Energy Requirements for Pavement Construction

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T H E   U N I V E R S I T Y   O F   M I C H I G A N

COLLEGE OF ENGINEERING

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ABSTRACT

ENERGY REQUIREMENTS FOR PAVEMENT CONSTRUCTION

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The work involved a search for numerical values for energy consumption for various materials and processes used in pavement construction. A number of references were consulted and the energies were compared and tabulated. As the first trial, graphical charts were set up for easy determination of energy requirements for bituminous and portland cement concrete pavements. Numerical examples are given for illustration.

ACKNOWLEDGMENT

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DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Michigan State Highway Commission or The University of Michigan.

INTRODUCTION

The manufacturing of materials for pavements, transporting them to the site and placement require certain amounts of energy. The increasing costs of fuel used in construction is already a factor and may become more so in the near future. Thus energy considerations could play an important role in choosing different materials and layer combinations to minimize energy consumption.

PURPOSE AND SCOPE

The main purpose of this research was to examine and compare energy requirements for bituminous and portland cement concrete pavements. The main emphasis was placed on literature survey coupled with attempts to obtain first-hand information from industry. The main points of emphasis were:

1. Using BTU as a base, the energy required to produce basic paving materials, i.e. asphaltic concrete, portland cement and concrete, aggregates and steel was searched in the literature.

2. The relative energy intensiveness among the following construction phases was checked:

   a. Procurement of basic paving materials.
   b. Production of paving mixes.
   c. Transportation of materials.
   d. Placing of materials.

3. Energy requirements for certain maintenance operations were considered.

4. A system of graphs was developed which can be used in different combinations to estimate energy requirements for different proposed pavement operations.

5. Illustrative examples are given for use of the graphs.

ENERGY EQUIVALENT UNITS

The basic equivalent unit used in this report will be British Thermal Unit or BTU*. Since bituminous concrete weight unit is usually one ton (2000 pounds) and portland cement concrete is usually sold by cubic yard (cy), the energy values per ton and per cubic yard will be shown in graphs dealing with bituminous mixes and portland cement concrete mixes respectively. In some cases BTU's per square yard, per inch will also be used.

ENERGY REQUIRED TO PRODUCE PAVEMENT MATERIALS

Information on energy required to produce basic materials used in pavement construction is not very abundant. Literature research revealed five primary sources which can be useful in calculations. The values are tabulated in Tables 1, 2 and 3. The numerical agreement between the sources in Table 1 is quite good, except for Fels (3) who admits using an "energy efficiency factor" which results in higher listed values.

Table 2 shows values for energy needs to make asphaltic products. There is a large discrepancy between the references listed depending whether asphalt is counted as a by-product (2) or a

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* One British Thermal Unit is equal to 1055 Joules in the SI System, which is presently being promoted as international system (SI=System International)

refinery or petroleum product (6). The data available on this subject appears to be varied and obscure and additional in-depth study and debate in this area is needed. Sample calculations in this report include both "high" and "low" values for the production energy of asphalt.

Table 3 gives additional tabulations for steel bars.

MISCELLANEOUS ENERGY VALUES

In addition to energy consumed in material production, mixing, transportation and placement of these materials involves additional energy. Table 4 lists the BTU equivalents for different types of fuel used. Actual energy requirements for transporting of materials are given in graphical form in this paper for various types of applications. Table 5 summarizes energy requirements for various types of operations for portland cement and bituminous concretes as well as granular bases. These were collected from the various references listed in the bibliography.

NEED FOR ADDITIONAL DATA

There is some data for energy requirements to manufacture various pavement materials. Except for the great discrepancies in energies consumed for making paving asphalt, the various sources are in quite acceptable agreement. Reliable information on energies for procurement, production and placing of materials is less documented and needs additional development. There is probably considerable amount of data available from private industry active on the area of pavement construction. Two paving contractors were contacted in the Ann Arbor area, asking for data on fuel consumption in various paving operations. This turned out to be a difficult task because (a) there was not an open willingness to divulge such "private data" and (b) the data available was in a form peculiar to each contractors operations. Studies encouraged by organizations such as NAPA (National Asphalt Paving Association) would be of great benefit for those concerned with minimizing energy consumption during pavement construction.

