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Comparison of Operational Energy Intensities and Consumption of Pipelines versus Coastal Tankers: U. S. Gulf Coast to Northeast Coast Routes

by

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COMPARISON OF OPERATIONAL ENERGY INTENSITIES AND CONSUMPTION OF PIPELINES VERSUS COASTAL TANKERS: U.S. GULF COAST TO NORTHEAST COAST ROUTES

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EXECUTIVE SUMMARY

This report compares the energy required to transport light petroleum products from the U.S. Gulf Coast to East Coast Mid-Atlantic states by pipeline with the energy required by coastal tanker and tanker-barge. It develops the operational energy intensities and route miles of these modes and determines how much energy each requires to deliver a ton of oil products. This analysis determines that the pipelines are significantly more energy efficient than the marine modes. It also estimates the additional petroleum savings that pipeline shipment could permit due to the fact that pipelines use electricity generated primarily from non-oil sources.

Detailed segment-by-segment analysis was used to develop energy intensities for the Colonial and Plantation pipelines, which are the pipelines that compete with coastal tankers.* The resulting system-wide energy intensities of 280 Btu per short ton-mile for the Colonial pipeline system and 330 Btu per short ton-mile for the Plantation system represent a new degree of accuracy in estimates of actual operating pipeline energy intensities. Energy intensities along specific pipeline routes in competition with coastal tankers were also estimated, as well as tanker energy intensities for corresponding tanker routes. The findings were as follows:

1. The portion of the pipeline systems competing with tankers operates at an average of 270 Btu per ton-mile, whereas tankers operate at a minimum of 480 Btu per ton-mile.
2. The tanker routes are an average of 53% longer than corresponding pipeline routes, and this compounds the pipeline energy advantage.
3. As a result of these two factors, tankers require 2.7 times as much energy to transport an average barrel of oil products from the Gulf to the Northeast than do the competing pipelines.
4. Some three-quarters of the energy that is used by pipelines is provided by fuels other than oil.
5. Given a fixed supply of oil products leaving the Gulf area, use of pipelines rather than tankers can, in effect, increase the amount of oil products delivered to the Northeast by 1.5%, since this represents the extra oil that tankers would have burned in order to move the cargo.
6. Using the amount of oil products that tankers shipped from the Gulf to the Northeast in 1977, as

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*Coastal tanker energy intensities were used for all of these domestic ocean movements because tanker barge volumes are small and their energy intensities are similar to tankers.

> an example, shipment of this oil using expanded pipeline capacities would result in an annual operational energy savings equivalent to 1.5 million barrels of distillate oil. An additional 0.64 million barrels of oil would also be freed in exchange for other fuels, due to the fact that pipelines are powered primarily by fuels other than oil.

The report concludes that the significant energy-use advantage of large-diameter pipelines over tankers (i.e., 2.7 to 1) should be a major consideration in the planning of these product movements or similar petroleum movements.

1 INTRODUCTION

This report is a comparative analysis of operational energy intensities and consumption for pipeline shipments versus coastal tanker and tanker-barge movements of light petroleum products from the U.S. Gulf Coast to U.S. East Coast Mid-Atlantic states. It has been prepared for the Office of Transportation Programs of the U.S. Department of Energy (DOE) as part of a project designed to develop energy conservation strategies in the areas of modal shifts and energy materials transport. It also answers an expressed interest of DOE's Office of Competition as to whether energy penalties are being paid in this region by the shipment of this oil by tanker rather than pipeline.

Detailed estimates are made of the 1977 energy intensities (EIs) for tankers and the two major pipelines serving these routes; these are the Colonial pipeline (from Houston) and the Plantation pipeline (from Baton Rouge). Estimates of potential operational energy savings gained from diverting these shipments from tankers to pipelines are figured from these EIs plus 1977 tanker short-ton volumes for these products. Also estimated for these diversions are additional savings of petroleum available through shifts from the fuel oil used to power tankers, to the other energy sources used by pipelines (e.g., coal, which is burned by the utilities serving them). Table 1 indicates that these tanker volumes have been large and steady as a whole; however, individual origin ports have had substantial variations since the 1973 Arab oil embargo.

Indirect energy requirements of the two modes are not included in this analysis because the methodology for calculating them is still an unresolved research area (e.g., disagreements exist as to how much supporting-infrastructure energy usage should be included for a mode).

Table 1. U.S. Gulf Coast to Northeast Coast Tanker Shipments of Light Petroleum Products[a]

Gulf Coast Origin Port	Annual Volumes				
	1973	1974	1975	1976	1977
	(10^3 Short Tons)				
Pascagoula, MS	58	90	103	20	111
New Orleans, LA	261	160	430	135	176
Baton Rouge, LA	2,726	2,616	3,859	2,907	2,965
Destrehan, LA	1,872	1,867	2,507	2,411	2,888
Gramercy, LA	41	6	29	19	--
Port Arthur, TX	4,354	2,028	2,406	2,228	1,969
Beaumont, TX	3,705	2,866	2,797	3,328	2,726
Lake Charles, LA	251	477	995	820	1,284
Freeport, TX	--	65	10	80	56
Corpus Christi, TX	2,513	3,163	4,865	3,965	4,166
Texas City, TX	1,154	996	2,365	1,557	1,620
Houston, TX	12,401	10,777	11,390	10,951	10,356
Others	74	6	39	22	182
Total[b]	29,369	25,111	31,526	28,484	28,500

[a] Gasoline, kerosene, naptha, jet fuel, distillate fuel oil.

[b] Totals may not add due to rounding.

Source: Special computer runs provided by the Division of Domestic Ocean Shipping, Office of Domestic Shipping, Maritime Administration, U.S. Department of Commerce, Washington, D.C. (March 1979).

2 ANALYSIS AND COMPARISONS OF PIPELINES AND TANKERS

In performing any intermodal comparisons, it is of the upmost importance that the analysis be carried out at the route and equipment-specific level, and that it be limited to the directly competing segments of the alternative transportation modes. Failure to comply with these basic principles will almost invariably lead to erroneous and misleading results. In the case of this study, for example, failure to evaluate the distance advantage that pipelines have over tankers for the routes considered would have resulted in a 34% error in the final results. Furthermore, energy intensities vary considerably across the subsectors of transportation modes and applying aggregate modal values to a particular subsector may lead to errors of 50% or more. For example, using a national average EI for the highly efficient large diameter pipelines analyzed here would lead to substantial errors.

The first four sections of this chapter present the basic descriptive data for coastal-tanker and pipeline movements of light petroleum products from the U.S. Gulf Coast to the East Coast Mid-Atlantic states. These data are then brought together in Section 2.5, where the direct comparison of the respective energy uses and efficiencies is carried out.

2.1 COASTAL TANKER VOLUMES AND DISTANCES

A time series of shipment data is available through the U.S. Maritime Administration's Division of Domestic Ocean Shipping. All tanker-shipment data presented in this report are directly derived from special computer runs requested from that office and cover U.S. Gulf Coast to Northern East Coast ports (Norfolk northward) tanker and tanker-barge shipments of light petroleum products. Table 2 provides a summary of the origin-destination matrix for these movements in 1977. The data for movements originating south of Galveston, Texas, and for movements terminating north of New York City are aggregated and included in this table for illustrative purposes only. No pipeline alternative exists for these movements, and they were not included in any analysis.

In addition, to reduce the size of the tables, the volumes of smaller ports were combined with those of nearby larger ports. All geographical aggregations, their components, and the justification for their treatment are as follows:

Origin Areas:

Aggregation	Components	Treatment Justification
South of Galveston	Freeport, Corpus Christi, TX	No viable, large diameter pipeline alternative exists for movements originating in these areas, so they were not included in tanker energy consumption calculations.

Table 2. 1977 Domestic Ocean Shipments of Light Petroleum Products,[a] U.S. Gulf Coast to Northeastern Ports: Origin-Destination Matrix (10^3 short tons)

	Norfolk, VA	Newport News, VA	Washington, D.C.	Baltimore, MD	Philadelphia, PA	New York, NY	North[b] of NY	Total[c]
South of Galveston[b]	17	13	--	--	370	2,479	1,343	4,222
Houston, TX	637	--	25	1,245	1,610	3,052	3,786	10,356
Texas City, TX[b]	--	253	16	19	--	582	790	1,660
Beaumont, TX	59	22	--	--	401	709	1,535	2,726
Port Arthur, TX[b]	159	--	--	65	277	566	901	1,969
Lake Charles, LA	--	--	--	20	124	357	782	1,284
Baton Rouge, LA	503	--	--	184	260	1,124	894	2,965
Gramercy, LA	--	--	--	--	--	--	--	--
New Orleans, LA[b]	26	--	--	--	127	1,425	1,629	3,207
Pascagoula, MS	--	--	9	--	--	70	32	111
Mobile, AL	--	--	--	--	--	--	--	--
Total[c]	1,400	288	50	1,533	3,170	10,366	11,694	28,500

[a] Gasoline, jet fuel, kerosene, distillate fuel oil and naptha.

[b] See text for explanation of aggregations of ports and their volumes.

[c] Totals were rounded.

Source: Division of Domestic Ocean Shipping, Office of Domestic Shipping, Maritime Administration, U.S. Department of Commerce, special computer runs, Washington, D.C. (March 1979).

