are estimated on the basis of sample data like those in Table 8.2. Consequently if $\varepsilon_1,\ldots,\varepsilon_m$ are the errors in a sample of m observations, the error variance σ^2 is estimated by

$$\hat{\sigma}^2 = \frac{1}{m} \sum_{i=1}^{m} \varepsilon_i^2 \, . \tag{8.4}$$

One divides by m, not by m — 1, since the mean is not estimted from sample data but is presumed to be zero.

It is arguable, however, that one cannot assume an equal variance for each error variable ε_i. Consider, for example, two pipeline companies, each consisting of a single pipeline segment. If one segment carries twice as much oil as the other, then one would expect its estimated energy consumption to show more error than that of the other. Since each segment's energy estimate involves the same number of estimates of physical parameters (flow rate, viscosity, etc.), one would expect the percentage or relative error in its estimate, not the absolute error, to be about the same for the two estimates. The standard deviation σ_i, then, can plausibility be viewed as proportional to E_i.

Yet there is a further complication. While some pipeline companies consist of a single segment, others consist of many segments, each receiving a separate energy estimate. To be sure, the error distributions corresponding to the individual segments cannot be presumed independent, since segments are often segments of the same pipeline, so that an error in one segment's estimate is likely to be highly correlated with errors in the other segments' estimates. Nonetheless one may expect errors in some of the segment estimates partially to offset errors in other segments, so that the relative or percentage error for the entire company should be smaller than the relative errors for the individual segments. If this is true, then energy estimates for companies having many segments should show smaller relative errors than those for companies having few segments. In other words, σ_i is not proportional to E_i but depends somehow on both E_i and the number of segments in company i.

Despite the plausibility of the above argument, Table 8.2 does not conform its conclusion. If anything, these data suggest that companies with fewer segments receive energy estimates with smaller relative errors. One must also consider that errors derive not only from mistakes associated with the individual segments, but also from any error that may exist in a company's reported total movements, on which segment flow rates are based. An error in the company flow rate would not be mitigated by the fact that a company has many segments, since each segment would suffer the same systematic error. Moreover, a company owning many segments may have greater difficulty arriving at an accurate reckoning of its total movements. It is easily possible that the accuracy of reported movements decreases rapidly enough as the number of segments increases so as to offset the tendency of numerous segments to result in a smaller relative error, with the consequence that the relative error in a company's energy estimate is more or less independent of the number of its segments.

In view of these considerations it seems best to assume that the standard deviation of the relative error ε_i/E_i has a constant value τ for all companies i. The relative error of the estimate of national energy use (for n companies) is given by

$$\varepsilon/E = \left(\sum_{i=1}^{n} \frac{\varepsilon_i}{E_i} \cdot E_i \right) / \left(\sum_{i=1} E_i \right) . \tag{8.5}$$

If the distributions of ε_i/E_i are independent, which seems a reasonable assumption, then (8.5) implies that the variance $\bar{\tau}^2$ of the distribution of ε/E is

$$\bar{\tau}^2 = \tau^2 \frac{\sum_{i=1}^{n} E_i^2}{\left(\sum_{i=1}^{n} E_i \right)^2} . \tag{8.6}$$

τ^2 is easily estimated from sample data using the formula,

$$\hat{\tau}^2 = \frac{1}{m} \sum_{i=1}^{m} \left(\frac{\varepsilon_i}{E_i} \right)^2 . \tag{8.7}$$

Again one divides by m rather than m − 1, because the mean is not estimated from sample data but is presumed to be zero.

The results of calculating the standard deviation $\bar{\tau}$ of the national error distribution for crude and products lines according to Eqs. (8.6) and (8.7) appear in Table 8.3. The table also shows 95% confidence bands, on the assumption that errors are normally distributed. Numbers in parentheses show the confidence bands that result when Eqs. (8.3) and (8.4) are used instead. That is, the confidence bands in parentheses

are based on the assumption that the absolute error variance σ_i^2 is the same for all companies i, which is to say that equal absolute errors are given equal weight. The other confidence bands (not in parentheses) assume the relative eror variance τ_i^2 is the same for all companies, which is to say that equal relative errors are given equal weight. The latter assumption is the one recommended here, and it is the one made in the previous section.

Table 8.3. Estimated errors in national pipeline energy use estimates[a]

	Crude	Products
Number of companies[b]	121	108
Standard deviation τ of the distribution of relative errors in company energy use estimates	18.9%	18.9%
Standard deviation τ of the distribution of relative errors in national energy use estimates	1.13%	2.34%
Error range for company estimates at 95% confidence level[c]	±37%	±37%
Error range for national estimates at 95% confidence level[c]	±2.2% (±4.5%)	±4.6% (±6.1%)
Conservative error range for national estimates	±10%	±15%

[a]Calculated on the assumptions that errors for different companies are independent and that the distribution of relative (percent) errors in company energy use estimates has a variance independent of company characteristics. Numbers in parentheses assume independence of company errors and that the distribution of absolute errors has a variance independent of company.

[b]A crude pipeline company that owns portions of the Alyeska Pipeline or Capline, as well as other pipelines, is counted as two companies.

[c]Assumes normality of error distributions.

There are two reasons why these confidence bands may be overoptimistic.

1. The nine observed errors from which the confidence bands are derived here are, in a sense, not randomly chosen. It is true that the companies are randomly chosen, at least in a sense relevant here. But the observed errors are deliberately taken to be those resulting from a choice of the flow schedule that best fits the observed energy use data (best among the three schedules — 4, 5, and 9— that result in reasonable wire-to-oil efficiencies). These observed errors, then, can be expected to be less than those that would be observed if nine more companies were investigated and schedule 4 were used, without regard to which schedule best fits the data for those nine. This is not to say that one should use all 27 observed errors corresponding to schedules 4, 5, and 9 as a basis for error estimation, since schedule 4 was picked precisely because there is reason to believe it accounts for the energy use of all companies better than the other schedules do. Nonetheless an estimate of error based on the nine observed errors produced by schedule 4 should be increased somewhat to reflect the manner in which these nine were chosen. An investigation that would quantify the appropriate increase is beyond the scope of this project.

2. The company errors may not be entirely independent, as assumed. It is likely, for instance, that the method in question produces estimates that are biased somewhat in one direction or the other.

To offset possible overoptimism, Table 8.3 enlarges the 95% confidence bands to produce more conservative estimates of the range in which the true energy consumption of oil pipelines probably lies.

It should be understood that the error estimates in Table 8.3 do not account for potential errors in the estimate of fuel-to-wire efficiency. But this is not of great concern, since fuel-to-wire efficiency is not properly a part of a pipeline energy investigation and is best treated as exogenous.

It should also be understood that energy estimates for individual states or individual pipe diameters are less reliable than the national estimates. Since deriving a confidence band for a state requires determining the movements of each company within the borders of that state, such a derivation does not seem worth the labor, especially since the confidence band would probably have to be enalarged anyway. Suffice it to say that since the 95% confidence band for individual companies is ±37%, one can expect to see errors on the order of ±20 or 30% in the states in which only one or a few companies operate. States containing lines belonging to many companies can be expected to receive more accurate estimates.

9. FINAL CALCULATION OF ENERGY CONSUMPTION AND INTENSIVENESS

9.1 Fuel-to-Oil Efficiencies

Pipeline pumping energy, which has been defined as the mechanical energy actually delivered to the oil by the pumps, yields the total pipeline energy consumption when it is divided by the fuel-to-oil efficiency. This efficiency is that with which the energy derived from primary sources, such as coal or diesel fuel, is converted to the mechanical energy exerted on pipeline oil. Its estimation is the object of this section.

The energy path from primary sources to pipeline oil has either two or three segments, depending on whether the pumps are driven by electric motors or otherwise. In the latter case the path is

```
primary ------ shaft ------ oil .
source   driver      pump
```

For electrically driven pumps the path is

```
primary -------------- wire -------- shaft ------ oil .
source     electrical         motor          pump
           generation
              and
          transmission
```

Thus there are four component efficiencies to be considered: direct fuel-to-shaft, shaft-to-oil, wire-to-shaft, and fuel-to-wire. These are estimated below and then combined to yield a composite fuel-to-oil efficiency for crude and for products pipelines.

9.1.1 Direct fuel-to-shaft efficiency

The direct fuel-to-shaft efficiency is the efficiency of fuel-burning engines in pipeline pump stations. One accounting of the fraction of installed pumping power provded by each type of engine is shown in Table 9.1 (McGowin 1973, p. 32). These figures cannot be very accurate, since they are reportedly based on the Annual Directory of Pipelines (Pipeline 1972). Only a portion of the company descriptions in this directory specify installed pumping horsepower in a way that indicates the type of driver. Also the distribution of power sources may have changed somewhat since 1972. Nonetheless these figures are probably adequate for present purposes, since the equipment efficiencies

Table 9.1. Sources of pipeline pumping power and their efficienices

	Crude lines		Products lines	
	Fraction of installed pumping power	Approximate efficiency	Fraction of installed pumping power	Approximate efficiency
Electric motors	0.7694	0.93	0.8150	0.93
Other sources, total	0.2306	0.303	0.1850	0.268
Gas turbine	0.0125	0.18	0.0594	0.18
Reciprocating engine	0.2179	0.31	0.1256	0.31
Steam turbine	0.0002	0.36	0	

can only be approximated. The driver efficiencies appearing in Table 9.1 are extracted from an engineering handbook (American Gas Association, 1966, p. 12/359). The weighted fuel-to-shaft efficiency for all non-electric drivers is 0.303 for crude lines and 0.268 for products lines.

9.1.2 Shaft-to-oil efficiencies

The great majority of trunk pipeline pumps are centrifugal pumps. Their efficiencies are somewhat difficult to estimate, since they vary with the type and condition of pump, the properties of the oil, and the load under which the pump is operating. Peak efficiencies for pipeline pumps are generally in the neighborhood of 0.86 to 0.89 (Kerassik et al. 1976, p. 10-100). A rule-of-thumb operating efficiency one hears mentioned is 0.80 (e.g., Leilich et al. 19797, p. E-15). This suggests that the average pump efficency probably lies in the range of 0.80 to 0.86. The results of Sect. 8.3 imply that pumps can be assumed to operate near the upper end of this range, and this matter will be taken up shortly.

9.1.3 Wire-to-shaft efficiency

Estimates of the efficiency of industrial electric motors generally are close to 0.93 (Baumeister et al. 1966, p. 15—46).

9.1.4 Fuel-to-wire efficiency

Probably the best way to estimate the efficiency with which primary energy is converted to delivered electricity is to appeal to the operating statistics of the electric utilities (Edison Electric Institute 1977). The relevant figures for 1977 (the most recent in the library) appear in Table 9.2. The efficiency of conventional steam-generation is estimated by the Edison Electric Institute to be 32.7%. The thermal efficiency of a boiling water nuclear reactor has been put at 33%, and that of a pressurized water reactor at 34% (McRae, Dudas, and Rowland 1977, p. 346). But due to serious definitional difficulties to be discussed shortly, the efficiency of nuclear generation is equated with that of other steam generation. The efficiency with which a hydro-electric plant converts the potential energy in a head of water to electricity is probably about 80% (Hooker 1979), but since the plant consumes no energy resources that nature would not consume otherwise, its efficiency is put at 100%. The resulting overall efficiency of electrical generation is 35.2%. Since 92.0% of this electricity reaches the customer, it is reasonable to infer that the transmission loss is 8.0%. The resultant efficiency of both generation and transmission is 32.3%.

The difficulties that arise in the very definition of such a measure of efficiency are manifold and infamous. To begin with, popular estimates

Table 9.2. Efficiency of electrical generation and transmission, 1978

	Production[a] (10^6 kwh)	Efficiency (%)
All sources	2,124,026	35.2
Hydroelectric	220,436	100
Nuclear	250,882	32.7
Other	1,652,708	32.7[b]
Total sales[a] = 1,953,535 × 10^6 kwh		
Efficiency of transmission = sales/production = 92.0%		
Efficiency of generation and transmission = (36.2) (92.0) = 32.3%		

[a]From Edison Electric Institute (1978, pp. 18, 31).

[b]10,449 Btu/kwh, estimated by Edison Electric Institue.

of generation and transmission efficiency seem to consider only generation from fossil fuels and consequently arrive at a number near 30%. But this practice is inexplicable, in that part of our electricity is, after all, derived from water power. Since no energy is wasted in the production of hydroelectricity that nature would not be waste just as quickly if the power were not harnessed, the efficiency of this process is 100% and serves to improve the overall efficiency of electrical generation from 32.7 to 35.2%.

Other definitional problems are more baffling. It is unclear why the energy cost of mining and tranpsorting coal to the power plant should not be counted. If it is not counted, then it is unclear what portions of the complex nuclear fuel cycle should figure into the calculation of efficiency. In particular, it is difficult to know how to account for the electricity consumed in refining nuclear fuel. It seems unfair to coal to omit this energy cost, since it is quite large, but if it is all included then the mine-to-plant energy efficiency of coal production should be taken into account. On the other hand, perhaps it is unfair to nuclear energy to count the waste heat in the plant as a loss, since whereas at least some of the coal's waste heat could have been used by burning the coal in household stoves, there is little one could do with nuclear waste heat -- at least until nuclear household furnaces are developed. Finally, the practice of counting electrical transmission loss seems odd in view of the fact that the energy cost of transporting diesel fuel to an engine is seldom taken into account in computing fuel-to-shaft efficiency. Presumably the transport of fuel to the engine parallels the transport of coal to the plant, but the former requires more energy and this should be acknowledged.

Obviously, such considerations could go on at some length. Since there seems to be no definitive resolution of the problem, the efficiency of conventional steam-generated electricity has been computed according to the usual definition, and the efficiency of nuclear-generated electricity has been equated with it so as to avoid the thorny question of how to view the nuclear fuel cycle.

9.1.5 Overall efficiency

The four efficiencies just developed are depicted in Fig. 9.1. It is evident that the overall fuel-to-oil efficiency may be estimated,

$$e_{fo} = (a_e e_{fw} e_{ws} + a_{ne} e_{fs}) e_{so} \, , \tag{9.1}$$

where a_e = fraction of installed pumping powr supplied by electric motors, given in Table 9.1;
a_{ne} = fraction of installed pumping power otherwise supplied, or $1 - a_e$; and
e_{xy} = x-to-y efficiency, where f = fuel, w = wire, s = shaft, and o = oil.

The results are

$$e_{fo} = \begin{cases} 0.259 \text{ for crude lines} \\ 0.253 \text{ for products lines} \end{cases} . \tag{9.2}$$

If a given energy use figure assuming an electrical generation and transmission efficiency of e_{fw} is to be converted to one assuming e'_{fw}, then (9.1) implies that the figure must be multiplied by a factor k, given by

$$k = (a_e e_{fw} e_{ws} + a_{ne} e_{fs}) / (a_e e'_{fw} e_{ws} + a_{ne} e_{fs}) \, . \tag{9.3}$$

When $e_{fw} = 0.323$, as recommended above, this conversion factor evaluates,

$$k = \begin{matrix} (2.377\, e'_{fw} + 0.232)^{-1} & \text{for crude lines} \\ (2.575\, e'_{fw} + 0.168)^{-1} & \text{for products lines} \end{matrix} \, . \tag{9.4}$$

Equation (9.4) is used throughout this report to convert from one fuel-to-wire efficiency to another.

Recall that the pump efficiency e_{so} was estimated earlier to lie in the range of 0.80 to 0.86. This means that the wire-to-oil efficiency

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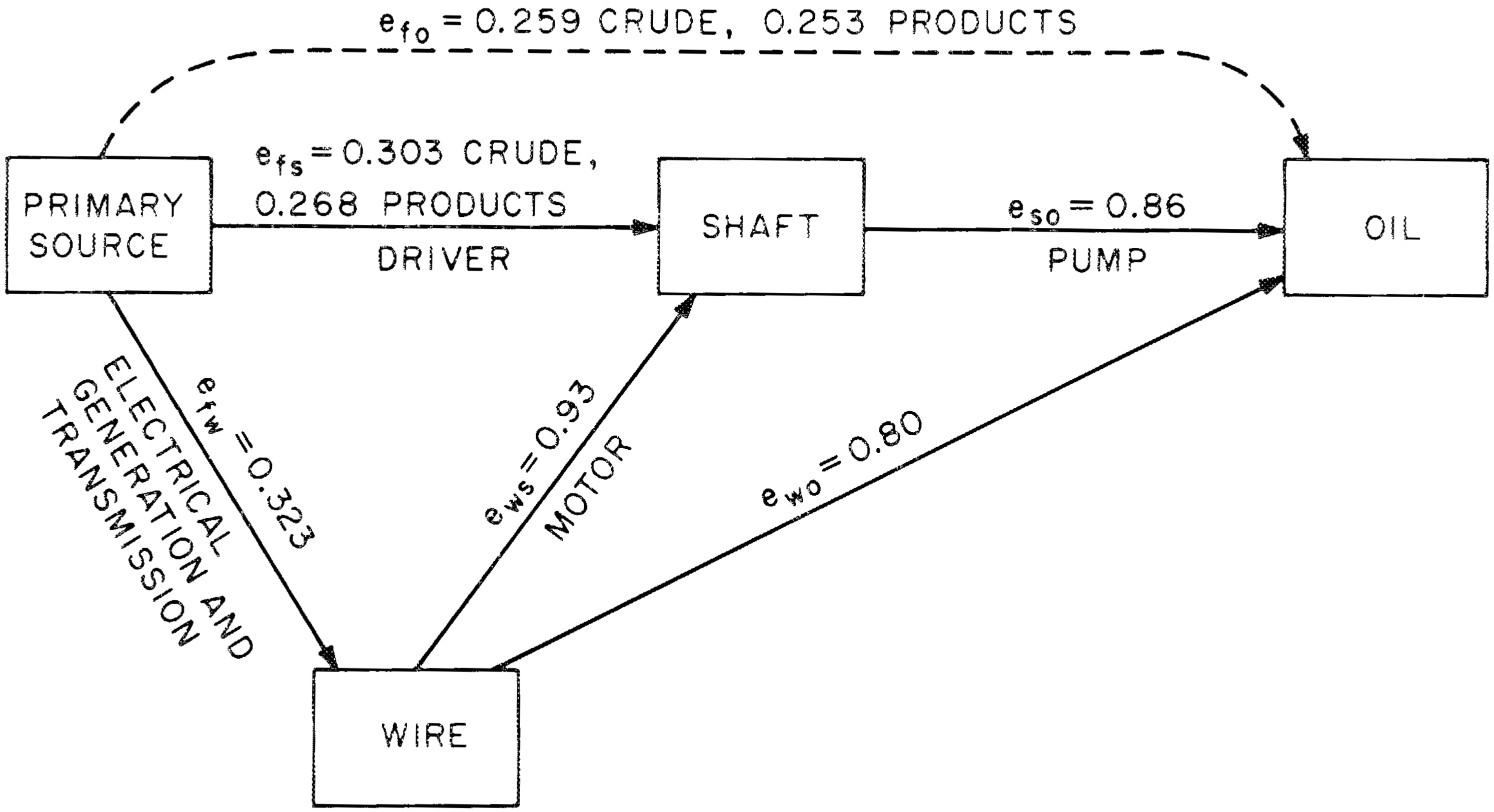

Fig. 9.1. Pipeline system efficiencies.

lies in the range of 0.74 to 0.80. Since the evidence adduced in Sect. 8.3 suggests that wire-to-oil efficiency is at the upper end of this range, pump efficiency has been set above at 0.86.

9.2 Energy Consumption

The calculation of pumping energy consumption is described in Chap. 7. When divided by fuel-to-oil efficiency it becomes total energy consumption:

$$E_s = PE_s/e_{fo} \ , \tag{9.5}$$

where E_s = pipeline energy consumption in state s (or the nation) in 1978 (crude oil trunk lines, crude oil gathering lines, or products lines);

PE_s = pipeline pumping energy consumption in state s (or the nation), given by (7.13) in Sect. 7.8 for crude and products trunk lines and by Table 7.6 in Sect. 7.9 for crude gathering lines; and

e_{fo} = fuel-to-oil efficiency for crude lines for products lines, as given by (9.2) in Sect. 9.1.

Tables and graphs showing the results of these calculations appear in this chapter and in the Summary. Table S.1 presents an energy overview, while Tables 9.3 through 9.6 show oil movements and energy consumption and intensiveness by state and by pipe diameter. Appendix B contains a computer printout showing oil movements and pumping energy consumed to overcome friction for each pipe size in each state. Figures S.2 and S.3 depict the relationship between pipe diameter and energy intensiveness. Table S.2 shows estimated oil movements by type of carrier, and Table S.3 compares pipeline energy intensiveness with that of other carriers of energy materials. Table 9.10 shows the oil movements and energy consumption and intensiveness that would result if all U.S. pipelines ran at capacity. Finally, Tables 9.7 through 9.9 show not actual energy intensiveness but the energy intensiveness that results when pipelines carry a capacity throughput of crude oil, gasoline or fuel oil that is predicted by the regression study of Chap. 6 to be typical of each pipe diameter. These tables and figures are interpreted in the next section.

9.3 Discussion of Results

The Conclusions section of the Summary interprets the results of this study in general and sometimes in specific terms. This section is intended to supplement the Summary and should not be read in isolation from it. What follows is a discussion of each table showing results.

Table 9.3. Crude oil pipeline energy consumption and intensiveness in 1978, by state

	Pipe miles[a]		Estimated movements		Energy consumption[b]		Gravity ratio[c]	Energy intensiveness[b]					Gathering lines energy consumption[d]	
	km	mile	10^9 m^3-km	10^9 bbl-mile	10^{12} J	10^9 Btu		J/kg-km	m/km	J/m^4	Btu/ton-mile	Btu/bbl-mile	10^{12} J	10^9 Btu
United States	116,776	72,561	558.8	2184	86,190	81,690	0.97	181	18.5	154	251	37.4	10,120	9,600
Alabama	282	175	0.86	3.4	160	160	1.02	230	23	190	310	46	12	11
Alaska	1,081	672	68.5	268	4,590	4,360	1.00	79	8	67	110	16	8[f]	7[f]
Arizona[e]	806	501	0.45	1.8	3	3	0.48	9	0.9	7	12	2	0	0
Arkansas	1,102	685	3.19	12.5	410	390	1.02	150	15	130	210	31	130	120
California	4,587	3,018	10.1	39.3	1,720	1,630	1.04	200	20	170	280	41	780	740
Colorado	2,052	1,275	3.01	11.8	530	500	1.04	210	21	180	290	42	130	120
Florida	342	213	0.43	1.7	120	110	0.99	330	34	280	460	68	8	7
Illinois	6,061	3,766	45.2	176	7,730	7,330	1.00	200	21	170	280	42	130	120
Indiana	1,312	815	8.21	32.1	1,650	1,560	1.06	240	24	200	330	49	27	26
Iowa	105	65	0.48	1.9	78	74	1.34	190	20	160	260	39	0	0
Kansas	7,998	4,970	19.2	75.1	2,480	2,350	0.95	150	16	130	210	31	310	300
Kentucky	1,127	700	12.7	49.7	2,280	2,160	1.00	210	22	180	290	44	35	33
Louisiana	7,851	4,878	42.1	165	10,200	9,670	1.02	290	29	240	400	59	1,080	1,020
Maine	348	216	1.13	4.40	100	95	1.88	100	11	88	140	21	0	0
Michigan	2,700	1,678	31.1	121	4,360	4,140	0.97	170	17	140	230	34	150	150
Minnesota	2,421	1,504	34.1	133	4,910	4,660	0.97	170	17	140	240	35	0	0
Mississippi	2,073	1,288	31.0	121	4,240	4,020	1.01	160	16	140	220	33	90	80
Missouri	4,912	3,052	22.8	89.0	3,960	3,750	1.04	200	21	170	280	42	0	0
Montana	3,071	1,908	2.54	9.93	440	420	0.98	200	21	170	280	42	140	130
Nebraska	1,136	706	4.49	17.5	260	250	0.56	70	7	59	95	14	20	20
New Hampshire	172	107	0.56	2.17	64	60	2.41	130	14	110	190	28	0	0
New Mexico	2,647	1,645	3.14	12.3	490	470	1.00	190	19	160	260	38	530	500
New York	186	116	0.23	0.91	46	44	1.02	240	24	200	300	49	8	7
North Dakota	1,529	950	4.07	15.9	370	350	0.89	110	11	92	150	22	0	0
Ohio	1,457	906	6.57	25.7	1,610	1,530	1.02	290	29	240	400	60	54	51

Table 9.3. (Continued)

	Pipe miles[a]		Estimated movements		Energy consumption[b]		Gravity ratio[c]	Energy intensiveness[b]					Gathering lines energy consumption[d]	
	km	mile	10^9 m^3-km	10^9 bbl-mile	10^{12} J	10^9 Btu		J/kg-km	m/km	J/m^4	Btu/ton-mile	Btu/bbl-mile	10^{12} J	10^9 Btu
Oklahoma	10,284	6,930	30.1	118	5,750	5,450	0.98	230	23	190	310	46	870	830
Pennsylvania	53	33	0.09	0.34	14	14	0.83	190	19	160	260	38	27	26
Tennessee	738	458	29.5	115	3,860	3,660	1.01	150	16	130	210	32	0	0
Texas	38,014	23,621	110	428	19,450	18,440	0.89	210	21	180	290	43	4,950	4,690
Utah	1,268	788	1.70	6.62	200	190	0.64	140	14	120	190	28	46	44
Vermont	306	190	0.99	3.87	27	26	0.59	33	3.3	28	45	6.7	0	0
Washington	130	81	0.23	0.89	12	11	0.55	62	6.3	52	85	13	0	0
West Virginia	893	555	0.64	2.50	270	260	1.02	500	51	430	700	100	19	18
Wisconsin	778	483	19.2	75.0	2,240	2,120	1.06	140	14	120	190	28	0	0
Wyoming	6,686	4,155	10.6	41.3	1,800	1,170	1.03	200	20	170	280	41	480	450

[a] As determined by the present study (Sect. 7.1). Mileages published by the Energy Department (Energy Information Administration 1978) differ somewhat.

[b] Assumes an efficiency of 32.3% for the generation and transmission of electricity.

[c] Ratio of total energy consumption to energy that would be used if pipes were level. Ratios less than one indicate that more oil flows downhill than uphill, so that the net effect of gravity is to reduce energy consumption.

[d] Gathering line energy is difficult to estimate, and the state figures could show errors as large as 30–50%.

[e] The Arizona energy consumption and intensiveness numbers are unnaturally low because the major crude oil pipeline in the state, a Four Corners 16-in. line, is reported to have surprisingly low 28,000 bbl/d capacity and because the Four Corners Company reports a surprisingly low 3792×10^6 bbl-mile for 1978. Since the fraction of this Four Corners movement that occurs in Arizona is not known even approximately, the above Arizona estimates should not be given much credence.

[f] Alaska's gathering line energy use estimate, like those for the other states, is based on pipeline stock at the end of 1976. It is therefore a substantial underestimate of energy use in 1978, due to the rapid growth of oil drilling in Alaska.

Table 9.4. Oil products pipeline energy consumption and intensiveness in 1978, by state

	Pipe miles[a]		Estimated movements		Energy consumption[b]		Gravity ratio[c]	Energy intensiveness[b]				
	km	mile	10^9 m^3-km	10^9 bbl-mile	10^{12} J	10^9 Btu		J/kg-km	m/km	J/m^4	Btu/ton-mile	Btu/bbl-mile
United States	132,954	82,614	388.2	1517	63,850	60,520	1.00	219	22.4	164	304	39.9
Alabama	2,235	1,389	29.5	115	4,020	3,810	1.36	180	19	140	250	33
Arizona	1,351	840	2.39	9.33	450	430	0.93	250	26	190	350	46
Arkansas	1,709	1,062	5.87	23.0	930	880	0.91	200	21	160	280	38
California	3,591	2,232	6.81	26.6	1,510	1,430	1.02	290	30	220	400	54
Colorado	1,667	1,036	2.34	9.13	500	470	1.09	280	28	210	380	52
Connecticut	192	119	0.20	0.78	32	30	1.10	200	20	160	280	39
Florida	256	159	0.53	2.08	105	100	1.02	250	26	200	350	48
Georgia	3,059	1,901	37.3	107	3,080	2,920	0.85	150	15	110	210	27
Idaho	97	563	1.22	4.76	240	230	0.86	260	26	200	360	48
Illinois	7,083	4,401	16.0	62.4	2,830	2,690	1.03	240	24	180	330	43
Indiana	4,696	2,918	8.97	35.1	1,440	1,360	1.04	210	22	160	290	39
Iowa	6,156	3,825	8.23	32.2	2,040	1,930	0.98	340	35	250	470	60
Kansas	10,179	6,325	17.3	67.7	4,420	4,190	0.99	350	36	260	490	62
Kentucky	227	141	0.26	1.02	72	68	1.16	350	36	280	480	67
Louisiana	3,912	2,431	35.2	137	5,160	4,890	1.04	190	20	150	270	36
Maine	217	135	0.16	0.62	45	43	1.00	360	37	280	500	69
Maryland	340	211	6.35	24.8	1,270	1,210	0.90	260	27	200	360	49
Massachusetts	350	218	0.19	0.74	73	69	1.06	500	51	380	690	93
Michigan	2,575	1,600	5.23	20.5	1,180	1,120	0.97	300	31	230	420	55
Minnesota	2,908	1,807	2.46	9.62	350	340	0.87	200	21	140	280	35
Mississippi	5,470	3,399	40.2	157	4,250	4,030	0.96	140	15	110	200	26
Missouri	6,170	3,834	12.7	49.5	1,730	1,640	0.97	180	19	140	260	33
Montana	1,602	995	2.69	10.5	580	550	0.99	280	29	210	390	52
Nebraska	2,920	1,815	3.27	12.8	840	800	0.98	340	35	260	470	62
Nevada	286	178	0.32	1.25	48	45	0.75	190	20	150	270	36
New Jersey	1,055	655	6.78	26.5	1,130	1,070	1.01	220	22	170	300	40
New Mexico	2,584	1,605	2.58	10.1	640	610	1.10	320	33	250	450	60
New York	2,426	1,508	2.72	10.6	730	690	0.94	350	36	270	490	65
North Carolina	1,794	1,115	20.3	79.3	2,030	1,920	0.84	130	13	100	180	24
North Dakota	797	495	0.96	3.75	200	190	0.92	280	29	210	390	50
Ohio	6,320	3,927	7.97	31.1	1,380	1,310	1.01	230	23	170	320	42
Oklahoma	6,114	3,799	11.9	46.5	2,320	2,200	1.03	270	27	200	370	47
Oregon	724	450	0.57	2.23	85	81	0.86	200	20	150	270	36
Pennsylvania	6,892	4,282	11.4	44.4	2,170	2,060	1.04	250	26	190	350	46
Rhode Island	77	48	0.05	0.20	35	34	1.12	900	91	710	1,240	170

Table 9.4. (Continued)

	Pipe miles[a]		Estimated movements		Energy consumption[b]		Gravity ratio[c]	Energy intensiveness[b]				
	km	mile	10^9 m^3-km	10^9 bbl-mile	10^{12} J	10^9 Btu		J/kg-km	m/km	J/m^4	Btu/ton-mile	Btu/bbl-mile
South Carolina	1,422	883	18.1	70.8	1,580	1,500	0.90	120	12	87	160	21
South Dakota	1,242	772	0.76	2.97	170	160	1.07	300	30	220	410	53
Tennessee	662	412	1.48	5.77	380	360	1.01	330	34	250	460	62
Texas	23,616	14,674	41.2	161	7,250	6,870	1.02	240	24	180	330	43
Utah	532	330	0.69	2.68	130	130	0.75	64	6.6	50	89	12
Virginia	1,379	857	16.8	65.7	3,740	3,550	1.00	290	30	220	410	54
Washington	1,208	751	3.89	15.2	750	710	1.02	260	26	190	350	47
West Virginia	97	60	0.05	0.21	17	16	1.00	420	43	330	580	81
Wisconsin	1,073	667	1.99	77.9	540	510	0.99	360	37	270	500	66
Wyoming	2,882	1,791	2.44	9.53	1,160	1,100	1.04	620	64	480	860	120

[a]As determined by the present study (Sect. 7.1). Mileages published by the Energy Department (Energy Information Administration 1978) differ somewhat.

[b]Assumes an efficiency of 32.3% for the generation and transmission of electricity.

[c]Ratio of total energy consumption to energy that would be used if pipes were level. Ratios less than one indicate more oil flows downhill than uphill, so that the net effect of gravity is to reduce energy consumption.

Table 9.5. Crude oil trunk pipeline energy consumption and intensiveness in 1978, by pipe diameter

	Pipe miles[a]		Estimated movements		Average throughput		Energy consumption[b]		Energy intensiveness[b]				
	km	mile	10^9 m^3-km	10^9 bbl-mile	10^3 m^3/d	10^3 bbl/d	10^{12} J	10^9 Btu	J/kg-km	m/km	J/m^4	Btu/ton-mile	Btu/bbl-mile
All diameters	116,776	72,561	558.8	2,184	13	82	86,190	81,690	181	18.5	154	251	37.4
2"	29	18	0.002	0.008	0.19	1.2	1.9	1.8	1,120	114	946	1,550	229
4"	944	587	0.25	0.97	0.73	4.6	128	122	608	62.1	518	842	126
6"	8,657	5,379	5.05	19.7	1.6	10	1,780	1,680	414	42.2	352	573	85.4
8"	28,689	17,827	28.3	110	2.7	17	7,530	7,140	313	31.9	266	434	64.6
10"	19,564	12,156	35.9	140	5.0	32	9,950	9,430	326	33.2	277	451	67.2
12"	18,791	11,676	42.1	165	6.1	39	7,430	7,050	208	21.2	177	288	42.9
14"	847	526	2.60	10.2	8.4	53	382	362	173	17.6	147	239	35.6
16"	10,851	6,742	36.1	141	9.1	57	5,930	5,620	193	19.7	164	268	39.9
18"	3,594	2,233	18.4	71.8	14	88	2,630	2,490	168	17.2	143	233	34.7
20"	8,930	5,549	58.1	227	18	110	9,990	9,390	200	20.4	170	278	41.4
22"	4,687	2,912	58.8	230	34	220	13,060	12,380	261	26.6	222	362	53.9
24"	2,806	1,743	24.2	94.5	24	150	2,260	2,140	110	11.2	93	152	22.7
26"	1,805	1,121	25.6	100	39	240	3,890	3,690	179	18.2	152	248	36.9
30"	2,363	1,468	44.4	174	51	320	5,220	4,950	138	14.1	118	192	28.5
34"	1,298	806	34.9	136	74	460	3,700	3,500	125	12.7	106	172	25.7
40"	1,316	818	70.4	275	150	920	7,940	7,530	133	13.5	113	184	27.4
48"	1,081	672	68.5	268	170	1,100	4,250	4,033	73	7.5	62	101	15.1

[a]As determined by the present study (Sect. 7.1). Mileages published by the Energy Department (Energy Information Administration 1978) differ somewhat.

[b]Assumes an efficiency of 32.3% for the generation and transmission of electricity. Also takes the national average gravity head of −0.152 m/km as the average gravity head for each diameter.

Table 9.6. Oil products pipeline energy consumption and intensiveness in 1978, by pipe diameter

	Pipe miles[a]		Estimated movements		Average throughput		Energy consumption[b]		Energy intensiveness[b]				
	km	mile	10^9 m^3-km	10^9 bbl-mile	10^3 m^3/d	10^3 bbl/d	10^{12} J	10^9 Btu	J/kg-km	m/km	J/m^4	Btu/ton-mile	Btu/bbl-mile
All diameters	132,954	82,614	388.2	1,517	8.0	50	63,850	60,520	219	22.4	164	304	39.9
2"	51	32	0.004	0.015	0.21	1.4	2.8	2.6	920	93.8	690	1,270	167
4"	3,199	1,988	0.87	3.40	0.75	4.7	431	408	660	67.3	495	913	120
6"	27,494	17,084	15.7	61.5	1.6	9.8	4,870	4,620	414	42.2	310	573	75.3
8"	44,496	27,649	47.1	184	2.9	18	11,690	11,080	331	33.7	248	458	60.2
10"	19,558	12,153	37.4	146	5.2	33	7,690	7,290	274	28.0	206	380	49.9
12"	15,417	9,579	40.9	160	7.3	46	7,880	7,470	257	26.2	193	356	46.8
14"	3,797	2,359	9.87	38.6	7.1	45	1,730	1,640	233	23.8	175	323	42.4
16"	3,620	2,249	18.0	70.2	14	86	3,030	2,870	225	22.9	168	311	40.9
18"	1,405	873	7.0	27.4	14	86	1,010	955	192	19.6	144	266	34.9
20"	5,943	3,693	27.7	108	13	80	3,480	3,290	167	17.1	125	232	30.4
22"	14	9	0.16	0.64	31	200	18	17	148	15.1	111	204	26.9
24"	1,400	870	10.3	40.4	20	130	1,120	1,060	145	14.8	109	200	26.3
26"	599	372	6.88	26.9	31	200	671	636	130	13.3	97	180	23.7
28"	941	585	8.75	34.2	25	160	685	649	104	10.6	78	145	19.0
30"	818	508	18.0	70.4	60	380	2,630	2,500	195	19.9	146	270	35.5
32"	447	278	18.5	72.2	110	710	4,310	4,080	310	31.7	233	430	56.5
36"	2,635	1,638	87.5	381	91	570	10,600	10,050	162	16.5	121	224	29.4
40"	540	336	23.3	91.0	120	740	1,970	1,870	113	11.5	85	156	20.5

[a] As determined by the present study (Sect. 7.1). Mileages published by the Energy Department (Energy Information Admnistration 1978) differ somewhat.

[b] Assumes an efficiency of 32.3% for the generation and transmission of electricity. Also takes the national average gravity head of 0.017 m/km as the average gravity head for each diameter.

Table 9.7. Typical crude oil pipeline energy intensiveness at capacity, by pipe diameter[a]

Nominal diameter (in.)	Typical capacity rate of flow[b]		Energy intensiveness				
	10^3 m^3/d	10^3 bbl/d	J/kg-km	m/km	J/m^4	Btu/ton-mile	Btu/bbl-mile
4	0.16	0.99	529	53.9	449	732	109
6	1.87	11.8	409	41.7	348	566	84.4
8	3.62	22.8	341	34.8	290	472	70.3
10	6.23	39.2	294	30.0	250	407	60.6
12	9.46	59.5	262	26.7	223	363	54.1
14	11.6	73.1	248	25.3	211	343	51.1
16	16.1	101	228	23.3	194	316	47.0
18	21.4	135	212	21.6	180	293	43.7
20	27.6	174	197	20.1	168	273	40.7
22	34.8	219	186	19.0	158	258	38.5
24	42.9	270	177	18.0	150	244	36.4
26	51.4	323	169	17.2	144	234	34.8
28	61.4	386	161	16.4	137	223	33.2
30	72.4	456	155	15.8	131	214	31.9
34	97.7	615	144	14.6	122	199	29.6
36	112	702	139	14.2	118	193	28.7
40	144	903	130	13.3	111	181	26.9
48	220	1,387	117	12.0	100	162	24.2

[a]Oil specific gravity = 0.85, viscosity = 7.5 cSt, pipe roughness = 0.0018 in., wall thickness as in Sect. 7.1, zero gravity head.

[b]As predicted by regression formula (6.40) in Sect. 6.5, assuming no interruptions of flow.

Table 9.8. Typical gasoline pipeline energy intensiveness at capacity, by pipe diameter[a]

Nominal diameter (in.)	Typical capacity rate of flow[b]		Energy intensiveness				
	10^3 m^3/d	10^3 bbl/d	J/kg-km	m/km	J/m^4	Btu/ton-mile	Btu/bbl-mile
4	0.97	6.09	587	59.8	429	812	104
6	2.48	15.6	483	49.2	353	668	85.6
8	4.87	30.6	422	43.0	308	584	74.8
10	8.47	53.3	378	38.6	277	524	67.1
12	13.0	81.5	349	35.5	255	483	61.8
14	16.0	101	331	33.7	242	458	58.7
16	22.3	140	311	31.7	227	431	55.2
18	29.8	188	294	30.0	215	408	52.2
20	38.7	243	280	28.6	205	388	49.7
22	48.8	307	268	27.3	196	371	47.5
24	60.4	380	258	26.3	188	357	45.7
26	72.6	457	249	25.4	182	342	44.2
28	87.1	548	241	24.6	176	334	42.8
30	103	649	234	23.8	171	323	41.4
32	121	759	227	23.1	166	314	40.2
34	140	880	220	22.5	161	305	39.1
36	160	1,007	216	22.0	158	299	38.3
40	207	1,302	205	20.9	150	284	36.3
42	233	1,466	200	20.4	146	277	35.5
48	289	1,818	155	15.8	113	215	27.5

[a]Gasoline specific gravity = 0.731, kinematic viscosity = 0.64 cSt, pipe roughness = 0.0018 in., wall thickness as in Sect. 7.1, zero gravity head.

[b]As predicted by formulas (6.40) in Sect. 6.5 and (7.6) in Sect. 7.4, assuming no interruptions of flow.

Table 9.9. Typical fuel oil pipeline energy intensiveness at capacity, by pipe diameter[a]

Nominal diameter (in.)	Typical capacity rate of flow[b]		Energy intensiveness				
	10^3 m^3/d	10^3 bbl/d	J/kg-km	m/km	J/m^4	Btu/ton-mile	Btu/bbl-mile
4	0.78	4.88	486	49.5	403	673	97.9
6	1.99	12.5	391	39.8	324	541	78.7
8	3.90	24.5	335	34.2	278	464	67.5
10	6.78	42.7	297	30.2	246	411	59.7
12	10.4	65.3	270	27.5	224	374	54.4
14	12.8	80.5	259	26.4	215	359	52.2
16	17.8	112	241	24.6	200	334	48.6
18	23.9	150	227	23.1	188	314	45.7
20	30.9	195	215	21.9	178	297	43.2
22	39.1	246	205	20.9	170	284	41.2
24	48.4	304	196	20.0	163	271	39.5
26	58.2	366	189	19.3	157	262	38.1
28	69.7	439	183	18.6	152	253	36.8
30	82.6	519	177	18.1	147	245	35.7
32	96.6	608	172	17.5	142	238	34.6
34	112	705	166	16.9	138	230	33.4
36	128	807	163	16.6	135	225	32.8
40	166	1,043	155	15.8	129	215	31.2
42	187	1,174	152	15.5	126	210	30.5
48	231	1,458	117	12.0	97	162	23.6

[a]Oil specific gravity = 0.83, kinematic viscosity = 3 cSt, pipe roughness = 0.0018 in., wall thickness as in Sect. 7.1, zero gravity head.

[b]As predicted by formulas (6.40) in Sect. 6.5 and (7.6) in Sect. 7.4, assuming no interruptions of flow.

Table 9.10. Energy consumption and intensiveness of oil pipelines if they had been running at capacity in 1978

	Capacity movements		Capacity utilization	Energy consumption at capacity		Power utilization	Energy intensiveness at capacity	
	10^9 m^3-km	10^9 bbl-mile	(%)	10^{15} J	10^{12} Btu	(%)	J/kg-km	Btu/ton-mile
Crude oil	762	2,980	73	150	142	57	233	322
Oil products	679	2,660	57	156	148	41	309	427

Table S.1. Oil pipeline energy consumption and intensiveness in 1978. This table presents an overview of oil pipeline energy use. Two significant digits only are shown, since there is no point in showing more when errors could be ±10–15% (Sect. 8.3), more for crude oil gathering lines. As stated in the Summary, this table contains a separate set of figures predicated on an electrical generation and transmission efficiency of 30% to permit comparison with studies that use the more popular 30% figure. All subsequent tables, however, assume a 32.3% efficiency, as do the figures in the left half of Table S.2.

Note that crude and products trunk lines require about the same amount of energy to move a given volume of oil over a given distance. Crude lines move a ton of oil with less energy than products lines because a ton of crude oil has less volume than a ton of the typical mix of products. One might expect crude lines to be less efficient by volume, due to the greater viscosity of crude oil, but this is offset by the fact that oil products are generally pumped at higher velocities than crude oil (see Fig. 3.1).

Table S.2. Estimated oil pipeline movements by type of carrier, 1978. This is an accounting table intended to help assess the completeness with which this study covers the pipeline industry. This study includes all and only pipeline carriers represented on API maps (see Chap. 4). The table provides two indications of how much oil movement is missed in this way. One indication is that a few regulated carriers do not appear on the maps (Sect. 7.4 lists them), and their oil movements are about 3% of the total for crude oil and 1% for oil products.

Another, less reliable indication is that only 9% of crude oil and 5% of oil products movements accounted for in this study were those of unregulated pipelines. (Recall that since unregulated companies do not report movements, thorughput in their lines is estimated as described in Sect. 7.4 and total movements computed on that basis. It turns out that throughputs assigned pipes in unregulated companies are generally very near capacity.) Sect. 7.1 notes that inaccuracy in the measurement of unregulated pipeline lengths may result in a 10–15% underestimate of unregulated movements. But even once a correction is made for this, the share of movements allotted here to unregulated carriers of both crude and products (8.6%) is considerably less than the 16% figure traditionally used by the Department of Transportation (e.g., U.S. Department of Transportation 1977). It is possible, then, that as much as 7 or 8% of oil movements, all unregulated, have been overlooked in this study.

It can be argued, however, that the 16% figure is too large. To begin with, it is only a guess that had been used without alteration over the last several years. No one knows the true fraction. Moreover, pipe inventory figures suggest that the coverage of this study is too nearly complete to allow a 7 or 8% omission of oil movements. This study accounts for 116,776 km of crude oil trunk lines and 132,954 km of products lines (Tables 9.3, 9.4). If the pipe inventory of the omitted regulated carriers (mentioned above) is added to this, the result is

118,794 km of crude lines and 136,192 km of products lines for 1978. The Department of Energy accounting, which purports to cover both regulated and unregulated carriers, sees 125,484 km of crude lines and 130,833 km of products lines as of Jan. 1, 1977 (Energy Information Administration 1978). Coverage of unregulated products lines in this study therefore appears complete, since it is highly unlikely that more than 5,359 km of unregulated products lines would have been constructed during 1977 and 1978.

Coverage of unregulated crude lines, however, appears incomplete, since this study's inventory of crude lines comes up several thousand kilometers short. It may be suggested that vagueness in the distinction of trunk and gathering lines could explain the discrepancy, since nearly all the discrepancy occurs in diameters ranging from 2 to 8 in. That is, it could be that when the API maps were reduced to code, a few trunk lines (both regulated and unregulated) were counted as gathering lines and thereby missed (see Appendix F). But if the crude trunk line inventory used here were increased to match the Department of Energy figures (by 14,195 km in diameters ranging from 2 to 8 in.), and if the added pipes were given capacity throughput [as defined by Eq. (6.40)], the resulting increase in oil movements (9×10^6 m^3-km) would raise the total in Table S.2 by only 1.5%, not by 7 or 8%.

All this suggests that the Department of Transportation's 16% figure is an overestimate. The issue must be considered unresolved, and it is likely that crude oil trunk line movements are somewhat underestimated here, but there is certainly no warrant for invoking the government's 16% guess as grounds for claiming a 7 or 8% omission in this study.

In the meantime, it is clear that this study omits at least 3% of crude movements and 1% of products movements by omitting a few regulated companies. It should be understood that such omissions discernibly affect only the estimates of energy consumption (by a roughly proportional amount) and have no discernible effect on estimates of energy intensiveness.

Table S.3. Comparison of energy intensiveness for several modes of energy transport. The superiority of oil pipelining, in point of energy efficiency, is evident in this table. The caveat at the bottom, however, should be taken seriously: "The energy intensiveness of a mode of transport is highly sensitive to the route, speed, size of vehicle, etc. These figures are rough averages, in some cases very rough."

Tables 9.3, 9.4. Crude oil and oil products pipeline energy consumption and intensiveness in 1978, by state. As noted in Sect. 8.3, the state figures are not nearly as reliable as the national figures. States in which one or a few pipeline companies operate may show errors as large as ±20–40%, while errors should be less in other states. A rule of thumb is that states containing fewer pipeline segments, as indicated in Appendix F, should be subject to greater error, since the number of segments' is a rough indication of the number of companies operating in the state. States such as Texas and Oklahoma should receive estimates nearly as reliable as the national figures.

Tables 9.5, 9.6. Crude oil and oil products pipeline energy consumption and intensiveness in 1978, by pipe diameter. The energy intensiveness figures in these tables are plotted in Figs. S.2 and S.3, which are discussed in the summary. It should be noted that all pipe sizes are assumed to experience the same average gravity head per kilometer.

A anomaly obvious in Fig. S.3 is the high energy intensiveness calculated for 32-in. products lines. In 1978 there was only one 32-in. products line, the Colonial line extending from Greensboro, North Carolina, to the outskirts of Baltimore, Maryland. This study calculates an average throughput of 139,200 m^3/d (875,500 bbl/d) for most of this line. The high figure results from a highly reported capacity of 152,600 m^3/d (960,000 bbl/d) for the line. Given this throughput, energy intensiveness for the line should in fact be about 310 J/kg-km (530 Btu/ton-mile) if it carries the same mix of products as does the Colonial system generally. If it carried relatively more gasoline at this rate, the energy intensiveness would be less. The stretch from Greensboro to Mitchell Junction, Virginia (near Richmond), has been looped with a 36-in. line since 1978, and the stretch from Mitchell Junction to Baltimore is now being looped with 36-in. line (Pipeline Industry 1980, p. 31). These additions should substantially improve energy efficiency.

Tables 9.7, 9.8, 9.9. Typical crude oil, gasoline, and fuel oil pipeline energy intensiveness at capacity, by pipe diameter. These tables represent an attempt to determine the "inherent" efficiencies associated with the various pipe diameters. Each pipe is given capacity flow, as predicted by regression formula (6.40) and corrected for viscosity by Eq. (7.6). The resulting friction head is calculated according to formula (2.2) in Sect. 7.6. Pumping energy is calculated according to Eqs. (7.12) and (7.13), where the throughput V(p) is set at capacity flow and the gravity head is presumed zero. The result is divided by fuel-to-oil efficiency, as per Eq. (9.5), to obtain the figures in these tables.

Table 9.10. Energy consumption and intensiveness of oil pipelines if they had been running at capacity in 1978. The figures in this table are obtained by supposing that each pipeline continuously carries capacity flow, as estimated by Eq. (7.6). The table requires careful intepretation, since it suggests a misleadingly low utilization of capacity. It is discussed at length in the Summary.

The results displayed in this table are useful for gauging the sensitivity of energy use estimates to errors in reported oil movements. Equation (2.6) implies that, in a given pipeline running continuously, energy intensiveness varies with the 1.748 power of the flow rate, which means that energy consumption varies with the 2.748 power of the flow rate. But a given increase in oil movmeents (m^3-km) nationwide does not correspond to an equal increase in flow rate in each pipe. The relation between flow rate and movements is determined by the flow scheduling model chosen in Chap. 8 as described in Sect. 7.5. One implication of this model is that when oil movements increase, pipelines run longer hours, so that the increase in flow rate is less than proportional to the increase in movements.

This is reflected in the energy figures. If crude oil movements were to increase from the actual to the capacity volume, an increase of 35%, a proportional increase in flow rate in all lines would result in a 72% increase in energy intensiveness. The energy intensiveness increase shown in Table 9.10, however, is only 29%. If oil products movements increased 75% to achieve capacity flow, a proportional increase in flow rate would bring a 166% increase in energy intensiveness, whereas the increase actually predicted is 41%. It can be safely inferred, then, that each 10% error in reported oil movements results in no more than a (proportional) 10% error in energy intensiveness, and consequently no more than a 20% error in total energy consumption.