USE OF AVAILABLE DATA

Although additional data still has to be obtained and agreed upon, a start can be made to compare different pavement cross sections from energy standpoint. The best and most thorough approach would be to include energy comparison in the total design-construction-maintenance package. In other words it could be a part of frequently discussed and used "Pavement Management System". All data would be handled by a computer providing energy values for different pavement systems, or even designing systems with minimum energy requirements. Since Michigan at this time is not using a "pavement management" approach, it would be a big task to develop a package including energy subsystems. The funding of this project does not permit such an undertaking. Therefore it was decided as the first attempt, to use a series of graphical charts for determination of energy needed on different layered pavements. The description of the graphical approach follows:

BITUMINOUS MIXES

Graphical method for estimating energy consumed for bituminous concrete pavement in place is given by Figures 1 to 7.

Figure 1 gives the energy for asphalt manufacture as reported by The Asphalt Institute (Reference 2), assuming 1.05×10^5 BTU/Bbl or about 300 BTU per pound of asphalt. If the pounds of asphalt per ton of mix is known, the BTU per ton of mix can be obtained directly from the graph.

Figure 2 is similar to Figure 1, except that 6.64×10^6 BTU/Bbl or about 18,600 BTU per pound of asphalt is the assumed required energy (from Reference 6).

Figure 2 summarizes energy needed for producing three different types of aggregates. The values for the Bank Run Aggregates (Natural Aggregates) and Crushed Bank Run Aggregates (Crushed Gravel) were obtained from Reference 2, while the curve for Crushed Quarried aggregates is based on data from Reference 1 and Reference 2.

Figures 3 and 4 were obtained from References 9 and 10.

Figures 5 and 5A depicts Mixing and Miscellaneous Plant Operations and Placement Energy. Primary source for this Figure is Reference 2.

Figures 6A, 6B, 6C and 6D are also based on Reference 2.

Figure 7 ends the series of graphs on bituminous concrete with a conversion from BTU per ton of Mix to BTU per square yard per inch of thickness.

SAMPLE CALCULATIONS - ASPHALT CONCRETE

Given:

Mix proportions and weights - 2000 pound basis

Asphalt cement	5 percent	100 pounds
Crushed, quarried agg.	65 percent	1235 pounds
Sand	35 percent	665 pounds
	100 percent	2000 pounds

Aggregate temperature, start 65 F
Aggregate temperature, end 350 F
Moisture in aggregate 6 percent

Haul distances - asphalt cement, 100 miles, 4 axle diesel
Haul distances - aggregates, 20 miles, 5 axle diesel
Haul distances - mix, 10 miles, 3 axle, single, diesel

In place density - 145 pounds per cubic foot

Calculations

Figure 1	A.C. manufacture	31,000 BTU per ton of mix
Figure 2	Aggregate production	43,000 BTU per ton of mix
Figure 2	Sand	5,000 BTU per ton of mix
Figure 3	Drying	163,000 BTU per ton of mix
Figure 4	Heating (65 to 350 F)	127,000 BTU per ton of mix
Figure 5	Mixing	19,800 BTU per ton of mix
Figure 5A	Placing	16,700 BTU per ton of mix
Figure 6C	Asphalt hauling	16,300 BTU per ton of mix
Figure 6D	Aggregate hauling	38,000 BTU per ton of mix
Figure 6A	Mix hauling	38,000 BTU per ton of mix
	Total	497,800 BTU (500,000 BTU)

Figure 7 can be used to convert the BTU per ton to BTU per square yard per inch of thickness. This comes out to be about 26,000 BTU.

From the calculations above we see that most of the energy (about 58 percent) goes to drying and heating of the aggregates. However, this picture changes if Figure 1A instead of Figure 1 is used for obtaining the quantity of energy for manufacturing asphalt. According to this figure it would take about 1,900,000 BTU to make 100 pounds of asphalt cement, raising the total energy required to produce one ton of mix to approximately 2,400,000 BTU. Thus the asphalt cement becomes the most energy consuming ingredient in the mix. This discrepancy reminds us of necessity to agree on a common acceptable value for energy in manufacture of asphalt.

CALCULATIONS FOR CONCRETE

Graphical representation of energy for components used in portland cement concrete are given in Figures A to N.

Figure 4 shows the energy required to manufacture portland cement. The curve is based on values obtained from Reference 8.

Data for Figure B was obtained from References 1 and 2 while Reference 2 was used for Figures C to N.