Texas City	Texas City, Galveston, TX	Galveston has negligible tanker volumes and is very near Texas City.
Port Arthur	Port Arthur, Sabine, TX	Sabine has negligible volumes and is reasonably near Port Arthur.
New Orleans	New Orleans, Destrehan, and St. Rose, LA	These three ports are in close proximity and can be treated as one.
Destination Areas:		
Philadelphia	Philadelphia, PA Marcus Hook, PA Camden, NJ Paulsboro, NJ Wilmington, DE	These ports are all in close proximity and can be treated as one.
North of New York City	Boston, MA Portland, ME New Haven, CT Portsmouth, NH Searsport, ME Fall River, MA Providence, RI Bridgeport, CT Albany, NY Salem, MA Melville, RI	No pipeline alternative to waterborne movements exists north of New York City; therefore, they were not included in tanker energy consumption calculations.

Appendix B presents comparative data for these Gulf Coast to Northeast Coast movements in 1975 and 1976 with Tables B.1 and B.2, respectively. The data in these tables indicate that the 1977 tanker movement data in Table 2 (used for the tanker-pipeline energy consumption comparisons in this analysis) were representative of recent trends. Table B.3 in Appendix B provides a sample of the complete origin-destination movements for 1976, prior to aggregation.

The route distances between the ports for deep-draft vessels are given in Table 3. When combined with the tons shipped these yield the ton-mile flows (see Tables 2 and 4, respectively). Dividing the total ton-miles from Table 4 by the corresponding tons-shipped from Table 2* yields a weighted

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*Table 4 total volume of 28,500,000 short tons minus north-of-New York and south-of-Galveston volumes of 11,694,000 and 4,222,000 short tons, respectively, plus the 1,343,000 short tons common to both of these aggregations, equals 13,927,000 short tons. This total, divided into the 29,388 billion ton-miles, results in the 2,110 mile-weighted average.

Table 3. Deep-Draft Vessel Distances: U.S. Gulf Coast to Northeastern Ports[a] (great-circle-miles)

	Norfolk, VA	Newport News, VA	Washington, D.C.	Baltimore, MD	Philadelphia, PA[b]	New York NY
Houston, TX	1978	1975	2129	2120	2183	2210
Texas City, TX[b]	1930	1927	2084	2075	2135	2161
Beaumont, TX	1951	1948	2106	2097	2156	2182
Port Arthur, TX[b]	1921	1918	2076	2067	2126	2152
Lake Charles, LA	1938	1935	2093	2084	2143	2169
Baton Rouge, LA	1869	1866	2019	2010	2074	2100
Gramercy, LA	1806	1803	1958	1949	2007	2033
New Orleans, LA[b]	1741	1738	1893	1884	1942	1968
Pascagoula, MS	1659	1656	1812	1803	1860	1886

[a] Ports south of Galveston and north of New York are not directly competitive with pipelines and are excluded here. Mobile, AL, had no tanker volumes in the analysis year (1977), so its mileages are also excluded.

[b] See text for explanation of aggregations of ports.

Source: U.S. Department of Commerce, National Ocean Survey, *Distances Between U.S. Ports*, Sixth Edition (1978), Washington, D.C.

Table 4. 1977 Domestic Ocean Ton-Miles Shipped for Light Petroleum Products,[a] U.S. Gulf Coast to Northeastern Ports: Origin-Designation Matrix (10^6 short ton-miles)

	Norfolk, VA	Newport News, VA	Washington, D.C.	Baltimore, MD	Philadelphia, PA[c]	New York NY	Total[b]
Houston, TX	1,260	-	54	2,640	3,515	6,746	14,215
Texas City, TX[c]	-	488	33	39	-	1,258	1,818
Beaumont, TX	114	44	-	0	865	1,547	2,570
Port Arthur, TX[c]	306	-	-	132	589	1,219	2,246
Lake Charles, LA	-	-	-	42	267	774	1,083
Baton Rouge, LA	939	-	-	369	541	2,361	4,210
Gramercy, LA	-	-	-	-	-	-	-
New Orleans, LA[c]	46	-	-	-	247	2,804	3,097
Pascagoula, MS	-	-	17	-	-	132	149
Mobile, AL	-	-	-	-	-	-	-
Total[b]	2,664	531	103	3,224	6,025	16,841	29,388[d]

[a] Gasoline, jet fuel, kerosene distillate fuel oil and naptha.

[b] Totals may not add up due to rounding.

[c] See text for explanation of aggregations of ports.

[d] Note that the ports south of Galveston and north of New York are eliminated from this data because they do not compete directly with pipelines. Including them in this table would have added 9.957 billion and 28.276 billion ton-miles (3,402 ton-miles are common to both) to this total, raising it to 64.213 billion ton-miles.

Source: Special computer runs provided by Division of Domestic Ocean Shipping, Office of Domestic Shipping, Maritime Administration, U.S. Department of Commerce, Washington, D.C. (March 1979).

mean-shipment distance of 2,110 miles. Note that this distance involves a considerable circuity, because the tankers must circle the Florida peninsula before heading northward. This aspect has a major influence on the outcome of the energy use comparison in Section 2.5.

2.2 PIPELINE VOLUMES AND DISTANCES

The origin-destination pipeline distances for the routes under study are given in Table 5. In addition to the trunk-line segments of the Colonial and Plantation Pipelines which are outlined in Appendix A,* several shorter, smaller-diameter lines not owned by these companies were included to complete needed links in the system. These lines are:

Origin-Destination	Distance (mi)	Pipeline Diameter (in)
Texas City to Houston, TX	39	6,8
New Orleans, LA, to Covington, MS	118	16
Gramercy, LA to Baton Rouge, LA	50	16

The flow volumes of piplines are not generally available because such data are normally considered confidential by the operating companies. However, given the availability of the tanker origin-destination data by which the respective modal energy intensities and distances may be weighted and normalized to a common basis, such flow information are not of primary interest to this study. Therefore, no attempts were made to estimate the individual origin-destination flows for the Colonial and Plantation pipelines.

2.3 COASTAL TANKER OPERATIONAL ENERGY INTENSITIES

This section develops operational energy intensity (EI) estimates for 20,000 to 80,000 dead-weight ton (DWT) class coastal tankers.** This size class of tankers was selected for study on the basis of communications with officials at the major Northeastern ports (i.e., Norfolk and northward). They revealed that this class handles a vast majority of the movements, with 40,000 DWT being a good average tanker size. (Refs. 2-6)

Unfortunately, it is not possible to develop energy-intensity values based on actual operational data at the systems level because the necessary data are either not available or are not collected. Furthermore, a review of the literature revealed a lack of reliable tanker energy intensity estimates based on modeling or other techniques. However, two recent studies of marine energy use were found to be useful in formulating a reasonable basis for developing viable energy intensity estimates for this report. (Refs. 7 and 8)

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*Appendix A develops energy intensities for these pipelines. Section 2.4 summarizes the methodology used in the Appendix.

**No separate energy intensity estimates were developed for tanker-barge movements because these only account for a small share of the light petroleum product ton-miles carried (3% in 1976), and it was assumed that they operate at the same EI values as tankers.

Table 5. Pipeline Distances: U.S. Gulf Coast to Northeastern Ports[a] (miles)

	Norfolk, VA	Newport News, VA	Washington,[b] D.C.	Baltimore, MD	Philadelphia, PA[c]	New York[c] NY
Houston, TX	1342	1304	1366/NA	1369	1432	1531[d]
Texas City, TX[c]	1381	1343	1405/NA	1408	1471	1570
Beaumont, TX	1264	1226	1288/NA	1291	1354	1453
Port Arthur, TX[c]	1272	1234	1296/NA	1299	1362	1461
Lake Charles, LA	1213	1175	1237/NA	1240	1303	1402
Baton Rouge, LA	1081	1043	1105/1047	1108	1171	1270
Gramercy, LA	1131	1093	1155/1097	1158	1221	1320
New Orleans, LA[c]	1074	1035	1097/1039	1100	1163	1262
Pascagoula, MS	1066	1028	1090/1032	1093	1156	1255

NA = Not applicable.

[a] Locations south of Galveston do not have large-diameter pipelines and those north of New York do not have pipelines. Both are excluded here. Mobile, AL, is excluded because it had no directly competitive tanker movements in the analysis year.

[b] Values above and below slash pertain to the Colonial and Plantation lines respectively.

[c] See Section 2.1 for explanation of aggregations of locations.

[d] As an example of comparative pipeline versus tanker distances, note that the pipeline distance to New York is 1531 miles, whereas the great circle tanker distance is 2210 in Table 5.

Source: Ref. 10 and American Petroleum Institute, *Products Pipeline Map of the United States and Southern Canada*, Washington, D.C. (Jan. 1975).

In 1977, Metrics Inc., conducted a maritime shipping industry survey for the U.S. Maritime Administration. The data received from one of the 48 responding firms was sufficiently detailed to allow calculation of the energy intensity of its coastal tanker movements in the 20,000 to 80,000 DWT category. Table 6 summarizes how the EIs of 587 and 638 Btu/route-ton-mile were calculated for that firm for 1972 and 1975, respectively.

The second source, a study performed by Booz, Allen and Hamilton, estimates an average energy intensity of 355 Btu/route-ton-mile based on a rather simple model and on idealized operating conditions. This estimate can be shown to be too low and a methodology can be devised for revising it to a more realistic level (see Refs. 8 and 11).