It is likely that reported oil movements figures do in fact contain errors. One indication is that one of the companies contacted for the purposes of Chap. 8 supplied a 1978 barrel-mile figure that differs by 24% from the 1978 figure submitted by the same company to the Department of Energy. Another indication is that oil movements is not the sort of statistic a pipeline company must maintain to carry out its business. Only throughput statistics need be kept, and barrel-miles must then be computed by multiplying the recorded throughput in each segment of pipe by the pipe's length and adding the results. There is no guarantee that every company carries out these calculations carefully or has the necessary information at the time the government forms are due.

Yet there is no evidence that there is systematic error in the reporting of oil movements. The errors in the estimates of energy consumed by the nine pipelines discussed in Chap. 8, which probably derive in part from inaccurate barrel-mile figures, are negative as often as positive. Also there is no obvious reason why inadvertent errors should tend in one direction more than the other, nor is there any clear incentive for a pipeline company deliberately to adjust figures in one direction or the other.

Appendix A. CONVERSION TABLES

Table A.1. Selected conversion factors

Multiply by the first factor given to convert from the unit on the left to the one on the right. Use the other factor to convert in the opposite direction.

Length	meter (m)	3.281	0.3058	feet (ft)
	kilometer (km)	0.6214	1.609	mile
Volume	cubic meter (m^3)	6.291	0.1590	barrel (bbl)[e]
	cubic meter (m^3)	264.2	0.003785	gallon (gal)
Mass	kilogram (kg)	2.205	0.4536	pound (lb)
	metric ton (t)	2.205	0.4536	short ton (ton)
Energy	kilojoule (kJ)[a]	0.9478	1.055	British thermal unit (Btu)
	kilowatt-hour (kwh)	3412	293.1×10^{-6}	Btu
Density	kilograms per cubic meter (kg/m^3)[b]	0.06243	16.02	pounds per cubic foot (lb/ft^3)
	degrees API (°API)[c] = $\frac{141.5}{\text{sp. gr. } 60/60°F} - 131.5$			
Kinematic viscosity	centistoke (cSt)[d]	10.76×10^{-6}	92,900	square foot per second (ft^2/sec)
Measures of transportation				
	metric ton-kilometer (t-km)[f]	0.6849	1.460	short ton-mile (ton-mile)
	cubic meter-kilometer (m^3-km)	3.909	0.2558	barrel-mile (bbl-mile)

[a] Multiply by 1000 to get joules (J).

[b] Divide by 1000 to get a figure very close to specific gravity (sp. gr.) relative to water at 60°F.

[c] Note that API gravity of an oil does not vary with its temperature.

[d] Divide by 100 to get stokes (St) = square centimeters per second (cm^2/sec).

[e] Forty-two gallons per barrel.

[f] Multiply by 1000 to get kilogram-kilometers (kg-km).

Table A.2. Conversion chart for units of energy intensiveness

From	To	Hylimetric (J/kg-km = mm/sec^2)	Hylimetric (Btu/ton-mile)	Barimetric (J/N-km = m/km)	Barimetric (ft/mile)	Volumetric (J/m^4 = N/m^3)	Volumetric (Btu/ton-mile)	Volumetric (psi/mile)
Hylimetric,	J/kg-km	1	1.3847	0.10197	0.53843	s[a]	0.24268s	0.23342s
	Btu/ton-mile	0.72217	1	0.073641	0.38882	0.72217s	0.17525s	0.16857s
Barimetric,	J/N-km	9.8067	13.579	1	5.2800	9.8067s	2.3798s	2.2890s
	ft/mile	1.8572	2.5719	0.18939	1	1.8572s	0.45073s	0.43353s
Volumetric,	J/m^4	1/s	1.3847/s	0.10197/s	0.53841/s	1	0.24268	0.23342
	Btu/bbl-mile	4.1207/s	5.7060/s	0.42020/s	2.2186/s	4.1207	1	0.96184
	psi/mile	4.2842/s	5.9324/s	0.43687/s	2.3067/s	4.2842	1.0397	1

[a] s = specific gravity with respect to H_2O at 3.98°C.

Appendix B. PIPELINE FLOW AND PUMPING ENERGY BY STATE BY PIPE DIAMETER

The following computer printout shows the calculated pumping energy used to overcome friction, as well as other data, in each state and for each pipe diameter in 1978. Pumping energy is mechanical energy actually delivered to the oil. No account is taken of gravity head or losses in pumps drivers and electrical generation and transmission. Gravity head is ignored because average elevation gain was not estimated for particular diameters. If one wishes to assume equal gravity head for all diameters, he may perform the calculation:

$$E = [PE \cdot (3.6 \times 10^9) + h_g V \rho g]/e$$

where E = total energy consumed by pipes of a given diameter in a given state (J),
PE = pumping energy consumed to overcome friction (mwh), given in the following printout,
h_g = gravity head per km (m/km), given in Table 7.5,
V = throughput for the diameter in question (m^3-km), given in the printout,
ρ = average oil density for the state in question (kg/m^3), given in the printout,
g = gravitational acceleration, 9.8067 m/sec^2, and
e = fuel-to-oil efficiency, 0.259 for crude oil and 0.253 for oil products.

The columns of the printout are as follows:

diam	nominal pipe diameter in inches. A zero represents a sum over all diameters.
km on map miles on map	total length of pipes of each size as measured on API maps.
adjusted km, mi	total length after adjustment (Sect. 7.1).
kw, hp	average pumping power consumption in kilowatts, horsepower.
mwh	total 1978 pumping energy consumption in megawatt-hours.
cu. m-km/yr bbl-mi/yr	1978 oil movements in millions of cubic meter-kilometers or millions of barrel-miles.
ton-km/yr ton-mi/yr	1978 oil movements in millions of metric ton-kilometers or millions of ton-miles.

kJ/ton-km Btu/ton-mi	pumping energy intensiveness (ignoring gravity) in kilojoules per metric ton-kilometer (= J/kg-km) or British Thermal Units per ton-mile.

The number of pipes at the upper right corner refers to the number of pipeline segments in that state (see Sect. 7.1).

Table B.1. Crude pipeline flow and pumping energy by state by pipe diameter

1

ALABAMA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 3 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	270.	168.	282.	175.	1294.	1722.	11246.	863.	3371.	734.	502.	55.2	76.4
12	162.	101.	169.	105.	583.	781.	5104.	470.	1836.	400.	273.	46.0	63.7
14	53.	33.	55.	34.	167.	224.	1460.	150.	587.	123.	87.	41.2	57.0
16	55.	34.	58.	36.	534.	717.	4692.	243.	948.	207.	141.	81.8	113.1

2

ALASKA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 7 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1081.	672.	1081.	672.	37738.	50607.	330584.	68450.	267523.	58283.	39837.	20.5	28.3

3

ARIZONA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 2 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	589.	366.	806.	501.	49.	65.	426.	452.	1766.	385.	263.	4.0	5.5
12	39.	24.	53.	33.	5.	6.	41.	25.	96.	21.	14.	7.1	9.8
16	550.	342.	753.	468.	44.	59.	385.	427.	1670.	364.	249.	3.3	5.3

Table B.1. (Continued)

4

ARKANSAS

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 16 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	979.	609.	1102.	695.	3299.	4424.	28898.	3191.	12472.	2717.	1857.	38.4	53.1
6	127.	79.	143.	89.	331.	444.	2899.	103.	404.	88.	60.	113.7	164.2
8	331.	206.	373.	232.	974.	1306.	8530.	458.	1791.	390.	267.	78.9	109.1
10	26.	16.	29.	18.	95.	114.	747.	56.	218.	48.	33.	56.6	78.3
20	495.	308.	557.	346.	1909.	2560.	16723.	2574.	10058.	2191.	1498.	27.5	38.1

5

CALIFORNIA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 66 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	4363.	2713.	4857.	3018.	13639.	18290.	119478.	10068.	39349.	8573.	5859.	50.3	69.6
6	252.	157.	281.	175.	597.	801.	5232.	139.	740.	161.	110.	117.0	161.9
8	1087.	676.	1210.	752.	2697.	3617.	23627.	1374.	5369.	1170.	799.	72.9	100.8
10	1023.	636.	1139.	708.	4189.	5619.	36697.	2315.	9049.	1971.	1347.	67.1	92.9
12	290.	180.	323.	200.	986.	1323.	8639.	803.	3138.	684.	467.	45.6	63.1
14	163.	101.	181.	112.	886.	1188.	7759.	664.	2594.	565.	386.	49.5	68.5
16	962.	598.	1071.	665.	2146.	2878.	18793.	2411.	9422.	2053.	1403.	33.0	45.7
18	299.	186.	333.	207.	1787.	2396.	15651.	1895.	7404.	1613.	1103.	35.0	48.4
20	252.	156.	280.	174.	72.	97.	631.	82.	319.	70.	48.	32.7	45.3
22	35.	22.	39.	24.	279.	374.	2444.	336.	1312.	286.	195.	30.8	42.7

Table B.1. (Continued)

6

COLORADO

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 44 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	MI	KW	HP	MWH	CU.M-KM/YR (BILLIONS)	BBL-MI/YR (BILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1919.	1193.	2052.	1275.	4159.	5578.	36437.	3009.	11760.	2562.	1751.	51.3	71.0
2	27.	17.	29.	18.	16.	21.	137.	2.	8.	2.	1.	291.4	403.2
4	136.	84.	145.	90.	221.	296.	1935.	46.	178.	39.	27.	179.7	248.7
6	563.	350.	602.	374.	1382.	1853.	12107.	434.	1695.	369.	252.	118.3	163.7
8	273.	170.	292.	181.	503.	674.	4401.	238.	931.	203.	139.	78.3	108.3
10	483.	300.	516.	321.	991.	1329.	8679.	656.	2563.	559.	382.	56.1	77.6
12	123.	77.	132.	82.	140.	188.	1227.	140.	547.	119.	81.	37.2	51.4
18	154.	96.	165.	102.	312.	419.	2735.	363.	1417.	309.	211.	32.0	44.2
22	159.	99.	170.	106.	596.	799.	5217.	1131.	4422.	963.	659.	19.5	27.3

9

FLORIDA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 5 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	MI	KW	HP	MWH	CU.M-KM/YR (BILLIONS)	BBL-MI/YR (BILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	338.	210.	342.	213.	1037.	1391.	9083.	433.	1694.	369.	252.	88.8	122.9
16	52.	32.	52.	33.	486.	652.	4255.	221.	862.	188.	128.	81.8	113.1

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ILLINOIS

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 114 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	MI	KW	HP	MWH	CU.M-KM/YR (BILLIONS)	BBL-MI/YR (BILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	5689.	3537.	6061.	3766.	63840.	85613.	559236.	45156.	176482.	38449.	26290.	52.5	72.6
4	66.	41.	70.	43.	27.	36.	233.	11.	44.	10.	7.	88.0	121.8
6	18.	11.	19.	12.	63.	84.	548.	16.	62.	13.	9.	146.7	203.0
8	485.	302.	517.	321.	2050.	2749.	17960.	675.	2639.	575.	393.	112.7	156.0
10	952.	592.	1014.	630.	4287.	5749.	37554.	2074.	8106.	1766.	1207.	76.7	106.1
12	1582.	984.	1686.	1047.	6020.	8072.	52731.	4232.	16539.	3603.	2463.	52.8	73.0
14	19.	12.	20.	12.	79.	106.	691.	66.	256.	56.	38.	44.7	61.8
16	100.	62.	106.	66.	447.	599.	3915.	434.	1696.	369.	253.	38.2	52.9
18	384.	239.	409.	254.	2935.	3936.	25709.	2427.	9484.	2066.	1412.	44.9	62.1
20	745.	463.	794.	493.	16049.	21522.	140588.	7221.	28223.	6149.	4203.	82.5	114.1
22	619.	385.	660.	410.	9637.	12923.	84418.	7328.	28640.	6240.	4265.	48.8	67.5
26	355.	221.	378.	235.	10379.	13919.	90921.	6850.	26773.	5833.	3987.	56.2	77.8
30	42.	26.	45.	28.	366.	491.	3210.	532.	2079.	453.	310.	25.6	35.4
34	150.	93.	159.	99.	3472.	4655.	30413.	4151.	16222.	3534.	2416.	31.0	43.0
40	172.	107.	183.	114.	8030.	10769.	70345.	9139.	35719.	7782.	5319.	32.6	45.1

Table B.1. (Continued)

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INDIANA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 10 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1153.	717.	1312.	815.	12702.	17034.	111272.	8214.	32102.	6994.	4780.	57.4	79.4
6	124.	77.	141.	88.	205.	275.	1799.	71.	277.	60.	41.	107.5	148.7
12	392.	244.	446.	277.	468.	628.	4104.	777.	3036.	661.	452.	22.4	31.0
20	323.	201.	367.	228.	2755.	3694.	24134.	1554.	6074.	1323.	904.	65.8	91.0
22	229.	143.	261.	162.	8113.	10879.	71068.	4127.	16129.	3514.	2402.	73.0	100.9
30	85.	53.	97.	60.	1161.	1557.	10169.	1685.	6587.	1435.	981.	25.6	35.4

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IOWA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 5 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	101.	63.	105.	65.	476.	638.	4168.	483.	1886.	411.	281.	36.6	50.6
12	48.	30.	50.	31.	180.	242.	1580.	137.	535.	117.	80.	48.9	67.6
16	14.	9.	15.	9.	71.	96.	626.	65.	256.	56.	38.	40.5	56.0
20	39.	24.	40.	25.	224.	300.	1962.	280.	1095.	239.	163.	29.7	41.1

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KANSAS

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 145 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	7691.	4782.	7998.	4970.	21396.	28692.	187425.	19227.	75145.	16371.	11190.	41.3	57.1
4	37.	23.	39.	24.	51.	63.	447.	12.	45.	10.	7.	163.7	226.5
6	1279.	795.	1330.	827.	1343.	1800.	11761.	586.	2290.	499.	341.	85.0	117.7
8	2289.	1423.	2380.	1479.	5558.	7454.	48690.	2154.	8420.	1834.	1254.	95.7	132.5
10	1214.	755.	1263.	785.	2800.	3755.	24531.	1880.	7347.	1601.	1094.	55.3	76.5
12	1007.	626.	1048.	651.	2549.	3417.	22318.	2104.	8223.	1791.	1224.	44.9	62.2
16	72.	45.	75.	47.	371.	497.	3247.	342.	1338.	292.	199.	40.2	55.6
18	348.	217.	362.	225.	1942.	2604.	17012.	2059.	8048.	1753.	1198.	35.7	49.4
20	762.	474.	793.	493.	4606.	6176.	40347.	5336.	20857.	4544.	3106.	32.0	44.3
22	212.	132.	221.	137.	771.	1033.	6750.	1464.	5723.	1247.	852.	19.5	27.0
24	469.	291.	487.	303.	1407.	1886.	12321.	3289.	12854.	2800.	1914.	15.9	22.0

Table B.1. (Continued)

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KENTUCKY

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 7 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	907.	564.	1127.	700.	18827.	25248.	164927.	12722.	49722.	10833.	7404.	54.9	76.0
8	56.	35.	70.	43.	177.	238.	1554.	63.	247.	54.	37.	104.1	144.1
20	186.	116.	231.	144.	9585.	12853.	83961.	3432.	13414.	2922.	1997.	103.6	143.4
22	113.	70.	141.	87.	3333.	4469.	29195.	2030.	7935.	1729.	1182.	60.9	84.3
24	478.	297.	593.	369.	865.	1160.	7576.	2239.	8753.	1907.	1303.	14.3	19.8
40	74.	46.	92.	57.	4868.	6528.	42642.	4957.	19374.	4221.	2885.	36.4	50.4

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LOUISIANA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 121 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	5993.	3726.	7851.	4878.	81965.	109917.	718017.	42147.	164722.	35896.	24529.	72.2	99.9
6	245.	153.	321.	200.	592.	794.	5185.	203.	794.	173.	118.	108.1	149.5
8	893.	555.	1170.	727.	3786.	5077.	33168.	1417.	5540.	1207.	825.	99.1	137.2
10	420.	261.	550.	342.	2013.	2700.	17637.	1057.	4131.	900.	615.	70.7	97.8
12	1725.	1073.	2260.	1404.	11457.	15365.	100367.	6508.	25435.	5541.	3787.	65.3	90.4
14	152.	95.	199.	124.	738.	990.	6467.	661.	2585.	563.	385.	41.4	57.3
16	728.	452.	953.	592.	7284.	9768.	63809.	4171.	16300.	3551.	2427.	64.8	89.7
18	223.	138.	292.	181.	1448.	1941.	12680.	1526.	5963.	1299.	888.	35.2	48.7
20	848.	527.	1111.	690.	11751.	15758.	102937.	8070.	31540.	6871.	4697.	54.0	74.8
22	678.	421.	888.	552.	37260.	49966.	326395.	12794.	50001.	10393.	7446.	108.1	149.6
40	81.	50.	106.	66.	5636.	7559.	49375.	5740.	22433.	4887.	3340.	36.4	50.4

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MAINE

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 3 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	362.	225.	349.	216.	438.	587.	3833.	1126.	4401.	959.	655.	14.4	20.0
12	121.	75.	116.	72.	106.	142.	925.	166.	647.	141.	96.	23.7	32.7
18	121.	75.	116.	72.	144.	193.	1262.	339.	1324.	288.	197.	15.8	21.8
24	121.	75.	116.	72.	189.	252.	1646.	622.	2430.	529.	362.	11.2	15.5

Table B.1. (Continued)

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MICHIGAN

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 30 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	2639.	1641.	2700.	1678.	36904.	49489.	323290.	31092.	121479.	26465.	18089.	44.1	61.0
4	90.	50.	82.	51.	75.	100.	656.	39.	75.	36.	11.	145.0	200.7
6	439.	273.	449.	279.	527.	706.	4614.	235.	842.	183.	125.	90.7	125.6
8	462.	288.	473.	294.	256.	344.	2246.	244.	952.	207.	142.	39.1	54.1
12	152.	94.	155.	96.	850.	1140.	7450.	509.	1990.	434.	296.	62.0	85.8
16	269.	167.	275.	171.	892.	1182.	7721.	1050.	4102.	904.	611.	31.2	43.1
30	1237.	769.	1265.	786.	34314.	46016.	300591.	29045.	113518.	24731.	16904.	43.8	60.7

23

MINNESOTA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 55 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	2237.	1391.	2421.	1504.	41872.	56151.	366798.	34127.	133379.	29058.	19861.	45.5	63.0
16	668.	415.	723.	449.	8615.	11553.	75466.	3749.	14653.	3192.	2182.	95.3	131.8
18	463.	285.	501.	311.	7565.	10145.	66270.	3649.	14260.	3107.	2122.	76.3	105.5
26	463.	288.	501.	311.	10663.	14299.	93403.	7844.	30657.	6679.	4565.	50.4	69.8
34	463.	288.	501.	311.	13775.	18472.	120567.	13783.	53868.	11736.	8022.	37.1	51.3

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MISSISSIPPI

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 26 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1973.	1227.	2073.	1288.	34508.	46276.	302287.	31048.	121346.	26437.	18070.	41.2	57.1
6	209.	130.	219.	136.	366.	490.	3203.	141.	550.	120.	82.	96.5	133.5
9	441.	274.	463.	288.	923.	1237.	8083.	463.	1808.	394.	269.	74.0	102.4
10	457.	284.	480.	299.	832.	1116.	7288.	670.	2619.	571.	390.	46.1	63.8
12	20.	12.	21.	13.	97.	131.	853.	49.	190.	41.	28.	74.3	102.8
14	105.	65.	110.	68.	333.	447.	2921.	300.	1174.	256.	175.	41.2	57.0
22	306.	190.	321.	200.	7618.	10215.	66731.	4641.	18137.	3951.	2701.	60.9	84.3
40	437.	271.	459.	285.	24339.	32639.	213209.	24785.	96868.	21104.	14425.	36.4	50.3

Table B.1. (Continued)

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MISSOURI

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 79 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	[illegible]/TON-KM	BTU/TON-MI
0	4540.	2823.	4912.	3052.	31177.	41809.	273112.	22768.	88970.	19393.	13248.	50.8	70.3
8	62.	38.	67.	42.	194.	261.	1702.	55.	331.	72.	49.	95.3	118.0
10	849.	528.	918.	570.	8094.	10854.	70904.	2546.	9952.	2169.	1492.	118.0	163.2
12	1799.	1118.	1946.	1209.	5733.	7688.	50213.	4370.	17080.	3721.	2543.	48.7	67.4
16	57.	36.	62.	38.	589.	790.	5162.	353.	1381.	301.	206.	61.9	85.6
20	993.	618.	1075.	668.	4003.	5369.	35070.	5445.	21280.	4636.	3169.	27.3	37.8
22	576.	358.	623.	387.	10312.	13828.	90332.	7374.	28818.	6278.	4291.	51.9	71.8
24	205.	127.	222.	138.	2252.	3019.	19724.	2591.	10127.	2206.	1508.	32.2	44.6

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MONTANA

DENSITY - - 849.32 KG/CU-M 53.02 LB/CU-FT 52 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	3032.	1885.	3071.	1908.	3697.	4957.	32382.	2540.	9926.	2162.	1479.	54.0	74.3
4	100.	62.	102.	63.	109.	146.	954.	28.	109.	24.	16.	145.6	201.5
6	869.	540.	880.	547.	1100.	1475.	9637.	468.	1830.	399.	272.	87.2	120.7
8	740.	460.	750.	466.	973.	1305.	8525.	495.	1935.	421.	288.	73.0	101.0
10	190.	118.	193.	120.	216.	290.	1892.	171.	669.	145.	100.	46.8	64.8
12	960.	597.	972.	604.	1040.	1395.	9114.	994.	3884.	846.	578.	38.9	53.8
16	153.	95.	155.	96.	255.	341.	2230.	382.	1494.	325.	222.	24.7	34.2

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NEBRASKA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT [illegible] PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1147.	713.	1136.	706.	3895.	5223.	34121.	4485.	17528.	3819.	[illegible]	32.7	44.6
4	34.	21.	34.	21.	45.	60.	391.	10.	40.	9.	6.	163.7	226.5
6	102.	63.	101.	62.	46.	61.	399.	25.	97.	21.	14.	67.9	94.0
8	59.	36.	58.	36.	87.	116.	759.	36.	142.	31.	21.	88.5	122.4
10	20.	13.	20.	12.	56.	75.	492.	38.	149.	32.	22.	54.9	75.9
12	65.	40.	64.	40.	111.	148.	969.	107.	419.	91.	62.	38.4	53.1
20	767.	477.	759.	472.	3201.	4293.	28042.	3605.	14091.	3068.	2097.	33.0	45.6
22	101.	63.	100.	62.	350.	470.	3065.	666.	2601.	567.	387.	[illegible]	27.0

Table B.1. (Continued)

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NEW HAMPSHIRE

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 3 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	179.	111.	172.	107.	216.	289.	1891.	555.	2171.	473.	323.	14.4	20.0
12	60.	37.	57.	36.	52.	70.	456.	82.	319.	70.	48.	23.7	32.7
18	60.	37.	57.	36.	71.	95.	622.	167.	653.	142.	97.	15.8	21.8
24	60.	37.	57.	36.	93.	124.	812.	307.	1199.	261.	179.	11.2	15.5

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NEW MEXICO

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 29 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1901.	1182.	2647.	1645.	4075.	5464.	35695.	3139.	12270.	2673.	1827.	48.2	66.6
6	50.	31.	70.	44.	83.	111.	726.	34.	134.	29.	20.	89.8	124.2
8	686.	427.	956.	594.	2066.	2770.	18095.	940.	3673.	800.	547.	81.6	112.9
10	153.	95.	213.	132.	892.	1196.	7815.	464.	1813.	395.	270.	71.4	98.8
12	100.	62.	139.	86.	17.	23.	152.	73.	283.	62.	42.	8.9	12.3
14	138.	86.	193.	120.	789.	1059.	6915.	565.	2208.	481.	329.	51.8	71.7
16	773.	481.	1077.	669.	227.	305.	1991.	1064.	4159.	906.	619.	7.9	11.0

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NEW YORK

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 2 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	169.	105.	186.	116.	373.	500.	3266.	234.	914.	199.	136.	59.2	81.9
6	51.	32.	56.	35.	37.	50.	324.	20.	79.	17.	12.	68.0	94.0
12	119.	74.	130.	81.	336.	450.	2942.	214.	835.	182.	124.	58.3	80.7

Table B.1. (Continued)

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NORTH DAKOTA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 20 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1518.	944.	1529.	950.	3438.	4611.	30119.	4068.	15897.	3463.	2367.	31.4	43.4
6	358.	223.	360.	224.	553.	741.	4841.	211.	825.	180.	123.	97.1	134.4
10	144.	89.	145.	90.	197.	264.	1722.	150.	585.	127.	87.	48.7	67.5
12	291.	181.	293.	182.	597.	801.	5233.	489.	1911.	416.	285.	45.3	62.7
16	538.	334.	542.	337.	208.	279.	1825.	606.	2368.	516.	353.	12.8	17.7
18	62.	39.	63.	39.	447.	599.	3913.	377.	1474.	321.	219.	44.0	60.9
26	62.	39.	63.	39.	628.	842.	5499.	811.	3168.	690.	472.	28.7	39.8
34	62.	39.	63.	39.	809.	1085.	7087.	1424.	5566.	1213.	829.	21.1	29.2

35

OHIO

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 16 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1303.	810.	1457.	906.	12981.	17403.	113716.	6567.	25666.	5592.	3822.	73.4	101.5
4	104.	64.	116.	72.	140.	187.	1222.	34.	131.	29.	20.	154.4	213.6
6	117.	72.	130.	81.	222.	298.	1946.	85.	331.	72.	49.	97.2	134.5
8	194.	121.	217.	135.	585.	785.	5129.	264.	1031.	225.	154.	82.4	114.0
12	425.	264.	476.	296.	1300.	1744.	11390.	874.	3417.	744.	509.	55.2	76.4
20	291.	181.	325.	202.	7788.	10443.	68223.	3101.	12120.	2641.	1805.	93.2	129.0
22	173.	107.	193.	120.	2946.	3951.	25809.	2209.	8635.	1881.	1286.	43.5	63.5

Table B.1. (Continued)

36

OKLAHOMA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 157 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	9323.	5800.	10284.	6390.	48467.	64995.	424570.	30083.	117574.	25615.	17508.	59.8	82.7
4	57.	35.	63.	39.	15.	21.	135.	6.	22.	5.	3.	103.7	143.5
6	711.	442.	736.	457.	1547.	2075.	13556.	465.	1817.	396.	271.	123.5	170.9
8	3835.	2385.	4228.	2627.	9818.	13166.	86006.	4121.	16107.	3509.	2399.	88.4	122.3
10	1833.	1139.	2019.	1255.	12030.	16133.	105383.	4304.	16822.	3665.	2505.	103.7	143.5
12	982.	610.	1082.	673.	3682.	4937.	32252.	2742.	10716.	2335.	1596.	49.9	69.0
16	863.	536.	974.	605.	8118.	10886.	71113.	5238.	20473.	4460.	3049.	57.5	79.6
18	42.	26.	47.	29.	290.	388.	2538.	293.	1146.	250.	171.	36.6	50.7
20	121.	75.	134.	83.	997.	1337.	8733.	1050.	4102.	894.	611.	35.2	48.8
22	206.	128.	227.	141.	3602.	4830.	31550.	2607.	10190.	2220.	1517.	51.3	70.9
24	355.	221.	392.	243.	6039.	8098.	52900.	5158.	20159.	4392.	3002.	43.4	60.1
30	304.	189.	335.	208.	2329.	3124.	20404.	4099.	16021.	3490.	2386.	21.1	29.2

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PENNSYLVANIA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 1 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	53.	33.	53.	33.	137.	184.	1199.	87.	340.	74.	51.	58.4	80.8
12	53.	33.	53.	33.	137.	184.	1199.	87.	340.	74.	51.	58.4	80.8

42

TENNESSEE

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 2 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	727.	452.	738.	458.	31468.	42199.	275657.	29512.	115343.	25129.	17176.	39.6	54.8
22	257.	160.	261.	162.	6189.	8300.	54219.	3771.	14736.	3211.	2194.	60.9	84.3
40	470.	292.	476.	296.	25278.	33899.	221438.	25742.	100607.	21918.	14981.	36.4	50.4

Table B.1. (Continued)

47

WASHINGTON STATE

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 5 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	130.	81.	130.	81.	188.	252.	1649.	228.	892.	194.	133.	30.6	42.3
16	39.	24.	39.	24.	16.	22.	141.	16.	62.	13.	9.	37.8	52.3
20	77.	48.	77.	48.	45.	60.	393.	51.	199.	43.	30.	32.7	45.3
24	14.	9.	14.	9.	127.	171.	1114.	162.	631.	138.	94.	29.2	40.4

48

WEST VIRGINIA

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 20 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	893.	555.	893.	555.	2211.	2964.	19365.	633.	2494.	543.	371.	123.6	177.9
4	63.	39.	63.	39.	104.	140.	912.	20.	80.	17.	12.	189.6	262.3
6	830.	516.	830.	516.	2106.	2825.	18453.	618.	2414.	526.	359.	126.6	175.1

49

WISCONSIN

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 5 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	777.	483.	778.	483.	17294.	23191.	151494.	19185.	74982.	16335.	11166.	33.5	46.3
18	29.	18.	29.	18.	206.	276.	1806.	174.	680.	148.	101.	44.0	60.8
26	29.	18.	29.	18.	290.	389.	2539.	374.	1462.	319.	218.	28.7	39.8
30	145.	90.	145.	90.	3045.	4084.	26676.	3090.	12036.	2622.	1792.	36.7	50.8
34	574.	357.	575.	357.	13753.	18443.	120475.	15558.	60804.	13247.	9054.	32.8	45.4

Table B.1. (Continued)

50

WYOMING

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 107 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	6094.	3789.	6696.	4155.	14303.	19180.	125293.	10577	41337.	9006.	6155.	50.2	69.4
4	211.	131.	232.	144.	275.	368.	2406.	62.	244.	53.	36.	163.4	226.1
6	866.	538.	950.	590.	1138.	1526.	9971.	461.	1801.	392.	268.	91.6	126.8
8	2355.	1464.	2584.	1605.	4922.	6601.	43121.	2331.	9109.	1984.	1356.	78.4	109.5
10	405.	252.	444.	276.	1008.	1352.	8834.	726.	2837.	618.	423.	51.5	71.3
12	1051.	654.	1153.	717.	3196.	4286.	27996.	2343.	9157.	1995.	1364.	50.6	70.0
14	81.	50.	89.	55.	247.	331.	2165.	198.	774.	169.	115.	46.3	64.1
16	657.	408.	721.	448.	1662.	2228.	14555.	1978.	7730.	1684.	1151.	31.2	43.1
20	468.	291.	514.	319.	1954.	2487.	16244.	2478.	9685.	2110.	1442.	27.8	38.4

Table B.2. Products pipeline flow and pumping energy by state by pipe diameter

1

ALABAMA

DENSITY - - 751.35 KG/CU-M 46.91 LB/CU-FT 23 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	2239.	1392.	2235.	1389.	23738.	31833.	207946.	29547.	115479.	22249.	15207.	33.7	46.7
6	65.	41.	65.	41.	88.	118.	770.	54.	210.	40.	28.	68.7	95.1
8	135.	84.	135.	84.	249.	334.	2183.	142.	553.	107.	73.	73.9	102.2
10	55.	34.	54.	34.	150.	201.	1316.	121.	471.	91.	62.	52.3	72.3
12	627.	390.	626.	389.	2424.	3251.	21235.	1923.	7517.	1448.	990.	52.9	73.2
18	464.	289.	463.	288.	2506.	3361.	21956.	2319.	9064.	1746.	1194.	45.4	62.9
30	305.	189.	304.	189.	3500.	4693.	30659.	4825.	18856.	3633.	2483.	30.4	42.1
36	588.	365.	587.	365.	14821.	19875.	129828.	20164.	78808.	15183.	10378.	30.8	42.7

3

ARIZONA

DENSITY - - 752.76 KG/CU-M 46.99 LB/CU-FT 13 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1235.	768.	1351.	840.	3878.	5200.	33968.	2386.	9326.	1800.	1230.	68.1	94.2
6	297.	184.	324.	202.	382.	513.	3351.	212.	829.	160.	109.	75.6	104.6
8	503.	313.	551.	342.	600.	804.	5255.	525.	2053.	396.	271.	47.8	66.2
12	435.	271.	476.	296.	2895.	3883.	25363.	1649.	6445.	1244.	850.	73.5	101.8

4

ARKANSAS

DENSITY - - 783.20 KG/CU-M 48.89 LB/CU-FT 10 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1375.	855.	1709.	1062.	8151.	10931.	71403.	5873.	22953.	4610.	3151.	55.9	77.3
6	27.	17.	34.	21.	29.	39.	253.	17.	66.	13.	9.	68.8	95.2
8	69.	43.	86.	53.	56.	75.	492.	56.	218.	44.	30.	40.5	56.1
10	418.	260.	520.	323.	331.	444.	2898.	487.	1904.	382.	261.	27.3	37.8
12	342.	213.	425.	264.	763.	1023.	6682.	835.	3265.	656.	448.	36.8	50.9
20	519.	323.	645.	401.	6972.	9350.	61078.	4477.	17499.	3514.	2402.	62.7	86.7

Table B.2. (Continued)

5

CALIFORNIA

DENSITY - - 763.32 KG/CU-M 47.65 LB/CU-FT 56 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	3440.	2139.	3591.	2232.	11874.	15924.	104019.	6805.	26594.	5205.	3558.	72.1	99.7
4	201.	125.	210.	130.	127.	170.	1109.	38.	150.	29.	20.	136.6	189.0
6	399.	248.	417.	259.	667.	895.	5844.	253.	937.	193.	132.	109.2	151.0
8	1209.	752.	1262.	784.	1951.	2617.	17095.	1378.	5385.	1054.	720.	58.5	80.9
10	677.	421.	707.	439.	4491.	6023.	39345.	1853.	7242.	1418.	969.	100.1	138.5
12	456.	283.	476.	296.	3849.	5161.	33712.	1960.	7659.	1499.	1025.	81.1	112.2
14	383.	238.	400.	248.	615.	824.	5384.	985.	3849.	753.	515.	25.8	35.7
16	66.	41.	69.	43.	145.	194.	1267.	259.	1012.	198.	135.	23.1	31.9
24	20.	13.	21.	13.	5.	7.	45.	74.	288.	56.	39.	2.9	4.0

6

COLORADO

DENSITY - - 773.95 KG/CU-M 48.32 LB/CU-FT 10 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1544.	960.	1667.	1036.	3660.	4908.	32064.	2336.	9131.	1812.	1233.	63.8	88.3
6	134.	83.	145.	90.	253.	339.	2216.	108.	423.	84.	57.	95.3	131.9
8	692.	430.	747.	464.	568.	762.	4973.	330.	1433.	234.	201.	61.0	84.4
10	718.	446.	775.	481.	2839.	3807.	24969.	1849.	7225.	1434.	930.	62.6	86.6

7

CONNECTICUT

DENSITY - - 802.48 KG/CU-M 50.10 LB/CU-FT 2 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	135.	84.	192.	119.	230.	309.	2018.	201.	734.	161.	110.	45.1	62.4
6	24.	15.	34.	21.	16.	21.	137.	36.	62.	13.	9.	38.8	53.6
12	111.	69.	158.	98.	215.	288.	1881.	185.	722.	149.	102.	45.7	63.2

Table B.2. (Continued)

9

FLORIDA

DENSITY - - 791.31 KG/CU-M 49.40 LB/CU-FT 3 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	256.	159.	256.	159.	826.	1107.	7232.	532.	2079.	422.	288.	61.8	85.6
6	39.	24.	39.	24.	67.	90.	591.	29.	113.	23.	16.	93.2	129.0
10	217.	135.	217.	135.	759.	1017.	6641.	503.	1967.	399.	273.	60.0	83.1

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GEORGIA

DENSITY - - 755.26 KG/CU-M 47.15 LB/CU-FT 35 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	3078.	1914.	3059.	1901.	29000.	38890.	254043.	27268.	106571.	20639.	14137.	44.4	61.4
4	29.	18.	29.	18.	30.	40.	262.	9.	35.	7.	5.	137.7	190.5
6	331.	206.	329.	204.	434.	582.	3805.	260.	1016.	197.	134.	69.3	96.5
8	1048.	652.	1041.	647.	2615.	3507.	22911.	1376.	5380.	1042.	712.	79.3	109.8
10	344.	214.	341.	212.	974.	1307.	8536.	650.	2542.	492.	336.	62.6	86.6
12	296.	184.	294.	183.	6749.	9051.	59123.	1470.	5746.	1113.	761.	191.6	265.2
14	233.	145.	232.	144.	906.	1215.	7937.	669.	2616.	507.	346.	56.5	78.2
18	24.	15.	24.	15.	142.	190.	1240.	124.	484.	94.	64.	47.7	66.1
26	233.	145.	232.	144.	2185.	2931.	19145.	2705.	10572.	2048.	1399.	33.7	46.7
30	24.	15.	24.	15.	292.	392.	2560.	389.	1519.	294.	201.	31.4	43.4
36	328.	204.	326.	203.	9259.	12417.	81113.	11587.	45285.	8770.	5994.	33.4	46.2
40	187.	117.	186.	116.	5412.	7258.	47412.	8028.	31377.	6077.	4153.	28.1	38.9

12

IDAHO

DENSITY - - 771.30 KG/CU-M 48.15 LB/CU-FT 9 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	897.	558.	907.	563.	2256.	3026.	19766.	1218.	4762.	942.	644.	75.7	104.8
8	836.	520.	845.	525.	1984.	2661.	17383.	1068.	4176.	826.	565.	75.9	105.1
10	61.	38.	62.	38.	272.	365.	2384.	150.	586.	116.	79.	74.2	102.7

Table B. 2. (Continued)

13

ILLINOIS

DENSITY - - 740.82 KG/CU-M 46.25 LB/CU-FT 90 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	6174.	3839.	7083.	4401.	22201.	29772.	194481.	15959.	62374.	11849.	8099.	59.2	81.9
6	440.	273.	505.	314.	997.	1336.	8730.	341.	1333.	253.	173.	124.3	172.1
8	2110.	1312.	2420.	1504.	5320.	7134.	46601.	2927.	11438.	2173.	1485.	77.4	107.0
10	1200.	746.	1377.	856.	5464.	7327.	47862.	2783.	10877.	2066.	1412.	83.5	115.6
12	1173.	729.	1346.	836.	4017.	5387.	35191.	3376.	13195.	2507.	1713.	50.6	70.1
14	456.	284.	523.	325.	825.	1107.	7229.	709.	2770.	526.	360.	40.6	63.6
16	181.	112.	207.	129.	1085.	1455.	9502.	984.	3844.	730.	499.	46.9	64.9
20	251.	156.	287.	179.	1501.	2013.	13147.	1553.	6070.	1153.	788.	41.1	56.9
24	364.	226.	417.	259.	2993.	4014.	26213.	3287.	12846.	2440.	1669.	38.8	53.6

14

INDIANA

DENSITY - - 759.22 KG/CU-M 47.40 LB/CU-FT 76 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	4249.	2642.	4696.	2918.	11179.	14992.	97931.	8972.	35066.	6827.	4666.	51.7	71.6
4	4.	3.	5.	3.	2.	3.	19.	1.	4.	1.	1.	86.0	119.0
6	196.	122.	217.	135.	342.	459.	2996.	107.	418.	81.	56.	132.7	183.6
8	1593.	990.	1760.	1094.	2244.	3009.	19658.	1448.	5660.	1102.	753.	64.3	89.0
10	1047.	651.	1157.	719.	3173.	4255.	27793.	2224.	8691.	1692.	1156.	59.3	82.0
12	408.	254.	451.	281.	842.	1130.	7378.	696.	2722.	530.	362.	50.2	69.5
14	397.	247.	438.	272.	1075.	1442.	9419.	970.	3789.	739.	504.	46.1	63.7
16	240.	149.	265.	165.	1543.	2070.	13521.	1410.	5510.	1071.	733.	45.5	62.9
20	363.	226.	402.	249.	1957.	2625.	17147.	2116.	8271.	1610.	1101.	38.4	53.2

15

IOWA

DENSITY - - 729.35 KG/CU-M 45.47 LB/CU-FT 83 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	5713.	3552.	6156.	3825.	16645.	22322.	145813.	8226.	32150.	6004.	4104.	87.6	121.2
4	52.	33.	56.	35.	16.	21.	137.	7.	28.	5.	4.	94.2	130.4
6	1736.	1079.	1871.	1163.	1824.	2446.	15978.	919.	3594.	671.	459.	85.9	118.8
8	1932.	1201.	2082.	1294.	6881.	9227.	60274.	2718.	10624.	1984.	1356.	109.6	151.6
10	696.	433.	750.	466.	4729.	6342.	41429.	1890.	7385.	1379.	943.	108.3	149.9
12	1174.	730.	1265.	786.	2774.	3720.	24302.	2269.	8868.	1656.	1132.	52.9	73.2
16	122.	76.	131.	82.	422.	565.	3694.	422.	1651.	308.	211.	43.2	59.8

Table B.2. (Continued)

16

KANSAS

DENSITY - - 725.43 KG/CU-M 45.29 LB/CU-FT 108 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	9467.	5836.	10179.	6325.	35744.	47934.	313119.	17328.	67723.	12598.	8611.	89.7	124.1
4	386.	240.	415.	258.	367.	493.	3219.	112.	438.	81.	56.	142.5	197.2
6	2092.	1301.	2250.	1398.	5054.	6777.	44270.	1692.	6612.	1230.	841.	129.8	179.7
8	3423.	2128.	3681.	2287.	11187.	15002.	98000.	4861.	19000.	3534.	2416.	100.0	138.4
10	2044.	1271.	2198.	1365.	8154.	10935.	71428.	4854.	18973.	3529.	2412.	73.0	101.0
12	1155.	718.	1242.	772.	9496.	12734.	83184.	4465.	17449.	3246.	2219.	92.4	127.9
16	367.	228.	394.	245.	1486.	1993.	13017.	1344.	5252.	977.	668.	48.1	66.5

17

KENTUCKY

DENSITY - - 791.31 KG/CU-M 49.40 LB/CU-FT 3 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	227.	141.	227.	141.	496.	666.	4348.	261.	1021.	207.	142.	75.7	104.7
8	174.	108.	174.	108.	423.	567.	3707.	234.	916.	186.	127.	71.9	99.5

18

LOUISIANA

DENSITY - - 755.80 KG/CU-M 47.18 LB/CU-FT 39 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	3701.	2301.	3912.	2431.	39976.	53609.	350190.	35162.	137423.	25633.	18204.	47.4	65.6
4	126.	79.	134.	83.	59.	79.	513.	19.	75.	15.	10.	126.6	175.2
6	398.	248.	421.	261.	422.	566.	3699.	206.	804.	156.	107.	85.6	118.4
8	757.	471.	800.	497.	722.	968.	6320.	577.	2254.	437.	299.	52.2	72.2
10	486.	302.	514.	319.	1701.	2281.	14903.	1249.	4882.	946.	647.	56.8	78.6
12	348.	216.	368.	229.	1156.	1551.	10130.	864.	3377.	654.	447.	55.9	77.3
16	476.	296.	503.	313.	3950.	5298.	34605.	3021.	11809.	2289.	1560.	54.5	75.5
18	164.	102.	174.	108.	1422.	1908.	12461.	1041.	4070.	789.	539.	57.0	78.8
20	358.	222.	378.	235.	3643.	4886.	31914.	2507.	9797.	1899.	1298.	60.6	83.9
36	587.	365.	621.	386.	26903.	36074.	235645.	25677.	100356.	19449.	13294.	43.7	60.5

Table B.2. (Continued)

19

MAINE

DENSITY - - 791.31 KG/CU-M 49.40 LB/CU-FT 1 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	217.	135.	217.	135.	363.	487.	3181.	160.	624.	127.	87.	90.6	125.3
6	217.	135.	217.	135.	363.	487.	3181.	160.	624.	127.	87.	90.6	125.3

20

MARYLAND

DENSITY - - 762.22 KG/CU-M 47.58 LB/CU-FT 9 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	352.	219.	340.	211.	11381.	15263.	99701.	6346.	24804.	4848.	3314.	74.2	102.6
6	77.	48.	74.	46.	121.	162.	1058.	56.	218.	43.	29.	89.7	124.1
8	53.	33.	51.	32.	178.	239.	1559.	77.	299.	59.	40.	96.1	133.0
12	53.	33.	51.	32.	214.	287.	1875.	176.	687.	134.	92.	50.4	69.7
30	111.	69.	107.	67.	6315.	8469.	55324.	3667.	14331.	2801.	1914.	71.2	98.6
32	58.	36.	56.	35.	4553.	6106.	39885.	2372.	9269.	1812.	1238.	79.4	109.9

21

MASSACHUSETTS

DENSITY - - 772.84 KG/CU-M 48.25 LB/CU-FT 12 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	347.	216.	350.	218.	554.	743.	4853.	190.	742.	147.	101.	119.0	164.6
4	38.	24.	39.	24.	40.	54.	349.	12.	47.	9.	6.	134.5	186.2
6	297.	185.	299.	186.	489.	656.	4283.	162.	634.	126.	86.	123.0	170.1
8	5.	3.	5.	3.	17.	23.	149.	8.	29.	6.	4.	92.5	128.0
12	7.	5.	8.	5.	9.	11.	70.	9.	32.	6.	4.	40.5	56.1

Table B. 2. (Continued)

22

MICHIGAN

DENSITY - - 746.83 KG/CU-M 46.75 LB/CU-FT 40 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	2432.	1512.	2575.	1600.	9749.	13073.	85400.	5234.	20455.	3928.	2685.	78.4	108.5
6	634.	394.	671.	417.	1184.	1588.	10375.	395.	1542.	296.	202.	126.4	174.9
8	737.	458.	780.	485.	1761.	2361.	15426.	834.	3456.	664.	454.	83.8	116.0
10	532.	331.	564.	350.	718.	963.	6289.	690.	2696.	518.	354.	43.8	60.6
12	166.	103.	176.	109.	498.	668.	4363.	407.	1592.	306.	209.	51.5	71.2
16	330.	205.	349.	217.	5418.	7266.	47461.	2685.	10495.	2015.	1377.	84.9	117.5
18	33.	20.	35.	21.	170.	228.	1486.	172.	674.	129.	88.	41.4	57.3

23

MINNESOTA

DENSITY - - 708.39 KG/CU-M 44.22 LB/CU-FT 31 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	2721.	1692.	2908.	1807.	3293.	4415.	28843.	2462.	9623.	1748.	1195.	59.5	82.4
6	635.	395.	679.	422.	482.	647.	4227.	288.	1127.	205.	140.	74.4	103.0
8	1446.	900.	1547.	962.	2019.	2707.	17684.	1263.	4935.	896.	613.	71.2	98.5
10	231.	144.	247.	154.	302.	405.	2648.	237.	926.	168.	115.	56.8	78.6
12	407.	253.	435.	270.	489.	656.	4284.	674.	2633.	478.	327.	32.3	44.7

24

MISSISSIPPI

DENSITY - - 739.00 KG/CU-M 46.13 LB/CU-FT 17 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	2350.	1461.	5470.	3399.	35689.	47860.	312637.	40235.	157251.	29798.	20387.	37.8	52.4
12	364.	226.	848.	527.	3164.	4244.	27720.	2370.	9261.	1755.	1199.	57.0	78.8
16	50.	31.	115.	72.	439.	589.	3845.	473.	1848.	350.	239.	39.6	54.8
18	228.	142.	531.	330.	3391.	4548.	29707.	2850.	11137.	2110.	1443.	50.8	70.3
20	1410.	876.	3281.	2039.	10227.	13715.	89593.	12379.	48379.	9168.	6266.	35.2	48.8
30	66.	41.	154.	96.	1624.	2178.	14229.	2386.	9325.	1767.	1208.	29.0	40.2
36	232.	144.	540.	336.	16843.	22587.	147547.	19779.	77301.	14648.	10012.	36.3	50.3

Table B.2. (Continued)

25

MISSOURI

DENSITY - - 739.25 KG/CU-M 46.15 LB/CU-FT 35 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	5668.	3524.	6170.	3834.	14258.	19120.	124898.	12660.	49478.	9379.	6411.	48.0	66.5
6	152.	95.	166.	103.	114.	152.	995.	73.	285.	54.	37.	66.4	91.9
8	2169.	1348.	2361.	1467.	3295.	4419.	28866.	2084.	8144.	1544.	1055.	67.4	93.3
10	1780.	1107.	1939.	1204.	3576.	4796.	31330.	2909.	11367.	2155.	1473.	52.4	72.6
12	799.	497.	870.	540.	2602.	3489.	22794.	2262.	8841.	1676.	1146.	49.1	67.9
16	93.	58.	101.	63.	324.	435.	2841.	325.	1270.	241.	165.	42.6	58.9
20	145.	90.	158.	98.	825.	1106.	7226.	854.	3336.	632.	432.	41.2	57.0
24	503.	313.	547.	340.	3514.	4713.	30785.	4151.	16223.	3075.	2102.	36.1	50.0

26

MONTANA

DENSITY - - 762.05 KG/CU-M 47.57 LB/CU-FT 8 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1472.	915.	1602.	995.	4681.	6277.	41005.	2690.	10513.	2054.	1404.	72.0	99.6
6	204.	127.	222.	138.	307.	412.	2691.	155.	606.	118.	81.	82.0	113.5
8	565.	352.	615.	382.	1010.	1355.	8848.	681.	2663.	520.	356.	61.3	84.9
10	702.	437.	765.	475.	3364.	4511.	29465.	1854.	7245.	1416.	968.	75.1	103.9

27

NEBRASKA

DENSITY - - 753.47 KG/CU-M 47.04 LB/CU-FT 34 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	2893.	1799.	2920.	1815.	6924.	9285.	60654.	3267.	12768.	2467.	1686.	88.7	122.7
6	1248.	776.	1259.	783.	2639.	3539.	23120.	902.	3524.	681.	465.	122.5	169.5
8	1344.	835.	1356.	843.	3106.	4165.	27208.	1656.	6474.	1251.	855.	78.5	108.6
10	72.	45.	72.	45.	501.	672.	4388.	202.	789.	153.	104.	103.8	143.6
12	230.	143.	232.	144.	678.	909.	5938.	507.	1981.	383.	262.	56.0	77.4

Table B.2. (Continued)

29

NEVADA

DENSITY - - 770.35 KG/CU-M 48.09 LB/CU-FT 6 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	275.	171.	286.	178.	511.	686.	4480.	319.	1245.	246.	168.	65.7	90.9
6	136.	84.	141.	88.	338.	454.	2964.	115.	451.	99.	61.	120.0	166.1
8	79.	49.	82.	51.	136.	182.	1188.	78.	306.	60.	41.	70.9	98.2
14	60.	38.	63.	39.	37.	50.	328.	125.	489.	97.	66.	12.3	17.0

30

NEW JERSEY

DENSITY - - 765.45 KG/CU-M 47.79 LB/CU-FT 40 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	938.	583.	1055.	655.	8927.	11971.	78197.	6779.	26493.	5200.	3554.	54.2	75.1
4	21.	13.	24.	15.	12.	16.	101.	5.	20.	4.	3.	94.2	130.4
6	354.	220.	399.	248.	532.	714.	4665.	164.	641.	126.	86.	133.8	185.1
8	54.	33.	61.	38.	144.	193.	1258.	84.	329.	65.	44.	70.2	97.2
12	30.	19.	34.	21.	150.	201.	1316.	116.	453.	39.	61.	53.4	73.9
14	90.	56.	101.	63.	590.	792.	5171.	349.	1363.	267.	183.	69.7	96.5
16	199.	124.	224.	139.	1873.	2512.	16406.	1265.	4946.	971.	663.	61.0	84.4
20	44.	27.	49.	31.	213.	286.	1867.	279.	1098.	214.	146.	31.5	43.6
30	145.	90.	163.	101.	5412.	7258.	47413.	4517.	17654.	3465.	2368.	49.4	68.3