SAMPLE CALCULATION - PORTLAND CEMENT CONCRETE

Given:

Weights of components per cubic yard of mix

Cement	520 pounds
Crushed, Quarried Agg.	2,300 pounds
Sand	1,150 pounds
	3,970 pounds

Haul distance - cement, 100 miles, 4 axle diesel
Haul distance - aggregates, 20 miles, 5 axle diesel
Haul distance - mix, 10 miles, 4 axle diesel

Unit weight of concrete - 150 pounds per cubic foot

Calculations:

Figure A	P.C. manufacture	2,030,000 BTU per cu. yd.
Figure B	Agg. production	80,000 BTU per cu. yd.
Figure B	Sand production	8,500 BTU per cu. yd.
Figure E	Hauling cement	90,000 BTU per cu. yd.
Figure F	Hauling aggregates	63,000 BTU per cu. yd.
Figure H	Hauling concrete	68,000 BTU per cu. yd.
Figure I, J, K	Placing concrete	11,000 BTU per cu. yd.
		2,355,800 BTU per cu. yd.

This is 63,000 BTU per square yard per inch of thickness (Figure L) or 630,000 BTU per square yard for 10-inch slab. If pavement width is 24 feet and transverse joint spacing is 30 feet, additional 300 BTU per square yard will be needed (Figures M and N).

GRAPHS FOR GRANULAR BASES

Graphical representation of energy needed for components used in granular bases is given in Figures I, II, III, IV, V and VI. The first five figures are already familiar from previous discussion. Figure VI was obtained from Reference 2. The unit used here is BTU per square yard per inch of thickness of the base.

Sample calculations are rather simple for granular bases and will be omitted. The final example will contain calculations (and computations) for a layered pavement.

SAMPLE CALCULATION AND COMPARISON FOR LAYERED P.C. AND B.C. PAVEMENTS

Design Data

Subgrade: AASHTO classification = A-6(16)
CBR = 6
K = 125

Subbase: Sand, modulus = 30,000 psi

Base: Crushed Rock, modulus = 30,000 psi

Surfacing: Asphaltic Concrete, modulus = 400,000 psi

Portland Cement concrete, E = 4,000,000 psi
modulus of rupture = 650 psi

Traffic: ADT = 15,000 for both directions, 20% trucks, 90% of one - direction trucks in design lane. Axle loadings and distribution of axle loadings are fixed.

Growth rate expected at 4% per year.

Design No. 1 - PCA criteria (40 year design life)*

Portland Cement Concrete	8.5"
Sand subbase	6.0"

12' lanes; Transverse Jts. @ 80'; cut longitudinal jt.

Design No. 2 - AASHTO criteria (20 year design life)

Portland Cement Concrete	10.5"
Sand subbase (100 pcf)	6.0"

12' lanes; Transverse Jts. @ 80' cut longitudinal jt.

Design No. 3 - AASHTO criteria (20 year design life)

Bituminous Concrete	6.5"
Crushed Rock Base (125 pcf)	4.5"
Sand subbase (100 pcf)	20.0"

Design No. 4 - Asphalt Institute criteria (20 year design life)

Bituminous Concrete	6.5"
Crushed Rock base	9.0"

* The four design examples were taken from student home problem calculations and are given here for illustration only.

Material Transportation

Asphalt Cement : (5 axle diesel) 100 miles round trip

Portland Cement : (5 axle diesel) 100 miles

Base, subbase and constituent aggregates – 25 miles round trip

Mix : (3 axle diesel – AC) 15 miles round trip
(4 axle diesel – PCC)

Mix Proportions

Bituminous Concrete

	Pounds/Ton of Mix	
AC	110	
Crushed Gravel	1512	
Sand	393	1890
Mineral Filler	15	

Mixing Temperature 350F

Average moisture content of Agg. 7%

Portland Cement Concrete

	Pounds/cubic Yard of Mix	
Cement	560	
Coarse Agg. (gravel)	1954	3050
Fine Agg. (sand)	1096	

U.W. 145 pcf

ENERGY DETERMINATION - MIXES

Portland Cement Surface

Figure	Description	$BTU/yd^2 x 10^3$
A	P.C. Manufacture	2225
F	P.C. Transportation	56
B	C.A. Manufacture	15
E	C.A. Transport	80
B	F.A. Manufacture	8
E	F.A. Transportation	48
I	Agg. Handling - Plant	7.4
J	Mixing & Plant Operation	3.6
H	PCC - Transport	96
K	PCC - Placement	5.2
	Total	2544.2 $BTU/yd^2 x 10^3$