Given that the model also provides energy use and intensity estimates for all other sectors of the marine mode by fuel type, one would expect that if the model results were accurate the total energy use estimates by fuel type would match the known consumption levels for those fuel types; however, this is not the case. From References 9 and 10, the actual total use of residual fuel oils in 1974 was 0.187×10^{15} Btu, while the model estimate was 0.124×10^{15} Btu (See Table 7 for a derivation of this value). The model's underestimate of the consumption of residual fuel may be due to the use of preliminary ton-mile data. However, use of updated ton-mile data from the Army Corps of Engineers (COE) with the model's energy intensity values only raises the total oil energy use value for residual fuel to 0.138×10^{15} Btu, even if one assumes that all the additional ton-miles were carried by vessels powered strictly by residual fuel oil.(Ref. 11)

Considering that more than 74% of domestic residual fuel oil use is in the coastal sector, that approximately 77% of coastwise ton-miles were carried by tankers, and that virtually all coastal tankers are powered by residual fuel oil, it is safe to conclude that a major cause of the model's underestimation of residual fuel use must be due to its underestimate of the energy intensity of the coastal tankers. Assuming that the error is distributed evenly across all residual-fuel-powered vessels serving in the Great Lakes and Coastal fleets, one may recalculate the original estimate to yield 480 Btu/route-ton-mile.

Table 6. Average Energy Intensities of Coastal Tankers for One U.S. Firm

Year	Total Short Ton-Miles (10^9)	Total Energy Consumed (10^{12} Btu)	Average Energy Intensity (Btu/short ton-mile)
1972	15.600	9.150	587
1975	9.810	6.260	638

Source: Ref. 7

$$(355 \text{ Btu/route-ton-mile})^{*} \times \frac{0.187 \text{ quads}^{**}}{0.138 \text{ quads}^{***}}$$

$$= 480 \text{ Btu/route-ton-mile} \quad \text{Corrected minimum energy use of coastal tankers.}$$

While the adjusted energy intensity value for coastal tankers of 480 Btu/route-ton-mile will be used throughout the remainder of this report, it should be noted that, in all likelihood, the value represents a lower-bound rather than an absolute value because of the following assumptions in its derivation:

1. All the additional ton-miles reported in the revised figures from the Army Corps of Engineers were carried by residual-fuel-oil-powered vessels.
2. The 0.187×10^{15} Btu use value for residual-fuel oil from References 10 and 11 is totally accurate. These sources are considered, even by Ref. 8, to underreport energy use.

2.4 PIPELINE OPERATIONAL ENERGY INTENSITIES

The 1977 operational energy intensities for pipelines are developed in Appendix A for the specific Colonial and Plantation routes using the following methodology:

1. The pipeline routes were disaggregated into homogeneous segments based upon the logical break points indicated by system characteristics.
2. The fraction of a given company's total energy bill consumed in each segment was determined by means of engineering calculations based on pipe diameters and on the 1974 volume of flow in that segment.†
3. Since both companies were electric, electric rate schedules that applied along the pipeline routes in mid-1977 and each company's total 1977 fuel cost were used to find the company-wide energy consumption figure. This, when allotted appropriately to each segment, results in power rates that generate the company's total power bill.

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*See Ref. 8, energy intensity estimate.

**See Refs. 10 and 11, minimum energy use.

***See Ref. 8, energy use.

†It should be noted that 1974 segment flows were used because they were the most recent data publicly available. A recent Colonial pipeline publication indicates that its flows did not radically change between 1974 and 1977. (Appendix A, Ref. 10)

4. Relative energy intensities for each pipeline segment were calculated from the relative consumption figures derived in step 2. These intensities were used to derive the energy intensity of selected routes relative to the energy intensity of the system as a whole.
5. The relative energy intensity of each route calculated in step 4, and a company's total energy consumption, defines the average amounts of energy required to transport a barrel or ton of oil products over each mile of that route and the overall system.

The resulting systemwide EIs are 283 and 326 Btu/route-ton-mile for the Colonial and Plantation pipelines, respectively. For the pipeline segments of both companies that are in direct competition with tankers, the weighted EI is 270 Btu/short ton-mile (see Tables A.4, A.5, and A.6).*

2.5 ENERGY USE COMPARISONS

The information developed in the preceding sections and in Appendix A allows a direct comparison of the energies used by pipelines and coastal tankers over the competing routes. Because of the superior quality of the tanker origin-destination data, all comparisons will be made on that basis. In other words, the actual energy used by coastal tankers will be compared to the energy which would have been used by pipelines if they had moved the cargoes carried by the tankers.

In general, differences in energy use, while providing equal services, will arise between competing modes when: one mode is more efficient than the other on an energy use per route-ton-mile basis; and/or the distances from the origin to the destination are not the same. In the interest of clarity, the effects of these two factors will be calculated separately before the final comparisons are made.

The tanker energy intensity of 480 Btu/route-ton-mile may be assumed to remain constant over all routes because of the small variations in operating conditions over these routes. However, as detailed in Appendix A, variations do exist within the pipeline system and a ton-mile weighted energy intensity must be calculated.

$$\overline{EI}_p = \frac{\sum_{i=1}^{n} EI_i \cdot TM_i}{\sum_{i=1}^{n} TM_i} \qquad (1)$$

---

*These tables indicate that for most routes on which pipelines compete directly with tankers, pipeline energy intensity ranges from 257 to 276 Btu/ton-mile. The systemwide values are higher because they include smaller-diameter, less-efficient, spur-line movements which are not in competition with coastal tankers.

where:

$\overline{EI}_p$ = weighted mean energy intensity of pipeline movements in Btu per route-ton-mile,

EI_i = pipeline energy intensity over route i (from Appendix A),

TM_i = ton-miles moved over route i by tankers (from Table 4).

Utilizing this procedure yields a mean of 270 Btu per route-ton-mile, implying that even if all other factors were equal, tankers would use 1.78 times the energy that pipelines would in providing identical services over the Gulf Coast to Northeast routes.

In order to calculate the effects of the different distances by pipelines and tankers, the shipment weighted mean distances must first be calculated from equation 2.

$$\overline{D} = \frac{\sum_{i=1}^{n} D_i \cdot TM_i}{\sum_{i=1}^{n} TM_i} \qquad (2)$$

where:

$\overline{D}$ = weighted mean distance for the mode being evaluated,

D_i = distance of route i for the mode being evaluated (see Tables 3 and 6),

TM_i = ton-miles moved over route i by tankers (see Table 4).

The resultant values of 2,115 and 1,390 miles in Table 7 for tankers and pipelines, respectively, show that tankers would be expected to use 1.5 times the energy of pipelines while providing identical services purely on the basis of the additional circuities involved.

Combining the distance and energy intensity effects yields the final line of Table 7. The values for the energy used per-ton-shipped, show that a potential energy savings potential of 0.64×10^6 Btu or 63.1% of the current energy use exists for every ton diverted from coastal tankers to pipelines over the U.S. Gulf Coast to East Coast Mid-Atlantic states routes. The final ratio indicates that on these routes, pipelines have an overall energy-use advantage of 2.7 to 1.

The route-specific ratios of tanker distance over pipeline distance and total tanker-energy use over total pipeline-energy use per-ton-shipped are given in Tables 8 and 9, respectively.

Table 7. Comparison of Tanker and Pipeline Operational Parameters, U.S. Gulf Coast to Northeastern Ports

Parameter	Tanker	Pipeline	Ratio (tanker/pipeline)
Mean EI (Btu/route-ton/mile)	480	270	1.8
Mean shipment distance (miles)	2115	1390	1.5
Energy used per ton shipped (10^6 Btu)	1.01	0.37	2.7

Table 8. Pipeline Distances Advantages Versus Coastal Tankers – U.S. Gulf Coast to Northeastern Ports

	Norfolk, VA	Newport News, VA	Washington,[a] D.C.	Baltimore, MD	Philadelphia, PA[b]	New York NY
Houston, TX	47	51	56/NA	55	52	44
Texas City, TX[b]	40	44	48/NA	47	45	38
Beaumont, TX	54	59	64/NA	62	59	50
Port Arthur, TX[b]	51	55	60/NA	59	56	47
Lake Charles, LA	60	65	69/NA	68	64	55
Baton Rouge, LA	73	79	83/93	81	77	65
Gramercy, LA	60	65	69/78	68	64	54
New Orleans, LA[b]	62	68	73/82	71	67	56
Pascagoula, MS	56	61	66/76	65	61	50

NA = Not applicable.

[a] Values above and below slash pertain to the Colonial and Plantation lines respectively.

[b] See Section 2.3.1 for explanation of aggregations of locations.

[c] Locations south of Galveston and north of New York City are not directly competitive between pipelines and tankers and are excluded here. Mobile, AL, had no analysis year tanker volumes and is also excluded.

Source: Ref. 20 and American Petroleum Institute, *Products Pipeline Map of the United States and Southern Canada*, Washington, D.C. (Jan. 1975).

Table 9. Energy Use Ratios[a], from U.S. Gulf Coast to Northeastern Ports[b] (tanker energy use/pipeline energy use - per unit output)

	Norfolk, VA	Newport News, VA	Washington, D.C.[c]	Baltimore, MD	Philadelphia, PA	New York, NY	Total
Houston, TX	2.8	2.8	2.8 / NA	2.8	2.8	2.5	2.7
Texas City, TX	2.6	2.7	2.7 / NA	2.7	2.6	2.39	2.4
Beaumont, TX	2.9	3.0	3.0 / NA	3.0	2.9	2.61	2.8
Port Arthur, TX	2.8	2.9	2.9 / NA	2.9	2.8	2.56	2.7
Lake Charles, LA	3.0	3.1	3.1 / NA	3.1	2.1	2.69	2.7
Baton Rouge, LA	3.2	3.4	3.4 / NA	3.4	3.3	2.88	3.1
Gramercy, LA	3.0	3.1	3.1 / NA	3.1	3.0	2.68	2.7
New Orleans, LA	3.0	3.1	3.2 / NA	3.2	3.1	2.71	2.7
Pascagoula, MS	2.9	3.0	3.0 / NA	3.0	2.9	2.61	2.6
All competitive routes							2.7

[a] It is assumed that the only routes over which the Plantation line competes directly with coastal tankers are those terminating in Washington, D.C. Even over these routes, the volume carried by the Plantation line is small, amounting to ≈ 20 x 10^6 barrels per year.