31

NEW MEXICO

DENSITY - - 770.50 KG/CU-M 48.10 LB/CU-FT 13 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	2393.	1488.	2584.	1605.	4676.	6271.	40964.	2579.	10081.	1992.	1361.	74.2	102.7
4	94.	58.	101.	63.	105.	140.	917.	32.	124.	25.	17.	134.9	186.7
6	1162.	723.	1255.	780.	2413.	3236.	21141.	799.	3124.	617.	422.	123.5	170.9
8	877.	545.	947.	588.	1867.	2503.	16353.	1163.	4546.	898.	614.	65.7	90.9
12	260.	162.	281.	174.	291.	391.	2553.	595.	2236.	452.	309.	20.4	28.2

Table B.2. (Continued)

32

NEW YORK

DENSITY - - 757.89 KG/CU-M 47.31 LB/CU-FT 40 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	2076.	1291.	2426.	1508.	6219.	8339.	54471.	2716.	10614.	2063.	1412.	95.3	131.8
4	25.	15.	29.	18.	41.	55.	362.	10.	40.	8.	5.	169.2	234.1
6	767.	477.	897.	557.	1880.	2521.	16471.	617.	2413.	469.	321.	126.7	175.3
8	863.	537.	1009.	627.	2547.	3416.	22311.	1046.	4089.	795.	543.	101.3	140.1
10	317.	197.	370.	230.	1194.	1602.	10464.	659.	2575.	500.	342.	75.4	104.4
12	3.	2.	3.	2.	14.	19.	125.	11.	43.	8.	6.	53.9	74.7
14	101.	63.	119.	74.	541.	725.	4738.	372.	1456.	283.	193.	60.5	83.7

33

NORTH CAROLINA

DENSITY - - 760.56 KG/CU-M 47.48 LB/CU-FT 22 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1824.	1134.	1794.	1115.	19401.	26017.	169949.	20297.	79326.	15470.	10574.	39.6	54.8
6	219.	136.	215.	134.	310.	416.	2716.	171.	669.	130.	89.	75.1	103.9
8	390.	242.	384.	238.	908.	1218.	7959.	522.	2033.	398.	272.	72.2	99.9
10	186.	116.	183.	114.	457.	613.	4003.	287.	1123.	219.	150.	65.9	91.2
14	270.	168.	266.	165.	1123.	1505.	9834.	798.	3120.	609.	416.	58.3	80.7
16	175.	109.	172.	107.	1912.	2564.	16748.	1170.	4571.	891.	609.	67.8	93.8
26	186.	116.	183.	114.	1586.	2127.	13896.	2085.	8149.	1589.	1086.	31.5	43.6
32	47.	29.	47.	29.	3794.	5088.	33238.	1976.	7724.	1506.	1030.	79.6	110.1
36	175.	109.	172.	107.	4304.	5771.	37703.	5961.	22907.	4467.	3054.	30.4	42.1
40	175.	109.	172.	107.	5006.	6714.	43856.	7426.	29023.	5660.	3869.	27.9	38.7

34

NORTH DAKOTA

DENSITY - - 738.99 KG/CU-M 46.13 LB/CU-FT 5 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	762.	474.	797.	495.	1761.	2361.	15424.	958.	3746.	710.	485.	78.4	108.5
6	217.	135.	227.	141.	573.	768.	5018.	164.	641.	121.	83.	149.0	206.2
8	209.	129.	217.	135.	554.	743.	4855.	302.	1180.	224.	153.	73.3	101.4
10	337.	210.	352.	219.	634.	850.	5551.	492.	1924.	365.	249.	54.9	76.0

Table B.2. (Continued)

35

OHIO

DENSITY - - 761.86 KG/CU-M 47.56 LB/CU-FT 132 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (BILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	5878.	3655.	6320.	3927.	10978.	14722.	96167.	7969.	31143.	6084.	4158.	57.0	78.9
4	71.	44.	76.	47.	28.	38.	249.	13.	50.	10.	7.	91.1	126.1
6	1271.	790.	1367.	849.	1777.	2383.	15569.	740.	2892.	565.	386.	99.4	137.5
8	2135.	1328.	2296.	1426.	4461.	5982.	39079.	2502.	9777.	1910.	1306.	73.8	102.1
10	1244.	773.	1337.	831.	2611.	3502.	22875.	2160.	8443.	1649.	1127.	50.0	69.2
12	764.	475.	822.	511.	1346.	1805.	11791.	1453.	5679.	1109.	758.	38.3	53.0
14	115.	72.	124.	77.	125.	168.	1097.	157.	613.	120.	82.	33.0	45.7
16	119.	74.	128.	80.	259.	347.	2266.	381.	1489.	291.	199.	28.1	38.9
20	127.	79.	137.	85.	324.	434.	2834.	546.	2132.	417.	285.	24.5	34.0

36

OKLAHOMA

DENSITY - - 731.76 KG/CU-M 45.68 LB/CU-FT 75 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (BILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	5743.	3571.	6114.	3799.	18104.	24278.	158590.	11894.	46484.	8722.	5962.	65.6	90.8
4	182.	113.	194.	120.	238.	320.	2088.	63.	248.	46.	32.	162.2	224.4
6	1408.	876.	1499.	932.	2156.	2891.	19385.	847.	3310.	621.	425.	109.7	151.8
8	1960.	1156.	1980.	1230.	5571.	7470.	49799.	2262.	8841.	1659.	1134.	106.1	146.8
10	985.	612.	1048.	651.	3071.	4119.	26905.	1790.	6994.	1312.	897.	73.9	102.3
12	781.	486.	831.	517.	3713.	4979.	32522.	2297.	8978.	1685.	1151.	69.6	96.4
16	47.	30.	51.	31.	162.	217.	1421.	162.	635.	119.	81.	43.0	59.5
24	194.	121.	207.	129.	1315.	1763.	11517.	1563.	6107.	1146.	783.	36.2	50.2
28	286.	178.	304.	189.	1878.	2519.	16453.	2909.	11371.	2134.	1458.	27.8	38.5

37

OREGON

DENSITY - - 760.65 KG/CU-M 47.49 LB/CU-FT 10 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (BILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	704.	438.	724.	450.	795.	1066.	6965.	569.	2225.	434.	297.	57.9	80.1
6	75.	47.	77.	48.	27.	36.	232.	32.	126.	25.	17.	34.1	47.2
8	624.	388.	641.	398.	744.	997.	6514.	516.	2016.	393.	269.	59.7	82.7
14	5.	3.	5.	3.	25.	34.	220.	21.	82.	16.	11.	49.4	69.3

Table B.2. (Continued)

38

PENNSYLVANIA

DENSITY - - 757.20 KG/CU-M 47.27 LB/CU-FT 105 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (BILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	6586.	4095.	6892.	4282.	16735.	22442.	146598.	11357.	44387.	8618.	5891.	61.3	84.9
4	45.	28.	47.	29.	14.	19.	124.	7.	28.	5.	4.	83.6	115.7
6	2323.	1444.	2431.	1510.	1459.	1957.	12783.	843.	3296.	640.	437.	72.0	99.7
8	2144.	1333.	2243.	1394.	4747.	6365.	41580.	2248.	8787.	1706.	1166.	87.9	121.6
10	439.	273.	459.	285.	1311.	1758.	11487.	849.	3317.	644.	440.	64.3	89.0
12	268.	167.	281.	174.	997.	1337.	8732.	689.	2692.	523.	357.	60.3	83.4
14	572.	356.	599.	372.	1594.	2137.	13962.	1320.	5159.	1002.	685.	50.3	69.6
16	184.	114.	193.	120.	645.	865.	5651.	680.	2658.	516.	353.	39.5	54.6
18	152.	94.	159.	99.	350.	470.	3070.	435.	1701.	330.	226.	33.5	46.4
20	199.	124.	208.	129.	597.	801.	5233.	790.	3088.	599.	410.	31.5	43.6
24	198.	123.	207.	129.	1119.	1500.	9799.	1255.	4904.	952.	651.	37.1	51.4
30	62.	39.	65.	41.	3902.	5232.	34177.	2241.	8757.	1700.	1162.	72.5	100.3

39

RHODE ISLAND

DENSITY - - 791.31 KG/CU-M 49.40 LB/CU-FT 17 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (BILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	77.	48.	77.	48.	253.	339.	2215.	50.	197.	40.	27.	199.6	276.2
6	39.	24.	39.	24.	225.	302.	1972.	44.	172.	35.	24.	204.4	282.8

40

SOUTH CAROLINA

DENSITY - - 756.83 KG/CU-M 47.25 LB/CU-FT 15 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (BILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1433.	891.	1422.	883.	14056.	18849.	123127.	18111.	70782.	13737.	9337.	32.3	44.7
8	400.	248.	396.	246.	849.	1139.	7439.	585.	2286.	444.	303.	60.5	83.7
10	185.	115.	183.	114.	457.	613.	4003.	287.	1123.	218.	149.	65.2	91.7
14	185.	115.	183.	114.	658.	882.	5764.	516.	2017.	391.	267.	53.1	73.5
16	113.	70.	112.	69.	692.	928.	6059.	632.	2470.	479.	324.	45.6	63.1
26	185.	115.	183.	114.	1586.	2127.	13897.	2085.	8149.	1581.	1087.	31.7	43.9
36	183.	114.	182.	113.	4536.	6083.	39738.	6178.	24145.	4686.	3203.	30.6	42.3
40	183.	114.	182.	113.	5277.	7077.	46227.	7927.	30592.	5937.	4059.	28.1	38.9

Table B.2. (Continued)

41

SOUTH DAKOTA

DENSITY - - 734.66 KG/CU-M 45.86 LB/CU-FT 14 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1158.	720.	1242.	772.	1279.	1713.	11191.	760.	2971.	560.	383.	72.1	99.8
6	1007.	626.	1080.	671.	1161.	1557.	10174.	621.	2429.	458.	313.	80.2	111.0
8	75.	47.	81.	50.	42.	57.	370.	40.	156.	29.	20.	45.2	62.6
12	75.	47.	81.	50.	74.	99.	648.	99.	386.	73.	50.	32.1	44.5

42

TENNESSEE

DENSITY - - 761.87 KG/CU-M 47.56 LB/CU-FT 12 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	680.	423.	662.	412.	3015.	4044.	26415.	1475.	5765.	1126.	770.	84.6	117.1
8	346.	215.	336.	209.	1067.	1431.	9346.	467.	1824.	356.	244.	94.5	130.9
10	230.	143.	223.	139.	1598.	2143.	13999.	680.	2656.	519.	355.	97.3	134.7
12	105.	65.	102.	64.	350.	470.	3070.	329.	1285.	251.	172.	44.1	61.0

43

TEXAS

DENSITY - - 739.17 KG/CU-M 46.14 LB/CU-FT 323 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	20815.	12942.	23616.	14674.	56877.	76274.	498245.	41177.	160932.	30503.	20849.	58.9	81.5
2	45.	28.	51.	32.	22.	30.	194.	4.	15.	3.	2.	252.2	349.0
4	1558.	969.	1767.	1098.	2298.	3081.	20127.	518.	2024.	384.	262.	189.2	261.8
6	4636.	2882.	5260.	3268.	7275.	9756.	63728.	2818.	11016.	2088.	1427.	110.1	152.3
8	7959.	4948.	9029.	5611.	14540.	19499.	127373.	3155.	31873.	6041.	4129.	76.0	105.2
10	2554.	1588.	2897.	1800.	7565.	10145.	66271.	5158.	20159.	3821.	2612.	62.6	86.6
12	2525.	1570.	2864.	1780.	11264.	15106.	98676.	8248.	32237.	6110.	4176.	53.2	80.6
14	176.	109.	200.	124.	454.	609.	3980.	434.	1697.	322.	220.	44.6	61.8
16	154.	96.	175.	109.	830.	1112.	7267.	652.	2548.	483.	330.	54.3	75.1
18	17.	10.	19.	12.	53.	72.	469.	56.	221.	42.	29.	40.3	55.8
20	176.	109.	200.	124.	754.	1012.	6609.	980.	3832.	726.	496.	32.8	45.4
28	561.	349.	637.	396.	3584.	4807.	31400.	5835.	22806.	4323.	2955.	25.2	35.3
36	183.	114.	208.	129.	8067.	10818.	70666.	8269.	32318.	6126.	4187.	41.6	57.6

Table B.2. (Continued)

43

TEXAS

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 412 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	31224.	19414.	38014.	23621.	180302.	241789.	1579449.	109605.	429370.	93325.	63788.	61.0	84.5
6	812.	505.	989.	614.	2562.	3435.	22440.	703.	2746.	598.	409.	135.3	187.2
8	10329.	6422.	12574.	7813.	26437.	35452.	231584.	12491.	48818.	10635.	7269.	78.5	108.7
10	8000.	4974.	9740.	6052.	44096.	59134.	386284.	17531.	68517.	14927.	10203.	93.3	129.2
12	4819.	2996.	5866.	3645.	23086.	30959.	202235.	13712.	53591.	11675.	7980.	62.5	86.5
16	2586.	1608.	3149.	1956.	18315.	24561.	160441.	13300.	51979.	11324.	7740.	51.1	70.7
18	897.	558.	1092.	679.	5059.	6785.	44321.	4767.	18632.	4059.	2774.	39.4	54.5
20	1539.	957.	1873.	1164.	18934.	25391.	165859.	13870.	54209.	11810.	8072.	50.7	70.1
22	478.	297.	582.	362.	18767.	25167.	164401.	8316.	32503.	7081.	4840.	83.7	115.9
24	675.	420.	822.	511.	8412.	11280.	73686.	9254.	36167.	7879.	5386.	33.7	46.7
26	685.	426.	834.	518.	11113.	14903.	97350.	9708.	37943.	8266.	5650.	42.5	58.8
30	391.	243.	476.	296.	3516.	4715.	30801.	5951.	23259.	5067.	3464.	21.9	30.3

44

UTAH

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 11 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1019.	633.	1268.	788.	2532.	3395.	22179.	1695.	6624.	1443.	986.	55.4	76.7
8	247.	153.	307.	191.	1075.	1441.	9414.	415.	1622.	353.	242.	96.1	133.0
10	707.	439.	880.	547.	1450.	1944.	12699.	1220.	4769.	1039.	710.	44.1	61.0
16	42.	26.	53.	33.	3.	4.	27.	30.	117.	26.	17.	3.8	5.3
18	22.	14.	27.	17.	5.	6.	40.	30.	117.	26.	17.	5.7	7.8

45

VERMONT

DENSITY - - 849.62 KG/CU-M 53.04 LB/CU-FT 3 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	318.	198.	306.	190.	385.	516.	3373.	991.	3872.	844.	577.	14.4	20.0
12	106.	66.	102.	63.	93.	125.	814.	146.	569.	124.	85.	23.7	32.7
18	106.	66.	102.	63.	127.	170.	1110.	298.	1165.	254.	173.	15.8	21.8
24	106.	66.	102.	63.	165.	222.	1449.	547.	2139.	466.	318.	11.2	15.5

Table B.2. (Continued)

44

UTAH

DENSITY - - 770.45 KG/CU-M 48.10 LB/CU-FT 11 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	521.	324.	532.	330.	1471.	1973.	12886.	686.	2681.	530.	362.	87.7	121.4
6	43.	26.	43.	27.	69.	93.	605.	31.	122.	24.	16.	90.6	125.4
8	479.	298.	488.	303.	1402.	1880.	12281.	655.	2559.	506.	346.	87.6	121.2

46

VIRGINIA

DENSITY - - 762.06 KG/CU-M 47.57 LB/CU-FT 16 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1409.	876.	1379.	857.	30014.	40249.	262922.	16808.	65692.	12837.	8774.	73.9	102.2
6	89.	55.	87.	54.	94.	126.	822.	49.	193.	38.	26.	78.5	108.7
8	257.	160.	251.	156.	310.	415.	2712.	205.	802.	157.	107.	62.4	86.4
12	282.	175.	276.	171.	1447.	1940.	12673.	686.	2682.	524.	359.	87.2	120.7
14	330.	205.	322.	200.	1382.	1853.	12107.	1113.	4352.	850.	581.	51.4	71.1
16	86.	53.	84.	52.	519.	696.	4545.	474.	1852.	362.	247.	45.3	62.7
22	14.	9.	14.	9.	145.	194.	1268.	163.	637.	124.	85.	36.7	50.8
32	352.	219.	345.	214.	26118.	35025.	228797.	14117.	55175.	10782.	7369.	76.5	105.9

47

WASHINGTON STATE

DENSITY - - 757.44 KG/CU-M 47.29 LB/CU-FT 21 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	1172.	729.	1206.	751.	5895.	7907.	51649.	3889.	15201.	2952.	2018.	63.1	87.3
6	265.	165.	273.	170.	151.	202.	1321.	134.	522.	101.	69.	47.0	65.0
8	239.	149.	246.	153.	164.	220.	1439.	196.	766.	149.	102.	34.9	48.3
10	22.	14.	22.	14.	99.	133.	866.	55.	213.	41.	28.	75.5	104.5
12	29.	17.	29.	18.	112.	151.	983.	91.	356.	69.	47.	51.3	71.0
14	216.	134.	222.	138.	3697.	5226.	34138.	1331.	5200.	1010.	690.	121.9	168.7
16	211.	131.	217.	135.	684.	917.	5992.	845.	3303.	641.	438.	33.7	46.6
20	192.	119.	198.	123.	789.	1058.	6910.	1238.	4840.	940.	643.	26.5	36.7

Table B.2. (Continued)

48

WEST VIRGINIA

DENSITY - - 791.31 KG/CU-M 49.40 LB/CU-FT 2 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	97.	60.	97.	60.	135.	182.	1186.	54.	213.	43.	30.	99.0	137.0
8	10.	6.	10.	6.	16.	21.	137.	11.	41.	8.	6.	58.8	81.3

49

WISCONSIN

DENSITY - - 755.42 KG/CU-M 47.16 LB/CU-FT 10 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	968.	602.	1073.	667.	4458.	5978.	39050.	1992.	7787.	1508.	1031.	93.4	129.2
6	341.	212.	378.	235.	661.	886.	5787.	282.	1104.	214.	146.	97.6	135.1
8	277.	172.	307.	190.	281.	376.	2459.	230.	898.	174.	119.	51.0	70.5
10	175.	109.	194.	120.	1094.	1467.	9581.	456.	1784.	346.	236.	100.0	138.4
12	60.	37.	66.	41.	522.	700.	4570.	235.	917.	178.	121.	92.8	128.4
16	116.	72.	128.	80.	1901.	2549.	16652.	789.	3084.	597.	408.	100.6	139.1

50

WYOMING

DENSITY - - 764.91 KG/CU-M 47.75 LB/CU-FT 15 PIPES

DIAM	KM ON MAP	MILES ON MAP	ADJUSTED KM	ADJUSTED MI	KW	HP	MWH	CU.M-KM/YR (MILLIONS)	BBL-MI/YR (MILLIONS)	TON-KM/YR (MILLIONS)	TON-MI/YR (MILLIONS)	KJ/TON-KM	BTU/TON-MI
0	2670.	1660.	2882.	1791.	8890.	11922.	77877.	2437.	9526.	1868.	1277.	150.3	208.0
4	67.	42.	72.	45.	75.	100.	655.	23.	89.	17.	12.	135.9	188.1
6	1471.	915.	1589.	987.	1618.	2170.	14173.	860.	3362.	659.	451.	77.5	107.3
8	1106.	687.	1193.	742.	7149.	9587.	62628.	1517.	5930.	1163.	795.	194.2	268.8
10	26.	16.	28.	17.	48.	64.	421.	37.	146.	29.	20.	53.0	73.4