		$BTU/yd^2/in$
L	Conversion	70
M	Joint Sawing	.14
		70.1 $BTU/yd^2/in$

ENERGY DETERMINATION - MIXES

Asphalt Concrete Surface

Figure	Description	BTU/Ton x 10^3
1	Asphalt Institute data, AC Manufacture	33
1A	DOT Data, AC - Manufacture	(1950)
6D	AC - Transportation	12
2	Agg. Production	
	a) Crushed Gravel	31.5
	b) Sanol	3.0
	c) M.F. (assumed Fly ash)	0
6C	Agg. Transportation	78
3	Agg. Drying	190
4	Heating - assume Pile Temp. = 60F	133
5	Mixing & Misc. Plant	19.8
6A	Mix Transportation	56
5A	Placement	16.7
	Σ	573* (2490)**
7	Conversion	32 BTU/yd^2/in* (137.5 BTU/yd^2/in**)

*Using AC energy cost from Asphalt Institute
** Using AC energy cost from DOT

ENERGY DETERMINATION - DESIGN STRUCTURES

Design No. 1

			BTU/sq.yd x 10^3
PCC	70.74 BTU/yd^2/in	@8.5"	596.2

Sand Subbase - dry density = 100pcf

a) Production	.055	Thousand BTU/yd^2/in
b) Transportation	.31	
c) Placement	.64	
Σ	1.005	@6" 6

Total Energy per Square Yard **602.2** BTU/ sq. ydx10^3

Design No. 2

PCC	70.14 BTU/yd^2/in	@10.5	736.47
Sand Subbase - see above			6.00
Total Energy per Square Yard			**742.5**

Design No. 3

Bit. Surface	32 BTU/yd^3/in	@6.5"	208*
(Bit. Surface	137.5 BTU/yd^2/in	@6.5"	(893.8)**

Crushed Rock Base

a) Production	3.2		
b) Transportation	3.8		
	7.0	@4.5"	31.5

Sand Subbase

a) Production	.55		
b) Transportation	.31		
	.86	@20"	17.2

Total Energy per Square Yard **256.7*** (942.5)**

Design No. 4

Bit. Surface	32 BTU/yd^2/in	@6.5"	208*
(Bit. Surface	137.5 BTU/yd^2/in	@6.5"	893.8)**

Crushed Rock Base

a) Production	3.2		
b) Transportation	3.8		
	7.0	@7"	63

Total Energy per Square Yard **271.0*** (956.8)**

* Using AC Energy Cost from Asphalt Institute
** Using AC Energy Cost from DOT

DISCUSSION

There is enough data available to start to consider energy estimates in pavement construction parallel to cost estimates. This paper has presented examples for the major materials used. If graphical procedure is found to be convenient other sets of graphs can be easily developed for different stabilized materials, various maintenance operations (such as sealcoats) and so on. Data for such graphs can be found in the tables presented in this paper and from the references.

In the case of layered pavement it is assumed that a structural design method is available to calculate the individual layer thickness. As shown by the last example energy comparisons can be made between various designs if the materials and thicknesses are known. Again, it should be pointed out that the best solution may be a computerized "pavement management" approach with energy consideration as a subsystem.

One of the big problems still remaining is the large discrepancy in energy requirements to manufacture asphalt. If the Asphalt Institute energy values are accepted, heating and drying of the aggregates will consume the largest quantity of energy. If, on the other hand, the value of DOT is used (Reference 6) the asphalt itself becomes the most energy consuming component in the mix, as it is also in the case of portland cement concrete. Calculations for the layered pavement examples show that the energy needed to construct a bituminous pavement may be 2 to 3 times lower if the

Asphalt Institute value (low value) for asphalt is used while the energy may be about 25-30 percent higher for the asphalt pavement of the high DOT figure is used. Maybe and energy value between the A.I. and the DOT numbers should be used as a compromise.

In spite of some uncertainties, the use of energy data to calculate energy for pavement systems on comparative basis still can be used, especially if only one binding agent (cement or asphalt) is used in construction.

CONCLUSIONS AND RECOMMENDATIONS

(1) This limited study includes energy tabulations and graphical plots for obtaining energy consumed by materials and processes in highway pavement construction.

(2) At this stage simple graphical procedure is suggested for estimating and comparing energy values for different pavement cross-sections.

(3) Further studies are necessary to clarify the proper manufacturing energy needed for asphalt. Also additional energy data from industry should be collected.