[b] Locations south of Galveston and north of New York City are not directly competitive and are excluded. Mobile, AL, had no analysis year tanker volumes and is also excluded.

[c] Values above and below the slash pertain to the Colonial and Plantation lines respectively.

NA = Not applicable.

3 FINDINGS AND RECOMMENDATIONS

The findings of this report can be summarized as follows:

1. Large-diameter pipelines are considerably more energy efficient than tankers. Coastal tankers traveling the routes between the U.S. Gulf Coast and the East Coast Mid-Atlantic states achieve at best 480 Btu/ton-mile, while competing pipeline routes achieve 270 Btu/ton-mile.
2. The Gulf to Mid-Atlantic states tanker routes are, on the average, 53% more circuitous than pipeline routes to the same destination, thus compounding the pipeline energy advantage. This distance advantage over tanker routes is likely to be true of pipelines in other settings as well.
3. The combined effect of the above factors is that oil product transportation from the Gulf Coast to the Mid-Atlantic states requires 2.7 times more energy by tanker than by pipeline. Similar advantages can be expected of large-diameter pipelines in other settings.
4. Not only does pipeline transport along these routes save energy over marine transport, but it allows much of the energy that is used to be supplied by fuels other than scarce oil. Tankers burn oil, whereas approximately 75% of the electricity consumed by the Colonial and Plantation pipelines is derived from sources other than oil (see Appendix C).

The significance of these results is evident when one considers the fraction of the energy value of a barrel of oil products that is consumed in its shipment from the Gulf coast to the Mid-Atlantic states. The average ton of oil pumped by the Colonial system (by far the principal supplier) has an energy content of 41.6 million Btu.* One million of these Btu, or 2.4%, would be consumed in tanker transportation to the Mid-Atlantic states, whereas 0.37 million, or 0.9%, would be consumed by pipeline. Therefore, shipment by pipeline rather than tanker would increase the supply of petroleum products available at the destination by 1.5% (the difference between 2.4% and 0.9%). Furthermore, since three-quarters of the pipeline energy is not supplied by oil, pipeline shipment would free another 0.7% (three-quarters of 0.9%) of the oil for energy needs which fuels other than oil cannot meet.

Current tanker movements on these routes provide a basis for converting these percentage savings to barrels. For example, suppose that the 14 million short tons shipped to the Mid-Atlantic states by tanker in 1977 had been shipped by pipeline instead. Such a diversion would have required approximately a 34% increase in available pipeline capacity because Colonial is

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*This assumes energy contents of 125,000 Btu/gal for gasoline, 135,000 Btu/gal for kerosene (jet fuel), and 138,700 Btu/gal for distillate oil. It also assumes 7.66 bbl/ton, a figure based on the average Colonial product density of 46.5 lb/ft^3 and the Colonial product mix calculated in Appendix A.

reportedly operating at capacity (Ref. 10, Appendix A),and delivered roughly 41 million tons to the Mid-Atlantic states in 1977.* If it is observed that the energy saved per ton diverted is the difference between 1.01 million and 0.37 million Btu, or 0.64 million Btu, the fuel savings can be calculated as follows:

0.64 million Btu/ton	energy savings per ton diverted
x 14 million tons	oil diverted to pipeline
8.96 trillion Btu	total energy saved
5.80 million Btu/bbl	approximate energy content of distillate oil**
1.5 million bbl	barrels of fuel saved in one year

A parallel calculation shows that in moving 14 million tons of oil, the pipelines would use energy equivalent to 0.87 million bbl of distillate oil. Since three-quarters of this energy is not supplied by oil, the shift to pipeline would annually free an additional 0.64 million bbl of oil (three-quarters of 0.87 million) in exchange for other fuels.

Two caveats are in order. One is that the above figures account only for operational energy use and they omit any energy that may be consumed in the construction of pipelines or oil tankers. Although such indirect energy requirements are difficult to estimate, they should not be ignored when a choice of mode involves possible construction. Secondly, if pipeline movements from the Gulf to the Northeast were to increase beyond their present level, the foregoing calculations would remain accurate only if the pipelines were to continue to operate at the efficiency at which they now operate. In general, the efficiency of a pipeline is degraded when its flow is increased without a corresponding increase in the number or diameter of pipes. However, Colonial (the principal supplier) is already operating at capacity (Ref. 10, Appendix A), and any significant increase in flow would require the laying of new mainline pipes. It is very likely that these pipes would be of comparable diameter, since the new mainline pipes Colonial is now installing are of the same, energy-efficient, large diameters as the old ones (i.e., 36", 40", 42", reported in Ref. 10, Appendix A). Also, the fact that Colonial's power bill rose from $17 million to $63 million in a few short years provides ample incentive to avoid the energy penalty of small-diameter mainline pipes. (Ref. 9, Appendix A)

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*These are actually estimated 1974 deliveries (Ref. 4, Appendix A), but as indicated in Section 2.1, 1977 volumes are similar. The estimate assumes about 7.7 bbl/ton for each of Colonial's 220 million bbl delivered to Linden, N.J., from points south of Philadelphia, plus 95 million bbl of final deliveries to Norfolk, Baltimore, and Washington, D.C. It is also assumed here that because oil is turned into the Colonial line in the Philadelphia area, the amount of oil reaching Linden from south of Philadelphia is the amount that enters Philadelphia from the south.

**Based on 138,700 Btu/gal, 42 gal/bbl and a density of 55.3 lb/ft^3 (see Table A.3).

It is recommended that the significant operational energy use advantage of large-diameter pipelines be given strong consideration in planning for the transportation of oil products from the Gulf Coast to the Mid-Atlantic states and along similar routes.

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APPENDIX A*

CALCULATION OF PIPELINE ENERGY INTENSITIES

A.1 OVERVIEW

This Appendix describes the methodology used to estimate the operational energy required to transport a barrel of light petroleum products via pipeline from Houston and Baton Rouge to Hampton Roads, Baltimore, Philadelphia, and New York. The Colonial, Plantation, and Dixie pipelines connect these areas, but since the smaller Dixie pipeline terminates at Apec, NC, only the first two will be considered. The energy efficiencies of these two pipeline systems are investigated separately.

The energy (E_r) required to move a barrel of petroleum products along a certain route (r) is the product of the energy intensity (I_r) [energy consumed per barrel-mile] along that route and the route's length (d_r):

$$E_r = I_r d_r .$$

The energy intensity (I_r) is taken to be the intensity (I_s) of that company's whole system multiplied by some correction factor (K_r):

$$I_r = K_r I_s .$$

This is necessary because different segments of a pipeline system, especially branch lines, are more energy-intensive than others. The system intensity (I_s) is the system's total energy use (E_s) in a given year divided by the number of barrel-miles (bm) transported (available from Form P, Ref. 1):

$$I_s = \frac{E_s}{bms} .$$

The basic method for estimating the total energy consumption (E_s) is to divide one company's total electric bill for a certain year (1977) by the price of electricity in that year. Only electricity need be considered because both Plantation and Colonial state that their prime movers are all electric. (Ref. 2, 3) The electric rates vary along the pipeline route, however, and more importantly, the rates depend on consumption.

Electric rates were calculated by first estimating the fraction of each company's total energy consumed at each pumping station. The total energy

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*This Appendix is followed by its own reference list.

consumption was allotted to each pumping station and the power rates for each station calculated to match the companies' 1977 power costs (available from Form P, Ref. 1). This enabled calculation of specific origin to destination and system-wide pipeline energy intensities.

A.2 CALCULATION OF PIPELINE ROUTE SEGMENT AND PUMPING STATION ENERGY CONSUMPTIONS

To distribute energy consumption among pumping stations, the pipeline was divided into several homogeneous segments (i.e., the number of pipes running parallel and the size of each does not vary within a segment). The Colonial segments used are shown in Table A.1, and the Plantation segments in Table A.2. The fraction of energy used along each segment was then computed and divided evenly among the pumping stations on the segment.

Engineering formulas were used to compute the relative energy consumption of each segment. Segments consisted of a certain number of pipes running parallel, possibly of different sizes. For each of these pipes, the friction head (H) in feet is given by the Darcy-Weisbach formula,

$$H = f \frac{L}{d} \frac{v^2}{2g}, \qquad (1)$$

where:

L = length in feet,

d = inside diameter in feet,

v = average flow velocity in ft/sec,

g = 32.2 ft/sec^2, and

f = friction factor.

The friction head can be interpreted as the number of foot-pounds of work required per pound of oil pumped in order to overcome friction in the pipe.

The head depends on the velocity of flow and hence the distribution of the flow among the parallel pipes. Unfortunately, this information was not available; the pipeline companies consider it proprietary. The best data on this point are those indicated on a map of 1974 oil product pipeline flows developed in a report by the Congressional Research Service (Ref. 4). The information furnished by the pipeline companies for this map was, by prior agreement, destroyed once the map was made. The map allows one to infer the magnitude of flows only from the width of colored bands and from a scale printed in the legend. Parallel flows are lumped together into one band, so that Colonial and Plantation flows are not differentiated, nor are the flows in parallel pipelines within either system.