Appendix C. COMPUTER PROGRAMS

Listings of the Fortran computer programs developed for the project described herein follow. They were written for a DEC-10 computer using the Digital Equipment Corporation's version of Fortran, Fortran-10. Conversion to other Fortran dialects should be straightforward. The programs should be self-documenting.

```
*    PROGRAM FOR CREATING PIPELINE CAPACITY OBSERVATION FILE
*

C        PROGRAM DRVOBS
C
C
C--BY J.N. HOOKER, ENERGY DIVISION, OAK RIDGE NATIONAL LAB, TN.
C        DEVELOPED ON THE DEC-SYSTEM 10 COMPUTER, 1980.
C
C
C        THIS PROGRAM FORMS OBSERVATION GROUPS FOR THE
C        REGRESSION OF PIPELINE CAPACITY ON DIAMETER, OR THE
C        REGRESSION OF PIPELINE FLOW ON DIAMETER AND CAPACITY
C
C
         DOUBLE PRECISION FILE
         INTEGER WHICH, DIGITS
         TYPE 10
10       FORMAT(' PICK ONE:'
     -   /'    1 - FORM CAPACITY OBSERVATION GROUPS'
     -   /'    2 - FORM FLOW OBSERVATION GROUPS')
         ACCEPT *, WHICH
         TYPE 11
11       FORMAT(' NETWORK FILE NAME = ',S)
         ACCEPT 12, FILE
12       FORMAT(A10)
         OPEN(UNIT=1,DEVICE='DSK',FILE=FILE)
         DIGITS = 6 - WHICH
         CALL OBS(DIGITS,1,1,WHICH)
         STOP
         END
*
*
*
*
C
         SUBROUTINE OBS(DIGITS,UNIT,AGE,WHICH)

C
C
C        MAIN SUBROUTINE TO BE USED WITH OBS PROGRAM
C        BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C        THIS PROGRAM FORMS OBSERVATION GROUPS FOR THE
C        REGRESSION OF PIPELINE CAPACITY ON DIAMETER, OR THE
C        REGRESSION OF PIPELINE FLOW ON DIAMETER AND CAPACITY
C
C
*
         EXTERNAL FIRST4
*
         INTEGER RANDOM,AGE,NODE(2),NEW,LENGTH,PUMPS(2),COMPNY,
     -   COUNTY(3),NPIPES,DIAM(9),NFLOW,NCAP,ENODE1(2,9),ENODE2(2,9),
     -   END,PTR,NGROUP,IREC,NLINK,DLINK,NLINK1(3000),DLINK1(3000),
     -   INDEX(2000),DIAMS(50),UNIT,SEQ,NDXFLE,DIGITS,FIRST4,WHICH,
     -   NDX(50),HASH(9999)
*
         REAL CAP,FLOW,CAPS(3000)
         LOGICAL SAVE
         DOUBLE PRECISION FILE
*
*
*   DIGITS - NUMBER OF DIGITS HAD BY NODE NUMBERS IN THE EXTENSION
*            FIELD OF THE NETWORK DATA SET.
*   UNIT - UNIT NUMBER FOR READING THE NETWORK DATA.
*   AGE - CODE SHOWING THE AGE OF LINKS DESIRED.
*   WHICH - = 1 WHEN DOING CAPACITY GROUPS
*           = 2 WHEN DOING FLOW GROUPS.
*   DLINK1(X) - LOCATION OF HEAD OF LINKED LIST OF DIAMETERS IN
*               GROUP I.
*   NLINK1(X) - LOCATION OF HEAD OF LINKED LIST OF NODE PAIRS
*               CORRESPONDING TO GROUP I.
*
*
*
*   SET UP CONSTANTS NEEDE AND GET DATA FILE READY.
*
         IREC = 0            ! NUMBER OF RECORDS READ.
         TYPE 4322
4322     FORMAT(' ')
         RANDOM = 28         ! UNIT NUMBER FOR RANDOM ACCESS FILE
         SEQ = 29            ! UNIT NUMBER FOR OUTPUT FILE
         NDXFLE = 30         ! UNIT NUMBER FOR INDEX FILE
         PTR = 0
         NGROUP = 0          ! NUMBER OF OBSERVATION GROUPS FORMED.
         IF(UNIT.LE.RANDOM.OR.UNIT.GE.NDXFLE) GO TO 9
*   READ INDEX FILE IF DOING FLOW GROUPS.  (THE FILE WILL BE
*   WRITTEN IF DOING CAPACITY GROUPS.)
9        IF(WHICH.EQ.1) GO TO 10
         TYPE 21
21       FORMAT(' THE CAPACITY GROUP INDEX IS EXPECTED'
     -   ' TO BE IN FILE CAPS.NDX.')
         OPEN(UNIT=NDXFLE,DEVICE='DSK',FILE='CAPS.NDX')
         DO 22 I = 1,5000
22         READ(NDXFLE,2085,END=23) J, INDEX(J)
23       CONTINUE
*
*
10       CONTINUE
         OPEN(UNIT=RANDOM,DEVICE='DSK',ACCESS='RANDOM',RECORD
     -   SIZE=40,DISPOSE='SAVE')
*
*
*   START READING THE NETWORK DATA, FORMING FLOW OR CAPACITY GROUPS
*   AS YOU GO ALONG.
*
50       IREC = IREC + 1
         CALL READ(UNIT,NODE,NEW,LENGTH,PUMPS,COMPNY,COUNTY,
     -   NPIPES,DIAM,NFLOW,FLOW,NCAP,CAP,ENODE1,ENODE2,END,5,ICAP,
     -   IFLOW)
         IF(END.GE.1) GO TO 2000
         IF(MOD(IREC,100).EQ.0) TYPE 4321, IREC,LOOKS
```

```
9321     FORMAT(' RECORD',I5,', COMPLEXITY =',I5)
*
*  SOME ADJUSTMENTS ARE NECESSARY IF YOU ARE DOING FLOW GROUPS.
         IF(WHICH.EQ.1) GO TO 51
         NCAP = NFLOW
         CAP = FLOW
 51      IF(CAP.GT.0) GO TO 52
*  IF CAPACITY READ IS ZERO, THE DIAMETERS ON THAT RECORD CAN
*  BECOME PART OF NO GROUP.
         IF(WHICH.EQ.1) INDEX(IREC) = 0
         GO TO 50
 52      CONTINUE
*
*  USE THIS RECORD IF
*        AGE=1 OR AGE=2 AND NEW >= 0,  OR
*        AGE=3 AND NPIPES-NEW > 0
         IF(AGE.EQ.3) NPIPES = NPIPES - NEW
         IF(.NOT.((AGE.EQ.1).OR.
     -     ((AGE.EQ.2).AND.(NEW.GE.0)).OR.
     -     ((AGT.EQ.3).AND.(NPIPES.GT.0)))) GO TO 50
         IF(NGROUP.EQ.0) GO TO 300
*
*  CHECK THROUGH EXISTING GROUPS TO SEE IF PIPE LINK
*  ALREADY IS IN A GROUP.  END OF A GROUP IS
*  SIGNALLED BY A ZERO LINKFIELD.
*
         IF(DIGITS.EQ.4) GO TO 110
*
*  CODE FOR FIVE-DIGIT VERSION OF PROGRAM FOLLOWS.
*
         N1 = FIRST4(NODE(1))
         J = HASH(N1)
 71      IF(J.EQ.0) GO TO 300
           K = NLINK1(J)
           I = J
 75        IF(K.EQ.0) GO TO 71
             JTEMP = -1
             READ(RANDOM#K,80) INODE1,INODE2,INLINK,JIN
             IF(FIRST4(INODE1).EQ.N1) JTEMP = JIN
             LOOKS =  LOOKS + 1
 80          FORMAT(4(5X,I5))
             IF(INODE1.EQ.NODE(1).AND.INODE2.EQ.NODE(2)) GO TO 200
             K = INLINK
             IF(JTEMP.EQ.-1) GO TO 75
             IF(JTEMP.EQ.J) GO TO 75
             J = JTEMP
             GO TO 71
*  YOU WILL DROP THROUGH THE LOOP IF LINK IS NOT IN AN EXISTING
*  GROUP.  GO START A NEW GROUP.
         GO TO 300
*
*
*  CODE FOR THE FOUR-DIGIT VERSION FOLLOWS.
*
 110     IF(NGROUP.EQ.0) GO TO 300
         N1 = FIRST4(NODE(1))
         J = HASH(N1)
 101     IF(J.EQ.0) GO TO 300
           K = NLINK1(J)
           I = J
 125       IF(K.EQ.0) GO TO 101
             JTEMP = -1
             READ(RANDOM#K,80) INODE1,INODE2,INLINK,JIN
             IF(INODE1.EQ.N1) JTEMP = JIN
             LOOKS = LOOKS + 1
             IF(INODE1.EQ.N1.AND.
     -        INODE2.EQ.FIRST4(NODE(2))) GO TO 200
             K = INLINK
             IF(JTEMP.EQ.-1) GO TO 125
             IF(JTEMP.EQ.J) GO TO 125
             J = JTEMP
             GO TO 101
*  IF EXISTING GROUP NOT FOUND, GO START A NEW GROUP.
         GO TO 300
*
*
*  UPDATE OLD GROUP OF WHICH CURRENT RECORD IS A MEMBER.
*
 200     IF(WHICH.EQ.1) INDEX(IREC) = I
         DO 250 J = 1,NPIPES
           IF(I.EQ.0) TYPE 9999, IREC
9999       FORMAT(' I = 0 AT RECORD ',I5)
           DLINK = DLINK1(I)
           PTR = PTR + 1
           DLINK1(I) = PTR
           WRITE(RANDOM#PTR,80) DIAM(J), DLINK, INDEX(IREC)
 250       CONTINUE
         GO TO 50
*
*
*  START UP A NEW GROUP.  UPDATE FILE POINTERS
*  KEPT IN MEMORY.
*
 300     NGROUP = NGROUP + 1
         CAPS(NGROUP) = CAP
         DLINK1(NGROUP) = 0
         DO 350 J = 1,NPIPES
           DLINK = DLINK1(NGROUP)
           PTR = PTR + 1
           DLINK1(NGROUP) = PTR
           WRITE(RANDOM#PTR,80) DIAM(J), DLINK, INDEX(IREC)
 350       CONTINUE
*
*  ASSOCIATE WITH THE CURRENT GROUP THE NODE PAIRS READ
*  IF NCAP OR NFLOW = 1, THERE ARE NO EXTRA NODE PAIRS; SKIP TO
*  NEXT LOOP.
*
         IF(NCAP.EQ.1) GO TO 450

         NLINK1(NGROUP) = 0
         DO 400 J = 1,NCAP-1
           NLINK = NLINK1(NGROUP)
           PTR = PTR + 1
```

```
         NLINK1(NGROUP) = PTR
         K = ENODE1(3-WHICH,J)
         IF(K.EQ.0) TYPE 9998, IREC
9998     FORMAT(' K = 0 AT RECORD ',I5)
         IF(WHICH.EQ.1) K = FIRST4(K)
         WRITE(RANDOM#PTR,80) ENODE1(3-WHICH,J),
    -      ENODE2(3-WHICH,J), NLINK, HASH(K)
         HASH(K) = NGROUP
 400     CONTINUE
*
*  IF USING A 4-DIGIT CODE THEN RECORD THE FIRST 4 DIGITS OF THE
*  CURRENT NODES IN THE LIST OF EXTRA NODE PAIRS TO BE SEARCHED.
*
 450     IF(DIGITS.EQ.5) GO TO 500
         NLINK = NLINK1(NGROUP)
         PTR = PTR + 1
         NLINK1(NGROUP) = PTR
         N11ST = FIRST4(NODE(1))
         N21ST = FIRST4(NODE(2))
         WRITE(RANDOM#PTR,80) N11ST, N21ST, NLINK, HASH(N11ST)
         HASH(N11ST) = NGROUP
 500     IF(WHICH.EQ.1) INDEX(IREC) = NGROUP
1000     GO TO 50
*
*  CREATE A SEQUENTIAL OUTPUT FILE FROM THE RANDOM ACCESS FILE
*  CONTAINING THE LINKED LISTS.
*
2000     IF(END.GT.1) GO TO 5000
         TYPE 1234
1234     FORMAT(' NAME OF OUTPUT FILE = ',$)
         ACCEPT 1235, FILE
1235     FORMAT(A10)
         OPEN(UNIT=SEQ,DEVICE='DSK',FILE=FILE)
         IF(WHICH.EQ.2) GO TO 1237
         TYPE 1236
1236     FORMAT(' NAME OF INDEX FILE = ',$)
         ACCEPT 1235, FILE
         OPEN(UNIT=NDXFLE,DEVICE='DSK',FILE=FILE)
*
*
1237     DO 2100 I = 1,NGROUP
           DLINK = DLINK1(I)
           NDIA = 0
*          READ ALL THE DIAMETERS IN GROUP I.
2010         IF(DLINK.EQ.0) GO TO 2050
             NDIA = NDIA + 1
             READ(RANDOM#DLINK,80) DIAMS(NDIA), DLINK, NDX(NDIA)
             GO TO 2010
*  WRITE CAPACITY GROUP HERE.
2050       IF(WHICH.EQ.2) GO TO 2080
           WRITE(SEQ,2075) I, NDIA, CAPS(I), (DIAMS(J),J=1,NDIA)
2075       FORMAT(I5,I3,F8.1,3X,28I3)
           GO TO 2100
2080       WRITE(SEQ,2175) I, NDIA, CAPS(I), (DIAMS(J),NDX(J),
             J=1,NDIA)
2175       FORMAT(I5,I3,F8.1,3X,28(I3,I4))
2100       CONTINUE
         IF(WHICH.EQ.2) RETURN
*
* IF DOING CAPACITY GROUPS, RECORD INDEX ON A FILE.
         DO 2200 I = 1,IREC-1
           WRITE(NDXFLE,2085) I, INDEX(I)
2085       FORMAT(2X,I5,3X,I5)
2200       CONTINUE
         RETURN
*
*
5000     TYPE 5010, NODE
5010     FORMAT('  ABNORMAL TERMINATION DUE TO BAD DATA ON LINE',
           1X,I5,'-',I5)
         STOP ' EXECUTION ABORTED IN SUBROUTINE OBS'
         END
*
*
C-----------------------------------------------------------------
*
*
         INTEGER FUNCTION FIRST4(NUM)
C
C
C        FUNCTION TO BE USED WITH OBS PROGRAM
C        BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
*
*  EXTRACT THE FIRST 4 DIGITS OF NUM.
*
         INTEGER NUM
         FIRST4 = NUM
         FIRST4 = FIRST4/10
         RETURN
         END
*
*
C-----------------------------------------------------------------
*
*
       SUBROUTINE READ(UNIT,NODE,NEW,LENGTH,PUMPS,CMPANY,COUNTY,
      1NPIPES,DIAM,NFLOW,FLOW,NCAP,CAP,ENODE1,ENODE2,END,
      2IOUT,ICAP,IFLOW)
C
C
C        SUBROUTINE TO BE USED WITH OBS PROGRAM
C        BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C-----------PIPELINE FILE READER
C
C
C-----------EACH SUBROUTINE CALL CAUSES ONE RECORD TO BE READ
C-----------ONE RECORD MAY COVER 2 OR MORE CARDS
C
C-----------IOUT IS THE UNIT BEING USED FOR OUTPUT BY THE
```

```
C----------        CALLING PROGRAM
C----------         IOUT MAY BE USED FOR ERROR MESSAGES IN SUBR.
C----------IDD(16) IS ALPHANUMERIC COPY OF CURRENT CARD BEING
C----------         READ IN CASE OF ERROR
C----------UNIT (INTEGER) / FILE UNIT NO. FROM WHICH DATA ARE READ
C----------NODE(2) (INTEGER) / NODE(1) IS HEAD NODE NO.,COL 1-5
C----------              NODE(2) IS TAIL NODE NO., COL7-11
C----------NEW (INTEGER) / 0 IF BLANK,-1 IF ZERO, OTHERWISE N
C----------        NEW IS READ ALPHANUMERIC, COL 6
C----------LENGTH (INTEGER) / LENGTH OF SEGMENT,COL13-15
C----------PUMPS(2) (INTEGER) / PUMPS(1) IS NO. PUMPING STATIONS
C----------      AT HEAD NODE,COL26
C----------          PUMPS(2) IS NO. PUMPING STATIONS
C----------      AT TAIL NODE,COLS 28-29
C----------CMPANY (INTEGER) / COMPANY CODE, COL 31-33
C----------COUNTY(3) (INTEGER) /CONTAINS COUNTY NAME
C----------       5 CHARACTERS PER WORD IN ALPHANUMERIC FORMAT
C----------                 COL 35-49
C----------NPIPES (INTEGER) / NO. OF PARALLEL PIPES
C----------DIAM(9) (INTEGER) / DIAM(I) IS DIAMETER OF I-TH PIPE
C----------          COL. 17-18, OTHERS OPTIONALLY
C----------NFLOW  (INTEGER) / NO. OF LINKS IN FLOW GROUP,IF ANY
C----------NCAP (INTEGER) / NO. OF LINKS IN CAPACITY GROUP,IF ANY
C----------FLOW (REAL) / FLOW IN GROUP,COL 20-24
C----------CAP (REAL) /CAPACITY OF GROUP,COL 51-56,MILLION BBL PER YR
C----------ENODE1(2,9) (INTEGER) / ENODE1(1,I) IS HEAD NODE
C----------     OF I-TH EXTRA LINK IN FLOW GROUP
C----------         ENODE1(2,I)  SAME FOR CAPACITY GROUP
C----------ICAP=RECORD NO. FOR CAPACITY GROUP
C----------IFLOW=RECORD NO. FOR FLOW GROUP
C----------ENODE2(2,9) (INTEGER) / TAIL NODES
C----------END (INTEGER) / END=1 WHEN END OF FILE IS REACHED
C----------   END=2 FOR ERROR, END=0 OTHERWISE
C
C
      DIMENSION NODE(2),IDD(16)
      COMMON ID(79,6)
      INTEGER UNIT,PUMPS(2),CMPANY,COUNTY(3),DIAM(9),
     1ENODE1(2,9),ENODE2(2,9),END,EN1,EN2
      DATA IBLANK/' '/,IZERO/'0'/
C
C
      END=0
      ICD=0
C----SECTION A
C-INITIALIZE QUANTITIES WHICH ARE TO BE FOUND OPTIONALLY
      NPIPES=1
      NFLOW=1
      NCAP=1
      DO 26 I=1,9
      DIAM(I)=0
      ENODE1(1,I)=0
      ENODE1(2,I)=0
      ENODE2(1,I)=0
   26 ENODE2(2,I)=0
C-----SECTION B
C-READ A CARD OR CARDS(CONT) FOR A PIPELINE
      READ(UNIT,5,END=2000,ERR=1000)NODE(1),NEW,NODE(2),LENGTH,
     1DIAM(1),FLOW,
     2PUMPS(1),PUMPS(2),CMPANY,COUNTY,
     3CAP,ICAP,IFLOW,IC
    5 FORMAT(I5,A1,I5,1X,I3,1X,I2,1X,F5.1,1X,I1,1X,I2,1X,I3,
     11X,3A5,1X,F6.0,13X,2(I4,1X),I1)
      IF(NEW.EQ.IBLANK)GO TO 54
      IF(NEW.EQ.IZERO)GO TO 55
      DECODE(1,1999,NEW)NEW
 1999 FORMAT(I1)
      GO TO 59
   54 NEW=0
      GO TO 59
   55 NEW = -1
   59 IF(IC.LT.1)RETURN
   60 ICD=ICD+1
      IF(ICD.GE.7) GO TO 1400
      READ(UNIT,10,END=2000,ERR=1000) (ID(I,ICD),I=1,79),IC
   10 FORMAT(80I1)
      IF(IC.GE.1)GO TO 60
C-----SECTION C
C-START CHECK OF EXTENSION FIELD
C     ICD=NUMBER CONTINUATION CARD IMAGES IN THIS RECORD
C     NCD=CURRENT CARD IMAGE BEING PROCESSED
      NCD=1
      J=ID(1,1)
      ICHAR=2
      IF(J.GT.3.OR.J.EQ.0)GO TO 1500
  520 IF(J-1)24,525,625
   24 IF(NCD.EQ.ICD)RETURN
      WRITE(IOUT,14)
   14 FORMAT('  NUMBER OF CONTINUATIONS CONFLICTS WITH J VALUE',
     1 ' AND DATA')
      END=2
      RETURN
C-----SECTION D
C-CASE J=1. GET DIAM VALUES AND NEXT J VALUE.
  525 NPIPES=ID(2,1)+1
      I=1
  530 ICHAR=ICHAR+2
      I=I+1
      ICP1=ICHAR+1
      DIAM(I)=10*ID(ICHAR,1)+ID(ICP1,1)
      ICHAR=ICP1
      IF(I.LT.NPIPES)GO TO 530
      ICHAR=ICHAR+2
      J=ID(ICHAR,1)
      ICHAR=ICHAR+1
  519 IF(J.EQ.1.OR.J.GT.3)GO TO 1500
      GO TO 520
C-----SECTION E
C-CASE J=2 OR J=3.GET FLOW AND CAPACITY HEAD AND TAIL NODES.
  625 CONTINUE
      IDIG = 5
      IF(J.EQ.2) IDIG = 4
  630 NLINKS=ID(ICHAR,NCD)
      IF(J.EQ.2)NFLOW=NLINKS+1
```

```
      RETURN
      END
C
C
C-----------------------------------------------------------------------
C
C
      SUBROUTINE ENJ(NCD,ICHAR,EN1,IDIG)
C
C
C       SUBROUTINE TO BE USED WITH OBS PROGRAM
C       BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
      COMMON ID(79,6)
      INTEGER EN1
      EN1=ID(ICHAR+2,NCD)
      DO 640 I=3,IDIG+1
  640 EN1=EN1*10 + ID(ICHAR+I,NCD)
      ICHAR=ICHAR+IDIG+1
      RETURN
      END
```

```
      IF(J.EQ.3)NCAP=NLINKS+1
      K=J-1
      ILK=0
  635 ILK=ILK+1
      IF(ILK.GT.NLINKS) GO TO 735
      ILAST=78
      IF(NCD.EQ.ICD)ILAST=79
      IF(ILAST-ICHAR.LT.(2*IDIG+2))GO TO 650
  641 CALL ENJ(NCD,ICHAR,EN1,IDIG)
      ENODE1(K,ILK)=EN1
  645 CALL ENJ(NCD,ICHAR,EN2,IDIG)
      ENODE2(K,ILK)=EN2
      GO TO 635
  650 IEN1=0
      IF(ILAST-ICHAR.LT.(IDIG+1)) GO TO 680
      CALL ENJ(NCD,ICHAR,EN1,IDIG)
      ENODE1(K,ILK)=EN1
      IEN1=1
  680 IF(NCD.GE.ICD)GO TO 24
      NCD=NCD+1
      ICHAR=-1
      IF(IEN1.LE.0)GO TO 641
      GO TO 645
C-----SECTION F
C-CHECK TO SEE IF WE HAVE JUST DONE J=3
  735 IF(J.GE.3)GO TO 24
      ILAST=75
      IF(NCD.EQ.ICD)ILAST=76
      IF(ICHAR.GT.ILAST)GO TO 740
      ICHAR=ICHAR+2
      J=ID(ICHAR,NCD)
      ICHAR=ICHAR+1
      GO TO 741
  740 IF(NCD.GE.ICD)GO TO 24
      NCD=NCD+1
      J=ID(1,NCD)
      ICHAR=2
  741 IF(J.EQ.1.OR.J.EQ.2)GO TO 1500
      GO TO 520
C-----SECTION G
C-ERROR MESSAGES
 1000 WRITE(IOUT,1010)
 1010 FORMAT('    ERROR IN READ EXECUTION')
 1020 END=2
      REREAD 1030,(IDD(I),I=1,16)
 1030 FORMAT(16A5)
      WRITE(IOUT,1040)(IDD(I),I=1,16)
 1040 FORMAT(5X,16A5)
      RETURN
 1500 WRITE(IOUT,1510)
 1510 FORMAT('    J VALUE NOT ALLOWED')
      END=2
      RETURN
 1400 WRITE(IOUT,1410)
 1410 FORMAT('    NUMBER OF CONTINUATIONS EXCEEDS 6')
      GO TO 1020
 2000 END=1
```

```
*    PROGRAM FOR CALCULATING PIPELINE TEMPERATURE DROP
*

        PROGRAM HLOSS
C
C
C--BY J.N. HOOKER, ENERGY DIVISION, OAK RIDGE NATIONAL LAB, TN.
C       DEVELOPED ON THE DEC-SYSTEM 10 COMPUTER, 1980.
C
C
C--CALCULATE HEAT LOSS FROM A PIPELINE.
C
        IMPLICIT REAL(A-Z)
        REAL TEMP(5)
        INTEGER I, J, LIM
        DOUBLE PRECISION FILE
        TYPE 50
        ACCEPT 60, FILE
        OPEN(UNIT=1,DEVICE='DSK',FILE=FILE)
10      TYPE 70
        ACCEPT *, OD
        TYPE 80
        ACCEPT *, ID
        TYPE 90
        ACCEPT *, V
        TYPE 100
        ACCEPT *, RHO
        TYPE 110
        ACCEPT *, C
        TYPE 120
        ACCEPT *, L
        TYPE 130
        ACCEPT *, TI
        TYPE 140
        ACCEPT *, TA
        TYPE 150
        ACCEPT *, A
        TYPE 160
        ACCEPT *, B
        WRITE(1,170) OD, ID, V, RHO, C, L, TI, TA, A, B
        WRITE(1,180)
        TYPE 180
C
        G = 9.8067      ! M/SEC2
        DL = 1.         ! LENGTH INCREMENT
        LSAVE = L
        DO 20 I = 1,5
20        TEMP(I) = TI
C
C
30      CONTINUE
C-------PRINT SOMETHING EVERY 10 KM.
C-------DO THE CALCULATION EVERY DL KM.
        LIM = 10./DL
        DO 40 J = 1,LIM
C---------KEEP TRACK OF THE DISTANCE TRAVELED.
          L = L - DL
C---------TRY 5 DIFFERENT HEAT TRANSFER COEFFICIENTS.
          DO 40 I = 1,5
C-----------SET THE HEAT TRANSFER COEFFICIENT, KJ/M3-HR-DEG.
            K = 5. * FLOAT(I)
C-----------CALCULATE HEAT LOSS DUE TO HEAT FLOW.
            LOSS = (TEMP(I) - TA) * (1. -
     1            10. ** (-34.6*OD*K*DL/(V/24.)/RHO/C))
C-----------CALCULATE KINEMATIC VISCOSITY, CSTOKES
            NU = 92903. * A * (1.8*TI+32.)**B
C-----------CALCULATE FRICTION HEAD, M
            HEAD = 0.06953 * NU**(.252) * V**(1.748) * DL
     1            / ID**(4.748)
C-----------CALCULATE HEAT GAIN DUE TO FRICTION HEATING.
            GAIN = HEAD * G / (C*1000.)
C-----------CALCULATE NET HEAT GAIN.
            TEMP(I) = TEMP(I) - LOSS + GAIN
40          CONTINUE
C-----------PRINT DATA FOR THIS 10-KM STRETCH.
        LL = LSAVE - L
        WRITE(1,190) LL, (TEMP(I),I=1,5)
        TYPE 190, LL, (TEMP(I),I=1,5)
        IF(L.GT.0.)  GO TO 30
        TYPE 200
        ACCEPT 210, ANS
        IF(ANS.EQ.'YES')  GO TO 10
        STOP
50      FORMAT(' HEAT LOSS FROM PIPES.'
        1  //' OUTPUT FILE = ',$)
60      FORMAT(A10)
70      FORMAT(' OUTSIDE DIAMETER, IN = ',$)
80      FORMAT(' INSIDE DIAMETER, IN = ',$)
90      FORMAT(' FLOW RATE, M3/DAY = ',$)
100     FORMAT(' DENSITY, KG/M3 = ',$)
110     FORMAT(' SPECIFIC HEAT OF OIL, KJ/KG-DEG = ',$)
120     FORMAT(' LENGTH OF LINE, KM = ',$)
130     FORMAT(' INITIAL TEMPERATURE, DEG C = ',$)
140     FORMAT(' AIR TEMPERATURE, DEG C = ',$)
150     FORMAT(' KINEMATIC VISCOSITY REGRESSION PARAMETERS:'
        1  /'    A = ',$)
160     FORMAT('    B = ',$)
170     FORMAT('1HEAT LOSS CALCULATION.'
        1  //' OUTSIDE DIAMETER, IN =',F7.3
        2  /' INSIDE DIAMETER, IN =',F7.3
        3  /' FLOW RATE, M3/DAY =',F7.0
        4  /' DENSITY, KG/M3 =',F6.1
        5  /' SPECIFIC HEAT OF OIL, KJ/KG-DEG =',F6.3
        6  /' TOTAL LENGTH, KM =',F5.0
        7  /' INITIAL TEMPERATURE, DEG C =',F6.1
        8  /' AIR TEMPERATURE, DEG C =',F6.1
        9  /' KINEMATIC VISCOSITY REGRESSION COEFFICIENTS:'
        1  /'       A =',F11.7,'        B =',F11.7)
180     FORMAT(//' LENGTH, KM      HEAT TRANSFER COEFFICIENT,',
        1     ' KJ/M3-HR-DEG'
        2          /'                          5         10          15',
        3           '          20        25'/)
190     FORMAT(F10.0,4X,5F10.1)
200     FORMAT(' MORE? ',$)
210     FORMAT(A3)
        END
```

```
*     NETWORK FILE REFORMATTING PROGRAM
*

        PROGRAM SCOOT
C
C
C--BY J.N. HOOKER, ENERGY DIVISION, OAK RIDGE NATIONAL LAB, TN.
C       DEVELOPED ON THE DEC-SYSTEM 10 COMPUTER, 1980.
C
C
C---THIS IS A PROGRAM TO REORGANIZE THE PIPELINE DATA
C    SO THAT EXTENSIONS ARE ON SERIES OF CARDS AFTER THE PRIMARY
C    CARD.
C
C
        INTEGER DATA(10),EXT(423),PTR(423),LIMIT,SIZE,FIRST,
        1            LAST,CONT,FORM,FORMT(4),MAXMUM,ONE
C
        REAL*8  INPUT,OUTPUT
        DATA    FORMT(1)/'('/,FORMT(3)/'A1,T8'/,
        1            FORMT(4)/'0,A1)'/,ONE/'1'/
*
*
        TYPE 180
        ACCEPT 170,INPUT
        TYPE 190
*
        ACCEPT 170,OUTPUT
        OPEN (UNIT=1,DEVICE='DSK',FILE=INPUT)
        OPEN (UNIT=2,DEVICE='DSK',FILE=OUTPUT)
10      READ (1,200,END=160) DATA,(EXT(I), I=1,29),CONT
        IF (EXT(1) .NE. ' ')  GO TO 20
           WRITE (2,200) DATA
           GO TO 10
20      WRITE (2,210) DATA,ONE
        LIMIT=29
30      IF (CONT .NE. '1')  GO TO 40
        READ (1,220,END=160) (EXT(I), I=LIMIT+1,LIMIT+79),CONT
        LIMIT=LIMIT+79
        GO TO 30
40      DO 50 I=1,LIMIT
           PTR(I)=I+1
50      CONTINUE
        I=2
60      IF (I .GT. LIMIT)  GO TO 90
        IF (EXT(I) .NE. ' ')  GO TO 80
        IF (EXT(I+1) .NE. ' ')  GO TO 80
        J=I
70      I=I+1
        IF ((EXT(I) .EQ. ' ') .AND. (I .LT. LIMIT))  GO TO 70
        PTR(J)=I
80      I=I+1
        GO TO 60
90      PTR(J)=0
100     I=1
        K=1
110     IF (K .EQ. 0)  GO TO 120
        EXT(I)=EXT(K)
        I=I+1
        J=K
        K=PTR(J)
        GO TO 110
120     SIZE=I-1
        LAST=79
        FIRST=1
130     IF(LAST-79 .GE. SIZE)  GO TO 10
        J=LAST
140     IF (EXT(J) .EQ. ' ')  GO TO 150
           J=J-1
        GO TO 140
150     LAST=MIN0(J,SIZE)
        IF (LAST .LT. SIZE)  CONT='1'
        IF (LAST .GE. SIZE   CONT=' '
        FORM=LAST-FIRST+1
        ENCODE (5,230,FORMT(2)) FORM
        WRITE (2,FORMT) (EXT(I), I=FIRST,LAST),CONT
        FIRST=LAST+1
        LAST=LAST+79
        GO TO 130
160     CLOSE (UNIT=1,DEVICE='DSK',FILE=INPUT)
        CLOSE (UNIT=2,DEVICE='DSK',FILE=OUTPUT)
        STOP
170     FORMAT (A10)
180     FORMAT ('  PLEASE ENTER THE NAME OF THE FILE TO BE ',
        1           'REFORMATTED.     ',$)
190     FORMAT ('  PLEASE THE NAME WISHED FOR THE ',
        1           'REORGANIZED FILE   ',$)
200     FORMAT (10A5,29A1,A1)
210     FORMAT (10A5,29X,A1)
220     FORMAT (79A1,A1)
230     FORMAT (I2)
        END
```

```
*    NETWORK FILE INDEXING PROGRAM
*

        PROGRAM INDEX
C
C
C--BY J.N. HOOKER, ENERGY DIVISION, OAK RIDGE NATIONAL LAB, TN.
C       DEVELOPED ON THE DEC-SYSTEM 10 COMPUTER, 1980.
C
C
C--TRANSFER CAPACITY GROUP NUMBERS FROM INDEX FILE TO
C  NETWORK FILE
C
C

        INTEGER DUMMY, GROUP, TEXT1(14), TEXT2(48), TEXT3(80)
        DOUBLE PRECISION FILE

        TYPE 50
        ACCEPT 60, FILE
        OPEN(UNIT=1,DEVICE='DSK',FILE=FILE)
        TYPE 70
        ACCEPT 60, FILE
        OPEN(UNIT=2,DEVICE='DSK',FILE=FILE)
        OPEN(UNIT=3,DEVICE='DSK',FILE='NET.TMP')
10      READ(1,*,END=20) DUMMY, GROUP
        I = I + 1
        READ(2,80,END=30) TEXT1, DUMMY, TEXT2
        WRITE(3,80) TEXT1, GROUP, TEXT2
        GO TO 10
20      READ(2,80,END=40) DUMMY
        TYPE 90, I
        STOP
30      TYPE 100, I
        STOP
40      TYPE 110, I
        STOP
50      FORMAT(' MOVE CAPACITY GROUP NUMBERS FROM INDEX FILE',
        1           ' TO NETWORK FILE.'//
        2           ' INDEX FILE = ',$)
60      FORMAT(A10)
70      FORMAT(' NETWORK FILE = ',$)
80      FORMAT(13A5,A4,I4,48A5)
90      FORMAT(' PREMATURE END OF INDEX FILE; RECORD',I5)
100     FORMAT(' PREMATURE END OF NETWORK FILE; RECORD',I5)
110     FORMAT(I6,' RECORDS READ.'/
        1           /' OUTPUT IN FILE NET.TMP.')
        END
```

```
*    PROGRAM FOR CALCULATING PIPELINE PUMPING ENERGY CONSUMPTION
*

          PROGRAM DRVPOW
C
C--PROGRAM FOR THE CALCULATION OF POWER USE
C       AND OTHER QUANTITIES FOR OIL PIPELINE
C       COMPANIES, FOR EITHER CRUDE OIL PIPELINES
C       OR PRODUCTS  PIPELINES.
C
C--BY J.N. HOOKER, ENERGY DIVISION, OAK RIDGE NATIONAL LAB, TN.
C       DEVELOPED ON THE DEC-SYSTEM 10 COMPUTER, 1980.
C
C
C--     PROGRAM REPORTS SUMMARIES BY PIPE DIAMETER,
C       COMPANIES, STATES, AND NATION.
C       PROGRAM USES CAPACITY AND FLOW EQUATIONS
C       WITH PARAMETERS FOUND BY THE REGRESSION PROGRAM, REGJNH.
C
C       PROGRAMMING ASSISTANCE BY RUTH B. HOFSTRA, U. OF TENN.
C
C

          INTEGER CH
10        TYPE 20
          ACCEPT *,CH,X,Y,Z,W
          TYPE 30,CH,X,Y,Z,W
          IF(CH.LE.0)CALL EXIT
          CALL POWER(CH,X,Y,Z,W)
          GO TO 10
20        FORMAT('  TYPE IN CH,X,Y,Z,W'/
        1 '    CH = 0 SIGNALS STOP PROGRAM')
30        FORMAT('  CH,X,Y,Z,W='/I3,4E12.8)
          END
C
C
C-----------------------------------------------------------------
C
C

          SUBROUTINE POWER(CH,X,Y,Z,W)
C
C       MAIN SUBROUTINE TO BE USED WITH POWER PROGRAM
C       BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C--//COMPUTE POWER USE FOR EACH COMPANY//
C
C--FOLLOWING TYPES ARE INTEGER:
C--     CH//1-CRUDE,2-PRODUCTS//
C--     CONC//COMPANY CODE//
C--     NPIPES//NO. OF PARALLEL PIPES//
C--     NODE(2)//NODE NUMBER//
C--     S//STATE NUMBER//
C
C--FOLLOWING TYPES ARE REAL:
C--     RHO//DENSITY,LB/CU.FT.//
C--     NU//KINEMATIC VISCOSITY,CSTOKES//
C--     RATIO//(ADJUSTED MILES)/(MAP MILES),FOR COMPANY//
C--     SUML(0:48)//SUML(I)=PIPE MILES FOR DIAM I,COMPANY TOTAL//
C
C
C--     SUMHP(0:48)//SUMHP(I)=HORSEPOWER FOR DIAM I,COMPANY TOTAL//
C--     SUMVL(0:48)//SUMVL(I)=BBL-MI FOR DIAM I,COMPANY TOTAL//
C--     TOTL(0:50,0:48)//TOTL(I,J)=PIPE MILES FOR STATE I,DIAM J//
C--     TOTHP(0:50,0:48)//TOTHP(I,J)=HORSEPOWER FOR STATE I,DIAM J//
C--     TOTVL(0:50,0:48)//TOTVL(I,J)=BBL-MI FOR STATE I,DIAM J//
C--     TRATIO(0:50)//TRATIO(I)=RATIO FOR STATE I//
C--     TRHO(0:50)//TRHO(I)=WEIGHTED AVERAGE DENSITY FOR STATE I
C--     TUTIL(0:50)//TUTIL(I)=RATIO OF FLOW TO CAPACITY (UTILI-
C--             ZATION) IN STATE I, SUMMED OVER PIPES, UNWEIGHTED
C--     NUTIL(0:50)//NUTIL(I)=PIPE MILES IN STATE I
C--     TWUTIL(0:50)//TWUTIL(I)=UTILIZATION FOR STATE I, WEIGHTED
C--             BY RATE OF FLOW
C--     TVLUTL(0:50)//TVLUTL(I)=UTILIZATION FOR STATE I, WEIGHTED
C--             BY BBL-MI
C--     TMILES(0:50,-2:2)//TMILES(I,J)=PIPE MILES IN STATE S FOR
C--             COMPANIES IN CATEGORY J, WHERE
C--             J>0 FOR REGULATED COMMON CARRIERS
C--             J<0 FOR UNREGULATED CARRIERS
C--             J=0 FOR PIPES OF UNKNOWN OWNERSHIP
C--             J=1,-1 WHEN OIL& GAS JOURNAL GIVES PIPE MILES
C--             J=2,-2 WHEN IT DOES NOT.
C--     TFLOW(0:50,-2:2)//TFLOW(I,J)=A MEANING ANALOGOUS TO TMILES
C--             EXCEPT THAT BBL-MI ARE SUMMED.
C--     X,Y,Z,W//REGRESSION PARAMETERS:
C               CAP=X*(DIAM**Y)
C               FLOW=Z*CAP*(DIAM**W) //
C--     D(9)//DIAMETERS OF PARALLEL PIPES,IN.//
C--     V(9)//FLOWS OF PARALLEL PIPES,BBL/DA//
C--     L//LENGTH OF SEGMENT,MI.//
C--     EPS//ASPERITY HEIGHT,EPS=.00015 IN.//
C--     R//REYNOLD'S NUMBER//
C--     F//FRICTION FACTOR//
C--     P//PRESSURE DROP,LB/SQ.IN.//
C--     HF//FRICTION HEAD,FT.//
C--     HP//HORSEPOWER//
C--     FRAC//FRAC=FRACTION OF YEAR AT WHICH FLOW V(I)
C               IS IN EFFECT//
C
C--LOGICAL TYPE:LAST//END OF COMPANY FLAG//
C
C--FOLLOWING QUANTITIES ARE ONLY TEMPORARY LOCATIONS:
C       NODET,NEWT,LNGTHT,PUMPST,CONCT,CONTYT,NPIPST,
C       NFLOWT,FLOWT,NCAPT,CAPT,ENDE1T,ENDE2T,ICAPT,IFLOWT
C       FROM READ SUBROUTINE IN THIS SUBF.
C
C--FOLLOWING ARE SOME WORKING VARIABLES,DUMMIES,INDICES,ETC.
C       USED IN THE BODY OF THE PROGRAM AND OTHER SUBROUTINES:
C       IDEBUG,IPRINT,ISTOP,PMULT,IRG,EPIX,XPIX,NEWNET
C       NEWCO(250),IDATA(16),YL
C
C--FOLLOWING ARE RANDOM ACCESS FILE-NAMES AND UNITS:
C       CAP.TMP(22), CMPANY.TMP(23)
```

```
C
C--FOLLOWING ARE SEQUENTIAL FILE-NAMES AND UNITS:
C        CAP.OBS(20),CMPANY.IN(21),NETWRK(1),NTWRK2.TMP(2),
C        PIPES.TMP(3),STATES.IN(8),FOR17.DAT(17)
C
C
          INTEGER CH,CONO,S,PUMPST(2),CONOT,CONTYT(3),DIANT(9),
        1  ENDE1T(2,9),ENDE2T(2,9),FLOWT,CAPT,POL,
        2  CONAME(4),FLTYPE,REGULA
          DOUBLE PRECISION TITLE(4,2),NETWRK,NETBUG
          REAL MU,L,INSIDE
         LOGICAL LAST, PRINT(-1:300)
C
C
          DIMENSION NODE(2),SUML(0:48),SUMHP(0:48),SUMVL(0:48),
        1  TOTL(0:50,0:48),TOTHP(0:50,0:48),TOTVL(0:50,0:48),TRATIO(0:50)
        2  D(9),V(9),TRHO(0:50),
        3  NEWCO(250),IDATA(16),NODET(2),
        4  RS(9),PS(9),HPS(9),PS(9),HPS(9),TUTIL(0:50),NUTIL(0:50),
        5  TVUTIL(0:50),TVLUTL(0:50),UTIL(9),TMILES(0:50,-2:2),
        6  TFLOW(0:50,-2:2),TRATE(0:50)
C
C
          COMMON/TEMPRY/NODET,NEWT,LNGTHT,PUMPST,CONOT,CONTYT,NPIPST,
        1  DIANT,NFLOWT,FLOWT,NCAPT,CAPT,ENDE1T,ENDE2T,ICAPT,
        2  IFLOWT,ISTOP,IDEBUG
         COMMON /CAPS/ SAVCAP(5000)
         COMMON /ACC/ TMILES,TFLOW
         DATA TITLE/'CRUDE OIL ','PIPELINES:',' PUMPING E','NERGY     ',
        1                'OIL PRODUC','TS PIPELIN','ES: PUMPIN','G ENERGY'/
         DATA PRINT/302*.FALSE./
         DATA PRINT(32)/.TRUE./,PRINT(46)/.TRUE./,PRINT(72)/.TRUE./,
         PRINT(73)/.TRUE./,PRINT(84)/.TRUE./,PRINT(59)/.TRUE./
         DATA NETBUG/'JNHCRD.CO'/
C
C-------------INSTRUCTIONS START HERE----------------------
C
          ISTOP=0
          IDEBUG=0
C
10        TYPE 270
                  ACCEPT*,NEWNET
          IF(NEWNET.LT.1.OR.NEWNET.GT.2) GO TO 10
          TYPE 280,NEWNET
C
C
          CALL START(NEWNET,NEWCO)
C
C               NEWNET=1 TO USE POWER IN REGULAR WAY
C               NEWNET=2 TO REVISE NETWORK FILE FOR COMPANY
C               NEWNET WILL BE SUPPLIED BY USER FROM TERMINAL
C               NEWCO(CONO) IS REVISED COMPANY CODE CONO
C
         TYPE 290
C
C
          ACCEPT 300,NETWRK
C                TEMPORARY STATEMENT-REMOVE LATER
C        NETWRK=NETBUG
C
C
C
          TYPE 310,NETWRK
          OPEN(UNIT=1,DEVICE='DSK',FILE=NETWRK)
C
          IF(NEWNET.LE.1)GO TO 70
C
C        FOLLOWING SECTION OF CODE IS FOR USE WHEN NEWNET=2
C        REVISES NETWORK FILE BY REPLACING CONO WITH REPRNO
C        WHEN INDICATED BY CMPANY.IN FILE. THE NEW NETWORK
C        FILE IS NAMED 'NTWRK2.TMP' AND SHOULD NEXT BE SORTED
C        ON COMPANY CODE CONO. USE THIS FILE AS NETWORK FILE
C        IN ANOTHER RUN OF THIS PROGRAM WITH NEWNET SET = 1
C
          OPEN(UNIT=2,DEVICE='DSK',FILE='NTWRK2.TMP')
          ICARD=0
20        CONTINUE
          READ(1,320,END=50,ERR=60) (IDATA(I),I=1,6),ICO,   (IDATA(I),I=7
         116),IL
          IF(ICO.LT.-1.OR.ICO.GE. 250) GO TO 60
          IF(ICO.GE.191.AND.ICO.LT.200)GO TO 60
          IF(ICO.GT.0)ICO=NEWCO(ICO)
          WRITE(2,320,ERR=60) (IDATA(I),I=1,6),ICO,   (IDATA(I),I=7,16),I
30        ICARD=ICARD+1
          IF(IL.LE.0)GO TO 20
40        READ(1,330,END=50,ERR=60) (IDATA(I),I=1,16),IL
          WRITE(2,330,ERR=60) (IDATA(I),I=1,16),IL
          GO TO 30
50        CLOSE(UNIT=1)
          CLOSE(UNIT=2)
          TYPE 340,ICARD
          RETURN
60        TYPE 350,ICARD
          RETURN
C
C                INSTRUCTIONS FOR REGULAR USE OF POWER START HERE
C
C
70        CONTINUE
C
         TYPE 360
         ACCEPT *,POL
         TYPE 370,POL
C
         WRITE(6,380)  (TITLE(I,CH),I=1,4),POL,X,Y,Z,W
          OPEN(UNIT=23,DEVICE='DSK',FILE='CMPANY.TMP',
        1  ACCESS='RANDOM',MODE='ASCII',RECORD SIZE=92,
        2  ASSOCIATE VARIABLE=CONC,ERR=230)
C
          OPEN(UNIT=22,DEVICE='DSK',FILE='CAP.TMP',
        1  ACCESS='RANDOM',MODE='ASCII',RECORD SIZE=80,
        2  ASSOCIATE VARIABLE=IC,ERR=220)
C
          OPEN(UNIT=3,DEVICE='DSK',FILE='PIPES.TMP')
```

```
C
C       PIPES.TMP FILE WILL BE WRITTEN BY SUBROUTINE INIT
C       GIVING LINKS DATA FOR EACH COMPANY;
C       IT WILL BE READ BY INPUT SUBROUTINE IN FLOW SUBR.
C
C       GET FIRST COMPANY FROM NETWORK FILE TO BE PROCESSED
C
80        CALL READ2(1,NODET,NEXT,LNGTHT,PUMPST,CONOT,CONTYT,NPIPST,DIAMT,
        1  NFLOWT,FLOWT,NCAPT,CAPT,ENDE1T,ENDE2T,END,S,ICAPT,IFLOWT)
        IF(CONOT.EQ.0)   GO TO 80
C
C       READ2 SUBR. IS A SPECIAL VERSION OF THE USUAL READ
C       SUBR. USED TO READ A NETWORK FILE.
C       READ2 SUBR. GIVES CAP AND FLOW CONVERTED TO BBL/DAY
C
          IF(END.GT.0)GO TO 240
          CONO=CONOT
C
          IF(XDEBUG.GT.0)CALL TRYSUB
C
C       INITIALIZE TO ZERO SOME TOTALS; OTHER INITIALIZING ALSO
C
          DO 100 J=0,48
          DO 90 I=0,50
          TOTL(I,J)=0.0
          TOTHP(I,J)=0.0
90        TOTVL(I,J)=0.0
100       CONTINUE
          DO 110 I=0,50
        TRHO(I)=0.0
110       TRATIO(I)=0.0
C
          EPS=0.00015
          RMULT=1.0
          ZFIX=Z
          XFIX=X
          YFIX=Y
          WFIX=W
          ING=0
          IPRINT=6
        LAST=.FALSE.
C
C--     //START LOOP THRU COMPANIES//
C               LOOP WILL BE ACCOMPLISHED BY READING
C               NETWORK FILE IN SUBROUTINE INIT.
C               NETWORK FILE IS SORTED BY COMPANY CODE.
C
C
120       CONTINUE
          IF(CONO.EQ.0)GO TO 180
          Z=ZFIX
          X=XFIX
          TYPE 390,CONO
C
C       INITIALIZE SUMS TO ZERO FOR EACH NEW COMPANY
C
          DO 130 I=0,48
            SUMHP(I)=0.0
            SUML(I)=0.0
130         SUMVL(I)=0.0
          CUTIL=0.
          CTUTIL=0.
          CVLUTL=0.
          NCUTIL=0
          CRATE=0.
C--       //GET NEXT COMPANY CODE,DENSITY,VISCOSITY,MILES RATIO,Z,
C--                 PIPE MILES;PASS IN X, Y AND W//
        IF(PRINT(CONO)) WRITE(IPRINT,400)CONO,EPS
        IF(PRINT(CONO)) WRITE(IPRINT,410)
        IF(PRINT(CONO)) WRITE(IPRINT,420)
        IF(PRINT(CONO)) WRITE(IPRINT,430)
C
          CALL INIT(CH,CONO,RHO,NU,RATIO,SUML,X,Y,W,Z,CONAME,
         1          MITYPE,FLTYPE,REGULA)
C
C   MITYPE, FLTYPE ARE CATEGORIES J FOR TMILES(I,J), TFLOW(I,J), ETC.
C
C         //GET NEXT COMPANY CODE,DENSITY,VISCOSITY,
C         MILES RATIO,Z,PIPE MILES; PASS IN X,Y,AND W//
C
          IF(ISTOP.GT.0)RETURN
C         //ADJUST LENGTHS//
          DO 140 J=0,48,2
140         SUML(J)=SUML(J)*RATIO
          IF(IDEBUG.GT.0)  WRITE(6,440)CH,CONO,RHO,NU,RATIO,SUML,X,Y,W,Z
C
C         //START LOOP THRU COMPANY LINKS//
C         //GET NPIPES,NODE,D,L,V,S,LAST,FRAC;
C                 PASS IN Z,W,RATIO//
C
          J=0
150       CALL FLOW(POL,J,Z,W,RATIO,RHO,NU,EPS,NPIPES,
          1  NODE,D,L,V,S,RS,FS,HFS,PS,HPS,FRAC,UTIL,LAST)
C
C         //PASS IN POL,Z,W,RATIO,RHO,NU,EPS;
C                 GET NPIPES,NODE,...,LAST//
C
          IF(IDEBUG.GT.0)WRITE(6,450)POL,Z,W,RATIO,RHO,NU,EPS,  NPIPES,NODE,
          1D,L,V,S,RS,FS,HFS,PS,HPS,FRAC
C
            IF(LAST)GO TO 170
C
C         //WORK THROUGH PARALLEL PIPES IN LINK//
C
            DO 160 I=1,NPIPES
            R = RS(I)
            F = FS(I)
            HF = HFS(I)
            P = PS(I)
            HP = HPS(I)
C
C   MINILEXICON:
C         L = MAP MILES
```

```
C        AL = ADJUSTED MILES
C        V = DAILY THROUGHPUT WHILE PL IS RUNNING
C        AV = AVERAGE DAILY THROUGHPUT OVER THE YEAR.
C        //FIGURE ADJUSTED MILEAGE//
         AL = L * RATIO
C                 AVOID DIVIDING BY ZERO FOR ZERO-LENGTH LINKS.
         BL=AL
         IF(BL.EQ.0.)  BL=1.
         IF(L.LT.0..OR.R.LT.0.)  TYPE 460, NODE,L,R
         RP=HP*FRAC
         VL=V(I)*AL
         AV=V(I)*FRAC
         AVL=AV*AL
         VLMILL=VL*1.0E-6
         RPDL=RP/BL
         PDL=P/BL
C                 SWITCH HP TO KW.
         HPDL=0.46354*HP/BL
         IF(D(I).LE.12.5)ID=INT(D(I))
         IF(D(I).GT.12.5)ID=INT(D(I)+1.0)
         IL=INT(AL+0.5)
         IV=INT(V(I)+0.5)
         IHP=INT(HP+0.5)
         IP=INT(P+0.5)
C                 SWITCH HP TO KW.
        IHP=INT(HP*0.745+0.5)
       IF(PRINT(CONO))
     - WRITE(6,470)NODE,FRAC,ID,IL,IV,VLMILL,IHG,RHO,ND,R,F,HPDL,
     1IRP,PDL,IP,HPDI,IHP
C
           SUMHP(ID)=SUMHP(ID)+RP
           SUMHP(0)=SUMHP(0)+HP
           TOTHP(S,ID)=TOTHP(S,ID)+RP
           TOTHP(S,0)=TOTHP(S,0)+HP
           TOTHP(0,ID)=TOTHP(0,ID)+RP
           TOTHP(0,0)=TOTHP(0,0)+HP
           SUMVL(ID)=SUMVL(ID)+AVL
           SUMVL(0)=SUMVL(0)+AVL
           TOTVL(S,ID)=TOTVL(S,ID)+AVL
           TOTVL(S,0)=TOTVL(S,0)+AVL
           TOTVL(0,ID)=TOTVL(0,ID)+AVL
           TOTVL(0,0)=TOTVL(0,0)+AVL
           TRATIO(S)=TRATIO(S)+L
         TRATIO(0)=TRATIO(0)+L
           TOTL(S,ID)=TOTL(S,ID)+AL
           TOTL(0,ID)=TOTL(0,ID)+AL
           TOTL(S,0)=TOTL(S,0)+AL
           TOTL(0,0)=TOTL(0,0)+AL
         TRHO(0)=TRHO(0)+AVL*RHO
         TRHO(S)=TRHO(S)+AVL*RHO
           TUTIL(S)=TUTIL(S)+UTIL(I)
         TUTIL(0)=TUTIL(0)+UTIL(I)
         NUTIL(S)=NUTIL(S)+1
         NUTIL(0)=NUTIL(0)+1
         TVUTIL(S)=TVUTIL(S)+UTIL(I)*AV
         TVUTIL(0)=TVUTIL(0)+UTIL(I)*AV
         TVLUTL(S)=TVLUTL(S)+UTIL(I)*AVL
         TVLUTL(0)=TVLUTL(0)+UTIL(I)*AVL
         CUTIL=CUTIL+UTIL(I)
         NCUTIL=NCUTIL+1
         CVUTIL=CVUTIL+UTIL(I)*AV
         CVLUTL=CVLUTL+UTIL(I)*AVL
         TRATE(S)=TRATE(S)+AV
         TRATE(0)=TRATE(0)+AV
         CRATE=CRATE+AV
         TMILES(S,MITYPE)=TMILES(S,MITYPE)+AL
         TMILES(0,MITYPE)=TMILES(0,MITYPE)+AL
         TFLOW(S,FLTYPE)=TFLOW(S,FLTYPE)+AVL
         TFLOW(0,FLTYPE)=TFLOW(0,FLTYPE)+AVL
C
160        CONTINUE
           GO TO 150
170      LAST = .FALSE.
C
C        END OF LOOP THRU COMPANY LINKS,SIGNIFIED BY
C                 LAST=.TRUE.
C
           IF(IDEBUG.GT.0)CALL REPRT2(1,CONO,RHO,NU,SUML,RATIO,SUMHP,SUMVL)
         IF(PRINT(CONO))
     -   CALL REPORT(1,CONO,RHO,NU,SUML,RATIO,SUMHP,SUMVL,CONAME,
     -   NCUTIL,CUTIL,CVUTIL,CRATE,CVLUTL)
           CONO=CONOT
           GO TO 120
180        CONTINUE
C
C        END OF LOOP THROUGH COMPANIES, SIGNIFIED BY
C                 CONO = 0
C
C
C        NOTE THAT WE WILL USE SUML,SUMHP,AND SUMVL FOR
C        TEMPORARY LOCATIONS IN LAST TWO REPORTS, SINCE
C        THEY ARE NO LONGER NEEDED AT THIS POINT OF PROGRAM.
C
           DO 200 S=1,50
C
         IF(TOTL(S,0).LE.0.0)GO TO 200
C
           DO 190 J=0,48
           SUML(J)=TOTL(S,J)
           SUMHP(J)=TOTHP(S,J)
           SUMVL(J)=TOTVL(S,J)
190        CONTINUE
         TRATIO(S)=TOTL(S,0)/TRATIO(S)
         TRHO(S)=TRHO(S)/TOTVL(S,0)
           IST=S
           IF(IDEBUG.GT.0)CALL REPRT2(2,IST,0,0,SUML,TRATIO(IST),  SUMHP,
         1SUMVL)
           CALL REPORT(2,IST,TRHO(S),0,SUML,TRATIO(IST),
         1  SUMHP,SUMVL,CONAME,NUTIL(S),TUTIL(S),TVUTIL(S),TRATE(S),
         2  TVLUTL(S))
200      CONTINUE
           DO 210 J=0,48
           SUML(J)=TOTL(0,J)
```

```
      SUMHP(J)=TOTHP(0,J)
      SUMVL(J)=TOTVL(0,J)
210   CONTINUE
     TRATIO(0)=TOTL(0,0)/TRATIO(0)
     TRHO(0)=TRHO(0)/TOTVL(0,0)
      IF(IDEBUG.GT.0)CALL REPRT2(3,0,0,0,SUML,TRATIO(0),SUMHP,SUMVL)
      CALL REPORT(3,0,TRHO(0),0,SUML,TRATIO(0),SUMHP,SUMVL,
     1          CONAME,NUTIL(0),TUTIL(0),TVUTIL(0),TRATE(0),
     2          TVLUTL(0))
C
      RETURN
C           TROUBLE MESSAGES
220   TYPE 480
      RETURN
230   TYPE 490
      RETURN
240   IF(END.GT.1)GO TO 250
      TYPE 500
250   TYPE 510,CONO
      ISTOP=1
      RETURN
260  WRITE (5,460)L,R
      RETURN
C
270   FORMAT('  TYPE 1 FOR REGULAR USE OF POWER PROGRAM'/
     1 '  TYPE 2 FOR PRELIMINARY REVISION OF COMPANY CODES',
     2 /'  ON THE NETWORK FILE'$)
280   FORMAT('  CHOICE IS:'I3)
290   FORMAT('  TYPE NAME OF NETWORK FILE',/
     1 '  (SORTED BY COMPANY CODE):')
300   FORMAT(A10)
310   FORMAT('  NAME OF NETWORK FILE IS 'A10)
320   FORMAT(6A5,I3,9A5,A1,I1)
330   FORMAT(15A5,A4,I1)
340   FORMAT('  COMPANY CODES REVISED ON NETWORK FILE;'/
     1 '  NAME OF NEW NETWORK FILE IS NTWRK2.TMP'/
     2 '  NUMBER OF CARD-IMAGES READ WAS ' I7)
350   FORMAT('  TROUBLE WITH REVISING NETWORK FILE'/
     1 '  NUMBER OF CARD-IMAGES READ WAS'I7)
360   FORMAT(' WHICH CALCULATION METHOD?'$)
370   FORMAT(' POL='I4)
380   FORMAT('1',15(/,' '),29X,'*',/,30X,'*  ',4A10,
     1 /30X,'*',/,30X,'* ',
     2 ' CALCULATION METHOD NO. ',I2/30X,'*',5(/,' '),32X,
     3 'X =',F7.0,/,33X,'Y =',F9.5,/,33X,'Z =',F7.4,/,33X,
     4 'W =',F8.4)
390   FORMAT('  START PROCESSING FOR COMPANY CODE ',I4)
400  FORMAT('1   PIPELINE COMPANY - 'I4/
     1'     ROUGHNESS - ',F8.5,4(/,' '))
410   FORMAT(' NODE(1)  NODE(2)  FRACTION',2X,
     1 'DIAM LN   FLOW  BBL-MI  GRAV  DENS ',
     2' VISC  REYNOLDS  FRICTION  FRIC  FRIC PRESS  PR    AVG  ',
     3'  AVG ')
420  FORMAT(30X,'IN  MI   BBL/   /DAY   HEAD   LB/    C-    NUMBER   ',
     1' FACTOR   HEAD  HEAD DROP  DROP   POWER  POWER')
430  FORMAT(36X,'  DAY    MILL.   FT   CUFT  STOKES',19X,' FT/MI ',
     1'  FT PSI/MI  PSI   KW/KM   KW',2(/,' '))
440     FORMAT(' INIT OUTPUT-'2I5/(4E13.5))
450    FORMAT(' FLOW OUTPUT- 'I4/3E16.8/3E16.8/
     1  3I6/(3E16.8))
460    FORMAT(' CALCULATION TROUBLE:  NODES',2I6,'; L =',
     1              F5.0,'; R =',E8.2)
470    FORMAT(2X,I5,4X,I5,F10.4,4X,I2,I4,I8,F7.2,I6,F6.1,F7.3,E11.3,
     1F8.4,F7.2,I6,F6.2,I6,F6.1,I6)
480     FORMAT('  TROUBLE OPENING CAP.TMP FILE IN POWER')
490     FORMAT('  TROUBLE OPENING CMPANY.TMP FILE IN POWER')
500     FORMAT('  NO RECORDS APPEAR ON NETWORK FILE'/)
510     FORMAT('  TROUBLE WITH NETWORK FILE,CONO='I7)
        END
C
C
C-----------------------------------------------------------------
C
C
      SUBROUTINE READ2(UNIT,NODE,NEW,LENGTH,PUMPS,CMPANY,COUNTY,
     1NPIPES,DIAM,NFLOW,FLOW,NCAP,CAP,ENODE1,ENODE2,END,
     2IOUT,ICAP,IFLOW)
C
C     SUBROUTINE TO BE USED WITH POWER PROGRAM
C     BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
      DIMENSION NODE(2),IDD(16)
      COMMON ID(79,6)
      INTEGER UNIT,PUMPS(2),CMPANY,COUNTY(3),DIAM(9),
     1ENODE1(2,9),ENODE2(2,9),END,EN1,EN2
      DATA IBLANK/' '/,IZERO/'0'/
C
C*******SPECIAL VERSION OF READ SUBROUTINE USED FOR NETWORK FILE
C       THIS VERSION GIVES CAP AND FLOW IN BBL/DAY,
C       CONVERTED FROM THE UNITS FOUND ON THE FILE
C
C-----------PIPELINE FILE READER
C
C-----------EACH SUBROUTINE CALL CAUSES ONE RECORD TO BE READ
C-----------ONE RECORD MAY COVER 2 OR MORE CARDS
C
C-----------IOUT IS THE UNIT BEING USED FOR OUTPUT BY THE
C-----------      CALLING PROGRAM
C-----------       IOUT MAY BE USED FOR ERROR MESSAGES IN SUBR.
C-----------IDD(16) IS ALPHANUMERIC COPY OF CURRENT CARD BEING
C-----------       READ IN CASE OF ERROR
C-----------UNIT (INTEGER) / FILE UNIT NO. FROM WHICH DATA ARE READ
C-----------NODE(2) (INTEGER) / NODE(1) IS HEAD NODE NO.,COL 1-5
C-----------            NODE(2) IS TAIL NODE NO., COL7-11
C-----------NEW (INTEGER) / 0 IF BLANK,-1 IF ZERO, OTHERWISE N
C-----------       NEW IS READ ALPHANUMERIC, COL 6
C-----------LENGTH (INTEGER) / LENGTH OF SEGMENT,COL13-15
C-----------PUMPS(2) (INTEGER) / PUMPS(1) IS NO. PUMPING STATIONS
C-----------     AT HEAD NODE,COL26
C-----------          PUMPS(2) IS NO. PUMPING STATIONS
C-----------     AT TAIL NODE,COLS 28-29
C-----------CMPANY (INTEGER) / COMPANY CODE, COL 31-33
C-----------COUNTY(3) (INTEGER)  /CONTAINS COUNTY NAME
C-----------      5 CHARACTERS PER WORD IN ALPHANUMERIC FORMAT
```

```
C----------                    COL 35-49
C----------NPIPES (INTEGER) / NO. OF PARALLEL PIPES
C----------DIAM(9) (INTEGER) / DIAM(I) IS DIAMETER OF I-TH PIPE
C----------              COL.17-18, OTHERS OPTIONALLY
C----------NFLOW  (INTEGER) / NO. OF LINKS IN FLOW GROUP,IF ANY
C----------NCAP (INTEGER) / NO. OF LINKS IN CAPACITY GROUP,IF ANY
C----------FLOW (REAL) / FLOW IN GROUP,COL 20-24,MILLION BBL/YR
C----------CAP (REAL) /CAPACITY OF GROUP,COL 51-56,THOUSANDS BBL/DAY
C
C********BOTH CAP AND FLOW ARE CONVERTED TO BBL/DAY BY READ2 SUBR
C
C
C----------ENODE1(2,9) (INTEGER) / ENODE1(1,I) IS HEAD NODE
C----------      OF I-TH EXTRA LINK IN FLOW GROUP
C----------         ENODE1(2,I)  SAME FOR CAPACITY GROUP
C----------ICAP=RECORD NO. FOR CAPACITY GROUP
C----------IFLOW=RECORD NO. FOR FLOW GROUP
C----------ENODE2(2,9) (INTEGER) / TAIL NODES
C----------END (INTEGER) / END=1 WHEN END OF FILE IS REACHED
C----------    END=2 FOR ERROR, END=0 OTHERWISE
C
C
      END=0
      ICD=0
C----SECTION A
C-INITIALIZE QUANTITIES WHICH ARE TO BE FOUND OPTIONALLY
      NPIPES=1
      NFLOW=1
      NCAP=1
      DO 10 I=1,9
      DIAM(I)=0
      ENODE1(1,I)=0
      ENODE1(2,I)=0
      ENODE2(1,I)=0
10    ENODE2(2,I)=0
C-----SECTION B
C-READ A CARD OR CARDS(CONT) FOR A PIPELINE
      READ(UNIT,260,END=250,ERR=210)NODE(1),NEW,NODE(2),LENGTH,DIAM(1),
     1FLOW,PUMPS(1),PUMPS(2),CMPANY,COUNTY,CAP,ICAP,IFLOW,IC
C
C     CONVERT CAPACITY TO BBL/DAY
      CAP=CAP*1000.
C     CONVERT FLOW TO BBL/DAY
      FLOW=FLOW*1000000./365.
C
      IF(NEW.EQ.IBLANK)GO TO 20
      IF(NEW.EQ.IZERO)GO TO 30
      DECODE(1,270,NEW)NEW
      GO TO 40
20    NEW=0
      GO TO 40
30    NEW = -1
40    IF(IC.LT.1)RETURN
50    ICD=ICD+1
      IF(ICD.GE.7)  GO TO 240
      READ(UNIT,280,END=250,ERR=210)(ID(I,ICD),I=1,79),IC
      IF(IC.GE.1)GO TO 50
C-----SECTION C
C-START CHECK OF EXTENSION FIELD
C
C              ARRAY ID(79,6) CONTAINS CARD IMAGES, MAX 6
C              ICHAR IS A PLACE-MARKER ON THE CARD-IMAGE
C       J=1,2,3, IN THAT ORDER, ARE THE ONLY PERMISSIBLE VALUES
C
C    ICD=NUMBER CONTINUATION CARD IMAGES IN THIS RECORD
C    NCD=CURRENT CARD IMAGE BEING PROCESSED
      NCD=1
      J=ID(1,1)
      ICHAR=2
      IF(J.GT.3.OR.J.EQ.0)GO TO 230
60    IF(J-1) 70,80,110
70    IF(NCD.EQ.ICD)RETURN
      WRITE(IOUT,290)
      END=2
      RETURN
C-----SECTION D
C-CASE J=1. GET DIAM VALUES AND NEXT J VALUE.
80    NPIPES=ID(2,1)+1
      I=1
90    ICHAR=ICHAR+2
      I=I+1
      ICP1=ICHAR+1
      DIAM(I)=10*ID(ICHAR,1)+ID(ICP1,1)
      ICHAR=ICP1
      IF(I.LT.NPIPES)GO TO 90
      ICHAR=ICHAR+2
      J=ID(ICHAR,1)
      ICHAR=ICHAR+1
100   IF(J.EQ.1.OR.J.GT.3)GO TO 230
      GO TO 60
C-----SECTION E
C-CASE J=2 OR J=3.GET FLOW AND CAPACITY HEAD AND TAIL NODES.
110   CONTINUE
120   NLINKS=ID(ICHAR,NCD)
        IDIG=5
        IF(J.EQ.2)IDIG=4
        IDIGP1=IDIG+1
        IDIG2=2*IDIGP1
      IF(J.EQ.2)NFLOW=NLINKS+1
      IF(J.EQ.3)NCAP=NLINKS+1
      K=J-1
      ILK=0
C
C              K=1 FOR FLOW,K=2 FOR CAPACITY, IN
C              ENODE1(K,ILK) AND ENODE2(K,ILK)
C     ILK TRACKS THROUGH NUMBER OF LINKS
C
130   ILK=ILK+1
      IF(ILK.GT.NLINKS)  GO TO 180
      ILAST=78
      IF(NCD.EQ.ICD)ILAST=79
      IF(ILAST-ICHAR.LT.IDIG2)GO TO 160
140   CALL ENJ(NCD,ICHAR,EN1,IDIGP1)
      ENODE1(K,ILK)=EN1
```

```
150       CALL ENJ(NCD,ICHAR,EN2,IDIGP1)
          ENODE2(K,ILK)=EN2
          GO TO 130
160       IEN1=0
          IF(ILAST-ICHAR.LT.IDIGP1)   GO TO 170
          CALL ENJ(NCD,ICHAR,EN1,IDIGP1)
          ENODE1(K,ILK)=EN1
          IEN1=1
170       IF(NCD.GE.ICD)GO TO 70
          NCD=NCD+1
          ICHAR=-1
          IF(IEN1.LE.0)GO TO 140
          GO TO 150
C-----SECTION F
C-CHECK TO SEE IF WE HAVE JUST DONE J=3
180       IF(J.GE.3)GO TO 70
          ILAST=75
          IF(NCD.EQ.ICD)ILAST=76
          IF(ICHAR.GT.ILAST)GO TO 190
          ICHAR=ICHAR+2
          J=ID(ICHAR,NCD)
          ICHAR=ICHAR+1
          GO TO 200
190       IF(NCD.GE.ICD)GO TO 70
          NCD=NCD+1
          J=ID(1,NCD)
          ICHAR=2
200       IF(J.EQ.1.OR.J.EQ.2)GO TO 230
          GO TO 60
C-----SECTION G
C-ERROR MESSAGES
210       WRITE(IOUT,300)