(4) A computerized "pavement management" approach should be developed including the energy optimization in the system.

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TABLES

TABLE 1

ENERGY CONSUMPTION IN MATERIALS PROCESSING

Material	English: BTU/ton or unit stated SI: Joule/Newton or other stated unit									
	Reference 1		Reference 2		Reference 3		Reference 4		Reference 5	
	English	SI	English	SI	English	SI	English	SI	English	SI
Steel (Rolled)	4.300×10^7 BTU/ton	2.040×10^7 J/N	2.100×10^7	9.962×10^6	5.290×10^7 BTU/ton	2.509×10^7 J/N	4.300×10^7 BTU/ton	2.040×10^7 J/N	2.5×10^7	1.18×10^7
Cement	2.672×10^6	1.268×10^6	7.570×10^6	3.591×10^6			2.414×10^6	1.145×10^6		
Lumber	5.195×10^3 BTU/bf									
PC Concrete (ton-Newton)			1.343×10^6	6.372×10^5	1.256×10^6	5.958×10^5				
PC Concrete (cy-metre^3)			2.436×10^6	3.362×10^9	2.543×10^6/cy	$3.508 \times 10^9/m^3$				
Crushed or General Agg.	7.167×10^4	3.400×10^4	6.997×10^4	3.319×10^4			7.509×10^4	3.562×10^4		
Natural Agg.			1.498×10^4	7.108×10^3						
Crushed Gravel			4.000×10^4	1.898×10^4						
Lime			6.000×10^6	2.846×10^6					3.8×10^6	1.8×10^6
Asphalt Concrete			5.118×10^5		1.058×10^6	5.019×10^5				

Reference numbers refer to Bibliography
SI = International System   J = Joule   N = Newton   cy = cubic yards   m = metres

TABLE 2

ENERGY CONSUMPTION IN ASPHALTIC MATERIALS PROCESSING
(Ref. 2)

Asphalt: 300 BTU/pound - A.I. 18,600 BTU/pound - DOT

Cutback

Grade	Type (BTU/Gal)			Gal/Ton
	RC	MC	SC	
- 30		70,000		256
- 70	58,800	63,200	72,000	253
- 250	46,200	47,000	58,100	249
- 800	33,800	36,200	44,200	245
-3000	27,500	29,500	30,300	241

Emulsion

Anionic		Cationic	
Type	BTU/Gal	Type	BTU/Gal
RS-1	1950	CRS-1	2020
RS-2	2070	CRS-2	2100
MS-1	1950		
MS-2	2100	CMS-2	2100
MS2-h	2100	CMS-h	2100
SS-1	1980	CSS-1	1980
SS-1h	2100	CSS-1h	2100

TABLE 3

ENERGY CONSUMPTION IN MAKING STEEL BARS
(Ref. 2)

Steel

Bar Des. No.	Nominal Dia. (in.)	Unit Wt. lb./ft.	BTU/ft.	BTU/Ton
2	0.250	0.167	1,754	$21x10^6$
3	0.375	0.375	3,948	$21x10^6$
4	0.500	0.668	7,014	$21x10^6$
5	0.625	1.043	10,950	$21x10^6$
6	0.750	1.502	15,770	$21x10^6$
7	0.875	2.044	21,460	$21x10^6$
8	1.000	2.670	28,040	$21x10^6$

TABLE 4

BTU EQUIVALENTS FOR DIFFERENT TYPES OF FUEL

Fuel	English Units (BTU/Unit)	SI Units
Gasoline	125,000 BTU/gal.	3.484×10^{10} Joule/m^3
Kerosene	135,000 "	3.763×10^{10} "
Fuel Oil No. 1 (APL 42)	135,000 "	3.763×10^{10} "
Fuel Oil No. 2 (APL 35) Diesel	139,000 "	3.874×10^{10} "
Fuel Oil No. 3 (APL 28)	143,000 "	3.986×10^{10} "
Fuel Oil No. 4 (APL 20)	148,500 "	4.139×10^{10} "
Fuel Oil No. 5 (APL 14)	152,000 "	4.236×10^{10} "
Fuel Oil No. 6 (APL 10)	154,500 "	4.306×10^{10} "
Propane Gas	91,000 "	2.536×10^{10} "
Butane Gas	100,000 "	2.787×10^{10} "
Natural Gas	1,000 BTU/cu. ft.	3.726×10^{7} "
Coal		