These data constraints resulted in a decision to allocate the total flow carried by parallel pipes in such a way as to cause the same friction head in each pipe of a given segment. This introduces some error. However,

Table A.1. Characteristics of Colonial Pipeline Segments

Segment	Pipes In 1974[a]	Approx. Length[a] (mi)	Approx. 1974 Volume[b] (million bbl/yr)	Approx. Share of 1974 Energy	Relative Energy Intensity[b] x 10^{-12}	Relative Intensity Weighted by Length[b] x 10^{-12}
Houston to Beaumont[c]	36"	87	253	.0253	1.15	100
Beaumont to Baton Rouge[c]	36"	174	353	.1280	2.08	363
Baton Rouge to Collins[c]	2-36"	124	476	.0540	.92	113
Collins to Helena[c]	2-36"	200	455	.0864	.95	190
Helena to Bremen[c]	2-36"	106	441	.0411	.88	93
Bremen to Atlanta[c]	2-36"	31	432	.0157	1.17	36
Atlanta to Chattanooga	12",10"	99	54	.0328	6.14	607
Chattanooga to Nashville	10"	117	20	.0139	5.94	695
Chattanooga to Knoxville	10"	111	20	.0122	5.50	610
Atlanta to Macon	8"	87	15	.0139	10.7	927
Macon to Albany	8"	105	10	.0054	5.14	540
So. Albany to Bainbridge	8"	39	5	.0003	1.54	60
Atlanta to Belton[c]	36"	135	319	.0738	1.71	231
Belton to Augusta	8"	87	5	.0006	1.38	120
Belton to Spartanburg[c]	36"	46	315	.0251	1.73	80
Spartanburg to Charlotte[c]	36"	61	306	.0297	1.59	97
Charlotte to Greensboro[c]	36"	83	365	.0714	2.36	196
Greensboro to Apex	2-8"	66	30	.0210	10.6	700
Apex to Fayetteville	6"	48	5	.0015	6.25	300
Apex to Selma	2-8"	30	25	.0061	8.13	244

Table A.1. (Cont'd)

Segment	Pipes In 1974[a]	Approx. Length[a] (mi)	Approx. 1974 Volume[b] (million bbl/yr)	Approx. Share of 1974 Energy	Relative Energy Intensity[b] x 10^{-12}	Relative Intensity Weighted by Length[b] x 10^{-12}
Greensboro to Mitchell[c]	32"	148	297	.1196	2.72	403
Mitchell to Roanoke	8"	87	15	.0139	10.7	927
Mitchell to Richmond	16"	51	45	.0063	2.75	140
Richmond to Norfolk	14"	96	25	.0044	1.83	176
Mitchell to Chantilly[c]	32"	93	260	.0521	2.15	200
Chantilly to Dorsey[c]	30"	48	255	.0344	2.81	135
Dorsey to Washington	6"	30	10	.0064	21.3	640
Dorsey to Baltimore	12"	33	20	.0016	2.42	80
Dorsey to Belair[c]	30"	40	225	.0197	2.19	88
Belair to Philadelphia[c]	30"	55	210	.0224	1.94	107
Philadelphia to Linden[c]	30"	99	260	.0749	2.91	288

[a] See Ref. 5.

[b] Calculated, see text.

[c] Main line

Table A.2. Characteristics of Plantation Pipeline Segments

Segment	Pipes In 1974[a]	Approx. Length[a] (mi)	Approx. 1974 Volume[b] (million bbl/yr)	Approx. Share of 1974 Energy	Relative Energy Intensity[b] x 10^{-12}	Relative Intensity Weighted by Length[b] x 10^{-12}
Baton Rouge to Collins[c]	2-18",12"	126	81	.0540	5.28	665
Pascagoula to Collins	2-12"	111	30	.0227	6.82	757
Collins to Helena[c]	30",2-18",12"	198	221	.1972	4.51	893
Helena to Montgomery	8"	72	20	.0541	37.6	2710
Helena to Bremen	30",18",12"	105	176	.0790	4.27	448
Bremen to Chattanooga	8"	90	11	.0290	29.2	2620
Chattanooga to Knoxville	8"	102	10	.0286	26.7	2720
Bremen to Columbus	8"	84	10	.0203	24.2	2030
Bremen to Macon	8"	105	5	.0036	6.86	720
Bremen to Atlanta[c]	26",14",10"	27	120	.0157	4.85	131
Atlanta to Belton[c]	26",14",10"	138	167	.1877	8.16	1130
Belton to Spartanburg[c]	26",14",10"	48	165	.0653	8.25	396
Spartanburg to Charlotte[c]	26",14",10"	63	160	.0762	7.57	477
Charlotte to Greensboro[c]	14",10"	87	41	.0398	11.2	971
Greensboro to Roanoke	8"	93	10	.0225	24.2	2250
Greensboro to Richmond[c]	14"	159	33	.0652	12.4	1980
Richmond to Washington[c]	12"	96	20	.0182	9.7	929
Washington to Dulles	6"	24	5	.0032	26.7	640

[a] See Ref. 5

[b] Calculated, see text.

[c] Main line

this error is not significant and does not undermine analysis results because of the following factors:

1. Some of these pipes are looped (i.e., connected at the ends), and looped pipes will in fact have the same head, so long as they are about the same length.
2. Although one company's pipes are of course not looped with another's, the error resulting from a difference of head between the two companies is minimized by the separate treatment of each company. All that is needed is that the flow assigned to the segments within one pipeline company be such as to cause the correct fraction (i.e., relative amount) of that company's energy consumption to be allocated to each segment. Consequently, even if the friction head in one company is consistently overestimated, so that the flow is overestimated, the ratio of flows among the segments in that pipeline may still result in approximately the correct allocation of energy.
3. There is an economic incentive to equalize head within a company, because to do so is to choose the most energy-efficient allocation of flow, as will be demonstrated below. (See pages 30 and 31.)
4. An error in the allocation of flow, with a resulting error in the allocation of energy to different segments of a pipeline, does not cause a proportional error in the calculated energy consumption. It only changes the weights given to electric rates along the pipeline route when these rates are used to calculate a company's total power bill. The resulting error will then be relatively small, depending on the degree of variation in electric rates.

In order to equalize friction head mathematically, it is necessary to find an expression for the friction factor f, which depends on the Reynolds number R and on the relative roughness of the pipe. The friction factor can be read from tables (e.g., Ref. 11, p. 20-21). Pipelining calculations usually assume a smooth pipe, one with relative roughness on the order of 10^{-6}. An interpolation formula that approximates f fairly closely, at this relative roughness, is

$$f = aR^{t}, \qquad (2)$$

where $a = .173$ and $t = -.196$.

The formula is good when the Reynolds number R stays within the range exhibited by the pipes considered here; namely, in the range between 10^5 and 5×10^6. Using R defined as:

$$R = \frac{vd}{\nu},$$

where ν = kinematic viscosity of oil in ft^2/sec, and substituting Eq. 2 into Eq. 1,

$$H = a \left(\frac{vd}{\nu}\right)^t \frac{Lv^2}{2dg} . \tag{3}$$

The velocity v can be written

$$v = \frac{V}{\pi \left(\frac{d}{2}\right)^2} = \frac{4V}{\pi d^2} , \tag{4}$$

where V = volume rate of flow in ft^3/sec. Substitution of (4) into (3) yields

$$H = a \left(\frac{4V}{\pi \nu d}\right)^t \frac{8V^2L}{gd^5\pi^2}$$

or simplifying

$$H = AV^{2+t} \tag{5}$$

where

$$A = \frac{8a}{d^5} \left(\frac{4}{d}\right)^t \left[\frac{L}{g\nu^t\pi^{2+t}}\right] .$$

Since we are interested only in relative energy consumption, the quantity in the brackets can be set to 1.

The power usage P in ft-lb/sec is obtained by multiplying H by the number of pounds of oil pumped per second,

$$P = H\rho gV = A\rho g\ V^{3+t} \tag{6}$$

where ρ is the mass density in slugs/ft^3. If n parallel pipes have flows V_1, ..., V_n and if A_1, ..., An are the corresponding constants, then to equalize head is to require

$$A_1V_1^{2+t} = \ldots = A_nV_n^{2+t}$$

where $\sum_{i=1}^{n} V_i$ = total flow. (7)

The total flow is from the Congressional Research Service map in Ref. 4, as explained earlier. The pipe diameters are from the large map of the U.S. products pipeline network published by the American Petroleum Institute (5). (It should be noted that some of the parallel pipes belong to companies other than Colonial and Plantation, especially in the deep South.) Since the diameters provided are nominal diameters, inside diameters are calculated using the following typical pipe wall thicknesses:

nominal diameter (inches)	wall thickness (inches)
6-12	0.25
14-24	0.312
26-34	0.375
36-42	0.406

Solution of the equations in Eq. 7 yields the flows shown in Tables A.1 and A.2 in millions of barrels per year. If P_i is P as calculated in Eq. 6 for pipeline segment (i), then the share of energy used by segment i is simply

$$\frac{P_i L_i}{\sum_{j=1}^{m} P_j L_j} = e_i$$

where

L_j = length of segment j in miles.

m = number of segments.

The results are shown in column 4 of Tables A.1 and A.2.