220       END=2
          REREAD 310,(IDD(I),I=1,16)
          WRITE(IOUT,320)(IDD(I),I=1,16)
          RETURN
230       WRITE(IOUT,330)
          END=2
          RETURN
240       WRITE(IOUT,340)
          GO TO 220
250       END=1
          RETURN
260       FORMAT(I5,A1,I5,1X,I3,1X,I2,1X,F5.1,1X,I1,1X,I2,1X,I3,
          11X,3A5,1X,F6.0,13X,2(I4,1X),I1)
270       FORMAT(I5)
280       FORMAT(80I1)
290       FORMAT('  NUMBER OF CONTINUATIONS CONFLICTS WITH J VALUE',
          1 ' AND DATA')
300       FORMAT('   ERROR IN READ EXECUTION')
310       FORMAT(16A5)
320       FORMAT(5X,16A5)
330       FORMAT('   J VALUE NOT ALLOWED')
340       FORMAT('   NUMBER OF CONTINUATIONS EXCEEDS 6')
          END
C
C
C---------------------------------------------------------------------
C
C
          SUBROUTINE ENJ(NCD,ICHAR,EN1,IDIGP1)
C
C         SUBROUTINE TO BE USED WITH POWER PROGRAM
C         BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
          COMMON ID(79,6)
          INTEGER EN1
          EN1=ID(ICHAR+2,NCD)
          DO 10 I=3,IDIGP1
10        EN1=EN1*10 + ID(ICHAR+I,NCD)
          ICHAR=ICHAR+IDIGP1
          RETURN
          END
C
C
C---------------------------------------------------------------------
C
C
          SUBROUTINE PUMP2(DI,V,L,HG,RHO,NU,EPS,R,F,HF,P,HP,
          1UNIT2,IDEBUG)
C
C         SUBROUTINE TO BE USED WITH POWER PROGRAM
C         BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C************PUMP2 IS A SPECIAL VERSION OF SUBROUTINE PUMP
C         USED IN PIPLINE PROGRAM. PUMP2 RECEIVES INSIDE
C         DIAMETERS IN INCHES RATHER THAN NOMINAL DIAMETERS(IN.)
C
C
          INTEGER UNIT2
          REAL L,NU,LC,NUC
          DATA G/32.2/
C---/CALCULATE POWER CONSUMPTION AND HEAD OF A PARTICULAR
C--- SECTION OF PIPELINE/
C---VARIABLES PASSED IN TO SUBR:
C---------V - VOLUME RATE OF FLOW, BBL/DAY
C---------D - NOMINAL DIAMETER,IN.
C---------L - LENGTH,MI.
C---------HG - GRAVITY HEAD,FT.
C---------RHO - DENSITY,LB/CU.FT.
C---------NU - KINEMATIC VISCOSITY,CSTOKES
C---------EPS - ROUGHNESS
C---VARIABLES RETURNED BY SUBR:
C---------R - REYNOLD'S NUMBER
C---------F - FRICTION FACTOR
C---------HF - FRICTION HEAD,FT.
C---------P - PRESSURE DROP,LB/SQ.IN.
C---------HP - POWER CONSUMPTION
C---ALL VARIABLES REAL
          IF(IDEBUG.GT.0)WRITE(UNIT2,20)DI
          IF(DI.LE.0.0.OR.NU.LE.0.0)GO TO 10
          VC = 5.615*V/86400.0
C---VC IS V CONVERTED TO CU.FT./SEC(1BBL = 5.615 CU.FT.)
```

```
      DC = DI/12.0
C---DC IS D CONVERTED TO FT.
      LC = L*5280.0
C---LC IS L CONVERTED TO FT.
      NUC = NU/92903.0
C---NUC IS NU CONVERTED TO SQ.FT./SEC (1SQ.FT./SEC=92903 CSTOKES)
      PI=ACOS(-1.0)
C---CONVERTED QUANTITIES WILL BE USED IN CALCULATIONS
      IF(IDEBUG.GT.0)WRITE(UNIT2,30)DI,VC,DC,LC,NUC,PI
      R=4.0*VC/(PI*DC*NUC)
      IF(IDEBUG.GT.0)WRITE(UNIT2,40)R
      REPS=EPS/DC
C---------REPS IS ROUGHNESS RELATIVE TO CONVERTED DIAMETER
      F=FRIC(R,REPS)
      IF(F.LT.0.0)GO TO 10
      HF=F*(8.0*VC*VC*LC/(G*DC**5*PI*PI))
      P = (HF+HG)*RHO/144.0
      HP=P*72.0*VC/275.0
      IF(IDEBUG.GT.0)WRITE(UNIT2,50)R,F,HF,P,HP
      RETURN
10    H=-100.0
      IF(IDEBUG.GT.0)WRITE(UNIT2,50)R,F,HF,P,HP
C---H = -100 MEANS PROBLEM IN SUBR.
      RETURN
20    FORMAT('  DI = 'E15.8)
30    FORMAT('   DI,VC,DC,LC,NUC,PI= '/(4E15.8))
40    FORMAT('  R=  'E15.8)
50    FORMAT('   R,F,HF,P,HP= '/(4E15.8))
      END
C
C
C------------------------------------------------------------------
C
C
      FUNCTION FRIC(R,EPS)
C
C     FUNCTION TO BE USED WITH POWER PROGRAM
C     BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C
C---------/USE REGRESSION FORMULA TO COMPUTE FRICTION FACTOR/
C---R - REYNOLD'S NO.
C---EPS - ROUGHNESS RELATIVE TO CONVERTED DIAMETER
C---A(I,J) IS COEFFICIENT OF R**(I-1)E**(J-1) TERM IN F(R,E)
C---F(R,E) IS QUINTIC REGRESSION FORMULA FOR LOGS
C--   PROGRAM CALCULATES VALUE OF POLONOMIAL
C
C
      DIMENSION A(6,6),C(6),D(6)
       DATA(A(I,1),I=1,6)/-1.29717905,0.0,0.0,0.03979336,
     1 -0.00623620,.00005803/
      DATA(A(I,2),I=1,6)/0.0,-0.17592600,0.27704850,
     1 -0.03852152,0.00026943,0.0/
      DATA(A(I,3),I=1,6)/0.0,0.27214050,-0.01653602,
     1 -0.00326456,0.,0./
      DATA(A(I,4),I=1,6)/0.13828152,0.02264316,-0.00505742,
     1 3*0.0/,(A(I,5),I=1,6)/0.02515647,-0.00176603,4*0.0/,
     2 (A(I,6),I=1,6)/0.00088359,5*0.0/
      IF(R.LE.0.OR.EPS.LE.0)GO TO 10
      RR=ALOG10(R)
      REPS=ALOG10(EPS)
      D(6)=A(6,1)
      D(5)=A(5,2)*REPS+A(5,1)
      C(3)=A(4,3)
      C(2)=A(4,2)
      C(1)=A(4,1)
      D(4)=P(3,C,REPS)
      C(4)=A(3,4)
      C(3)=A(3,3)
      C(2)=A(3,2)
      C(1)=A(3,1)
      D(3)=P(4,C,REPS)
      C(5)=A(2,5)
      C(4)=A(2,4)
      C(3)=A(2,3)
      C(2)=A(2,2)
      C(1)=A(2,1)
      D(2)=P(5,C,REPS)
      C(6)=A(1,6)
      C(5)=A(1,5)
      C(4)=A(1,4)
      C(3)=A(1,3)
      C(2)=A(1,2)
      C(1)=A(1,1)
      D(1)=P(6,C,REPS)
      F=P(6,D,RR)
      FRIC=10.0**F
      RETURN
10    FRIC=-100.
C-------FRIC=-100 SIGNIFIES PROBLEMS IN CALCULATION
      RETURN
      END
C
C
C------------------------------------------------------------------
C
C
      FUNCTION P(N,C,X)
C
C     FUNCTION TO BE USED WITH POWER PROGRAM
C     BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
      DIMENSION C(N)
      DOUBLE PRECISION CC(6),XX,PP
C----------FUNCTION TO CALCULATE VALUE OF POLYNOMIAL IN X
C----------MAX DEGREE OF POLYNOMIAL IS QUINTIC
C----------N IS ONE DEGREE HIGHER THAN DEGREE OF POLYNOMIAL
C----------C(I) IS COEFFICIENT OF X**(I-1)
C----------CALCULATIONS DONE DOUBLE PRECISION
      DO 10 I=1,N
10    CC(I)=DBLE(C(I))
      XX=DBLE(X)
      PP=CC(N)
```

```
      NM1=N-1
      DO 20 I=1,NM1
20    PP=PP*XX+CC(N-I)
      F=SNGL(PP)
      RETURN
      END
C
C
C-----------------------------------------------------------------
C
C
      REAL FUNCTION INSIDE(D,UNIT2,IDEBUG)
C
C     FUNCTION TO BE USED WITH POWER PROGRAM
C     BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C
C---/CONVERT NOMINAL DIAMETER TO INSIDE DIAMETER/
C---D(REAL) /NOMINAL DIAM,IN./
C---WALL(48) (REAL) /TYPICAL WALL THICKNESS/
      DIMENSION WALL(48)
      INTEGER UNIT2
      DATA (WALL(I),I=1,48)/12*0.25,12*0.312,
      110*0.375,8*0.406,6*0.625/
      ID=INT(D+0.5)
C    IF(IDEBUG.GT.0)WRITE(UNIT2,222)ID
      IF(ID.LT.1.OR.ID.GT.48)GO TO 40
      IF(ID.LE.12)GO TO 10
       OD=D
      GO TO 30
10    IF(ID.LE.8)GO TO 20
      OD=D+0.75
      GO TO 30
20    OD = D+0.625
30    W = -WALL(ID)
      IF(IDEBUG.GT.0)WRITE(UNIT2,60)OD,W
      INSIDE=OD+W+W
      IF(IDEBUG.GT.0)   WRITE(UNIT2,70)INSIDE
      RETURN
40    INSIDE = -100.
C---INSIDE=-100 SIGNIFIES TROUBLE IN CALCULATIONS
      RETURN
50    FORMAT('  ID= 'I30)
60    FORMAT('   OD,W = '2E15.8)
70    FORMAT('  INSIDE = 'E15.9)
      END
C
C
C-----------------------------------------------------------------
C
C
        SUBROUTINE START(NEWNET,NEWCO)
C
C     SUBROUTINE TO BE USED WITH POWER PROGRAM
C     BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C--   SUBROUTINE USED BY POWER SUBROUTINE
C--   PREPARES FILES FOR INIT SUBR. IN POWER
C
C            NEWNET=1 FOR REGULAR RUN OF POWER SUBROUTINE
C            NEWNET=2 TO MAKE NEW NETWORK TAPE ONLY
C     FOR A REGULAR RUN OF POWER:
C
C
C--   WRITES EACH RECORD OF CAP.OBS IN THE RANDOM ACCESS
C--          FILE CAP.TMP
C--   EACH RECORD'S POSITION = CAPACITY NUMBER(IC)
C
C--   WRITES EACH RECORD OF CMPANY.IN IN THE RANDOM ACCESS
C--          FILE CMPANY.TMP
C--   EACH RECORD'S POSITION =COMPANY CODE
C
C--   CAP.OBS = CAPACITY GROUP FILE, NAME SUPPLIED BY USER
C            IC=CAPACITY GROUP NUMBER
C            NUMIC=NUMBER OF PIPES IN GROUP
C            CIC=TOTAL CAPACITY OF GROUP,E6 BBL,/YEAR
C            DIC(J)=DIAMETER OF PIPE J,NOMINAL, IN.
C
C--   CMPANY.IN=COMPANY INFO FILE
C            NAME(5)=NAME OF COMPANY
C            CONO=COMPANY NUMBER
C            CRFLOW(1)=CRUDE FLOW,E6 BBL-MI.(FORM P)
C            CRFLOW(2)=SAME(OIL & GAS JOURNAL)
C            PRFLOW(1)=PRODUCTS FLOW,E6 BBL-MI.(FORM P)
C            PRFLOW(2)=SAME(OIL & GAS JOURNAL)
C            REPPNO=ANOTHER COMPANY NUMBER FOR DATA
C            MIX(7)=CRUDE,GASOLINE,KEROSENE,FUEL OIL,
C                  JET FUEL,LPG,AMMONIA PERCENTAGES
C            NEWCO(CONO)=REF CODE ASSIGNED TO CONO
C                  BY REPPNO, IF ANY
C            MILES(1)=MILES OF CRUDE PIPELINE FOR CO.
C            MILES(2)=MILES OF PRODUCTS PIPELINE FOR CO.
C
C
        INTEGER CONO,REPPNO,
     1  CRFLOW(2),PRFLOW(2),REGULA
      DOUBLE PRECISION CAPOBS
        DIMENSION DIC(9),NAME(5),MIX(7),
     1  NEWCO(250),MILES(2)
C
        DATA IDEBUG/0/
        DO 10 I=1,250
10      NEWCO(I)=0
C
        IF(NEWNET.GE.2)GO TO 40
C
C            FIRST, CAPACITY DATA
C
        N=-1
      TYPE 110
      ACCEPT 120,CAPOBS
        OPEN(UNIT=20,DEVICE='DSK',FILE=CAPOBS,RPR=70)
```

```
C
C
      OPEN(UNIT=22,DEVICE='DSK',FILE='CAP.TMP',
     1  ACCESS='RANDOM',MODE='ASCII',RECORD SIZE=80,
     2  ASSOCIATE VARIABLE=IC,ERR=80)
      N=0
20    CONTINUE
      READ(20,*,ERR=70,END=30)IC,NUMIC,CIC,(DIC(J),J=1,NUMIC)
C
      IF(IDEBUG.GT.0)     WRITE(5,130,ERR=80)IC,NUMIC,CIC,(DIC(J),J=1,
     1NUMIC)
C
      N=N+1
      IF(IC.NE.N.OR.NUMIC.GT.9)GO TO 90
      WRITE(22#IC,130,ERR=80)IC,NUMIC,CIC,(DIC(J),J=1,NUMIC)
      GO TO 20
30    CLOSE(UNIT=22)
      CLOSE(UNIT=20)
      TYPE 140,N
      NCAPGP=N
C
40    CONTINUE
      N=-1
C
C
C           NEXT, COMPANY DATA
C
      OPEN(UNIT=21,DEVICE='DSK',FILE='CMPANY.IN',ERR=70)
      IF(NEWNET.LE.1)OPEN(UNIT=23,DEVICE='DSK',   FILE='CMPANY.TMP',
     1  ACCESS='RANDOM',MODE='ASCII',RECORD SIZE=92,
     2  ASSOCIATE VARIABLE=CONO,ERR=80)
      N=0
50    CONTINUE
      READ(21,150,ERR=70,END=60)NAME,CONO,CRFLOW,PRFLOW,   REPRNO,MIX,
     1MILES,REGULA
      N=N+1
      IF(CONO.LE.0.OR.CONO.GE.250)GO TO 70
      IF(CONO.GE.191.AND.CONO.LT.200)GO TO 70
      IF(REPRNO.LE.0)NEWCO(CONO)=CONO
      IF(REPRNO.GT.0)NEWCO(CONO)=REPRNO
      IF(NEWNET.GE.2)GO TO 50
C
      WRITE(23#CONO,150,ERR=80)NAME,CONO,CRFLOW,PRFLOW,REPRNO,   MIX,
     1MILES,REGULA
      IF(IDEBUG.GT.0)WRITE(5,150,ERR=80)NAME,CONO,CRFLOW,PRFLOW,
     1  REPRNO,MIX,MILES,REGULA
C
      GO TO 50
60    CLOSE(UNIT=21)
      IF(NEWNET.LE.1)CLOSE(UNIT=23)
      TYPE 160,N
      NCOMPY=N
      RETURN
70    TYPE 170,N
      RETURN
80    TYPE 180,N
      RETURN
90    TYPE 190,IC
      RETURN
100   TYPE 200,CONO
      RETURN
110   FORMAT(' TYPE NAME OF CAPACITY OBSERVATIONS FILE')
120   FORMAT(A10)
130   FORMAT(I4,I1,F12.7,9F7.3)
140   FORMAT('  NUMBER OF CAPACITY RECORDS IS 'I5)
150   FORMAT(4A5,A4,I3,2X,4I6,8I3,3X,2I5,I2)
160   FORMAT('  NUMBER OF COMPANY RECORDS IS 'I5)
170   FORMAT('  TROUBLE IN INPUT FILES',I5)
180   FORMAT('  TROUBLE IN OUTPUT FILES',I5)
190   FORMAT('  TROUBLE WITH CAPACITY NUMBER ' I5)
200   FORMAT('  TROUBLE WITH COMPANY CODE ',I5)
      END
C
C
C-----------------------------------------------------------------
C
C
      SUBROUTINE INIT(CR,CONO,RHO,NU,RATIO,STEL,XFIX,Y,W,Z,CON
     1            MITYPE,FLTYPE,REGULA)
C
C     SUBROUTINE TO BE USED WITH POWER PROGRAM
C     BY J.N. HOCKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C--   //COMPUTE RHO,NU,RATIO,PIPE LENGTHS AND PARAMETER Z//
C--   //PASS IN XFIX,ZFIX,Y,W(PARAMETERS)//
C
C--FOLLOWING QUANTITIES ARE TYPE INTEGER
C     CONO - COMPANY CODE
C     CR - VALUE 1 IS CRUDE,2 IS PRODUCTS
C     NODE(2) - NODE NUMBERS
C     LENGTH - PIPE SEGMENT LENGTH
C     FUMES(2)
C     COUNTY(3)
C     NPIPES - NO. OF PARALLEL PIPES
C     DIAM(9) - DIAMETERS OF PARALLEL PIPES
C     NFLOW - SIZE OF FLOW GROUP
C     NCAP - SIZE OF CAPACITY GROUP
C     ENODE1(2,9),ENODE2(2,9) - NOT USED HERE
C     END
C     IOUT - OUTPUT UNIT FOR RESULTS PRINTED
C     ICAP - RECORD NO. FOR CAPACITY GROUP
C     IFLOW - RECORD NO. FOR FLOW GROUP
C     S - STATE CODE
C     MIX(7) - % OF PRODUCT I DELIVERED BY COMPANY
C             I        PROD.
C             1        CRUDE OIL
C             2        GASOLINE
C             3        KEROSENE
C             4        FUEL OIL
C             5        JET FUEL
C             6        LPG
C             7        AMMONIA
C
```

```
C       MILES(1)=MILES OF CRUDE PIPELINE FOR COMPANY
C       MILES(2)=MILES OF PRODUCTS PIPELINE FOR COMPANY
C--FOLLOWING QUANTITIES ARE TYPE REAL
C       FLOW - FLOW IN FLOW GROUP,READ2 BBL/DAY BY READ2 SUBR.
C       CAP - CAPACITY OF GROUP,READ2 BBL/DAY BY READ2 SUBR.
C       COFLOW - COMPANY FLOW,MILLION BBL-MILES/YR IN CMPANY.IN FILE
C       RHO - DENSITY, LB/CU.FT.
C       NU - KINEMATIC VISCOSITY, CSTOKES
C       RATIO, ADJUSTED-MILES/MAP-MILES
C       SUML(0:48) - PIPE MILES OF DIAM(I);AND TOTAL FOR CO.
C       Y - PARAMETER IN REGRESSION FORMULA
C       DEN(7) - DENSITY OF PROD I ,LB/CU.FT.
C       VIS(I) - VISCOSITY OF PROD I, CSTOKES
C       L - SEGMENT LENGTH
C       D(9) - DIAMETER OF PIPE I
C       YPXT - GIVEN VALUE OF REGRESSION PARAMETER
C       DC(20) - DIAMETERS IN CAPACITY GROUP
C       JJ - PIPE COUNTER, IN THE ORDER THEY APPEAR IN NETWORK FILE
C       SAVCAP(JJ) = CAPACITY OF PIPE JJ; NEGATIVE IF ESTIMATED
C                     SOLELY FROM REGRESSION FORMULA.
C       C(20) - CAPACITIES IN GROUP
C
C--FOLLOWING QUANTITIES ARE ONLY TEMPORARY LOCATIONS:
C       NODET,NEWT,LNGTHT,PUMPST,CONOT,CONTYT,NPIPST,
C       NFLOWT,FLOWT,NCAPT,CAPT,ENDE1T,ENDE2T,ICAPT,IFLOWT
C
C
          INTEGER CONO,CH,REPRNO,CRFLOW(2),PRFLOW(2),BBLMI(2,2),
     1     PUMPS(2),COUNTY(3),DIAM(9),S,END,
     2     PUMPST(2),CONOT,CONTYT(3),DIAMT(9),ENDE1T(2,9),
     3     ENDE2T(2,9),ENODE1(2,9),ENODE2(2,9),CONAME(4),PLTYPE,
     4     REGULA
          REAL NU,L,INSIDE
          DIMENSION NAME(5),DEN(7),VIS(7),MIX(7),NODE(2),
     1     NODET(2),SUML(0:48),D(9),DC(20),C(20),MILES(2)
          EQUIVALENCE(BBLMI(1,1),CRFLOW(1)),(BBLMI(2,1),CRFLOW(2)),
     1     (BBLMI(1,2),PRFLOW(1)),(BBLMI(2,2),PRFLOW(2))
C
          COMMON/TEMPRY/NODET,NEWT,LNGTHT,PUMPST,CONOT,CONTYT,NPIPST,
     1     DIAMT,NFLOWT,FLOWT,NCAPT,CAPT,ENDE1T,ENDE2T,ICAPT,
     2     IFLOWT,ISTOP,IDEBUG
        COMMON / CAPS/ SAVCAP(5000)
C
        DATA DEN/53.04,45.6,50.5,51.8,48.7,33.7,40.9/,
     1            VIS/7.5,0.64,2.2,3.0,1.2,0.3,1.0/
C
C       //COMPUTE RHO,NU//
C
C       INITIALIZE PIPE COUNTERS
        J = 0
        JJ = 0
10      COFLOW=-1.0
          MITYPE=0
        PLTYPE=0
        IF(CONO.LT.0) GO TO 70
          READ(23'CONO,300,ERR=270)CONAME,CONO,CRFLOW,PRFLOW,REPRNO,  MIX,
     1MILES,REGULA
          IF(IDEBUG.GT.0)     WRITE(6,300)CONAME,CONO,CRFLOW,PRFLOW,REPR
     1     MIX,MILES,REGULA
C       MEANINGS OF VARIABLES READ FROM CMPANY.TMP
C       OF UNIT 23, ARE GIVEN IN COMMENTS OF START SUBR.
C
          IF(REPRNO.EQ.0)GO TO 20
          IF(CONO.NE.REPRNO)GO TO 250
C
C
C
C       WE USE FORM P FIGURE FOR COMPANY FLOW
C              ONLY WHEN IT IS POSITIVE AND
C              OIL AND GAS JOURNAL FIGURE IS ZERO
C
20        CONTINUE
          IF(BBLMI(2,CH).LE.0)GO TO 30
          COFLOW=BBLMI(2,CH)
          GO TO 40
30        IF(BBLMI(1,CH).LE.0)GO TO 40
          COFLOW=BBLMI(1,CH)
C
C
40        CONTINUE
C
C       DETERMINE CATEGORY OF COMPANY (SEE DICTIONARY ENTRY
C       FOR TUTIL, ETC., IN SUBROUTINE POWER).
C
        PLTYPE=1
        IF(COFLOW.LE.0.)  PLTYPE=2
        IF(REGULA.EQ.0)   PLTYPE=-PLTYPE
        MITYPE=1
        IF(MILES(CH).LE.0)   MITYPE=2
        IF(PLTYPE.LT.0)   MITYPE=-MITYPE
C                TREAT CRUDE LINES SEPARATELY.
        IF(CH.EQ.1)   GO TO 80
          MIXTOT=0
          DO 50 I=2,7
50        MIXTOT=MIXTOT+MIX(I)
        IF(MIXTOT+MIX(1).NE.100)   GO TO 70
        IF(MIXTOT.EQ.0)   GO TO 70
          RHO=0.0
          NU=0.0
C                PRODUCTS MIX FRACTIONS MUST BE NORMALIZED.
        FACTOR=100./FLOAT(MIXTOT)
          DO 60 I=2,7
          ZMIX=FLOAT(MIX(I))*FACTOR
          RHO=RHO+ZMIX*DEN(I)
          NU=NU+ZMIX*VIS(I)**0.252
60        CONTINUE
        RHO=RHO/100.
          NU=(NU/100.)**(1.0/.252)
          GO TO 90
70        RHO=49.4
          NU=1.5
        GO TO 90
80      RHO=DEN(1)
        NU=VIS(1)
```

```
90      CONTINUE
C
C
C       NETWORK FILE IS PRE-SORTED BY REVISED COMPANY CODES
C
C
C       UNIT 3 IS PIPES.TMP FILE WHICH WILL BE WRITTEN
C       BY SUBR. INIT FOR THE COMPANY
C
          REWIND 3
        SUM=0.0
          LASTCO=CONO
          GO TO 110
100       CONTINUE
          CALL READ2(1,NODET,RENT,LNGTHT,PUMPST,CONOT,CONTYT,NPIPST,DIAMT,
        1  NFLOWT,FLOWT,NCAPT,CAPT,ERDEIT,ERDEST,END,5,ICAPT,IFLOWT)
C
          IF(END.GT.0)GO TO 240
          IF(IDEBUG.GT.0)CALL TRYSUB
C
        IF(CONOT.EQ.0)GO TO 100
          IF(CONOT.NE.CONO) GO TO 200
C
110       CONTINUE
C
C                CONTINUE PROGRAM
          DO 120 I=1,9
120       DIAM(I)=DIAMT(I)
          DO 130 I=1,3
130       COUNTY(I)=CONTYT(I)
          DO 140 I=1,2
          NODE(I)=NODET(I)
140       PUMPS(I)=PUMPST(I)
          NEW=NENT
          LENGTH=LNGTHT
          NPIPES=NPIPST
          NFLOW=NFLOWT
          FLOW=FLOWT
          NCAP=NCAPT
          CAP=CAPT
          ICAP=ICAPT
          IFLOW=IFLOWT
C
          L=FLOAT(LENGTH)
          DO 150 I=1,NPIPES
        DCONV=INSIDE(FLOAT(DIAM(I)),6,IDEBUG)
        IF(DCONV.LE.-1.)  TYPE 310, NODET,DIAM(I)
        IF(DCONV.LE.-1.)  DCONV=1.
150       D(I)=DCONV
C
C       PROCESS THIS LINK IN THE CURRENT COMPANY
C
          X=XPIX
          S=NODE(1)/1000
        IF(S.EQ.99) S=43
C
C       SEE IF THERE IS A CAPACITY GROUP FOR THIS LINK
C       IF YES, GET CAPACITY GROUP DIAMETERS
C
          IF(ICAP.EQ.0)GO TO 170
          READ(22#ICAP,320,ERR=290)ICAP,NUMIC,RCAP,(DC(J),J=1,NUMIC)
C       CONVERT CAPACITY TO BBL/DAY
        RCAP=RCAP*1000.
C
          IF(CAP.NE.RCAP)GO TO 290
C              COMPUTE PARAMETER X
          DENOM=0.0
          DO 160 I=1,NUMIC
          DCONV=INSIDE(DC(I),6,IDEBUG)/12.0
        IF(DCONV.LE.-1.)  TYPE 330, NODET,DC(I)
        IF(DCONV.LE.-1)   DCONV=1.
160       DENOM=DENOM+DCONV**Y
          X=CAP/DENOM
        IF(IDEBUG.GT.0)  WRITE(6, 340)CAP,DENOM,X
C       ABOVE IS TEMPORARY DEBUG PRINT
C
C
C       SUM MILEAGE AND COMPUTE CAPACITIES
C
170     CONTINUE
          DO 180 I=1,NPIPES
          JJ = JJ + 1
          SUML(DIAM(I))=SUML(DIAM(I))+L
        SUML(0)=SUML(0)+L
          C(I)=X*(D(I)/12.)**Y
C-------IF ICAP = 0 THEN NO COMPANY CAPACITY INFO WAS AVAILABLE
        SAVCAP(JJ) = C(I)
180     IF(ICAP.EQ.0)  SAVCAP(JJ) = -C(I)
C
C       SAVE DATA FOR LATER USE BY WRITING ON PIPES.TMP FILE
C
          WRITE(3,350,ERR=260)NPIPES,S,NODE,L,   (D(I),C(I),I=1,NPIPES)
C
C       KEEP RUNNING TOTAL FOR COMPUTATION OF Z
C
          DO 190 I=1,NPIPES
190       SUM=SUM+C(I)*(D(I)/12.)**W*L
        IF(IDEBUG.GT.0)WRITE(6, 360)SUM
          GO TO 100
200       CONTINUE
          ENDFILE 3
          REWIND 3
C
C       COMPUTE RATIO
C
230     IF(SUML(0).LE.0.0)GO TO 290
        RATIO=1.0
        IF(CONO.GT.0.AND.MILES(CN).GT.0)     RATIO=FLOAT(MILES(CN))/SUM
C-------IF RATIO<0.95, THEN COMPANY MILES DATA FROM OIL & GAS
C-------JOURNAL MUST BE WRONG; THIS HAPPENED WITH SHELL PL.
        IF(RATIO.LT.0.95)  RATIO=1.
          SUM=SUM*RATIO
C
C       COMPUTE Z
```

```
C
          IF(COFLOW.LE.-1.0)RETURN
          Z=(COFLOW*1000000./365.)/STM
C
          RETURN
C
C       REMAINING INSTRUCTIONS ARE ERROR AND TROUBLE MESSAGES
C
220       TYPE 370,CONO,CONOT
          ISTOP=1
          RETURN
230     TYPE 330,NODET,ID,CONO,ICAP
C  993  FORMAT(' TROUBLE WITH INSIDE DIAMETER; NODES,ID,CONO,ICAP,
C     -              =',2I5,I4,I4,I5)
          ISTOP=1
          RETURN
240       IF(END.GT.1)GO TO 270
          CONOT=0
          GO TO 200
C
250       TYPE 380,CONO,REPRNO
          ISTOP=1
          RETURN
260       TYPE 390,CONO
          ISTOP=1
          RETURN
270       TYPE 400,CONO
          ISTOP=1
          RETURN
280       TYPE 410,ICAP,CAP,RCAP,NODE
          ISTOP=1
          RETURN
290     TYPE 420,CONO,SUML(0)
        ISTOP=1
        RETURN
C
300       FORMAT(4A5,4X,I3,2X,4I6,5I3,3X,2I5,I2)
310     FORMAT(' INSIDE DIAMETER TROUBLE; NODES=',2I6,';',
        1              ' DIAM =',I3)
320       FORMAT(I4,I1,F12.7,9F7.3)
330     FORMAT(' INSIDE DIAMETER TROUBLE; NODES = ',2I6,
        1              '; DIAM =',F6.2)
340     FORMAT('  CAP,DENOM,X= '3E15.7)
350       FORMAT(2I2,2I5,F6.0,(2F12.5))
360     FORMAT('  SUM= 'E15.8)
370       FORMAT('  TROUBLE WITH SEQUENCE COMPANY CODES',
        1  ' IN NETWORK FILE;CONO=',I5,' CONOT=',I5)
380       FORMAT('  TROUBLE WITH CONO= 'I5,'  REPRNO= 'I5)
390       FORMAT('  TROUBLE WRITING PIPES.TMP CONO='I5)
400       FORMAT('  TROUBLE WITH NETWORK FILE,CONO='I7)
410       FORMAT('  TROUBLE WITH CAP FILE;ICAP=',I5,
        1  '  CAP= 'F15.5,'RCAP= 'F15.5,/X,'NODES = ',2I6)
420     FORMAT(' COMPANY NO.' I4,' SUML(0)= 'E16.8)
          END
C
C
C-----------------------------------------------------------------
C
C
          SUBROUTINE INPUT(J,Z,W,NPIPES,RATIO,NODE,D,L,V,S,LAST)
C
C       SUBROUTINE TO BE USED WITH POWER PROGRAM
C       BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C--     REAL QUANTITIES:
C       Z,W, - REGRESSION PARAMETERS
C       D(9) - DIAMETERS,INCHES
C       L - LENGTH,MILES
C       V(9) - FLOWS,BBL/DAY AND C(9) - CAPACITIES OF PIPES
C--     INTEGER QUANTITIES
C       S - STATE CODE
C       NODE(2) - NODES
C--     LOGICAL QUANTITY LAST - END OF FILE CODE
C
          INTEGER S
          REAL L
          LOGICAL LAST
          DIMENSION C(9),NODE(2),D(9),V(9)
C
C                THIS SUBROUTINE RETURNS NECESSARY INFORMATION
C                FOR ONE LINK IN A COMPANY
C
C---------READ RECORD FROM PIPES.TMP PREPARED BY INIT SUBR.
C
          READ(3,40,ERR=20,END=30)NPIPES,S,NODE,L,  (D(I),C(I),I=1,NPIPES)
C
C       //COMPUTE FLOW//
          DO 10 I=1,NPIPES
        J = J + 1
10        V(I)=Z*C(I)*(D(I)/12.)**W
          RETURN
20        TYPE 50,CONO
          RETURN
30        LAST=.TRUE.
          RETURN
40        FORMAT(2I2,2I5,F6.0,(2F12.5))
50        FORMAT('  TROUBLE READING PIPES.TMP FILE IN INPUT SUBR.')
          END
C
C
C-----------------------------------------------------------------
C
C
          SUBROUTINE REPRT2(K,CONO,RHC,NU,SUML,RATIO,SUMHP,
        1  SUMVL,IUTIL,PUTIL,PVUTIL,PVLUTIL)
C
C       SUBROUTINE TO BE USED WITH POWER PROGRAM
C       BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C       TEMPORARY DEBUG SUBROUTINE
C
          REAL NU
          DIMENSION SUML(0:48),SUMHP(0:48),SUMVL(0:48),
```

```
      1              TMILES(0:50,-2:2),TFLOW(0:50,-2:2)
        GO TO (10,20,30)K
10      WRITE(6,50)CONO,RHO,NU
        GO TO 40
20      WRITE(6,60)CONO,CONO
        GO TO 40
30      WRITE(6,70)
40      CONTINUE
        WRITE(6,170)SUML
      IF(K.EQ.1)WRITE(6,80)
      IF(K.EQ.2)WRITE(6,90),CONO
      IF(K.EQ.3)WRITE(6,100)
        WRITE(6,170)RATIO
      IF(K.EQ.1)WRITE(6,110)
      IF(K.EQ.2)WRITE(6,120)CONO
      IF(K.EQ.3)WRITE(6,130)
        WRITE(6,170)SUMHP
      IF(K.EQ.1)WRITE(6,140)
      IF(K.EQ.2)WRITE(6,150)CONO
      IF(K.EQ.3)WRITE(6,160)
        WRITE(6,170)SUMVL
        RETURN
50      FORMAT(' COMPANY'I5,' SUMMARY'/
      1  ' RHO=' E13.5,' NU=' E13.5/' SUML(*)=')
60      FORMAT(' STATE'I4' TOTALS'/' TOTL(',I3,',*)=')
70      FORMAT(' NATIONAL TOTALS'/' TOTL(0,*)=')
80    FORMAT(' RATIO=')
90    FORMAT(' TRATIO(',I3,')=')
100   FORMAT(' TRATIO(0)=')
110   FORMAT(' SUMHP(*)=')
120   FORMAT(' TOTHP('I3,',*)=')
130   FORMAT(' TOTHP(0,*)=')
140   FORMAT(' SUMVL(*)=')
150   FORMAT(' TOTVL('I3,',*)=')
160   FORMAT(' TOTVL(0,*)=')
170     FORMAT(/,' ',/(8E15.5))
        END
C
C
C-----------------------------------------------------------------------
C
C
      SUBROUTINE TRYSUB
C
      SUBROUTINE TO BE USED WITH POWER PROGRAM
C     BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C-----------PRINT RESULTS OF READ OR READ2 SUBROUTINE----------
      DIMENSION NODE(2)
      REAL KRR
      INTEGER PUMPS(2),CMPANY,COUNTY(3),DIAM(9),
      1ENODE1(2,9),ENODE2(2,9),END
C
        COMMON/TEMPRY/NODE,NEW,LENGTH,PUMPS,CMPANY,COUNTY,NPIPES,
      1  DIAM,NFLOW,FLOW,NCAP,CAP,ENODE1,ENODE2,ICAP,
      2  IFLOW,ISTOP,IDEBUG
C
```

```
      WRITE(6,10)NEW,NODE(1),NODE(2),LENGTH,FLOW,PUMPS(1),PUMPS(2),
      1CMPANY,(COUNTY(I),I=1,3),CAP,ICAP,IFLOW
      WRITE(6,20)NPIPES,(DIAM(I),I=1,NPIPES)
      NFLOW=NFLOW-1
      WRITE(6,30)NFLOW,(ENODE1(1,I),ENODE2(1,I),I=1,NFLOW)
      NCAP=NCAP-1
      WRITE(6,40)NCAP,(ENODE1(2,I),ENODE2(2,I),I=1,NCAP)
        RETURN
10    FORMAT(/,' ',/'    NEW= ',I2,' NODE= '2I6,' LENGTH= 'I3,
      1' FLOW= 'E15.8,' PUMPS= ',2I2,' CONO= ',I3,/
      2'    COUNTY - ',3A5,'    CAP=  ',E15.8
      3' ICAP= 'I4,' IFLOW= 'I4)
20    FORMAT('    NPIPES= ',I1,'  DIAM= '9I3)
30    FORMAT('  NFLOW= 'I1,' HEAD AND TAIL NODES' 18I5)
40    FORMAT('  NCAP= 'I1,'  HEAD AND TAIL NODES ',18I6)
        END
C
C
C-----------------------------------------------------------------
C
C
      SUBROUTINE REPORT(WHICH,CONO,RHO,ANU,SUML,RATIO,SUMHP,SUMVL,
      1              CONAME,IUTIL,PUTIL,PVUTIL,PRATE,PVLUTL)
C
C     SUBROUTINE TO BE USED WITH POWER PROGRAM
C     BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C
C  THIS IS A SUBROUTINE TO WRITE A REPORT PAGE FOR EITHER
C  A STATE OR A COMPANY ON ALL DIAMETER PIPES USED.
C
C     PROGRAMMING ASSISTANCE BY F. R. ELLIOTT, U. OF TENN.
C
C
      INTEGER  WHICH, CONO, OUTDEV, CONAME(4), STNAME(0:50,4)
      REAL SUMVL(0:48), RATIO, RHO, NU, SUML(0:48), SUMHP(0:48),
      1        KAPMI, KMAPMI, KSUML, KW, KSUMVL, KRHO, KNU, THMITR,
      2           MICAKM, BTU, KJ, KSUMT, MWH, TMILES(0:50,-2:2),
      3           TFLOW(0:50,-2:2),SITMIL(-2:2),SITFLO(-2:2)
      COMMON /ACC/ TMILES,TFLOW
C
      DATA IREAD/0/
      IF(IREAD.EQ.0)  OPEN(UNIT=8,DEVICE='DSK',FILE='STATES.IN')
      IF(IREAD.EQ.0)  READ(8,190) ((STNAME(I,J),J=1,4),I=0,50)
      IREAD=1
C
      OUTDEV=6
      IF(WHICH.EQ.3)  CONO=0
C
C
C     CHECK FOR REPORT ON A COMPANY OR A STATE.
      IF (WHICH .EQ. 1)  GO TO 10
      IF (WHICH .EQ. 2)  GO TO 20
      IF (WHICH .EQ. 3)  GO TO 30
      RETURN
C
```

```
C     REPORT TO BE PRINTED FOR A PIPELINE COMPANY. PRINT HEADER
C     AND INFORMATION ON PRODUCT'S PHYSICAL PROPERTIES.
C
C
10       KRHO=RHO/(2.204622622*(0.3048**3))
         KU=KNU/92903.
         WRITE (OUTDEV,200) CONO, (CONAME(I),I=1,4),KRHO,RHO,IUTIL,
         1              KNU,NU
C
         GO TO 40
C
20       CONTINUE
30       CONTINUE
         KRHO = RHO/(2.204622622*(.3048*.3048*.3048))
         WRITE (OUTDEV,210) CONO,(STNAME(CONO,I),I=1,4),KRHO,RHO,
         1              IUTIL
C
         GO TO 40
C
C
40       WRITE (OUTDEV,220)
C
C   CALCULATE ALL CONVERSIONS NEEDED AND PRINT OUT A RECORD
C
         DO 140 I=0,48,2
           IF(SUML(I).EQ.0.)  GO TO 140
50          MAPMI=SUML(I)/RATIO
60          KMAPMI=MAPMI*1.609344
70          KSUML=SUML(I)*1.609344
80          KW=SUMHP(I)*0.7457
            MWH=KW*8.76
90          YSUMVL=SUMVL(I)*365.E-6
100         KSUMV=YSUMVL*0.25586477
110         TNMIYR=YSUMVL*RHO*0.0028075
120         MTONKM=TNMIYR*1.46304
           BTU=0.
           IF(TNMIYR.EQ.0.)  GO TO 130
           BTU=(SUMHP(I)*22285440.)/TNMIYR*1.E-6
130        KJ=BTU*0.7226547
C
         WRITE(OUTDEV,230) I,KMAPMI,MAPMI,KSUML,SUML(I),
         1                             KW,SUMHP(I),MWH,KSUMV,YSUMVL,
         2                             MTONKM,TNMIYR,KJ,BTU
C
C
140      CONTINUE
C
C        UTILIZATION.
         AUTIL=PUTIL/IUTIL*100.
         AVUTIL=PVUTIL/PRATE*100.
         AVLUTL=PVLUTL/SUMVL(0)*100.
         WRITE(OUTDEV,240) AUTIL,AVUTIL,AVLUTL
C
C        ACCOUNTING INFORMATION.
         IF(WHICH.EQ.1)  RETURN
         DO 150 I=-2,2
           SITMIL(I)=TMILES(CONO,I)*1.609344
           TFLOW(CONO,I)=TFLOW(CONO,I)*365.
150        SITFLO(I)=TFLOW(CONO,I)*0.25584
C
C               TEMPORARY DEBUG STATEMENT
C
C        WRITE(17,7676)  (KK,(TMILES(KK,LL),LL=-2,2),KK=0,50),
C      - (KK,(TFLOW(KK,LL),LL=-2,2),KK=0,50)
C        WRITE(OUTDEV,260)  (SITMIL(I),TMILES(CONO,I),
C     -  SITFLO(I),TFLOW(CONO,I),I=1,2),
C     -  (SITMIL(I),TMILES(CONO,I),SITFLO(I),TFLOW(CONO,I),
C     -  I=-2,0,2)
C
C
         WRITE(OUTDEV,260) SITMIL(1),TMILES(CONO,1),  SITFLO(1),TFLOW(CONO
         11)
         WRITE(OUTDEV,160) SITMIL(2),TMILES(CONO,2),  SITFLO(2),TFLOW(CONO
         12)
160      FORMAT
         1  ('     REGULATED CARRIERS, MILES (BBL-MI) NOT PROVIDED',
         2  T60,2F8.0,4X,2(-6PF8.0))
         WRITE(OUTDEV,170) SITMIL(-2),TMILES(CONO,-2),  SITFLO(-2),
         1TFLOW(CONO,-2)
         WRITE(OUTDEV,180) SITMIL(0),TMILES(CONO,0),  SITFLO(0),TFLOW(CONO
         10)
170      FORMAT
         1  ('     UNREGULATED CARRIERS',T60,2F8.0,4X,2(-6PF8.0))
180      FORMAT
         1  ('     PIPES OF UNKNOWN OWNERSHIP',
         2  T60,2F8.0,4X,2(-6PF8.0))
         RETURN
190      FORMAT(4A5)
200        FORMAT (10(/' '),59X,I3,/,51X,4A5,/' '/,20X,'DENSITY - - ',
         1            F8.2,' KG/CU-M',9X,F7.2,' LB/CU-FT',30X,I4,
         2            ' PIPES',/9X,
         3            'KINEMATIC VISCOSITY - -     ',F5.1,' CSTOKES',
         4            6X,F9.7,' SQ.FT/SEC',3(' '/))
210      FORMAT ('1',6(/' '),59X,I3,/' '/,51X,4A5,/' '/,
         1            21X,'DENSITY - - ',F8.2,' KG/CU-M',8X,F7.2,
         2            ' LB/CU-FT',30X,I4,' PIPES',2(/' '))
220      FORMAT(2X,'DIAM',3X,'KM ON',3X,'MILES',4X,'ADJUSTED',
         1            10X,'KW',6X,'HP',5X,'MWH',3X,'CU.M-KM/YR',1X,
         2            'BBL-MI/YR',1X,'TON-KM/YR',1X,'TON-MI/YR',3X,
         3            'KJ/TON-KM',3X,'BTU/TON-MI',/
         4            10X,'MAP',4X,'ON MAP',3X,'KM',6X,'MI',28X
         5            '(MILLIONS)',1X,'(MILLIONS)',1X,'(MILLIONS)',
         6            '(MILLIONS)',2(/' '))
230      FORMAT(I5,F9.0,F8.0,F8.0,F7.0,4F9.0,
         1            F12.0,F9.0,F11.0,2F12.1)
240      FORMAT('0AVG UTILIZATION - - ',F7.1,'% UNWEIGHTED,',
         1  F7.1,'% WEIGHTED BY FLOW,',F7.1,'% WEIGHTED BY',
         2  ' BBL-MI.')
250      FORMAT(51(/X,I5,5E16.8),
         1  51(/X,I5,5(E16.8)))
260      FORMAT(4E16.8)
280      FORMAT('0ACCOUNTING SUMMARY',T60,'    KM      MILES',
         1 '          CU.M-KM   BBL-MI'/
```

```
      2  X,T60,19X,'     (MILLIONS)'/,
      3  '     REGULATED CARRIERS, MILES (BBL-MI) PROVIDED',
      4  T60,2F8.0,9X,2(-6PF8.0))
      END
C
C
C-----------------------------------------------------------------------
C
C
      SUBROUTINE FLOW(POL,J,Z,W,RATIO,RHO,NU,EPS,NPIPES,NODE,
     1           D,L,V,S,HS,FS,HFS,US,HES,FRAC,UTIL,LAST)
C
C     SUBROUTINE TO BE USED WITH POWER PROGRAM
C     BY J.S. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C
C  THIS SUBROUTINE DETERMINES THE RATE OF FLOW IN THE PIPES
C  IN THE LINK PASSED IN AND COMPUTES THE ENERGY USE UNDER
C  THE CALCULATION METHOD SPECIFIED AS POL, WHERE
C     POL = 0 MEANS LET THE FLOW BE UNINTERRUPTED AND
C             UNTHROTTLED AND ITS RATE BE THE AVERAGE DAILY
C             THROUGHPUT.
C     POL = 1 MEANS LET THE FLOW BE CAPACITY FLOW FOR THE
C             FRACTION OF THE YEAR NECESSARY TO PROVIDE
C             TOTAL ANNUAL THROUGHPUT
C     POL = 2 MEANS LET THE FLOW BE UNINTERRUPTED AND
C           3 THROTTLED SO AS TO EQUAL THE AVERAGE DAILY
C             THROUGHPUT.  POL=2 FOR 2 PUMPS, =3 FOR 3.
C     POL = 4 MEANS USE POL=0 UNLESS THE ENERGY REQUIREMENT IS
C           5 LESS THAN A HALF (POL=4) OR A THIRD (POL=5) OF THE
C             ENERGY REQUIREMENT AT CAPACITY FLOW.
C     POL = 6 MEANS USE POL=4 WITH 90% DUTY CYCLE.
C           7 MEANS USE POL=5 WITH 90% DUTY CYCLE.
C     POL = 8 MEANS USE POL=4 WITH 95% DUTY CYCLE.
C         = 9 MEANS USE POL=5 WITH 95% DUTY CYCLE.
C     POL = 10 MEANS RUN EVERYTHING AT CAPACITY.
C     CAPFAC = CAPACITY ADJUSTMENT FACTOR FOR VISCOSITY.
C     DUTY = .TRUE. WHEN A <100% DUTY CYCLE IS IMPOSED
C             OTHERWISE, A 100% DUTY CYCLE IS USED.
C     RDUTY = DUTY CYCLE.
C
      INTEGER POL, NPIPES, NODE(2), S
      REAL Z, W, RATIO, RHO, NU, EPS, D(9), V(9), HS(9),
     1          HFS(9), FS(9), HPS(9), FRAC, L, US(9), CHPS(9),
     2          LOW, MID, HS(9), UTIL(9)
      LOGICAL LAST, DUTY
      COMMON /CAPS/ SAVCAP(5000)
C
C-------RATED CAPACITY MUST BE ADJUSTED TO ACCOUNT FOR
C-------VISCOSITY OF THE OIL.  THE CAPACITY FIGURES GIVEN ARE
C-------FOR NO. 2 FUEL OIL, VISC. = ABOUT 3 CSTOKES.
      CAPFAC=(3./NU)**0.134
C-------NO ADJUSTMENT FOR CRUDE OIL.
      IF(NU.EQ.7.5) CAPFAC=1.
C
C
      IPOL = POL + 1
      GO TO (10,30,60,70,140,150,151,152,153,154,300) IPOL
C
C
C
C  CALCULATION METHOD 0.
C
10      CALL INPUT(J,Z,W,NPIPES,RATIO,NODE,D,L,V,S,LAST)
        FRAC = 1.
        DO 20 I = 1,NPIPES
C---------LET CAPACITY SERVE AS UPPER BOUND ON FLOW IF
C---------CAPACITY FIGURE IS BASED ON COMPANY DATA.
C----------BUT ALLOW FLOWS AS MUCH AS 10% OVER CAPACITY.
          IF(SAVCAP(J-NPIPES+I)*CAPFAC.GT.0)
     -    V(I)=AMIN1(V(I),SAVCAP(J-NPIPES+I)*CAPFAC*1.1)
          V(I)=AMIN1(V(I),ABS(SAVCAP(J-NPIPES+I)*CAPFAC*1.2))
          UTIL(I)=V(I)/(ABS(SAVCAP(J-NPIPES+I)*CAPFAC))
          K = I
20        CALL PUMP2(D(K),V(K),L,0,RHO,NU,EPS,HS(K),FS(K),HFS(K),
     1               US(K),HPS(K),6,IDEBUG)
        RETURN
C
C
C  CALCULATION METHOD 1.
C
30      CALL INPUT(J,Z,W,NPIPES,RATIO,NODE,D,L,V,S,LAST)
        VSUM = 0.
        CAPSUM = 0.
        SUTIL = 0.
        XL=L*RATIO
C-------SUM TOTAL FLOW AND COMPARE WITH TOTAL CAPACITY.
        DO 40 I = 1,NPIPES
C----------LET CAPACITY SERVE AS UPPER BOUND ON FLOW IF
C----------CAPACITY FIGURE IS BASED ON COMPANY DATA.
C----------BUT ALLOW FLOWS AS MUCH AS 10% OVER CAPACITY.
          CAP = SAVCAP(J-NPIPES+I)*CAPFAC
          IF(CAP.GT.0) V(I)=AMIN1(V(I),ABS(CAP)*1.1)
          V(I)=AMIN1(V(I),ABS(CAP)*1.2)
          ACAP = AMAX1(V(I),ABS(CAP))
          VSUM = VSUM + V(I)
          SUTIL =  SUTIL + ABS(CAP)
40        CAPSUM = CAPSUM + ACAP
C-------FIGURE HOW LONG PUMPS MUST RUN AT CAPACITY TO PROVIDE
C-------TOTAL ANNUAL THROUGHPUT.
        FRAC = AMIN1(VSUM/CAPSUM,1.)
        DO 50 I = 1,NPIPES
          UTIL(I) = VSUM/SUTIL
          CAP = SAVCAP(J-NPIPES+I)*CAPFAC
          ACAP = AMAX1(V(I),ABS(CAP))
          V(I)=ACAP
          K = I
50        CALL PUMP2(D(K),ACAP,XL,0,RHO,NU,EPS,HS(K),FS(K),
     1               HFS(K),US(K),HPS(K),6,IDEBUG)
        RETURN
C
C
C
```

```
C  CALCULATION METHODS 2,3.
C
60        CONTINUE
70        CONTINUE
          CALL THPUT(J,Z,W,NPIPES,RATIO,NODE,D,L,V,S,LAST)
          FRAC = 1.
          HPSUM = 0.
          VHPSUM = 0.
          AL=L*RATIO
          DO 80 I = 1,NPIPES
C---------LET ACTUAL COMPANY CAPACITY DATA SERVE AS UPPER BOUND
C---------ON FLOW.
            CAP = SAVCAP(J-NPIPES+I)*CAPFAC
            IF(CAP.GT.0) V(I)=AMIN1(V(I),ABS(CAP)*1.1)
            V(I)=AMIN1(V(I),ABS(CAP)*1.2)
            K = I
            ACAP = AMAX1(ABS(CAP),V(I))
C---------FIRST COMPUTE POWER REQUIREMENT FOR AVERAGE DAILY FLOW.
            CALL PUMP2(D(K),V(K),AL,0,RHC,NU,EPS,RS(K),FS(K),
          1          HPS(K),PS(K),VHP,6,IDEBUG)
C---------NOW COMPUTE POWER FOR CAPACITY FLOW.
            CALL PUMP2(D(K),ACAP,AL,0,RHC,NU,EPS,R,F,HP,P,HPS(K),
          1          6,IDEBUG)
            UTIL(I) = V(I)/ABS(CAP)
            HPSUM = HPSUM + HPS(I)
80          VHPSUM = VHPSUM + VHP
          IF(POL.EQ.3)  GO TO 100
C-------IF POWER REQUIREMENT FOR FLOW IS GREATER THAN HALF OF THAT
C-------FOR CAPACITY FLOW, BOTH PUMPS MUST BE USED AND THE FLOW
C-------THROTTLED, AND THE POWER REQUIREMENT IS THAT OF CAPACITY
C-------FLOW.
          IF(VHPSUM.GT.(0.5)*HPSUM)   RETURN
C-------OTHERWISE, THE POWER REQUIREMENT IS THAT OF RUNNING ONE
C-------PUMP RATHER THAN TWO.
          DO 90 I = 1,NPIPES
90          HPS(I) = HPS(I) * 0.5
          RETURN
C
100       CONTINUE
C-------IF POWER REQUIREMENT IS GREATER THAN 2/3 CAPACITY
C-------POWER, USE ALL 3 PUMPS.
          IF(VHPSUM.GT.(0.66667)*HPSUM)   RETURN
C-------IF IT IS GREATER THAN 1/3 CAPACITY POWER, USE 2 PUMPS.
          IF(VHPSUM.GT.(0.33333)*HPSUM)   GO TO 110
C-------ELSE USE JUST 1 PUMP.
          PUMPS=0.33333
          GO TO 120
110       PUMPS=0.6666667
120       DO 130 I=1,NPIPES
130         HPS(I)=HPS(I)*PUMPS
          RETURN
C
C
C
C
C   CALCULATION METHODS 4,5.
C
C-------IF POL=4, SET MINIMUM PUMPING ENERGY AT 1/2 CAPACITY.
140       FLOOR=0.5
          DUTY=.FALSE.
          GO TO 160
C-------IF POL=5, MINIMUM IS 1/3.
150       FLOOR=0.33333
          DUTY=.FALSE.
          GO TO 160
151       FLOOR=0.5
          DUTY=.TRUE.
          FDUTY=0.9
          GO TO 160
152       FLOOR=0.33333
          DUTY=.TRUE.
          FDUTY=.9
          GO TO 160
153       FLOOR=0.5
          DUTY=.TRUE.
          FDUTY=.95
          GO TO 160
154       FLOOR=0.33333
          DUTY=.TRUE.
          FDUTY=.95
160       CALL THPUT(J,Z,W,NPIPES,RATIO,NODE,D,L,V,S,LAST)
          CAPSUM = 0.
          VSUM = 0.
          HPSUM=0.
          CHPSUM=0.
          FRAC=1.
          IF(DUTY) FRAC=FDUTY
          AL=L*RATIO
          DO 170 I=1,NPIPES
C---------LET ACTUAL CAPACITY DATA SERVE AS UPPER BOUND ON FLOW.
            CAP = SAVCAP(J-NPIPES+I)*CAPFAC
            IF(CAP.GT.0.) V(I)=AMIN1(V(I),ABS(CAP)*1.1)
            V(I)=AMIN1(V(I),ABS(CAP)*1.2)
            ACAP = AMAX1(V(I),ABS(CAP))
            IF(DUTY) V(I)=V(I)/FDUTY
            K=I
C---------COMPUTE POWER FOR AVERAGE DAILY FLOW.
            CALL PUMP2(D(K),V(K),AL,0,RHC,NU,EPS,RS(K),FS(K),
          1          HPS(K),PS(K),VPS(K),6,IDEBUG)
C---------COMPUTE POWER FOR CAPACITY FLOW.
            IF(DUTY) ACAP=ACAP/FDUTY
            CALL PUMP2(D(K),ACAP,AL,0,RHC,NU,EPS,R,F,HP,P,CHPS(K),6,
          1          IDEBUG)
            UTIL(I) = V(I)/ABS(CAP)
            CAPSUM=CAPSUM+ACAP
            VSUM=VSUM+V(K)
            HPSUM=HPSUM+HPS(I)
170         CHPSUM=CHPSUM+CHPS(I)
C-------IF POWER REQUIREMENT IS ABOVE MINIMUM, USE AVERAGE
C-------DAILY FLOW.
          IF(HPSUM.GE.(FLOOR*CHPSUM))   RETURN
C-------OTHERWISE USE JUST ONE PUMP.
C-------TO FIND THE FRACTION OF THE YEAR ONE PUMP MUST BE RUN,
C-------IT IS NECESSARY TO FIND THE THROUGHPUT USING ONE PUMP.
```

```
C-------DO THIS USING A BISECTION SEARCH.
        TEST=CHPSUM*FLOOR
        HIGH=CAPSUM
        LOW=VSUM
180     MID=(HIGH+LOW)*0.5
C-------TO FIND THE POWER REQUIREMENT FOR PUMPING A TOTAL FLOW

C-------OF MID, THE FLOW MUST BE APPORTIONED AMONG THE PIPES IN
C-------THE LINK, USING THE REGRESSION FORMULA.
        SUM=0.
        VHPSUM=0.
        DO 190 I=1,NPIPES
          CAP = ABS(SAVCAP(J-NPIPES+I)*CAPFAC)
190       SUM = SUM + CAP*(D(I)/12.)**W
        DO 200 I=1,NPIPES
C---------COMPUTE EACH PIPE'S FLOW HERE.
          CAP = ABS(SAVCAP(J-NPIPES+I)*CAPFAC)
          V(I)=(CAP*(D(I)/12.)**W/SUM)*MID
          K=I
C---------NOW FIGURE POWER REQUIREMENT FOR THIS FLOW.
          CALL PUMP2(D(K),V(K),AL,0,RHO,NU,EPS,RS(K),PS(K),HPS(K),
     1               PS(K),HPS(K),6,IDEBUG)
200       VHPSUM=VHPSUM+HPS(K)
C200      IF(NPIPES.EQ.5) TYPE 5555, K, V(K), HPS(K), VHPSUM
C5555     FORMAT(' K, V(K), HPS(K), VHPSUM =',I5,3F)
C-------SEE IF CORRECT POWER HAS BEEN FOUND.
        IF(TEST-VHPSUM.GT.0.1)  GO TO 220
        IF(TEST-VHPSUM.LT.-0.1)  GO TO 230
C-------CORRECT POWER REQUIREMENT IS THE RESULT OF THE
C-------THROUGHPUTS VS(I).    NOW COMPUTE FRAC.
        VVSUM=0.
        DO 210 I=1,NPIPES
210       VVSUM=VVSUM+V(I)
        FRAC=VSUM/VVSUM
        IF(DUTY) FRAC=FRAC*PDUTY
        RETURN
220     LOW=MID
        GO TO 180
230     HIGH=MID
        GO TO 180
C
C
C
C  CALCULATION METHOD 10.
300     CALL THPUT(J,Z,N,NPIPES,RATIO,NODE,D,L,V,S,LAST)
        AL = L * RATIO
        FRAC = 1.
        DO 301 I = 1,NPIPES
          UTIL(I) = 1.
          V(I) = ABS(SAVCAP(J-NPIPES+I)*CAPFAC)
          K = I
301       CALL PUMP2(D(K),V(K),AL,0,RHO,NU,EPS,RS(K),PS(K),HPS(K),
     -    PS(K),HPS(K),6,IDEBUG)
        RETURN
        END
```

```
*    THROUGHPUT AND CAPACITY REGRESSION PROGRAM
*

         PROGRAM REGJNH
C
C
C**** PROGRAM FOR ESTIMATION OF CAPACITY AND FLOW REGRESSION
C       PARAMETERS.
C
C
C       BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,TN.
C       DEVELOPED ON THE DEC-SYSTEM 10 COMPUTER,1980.
C
C
C       PROGRAMMING ASSISTANCE BY RUTH B. HOFSTRA, UNIV. OF TENN.
C
C**** METHOD OF J.N.HOOKER USING SIGMA=H*C**K
C              AND INTERVAL-SPLIT ERROR DISTRIBUTION
C
C**** X IS UNKNOWN TO BE FOUND BY 2 APPLICATIONS OF NEWTON
C       SUBROUTINE.
C
C

         REAL INSIDE,K,KOL
         INTEGER CP
         DOUBLE PRECISION NAME
         COMMON/R/NAME
         EQUIVALENCE(NAME,NAMFIL),(HOOKER,HK)
         DIMENSION X(50),NAMFIL(2),MAXM(2)
         COMMON/PIPES/M,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
       COMMON/ISTOP/NS
         COMMON/PPIPES/MM,NNUM(600),CC(600),DD(600,20),FACTOR(600)
         COMMON/WGHTS/IW,H(600,20),KIND(2),IWT
         COMMON/CALCS/P(600),Q(600),R(600),GK(600),ZNUMX,ZDENX,ZLNGK,
       1       EUZK(600),PDEDU(600),PDEDZ(600),
       2       COEFF(3),EXPON(3),K,HOOKER,A1,A2,PY,UFL,ZFL,IFL
         DATA(KIND(I),I=1,2)/'CAPS FLOWS'/
         DATA IN,IOUT,IDEBUG,ICHECK,MAXM/20,6,0,0,600,600/
C
C**** /PIPES/ COMMON AREA WILL BE USED FOR INCOMING DATA
C       FOR CAPACITY REGRESSION C=X*D**Y
C              (OR FLOW REGRESSION V=U*C*D**Z)
C       NOTATION IN OTHER PARTS OF PROGRAM IS C=X*D**Y
C              (OR V=X*C*D**Y)
C       M=NUMBER OF CAPACITY GROUPS (OR FLOW GROUPS)
C       NUM(I)=NUMBER OF PIPES IN CAPACITY GROUP I, (I=1,M)
C       C(I)=MEASURED SUM OF CAPACITIES (OR FLOWS) FOR GROUP(I),(I=1,M),
C       READ IN THOUSANDS BBL/DAY (OR MILLIONS OF BBL/YR) AND CONVERTED
C              PROGRAM TO BBL/DAY
C       D(I,J)=DIAMETER OF PIPE J IN CAPACITY GROUP I,(J=1,NUM(I)
C              I=1,M),READ AS NOMINAL INCHES AND CONVERTED BY
C              PROGRAM TO INSIDE DIAMETER FEET (OR FLOW GROUP)
C       /PIPES/ WILL ALSO BE USED FOR FLOW PIPELINE DATA
C              CP(I,J)=CAPACITY GROUP NUMBER FOR PIPE J IN
C              FLOW GROUP I
C
C**** /PPIPES/ COMMON AREA IS SECOND STORAGE FOR CAPACITY
C       PIPELINE DATA TO BE USED DURING FLOW REGRESSION
C              FACTOR(I) WILL BE CALCULATED IN CAPCAL
C              SUBROUTINE AND USED IN WEIGHT SUBROUTINE
C
C**** /WGHTS/ COMMON AREA GIVES A FACTOR H(I,J) CORRESPONDING
C       TO D(I,J) FOR REGRESSION
C       IW=1 FOR CAPACITY REGRESSION TO BE DONE BY PROGRAM
C       IW=2 FOR FLOW REGRESSION, FIRST METHOD
C       KIND(1) AND KIND(2) ARE ALPHANUMERICS FOR IDENTIFICATION
C       SUBROUTINE WEIGHT WILL BE USED TO PUT CORRECT VALUES
C       IN H(I,J) ACCORDING AS IW=1 OR 2
C
C**** /CALCS/ COMMON AREA CONTAINS SOME QUANTITIES USED IN
C       REGRESSIONS
C       P(I),Q(I), AND R(I),I=1,M)  ARE CALCULATED IN SUBR.PQR.
C       ZNUMX,ZDENX ARE CALCULATED BY FUNCTION CALCX.
C       COEFF(IWT) AND EXPON(IWT) ARE GIVEN CALCULATED VALUES
C       FROM CAPACITY REGRESSION(IWT=1) OR FLOW REGRESSION,
C       (IWT=2 FOR EXACT FLOWS,AND IWT=3 FOR FLOW INTERVALS).
C
C*******************---INSTRUCTIONS START HERE
C
C

         PY=ACOS(-1.0)
C
C       CALL NORMAL TO COMPUTE NORMAL CURVE AREAS FOR CHI-SQUARE
C       TEST OR KOLMOGOROV-SMIRNOV TEST.
        CALL NORMAL
C
C       A1 IS 0.5 MILLIONS BBL/YR CONVERTED TO BBL/DAY
C       A2 IS 2.5 SAME,DY IS 5 SAME. THESE ARE USED IN SUBR.
C       ZLIM TO GET INTEGRATION LIMITS IN SECOND FLOW REGRESSION
C
         A1=500000.0/365.
         A2=5.0*A1
        NS=0
C
C****** NS IS A SWITCH WHICH TELLS WHETHER OR NOT SOMETHING
C       IS WRONG. NS=0 FOR NO PROBLEMS, AND  NS=1 FOR TROUBLE.
C       WHEN NS=1,MAIN PROGRAM AND SOME SUBROUTINES MAY CEASE.
C
10       TYPE 10010
         ACCEPT *,IW
         IF(IW.EQ.0)GO TO 10
         IWT=IW
         IF(IW.NE.1.AND.IW.NE.2)GO TO 190
20       CONTINUE
         WRITE(IOUT,10020)KIND(IW)
         IF(IWT.EQ.2)WRITE(IOUT,10030)
         IF(IWT.EQ.3)WRITE(IOUT,10040)
       TYPE 10050,KIND(IW)
       READ(5,10060)NAMFIL
       TYPE 10070,NAMFIL
       MAXD=MAXM(IW)
         CALL READ(IN,IERR,MAXD)
```

```
      IF(IERR.GT.0)GO TO 170
C
      CALL WEIGHT
C
C------WEIGHT SUBROUTINE SETS H(I,L)=1 FOR ALL CAP.
C     GROUPS I, AND PIPES L,STORES IN COMMON/WGHTS/
C     FOR FLOW REGRESSIONS. WEIGHT SUBR. SETS H(I,L)=
C     CAPACITY FOR ALL FLOW GROUPS I AND PIPES L, BASED ON
C     CAPACITY REGRESSION. USES EXPCH(1) FROM COMMON/CALCS/
C     AND FACTOR(I) FOUND IN COMMON/PPIPES/.H(I,L) IS THE
C     CORRECT FACTOR IN THE EQUATION BEING FITTED.
C     IF PIPE DOES NOT BELONG TO A CAPACITY GROUP,AS
C     INDICATED BY CP(I,L)=0,THEN CAPACITY IS CALCULATED
C     FROM THE CAPACITY REGRESSION RESULT;FLOW GRP I, PIPE L
C
C
30    TYPE 10080,KIND(IW)
      ACCEPT *,K
      TYPE 10090,K
      IF(K.LT.0.0)GO TO 10
C
C
C     EVALUATE AND STORE GK(I) FOR EVERY GROUP
C     USE X TEMPORARILY FOR ARRAYS TO SUM
C     IN CALCULATION OF GK(I)
C
      ZLNGK=0.0
      TWOK=2.0*K
      I=0
40    IF(I.GE.M)GO TO 70
      I=I+1
      NI=NOB(I)
      J=0
50    IF(J.GE.NI)GO TO 60
      J=J+1
      X(J)=D(I,J)**TWOK
      GO TO 50
60    GKI=SUM(NI,X)
      ZLNGK=ZLNGK+ALOG(GKI)
      GK(I)=GKI
      GO TO 40
70    CONTINUE
C
C
      IF(IDEBUG.GT.0)WRITE(6,10100)K,(GK(I),I=1,M),ZLNGK
C
C
C
C     PREPARE TO USE NEWTON'S METHOD SUBROUTINE
C
80      NN=1
        IF(IWT.EQ.3)NN=2
90    WRITE(5,10110)NN,K,KIND(IW)
        ACCEPT *,IANS
      IF(IANS.EQ.0)GO TO 90
      IF(IANS.LT.0)GO TO 30
100   WRITE(5,10120)NN
      IF(NN.EQ.1)TYPE 10130
      IF(NN.EQ.2)TYPE 10140
      READ (5,*) (X(I),I=1,NN)
110   WRITE(5,10150) (X(I),I=1,NN)
      WRITE(5,10160)
        ACCEPT *,IANS
      IF(IANS.EQ.0)GO TO 110
      IF(IANS.LT.0)GO TO 100
120   WRITE (5,10170)
      READ(5,*)EPS
130   WRITE(5,10180)EPS
        ACCEPT *,IANS
      IF(IANS.EQ.0)GO TO 130
      IF(IANS.LT.0)GO TO 120
      CALL NEWTON(NN,X,EPS,NS)
      IF(NS.LE.0)WRITE(5,10190) (X(I),I=1,NN)
      IF(NS.GT.0)WRITE(5,10200)EPS,(X(I),I=1,NN)
        IF(IWT.EQ.3)GO TO 140
        Y=X(1)
      CALL PQR(Y)
        Z=CALCX(Y)
C
C                    FOLLOWING ARE TEMPORARY STATEMENTS
C
C
      IF(IN.NE.1)GO TO 135
      TYPE 136,Y,Z
136   FORMAT('  TYPE EXP AND COEFF FOR CAPACITY TO REPLACE'/
     -' CURRENT=' 2E16.8,' COEFF NEG KEEPS CURRENT VALUES'/
     -' THIS ONLY CHANGES CAPACITY REGRESSION PARAMETERS'/
     -'  WHICH WILL AFFECT FLOW REGRESSION. OTHER CAPACITY'/
     -' OTHER CAPACITY RESULTS MAY BE WRONG(KOLMO)')
      READ(5,137)EXPNEW,COENEW
137   FORMAT(2F)
      IF(COENEW.LT.0.0)GO TO 135
      Y=EXPNEW
      Z=COENEW
135   CONTINUE
      TYPE 138,Y,Z
138   FORMAT('  USING EXP='E16.8,' COEFF='E16.8)
C
C                    ABOVE STATEMENTS MAY BE DELETED
C
      YK=Y
      XK=Z
        GO TO 150
140     Y=X(2)
        Z=X(1)
      YK=Y
      XK=Z
      UFL=XK
      EFL=YK
      CALL EPSFLO(NONZER)
150     CONTINUE
        WRITE(5,10210)KIND(IW),XK,YK,K
        COEFF(IRT)=XK
        EXPON(IRT)=YK
```

```
      CALL CALCHK(XK,YK,HKSQ,KOL)
      WRITE(5,10220)HKSQ,HOOKER,KOL
      IF(NS.GT.0)GO TO 180
160   CONTINUE
        IF(IW.EQ.1)CALL CAPCAL(Y)
C
        CALL CHECK(Z,Y,RSQU)