TABLE 5

ENERGY REQUIREMENTS FOR ROADWAY PAVEMENTS

Operation	English Units	SI Units
Hot Mix Plant	19,820 BTU/ton	2.305×10^4 Joule/kg
Dryer-Drum Asphalt Mixing Plant	16,550 BTU/ton	1.925×10^4 "
Cold Mixes	6,630 BTU/ton	7.711×10^3 "
PCC Plants (Load & Convey)	4,650 BTU/ton	5.408×10^3 "
(Batching)	1,894 BTU/ton	2.203×10^3 "
	(3,580 BTU/cy)	
Spread & Compact (Hot Mix)	1,670 BTU/ton	1.942×10^3 "
Place, Spread, Compact & Float Finish PC Concrete	2,773 BTU/ton	3.225×10^3 "
	(5,240 BTU/cy)	
Spread & Compact Pre-Mixed Granular & Stabilized Bases	17,000 BTU/ton	1.977×10^4 "
Aggregate Spreading (12' width) for Sealcoats	9.4 BTU/yd^2	1.186×10^3 Joule/m^2
Blade Mixing (assume 12 passes/inch)	400 BTU/yd^2-in.	5.047×10^4 Joule/m^2
Cutting Concrete Joints	280 BTU/ft.	9.692×10^5 Joule/m