It can be shown that the most energy-efficient allocation of flow among parallel pipes is with equalized heads. The most efficient allocation is the solution of the nonlinear program

$$\min \sum_{i=1}^{n} A_i \rho g V_i^{3+t} \qquad \text{(from Eq. 6)}$$

$$\text{subject to} \quad \sum_{i=1}^{n} V_i = \text{total flow} = V_o$$

Solving the constraint for V_n, the program becomes

$$\min \left[\sum_{i=1}^{n-1} A_i \rho g V_i^{3+t} + A_n \rho g \left(V_o - \sum_{i=1}^{n-1} V_i \right)^{3+t} \right]$$

Setting the partial derivatives with respect to each V_i equal to zero,

$$*(3+t)A_j\rho g V_j^{2+t} = (3+t)A_n\rho g\left(V_o - \sum_{i=1}^{n-1} V_i\right)^{2+t} \quad \text{for } j=1,\ldots,n-1$$

or equivalently,

$$A_1V_1^{2+t} = \ldots = A_{n-1}V_{n-1}^{2+t} = A_n\left(V_o - \sum_{i=1}^{n-1} V_i\right)^{2+t}$$

which is identical to the system of equations in Eq. 7.* So, the head-equalizing flow minimizes energy consumption as long as the interpolating formula in Eq. 2 provides a good approximation of f.

It should be pointed out that gravity head has been ignored in the calculation of the segments of a pipe's relative energy consumption. The most elevated section of the main trunk lines is that which crosses the Piedmont Plateau, whose elevation is in the neighborhood of 600 feet. For both pipelines, the southern half expends a little extra energy pumping oil from sea level at the Gulf to the Plateau, and the northern half reclaims some of this energy as that portion of the oil not consumed in the South moves downhill to New York. The trip from the Gulf to the edge of the Piedmont is some 1100 miles, causing an average elevation gain of a half-foot a mile. Roughly, 1300 ft-lbs of electrical energy are required to lift a ton of oil one-half foot. The overall energy required to move a ton of oil a mile, however, is roughly .025 kWh (as will be seen later), or 66,000 ft-lbs. This means that the work of overcoming gravity adds about 2% to the energy consumption of the southern half of the pipeline route, and subtracts the same portion from the consumption of the northern half. Therefore, it is not necessary to take gravity head into account when allocating energy consumption to the various segments of the pipeline route.

A.3 CALCULATION OF PIPELINE ROUTE SEGMENT ENERGY INTENSITY CORRECTION FACTORS

The procedure for calculating energy intensity correction factors for pipeline route segments follows. Recall that if I_s is the energy intensity for a company's pipeline network, the intensity I_r for a certain route r in the network is given by

$$I_r = K_r I_s .$$

The lower portion of the Colonial and Plantation routes carry more oil and have a disproportionate influence on the system intensity I_s. Yet in calculating the route intensity I_r, the lower portions cannot be weighted

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*It is straightforward to show by the second order conditions that the solution of the equations is a minimum.

more than the upper portions, since we are interested in the energy required to move a barrel of oil from one end of the route to the other. To weight each section of pipeline by the volume it carries would allow the barrels that never make it to the upper end to affect I_r. Therefore, let

L_i = length of segment i in miles (col. 2, Tables A.1 & A.2)

V_i = volume of segment i in bbl/yr (col. 3)

e_i = fraction of energy used in section i. (col. 4)

For each segment i, Tables A.1 and A.2 show the relative energy intensity I_i of that segment (column 5). Then

$$I_i = \frac{e_i}{L_i V_i}$$

It should be emphasized that the intensities (I_i) in the Colonial system are not comparable with those in the Plantation system, since the total energy consumption of the two companies differs.

The relative energy intensity I_r for a route r is the average of the intensities of its segments, weighted by length only:

$$I_r = \frac{\sum_{i\varepsilon r} I_i L_i}{\sum_{i\varepsilon r} L_i} = \frac{\sum_{i\varepsilon r} \frac{e_i}{V_i}}{\sum_{i\varepsilon r} L_i}$$

The intensity I_s for the system s is the average of the intensities of all its segments, weighted by length and volume:

$$I_s = \frac{\sum_{i\varepsilon s} I_i L_i V_i}{\sum_{i\varepsilon s} L_i V_i} = \frac{\sum_{i\varepsilon s} e_i}{\sum_{i\varepsilon s} L_i V_i} = \frac{1}{\sum_{i\varepsilon s} L_i V_i}$$

K_r is the ratio I_r/I_s.

The results for a few routes follow:

<u>Plantation</u> $I_s = 7.317 \quad 10^{-12}$

Baton Rouge to Atlanta $K_r = .640$
to Richmond $K_r = 1.019$
to Washington $K_r = 1.047$

<u>Colonial</u> $I_s = 1.820 \quad 10^{-12}$

Houston to Atlanta $K_r = .681$
to Norfolk $K_r = .908$
to Baltimore $K_r = .930$
to Philadelphia $K_r = .933$
to New York $K_r = .977$

Unsurprisingly, relatively smaller pipe diameters in the upper reaches of the network cause intensities to rise. Also, the Colonial Houston-to-New York intensity is a little below the system intensity, no doubt because Colonial's many branch lines have higher intensities which elevate the system average above anything along the main line.

A.4 CALCULATION OF TOTAL PIPELINE ENERGY CONSUMPTIONS

Recall that the method for calculating the total energy consumption of each pipeline company was to find that consumption figure, which when correctly allotted among the pipeline segments, would generate a total cost that matches the cost reported on Form P (Ref. 1). The fraction of consumption allotted to each segment is shown in column 3 of Tables A.1 and A.2. For these two pipelines, nearly all of the pumping stations in nearly every segment are served by a single utility, and 14 utilities supply nearly all the electricity used by the pipelines in question. It is important to determine the electric rates exactly, since an error of 0.1¢ per kWh (versus approximate total costs of 2.5¢ per kWh) in the rate can cause a 5% error in the calculated energy consumption. Consequently, the rates were calculated from the actual rate schedules, which were readily available only for the year 1977. The schedules were taken from the most recent version of the National Electric Rate Book (Ref. 6), which provides schedules generally dated late 1976 and early 1977. The fuel cost adjustment rates were dated July 1, 1977, so that the application of the fuel cost adjustment makes the rate current as of that date.

Use of the 1977 fuel cost, while basing the allocation of energy on the 1974 network configuration, poses a minor difficulty in that the 1977 network is not quite the same. Apparently, the only changes are a Colonial addition of a 40" segment running from Beaumont to Baton Rouge (note in Table A.1 the high energy intensity along that stretch in 1977, indicating a bottleneck), an 8" segment running from Chattanooga to Nashville, and a 12" segment from Atlanta to Macon [another bottleneck indicated in Table A.1]. (Ref. 5, 9) These additions should have no serious effect on the distribution of energy consumption in the system as a whole. The additions have no repercussions at all elsewhere, except that the construction of five new pumping stations along these new segments has an effect on calculated electric rates, an effect that is discussed and accounted below.

Electric rates depend on an installation's power demand as well as on its consumption in kWh. Power demand is measured either in kilowatts (indicating real power) or in kilovolt-amperes (indicating apparent power), depending on the local arrangement. The demand figure that governs an installation's rates is usually some sort of peak demand, its method of determination again differing from one locale to another. For this analysis, the power demand at a given installation was determined by allotting the company's total installed horsepower to its pumping stations in the same ratio in which energy consumption is allotted, and by multiplying a station's horsepower allotment (converted to kW) by some factor p. It was expected that p would be somewhat greater than 1, since the inefficiency of the compressors and motors could result in a power demand greater than the output power.

Plantation Pipeline Company shows a total 1977 fuel cost of $11,525,117. Setting p = 1, a computer bisection search found that 458.7 million kWh would cost this much in 1977; the resulting average rate is 2.51¢/kWh. An official at Plantation subsequently stated that Plantation's actual consumption in 1977 was 452.3 million kWh, and the average rate 2.5¢/kWh (3). This indicates that p = 1 is very close to the mark; p = 1.028 yields the correct consumption figure more exactly.

It is unclear why p is not larger than 1.028. The inefficiency of the equipment should tend to raise p above unity, and the power factor of industrial motors would raise p further since some utilities bill according to the apparent demand (i.e., real demand divided by the power factor). An official at the Tennessee Valley Authority has said that the power factor is nearly always kept above 90%, often with the help of capacitors in the circuit with the motors, but there is yet some tendency here to increase p. The fact that p is only 1.028 (for Plantation) has at least three possible explanations.

1. The pipeline does not run at capacity. Colonial, however, has been "prorating" for some years (9) -- that is, rationing capacity among its users -- and this indicates that Colonial, at least, is running at capacity.
2. There were more pumping stations in 1977 than in 1974; so that when the 1977 total pumping horsepower is apportioned among the 1974 pumping stations, each station is assigned too much horsepower. Consequently, the value p must be decreased in order to assign the correct horsepower to the individual stations. This is likely to apply only to the Colonial system, which added five pumping stations (Refs. 5, 9, 10) during the 1974-77 period.
3. The system is designed in such a way that not all the available horsepower can be used.

It would be unwise to assume that p has the same value for Colonial as for Plantation, since Colonial's utilization of available horsepower may not be the same. A better course is to suppose that the ratio of the average rate of consumption to the peak power demand is about the same ratio in either system.

Plantation's annual consumption of 452.3 million kWh works out to an average rate of consumption of 51,632 kilowatts. The total power demand used in calculating the company's rates was the company's installed horsepower (175,000 hp) multiplied by p (= 1.028), which is 179,900 hp or 134,200 kW. The resulting ratio is 51,632/134,200 = .3847. To suppose that the Colonial system shows this same ratio is to suppose that the unevenness of power demand is about the same for the two systems; this seems to be a reasonable assumption.