C
        WRITE(5,10230)RSQU
       GO TO 90
170    WRITE(5,10240)KIND(IW)
        CALL EXIT
180   WRITE(5,10250)
      GO TO 90
C
C-----------INTERVAL METHOD OF FLOW REGRESSION
C
C             WHEN USING FLOW REGRESSION,INTERVAL METHOD,IW=2
C             INDICATES FLOW AND IWT=3 INDICATES INTERVAL
C             PROCEDURE
C
190     CONTINUE
        IF(IW.LT.0)CALL EXIT
        IF(IW.NE.3)GO TO 10
        IW=2
        GO TO 20
10010   FORMAT('      TYPE 1 FOR CAPACITY REGRESSION'/
     1 '      TYPE 2 FOR FLOW REGRESSION, EXACT FLOW'/
     2 '      TYPE 3 FOR FLOW REGRESSION,FLOW INTERVALS'/
     3 '      (1 MUST BE DONE BEFORE 2 OR 3)'/
     4'      TYPE -1 TO END PROGRAM')
10020   FORMAT(5X,A5,' REGRESSION TO BE DONE')
10030   FORMAT('    SINGLE FLOWS USED')
10040   FORMAT('    FLOWS INTERVALS USED')
10050 FORMAT('  WHAT IS NAME OF ',A5,' FILE?')
10060 FORMAT(2A5)
10070 FORMAT('  NAME OF FILE IS '2A5)
10080 FORMAT('  TYPE CHOICE OF K'/
     1        ' FOR SIGMA=H*D**K'/
     2        ' NEGATIVE K SIGNALS END 'A5' REGRESSION CALC.')
10090 FORMAT(' VALUE OF K IS 'E15.8)
10100 FORMAT('  GK(I) VALUES AND LOG(PRODUCT) ARE FOR K='E16.8/(4E16.8))
10110 FORMAT('      TYPE +1 TO USE NEWTON''S METHOD, N= 'I2,
     1        ' K= 'E16.8/
     2'      TYPE -1 TO END REGRESSION OR TO CHOOSE NEW K FOR ',
     3  A5,' REGRESSION CALCULATIONS')
10120 FORMAT('   TYPE INITIAL GUESS FOR ',I2,' X VALUES')
10130 FORMAT('  X(1)=EXPONENT')
10140 FORMAT('  X= COEFF.,EXPON.')
10150 FORMAT('   X VALUES ARE'/(2E16.8))
10160 FORMAT(
     1'   TYPE -1 TO RETYPE X VALUES, OR +1 TO CONTINUE')
10170 FORMAT('  TYPE DESIRED ERROR')
10180 FORMAT('   ERROR EPS = 'E20.8/
     1'   TYPE -1 TO RETYPE ERROR, OR +1 TO CONTINUE')
10190 FORMAT('   SOLUTION X= '/(3E20.8))
10200 FORMAT('COMING OUT OF NEWTON,ERROR='E16.8' X='/
     1          (2E16.8))
10210   FORMAT(7X,        A5,' REGRESSION PARAMETERS ARE:'/
     1 '    COEFFICIENT='E16.8,' EXPONENT='E16.8' K= 'E16.8)
10220 FORMAT('  HKSQR='E16.8,' HOOKER='E16.8,/
     1          '  KOL='E16.8)
10230   FORMAT(12X,' RSQUARE=',E20.8)
10240 FORMAT('   SOME KIND OF ERROR ',A5,' INPUT')
10250 FORMAT('  TROUBLE WITH HK OR LOG(LK) ')
      END
C
C
C-----------------------------------------------------------------
C
C
        SUBROUTINE READ(IN,IERR,MAXM)
C
C      SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C      BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C----------READ IN AND CONVERT PIPELINE DATA FOR
C              CAPACITY OR FLOW REGRESSION CALCULATIONS
C
        REAL INSIDE
        INTEGER CP
      DOUBLE PRECISION NAME
      COMMON/R/NAME
        COMMON/PIPES/M,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
      COMMON/ISTOP/NS
        COMMON/PPIPES/MM,NNUM(600),CC(600),DD(600,20),FACTOR(600)
        COMMON/WGHTS/IW,H(600,20),KIND(2),IWT
        OPEN(UNIT=IN,DEVICE='DSK',FILE=NAME)
C
        IERR=0
        M=0
10     IF(IW.EQ.1)READ(IN,*,END=30)I,NUM(I),C(I),(D(I,J),J=1,NUM(I))
       IF(IW.EQ.2)READ(IN,*,END=20)I,NUM(I),C(I),(D(I,J),  CP(I,J),J=1,
     1NUM(I))
        M=M+1
        IF(I.NE.M.OR.M.GT.MAXM.OR.NUM(I).GT.20)GO TO 90
C     CAP.DATA IS 1000 BBL/DAY AND MUST BE CONVERTED TO BBL/DAY
        IF(IW.EQ.1)C(I)=C(I)*1000.0
C
C     FLOW DATA IS MILLION BBL/YR AND MUST BE CONV. TO BBL/DAY
        IF(IW.EQ.2)C(I)=C(I)*1000000./365.
C
        L=0
20      IF(L.GE.NUM(I))GO TO 10
        L=L+1
      DIL=D(I,L)
      IF(DIL.LE.0.0)GO TO 100
        D(I,L)=INSIDE(DIL,IOUT,IDEBUG)/12.0
        GO TO 20
30      IF(IW.NE.1)GO TO 60
        MM=M
        I=0
40      IF(I.GE.M)GO TO 60
```

```
        I=I+1
      NUMI=NUM(I)
        NNUM(I)=NUMI
        CC(I)=C(I)
        J=0
50      IF(J.GE.NUMI)GO TO 40
        J=J+1
        DD(I,J)=D(I,J)
        GO TO 50
60    IF(IDEBUG.LE.0)GO TO 80
        WRITE(IOUT,10010)KIND(IW)
        DO 70 I=1,M
        IF(IW.EQ.1)WRITE(IOUT,10020)I,NUM(I),C(I),(D(I,J),   J=1,NUM(I))
70      IF(IW.EQ.2)WRITE(IOUT,10030)I,NUM(I),C(I),(D(I,J),   CP(I,J),J=1,
      1NUM(I))
80      CLOSE(UNIT=IN)
        RETURN
90      IERR=1
        GO TO 80
100   TYPE 10040,I,L,DIL
      IERR=1
      RETURN
10010   FORMAT(5X,A5,' PIPE INPUT DATA AFTER CONVERSION BY PROGRAM IS:')
10020   FORMAT(2I5,E15.7/(5E15.7))
10030   FORMAT(2I5,E15.7/(3(E15.7,I5)))
10040 FORMAT('  FLOW GROUP 'I4,' PIPE NO. 'I3,
      1        ' HAS DIAM = 'E15.8)
      END
C
C
C-----------------------------------------------------------------
C
C
      REAL FUNCTION INSIDE(D,UNIT2,IDEBUG)
C
C     FUNCTION TO BE USED WITH REGRESSION PROGRAM
C     BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C---/CONVERT NOMINAL DIAMETER TO INSIDE DIAMETER/
C---D(REAL) /NOMINAL DIAM,IN./
C---WALL(48) (REAL) /TYPICAL WALL THICKNESS/
      DIMENSION WALL(48)
      INTEGER UNIT2
      DATA (WALL(I),I=1,48)/12*0.25,12*0.312,
     110*0.375,8*0.406,6*0.416/
      ID=INT(D+0.5)
      IF(ID.LE.0.OR.ID.GT.48)GO TO 40
      IF(D.LE.12.0)GO TO 10
       OD=D
      GO TO 30
10    IF(D.LE.8.0)GO TO 20
      OD=D+0.75
      GO TO 30
20    OD = D+0.625
30    W = -WALL(ID)
      INSIDE=OD+W+W
```

```
      RETURN
40    INSIDE = -100.
      WRITE(5,10010) ID
      RETURN
10010 FORMAT(' ***TROUBLE IN PIPE INSIDE DIAMETER CALCULATIONS'/
     1'     ID = ',I7)
      END
C
C
C-----------------------------------------------------------------
C
C
        SUBROUTINE WEIGHT
C
C     SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C     BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C**** /WGHTS/ COMMON AREA GIVES A WEIGHT H(I,J) CORRESPONDING
C     TO D(I,J) FOR REGRESSION
C     IW=1 FOR CAPACITY REGRESSION TO BE DONE BY PROGRAM
C     IW=2 FOR FLOW REGRESSION, EITHER METHOD
C     KIND(1) AND KIND(2) ARE ALPHANUMERICS FOR PRINTOUTS
C     SUBROUTINE WEIGHT WILL BE USED TO PUT CORRECT VALUES
C     IN H(I,J) ACCORDING AS IW=1 OR 2
C
      REAL K
        INTEGER CP
        COMMON/PIPES/M,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
      COMMON/ISTOP/NS
        COMMON/PPIPES/MM,NNUM(600),CC(600),DD(600,20),FACTOR(600)
        COMMON/WGHTS/IW,H(600,20),KIND(2),IWT
        COMMON/CALCS/P(600),Q(600),R(600),GK(600),ZNORX,ZOEZX,ZLMOK,
     1        EUZK(600),PDEDU(600),PDEDZ(600),
     2        COEFF(3),EXPON(3),K,HOOKER,A1,A2,PY,UPL,ZPL,IPL
        GO TO (10,40) IW
C             IW=1 FOR CAPACITY REGRESSION
C             IW=2 FOR FLOW REGRESSION
C
C------WEIGHT SUBROUTINE SETS H(I,L)=1 FOR ALL CAP.
C     GROUPS I, AND PIPES L,STORES IN COMMON/WGHTS/
C
10      I=0
20      IF(I.GE.M)GO TO 80
        I=I+1
      NUMI=NUM(I)
        L=0
30      IF(L.GE.NUMI)GO TO 20
        L=L+1
        H(I,L)=1.0
        GO TO 30
C
C
C     FOR FLOW REGRESSIONS, WEIGHT SUBR. SETS H(I,L)=
C     CAPACITY FOR ALL FLOW GROUPS I AND PIPES L, BASED ON
C     CAPACITY REGRESSION. USES EXPON(1) FROM COMMON/CALCS/
C     AND FACTOR(I) FOUND IN COMMON/PPIPES/.H(I,L) IS THE
```

```
C         CORRECT FACTOR IN THE EQUATION BEING FITTED.
C         IF PIPE DOES NOT BELONG TO A CAPACITY GROUP,AS
C         INDICATED BY CP(I,L)=0,THEN CAPACITY IS CALCULATED
C         USING THE COEFF AND EXPON FROM THE CAPACITY REGRESSION
C
C
C
C
40          I=0
            EXPO=EXPON(1)
          COEF=COEFF(1)
50          IF(I.GE.N)GO TO 80
            I=I+1
          NUMI=NUM(I)
            L=0
60          IF(L.GE.NUMI)GO TO 50
            L=L+1
          IF(CP(I,L).LE.0)GO TO 70
            H(I,L)=(D(I,L)**EXPO)*FACTOR(CP(I,L))
            GO TO 60
70        H(I,L)=COEF*D(I,L)**EXPO
          GO TO 60
80        IF(IDEBUG.LE.0)RETURN
          WRITE(IOUT,10010)
          DO 90 I=1,N
90        WRITE(IOUT,10020)(H(I,L),L=1,NUM(I))
          RETURN
10010     FORMAT('  WEIGHT OUTPUT-H(I,L)')
10020     FORMAT(3E16.8)
            END
C
C
C-----------------------------------------------------------------
C
C

            SUBROUTINE CAPCAL(Y)
C
C         SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C         BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C         THIS SUBROUTINE CALCULATES THE FACTOR WHICH WILL BE USED
C         TO COMPUTE CAPACITY CORRESPONDING TO PIPE J
C                   OF FLOW GROUP I.
C         Y IS THE EXPONENT DERIVED BY THE CAPACITY REGRESSION
C         CP(I,J) WILL BE USED IN WEIGHT SUBROUTINE TO INDICATE
C                   WHICH CAPACITY GROUP F IS TO BE USED FOR FACTOR
C
            INTEGER CP
            COMMON/PIPES/N,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
          COMMON/ISTOP/NS
            COMMON/PPIPES/NN,NNUM(600),CC(600),DD(600,20),FACTOR(600)
            I=0
10          IF(I.GE.N)RETURN
            I=I+1
          NUMI=NUM(I)
            DSUM=0.0
            J=0
20          IF(J GE NUMI) GO TO 30
            J=J+
            DSUM=DSUM+D(I,J)**Y
            GO TO 20
30          FACTOR(I)=C(I)/DSUM
            GO TO  0
            END
C
C
C-----------------------------------------------------------------
C
C

            FUNCTION SUM(N,Z)
C
C         FUNCTION TO BE USED WITH REGRESSION PROGRAM
C         BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C----------FUNCTION TO CALCULATE SUM OF ANY ARRAY
C
            DIMENSION Z(N)
            SUM=0.0
            I=0
10          IF(I.GE.N)RETURN
            I=I+1
            SUM=SUM+Z(I)
            GO TO 10
            END
C
C
C-----------------------------------------------------------------
C
C

            SUBROUTINE PQR(Y)
C
C         SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C         BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C----------SUBROUTINE TO CALCULATE 3 ARRAYS OF SUMS
C
C                   AND STORE IN /CALCS/ COMMON AREA
C                   TO BE USED IN CALCULATIONS FOR CAPACITY
C                   OR FLOW REGRESSION PARAMETERS
C
C         P(I)=SUM OF(H(I,J)*D(I,J)**Y),J=1,NUM(I)
C         Q(I)=SUM OF(H(I,J)*D(I,J)**Y*LN(D(I,J))),J=1,NUM(I)
C         R(I)=SUM OF(H(I,J)*D(I,J)**Y*(LN(D(I,J))**2),J=1,NUM(I)
C
          REAL K
            INTEGER CP
            COMMON/PIPES/N,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20
          COMMON/ISTOP/NS
            COMMON/CALCS/P(600),Q(600),R(600),CK(600),ZNUMX,ZDENX,ZLNGK,
          1         NUZK(600),PDEDB(600),PDEDK(600),
          2         COEFF(3),EXPON(3),K,NCOEFB,A1,A2,PY,UPL,ZPL,IPL
```

```
      COMMON/WGHTS/IW,H(600,20),KIND(2),IWT
      DIMENSION W(20),U(20),V(20)
      I=0
10    IF(I.GE.M.AND.IDEBUG.GT.0)GO TO 50
     IF(I.GE.M)RETURN
      I=I+1
      NI=NUM(I)
      J=0
20    IF(J.GE.NI)GO TO 30
      J=J+1
      DIJ=D(I,J)
     IF(DIJ.LE.0.0)GO TO 40
      ZLNDIJ=ALOG(DIJ)
      WJ=H(I,J)*DIJ**Y
      UJ=WJ*ZLNDIJ
      V(J)=UJ*ZLNDIJ
      W(J)=WJ
      U(J)=UJ
      GO TO 20
30    P(I)=SUM(NI,W)
      Q(I)=SUM(NI,U)
      R(I)=SUM(NI,V)
      GO TO 10
40   TYPE 10010,KIND(IW),I,J,DIJ
     RETURN
50   WRITE(6,10020)M
     WRITE(6,10030)(P(I),I=1,M)
     WRITE(6,10030)(Q(I),I=1,M)
     WRITE(6,10030)(R(I),I=1,M)
     RETURN
10010 FORMAT(' PIPE DIAM IN 'A5' GROUP NO.'I5,
     1      ' PIPE NO.'I3' ='E15.7/' SET P(1)=-100 AND RETURN')
10020 FORMAT(' P,Q,R,VALUES FOR'I4' GROUPS,-')
10030 FORMAT(3E16.8)
      END
C
C
C-----------------------------------------------------------------
C
C
      FUNCTION CALCX(Y)
C
C       FUNCTION TO BE USED WITH REGRESSION PROGRAM
C       BY J.R HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C----------FUNCTION TO CALCULATE COEFFICIENT X FROM EXPONENT Y
C           FOR OBTAINING CAPACITY OR FLOW REGRESSION PARAMETERS
C
     REAL K
      INTEGER CP
      COMMON/PIPES/M,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
     COMMON/ISTOP/NS
      COMMON/CALCS/P(600),Q(600),R(600),GK(600),ZNUMX,ZDENX,ZLNGK,
     1       ZUZK(600),PDEDU(600),PDEDZ(600),
     2       COEFF(3),EXPON(3),K,HCOKER,A1,A2,PY,UPL,ZPL,IPL
      DIMENSION W(600),U(600)
10    I=0
20    IF(I.GE.M)GO TO 30
      I=I+1
      PI=P(I)
      CI=C(I)
      WI=PI*CI/GK(I)
      U(I)=WI*PI/CI
      W(I)=WI
      GO TO 20
30    ZNUMX=SUM(M,W)
      ZDENX=SUM(M,U)
      CALCX=ZNUMX/ZDENX
      RETURN
      END
C
C
C-----------------------------------------------------------------
C
C
      FUNCTION CALCDX(Y)
C
C       FUNCTION TO BE USED WITH REGRESSION PROGRAM
C       BY J.R.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C----------FUNCTION TO CALCULATE DX/DY = DERIVATIVE OF
C                COEFFICIENT X W.R. TO EXPONENT Y
C
     REAL K
      INTEGER CP
      COMMON/PIPES/M,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
     COMMON/ISTOP/NS
      COMMON/CALCS/P(600),Q(600),R(600),GK(600),ZNUMX,ZDENX,ZLNGK,
     1       ZUZK(600),PDEDU(600),PDEDZ(600),
     2       COEFF(3),EXPON(3),K,HCOKER,A1,A2,PY,UPL,ZPL,IPL
      DIMENSION W(600),U(600)
      X=CALCX(Y)
      I=0
10    IF(I.GE.M)GO TO 20
      I=I+1
      CI=C(I)
      WI=CI*Q(I)/GK(I)
      U(I)=2.0*WI*P(I)/CI
      W(I)=WI
      GO TO 10
20    A=SUM(M,W)
      B=SUM(M,U)
      CALCDX=(ZDENX*A-ZNUMX*B)/(ZDENX*ZDENX)
     IF(IDEBUG.GT.0)WRITE(IOUT,10010)ZNUMX,ZDENX,A,B,CALCDX
C
      RETURN
10010 FORMAT(' ZNUMX,ZDENX,A,B,CALCDX= '/(4E16.8))
      END
C
C
C-----------------------------------------------------------------
C
```

```
C
          FUNCTION DFN(NN,II,JJ,Z)
C
C       FUNCTION TO BE USED WITH REGRESSION PROGRAM
C       BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C----------FUNCTION TO CALCULATE DERIVATIVE OF FUNCTION
C               OF EXPONENT Y WHICH IS BEING SOLVED BY
C               NEWTON METHOD SUBROUTINE,WITH NN=1
C               FOR CAPACITY REGRESSION PARAMETERS OR
C               FLOW REGRESSION, FIRST METHOD
C
C       FUNCTION ALSO CALCULATES ALL PARTIAL DERIV.
C       FOR INTERVAL METHOD OF FLOW REGRESSION,NN=2
C
        REAL K
          INTEGER CP
          COMMON/PIPES/M,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
        COMMON/ISTOP/NS
          COMMON/CALCS/P(600),Q(600),R(600),GK(600),ZNUMX,ZDENX,ZLNGK,
        1       EUZK(600),PDEDQ(600),PDEDZ(600),
        2       COEFF(3),EXPON(3),K,HOOKER,A1,A2,PT,UFL,ZFL,IFL
          COMMON/WGHTS/IW,H(600,20),KIND(2),IWT
          DIMENSION Z(NN)
          DIMENSION W(600)
          IF(IWT.GE.3)GO TO 40
          Y=Z(1)
          X=CALCX(Y)
          DXDY=CALCDX(Y)
        IF(IDEBUG.GT.0)WRITE(IOUT,10010)DXDY
C
          I=0
10        IF(I.GE.M)GO TO 20
          I=I+1
          QI=Q(I)
          PI=P(I)
          W(I)=((C(I)-X*PI)*R(I)-QI*(X*QI+DXDY*PI))/GK(I)
C
        IF(IDEBUG.GT.0)WRITE(IOUT,10020)I,W(I)
C
          GO TO 10
20        DFN=SUM(M,W)
            IF(IDEBUG.LE.0)RETURN
30        CONTINUE
          WRITE(IOUT,10030)DFN
          RETURN
C
C       FUNCTION FN MUST BE USED BEFORE DFN WHEN NN=2
C
40      IF(II.EQ.2)GO TO 80
        IF(JJ.EQ.2)GO TO 60
C
C       GET DFN(2,1,1,X)
C
        DO 50 I=1,M
50      W(I)=PDEDQ(I)*P(I)/GK(I)
        DFN=SUM(M,W)
        WRITE(IOUT,10040)NN,II,JJ,DFN
        RETURN
C
C       GET DFN(2,1,2,X)
C
60      DO 70 I=1,M
70      W(I)=(EUZK(I)*Q(I)+PDEDZ(I)*P(I))/GK(I)
        DFN=SUM(M,W)
        WRITE(IOUT,10040)NN,II,JJ,DFN
        RETURN
80      IF(JJ.EQ.2)GO TO 100
C
C       GET DFN(2,2,1,X)
C
        DO 90 I=1,M
90      W(I)=PDEDQ(I)*Q(I)/GK(I)
        DFN=SUM(M,W)
        WRITE(IOUT,10040)NN,II,JJ,DFN
        RETURN
C
C       GET DFN(2,2,2,X)
C
100     CONTINUE
        DO 110 I=1,M
110     W(I)=(EUZK(I)*R(I)+PDEDZ(I)*Q(I))/GK(I)
        DFN=SUM(M,W)
        WRITE(IOUT,10040)NN,II,JJ,DFN
        RETURN
10010   FORMAT('   DXDY= ' E16.8)
10020   FORMAT('   W(',I3,' )='E15.8)
10030     FORMAT('    DFN='E15.7)
10040   FORMAT(' DFN('I2,',',I2,',',I2,')='E16.8)
        END
C
C
C-----------------------------------------------------------------
C
C
          FUNCTION FN(NN,II,Z)
C
C       FUNCTION TO BE USED WITH REGRESSION PROGRAM
C       BY J.N HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C----------FUNCTION TO CALCULATE THE FUNCTION F OF EXPONENT Y
C               WHICH IS BEING SOLVED BY NEWTON SUBROUTINE,
C               WITH NN=1 FOR CAPACITY REGRESSION PARAMETERS OR
C               FLOW REGRESSION, FIRST METHOD
C
C       FUNCTION ALSO CALCULATES 2 COMPONENT FUNCTIONS OF
C       FUNCTION F OF COEFF. AND EXPON. FOR
C       INTERVAL METHOD OF FLOW REGRESSION(CALLED SECOND METHOD)
C
        REAL K
          INTEGER CP
          COMMON/PIPES/M,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
```

```
      COMMON/ISTOP/NS
        COMMON/CALCS/P(600),Q(600),R(600),GK(600),ZNUMX,ZDENX,ZLNGK,
     1        EUZK(600),PDEDU(600),EDEDZ(600),
     2        COEFF(3),EXPON(3),K,RCOKER,A1,A2,PY,UPL,ZPL,IFL
        COMMON/WGHTS/IW,H(600,20),KIND(2),IWT
        DIMENSION Z(NN)
        DIMENSION W(600)
        IF(IWT.GE.3)GO TO 40
        Y=Z(1)
        CALL PQR(Y)
      IF(P(1).LE.0.0) RETURN
        X=CALCX(Y)
      IF(IDEBUG.GT.0)WRITE(IOUT,10010)ZNUMX,ZDENX,X
        I=0
10      IF(I.GE.N)GO TO 20
        I=I+1
        W(I)=(C(I)-X*P(I))*Q(I)/GK(I)
        GO TO 10
20      FN=SUM(N,W)
          IF(IDEBUG.LE.0) RETURN
30      CONTINUE
        WRITE(IOUT,10020)NN,II,FN
        RETURN
40      NS=0
        UPL=Z(1)
        ZPL=Z(2)
      IF(II.GT.1)GO TO 60
      CALL PQR(Z(2))
      CALL EPSPLO(NONZER)
      IF(NS.GT.0)RETURN
      DO 50 I=1,N
50    W(I)=EUZK(I)*P(I)/GK(I)
      FN=SUM(N,W)
        GO TO 30
        RETURN
60    DO 70 I=1,N
70    W(I)=EUZK(I)*Q(I)/GK(I)
      FN=SUM(N,W)
        GO TO 30
        RETURN
10010 FORMAT(' ZNUMX,ZDENX,X='3E16.8)
10020   FORMAT('    FN('I2,',',I2,')='E16.8)
        END
C
C
C------------------------------------------------------------------
C
C
      SUBROUTINE NEWTON(N,X,EPS,NS)
C
C     SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C     BY J.N HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
      COMMON F(50),DF(50,50),B(50)
      DIMENSION X(50)
      LOGICAL DEBUG
      DATA DEBUG/'F'/,IOUT/5/,ICR/1/
C
C-----------SUBROUTINE FOR SOLVING NONLINEAR SYSTEM OF
C----------       EQUATIONS BY ORDINARY NEWTON'S METHOD
C----------       X IS AN ARRAY AND X(J) IS RETURNED AS
C----------       SOLUTION
C
C----------THE FUNCTION VALUES ARE GOTTEN BY FUNCTION
C----------       FN(N,I,X), WHICH RETURNS COMPONENT-I
C----------       OF F(X), WHERE X HAS N COMPONENTS
C----------       CONTAINED IN ARRAY X
C
C----------PARTIAL DERIVATIVES ARE GOTTEN BY FUNCTION
C----------       DFN(N,I,J,X) WHICH RETURNS PARTIAL DERIV.
C----------       OF I-TH COMPONENT OF F WITH RESPECT TO X(J)
C
C
C----------SET ICR.GT.0 TO USE CRAMER'S RULE FOR N=2
C----------IF CRAMER'S RULE FAILS,PROGRAM USES LINEAR SUB.
C
C****** NS IS A SWITCH WHICH TELLS WHETHER OR NOT SOMETHING
C       IS WRONG  NS=0 FOR NO PROBLEMS, AND  NS=1 FOR TROUBLE.
C       WHEN NS=1,MAIN PROGRAM AND SOME SUBROUTINES MAY CEASE.
C
      NS=0
        ANORM=0.0
        IF(IOUT.NE.5)WRITE(IOUT,10010)(X(I),I=1,N)
      NTRIES=0
10    I=0
20    I=I+1
      F(I)=FN(N,I,X)
      J=0
30    J=J+1
      DF(I,J)=DFN(N,I,J,X)
      IF(J.LT.N)GO TO 30
      IF(I.LT.N)GO TO 20
      ERR=ERROR(N,F)
40    WRITE(IOUT,10020)ERR
        IF(ANORM.LE.1000000.0)GO TO 50
      NS=1
      EPS=ERR
      RETURN
50    CONTINUE
      IF(ERR.GE.EPS)GO TO 60
        WRITE(IOUT,10030)
        RETURN
60     IF(IOUT.NE.5)GO TO 70
      WRITE(5,10040)
        ACCEPT*,IANS
      IF(IANS.EQ.0)GO TO 40
      IF(IANS.LT.0)RETURN
70    CALL MULT2(N,N,1,X)
      DO 80 I=1,N
80    B(I)=-F(I) + B(I)
90      CONTINUE
      IF(N.EQ.1)CALL LINEAR(N,DF,B,X,ANORM,DEBUG)
      IFAIL=0
```

```
      IF(N.EQ.2.AND.ICR.GT.0)CALL CRAMER(DF(1,1),DF(1,2),      DF(2,1),
     1DF(2,2),B(1),B(2),X(1),X(2),DEBUG,ANORM,IFAIL)
      IF(IFAIL GT.0)CALL LINEAR(N,DF,B,X,ANORM,DEBUG)
      IF(N.EQ.2.AND ICR.LE.0)CALL LINEAR(N,DF,B,X,ANORM,DEBUG)
100     CONTINUE
      IF(ANORM.LE.1000000.0)GO TO 110
        WRITE(IOUT,10050)ANORM
110     CONTINUE
      WRITE(IOUT,10060)(X(I),I=1,N)
      NTRIES=NTRIES+1
      IF(NTRIES.LT.25)GO TO 10
      WRITE(IOUT,10070)
      IF(IOUT.EQ.5)GO TO 10
      RETURN
10010  FORMAT('   INITIAL ESTIMATE OF X IS'/(3E20.8))
10020 FORMAT('   CALCULATED ERROR = 'E15,8)
10030  FORMAT('   SOLUTION FOUND')
10040 FORMAT('   TYPE -1 TO STOP NEWTON SUBROUTINE, +1 TO CONTINUE')
10050   FORMAT('    ANORM='E15.7/
     1 '   RETURN FROM NEWTON WHEN ANORM.GT.1000.0')
10060 FORMAT('   NEW ESTIMATE OF X IS '/(3E16.8))
10070 FORMAT('   25 ITERATIONS HAVE BEEN MADE IN NEWTON SUB')
      END
C
C
C----------------------------------------------------------------
C
C
      FUNCTION ERROR(N,F)
C
C     FUNCTION TO BE USED WITH REGRESSION PROGRAM
C     BY J.N HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
      DIMENSION F(N)
      ERROR=0.0
      DO 10 I=1,N
10    ERROR=ERROR+F(I)*F(I)
      DN=N
      ERROR=SQRT(ERROR/DN)
      RETURN
      END
C
C
C----------------------------------------------------------------
C
C
      SUBROUTINE MULT2(M,N,P,D)
C
C     SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C     BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
      COMMON F(50),A(50,50),C(50)
      DIMENSION D(50)
      INTEGER P
      DO 10 J=1,P
      DO 10 I=1,M
10    C(I)=0.0
      J=0
20    J=J+1
      I=0
30    I=I+1
      Z=0.0
      DO 40 K=1,N
40    Z=Z+A(I,K)*D(K)
      C(I)=Z
      IF(I.LT.M)GO TO 30
      IF(J.LT.P)GO TO 20
      RETURN
      END
C
C
C----------------------------------------------------------------
C
C
        SUBROUTINE CHECK(ZZ,YY,RSQU)
C
C     SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C     BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C----------SUBROUTINE TO CALCULATE RSQU;
C     ZZ IS COEFFICIENT AND YY IS EXPONENT
C     OF CAPACITY OR FLOW REGRESSION.
C
C     RSQU='COEFFICIENT OF DETERMINATION'
C     RSQU IS SQUARE OF CORRELATION BETWEEN GIVEN AND DERIVED.
C
C
      INTEGER CP
      REAL K
        COMMON/PIPES/M,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
      COMMON/ISTOP/NS
        COMMON/PPIPES/MM,NNUM(600),CC(600),DD(600,20),FACTOR(600)
        COMMON/WGHTS/IW,H(600,20),KIND(2),IWT
        COMMON/CALCS/P(600),Q(600),R(600),GK(600),ZNUMX,ZDENX,ZLNGK,
     1       EUZK(600),PDEDU(600),PDEDZ(600),
     2       COEFF(3),EXPON(3),K,HCOKER,A1,A2,PY,UFL,ZFL,IFL
      DIMENSION PP(600),QQ(600),RR(600)
C
      ZM=FLOAT(M)
        GIVSUM=0.0
        DO 10 I=1,M
10      GIVSUM=GIVSUM+C(I)
        CAPBAR=GIVSUM/ZM
20      I=0
30      IF(I.GE.M)GO TO 60
        I=I+1
      NUMI=NUM(I)
        J=0
        SUMM=0.0
40      IF(J.GE.NUMI)GO TO 50
        J=J+1
```

```
          DIJ=D(I,J)
          DIJX=DIJ**YY
          CRIJ=ZZ*H(I,J)*DIJX
          SUMN=SUMN+CRIJ
          GO TO 40
50        CONTINUE
          QQ(I)=SUMN
          GO TO 30
60        CONTINUE
          QBAR=SUM(M,QQ)/ZM
          RSNUM=0.0
          I=0
70        IF(I.GE.M)GO TO 80
          I=I+1
          PI=C(I)-CAPBAR
          RI=QQ(I)-QBAR
          RSNUM=RSNUM+PI*RI
          PP(I)=PI*PI
          RR(I)=RI*RI
          GO TO 70
80        RSDEN=SQRT(SUM(M,PP)*SUM(M,RR))
          RSQU=RSNUM/RSDEN
          RSQU=RSQU*RSQU
          RETURN
          END
C
C
C-----------------------------------------------------------------
C
C
          SUBROUTINE ZLIM(V,VI,WI,NS)
C
C       SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C       BY J.N HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C       CALCULATE LIMITS ON FLOW INTERVALS FOR GIVEN V(BBL/DAY)
C
C****** NS IS A SWITCH WHICH TELLS WHETHER OR NOT SOMETHING
C       IS WRONG  NS=0 FOR NO PROBLEMS, AND  NS=1 FOR TROUBLE.
C       WHEN NS=1,MAIN PROGRAM AND SOME SUBROUTINES MAY CEASE.
C
        REAL K
          COMMON/CALCS/P(600),Q(600),R(600),GK(600),ZNUMI,ZDENI,ZLNGX,
        1        ZUZK(600),PDEDU(600),PDEDZ(600),
        2        COEFF(3),EXPON(3),K,HOOKER,A1,A2,PY,UPL,ZPL,IPL
C
        IF(IDEBUG.GT.0)WRITE(6,10010) A1,A2
          NS=0
        IF(V.LE.0.0)GO TO 30
C
C       A1=0.5 MILLION BBL/YEAR CONVERTED TO BBL/DAY
C
          IF(V.GT.A1)GO TO 10
          VI=0.0
          WI=A1
          RETURN
C
C       A2=2.5 MILLION BBL/YEAR CONVERTED TO BBL/DAY
C
10        IF(V.GT.A2)GO TO 20
          VI=A1
          WI=A2
          RETURN
C
C       VGIVEN WILL BE FLOW DATA IN MILLION BBL/YEAR
C
20      VGIVEN=V*0.000365
C
C       ID WILL BE CLOSEST MULTIPLE OF 5 FOR VGIVEN
C       CENTER IS CLOSEST MULTIPLE OF 5,CONVERTED TO BBL/DAY
C
        ID=INT(VGIVEN/5.0 + 0.5)
        CENTER=FLOAT(5000000*ID)/365.
C
C       VI TO WI IS INTERVAL LENGTH 5 MILLION BBL/YEAR,
C       CONVERTED TO BBL/DAY TO MATCH DATA V IN PROGRAM
C
        VI=CENTER-A2
        WI=CENTER+A2
          RETURN
30      WRITE(6,10020)V
        NS=1
        RETURN
10010   FORMAT('  A1,A2=' 2E16.8)
10020   FORMAT('  TROUBLE WITH FLOW VALUE V='E16.8)
          END
C
C
C-----------------------------------------------------------------
C
C
          SUBROUTINE CRAMER(A11,A12,A21,A22,B1,B2,X1,X2,DEBUG,
        1  ANORM,NS)
C
C       SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C       BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C****** NS IS A SWITCH WHICH TELLS WHETHER OR NOT SOMETHING
C       IS WRONG. NS=0 FOR NO PROBLEMS, AND  NS=1 FOR TROUBLE.
C       WHEN NS=1,MAIN PROGRAM AND SOME SUBROUTINES MAY CEASE.
C
C
          DIMENSION P(2)
          LOGICAL DEBUG
          DOUBLE PRECISION A,B,C,D,E,G,X,Y,DET
          NS=0
          A=DBLE(A11)
          B=DBLE(A12)
          C=DBLE(A21)
          D=DBLE(A22)
          E=DBLE(B1)
          G=DBLE(B2)
```

```
      DET=A*D-B*C
     IF(DET.EQ.0.D0)GO TO 10
      X=(E*D-B*G)/DET
      Y=(A*G-C*E)/DET
      X1=SNGL(X)
      X2=SNGL(Y)
      F(1)=SNGL(A*X+B*Y)-B1
      F(2)=SNGL(C*X+D*Y)-B2
      ANORM=ERROR(2,F)*SQRT(2.0)
      RETURN
 C    IF(DEBUG)WRITE(5,10010)DET
      NS=1
      RETURN
.10010    FORMAT('  DETERMINANT='D20.12/
     1    '  CRAMERS RULE DELETED.USE LINEAR SUBR.')
      END
C
C
C---------------------------------------------------------------
C
C
      SUBROUTINE CALCHK(XK,YK,HKSQ,KOL)
C
C     SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C     BY J.N HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C     CALCULATES COEFFICIENT HOCKER FOR HOOKER*D**K,
C     AND K=KOLMOGOROV-SMIRNOFF STATISTIC,
C     FOR A GIVEN VALUE OF K, COEFFICIENT XK,
C     AND EXPONENT YK IN CAF OR FLOW REGRESSION.
C     HOOKER IS PLACED IN COMMON/CALCS/
C
C****** NS IS A SWITCH WHICH TELLS WHETHER OR NOT SOMETHING
C     IS WRONG. NS=0 FOR NO PROBLEMS, AND  NS=1 FOR TROUBLE.
C     WHEN NS=1,MAIN PROGRAM AND SOME SUBROUTINES MAY CEASE.
C
      REAL K
      INTEGER CP
      EQUIVALENCE(HOOKER,HK)
       COMMON/PIPES/M,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
      COMMON/ISTOP/NS
       COMMON/CALCS/P(600),Q(600),R(600),GK(600),ZNUMX,ZDENX,ZLNGK,
     1       EUZK(600),PDZDU(600),PDEDZ(600),
     2       COEFF(3),EXPON(3),K,HOOKER,A1,A2,PY,UFL,ZFL,IFL
       COMMON/WGHTS/IW,H(600,20),KIND(2),IWT
      DIMENSION W(600)
      NS=0
      ZM=FLOAT(M)
      I=0
C
C     CALCULATIONS MUST BE DONE FOR EACH GROUP I
C
10    IF(I.GE.M)GO TO 40
      I=I+1
      GKI=GK(I)
      IF(IWT.GT.2)GO TO 20
      TEMP=C(I)-XK*P(I)
      GO TO 30
20    TEMP=C(I)-XK*P(I)
C     WRITE(27,2468) TEMP, GKI
30    CONTINUE
      W(I)=TEMP*TEMP/GKI
      GO TO 10
C
C     HKSQ IS A SUMMATION OVER ALL GROUPS
C
40    HKSQ=SUM(M,W)/ZM
      IF(HKSQ.LT.0.0)GO TO 60
      HK=SQRT(HKSQ)
C
      CALL KOLMO(XK,IWT,KOL)
      IF(IDEBUG.GT.0)WRITE(6,10020)HK,HKSQ,KOL
C
50    RETURN
60    WRITE(IOUT,10030)HKSQ
      NS=1
      RETURN
10010 FORMAT(2F10.0)
10020 FORMAT(' HOOKER='E16.8,' HKSQ='E16.8,' KOLMO='E16.8)
10030 FORMAT('  HK-SQU NEGATIVE, ='E16.8)
      END
C
C
C---------------------------------------------------------------
C
C
      SUBROUTINE EPSFLO(NONZFF)
C
C     SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C     BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C     CALCULATES EPSI(U,Z) AND 2 PARTIAL DERIVATIVES
C     AND STORES VALUES FOR EACH GROUP I IN COMMON/CALCS/
C
      REAL K
      INTEGER CP
       COMMON/PIPES/M,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
      COMMON/ISTOP/NS
       COMMON/CALCS/P(600),Q(600),R(600),GK(600),ZNUMX,ZDENX,ZLNGK,
     1       EUZK(600),PDEDU(600),PDEDZ(600),
     2       COEFF(3),EXPON(3),K,HOOKER,A1,A2,PY,UFL,ZFL,IFL
C
C****** NS IS A SWITCH WHICH TELLS WHETHER OR NOT SOMETHING
C     IS WRONG. NS=0 FOR NO PROBLEMS, AND  NS=1 FOR TROUBLE.
C     WHEN NS=1,MAIN PROGRAM AND SOME SUBROUTINES MAY CEASE.
C
      NONZER=0
C
C*****  NONZER IS THE NUMBER OF FLOW GROUPS WITH NONZERO EUZK
C
      I=0
C
```

```
C        MUST DO SOME CALCULATIONS FOR EACH FLOW GROUP I
C
10       IF(I.GE.M.AND.IDEBUG.GT.0)GO TO 50
         IF(I.GE.M)RETURN
         I=I+1
         PI=P(I)
C
C        GET ENDPOINTS VI AND WI OF INTERVAL OF FLOW
C
         CALL ZLIM(C(I),VI,WI,NS)
         IF(NS.GT.0)RETURN
C
C        CALCULATE VALUES OF EPSI AND DERIVATIVES FOR GROUP I
C
         VCALC=UPL*PI
         IF(VCALC.GE.VI)GO TO 30
         EUZK(I)=VCALC-VI
20       CONTINUE
         PDEDU(I)=PI
         PDEDZ(I)=UPL*Q(I)
         NONZER=NONZER+1
         GO TO 10
30       IF(VCALC.GT.WI)GO TO 40
C
C        VALUES INSIDE INTERVAL ARE 0
C
         EUZK(I)=0.0
         PDEDU(I)=0.0
         PDEDZ(I)=0.0
         GO TO 10
C
40       EUZK(I)=VCALC-WI
         GO TO 20
50       CONTINUE
         WRITE(6,10010)(EUZK(I),I=1,M)
         WRITE(6,10020)(PDEDU(I),I=1,M)
         WRITE(6,10030)(PDEDZ(I),I=1,M)
         WRITE(6,10040)NONZER
         RETURN
10010    FORMAT('  EUZK='/(3E16.8))
10020    FORMAT(' PDEDU='/(3E16.8))
10030    FORMAT('  PDEDZ='/(3E16.8))
10040    FORMAT('  NUMBER OF NONZERO EUZK ='I5)
         END
C
C
C------------------------------------------------------------------
C
C
         SUBROUTINE CHISQ(XK,INT,CHI)
C
C        SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C        BY J.N. HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C  THIS SUBROUTINE TESTS THE NORMALITY OF THE ERROR DISTRIBUTION
C  USING THE CHI-SQUARE TEST.  THE VALUE OF THE CHI-SQUARE RANDOM
C  VARIABLE IS RETURNED.
C
C  M = NUMBER OF GROUPS OF PIPES
C  XK = PARAMETER K
C  INT = 1 FOR CAPACITY GROUPS, 2 OR 3 FOR FLOW GROUPS
C  CHI = VALUE OF CHI SQUARE RANDOM VARIABLE.
C  EPS = NORMALIZED ERROR RANDOM VARIABLE = EPSILON/(H*G)
C  O(J) = NUMBER OF OBSERVATIONS IN J-TH SECTION OF NORMAL CURVE
C
         REAL NP, A(20)
         INTEGER O(0:1600),CP
           COMMON/PIPES/M,NOM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
         COMMON/ISTOP/NS
           COMMON/CALCS/P(600),Q(600),R(600),GK(600),ZNUMI,ZDENX,ZLNGX,
         1        EUZK(600),PDEDU(600),PDEDZ(600),
         2        COEFF(3),EXPON(3),K,HOOKER,A1,A2,PY,UPL,ZPL,IPL
         COMMON/NORM/AREAS(0:1600)
C
C  SET LIMITS OF NORMAL CURVE SECTIONS.
         DATA A/-1.645,-1.282,-1.036,-.842,-.675,-.542,-.385,
         1              -.253,-.126,0.,.126,.253,.385,.542,.675,.842,
         2              1.036,1.282,1.645,99999999./
C
C  INITIALIZE
         DO 10 I = 0,1600
10         O(I) = 0
         CHI = 0.
C
C
C  LOOP THROUGH THE GROUPS AND COUNT DATA IN EACH SECTION
C  OF THE STANDARD NORMAL DISTRIBUTION.
         DO 60 I = 1,M
C---------COMPUTE THE ERROR.  FIGURE ERROR FROM ACTUAL OBSERVATION,
C---------NOT FROM BOUNDARY OF OBSERVATION INTERVAL.
           ERROR = C(I) - XK * P(I)
20         EPS = ERROR / (HOOKER * SQRT(GK(I)))
           SUM = SUM + EPS*EPS
C---------LOOK THROUGH SECTIONS OF NORMAL CURVE.
           IF(EPS.LT.-4.0)  GO TO 40
           IF(EPS.GT.4.0)  GO TO 50
           DO 30 J = 1,1600
             IF(EPS.GT.(-4.0+(J)*0.005))  GO TO 30
             O(J) = O(J) + 1
             IF(ABS(EPS).GE.3.)  CALL OUCH(I,EPS)
             GO TO 60
30         CONTINUE
           GO TO 60
40         O(0) = O(0) + 1
           CALL OUCH(I,EPS)
           GO TO 60
50         O(1600) = O(1600) + 1
           CALL OUCH(I,EPS)
60       CONTINUE
         TYPE *, SUM
C
C
C  COMPUTE CHI-SQUARE VARIABLE.
```

```
      DO 70 I = 0,1600
        NP = N * AREAS(I)
70      CHI = CHI + (O(I) - NP) * (O(I) - NP) / NP
C
      TYPE 10010,O
C     IF(IDEBUG.GT.0)WRITE(6,100)O
      RETURN
10010 FORMAT(' ERROR SPREAD: ',1601A1)
      END
C
C
C------------------------------------------------------------------
C
C
      SUBROUTINE OUCH(I,EPS)
C
C     SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C     BY J.N HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
      TYPE 10010, I, EPS
      RETURN
10010 FORMAT(' OUCH! - STANDARD NORMAL VARIABLE FOR ',I3,
     1        '-TH GROUP =',F)
      END
C
C
C------------------------------------------------------------------
C
C
      SUBROUTINE KOLMO(XK,IWT,KOL)
C
C
C     SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C     BY J.N HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
C  M = NUMBER OF GROUPS OF PIPES
C  XK = PARAMETER X
C  IWT = 1 FOR CAPACITY GROUPS, 2 OR 3 FOR FLOW GROUPS
C  KOL = KOLMOGOROV-SMIRNOV STATISTIC
C  EPS = NORMALIZED ERROR RANDOM VARIABLE = EPSILON/(H*G)
C  O(J) = NUMBER OF OBSERVATIONS IN J-TH SECTION OF NORMAL CURVE
C
      REAL NP, A(20), KOL, AVG(0:1600)
      LOGICAL FIRST, SMOOTH
      INTEGER O(-1:1600),CP,CHAR(0:50)
        COMMON/PIPES/M,NUM(600),C(600),D(600,20),IOUT,IDEBUG,CP(600,20)
      COMMON/ISTOP/NS
        COMMON/CALCS/P(600),Q(600),R(600),GK(600),ZNUMI,ZDENX,ZLNGK,
     1        SUZK(600),PDEDU(600),PDEDZ(600),
     2        COEFF(3),EXPON(3),K,HOOKER,A1,A2,PY,UPL,ZPL,IPL
      COMMON/NORM/AREAS(0:1600)
      DATA CHAR/' ','1','2','3','4','5','6','7','8','9',
     1        'A','B','C','D','E','F','G','H','I','J','K',30*'*'/
C
C
C  INITIALIZE
      DO 10 I = 0,1600
10      O(I) = 0
C
C
C  LOOP THROUGH THE GROUPS AND COUNT DATA IN EACH SECTION
C  OF THE STANDARD NORMAL DISTRIBUTION.
      DO 60 I = 1,M
C---------COMPUTE THE ERROR.  FIGURE ERROR FROM ACTUAL OBSERVATION,
C---------NOT FROM BOUNDARY OF OBSERVATION INTERVAL.
        ERROR = C(I) - XK * P(I)
20      EPS = ERROR / (HOOKER * SQRT(GK(I)))
        SUM = SUM + EPS*EPS
C---------LOOK THROUGH SECTIONS OF NORMAL CURVE.
        IF(EPS.LT.-4.0)  GO TO 40
        IF(EPS.GT.4.0)  GO TO 50
        DO 30 J = 1,1600
          IF(EPS.GT.(-4.0+(J)*0.005))  GO TO 30
          O(J) = O(J) + 1
          IF(ABS(EPS).GE.3.5)  CALL OUCH(I,EPS)
          GO TO 60
30      CONTINUE
        GO TO 60
40      O(0) = O(0) + 1
        CALL OUCH(I,EPS)
        GO TO 60
50      O(1600) = O(1600) + 1
        CALL OUCH(I,EPS)
60    CONTINUE
C
      TYPE 10010
      ACCEPT 10020, DUMMY
      TYPE 10030, ((CHAR(O(I+32*J)),J=0,49),I=1,32)
      TYPE 10010
      ACCEPT 10020, DUMMY
      O(-1) = 0
C
C
C  COMPUTE KOLMOGOROV-SMIRNOV STATISTIC.
C  GET NUMBER N OF INTERVALS OVER WHICH AVERAGING IS TO TAKE PLACE.
C  IF N = 1, USE ORDINARY KOLMOGOROV-SMIRNOFF.
C  OTHERWISE, COMPUTE AVERAGE DEVIATION OF OBSERVED FROM IDEAL
C  CUMULATIVE DISTRIBUTION OVER LAST N INTERVALS.
      FIRST = .TRUE.
70    TYPE 10040
      ACCEPT *, N
      IF(N.EQ.0)  RETURN
      SMOOTH = .TRUE.
      IF(N.LT.0)  SMOOTH = .FALSE.
      N = IABS(N)
      AN = N
      BN = 1./FLOAT(N)
      KOL = 0.
      DO 80 I = 0,1600
80      AVG(I) = 0.
      IF(N.EQ.1)  GO TO 120
      DO 110 I = 0,N-2
        IF(FIRST)  O(I) = O(I) + O(I-1)
```

```
         IF((O(I)-O(I-1)).EQ.0)  GO TO 110
         IF(SMOOTH)  GO TO 90
         DIFF = ABS(FLOAT(O(I))/AM - AREAS(I))
         GO TO 100
90       DIFF1 = ABS(FLOAT(O(I-1)+1)/AM - AREAS(I))
         DIFF2 = ABS(FLOAT(O(I))/AM - AREAS(I))
         DIFF = 0.5*(DIFF1+DIFF2)*(O(I)-O(I-1))
100      AVG(I) = DIFF
         IF(I.EQ.0)  GO TO 110
         DO 110 J = 0,I-1
           AVG(J) = AVG(J) + DIFF
110        CONTINUE
120     KOL = 0.
        NKOL = 0
        DO 170 I = N-1,1600
C---------KEEP TRACK OF CUMULATIVE OBSERVED DISTRIBUTION.
         IF(FIRST)  O(I) = O(I) + O(I-1)
         IF((O(I)-O(I-1)).EQ.0)  GO TO 170
         IF(SMOOTH)  GO TO 130
         DIFF = ABS(FLOAT(O(I))/AM - AREAS(I))
         GO TO 140
130      DIFF1 = ABS(FLOAT(O(I-1)+1)/AM - AREAS(I))
         DIFF2 = ABS(FLOAT(O(I))/AM - AREAS(I))
         DIFF = 0.5*(DIFF1+DIFF2)*(O(I)-O(I-1))
140      AVG(I) = DIFF
         IF(N.EQ.1)  GO TO 160
         DO 150 J = I-N+1,I-1
150        AVG(J) = AVG(J) + DIFF
160      DIV = O(I) - O(I-N)
         IF(.NOT.SMOOTH)  DIV = 1.
         AVERGE = AVG(I-N+1) / DIV
         IF(ABS(AVERGE).LE.KOL)  GO TO 170
         KOL = ABS(AVERGE)
         NKOL = I
170      CONTINUE
        TYPE 10050, KOL, NKOL
        FIRST = .FALSE.
        GO TO 70
C
C       IF(IDEBUG.GT.0)WRITE(6,100)O
10010   FORMAT(' PAGE AND HIT RETURN.')
10020   FORMAT(A1)
10030   FORMAT(' ERROR SPREAD:'
        1                  32(/,X,50A1))
10040   FORMAT(' NUMBER OF AVERAGING INTERVALS (0 TO SKIP, -1',
        1        ' FOR NO SMOOTHING) = ',$)
10050   FORMAT(' KOLMOGOROV-SMIRNOV STATISTIC = ',F10.6,
        1                  '; I =',I5)
        END
C
C
C-----------------------------------------------------------------------
C
C
        SUBROUTINE NORMAL
C
C       SUBROUTINE TO BE USED WITH REGRESSION PROGRAM
C       BY J.N.HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C  THIS ROUTINE COMPUTES A CUMULATIVE NORMAL DISTRIBUTION AT
C  1600 POINTS FOR THE KOLMOGOROV-SMIRNOFF TEST.
C
        EXTERNAL GAUSS
        REAL AREAS(0:1600)
        DOUBLE PRECISION GAUSS,GAUSS1,GAUSS2,AA,SLICE
        COMMON /NORM/ AREAS
        TYPE 10010
        W1=0.0025
        AREAS(0)=(1.-0.9999366575)*0.5
C-------GET ACCURATE AREAS FOR 15 POINTS.
        DO 30 J=0,15
          JJ=J*100
          IF(J.EQ.0)  GO TO 10
          A1=-4.+FLOAT(J-1)*0.5
          B1=A1+0.5
          AREAS(JJ)=SIMPSN(GAUSS,A1,B1,W1,NP)
          AREAS(JJ)=AREAS(JJ)+AREAS(JJ-100)
          DIFF=DIFF-AREAS(JJ)
          TYPE 10020, J, DIFF
C---------NOW USE TRAPEZOIDS TO COMPUTE INTERMEDIATE POINTS.
10        AA=-4.0D0+DFLOAT(JJ)*0.005D0
          GAUSS1=GAUSS(AA)
          DO 20 I=1,100
            AA=-4.D0+DFLOAT(JJ+I)*0.005D0
            GAUSS2=GAUSS(AA)
            SLICE=(GAUSS1+GAUSS2)*0.0025D0
            GAUSS1=GAUSS2
20          AREAS(JJ+I)=AREAS(JJ+I-1)+SLICE
          DIFF=AREAS(JJ+100)
30        CONTINUE
        AREAS(1600)=1.D0-AREAS(0)
        RETURN
10010   FORMAT(' COMPUTING CUMULATIVE NORMAL DISTRIBUTION.'
        1                 /' ERRORS:   CHECKPOINT  ERROR')
10020     FORMAT(I19,2X,E9.2)
        END
C
C
C-----------------------------------------------------------------------
C
C
        DOUBLE PRECISION FUNCTION GAUSS(X)
C
C       FUNCTION TO BE USED WITH REGRESSION PROGRAM
C       BY J.N HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
        DOUBLE PRECISION X, PI
        PI=4.0D0*DATAN(1.D0)
        GAUSS=(1.D0/DSQRT(2.D0*PI))*DEXP(-X*X*0.5D0)
        RETURN
        END
C
C
C-----------------------------------------------------------------------
```

```
C
C
      FUNCTION SIMPSN(FUNC,A1,B1,W1)
C
C     FUNCTION TO BE USED WITH REGRESSION PROGRAM
C     BY J.N BOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C------------SIMPSON'S RULE FUNCTION
C------------RECEIVES SINGLE PRECISION, CALCULATES DOUBLE PREC.
C------------ANSWER IS RETURNED SINGLE PRECISION
C------------FUNC IS A DOUBLE PRECISION SUBROUTINE
C------------A1 IS FIRST LIMIT,B1 IS SECOND LIMIT,
C------------W IS WIDTH OF INTERVAL DESIRED FOR SIMPSON'S RULE
      DOUBLE PRECISION A,B,W,W2,Z,Z2,X,Y,ADD
      A=DBLE(A1)
      B=DBLE(B1)
      W=DBLE(W1)
      IF(B.LE.A)GO TO 50
      Z=0.D0
      Z2=0.D0
      X=A
      Y=FUNC(X)
      I=0
      IF(B-A.LE.W)GO TO 30
      K=IDINT((B-A)/W)
C----------K IS THE NUMBER OF INTERVALS WIDTH W
      IF(K.LT.2)GO TO 30
      L=MOD(K,2)
C----------L=0 IF K IS EVEN, L=1 IF K IS ODD
      K1=K-L
      Z=Y
10    I=I+1
      X=A+DFLOAT(I)*W
      ADD=FUNC(X)
      ADD=ADD+ADD
      Z=Z+ADD+ADD
      I=I+1
      X=A+DFLOAT(I)*W
      IF(I.EQ.K1)GO TO 20
      ADD=FUNC(X)
      ADD=ADD+ADD
      Z=Z+ADD
      GO TO 10
20    Y=FUNC(X)
      Z=Z+Y
      Z=Z*W/3.0D0
C------------END OF SIMPSON'S RULE USING GIVEN WIDTH W.
C------------FINISH REMAINING INTERVAL WITH ONE SIMPSON'S RULE.
30    W2=B-X
      IF(DABS(W2).LT.1.0D-15)GO TO 40
      ADD=FUNC((X+B)*0.5D0)
      ADD=ADD+ADD
      Z2=(Y+ADD+ADD+FUNC(B))*W2/6.0D0
40    SIMPSN=SNGL(Z+Z2)
      RETURN
50    TYPE 10010
      SIMPSN=-1.E10
      RETURN
10010 FORMAT('  TROUBLE IN SIMPSN FUNCTION')
      END
```

```
*    NETWORK DATA CHECK PROGRAM
*

        PROGRAM PDCJKR
C
C
C--BY J.N. HOOKER, ENERGY DIVISION, OAK RIDGE NATIONAL LAB, TN.
C       DEVELOPED ON THE DEC-SYSTEM 10 COMPUTER, 1980.
C
C
C--THIS PROGRAM CHECKS ORIGINALLY CODED NETWORK FOR SOME ERRORS
C
C
C       PROGRAMMING ASSISTANCE BY RUTH B. HOFSTRA,UNIV. OF TENN.
C
        DOUBLE PRECISION NAME
        DIMENSION NAMDAT(2)
        EQUIVALENCE(NAME,NAMDAT)
        DIMENSION IDD(16,6)
        COMMON ID(79,6),NODE1(200),KC(6)
        INTEGER EN1,EN2
        DATA BLANK/'     '/
C
C-----SECTION A
C-SETUP TO BEGIN
        IPRINT=0
        IOUT=6
        TYPE 440
        READ(5,480)NAMDAT
        TYPE 450,NAMDAT
        OPEN(UNIT=20,DEVICE='DSK',FILE=NAME)
        IFIN = 1
C
        KSTATE=0
10      WRITE(IOUT,460)
C
C-----SECTION B
C-READ A CARD OR CARDS(CONT) FOR A PIPELINE
20      DO 50 I=1,6
        DO 30 JJ=1,16
30      IDD(JJ,I)=BLANK
        DO 40 JJ=1,79
40      ID(JJ,I)=0
        KC(I)=0
50      CONTINUE
        ICD=1
        READ(20,470,END=80,ERR=90)IST,IN1,IST2,IN2,(ID(I,ICD),I=51,79)
       1KC(ICD)
        REREAD 480,(IDD(I,ICD),I=1,16)
        IF(IPRINT.LE.0)GO TO 60
        WRITE(IOUT,490)IST,IN1,IST2,IN2,(ID(I,ICD),I=51,79),KC(ICD)
        WRITE(IOUT,590)(IDD(I,ICD),I=1,16)
60      MAIN1=100*IST+IN1
        MAIN2=100*IST2+IN2
70      IC=KC(ICD)
        IF(IC.LT.1)  GO TO 100
        ICD=ICD+1
        IF(ICD.GE.7)  GO TO 380
        READ(20,500,ERR=90)(ID(I,ICD),I=1,79),KC(ICD)
        REREAD 480,(IDD(I,ICD),I=1,16)
        IF(IPRINT.LE.0)GO TO 70
        WRITE(IOUT,510)(ID(I,ICD),I=1,79),KC(ICD)
        WRITE(IOUT,590)(IDD(I,ICD),I=1,16)
        GO TO 70
80      IFIN=2
        GO TO 110
90      REREAD 480,(IDD(I,ICD),I=1,16)
        WRITE(IOUT,520)(IDD(I,ICD),I=1,16)
        GO TO 50
C
100     IF(KSTATE.LE.0)  GO TO 150
        IF(IST.EQ.KSTATE)GO TO 170
C
C-----SECTION C
C-FINISH REPORT OF THIS STATE
110     IF(NDUP.LE.0)WRITE(IOUT,560)
        WRITE(IOUT,530)KSTATE,MAX
        NMISS=0
        DO 120 I=1,MAX
        IF(NODE1(I).GT.0)GO TO 120
        NMISS=NMISS+1
        WRITE(IOUT,540)I
120     CONTINUE
        IF(NMISS.LE.0)GO TO 130
        WRITE(IOUT,550)NMISS
        GO TO 140
130     WRITE(IOUT,560)
140     IF(IFIN.GT.1)GO TO 420
C
C-----SECTION D
C-START NEW STATE
150     KSTATE=IST
        NSTATE=NSTATE+1
        NDUP=0
        WRITE(IOUT,570)KSTATE
        MAX=0
        DO 160 I=1,200
160     NODE1(I)=0
C
C-----SECTION E
C-CHECK ON OCCURRENCE AND MAX OF READ NODE NUMBERS
170     IF(IN1.GT.MAX)MAX=IN1
        NODE1(IN1)=1
C
C-----SECTION F
C-START CHECK OF EXTENSION FIELD
C     ICD=NUMBER CARD IMAGES IN THIS RECORD
C     NCD=CURRENT CARD IMAGE BEING PROCESSED
        NCD=1
        J=ID(51,1)
        ICHAR=52
180     IF(J-1)190,200,250
```

```
190     IF(NCD.EQ.ICD)GO TO 20
        WRITE(IOUT,580)
        GO TO 390
C
C-----SECTION G
C-CASE J=1. COUNT UP PLACES TO GET TO PLACE TO CHECK J=2
200     NPIPES=ID(52,1)
        ILAST=78
        IF(ICD.EQ.1)ILAST=79
        MOST=(ILAST-52)/3
        IF(NPIPES.GT.MOST)GO TO 230
        ICHAR=ICHAR+3*NPIPES
        IF(78-ICHAR.LT.3)GO TO 220
        ICHAR=ICHAR+2
        J=ID(ICHAR,NCD)
210     ICHAR=ICHAR+1
        GO TO 240
220     IF(NCD.GE.ICD)GO TO 190
        NCD=NCD+1
        J=ID(1,NCD)
        ICHAR=2
        GO TO 240
230     NCD=NCD+1
        J=ID(4,NCD)
        ICHAR=5
        IF(NCD.LE.ICD)GO TO 240
        WRITE(IOUT,580)
        GO TO 390
240     IF(J.EQ.1)GO TO 370
        GO TO 180
C
C-----SECTION H
C-CASEJ=2 OR 3  COMPARE HEAD-TAIL PAIRS OF EXTRA LINKS
C AGAINST HEAD-TAIL PAIR FOR PIPE
250     CONTINUE
260     NLINKS=ID(ICHAR,NCD)
        ILK=0
270     ILK=ILK+1
        IF(ILK.GT.NLINKS)   GO TO 320
        ILAST=78
        IF(NCD.EQ.ICD)ILAST=79
        IF(ILAST-ICHAR.LT.10)GO TO 300
        CALL ENJ(NCD,ICHAR,EN1)
280     IF(EN1.EQ.MAIN1)GO TO 290
        ICHAR=ICHAR+5
        GO TO 270
290     CALL ENJ(NCD,ICHAR,EN2)
        IF(EN2.EQ.MAIN2)GO TO 350
        GO TO 270
300     IEN1=0
        IF(ILAST-ICHAR.LT.5)   GO TO 310
        CALL ENJ(NCD,ICHAR,EN1)
        IEN1=1
310     IF(NCD.GE.ICD)GO TO 190
        NCD=NCD+1
        ICHAR=-1
        IF(IEN1.LE.0)CALL ENJ(NCD,ICHAR,EN1)
        GO TO 280
C-----SECTION I
C-CHECK TO SEE IF WE HAVE JUST DONE J=3
320     IF(J.GE.3)GO TO 190
        ILAST=75
        IF(NCD.EQ.ICD)ILAST=76
        IF(ICHAR.GT.ILAST)GO TO 330
        ICHAR=ICHAR+2
        J=ID(ICHAR,NCD)
        ICHAR=ICHAR+1
        GO TO 340
330     IF(NCD.GE.ICD)GO TO 20
        NCD=NCD+1
        J=ID(1,NCD)
        ICHAR=2
340     IF(J.EQ.1.OR.J.EQ.2)GO TO 370
        GO TO 180
C
C-----SECTION J
C-WRITE OUT RECORD WITH DUPLICATE HEAD AND TAIL NODES
350     NDUP=NDUP+1
        KCD=1
360     IF(KCD.GT.ICD)GO TO 20
        WRITE(IOUT,590)(IDD(I,KCD),I=1,16)
        KCD=KCD+1
        GO TO 360
C
C-----SECTION K
C-TROUBLE MESSAGES AND CLOSING PRINTOUTS
370     WRITE(IOUT,600)
        GO TO 390
380     WRITE(IOUT,610)
390     KCD=1
400     IF(KCD.GT.ICD)GO TO 410
        WRITE(IOUT,590)(IDD(I,KCD),I=1,16)
        KCD=KCD+1
        GO TO 400
410     WRITE(IOUT,620)MAIN1,MAIN2
        GO TO 20
420     WRITE(IOUT,630)NSTATE
430     CALL EXIT
440     FORMAT(' WHAT IS NAME OF PIPE DATA FILE?'$)
450     FORMAT(' NAME OF FILE IS '2A5)
460     FORMAT('1',9X,'PIPELINE DATA CHECK PROGRAM'//)
470     FORMAT(2I2,2X,2I2,40X,30I1)
480     FORMAT(16A5)
490     FORMAT(10X,2I2,2X,2I2,40X,30I1)
500     FORMAT(80I1)
510     FORMAT(10X,80I1)
520     FORMAT('   READ TROUBLE FOLLOWING RECORD:'16A5)
530     FORMAT(//'      STATE NO. ',I3,' HAS ',I3,' HEAD-NODES'//
        110X,      'NODE NUMBERS SKIPPED -')
540     FORMAT(10X,I8)
550     FORMAT(10X,      'TOTAL NUMBER OF NODES SKIPPED -',I4)
560     FORMAT('         NONE')
570     FORMAT(//'       STATE NO. ',I3//10X,
        1'SEARCH FOR DUPLICATE PAIR(S) OF NODE NUMBERS YIELDS ',
```

```
     2'THE FOLLOWING RECORDS:'/)
580  FORMAT('  NUMBER OF CONTINUATIONS CONFLICTS WITH J VALUE',
     1 ' AND DATA')
590  FORMAT(10X,16A5)
600  FORMAT('  SAME J VALUE OCCURS TWICE IN SAME RECORD')
610  FORMAT('   NUMBER OF CONTINUATIONS EXCEEDS 5')
620  FORMAT(' HEAD -'I5,'; TAIL -',I5)
630  FORMAT('   TOTAL NUMBER OF STATES -',I4)
     END
C
C
C-----------------------------------------------------------------------
C
C
     SUBROUTINE ENJ(NCD,ICHAR,EN1)
C
C
C    SUBROUTINE TO BE USED WITH DATA CHECK PROGRAM
C    BY J.N  HOOKER,ENERGY DIVISION,OAK RIDGE NATIONAL LAB,1980
C
C
     COMMON ID(79,6),NCDE1(200),KC(6)
     INTEGER EN1
     EN1=ID(ICHAR+2,NCD)
     DO 10 I=3,5
10   EN1=EN1*10 + ID(ICHAR+I,NCD)
     ICHAR=ICHAR+5
     RETURN
     END
```