BITUMINOUS CONCRETE

FIGURES

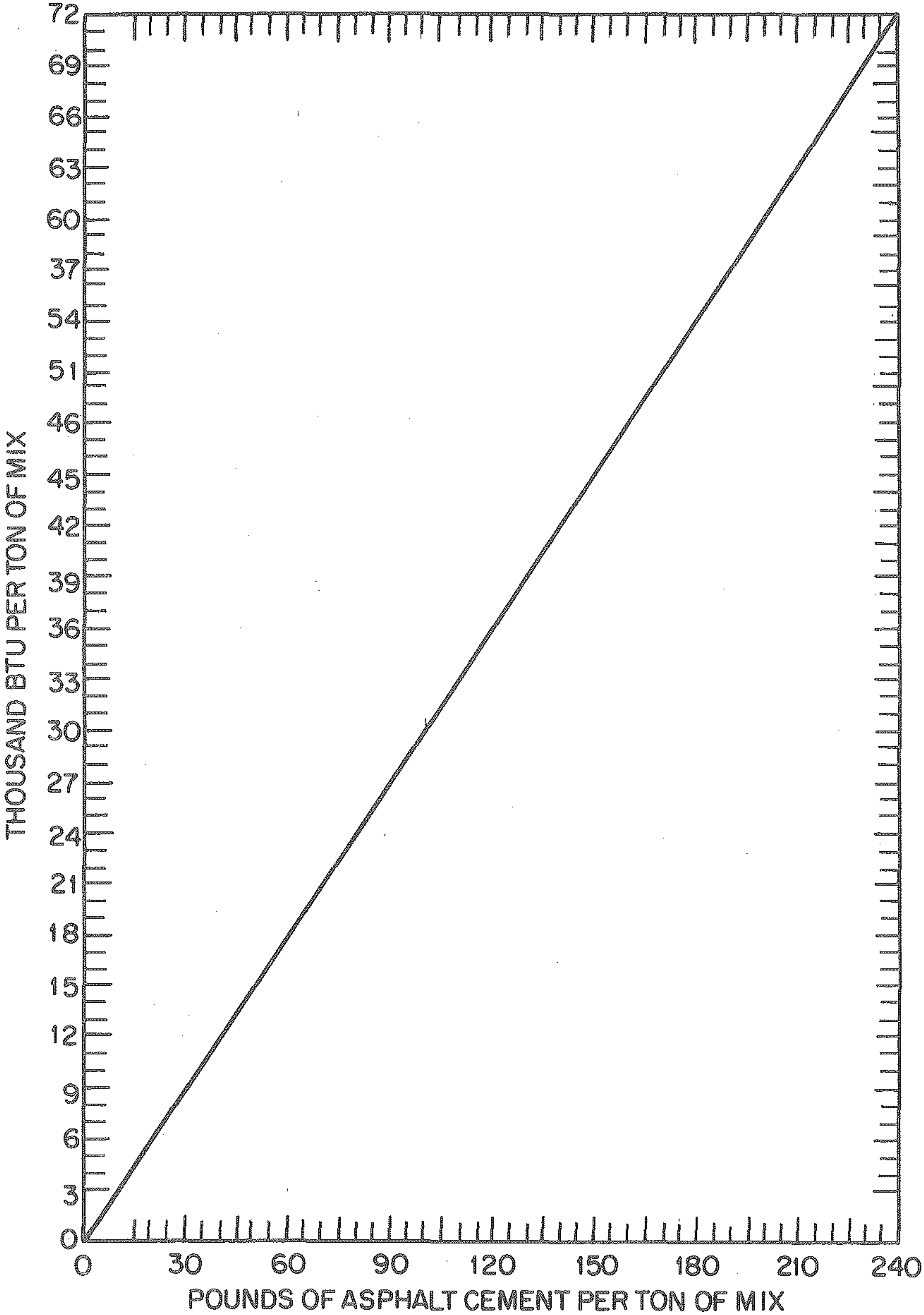

Figure 1. Energy for asphalt manufacture (Asphalt Institute data).

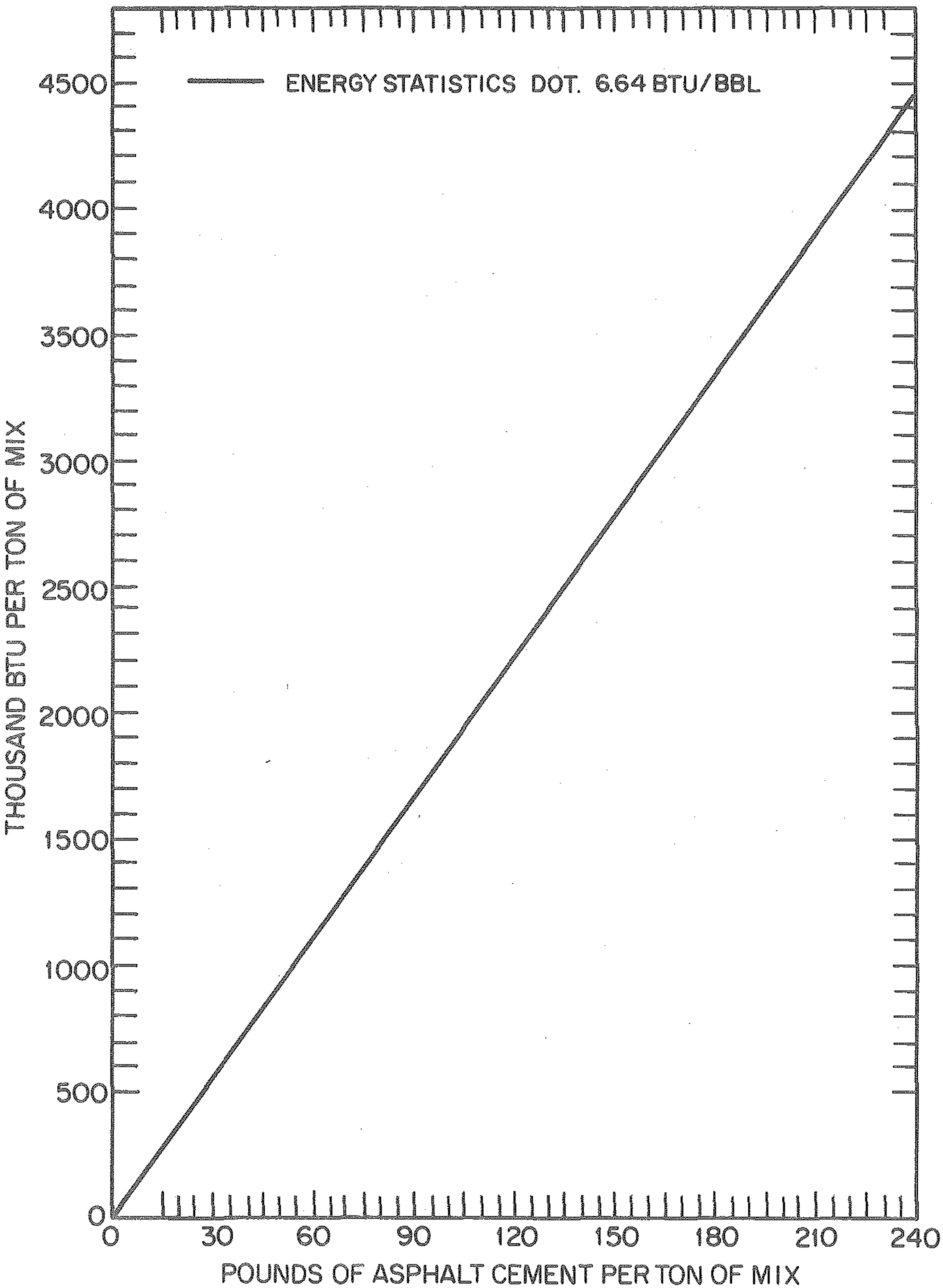

Figure 1A. Energy of asphalt manufacture (DOT. data)