One small correction must be made, however. Between 1974 and 1977 Colonial increased the number of pumping stations from about 80 to 85, so that the value of p must be decreased by a factor of 80/85 = 16/17 in order to assign the correct horsepower to the 80 individual stations used in calculations. This means that p must be set to a value such that the resulting average rate of consumption bears the ratio .3847 to the product of the installed horsepower h (converted to kW) and (17/16) p. For (17/16) ph represents the peak demand reduced by a factor of 16/17 in order to assign the correct horsepower to the individual stations.

Colonial's total installed horsepower in 1977 was 968,735 hp (= 722,676 kW). (Ref. 10) Then if p is set at .843 for Colonial, so that the total peak demand is (17/16)ph = (17/16)(.843)(722,676) = 647,000 kW, the resulting consumption is 2179 million kWh. This consumption figure indicates an average consumption rate of 248,800 kW, which bears the correct ratio .385 to the peak demand of 647,000 kW. The resulting average price of electricity paid by Colonial is 2.90¢/kWh.

A.5 CALCULATION OF PIPELINE SYSTEM ENERGY INTENSITIES

The system energy intensities are:

		Colonial	Plantation
Consumption	= E_s (millions of kWh)	2,179	452.3
Barrel-miles	= BM_s (millions)	614,918	111,609
Energy intensity (kWh per 1000 BM)	= E_s/BM_s	3.54	4.05

The barrel-miles figure is taken from Form P (Ref. 1). The energy consumption per ton-mile, rather than barrel-mile, can be calculated by taking into account the mix of products transported by each pipeline and their densities. These data are displayed in Table A.3. The weighted average of the weight densities is 46.5 lb/ft^3 for Colonial and 46.2 lb/ft^3 for Plantation. These are only median values, since the densities of oil products vary somewhat, as shown in Table A.3. The resulting intensities per route ton-mile are:

Energy Intensity	Colonial	Plantation
kWh per ton-mile	.0271	.0312
Btu per ton-mile	92.5	107

If one accepts that, on the average, 10,449 Btu were required to produce 1 kWh of electrical energy in 1977 (Ref. 8), we get:

Table A.3. 1977 Colonial and Plantation Product Mixes and Approximate Densities

	Colonial		Plantation[b]		Weight Density (lb/ft^3)	Median Weight Density (lb/ft^3)
	Barrels Delivered[a]	% by Volume	Barrels Delivered[a]	% by Volume		
Gasoline	372,005,869	64	131,889,563	65	41-43[c]	42
Kerosene	43,791,232	8	23,006,476	11	51.2[c]	51.2
Distillate Oil	166,134,054	28	47,375,599	24	51.2-59.3[d]	55.3

[a] From Ref. 1.

[b] Plantation's Form P shows "total delivered out of system" for each state and each product. This quantity evidently includes the oil shipped to the next state through the main truck line. Consequently, the figures shown, which are sums of the Form P figures across the states along the route, count some barrels twice or more. It is assumed, however, that oil which is counted more than once has the same product mix as the rest, so that the resulting percentage figures are correct.

[c] From Ref. 8.

[d] From Ref. 9.

	Colonial	Plantation
Fossil-fuel energy intensity (Btu per route ton-mile)	283	326

Finally, the energy intensities along selected routes were calculated, and are shown in Table A.4. Three significant digits are shown, but the third digit is for purposes of documentation only and is not meant to suggest that the numbers are accurate to the third digit.

Colonial has the more important intensities for purposes of comparison with the tanker route from the Gulf to the upper Atlantic seaboard. Plantation discharges most of its cargo in the deep South, and only a tiny fraction of its oil, 368,000 barrels or 0.2 percent (Form P), traveled as far north as North Carolina in 1977. Colonial, on the other hand, delivers more than 200 million barrels a year to New Jersey (Table A.1). However, the Plantation figures are more reliable, since Plantation's electricity consumption was directly available from the company.

Tables A.4. Energy Intensities for Selected Routes

	Length[a] = d_r (mi)	K_r[b]	Energy Intensity = I_r		Energy Consumption per Unit Transported = $E_r = I_r d_r$	
			(kWh per 1000 bbl-mi)[c]	(Btu per ton-mi)[d]	(kWh/bbl)[c]	(Btu/ton)[d]
Colonial Routes						
Entire System		1.000	3.54	283		
Houston to Atlanta	722	0.681	2.41	193	1.74	139,000
to Norfolk	1342	0.908	3.21	257	4.31	345,000
to Baltimore	1369	0.930	3.29	263	4.50	360,000
to Philadelphia	1432	0.933	3.30	264	4.73	378,000
to New York[e]	1531	0.977	3.46	276	5.30	423,000
Baton Rouge to Atlanta	461	0.515	1.82	146	0.84	67,300
to Norfolk	1081	0.892	3.16	252	3.47	272,000
to Baltimore	1108	0.919	3.25	260	3.60	288,000
to Philadelphia	1171	0.922	3.26	261	3.82	306,000
to New York[e]	1270	0.975	3.45	276	4.38	351,000
Plantation Routes						
Entire System		1.000	4.05	362		
Baton Rouge to Atlanta	456	0.640	2.59	209	1.18	95,300
to Richmond	951	1.019	4.13	332	3.93	316,000
to Washington	1047	1.047	4.25	341	4.44	357,000
Pensagoula to Atlanta	456	0.691	2.30	225	1.23	99,200
to Richmond	936	1.049	4.25	342	3.98	320,000
to Washington	1032	1.074	4.35	350	4.49	361,000

[a] From Ref. 5, 10.

[b] $K_r = I_r/I_s$, the ratio of segment energy intensity to route energy intensity.

[c] kWh of electrical energy.

[d] Btu of fossil fuel (or nuclear) energy. It is assumed that 10,449 Btu of fossil fuel energy is required to produce 1 kW of electrical power (Ref.9) and that the average weight density of petroleum products is 46.5 lb/ft^3 in the Colonial system and 46.2 lb/ft^3 in the Plantation system (as calculated in the text).

[e] Actually, Linden NJ.

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APPENDIX B

SUPPLEMENTARY COASTAL TANKER VOLUME DATA

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Table B.1. 1975 Domestic Ocean Shipments of Light Petroleum Products,[a] U.S. Gulf Coast to Northeastern Ports: Origin-Destination Matrix (10^3 short tons)

	Norfolk, VA	Newport News, VA	Washington, D.C.	Baltimore, MD	Philadelphia, PA	New York, NY	North[c] of NY	Total[b]
South of Galveston[c]	37	-	84	78	529	2,655	1,492	4,875
Houston, TX	665	-	104	1,641	2,484	2,579	3,916	11,390
Texas City, TX[c]	-	79	-	25	56	1,248	957	2,365
Beaumont, TX	103	-	-	-	383	790	1,520	2,797
Port Arthur, TX[c]	88	-	-	34	542	343	1,398	2,406
Lake Charles, LA	-	-	-	1	135	420	439	995
Baton Rouge, LA	18	-	-	197	777	1,389	1,209	3,590
Gramercy, LA	-	-	-	-	29	-	-	29
New Orleans, LA[c]	-	-	-	54	68	912	1,902	2,938
Pascagoula, MS	5	-	-	-	17	67	14	104
Mobile, AL	-	-	-	-	-	39	-	38
Total[b]	916	79	188	2,030	5,022	10,443	12,847	31,526

[a] Gasoline, jet fuel, kerosene, distillate fuel oil and naptha.

[b] Totals may not add up due to rounding.

[c] See text for explanation of aggregation of ports and their volumes.

Source: Special computer runs provided by Division of Domestic Ocean Shipping, Office of Domestic Shipping, Maritime Administration, U.S. Department of Commerce, Washington, D.C. (March 1979).

Table B.2. 1976 Domestic Ocean Shipments of Light Petroleum Products,[a] U.S. Gulf Coast to Northeastern Ports: Origin-Destination Matrix (10^3 short tons)

	Norfolk, VA	Newport News, VA	Washington, D.C.	Baltimore, MD	Philadelphia, PA	New York, NY	North[c] of NY	Total[b]
South of Galveston[c]	26	-	63	-	591	2,093	1,273	4,045
Houston, TX	711	24	76	1,012	2,205	3,114	3,810	10,951
Texas City, TX	-	87	-	39	21	805	604	1,556
Beaumont, TX	19	-	-	-	436	489	2,382	3,328
Port Arthur, TX[c]	-	6	9	132	541	481	1,082	2,250
Lake Charles, LA	-	-	-	-	90	469	261	820
Baton Rouge, LA	73	7	12	698	257	662	1,197	2,907
Gramercy, LA	9	-	-	-	-	-	10	19
New Orleans, LA[c]	-	-	132	-	50	810	1,697	2,589
Pascagoula, MS	-	-	6	-	-	14	-	20
Mobile, AL	-	-	-	-	-	-	-	-
Total[b]	838	123	199	1,881	4,191	8,937	12,316	28,484

[a] Gasoline, jet fuel, kerosene, distillate fuel oil and naptha.

[b] Totals may not add up due to rounding.

[c] See text for explanation of aggregation of ports and their volumes.

Source: Special computer runs provided by Division of Domestic Ocean Shipping, Office of Domestic Shipping, Maritime Administration, U.S. Department of Commerce, Washington, D.C. (March 1979).