Appendix D. PIPELINE COMPANY DATA

1978 data pertaining to oil pipeline companies are contained in the following data file. The format is as follows.

Character positions	Fortran format	Description
1–24	6A4	Company name
25–27	I3	Company number
30–35	I6	Crude oil movements (10^6 bbl-mi) as reported on 1978 Form P.
36–41	I6	Crude oil movements (10^6 bbl-mi) as transcribed from Form P by Oil and Gas Journal (1979).
42–47	I6	Oil products movements (10^6 bbl-mi) from Form P.
48–53	I6	Oil products movements (10^6 bbl-mi) from Oil and Gas Journal.
54–56	I3	If pipelines ascribed to this company by the maps should be counted as belonging to another company for reporting purposes, the number of that other company is entered here. Otherwise a zero is entered.
57–80	8I3	Percent of company throughput consisting of crude oil, gasoline, kerosine, fuel oil, jet fuel, LPG and ammonia, respectively, as reported on 1978 Form P.
81–90	2I5	Total company pipeline mileage, from Oil and Gas Journal (1979).
92	I1	A one is entered for federally regulated companies, a two for other companies.

* PIPELINE COMPANY DATA FILE
*

ACORN	1	8205	8205	0	0	0	100	0	0	0	0	0	0	0	0	0	1
AIR FORCE	2	0	0	7	7	0	0	100	0	0	0	0	0	0	0	0	1
ALLEGHENY	3	0	0	0	2831	0	0	0	0	0	0	0	0	0	0	0	1
AMDEL	4	6886	6886	0	0	0	63	14	0	0	12	11	0	0	529	28	1
AMERICAN PETROFINA, TEX	5	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	1
AMERICAN PETROFINA	6	0	2284	0	0	0	0	0	0	100	0	0	0	0	538	0	1
AMOCO	7	173777	173777	7916	8439	0	76	10	0	5	0	9	0	0	8349	1685	1
ARAPAHOE	8	2814	2814	0	0	0	100	0	0	0	0	0	0	0	267	0	1
ARCO	9	89045	89045	17760	17760	0	74	12	0	5	1	8	0	0	2887	3752	1
ASHLAND	10	12198	12198	0	0	0	100	0	0	0	0	0	0	0	359	0	1
BADGER	11	0	0	4723	4723	0	0	63	0	35	0	2	0	0	0	328	1
BELLE FOURCHE	12	3160	3160	0	0	0	100	0	0	0	0	0	0	0	704	0	1
BLACK LAKE	13	1503	1503	0	0	0	100	0	0	0	0	0	0	0	255	0	1
BLACK MESA	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BUCKEYE	15	8069	10142	33994	34103	0	30	49	0	16	1	4	0	0	353	3133	1
BUTTE	16	5201	5201	0	0	0	100	0	0	0	0	0	0	0	373	0	1
CALNEV	17	0	0	3981	0	0	0	52	0	48	0	0	0	0	0	354	1
CHASE TRANSPORTATION CO.	18	0	0	7291	7291	0	0	82	0	18	0	0	0	0	0	478	1
CHEROKEE	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CHEVRON	20	20239	20239	9716	9717	0	77	13	0	10	0	0	0	0	1201	1491	1
CHEYENNE	21	9	9	897	897	0	4	51	0	45	0	0	0	0	34	220	1
CHICAP	22	26773	26773	0	0	0	100	0	0	0	0	0	0	0	235	0	1
CITIES SERVICE	23	11981	11981	801	801	0	92	0	0	3	0	5	0	0	665	110	1
COLLINS	24	0	0	3315	3315	0	0	54	0	28	18	0	0	0	0	124	1
COLONIAL	25	0	0	0	614917	0	0	64	0	29	8	0	0	0	0	4173	1
CONTINENTAL	26	11136	11136	12018	12019	0	75	15	0	2	5	3	0	0	1395	1792	1
COOK INLET	27	1175	1175	0	0	0	100	0	0	0	0	0	0	0	55	0	1
CRA INC.	28	475	475	0	0	0	100	0	0	0	0	0	0	0	242	1	1
CROWN CENTRAL	29	0	0	0	5476	0	0	0	0	0	0	0	0	0	0	0	1
CROWN-RANCHO	30	4436	4436	0	0	0	100	0	0	0	0	0	0	0	0	0	1
DIAMOND SHAMROCK	31	0	0	7317	7317	0	0	15	0	3	0	82	0	0	0	622	1
DIXIE	32	0	0	18725	18725	0	0	0	0	0	0	100	0	0	0	1300	1
DOME	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EMERALD	34	0	0	282	282	0	0	33	0	17	0	50	0	0	0	113	1
EUREKA	35	0	0	0	0	158	0	0	0	0	0	0	0	0	242	0	1
EXPLORER	36	16165	16165	0	68799	0	13	63	0	23	1	0	0	0	0	1389	1
EXXON	37	54724	54724	1450	1450	0	91	3	0	4	0	2	0	0	5027	2022	1
FOUR CORNERS	38	0	3792	0	125	0	80	14	0	2	4	0	0	0	989	36	1
GETTY PIPE COMPANY	39	0	0	119	118	0	0	0	0	98	2	0	0	0	0	571	1
GULF CENTRAL	40	0	0	7247	7247	0	0	0	0	0	0	0	100	0	0	176	1
GULF REFINING	41	14098	14098	48380	48380	0	53	25	0	9	1	12	0	0	1054	2039	1
HESS	42	0	3759	0	0	0	100	0	0	0	0	0	0	0	339	0	1
HYDROCARBON TRANSPORTAT.	43	0	0	25267	25267	0	0	100	0	0	0	0	0	0	0	1271	1
JAYHAWK	44	2790	2790	0	0	0	100	0	0	0	0	0	0	0	513	0	1
JET LINES	45	0	0	754	754	0	0	26	0	73	1	0	0	0	0	103	1
KANEB	46	0	0	9321	0	0	0	54	0	32	0	14	0	0	0	0	0
KAW	47	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	1
KENAI	48	123	123	0	0	0	100	0	0	0	0	0	0	0	24	0	1
KERR-MCGEE	49	0	11	0	0	0	100	0	0	0	0	0	0	0	33	0	1
KIANTONE	50	1175	1175	0	0	0	100	0	0	0	0	0	0	0	78	0	1
LAKE CHARLES	51	0	0	252	252	0	0	68	0	28	4	0	0	0	0	12	1
LAKE HEAD	52	343294	337195	0	0	0	100	0	0	0	0	0	0	0	2571	0	1

LAUREL	53	0	0	9603	9603	0	0	62	0	38	0	0	0	0	0	451	1
LION	54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAPCO	55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MARATHON	56	41187	41187	17136	17136	0	69	20	0	9	1	1	0	0	586	601	1
MICHIGAN-OHIO	57	845	844	316	316	0	71	18	0	3	8	0	0	0	275	64	1
MID-VALLEY	58	84022	84022	0	0	0	100	0	0	0	0	0	0	0	1004	0	1
MINNESOTA	59	14418	14418	0	0	0	100	0	0	0	0	0	0	0	365	0	1
MOBIL	60	82253	72007	13075	23323	0	71	0	0	0	0	0	0	0	5230	2411	1
NATIONAL TRANSIT	61	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	1
OHIO RIVER	62	0	0	1340	1340	0	0	81	0	17	2	0	0	0	0	458	1
OKAN	63	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	1
ONIE	64	0	232	727	816	0	64	14	0	0	0	22	0	0	158	383	1
OLYMPIC	65	0	0	13812	13812	0	0	67	0	20	13	0	0	0	0	391	1
OWENSBORO-ASHLAND	66	16311	16311	0	0	0	100	0	0	0	0	0	0	0	295	0	1
PALOMA	67	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	1
PASCO	68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PHILLIPS PETROLEUM	69	0	0	0	0	70	0	0	0	0	0	0	0	0	0	0	0
PHILLIPS PIPE LINE	70	20704	20704	41253	41253	0	36	30	0	8	1	25	0	0	2050	2819	1
PIONEER	71	0	0	2478	2478	0	0	72	0	28	0	0	0	0	0	303	1
PLANTATION	72	0	0	0	111609	0	0	65	0	24	11	0	0	0	0	3155	1
PLATTE	73	28893	28893	0	0	0	100	0	0	0	0	0	0	0	1258	0	1
PORTAL	74	2536	2536	0	0	0	100	0	0	0	0	0	0	0	551	0	1
PORTLAND	75	10444	10444	0	0	0	100	0	0	0	0	0	0	0	513	0	1
POWDER RIVER CORP.	76	0	0	0	2275	0	0	0	0	0	0	0	0	0	0	679	1
PURE TRANSPORTATION	77	22048	22048	286	286	0	73	15	0	9	1	2	0	0	490	17	1
SANTA FE	78	0	0	11895	11325	0	0	0	0	4	0	96	0	0	0	899	1
SHAMROCK	79	702	702	618	618	0	60	28	0	1	11	0	0	0	273	181	1
SHELL	80	93149	94289	6944	6184	0	77	13	0	1	0	9	0	0	5116	188	1
SKELLY	81	473	473	222	222	0	79	0	0	11	0	10	0	0	188	137	1
SOHIO	82	0	15417	0	1408	0	83	10	0	4	3	0	0	0	572	47	1
SOUTHCAP	83	51508	51508	0	0	0	100	0	0	0	0	0	0	0	0	0	1
SOUTHERN PACIFIC	84	0	0	31529	31529	0	0	72	0	16	12	0	0	0	0	2478	1
STANDARD TRANSMISSION	85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SUN OIL OF MICHIGAN	86	0	0	99	99	0	0	97	0	3	0	0	0	0	0	9	1
SUN PIPE LINE	87	7066	7066	15273	15273	0	65	24	0	7	1	3	0	0	1435	0	1
TECUMSEH	88	1450	1450	0	0	0	100	0	0	0	0	0	0	0	206	0	1
TEXACO-CITIES SERVICE	89	27385	27385	298	298	0	97	3	0	0	0	0	0	0	1787	106	1
TEXAS EASTERN TRANSMISS.	90	0	0	0	63803	0	0	0	0	0	0	0	0	0	0	3089	1
TEXAS PIPE LINE	91	110392	112063	7851	8787	0	68	19	0	7	6	0	0	0	2314	539	1
TEXAS-NEW MEXICO	92	16586	16586	0	0	0	100	0	0	0	0	0	0	0	2226	0	1
TEXAS MOUNTAIN OIL	93	326	326	0	0	0	100	0	0	0	0	0	0	0	64	0	1
TRANS-OHIO	94	0	0	0	439	0	0	0	0	0	0	0	0	0	0	0	1
UCAR	95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WESCO	96	1057	1057	0	0	0	100	0	0	0	0	0	0	0	507	0	1
WEST EMERALD	97	0	0	531	531	0	0	78	0	0	0	22	0	0	0	296	1
WEST SHORE	98	0	0	8212	8212	0	0	74	0	26	0	0	0	0	0	326	1
WEST TEXAS GULF	99	40449	40449	0	0	0	100	0	0	0	0	0	0	0	582	0	1
WESTERN OIL	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
WHITE SHOAL	101	136	136	0	0	0	100	0	0	0	0	0	0	0	0	0	1
WILLIAMS	102	10249	10249	65111	65111	0	10	33	0	15	12	25	0	0	82	8149	1
WOLVERINE	103	0	0	15647	15647	0	0	72	0	25	3	0	0	0	0	20	1
WYCO	104	0	0	4429	4429	0	0	69	0	27	4	0	0	0	0	731	1
YELLOWSTONE	105	0	0	8878	8878	0	0	72	0	21	7	0	0	0	0	751	1
EL PASO NATURAL GAS	106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NAVAJO	107	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NAPCOR	108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KENTUCKY HYDROCARBON	109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

INLAND	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LEONARD	111	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MIAMI VALLEY	112	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MASSACHUSETTS	113	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INDIANA FARM BUREAU	114	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GENERAL AMERICAN TRANSIT	115	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SOUTHEASTERN	116	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SIECN	117	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GREAT NORTHERN OIL	118	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BAYOU	119	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RIVER PIPE	120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ANDERSON PRITCHARD	121	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TRUST COMPANY	122	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CASA	123	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SEA DRIFT	124	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BAY	125	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
COASTAL STATES	126	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MEDICINE BOW	127	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HUSKY	128	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CENEX	129	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CHAMPLIN	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NATIONAL CO-OP	131	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SAN DIEGO	133	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MATADOR	134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OZARK	135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DEFET	136	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PHILLIPS SHAMROCK	137	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AMERICAN OIL	138	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ONIE	139	0	0	0	0	64	0	0	0	0	0	0	0	0	158	383	1
EASTERN DOUGLAS	140	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESSO STANDARD	141	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LONG ISLAND	142	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KENTUCKY PIPE LINE	143	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVERGLADES	144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
STANDARD OHIO	145	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INTERSTATE ENERGY CO.	146	174	174	726	726	0	19	0	0	81	0	0	0	0	0	94	1
T.T.	147	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PANAM	148	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
REEC	149	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DOW	150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WAPC	151	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TUIOMA	152	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SEA DRIFT	153	0	0	0	0	124	0	0	0	0	0	0	0	0	0	0	0
WANDA	154	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UNION	155	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BI-PETRO	156	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	1
CIRECO	157	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	1
MOBEKA	158	5981	0	0	0	0	100	0	0	0	0	0	0	0	242	0	1
GETTY PIPE LINE	159	473	473	222	222	81	79	0	0	11	0	10	0	0	0	571	1
MINDEN	132	0	0	11	11	0	0	0	0	0	0	0	0	0	0	24	1
MOBIL ALASKA	160	16000	16000	0	0	0	100	0	0	0	0	0	0	0	40	0	1
MOBIL EUGENE ISLAND	161	545	545	0	0	0	100	0	0	0	0	0	0	0	0	0	1
OSAGE	162	7639	7639	0	0	0	100	0	0	0	0	0	0	0	136	0	1
PHILLIPS ALASKA	163	5312	5312	0	0	0	100	0	0	0	0	0	0	0	13	0	1
PIRIO	164	0	0	2104	2104	0	0	54	0	34	12	0	0	0	0	251	1
PLAINS	165	103	103	0	0	0	100	0	0	0	0	0	0	0	133	0	1
POGO	166	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

WASCANA	167	115	115	0	0	0	100	0	0	0	0	0	0	0	59	0	1
AMERADA HESS	168	4800	4800	0	0	0	100	0	0	0	0	0	0	0	12	0	1
SUNNILAND PIPE LINE CO.	169	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HUNT	170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WOOD RIVER-PATOKA SYS.	171	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
ARAPAHOE(PURE)	172	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARCO	173	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WASCO	174	0	0	0	0	96	0	0	0	0	0	0	0	0	0	0	0
BIGHEART (P.L.)	175	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOUISIANA-MISSISSIPPI	176	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PARISH P.L.	177	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCURLOCK	178	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ATLAS	179	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WHITECAP	180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SHIP SHOAL	181	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OHIO	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CALIFORNIA	183	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CATC.	184	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PENNZOIL	185	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CAGC	186	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MID-CONT.	187	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VICKERS	188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
TEXOMA	189	0	39280	0	0	0	100	0	0	0	0	0	0	0	504	0	1
INTERSTATE ST. & PL	190	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	1
PERMIAN	200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HOMESTAKE	201	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
STANDARD CALIF.	202	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UNION CALIF.	203	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TEXACO	204	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SIGNAL	205	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VENTURA	206	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GOLDEN EAGLE	207	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FT.COLLINS	208	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KOCH	209	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WESCANA	210	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BELL CREEK	211	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ROCK ISLAND	212	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WESTERN CRUDE OIL(WCOI)	213	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FAIRVIEW	214	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PLAINS	215	0	0	0	0	165	0	0	0	0	0	0	0	0	133	0	1
OZARK	216	0	0	0	0	135	0	0	0	0	0	0	0	0	0	0	0
QUAKER STATE	217	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SOUTHERN P.L. CO.	218	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BRILEAC	219	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CAPLINE	220	275000	275000	0	0	0	100	0	0	0	0	0	0	0	655	0	1
BASIN	221	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MESA	222	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RANCHO	223	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TESORO	224	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAGNOLIA	225	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EAST TEXAS	226	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PALINE	227	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NOBLE	228	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TYLER	229	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARCO (ALASKA)	230	67200	67200	0	0	0	100	0	0	0	0	0	0	0	166	0	1
SOHIO, ALASKA	231	106688	106688	0	100	0	0	0	0	0	0	0	0	0	266	0	1
UNION ALASKA	232	5312	5312	0	0	0	100	0	0	0	0	0	0	0	13	0	1

EXXON (ALASKA)	233	64000	64000	0	0	0100	0	C	0	0	0	0	0	160	0	1
BRITISH PETROLEUM	234	50698	50698	0	0	0100	0	C	0	0	0	0	0	126	0	1

Appendix E. CAPACITY AND THROUGHPUT OBSERVATIONS

The following four data files contain capacity vs. diameter observations and throughput vs. diameter observations for crude and for products pipelines. The capacity vs. diameter observations are taken from a 1979 study of pipeline capacities (National Petroleum Council, 1979). The throughput vs. diameter observations are read from maps showing 1974 oil movements (Congressional Research Service, 1975). See Chap. 4 for further explanation.

Note that capacities or throughputs of individual pipes are often not known, but only those of groups of pipes. Note also that throughputs are given in multiples of 5×10^6 bbl/yr, except for a few entered as 0.7 or 0.3×10^6 bbl/yr. These last two represent the categories "between 0.5×10^6 and 1×10^6 bbl/yr" and "less than 0.5×10^6 bbl/yr." The formats of the files are as follows.

Character positions	Fortran format	Description
Capacity observation files		
1–5	I5	Capacity group number.
6–8	I3	Number n of segments in this capacity group.
9–16	F8.1	1979 average daily throughput capacity, in thousands of barrels of no. 2 fuel oil, of the segments in this capacity group.
20–80	nI3	Diameters of segments in this capacity group.
Throughput observation files		
1–5	I5	Flow group number.
6–8	I3	Number n of segments in this flow group
9–16	F8.1	1974 throughput, in millions of barrels, of the segments in this flow group.
20–80	n(I3,I4)	Diameters of segments in this flow group, each followed by the number of the capacity group containing the segment having that diameter (or by a zero, if that segment lies in no capacity group whose capacity is known).

CRUDE PIPELINE CAPACITY OBSERVATION FILE

1	1	155.0	16				
2	1	28.0	16				
3	2	70.0	18	12			
4	1	158.0	20				
5	1	28.0	15				
6	1	43.0	10				
7	1	43.0	10				
8	1	13.0	6				
9	1	170.0	22				
10	1	36.0	12				
11	1	170.0	22				
12	2	70.0	12	18			
13	1	42.0	10				
14	2	48.0	10	10			
15	1	155.0	16				
16	1	1200.0	40				
17	2	112.0	12	12			
18	2	112.0	12	12			
19	1	297.0	22				
20	2	112.0	12	12			
21	1	297.0	22				
22	1	297.0	22				
23	1	161.0	18				
24	1	297.0	22				
25	2	161.0	12	12			
26	2	220.0	12	12			
27	1	315.0	22				
28	3	220.0	12	12	20		
29	2	220.0	12	20			
30	3	220.0	12	12	20		
31	3	220.0	10	10	20		
32	3	220.0	12	12	20		
33	3	220.0	10	12	22		
34	3	220.0	10	12	22		
35	3	220.0	12	12	22		
36	1	158.0	20				
37	1	490.0	26				
38	1	161.0	18				
39	1	315.0	20				
40	1	158.0	20				
41	1	26.0	10				
42	1	26.0	10				
43	1	26.0	10				
44	1	34.0	10				
45	1	490.0	26				
46	1	161.0	18				
47	1	490.0	26				
48	1	161.0	18				
49	1	490.0	26				
50	1	161.0	18				
51	1	26.0	12				
52	1	329.0	20				
53	1	740.0	34				
54	1	117.0	20				
55	1	315.0	20				
56	1	26.0	12				
57	1	315.0	22				
58	1	275.0	22				
59	1	50.0	12				
60	1	170.0	22				
61	1	173.0	20				
62	1	25.0	10				
63	1	45.0	12				
64	1	19.0	8				
65	1	15.0	6				
66	2	36.0	8	10			
67	1	291.0	24				
68	5	374.0	8	10	10	12	20
69	2	36.0	8	10			
70	2	80.0	8	10			
71	2	36.0	10	10			
72	4	291.0	8	12	12	20	
73	4	374.0	8	12	16	20	
74	4	291.0	8	12	12	20	
75	5	374.0	8	10	10	12	20
76	4	374.0	8	12	12	20	
77	5	374.0	8	10	12	12	20
78	1	158.0	24				
79	1	170.0	22				
80	1	25.0	6				
81	1	158.0	24				
82	1	158.0	24				
83	3	80.0	6	8	10		
84	1	36.0	8				
85	1	42.0	10				
86	2	50.0	8	10			
87	2	80.0	8	8			
88	1	42.0	12				
89	1	42.0	12				
90	3	36.0	6	8	8		
91	2	80.0	8	10			
92	1	15.0	8				
93	1	15.0	8				
94	2	19.0	6	5			
95	1	15.0	8				
96	1	25.0	6				
97	2	36.0	6	10			
98	1	25.0	6				
99	2	36.0	8	12			
100	1	36.0	8				
101	1	42.0	10				
102	2	50.0	8	10			
103	1	36.0	12				
104	1	168.0	24				
105	1	1200.0	40				
106	1	187.0	24				
107	1	278.0	20				
108	1	32.0	8				
109	1	278.0	22				
110	1	278.0	20				
111	1	140.0	18				
112	1	278.0	20				
113	1	80.0	16				
114	1	140.0	22				
115	1	30.0	12				
116	1	34.0	6				
117	1	278.0	20				
118	1	32.0	8				
119	1	32.0	8				
120	1	140.0	22				
121	1	140.0	20				
122	1	140.0	22				
123	1	140.0	20				
124	2	140.0	12	12			
125	1	140.0	22				
126	1	140.0	20				
127	2	199.0	16	16			
128	1	140.0	22				
129	2	341.0	20	20			
130	1	360.0	22				
131	1	360.0	22				
132	1	360.0	22				
133	2	175.0	12	20			
134	1	24.0	8				
135	1	1200.0	40				
136	2	383.0	16	22			
137	2	230.0	20	20			
138	1	164.0	16				
139	3	292.0	12	18	24		
140	1	555.0	30				
141	1	555.0	30				
142	1	555.0	30				
143	1	555.0	30				
144	1	555.0	30				
145	1	85.0	16				
146	1	710.0	30				
147	1	15.0	8				
148	1	15.0	8				
149	1	710.0	30				
150	1	8.0	8				
151	1	85.0	16				
152	1	555.0	30				
153	4	1560.0	18	26	34	48	
154	1	19.0	16				
155	3	1560.0	18	26	34		
156	4	1560.0	18	26	34	48	
157	3	1560.0	18	26	34		
158	4	1560.0	18	26	34	48	
159	3	1560.0	18	26	34		
160	4	1560.0	18	26	34	48	
161	3	1560.0	18	26	34		
162	1	160.0	16				
163	4	1560.0	18	26	34	48	
164	3	1560.0	18	26	34		
165	4	1560.0	18	26	34	48	
166	3	1560.0	18	26	34		

167	4	1560.0	18	26	34	48	
168	3	1560.0	18	26	34		
169	3	1560.0	18	26	34		
170	1	1200.0	40				
171	1	80.0	12				
172	1	278.0	22				
173	1	1200.0	40				
174	1	278.0	22				
175	1	1200.0	40				
176	1	34.0	8				
177	2	34.0	8	10			
178	2	68.0	12	12			
179	1	173.0	20				
180	1	158.0	24				
181	4	374.0	8	12	12	20	
182	1	291.0	24				
183	2	341.0	22	10			
184	1	158.0	20				
185	1	173.0	20				
186	3	326.0	12	12	20		
187	1	150.0	20				
188	1	297.0	22				
189	1	150.0	20				
190	2	68.0	12	12			
191	1	150.0	20				
192	2	106.0	12	12			
193	3	326.0	12	12	20		
194	1	133.0	16				
195	4	326.0	12	12	12	20	
196	5	326.0	12	12	12	20	20
197	4	326.0	10	10	12	20	
198	3	326.0	12	12	20		
199	1	297.0	22				
200	2	106.0	12	12			
201	4	326.0	12	12	12	20	
202	5	326.0	10	10	12	12	20
203	4	326.0	12	12	20	20	
204	2	220.0	12	20			
205	1	106.0	12				
206	3	220.0	12	12	20		
207	2	220.0	12	20			
208	2	68.0	12	12			
209	1	106.0	12				
210	1	25.0	10				
211	1	45.0	12				
212	1	106.0	12				
213	2	106.0	12	12			
214	2	341.0	22	10			
215	3	118.0	8	12	12		
216	2	95.0	8	12			
217	2	95.0	8	12			
218	2	95.0	8	12			
219	1	25.0	12				
220	1	25.0	12				
221	1	25.0	10				
222	1	25.0	12				
223	1	25.0	12				
224	1	80.0	16				
225	1	80.0	16				
226	1	185.0	20				
227	1	170.0	20				
228	1	170.0	22				
229	1	173.0	20				
230	1	36.0	8				
231	1	173.0	20				
232	1	185.0	20				
233	1	170.0	20				
234	1	36.0	12				
235	3	292.0	12	18	24		
236	2	70.0	12	16			
237	1	42.0	16				
238	1	42.0	16				
239	1	70.0	12				
240	1	19.0	16				
241	1	19.0	16				
242	1	19.0	12				
243	1	65.0	12				
244	1	65.0	16				
245	1	65.0	16				
246	1	117.0	20				
247	1	278.0	22				
248	1	275.0	22				
249	1	26.0	12				
250	1	278.0	20				
251	3	278.0	8	8	22		
252	1	76.0	12				
253	1	278.0	20				
254	2	278.0	20	20			
255	2	418.0	24	10			
256	1	47.0	12				
257	1	26.0	10				
258	1	24.0	8				
259	1	25.0	8				
260	1	25.0	8				
261	1	13.0	6				
262	1	26.0	10				
263	2	270.0	16	16			
264	2	270.0	16	16			
265	2	270.0	16	16			
266	2	270.0	16	16			
267	4	374.0	8	12	12	20	
268	1	45.0	12				
269	5	374.0	8	10	12	16	20
270	1	47.0	12				
271	2	418.0	10	24			
272	1	47.0	12				
273	5	119.0	6	6	8	8	8
274	4	119.0	8	8	8	8	
275	2	341.0	22	10			
276	1	291.0	24				
277	1	45.0	12				
278	2	80.0	8	10			
279	1	9.0	10				
280	3	119.0	8	8	12		
281	3	119.0	6	8	10		
282	3	119.0	6	8	12		
283	4	119.0	6	8	8	12	
284	4	119.0	6	8	10	12	
285	4	374.0	8	10	12	20	
286	5	374.0	8	10	12	16	20
287	1	410.0	30				
288	1	70.0	12				
289	1	1200.0	40				
290	1	278.0	22				
291	3	383.0	20	10	10		
292	1	80.0	10				
293	1	110.0	20				
294	4	383.0	20	10	8	6	
295	1	47.0	10				
296	4	213.0	8	10	12	12	
297	3	632.0	24	22	10		
298	3	501.0	18	12	24		
299	1	100.0	12				
300	1	100.0	12				
301	1	26.0	8				
302	2	270.0	16	16			
303	3	632.0	10	22	22		
304	4	213.0	8	10	12	12	
305	4	213.0	8	10	12	12	
306	2	435.0	22	10			
307	1	440.0	26				
308	3	213.0	12	12	16		
309	1	440.0	26				
310	3	213.0	8	12	16		
311	1	53.0	12				
312	3	510.0	18	24	12		
313	4	510.0	18	12	12	24	
314	1	53.0	12				
315	1	28.0	10				
316	4	503.0	10	30	8	10	
317	3	503.0	10	10	30		
318	1	175.0	20				
319	2	270.0	16	16			
320	1	47.0	12				
321	1	26.0	10				
322	1	440.0	26				
323	2	45.0	8	12			
324	2	203.0	12	18			
325	2	45.0	8	12			
326	1	88.0	16				
327	2	30.0	8	8			
328	2	28.0	8	10			
329	1	88.0	16				
330	1	88.0	16				
331	1	47.0	10				
332	1	22.0	10				
333	1	22.0	10				
334	1	30.0	8				
335	2	48.0	10	10			
336	1	28.0	16				
337	2	48.0	10	10			

338	3	292.0	12	18	24
339	1	555.0	30		
340	1	740.0	34		
341	1	80.0	16		
342	1	80.0	16		
343	1	80.0	16		
344	1	80.0	16		
345	1	170.0	20		
346	2	43.0	8	8	
347	1	185.0	20		
348	2	95.0	8	12	
349	1	110.0	20		
350	1	96.0	20		
351	1	20.0	8		
352	1	20.0	8		
353	1	30.0	8		
354	2	42.0	6	10	
355	1	30.0	8		
356	1	30.0	8		
357	1	110.0	20		
358	1	96.0	20		
359	2	43.0	8	10	
360	1	185.0	20		
361	1	170.0	20		
362	1	96.0	16		
363	1	78.0	12		
364	1	78.0	14		
365	1	12.0	8		
366	1	12.0	8		
367	1	96.0	16		
368	1	96.0	16		
369	2	585.0	26	20	
370	1	158.0	20		
371	2	235.0	20	16	
372	1	147.0	20		
373	1	70.0	12		
374	1	43.0	10		
375	1	140.0	18		
376	1	278.0	20		
377	1	410.0	30		
378	3	47.0	12	8	8
379	1	70.0	12		
380	1	43.0	10		
381	1	32.0	8		
382	1	32.0	8		
383	1	147.0	20		
384	2	175.0	12	20	
385	1	360.0	22		
386	1	360.0	22		
387	1	24.0	8		
388	1	158.0	20		
389	1	36.0	16		
390	1	13.0	8		
391	1	13.0	8		

PRODUCTS PIPELINE CAPACITY OBSERVATION FILE

1	6	2396.0	36 36 12 18 18 30
2	5	2396.0	36 36 12 18 30
3	1	27.0	8
4	1	87.0	12
5	2	57.0	8 12
6	2	38.0	6 8
7	1	8.0	8
8	1	8.0	6
9	1	56.0	12
10	1	20.0	8
11	1	250.0	20
12	1	250.0	20
13	1	30.0	10
14	1	30.0	10
15	1	56.0	12
16	1	56.0	12
17	1	250.0	20
18	1	55.0	10
19	1	78.0	14
20	1	65.0	10
21	1	65.0	10
22	1	14.0	8
23	1	25.0	8
24	1	22.0	8
25	1	23.0	8
26	1	78.0	24
27	1	62.0	10
28	1	78.0	16
29	1	87.0	12
30	2	46.0	8 14
31	1	87.0	12
32	1	18.0	6
33	1	7.0	6
34	5	2346.0	10 14 26 36 36
35	1	23.0	8
36	1	22.0	8
37	1	36.0	8
38	1	49.0	12
39	1	150.0	12
40	5	2280.0	10 14 26 36 40
41	1	29.0	8
42	2	59.0	8 8
43	2	59.0	8 8
44	1	17.0	8
45	1	50.0	10
46	1	32.0	8
47	2	37.0	8 8
48	1	17.0	8
49	2	37.0	8 12
50	2	37.0	8 10
51	2	37.0	8 12
52	2	37.0	8 10
53	1	75.0	14
54	1	180.0	20
55	1	108.0	16
56	4	200.0	8 8 12 12
57	1	14.0	8
58	3	101.0	8 12 6
59	3	96.0	6 8 12
60	1	10.0	6
61	2	97.0	6 12
62	1	14.0	6
63	1	14.0	6
64	1	10.0	6
65	3	82.0	6 8 12
66	4	92.0	6 6 12 12
67	1	14.0	8
68	3	82.0	6 8 12
69	3	59.0	6 8 12
70	1	11.0	6
71	1	59.0	8
72	1	10.0	6
73	1	82.0	12
74	1	8.0	6
75	1	113.0	12
76	1	108.0	16
77	1	23.0	8
78	1	23.0	8
79	4	240.0	8 8 12 12
80	2	113.0	8 12
81	3	185.0	10 16 6
82	2	29.0	10 8
83	2	134.0	8 12
84	1	40.0	10
85	1	93.0	10
86	2	93.0	8 10
87	1	60.0	10
88	2	75.0	6 10
89	1	18.0	6
90	1	108.0	16
91	1	108.0	16
92	2	108.0	8 12
93	6	263.0	8 8 8 12 12 8
94	1	23.0	8
95	1	40.0	10
96	1	20.0	8
97	2	1920.0	36 36
98	1	250.0	20
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102	1	960.0	32
103	1	768.0	30
104	2	768.0	8 30
105	1	768.0	30
106	1	60.0	12
107	1	17.0	6
108	1	17.0	6
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124	3	75.0	6 6 12
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128	1	27.0	8
129	2	70.0	8 12
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131	5	2313.0	12 18 18 36 36
132	2	282.0	20 16
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134	6	2396.0	12 18 18 30 36 36
135	1	14.0	8
136	1	108.0	16
137	4	200.0	8 8 12 12
138	2	108.0	8 12
139	3	96.0	8 10 12
140	1	32.0	8
141	1	23.0	8
142	3	374.0	24 10 10
143	3	95.0	8 10 12
144	1	21.0	8
145	1	11.0	6
146	1	14.0	8
147	1	23.0	8
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155	1	47.0	8
156	1	28.0	8
157	1	18.0	6
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159	2	108.0	8 12
160	1	18.0	6
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162	3	101.0	8 12 6
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164	2	46.0	6 8
165	1	22.0	6
166	3	930.0	14 30 16

167	3	930.0	14 30 16
168	3	930.0	30 16 14
169	2	273.0	16 20
170	2	10.0	6 6
171	2	57.0	8 12
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189	5	2280.0	36 40 10 14 26
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198	2	63.0	10 8
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208	1	42.0	8
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215	1	74.0	12
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217	2	74.0	12 12
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233	1	92.0	14
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235	1	8.0	6
236	2	113.0	8 12
237	2	113.0	8 12
238	2	113.0	8 12
239	1	11.0	6
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244	1	5.0	8
245	1	23.0	8
246	1	24.0	8
247	1	8.0	6
248	1	23.0	8
249	1	17.0	6
250	2	108.0	8 12
251	1	28.0	6
252	1	84.0	12
253	1	29.0	8
254	3	181.0	8 12 12
255	3	374.0	10 10 28
256	1	108.0	16
257	4	206.0	8 8 12 12
258	1	23.0	8
259	1	20.0	8
260	1	20.0	8
261	1	67.0	12
262	3	374.0	24 10 10
263	2	17.0	8 8
264	1	17.0	8
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266	2	17.0	6 6
267	1	29.0	8
268	1	768.0	30
269	2	273.0	14 20
270	2	53.0	8 8
271	2	19.0	6 6
272	1	49.0	14
273	1	61.0	12
274	2	53.0	8 8
275	2	19.0	6 6
276	2	51.0	12 14
277	4	193.0	14 16 8 6
278	1	61.0	12
279	2	69.0	8 14
280	1	49.0	8
281	2	6.0	6 6
282	1	44.0	8
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284	3	157.0	8 8 20
285	2	140.0	8 18
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290	1	17.0	6
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292	5	2280.0	36 40 10 14 26
293	5	2280.0	36 40 10 14 26
294	1	24.0	8
295	1	9.0	6
296	1	14.0	6
297	1	13.0	6
298	3	97.0	6 8 12
299	2	30.0	8 12
300	1	10.0	6
301	2	84.0	8 12
302	2	90.0	8 10
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304	2	84.0	8 12
305	2	98.0	8 10
306	2	94.0	8 12
307	1	37.0	8
308	1	20.0	8
309	1	7.0	8
310	1	13.0	6
311	2	11.0	6 6
312	2	11.0	6 6
313	2	11.0	6 8
314	2	11.0	6 8
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321	1	8.0	6
322	2	113.0	8 12
323	1	16.0	8
324	1	13.0	8
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327	1	26.0	8
328	1	33.0	10
329	1	23.0	8
330	1	180.0	28
331	2	99.0	6 12
332	3	120.0	10 10 8
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339	1	12.0	6					
340	1	26.0	8					
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342	1	19.0	8					
343	1	9.0	6					
344	1	19.0	12					
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346	1	4.0	4					
347	1	4.0	4					
348	1	19.0	8					
349	1	32.0	8					
350	2	59.0	8	8				
351	2	59.0	8	8				
352	2	59.0	8	8				
353	1	29.0	8					
354	1	960.0	32					
355	1	96.0	14					
356	1	960.0	32					
357	2	29.0	8	12				
358	1	67.0	14					
359	1	96.0	12					
360	1	50.0	10					
361	1	15.0	8					
362	1	8.0	6					
363	2	198.0	16	20				
364	2	132.0	16	20				
365	1	132.0	14					
366	1	132.0	14					
367	1	22.0	8					
368	1	90.0	12					
369	1	176.0	16					
370	1	176.0	16					
371	1	58.0	10					
372	1	30.0	8					
373	1	22.0	8					
374	1	9.0	6					
375	1	61.0	8					
376	1	9.0	6					
377	2	16.0	6	8				
378	1	14.0	6					
379	1	32.0	8					
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382	1	80.0	12					
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384	1	80.0	12					
385	3	144.0	10	12	8			
386	1	19.0	8					
387	1	380.0	28					
388	2	367.0	12	28				
389	2	1030.0	36	16				
390	1	101.0	12					
391	1	14.0	8					
392	2	250.0	14	20				
393	1	48.0	10					
394	2	1920.0	36	36				
395	1	48.0	12					

CRUDE PIPELINE THROUGHPUT OBSERVATION FILE

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3	1	5.0	16	2																
4	1	5.0	12	3																
5	1	50.0	20	4																
6	1	5.0	8	0																
7	3	25.0	20	0	18	0	16	0												
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10	1	50.0	10	0																
11	1	30.0	10	0																
12	1	5.0	15	5																
13	1	25.0	10	6																
14	1	25.0	10	7																
15	2	5.0	10	0	12	0														
16	1	40.0	22	9																
17	1	5.0	12	10																
18	1	40.0	22	11																
19	1	30.0	18	0																
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21	1	5.0	8	0																
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24	1	5.0	12	0																
25	1	5.0	18	12																
26	1	30.0	10	13																
27	2	25.0	10	14	10	14														
28	1	50.0	16	15																
29	1	260.0	40	16																
30	4	180.0	10	31	10	31	20	31	22	21										
31	2	80.0	20	0	22	27														
32	1	50.0	20	36																
33	1	50.0	20	0																
34	1	20.0	10	0																
35	1	260.0	40	0																
36	1	70.0	20	39																
37	1	50.0	20	40																
38	2	5.0	10	41	8	0														
39	1	50.0	20	0																
40	1	5.0	10	42																
41	2	5.0	10	0	12	0														
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44	2	160.0	18	48	26	47														
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47	1	50.0	20	0																
48	1	5.0	12	51																
49	1	70.0	20	52																
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65	2	5.0	8	70	10	70														
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68	1	25.0	24	78																
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70	1	40.0	22	79																
71	1	25.0	24	81																
72	1	25.0	24	82																
73	3	40.0	8	83	8	83	10	83												
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75	1	5.0	6	0																
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81	1	30.0	20	0																
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83	1	25.0	12	88																
84	1	25.0	12	89																
85	1	5.0	8	0																
86	2	5.0	8	91	10	91														
87	1	5.0	8	92																
88	1	50.0	24	104																
89	1	260.0	40	105																
90	1	50.0	24	106																
91	1	100.0	20	107																
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105	1	5.0	8	118																
106	1	5.0	8	119																
107	1	40.0	22	120																
108	1	40.0	20	121																
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110	1	40.0	20	123								
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113	1	40.0	20	126								
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119	1	35.0	12	0								
120	1	80.0	22	131								
121	1	80.0	22	132								
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123	1	30.0	10	0								
124	1	5.0	8	0								
125	1	5.0	8	0								
126	1	35.0	16	0								
127	1	35.0	12	0								
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131	1	5.0	12	0								
132	2	35.0	16	138	14	0						
133	3	150.0	12	139	18	139	24	139				
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135	1	130.0	30	141								
136	1	5.0	12	0								
137	1	5.0	12	0								
138	1	130.0	30	142								
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141	1	130.0	30	144								
142	1	30.0	16	145								
143	1	5.0	6	0								
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147	1	5.0	8	0								
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165	3	300.0	18	161	26	161	34	161				
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170	3	300.0	18	166	26	166	34	166				
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172	3	300.0	18	168	26	168	34	168				
173	3	300.0	18	169	26	169	34	169				
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175	1	20.0	12	171								
176	1	5.0	14	0								
177	1	100.0	22	172								
178	1	260.0	40	173								
179	1	100.0	22	174								
180	1	260.0	40	175								
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183	1	5.0	10	0								
184	1	60.0	20	179								
185	1	25.0	24	180								
186	5	200.0	12	195	12	195	12	195	20	195	24	182
187	2	5.0	22	183	10	183						
188	1	50.0	20	184								
189	1	60.0	20	185								
190	4	180.0	22	188	12	186	12	186	20	186		
191	1	60.0	20	187								
192	1	60.0	20	189								
193	3	90.0	12	192	12	192	20	191				
194	1	25.0	16	194								
195	3	180.0	12	204	20	204	22	199				
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197	1	30.0	12	205								
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199	1	5.0	10	210								
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201	2	30.0	12	213	12	213						
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212	1	5.0	12	222								
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214	1	40.0	16	224								
215	1	40.0	16	225								
216	2	5.0	8	0	8	0						
217	1	5.0	12	0								
218	1	60.0	20	226								
219	1	40.0	20	227								
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221	1	40.0	22	228								
222	1	60.0	20	229								
223	1	5.0	8	230								

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225  1    60.0     20 232
226  1    40.0     20 233
227  1     5.0     12 234
228  3   150.0     12 235 18 235 24 235
229  1     5.0     16 236
230  1     5.0     16 237
231  1     5.0     12 236
232  1     5.0     12  12
233  1     5.0     16 238
234  1     5.0      8   0
235  1     5.0      8   0
236  2    35.0      8   0 10   0
237  1     5.0      8   0
238  1     5.0     12 239
239  2     5.0      6   0  6   0
240  3   260.0     18   0 26   0 34   0
241  1     5.0     16 240
242  1     5.0     16 241
243  1     5.0     12 242
244  1     5.0     10   0
245  1     5.0      6   0
246  1     5.0     10   0
247  1     5.0      6   0
248  1    25.0     20 246
249  1    80.0     22 247
250  1    70.0     22 248
251  1     5.0     12 249
252  1    75.0     20 250
253  3    80.0      8 251  8 251 22 251
254  1    25.0     12 252
255  1    75.0     20 253
256  2    75.0     20 254 20 254
257 13   240.0      8   0  8   0  6 273  6 273  8 273  8 273  8 273  8   0 12   0 16   0 10 271 12
258  1     5.0     12   0
259  1     5.0     10 257
260  1     5.0      8 258
261  1     5.0      8 259
262  1     5.0      8   0
263  2    20.0     10   0 10 262
264  2   100.0     16 263 16 263
265  1     5.0      8   0
266  3     5.0      8   0  8   0 16   0
267  1     5.0      8   0
268  1    20.0      8   0
269  1     5.0      8   0
270  2     5.0      8   0  8   0
271  1     5.0      8   0
272  1     5.0      8   0
273  1     5.0     10   0
274  1     5.0      8   0
275  2     5.0     22 275 10 275
276  7   195.0      8 286 10 286 12 286 16 286 20 286 12   0 24 276
277  1     5.0     12 277
278  1     5.0      8   0
279  1     5.0      8   0
280  1     5.0      8   0
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281	1	5.0	8	0								
282	1	20.0	10	0								
283	3	20.0	10	279	6	0	10	0				
284	1	5.0	12	288								
285	1	260.0	40	289								
286	1	100.0	22	293								
287	1	35.0	10	295								
288	3	170.0	18	298	12	298	24	298				
289	1	30.0	12	300								
290	2	100.0	16	302	16	302						
291	3	160.0	10	0	22	306	10	306				
292	1	20.0	10	0								
293	1	25.0	12	311								
294	1	5.0	8	0								
295	3	190.0	18	312	24	312	12	312				
296	1	30.0	10	315								
297	2	100.0	16	319	16	319						
298	1	5.0	5	0								
299	1	5.0	10	321								
300	4	5.0	8	0	8	0	8	0	8	0		
301	5	55.0	8	323	12	323	8	0	6	0	8	0
302	2	35.0	12	324	18	324						
303	1	5.0	8	0								
304	1	5.0	8	0								
305	2	5.0	8	0	8	0						
306	2	5.0	6	0	8	0						
307	1	5.0	8	0								
308	1	5.0	6	0								
309	1	5.0	8	0								
310	1	5.0	8	0								
311	1	25.0	10	0								
312	1	5.0	8	0								
313	3	25.0	8	327	8	327	16	326				
314	1	5.0	8	0								
315	1	5.0	6	0								
316	1	25.0	16	329								
317	2	5.0	6	0	8	0						
318	2	5.0	8	0	10	0						
319	2	5.0	6	0	8	0						
320	1	5.0	8	0								
321	1	5.0	10	333								
322	3	5.0	8	0	8	0	8	0				
323	2	30.0	5	334	8	0						
324	2	25.0	10	335	10	335						
325	1	5.0	18	3								
326	1	5.0	16	336								
327	1	5.0	10	0								
328	2	45.0	10	337	10	337						
329	1	20.0	8	0								
330	1	20.0	10	0								
331	3	150.0	12	338	18	338	24	336				
332	1	70.0	20	0								
333	1	50.0	20	0								
334	1	20.0	16	0								
335	1	20.0	24	0								
336	1	50.0	16	0								
337	2	1.0	6	0	6	0						
338	4	1.0	6	0	6	0	6	0	6	0		
339	1	5.0	4	0								
340	2	1.0	5	0	6	0						
341	3	1.0	6	0	6	0	6	0				
342	3	1.0	6	0	6	0	6	0				
343	2	1.0	4	0	6	0						
344	2	1.0	6	0	6	0						
345	1	5.0	6	0								
346	1	130.0	30	339								
347	1	180.0	34	340								
348	3	360.0	18	0	26	0	34	0				
349	1	40.0	16	341								
350	1	20.0	8	0								
351	1	5.0	8	0								
352	1	15.0	8	0								
353	2	40.0	8	0	16	342						
354	2	40.0	8	0	16	343						
355	1	40.0	16	344								
356	1	5.0	18	0								
357	1	40.0	20	345								
358	2	25.0	8	346	8	346						
359	1	60.0	20	347								
360	2	15.0	6	0	5	0						
361	1	30.0	12	348								
362	1	5.0	6	0								
363	1	5.0	6	0								
364	2	50.0	20	350	20	349						
365	1	5.0	8	0								
366	2	5.0	6	0	8	0						
367	1	5.0	8	0								
368	2	20.0	6	0	8	0						
369	1	5.0	8	0								
370	1	5.0	8	351								
371	1	5.0	6	0								
372	1	5.0	6	0								
373	1	5.0	3	0								
374	1	5.0	6	352								
375	1	30.0	8	353								
376	2	30.0	6	354	10	354						
377	1	30.0	9	355								
378	1	30.0	8	356								
379	2	5.0	6	0	8	0						
380	2	5.0	12	0	8	0						
381	3	1.0	20	358	8	0	20	357				
382	2	25.0	8	359	10	359						
383	1	60.0	20	360								
384	1	40.0	20	361								
385	1	5.0	6	0								
386	1	5.0	12	0								
387	1	5.0	8	0								
388	1	5.0	6	0								
389	1	5.0	8	0								
390	2	5.0	8	0	8	0						
391	3	50.0	16	362	12	0	12	0				
392	1	5.0	12	0								
393	1	25.0	12	363								
394	2	50.0	12	0	14	364						
395	1	1.0	8	365								
396	1	5.0	8	365								
397	1	5.0	8	0								
398	3	50.0	12	0	16	367	12	0				
399	2	55.0	12	0	16	368						
400	1	25.0	12	0								
401	2	5.0	8	0	8	0						
402	4	5.0	8	0	8	0	8	0	8	0		
403	2	5.0	12	0	12	0						
404	1	50.0	20	370								
405	1	20.0	20	372								
406	2	110.0	20	376	18	375						
407	1	5.0	8	381								
408	1	5.0	8	0								
409	1	20.0	20	383								
410	1	5.0	8	387								
411	1	5.0	8	0								
412	1	50.0	20	388								
413	1	5.0	8	0								
414	1	20.0	16	389								
415	2	5.0	8	0	8	0						
416	2	5.0	6	0	8	0						
417	1	5.0	8	0								
418	1	5.0	8	0								

PRODUCTS PIPELINE THROUGHPUT OBSERVATION FILE

1	7	685.0	36	1	36	1	12	1	18	1	18	1	30	1	12	0
2	2	45.0	8	0	10	0										
3	6	635.0	12	0	36	2	36	2	12	2	18	2	30	2		
4	1	20.0	8	3												
5	6	630.0	10	0	36	0	36	0	12	0	18	0	30	0		
6	1	5.0	6	0												
7	1	25.0	12	4												
8	2	25.0	8	5	12	5										
9	1	5.0	6	0												
10	2	5.0	6	6	8	6										
11	1	5.0	8	7												
12	1	0.7	6	0												
13	1	0.7	6	0												
14	1	30.0	12	9												
15	1	5.0	8	10												
16	1	50.0	20	11												
17	1	75.0	20	12												
18	1	25.0	10	13												
19	1	20.0	12	15												
20	1	15.0	12	16												
21	1	75.0	20	17												
22	1	20.0	10	18												
23	1	25.0	14	19												
24	3	30.0	6	0	10	0	12	0								
25	3	30.0	10	0	12	0	10	0								
26	4	30.0	10	0	10	0	12	0	10	0						
27	1	5.0	8	0												
28	1	5.0	8	0												
29	1	5.0	8	0												
30	1	25.0	10	21												
31	1	5.0	8	22												
32	1	5.0	8	23												
33	1	5.0	8	24												
34	1	5.0	8	25												
35	2	5.0	4	0	6	0										
36	3	65.0	10	0	24	26	8	0								
37	1	35.0	10	27												
38	1	65.0	16	28												
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40	1	5.0	6	0												
41	1	40.0	12	29												
42	2	35.0	8	30	14	30										
43	1	40.0	12	31												
44	1	5.0	6	32												
45	1	5.0	10	0												
46	1	20.0	10	0												
47	1	5.0	10	0												
48	1	5.0	6	0												
49	1	25.0	8	0												
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52	1	5.0	8	0												
53	1	5.0	8	0												
54	1	5.0	12	0												
55	1	0.3	6	33												
56	1	20.0	10	0												
57	1	5.0	6	0												
58	6	530.0	10	0	12	0	18	0	30	0	36	0	36	0		
59	6	625.0	10	0	10	34	14	34	26	34	36	34	36	34		
60	1	5.0	8	35												
61	1	5.0	8	36												
62	2	65.0	12	39	8	37										
63	2	25.0	8	0	12	38										
64	6	490.0	8	0	10	40	14	40	26	40	36	40	40	40		
65	1	5.0	8	41												
66	3	65.0	8	0	10	0	12	0								
67	2	20.0	9	0	8	0										
68	1	5.0	8	0												
69	2	20.0	8	42	8	42										
70	2	5.0	8	43	8	43										
71	1	5.0	8	44												
72	1	20.0	10	45												
73	1	5.0	6	0												
74	5	30.0	10	0	6	0	8	0	12	0	10	0				
75	1	5.0	8	0												
76	3	45.0	10	0	8	0	12	0								
77	5	85.0	8	0	8	0	12	0	24	0	14	0				
78	1	20.0	10	0												
79	1	5.0	8	0												
80	1	45.0	10	0												
81	1	70.0	20	0												
82	1	5.0	8	0												
83	1	70.0	20	0												
84	1	5.0	8	0												
85	5	70.0	10	0	10	0	10	0	8	0	12	0				
86	1	30.0	12	0												
87	5	95.0	12	0	24	0	8	0	8	0	14	0				
88	5	95.0	12	0	8	0	8	0	24	0	14	0				
89	2	25.0	10	0	10	0										
90	5	95.0	8	0	8	0	12	0	24	0	14	0				
91	1	20.0	10	0												
92	3	105.0	8	0	16	0	12	0								
93	1	50.0	12	0												
94	1	50.0	16	0												
95	2	30.0	8	0	12	0										
96	1	25.0	12	0												
97	1	5.0	10	0												
98	5	125.0	6	0	16	0	8	0	8	0	10	0				
99	1	25.0	10	0												
100	5	70.0	10	0	12	0	10	0	10	0	8	0				
101	2	5.0	6	0	10	0										
102	1	70.0	20	0												
103	1	5.0	8	0												
104	4	85.0	8	0	6	0	16	0	16	0						
105	1	5.0	8	46												
106	2	25.0	8	47	8	47										
107	1	5.0	8	48												
108	2	25.0	8	49	12	49										
109	2	25.0	8	50	10	50										

110	2	25.0	8	51	12	51										
111	2	25.0	8	52	10	52										
112	5	70.0	10	0	8	0	10	0	8	0	12	0				
113	1	25.0	14	0												
114	1	5.0	4	0												
115	5	55.0	10	0	8	0	10	0	8	0	12	0				
116	5	55.0	10	0	8	0	8	0	12	0	10	0				
117	5	55.0	10	0	8	0	8	0	12	0	10	0				
118	1	30.0	14	53												
119	1	5.0	20	54												
120	1	25.0	8	0												
121	1	5.0	6	0												
122	5	30.0	8	56	8	56	12	56	12	56	16	55				
123	1	5.0	12	0												
124	2	20.0	8	0	10	0										
125	1	5.0	8	57												
126	1	30.0	8	0												
127	1	30.0	8	0												
128	4	50.0	8	162	12	162	6	162	6	0						
129	4	50.0	6	0	8	0	12	0	6	0						
130	5	50.0	4	0	6	0	8	58	12	58	6	58				
131	2	20.0	8	0	8	0										
132	1	5.0	6	0												
133	2	5.0	8	0	8	0										
134	4	30.0	6	0	6	59	8	59	12	59						
135	1	5.0	6	60												
136	1	20.0	12	61												
137	1	5.0	6	0												
138	1	5.0	6	62												
139	4	30.0	8	0	12	0	6	0	6	0						
140	2	5.0	6	64	6	63										
141	2	30.0	8	0	8	0										
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143	4	40.0	6	66	6	66	12	66	12	66						
144	1	5.0	8	67												
145	4	50.0	10	0	6	68	8	68	12	68						
146	2	5.0	6	70	12	0										
147	7	50.0	8	0	10	0	6	0	10	0	6	69	8	69	12	69
148	1	50.0	10	0												
149	1	5.0	8	0												
150	2	20.0	8	0	10	0										
151	5	50.0	6	0	8	0	12	0	8	0	10	0				
152	1	50.0	10	0												
153	2	5.0	6	0	6	0										
154	1	25.0	6	72												
155	1	40.0	12	73												
156	1	5.0	10	0												
157	1	5.0	6	74												
158	1	5.0	6	0												
159	1	5.0	6	0												
160	2	5.0	6	0	4	0										
161	2	40.0	10	0	10	0										
162	1	40.0	12	75												
163	1	5.0	6	0												
164	2	5.0	6	0	8	0										
165	1	55.0	16	76												
166	5	5.0	8	77	8	0	8	0	12	0	12	0				

167	5	5.0	8	79	8	79	12	79	12	79	8	78												
168	2	20.0	6	0	8	0																		
169	2	40.0	8	80	12	80																		
170	3	110.0	10	81	16	81	6	81																
171	2	5.0	10	82	8	82																		
172	2	40.0	8	83	12	83																		
173	1	5.0	10	84																				
174	2	5.0	6	0	10	0																		
175	1	20.0	10	87																				
176	2	30.0	8	0	10	0																		
177	1	5.0	6	0																				
178	1	5.0	6	89																				
179	1	65.0	16	91																				
180	2	25.0	8	92	12	92																		
181	6	5.0	8	93	8	93	8	93	12	93	12	93	8	93										
182	1	5.0	8	94																				
183	11	65.0	8	0	8	0	8	0	12	0	12	0	8	0	12	0	6	0	8	0	10	0	8	0
184	9	30.0	6	0	6	0	8	0	10	0	8	0	8	0	8	0	12	0	12	0				
185	2	40.0	8	0	12	0																		
186	1	5.0	10	95																				
187	1	5.0	4	0																				
188	1	5.0	8	0																				
189	1	5.0	8	0																				
190	1	5.0	6	96																				
191	1	50.0	20	98																				
192	1	5.0	8	99																				
193	6	580.0	12	0	12	100	18	100	18	100	36	100	36	100										
194	2	80.0	16	0	20	0																		
195	1	5.0	6	101																				
196	1	260.0	32	102																				
197	1	25.0	12	0																				
198	1	5.0	6	0																				
199	1	225.0	30	103																				
200	1	5.0	6	0																				
201	1	15.0	8	0																				
202	2	210.0	8	104	30	104																		
203	1	210.0	30	105																				
204	1	5.0	12	106																				
205	1	5.0	6	107																				
206	1	5.0	6	108																				
207	1	5.0	6	0																				
208	1	0.3	6	0																				
209	1	40.0	10	109																				
210	1	5.0	8	0																				
211	2	70.0	10	0	16	110																		
212	1	25.0	16	112																				
213	2	40.0	16	113	10	0																		
214	5	30.0	8	0	8	0	6	0	6	0	12	0												
215	1	5.0	8	114																				
216	1	5.0	8	115																				
217	1	5.0	8	0																				
218	1	5.0	8	119																				
219	1	5.0	8	120																				
220	1	5.0	6	121																				
221	1	5.0	10	0																				
222	1	5.0	6	122																				
223	2	25.0	6	123	12	123																		

224	1	5.0	8	0												
225	1	5.0	6	0												
226	3	25.0	6	124	8	124	12	124								
227	2	35.0	8	125	10	0										
228	1	5.0	8	0												
229	1	20.0	12	126												
230	1	5.0	8	127												
231	3	5.0	8	0	8	0	8	0								
232	2	5.0	8	0	8	0										
233	1	5.0	8	128												
234	1	5.0	8	0												
235	2	5.0	8	129	12	129										
236	2	5.0	6	130	8	130										
237	6	575.0	12	0	12	131	18	131	18	131	36	131	36	131		
238	2	80.0	20	132	16	132										
239	2	35.0	12	133	12	133										
240	7	685.0	12	134	15	134	18	134	30	134	36	134	36	134	12	0
241	1	5.0	8	135												
242	1	55.0	16	136												
243	4	35.0	6	137	8	137	12	137	12	137						
244	2	25.0	8	138	12	138										
245	1	5.0	12	0												
246	1	25.0	8	0												
247	4	40.0	8	140	8	139	10	139	12	139						
248	1	5.0	8	141												
249	4	65.0	24	142	10	142	10	142	10	0						
250	1	75.0	20	0												
251	4	30.0	8	144	8	143	10	143	12	143						
252	1	5.0	8	146												
253	1	0.7	8	147												
254	2	30.0	8	0	10	0										
255	1	25.0	8	0												
256	1	5.0	6	0												
257	4	65.0	10	0	24	0	10	0	10	0						
258	1	5.0	6	0												
259	1	20.0	10	148												
260	1	5.0	8	149												
261	1	5.0	8	150												
262	1	20.0	10	151												
263	1	0.7	6	0												
264	1	5.0	6	152												
265	1	5.0	6	153												
266	1	5.0	6	0												
267	1	20.0	10	154												
268	1	20.0	8	155												
269	4	20.0	8	0	6	0	8	0	8	0						
270	1	5.0	8	156												
271	4	30.0	8	159	12	159	8	158	6	157						
272	2	20.0	8	0	8	0										
273	3	30.0	8	161	12	161	6	160								
274	2	35.0	8	163	14	163										
275	2	35.0	6	164	8	164										
276	1	5.0	6	165												
277	1	0.7	6	0												
278	1	210.0	30	0												
279	2	255.0	16	0	30	0										
280	2	255.0	30	166	16	166										
281	3	255.0	14	167	30	167	16	167								
282	3	255.0	30	168	16	168	14	168								
283	3	70.0	6	0	6	0	16	0								
284	2	70.0	16	169	20	169										
285	2	0.3	6	170	6	170										
286	1	5.0	6	171												
287	1	5.0	6	172												
288	1	5.0	6	173												
289	1	25.0	10	174												
290	1	5.0	8	0												
291	1	20.0	6	175												
292	1	5.0	8	0												
293	1	10.0	10	0												
294	1	5.0	8	176												
295	1	5.0	6	0												
296	2	65.0	14	177	6	178										
297	1	5.0	6	179												
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300	1	35.0	10	183												
301	1	35.0	10	0												
302	1	5.0	8	0												
303	1	5.0	8	0												
304	1	20.0	8	175												
305	1	5.0	8	184												
306	6	490.0	6	0	36	185	40	185	10	185	14	185	26	185		
307	6	410.0	6	0	36	186	40	186	10	186	14	186	26	186		
308	1	5.0	8	187												
309	2	330.0	32	190	14	188										
310	3	35.0	8	0	8	0	16	189								
311	1	5.0	6	0												
312	3	35.0	8	0	8	0	16	0								
313	1	5.0	8	0												
314	1	25.0	10	0												
315	1	5.0	6	191												
316	1	5.0	10	0												
317	1	5.0	6	192												
318	1	5.0	8	193												
319	2	25.0	8	194	10	194										
320	5	55.0	10	0	10	195	8	195	8	0	12	0				
321	1	5.0	20	196												
322	1	0.7	6	0												
323	1	5.0	10	197												
324	1	5.0	8	0												
325	1	0.7	8	0												
326	1	0.7	6	0												
327	2	20.0	10	0	8	198										
328	2	5.0	8	0	8	0										
329	6	30.0	8	0	10	0	10	199	10	199	10	199	12	199		
330	2	5.0	6	0	8	0										
331	1	5.0	8	0												
332	2	10.0	10	200	12	0										
333	1	5.0	6	201												
334	1	5.0	8	0												
335	3	5.0	6	0	6	0	8	0								
336	1	5.0	10	202												
337	1	5.0	8	0												

338	4	30.0	8	203	10	203	10	203	12	203				
339	2	30.0	8	0	10	0								
340	3	50.0	6	0	10	0	8	204						
341	6	50.0	8	206	8	206	10	206	12	206	16	206	8	206
342	1	5.0	8	0										
343	1	45.0	16	210										
344	1	5.0	6	211										
345	4	70.0	20	213	12	213	12	213	8	0				
346	1	5.0	6	216										
347	1	5.0	6	217										
348	1	5.0	6	222										
349	2	5.0	8	223	8	223								
350	1	5.0	8	224										
351	1	20.0	10	225										
352	6	25.0	12	0	6	0	10	0	6	0	14	230	4	0
353	1	5.0	14	0										
354	1	20.0	10	0										
355	1	5.0	8	231										
356	2	45.0	10	0	10	0								
357	1	5.0	6	0										
358	2	5.0	10	0	10	0								
359	1	5.0	6	0										
360	2	45.0	8	233	12	233								
361	2	45.0	8	234	12	234								
362	1	5.0	6	0										
363	2	40.0	8	235	12	235								
364	1	5.0	6	0										
365	1	5.0	8	0										
366	1	0.7	6	236										
367	1	20.0	10	237										
368	1	0.7	8	238										
369	1	70.0	28	239										
370	1	5.0	8	240										
371	1	5.0	8	242										
372	1	5.0	6	244										
373	2	5.0	8	245	6	0								
374	1	5.0	6	0										
375	2	20.0	8	250	6	0								
376	2	5.0	6	248	8	0								
377	2	25.0	8	247	12	247								
378	1	35.0	12	249										
379	3	50.0	8	251	12	251	12	251						
380	5	65.0	10	252	10	252	24	252	10	0	10	0		
381	1	55.0	16	253										
382	5	5.0	8	255	8	254	8	254	12	254	12	254		
383	1	5.0	8	256										
384	1	5.0	8	257										
385	1	20.0	12	258										
386	5	65.0	24	259	10	259	10	259	10	0	10	0		
387	2	5.0	8	260	8	260								
388	1	5.0	8	261										
389	2	5.0	6	262	8	262								
390	2	5.0	6	263	6	263								
391	1	5.0	14	0										
392	1	5.0	8	264										
393	1	210.0	30	265										
394	2	5.0	6	0	8	0								
395	4	105.0	12	0	8	0	8	0	24	0				
396	2	70.0	14	266	20	266								
397	6	105.0	6	0	8	267	8	267	8	0	8	0	24	0
398	4	85.0	12	270	6	0	24	0	10	0				
399	1	5.0	8	0										
400	4	105.0	8	271	8	271	6	268	6	268				
401	2	20.0	8	0	14	269								
402	1	5.0	6	0										
403	5	65.0	8	0	14	0	16	0	6	272	6	272		
404	2	25.0	12	273	14	273								
405	4	65.0	14	274	16	274	8	274	6	274				
406	4	85.0	12	275	10	0	24	0	5	0				
407	2	5.0	8	276	14	276								
408	1	5.0	8	277										
409	2	0.3	6	278	6	278								
410	4	65.0	8	279	8	0	20	0	6	0				
411	4	65.0	12	0	8	280	20	280	8	280				
412	4	65.0	8	281	10	0	8	281	20	281				
413	4	55.0	8	283	8	282	18	282	10	0				
414	1	5.0	12	0										
415	4	55.0	10	0	8	0	18	0	8	0				
416	4	40.0	10	0	8	0	18	0	8	0				
417	1	5.0	8	0										
418	1	20.0	10	0										
419	3	5.0	6	0	6	0	6	0						
420	1	5.0	14	0										
421	1	5.0	6	284										
422	1	5.0	10	285										
423	1	5.0	8	0										
424	1	5.0	6	0										
425	2	5.0	6	0	6	0								
426	1	5.0	6	286										
427	1	5.0	6	287										
428	1	5.0	6	288										
429	6	490.0	8	0	36	289	40	289	10	299	14	259	26	299
430	6	490.0	8	0	36	290	40	290	10	290	14	290	26	290
431	1	5.0	8	291										
432	1	5.0	6	292										
433	1	5.0	6	293										
434	1	5.0	6	294										
435	4	20.0	5	0	6	295	8	295	12	295				
436	2	20.0	8	296	12	296								
437	2	20.0	6	0	6	61								
438	1	5.0	6	297										
439	1	5.0	6	0										
440	2	20.0	8	298	12	298								
441	2	30.0	8	299	10	299								
442	2	20.0	8	300	10	300								
443	2	20.0	8	301	12	301								
444	2	20.0	8	302	10	302								
445	2	20.0	8	303	12	303								
446	1	5.0	8	304										
447	1	5.0	8	0										
448	1	5.0	8	305										
449	3	5.0	6	0	6	0	4	0						
450	2	5.0	8	0	6	0								
451	2	5.0	6	0	8	0								

452	2	30.0	8	0	10	0				
453	1	5.0	10	0						
454	1	5.0	10	0						
455	1	5.0	6	0						
456	3	30.0	8	0	8	0	12	0		
457	3	30.0	8	0	12	0	8	0		
458	2	5.0	8	306	6	0				
459	1	25.0	12	0						
460	1	20.0	12	0						
461	2	35.0	6	307	12	0				
462	3	35.0	6	308	6	308	12	0		
463	1	5.0	4	0						
464	4	60.0	12	0	6	309	6	309	12	0
465	4	60.0	12	0	12	0	6	310	8	310
466	4	65.0	12	0	12	0	6	311	8	311
467	1	5.0	4	0						
468	1	30.0	12	0						
469	1	5.0	6	312						
470	1	5.0	8	0						
471	1	5.0	6	0						
472	2	5.0	8	0	6	315				
473	1	0.7	6	316						
474	2	45.0	8	319	12	319				
475	1	5.0	8	0						
476	4	45.0	10	0	10	0	6	0	8	0
477	1	5.0	8	321						
478	3	45.0	10	322	10	322	8	322		
479	1	5.0	8	323						
480	1	5.0	8	0						
481	1	0.7	8	326						
482	1	30.0	8	0						
483	1	70.0	28	327						
484	3	30.0	10	329	10	329	8	329		
485	1	5.0	6	328						
486	1	5.0	8	331						
487	1	5.0	8	332						
488	1	5.0	6	0						
489	1	19.0	8	345						
490	1	5.0	8	346						
491	2	20.0	8	347	8	347				
492	2	20.0	8	348	8	348				
493	2	20.0	8	349	8	349				
494	1	0.7	6	0						
495	1	5.0	8	350						
496	2	330.0	14	352	32	351				
497	1	40.0	16	0						
498	2	275.0	12	356	32	353				
499	1	25.0	14	355						
500	1	5.0	6	0						
501	1	260.0	32	0						
502	2	20.0	8	0	22	0				
503	1	20.0	10	357						
504	2	5.0	6	0	6	0				
505	1	5.0	8	358						
506	1	5.0	8	0						
507	1	5.0	6	359						
508	2	45.0	16	0	20	0				

509	1	40.0	16	0																					
510	2	65.0	16	360	20	360																			
511	1	35.0	12	0																					
512	2	65.0	16	361	20	361																			
513	1	50.0	14	362																					
514	1	5.0	6	0																					
515	1	45.0	14	363																					
516	1	5.0	8	0																					
517	1	5.0	8	364																					
518	1	5.0	6	0																					
519	1	5.0	6	0																					
520	1	30.0	12	365																					
521	1	50.0	16	366																					
522	1	20.0	10	368																					
523	1	5.0	8	369																					
524	2	25.0	8	0	10	0																			
525	1	5.0	8	370																					
526	1	5.0	6	371																					
527	1	25.0	8	372																					
528	1	5.0	6	373																					
529	1	25.0	8	0																					
530	2	5.0	6	374	8	374																			
531	1	5.0	6	375																					
532	1	5.0	8	376																					
533	1	5.0	6	0																					
534	3	35.0	10	382	12	382	8	382																	
535	1	5.0	8	383																					
536	1	70.0	28	384																					
537	10	420.0	10	0	8	0	36	386	6	0	8	0	8	0	8	0	16	386	12	385	28	385			
538	1	35.0	8	0																					
539	1	5.0	6	338																					
540	12	450.0	10	0	4	0	4	0	8	0	8	0	10	0	36	391	36	391	4	0	6	0	4	0	12
541	1	5.0	8	388																					
542	2	50.0	14	389	20	389																			

Appendix F. PIPELINE NETWORK DATA

The U.S. crude oil and oil products pipeline networks are described in two data sets. To reduce printing costs only one page of these data sets is reproduced here. Each pipeline is divided into segments as explained in Sect. 9.1, and one or more segments are represented by each record of the data set. Practically every oil products pipeline and ever crude oil trunk pipeline depicted on the American Petroleum Institute (API) maps (Chap. 4) is represented here.

Officials at the API have stated that their crude oil pipeline maps show trunk lines only, but they are wrong. A fairly large number of gathering lines appear, although coverage is far from complete. This requires distinguishing trunk from gathering lines in some way. The distinction is not well-defined in the first place, but generally gathering lines form that part of the pipeline network connecting the well with the first terminal, which may be a tank farm or a refinery. Trunk lines carry oil away from the tank farms. The following criteria were used to distinguish gathering and trunk lines:

1. All lines shown on the Congressional Research Service maps (1975) were presumed to be trunk lines.
2. All lines not shown on these maps were presumed to be gathering lines, unless no. 3, 5, or 6 below applies.
3. All long lines that connect terminals and that otherwise have the unmistakable look of trunk lines were so counted.
4. All lines obviously having the fine tree pattern typical of gathering lines were so counted.
5. All lines of diameter greater than 8 in. were counted trunk lines, unless the Energy Department's inventory of gathering lines by state (Energy Information Administration) indicated 10 or 12 in. gathering lines in the state in question that could not be more reasonably located elsewhere in the state.
6. All lines crossing state boundaries were counted trunk lines.

Errors made in distinguishing trunk from gathering lines are almost certainly not significant. See Sect. 9.3 on this.

The format of the network data files is not straightforward. Each record consists of one or more 80-character lines. It represents a <u>link</u>, which is a group of one or more pipe segments that are shown on the API map with a single line. All the segments represented by a given record have the same node numbers, length and ownership but may have different diameters.

To ease the coding of throughput data, nodes were distinguished from node <u>clusters</u>. A <u>node</u> is a terminus of a link. It is assigned a 5-digit node number. A node cluster is a group of nodes in the same area whose node numbers are alike in their first 4 digits. The node in a node cluster consisting of one node has a number whose last digit is zero, whereas the last digits of other node numbers are nonzero. Node clusters are useful in defining flow groups, which are groups of segments whose total throughput is known. All segments terminating in the same two node clusters are presumed to be in the same flow group, possibly along with segments connecting other node clusters. Capacity groups are groups of segments whose total capacity is known. It was found convenient not to follow this clustering convention when indicating which segments are in the same capacity group.

The first line of a record shows the physical properties and ownership of the corresponding segment(s). The remaining lines, if any, show the diameters of the second, third, etc., segments (if any) represented by the record, the segments in the same flow group other than those connecting the same two node clusters (if any), and the segments in the same capacity group.

The node numbers have no particular significance, except that the first 2 digits indicate the state in which the node lies. The states are coded thusly:

1.	Alabama	18.	Louisiana	35.	Ohio
2.	Alaska	19.	Maine	36.	Oklahoma
3.	Arizona	20.	Maryland	37.	Oregon
4.	Arkansas	21.	Massachusetts	38.	Pennsylvania
5.	California	22.	Michigan	39.	Rhode Island
6.	Colorado	23.	Minnesota	40.	South Carolina
7.	Connecticut	24.	Mississippi	41.	South Dakota
8.	Delaware	25.	Missouri	42.	Tennessee
9.	Florida	26.	Montana	43.	Texas
10.	Georgia	27.	Nebraska	44.	Utah
11.	Hawaii	28.	Nevada	45.	Vermont
12.	Idaho	29.	New Hampshire	46.	Virginia
13.	Illinois	30.	New Jersey	47.	Washington
14.	Indiana	31.	New Mexico	48.	West Virginia
15.	Iowa	32.	New York	49.	Wisconsin
16.	Kansas	33.	North Carolina	50.	Wyoming
17.	Kentucky	34.	North Dakota	99.	Texas (continued)

The format is as follows:

Character positions	Fortran format	Description
First line		
1–15	I5	Node number.
7–11	I5	Node number.

12	A1	'L' if the segment is an LPG line; 'A' if it is an ammonia line; blank otherwise.
13–15	I3	Segment length in miles, as measured from the map.
17–18	I2	Nominal diameter in inches of the largest pipe (or of the only pipe, if only one segment is represented).
20–24	F5.1	1974 throughput, in millions of barrels, of the flow group to which the segment(s) represented by this record belong (Congressional Research Service, 1975). A minus one indicates unknown throughput.
26	I1	In some records, the number of pump stations at the first node (0 or 1). The coding of pump stations was dropped early in the game, and zeros are coded in most records.
28–29	I2	In some records, the number of pump stations on this link other than at the nodes. Zeros are coded in most records.
31–33	I3	Pipeline company code, listed in Appendix C. A minus one indicates unknown ownership.
35–50	4A4	Name of county containing first node; used to ease location of nodes on the map. Some records show only the first node number and the county; they represent terminal nodes, i.e. nodes that are coded as the first node in no other record. They are included only for purpose of data checking (to see if all segments have been coded).
54–56	I3	Average daily throughput capacity, in thousands of barrels of no. 2 fuel oil, of the capacity group to which the segment(s) represented by this record belong (National Petroleum Council 1979). A minus one indicates unknown capacity.
80	I1	Contains a one if the record is continued on subsequent lines, a blank otherwise.

Subsequent lines (if any)

1–78	See below	Diameter field and/or flow group field and/or capacity group field. Any combination of these may appear, but always in this order. Continue

to subsequent lines if necessary. Squeeze as many numbers on a line as possible while leaving position 79 blank and without splitting a number (a number is a contiguous string of digits with no intervening blanks). A field, which contains many numbers, may be split between linkes. Fields must be separated by exactly one blank. The first field must begin at position one.

79	X	Always blank.
80	I1	Contains a one for continuation to next line, a blank otherwise.

The formats of the three fields are:

Diameter field

I1	The number one.
I1	The number n of diameters to follow.
nI3	The diameters of the pipe segments other than the one indicated in line 1, in descending order.

Flow group field

I1	The number two.
I1	The number n of pairs of node cluster numbers to follow.
n(2I5)	Pairs of 4-digit node cluster numbers. For each pair listed, all segments whose node numbers match this pair in the first 4 digits are taken to be in the same flow group as the segment(s) represented by this record. A pair of cluster numbers matching the node numbers of this record in their first four digits should not be listed, since it is already understood that all segments connecting these two clusters are in the same flow group as the segment(s) represented by this record.

Capacity group field

I1	The number three.
I1	The number n of pairs of node numbers to follow.

n(2I6) Pairs of 5-digit node numbers. For each pair listed, all segments connecting those two nodes are taken to be in the same capacity group as the segment(s) represented by this record.

All the other members of the flow group or capacity group are indicated for each member of the group, so that there is considerable redundancy in the coding.

```
*   PRODUCTS PIPELINE NETWORK DATA (SAMPLE PAGE)
*

99110 99120  36 05  -1.0 1 00 153 BRAZORIA          -1
99110 99266  41 12  -1.0 1 00  70 BRAZORIA          80
99120 99100  74 08  -1.0 0 00 150 BRAZORIA          -1
99120 99350   8 08  -1.0 0 00 153 BRAZORIA          -1
99130 99390  66 06  -1.0 1 00  60 BRAZORIA          -1
99140 99160  29 06  -1.0 1 00  80 FORT BEND         -1
99140 99269  51 06  -1.0 1 00  80 FORT BEND         -1
99140 99320  34 04  -1.0 1 00 150 FORT BEND         -1
99150                             CAMERON           -1
99160 43551  96 08  35.0 1 00  37 HARRIS           144                  1
23 9921 4355 9919 4355 9924 4355 32 99210 43553 99192 43551
99160 99310  22 06  -1.0 1 00  -1 HARRIS            -1
99170                             HARRIS            -1
99180                             BRAZORIA          -1
99181 43761 144 08   5.0 1 00  37 HARRIS            19
99181 99271  26 08  -1.0 1 00  37 HARRIS            -1
99191 43650 231 28  70.0 1 01  36 HARRIS           380
99191 99200   3 28  -1.0 1 00  36 HARRIS            -1
99191 99421  72 28 420.0 1 00  36 HARRIS           367                  1
27 9956 9957 9936 9947 9937 9941 9923 9946 9923 9949 9928 9945 9919 9947 31   1
99192 99470
99192 43551 102 12  35.0 1 00  60 HARRIS           144                  1
23 9916 4355 9921 4355 9924 4355 32 99160 43551 99210 43553
99192 99470  74 12 420.0 1 01  60 HARRIS           367                  1
27 9956 9957 9919 9942 9936 9947 9937 9941 9923 9946 9923 9949 9928 9945 31   1
99191 99421
99210 43553 119 10  35.0 1 01   9 HARRIS           144                  1
23 9916 4355 9919 4355 9924 4355 32 99160 43551 99191 99421
99210 99182   4 08  -1.0 1 00 126 HARRIS            -1                  1
11 06
99210 99375L 13 06  -1.0 1 00   9 HARRIS            -1                  1
11 06
99220 99266   2 06  -1.0 1 00  70 HARRIS            -1
99231 99371L  4 08  -1.0 0 00  37 HARRIS            -1
99233 99373   4 16  -1.0 0 00  90 HARRIS            -1                  1
17 12 12 10 10 06 06 04
99233 99460  61 16 420.0 1 00  90 HARRIS          1330                  1
27 9956 9957 9919 9942 9936 9947 9937 9941 9923 9949 9928 9945 9919 9947 31   1
99361 99470
99234 99490  62 08 420.0 1 00 119 HARRIS            -1                  1
27 9956 9957 9919 9942 9936 9947 9937 9941 9923 9946 9928 9945 9919 9947
99241 43793L126 08  -1.0 1 00  37 HARRIS            -1
99241 99231   2 08  -1.0 0 00  37 HARRIS            -1
99241 99250L  4 08  -1.0 1 00  37 HARRIS            -1                  1
11 08
99243 99233L  2 06  -1.0 0 00  90 HARRIS            -1
99250                             CHAMBERS          -1
99260 99275   4 04  -1.0 0 00   9 HARRIS            -1
99261 99180  15 06  -1.0 1 01  80 HARRIS            -1
99264 99183   6 06  -1.0 1 00 154 HARRIS            -1                  1
11 06
99270 99130  15 06  -1.0 0 00  60 GALVESTON         -1
99271 99241   1 10  -1.0 1 00  37 HARRIS            -1                  1
14 08 08 06 04
```

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