Table B.3. Non-Aggregated 1976 Domestic Ocean Shipments of Light Petroleum Products,[a] U.S. Gulf Coast to Northeastern Ports: Origin-Destination Matrix (10^3 short tons)

	New York, NY	Philadelphia, PA	Boston, MA	Washington, DC	Baltimore, MD	Norfolk, VA	Portland, ME
Pascagoula, MS	14	-	-	6	-	-	-
New Orleans, LA	14	33	57	32	-	-	-
Baton Rouge, LA	662	293	1,055	12	698	73	-
Port Arthur, TX	481	-	458	9	132	-	205
Sabine, TX	-	93	22	-	-	-	-
Beaumont, TX	489	25	1,133	-	-	19	360
Lake Charles, LA	470	46	229	-	-	-	14
Corpus Christi, TX	2,014	267	874	63	-	26	79
Houston, TX	3,114	-	2,152	76	1,012	711	145
Destrehan, LA	754	-	114	-	-	-	104
St. Rose, LA	43	-	-	-	-	-	-
Mobile, AL	-	-	-	-	-	-	-
Freeport, TX	69	21	11	-	-	-	-
Texas City, TX	805	-	103	-	39	-	144
Gramercy, LA	9	-	-	-	-	-	-

Table B.3. (Cont'd)
(10^3 short tons)

	Fall River, MA	Providence, RI	Bridgeport, CT	Albany, NY	Marcus Hook, PA	Salem, MA
Pascagoula, MS	-	-	-	-	-	-
New Orleans, LA	-	-	-	-	-	-
Baton Rouge, LA	-	-	-	-	-	-
Port Arthur, TX	-	173	-	42	8	-
Sabine, TX	-	-	-	-	-	-
Beaumont, TX	30	602	-	25	-	-
Lake Charles, LA	-	-	-	-	17	15
Corpus Christi, TX	17	103	-	-	229	16
Houston, TX	541	98	144	76	-	-
Destrehan, LA	531	78	437	91	-	-
St. Rose, LA	-	-	-	-	-	-
Mobile, AL	-	-	-	-	-	-
Freeport, TX	-	-	-	-	-	-
Texas City, TX	-	26	-	232	-	-
Gramercy, LA	-	10	-	-	-	-

Table B.3. (Cont'd)
(10^3 short tons)

	New Haven, CT	Paulsboro, NJ	Camden, NJ	Wilmington, DE	Newport News, VA	Portsmouth, NH	Searsport, ME
Pascagoula, MS	-	-	-	-	-	-	-
New Orleans, LA	-	-	-	-	-	-	-
Baton Rouge, LA	132	218	15	24	7	-	-
Port Arthur, TX	166	239	-	-	6	15	-
Sabine, TX	-	-	-	-	-	-	-
Beaumont, TX	77	319	4	21	-	149	-
Lake Charles, LA	2	-	-	48	-	-	-
Corpus Christi, TX	87	285	-	30	-	86	-
Houston, TX	622	1,938	-	-	24	-	31
Destrehan, LA	138	-	-	17	-	81	66
St. Rose, LA	-	-	-	-	-	-	-
Mobile, AL	-	-	-	-	-	-	-
Freeport, TX	-	-	-	-	-	-	-
Texas City, TX	97	-	-	-	57	-	-
Gramercy, LA	-	-	-	-	-	-	-

[a] Gasoline, jet fuel, kerosene, distillate fuel oil and naptha.

Source: Special computer runs provided by Division of Domestic Ocean Shipping, Office of Domestic Shipping, Maritime Administration, U.S. Department of Commerce, Washington, D.C. (March 1979).

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APPENDIX C

THE FRACTION OF EACH PIPELINE'S ELECTRICITY GENERATED BY FUEL TYPE

It is possible to estimate the fraction of a pipeline company's electricity generated by burning oil by equating it to the fraction generated from oil in the utilities serving the pipeline. The same assumption can be made for coal, water power, nuclear power, and other fuels.

Table C.1 lists the 11 electric utilities serving the various segments of the Colonial and Plantation pipeline systems. Table C.2 shows the share of each pipeline's electricity provided by each utility and the rated powerplant capacities using each type of fuel. The percentage contribution of each fuel to utility total capacity is also shown.

The fraction of a pipeline's energy provided by a particular fuel is the sum of the product of the share provided by each utility and the fraction of the fuel type used by the utility.

The results are:

Fuels	Colonial	Plantation
Oil	26%	15%
Coal	41%	66%
Nuclear	13%	8%
Hydro	4%	6%
Other	16%	5%

These calculations are necessarily rough because:

(1) A plant may not produce at its rated capacity;

(2) A utility may import electricity from other utilities, and this electricity may be generated from different fuels;

(3) Only primary fuels are considered, but some plants may occasionally switch to alternate fuels and such switches are not accounted for here.

Based on the distribution of shipments between the two pipeline companies, a good estimate is 25% for the oil fraction of utility-energy inputs.

Table C.1. Electric Utilities Serving Colonial and Plantation Pipelines

Utility (and States of Operation)	Colonial Pipeline Segments Served[a]	Plantation Pipeline Segments served[a]
Public Services Electric & Gas (NJ)	Philadelphia to Linden, NJ	None
Duke Power Company (NC, SC)[b]	Belton, GA, to Augusta and to Apex, NC	Spartanburg to Greensboro
Carolina Power and Light (NC, SC)	Apex to Fayetteville and to Selma, NC	None
Virginia Electric & Power Co. (VA)	Greensboro to Chantilly, VA	Greensboro to Washington and Dulles, VA
Gulf States Utility Co. (TX, LA)[b]	Houston to Baton Rouge	None
Mississippi Power Co. (MS)	Baton Rouge to Helena, MS	Baton Rouge & Pascagoula to Helena
Alabama Power Co. (AL)	Helena to Bremen, AL	Helena to Montgomery & to Bremen
Georgia Power Co. (GA)	Bremen, AL, to Belton, GA, and Atlanta to Chattanooga and to Bainbridge, GA	Bremen to Belton, Columbus and Macon, GA
Appalachian Power Co. (VA,WV)	Mitchell to Roanoke	Greensboro to Roanoke
Baltimore Gas and Electric (MD)	Chantilly, VA, to Philadelphia, and Dorsey, MD to Washington and to Baltimore	None
Tennessee Valley Authority[b] (TN, MS, AL, GA, KY, NC)	Chattanooga to Nashville and to Knoxville	Chattanooga to Knoxville

[a] The pipeline segments are those defined in Tables A.1 and A.2 of Appendix A. If a single segment is served by two utilities, the utility shown is the one that provides it with the most power.

[b] Each of these three utilities serves the pipelines under two different rate schedules. Consequently 14 rather than 11 rate schedules were used in the computation of each company's power bill in Appendix A.

Table C.2. 1977 Rated Power Capacities by Fuel of Electric Utilities Serving Colonial and Plantation Pipelines

Utility (and States of Operation)	Share of Pipeline Energy Furnished[a]		Total Rated Power Capacity by Fuel in Megawatts and Percent[b]					
	Colonial	Plantation	Oil[c]	Coal	Nuclear	Hydro	Other[d]	Total
Public Services Electric & Gas (NJ)	7	0	5,819 (66)	1,755 (20)	1,090 (12)	0 (0)	132 (2)	8,796 (100)
Duke Power Company (NC, SC)	15	18	979 (8)	7,812 (60)	2,661 (20)	1,590 (12)	0 (0)	13,042 (100)
Carolina Power and Light (NC, SC)	1	0	1,761 (22)	3,339 (42)	2,503 (32)	222 (3)	57 (1)	7,882 (100)
Virginia Electric & Power (VA)	18	9	3,871 (54)	1,307 (18)	1,696 (24)	13 (0)	216 (3)	7,103 (100)
Gulf States Utility Co. (TX, LA)	15	0	1,087 (16)	0 (0)	0 (0)	0 (0)	5,536 (84)	5,623 (100)
Mississippi Power Co. (MS)	14	28	721 (28)	1,722 (67)	0 (0)	0 (0)	118 (5)	2,561 (100)
Alabama Power Co. (AL)	4	14	108 (1)	5,990 (71)	888 (11)	129 (15)	138 (2)	8,420 (100)
Georgia Power Co. (GA)	14	26	149 (1)	10,387 (82)	0 (0)	751 (6)	1,421 (11)	12,708 (100)
Appalachian Power Co. (VA,WV)	1	2	0 (0)	4,689 (84)	0 (0)	597 (14)	68 (2)	4,254 (100)
Baltimore Gas and Electric (MD)	8	0	2,420 (51)	359 (8)	1,829 (38)	0 (0)	168 (3)	4,776 (100)
Tennessee Valley Authority (TN, MS, AL, GA, KY, NC)	3	3	0 (0)	7,667 (58)	3,456 (26)	1,729 (13)	480 (4)	13,332 (100)
Totals	100	100	16,915 (19)	43,927 (49)	14,123 (16)	6,198 (7)	8,334 (9)	89,497 (100)

[a] Aggregated from Column 4 of Tables A.1 and A.2 Appendix A and map in Appendix A, Ref. 5.

[b] Derived from source given below. Power plants capable of burning alternate fuels are listed as producing power with their primary fuel only. Totals shown are subject to errors caused by rounding.

[c] Includes fuel oil of all types, as well as kerosene.

[d] Mostly natural gas.

Source: Department of Energy, Office of Utility Project Operations, *Inventory of Power Plants in the United States*, December 1977.