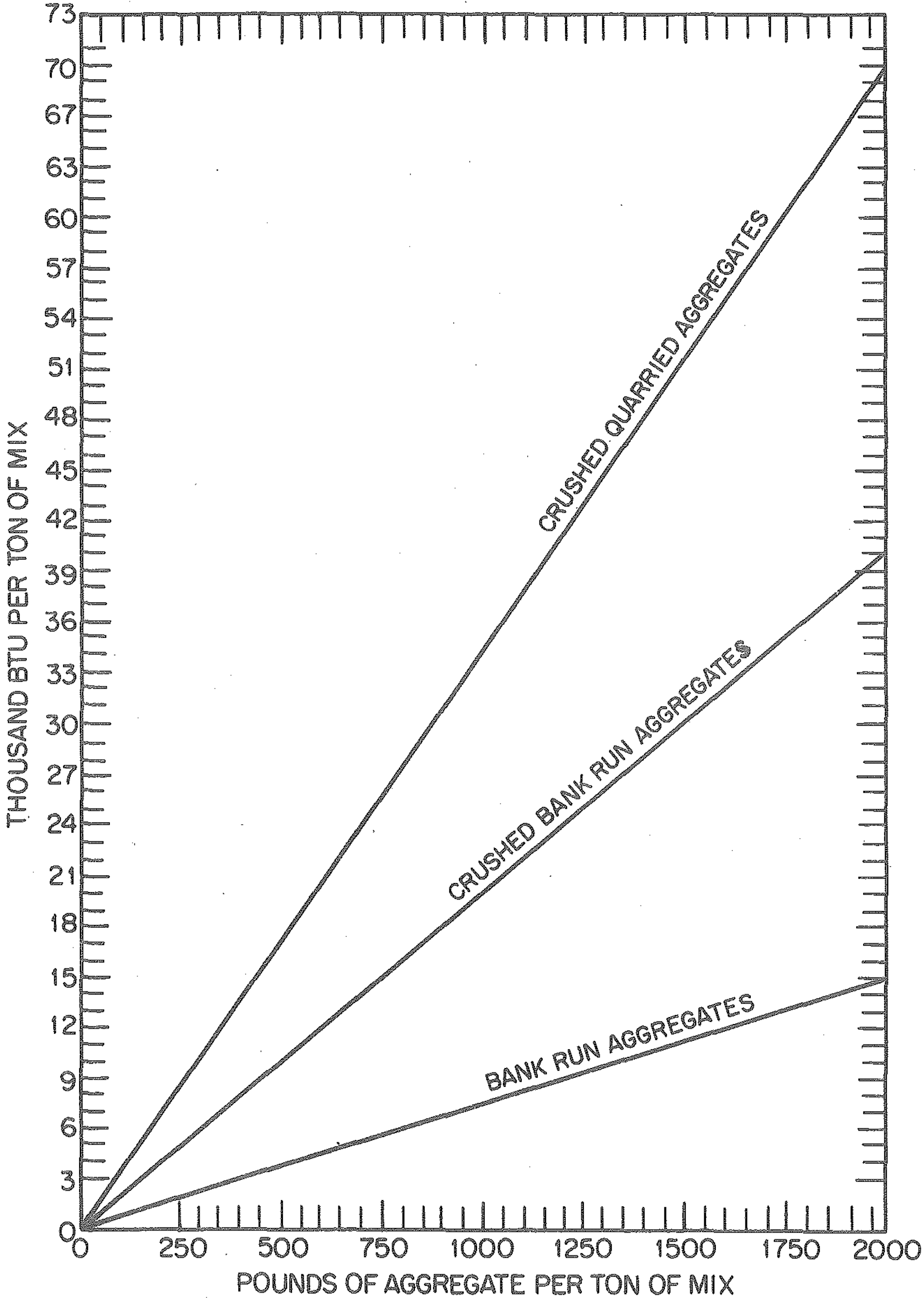

Figure 2. Aggregate production energy.

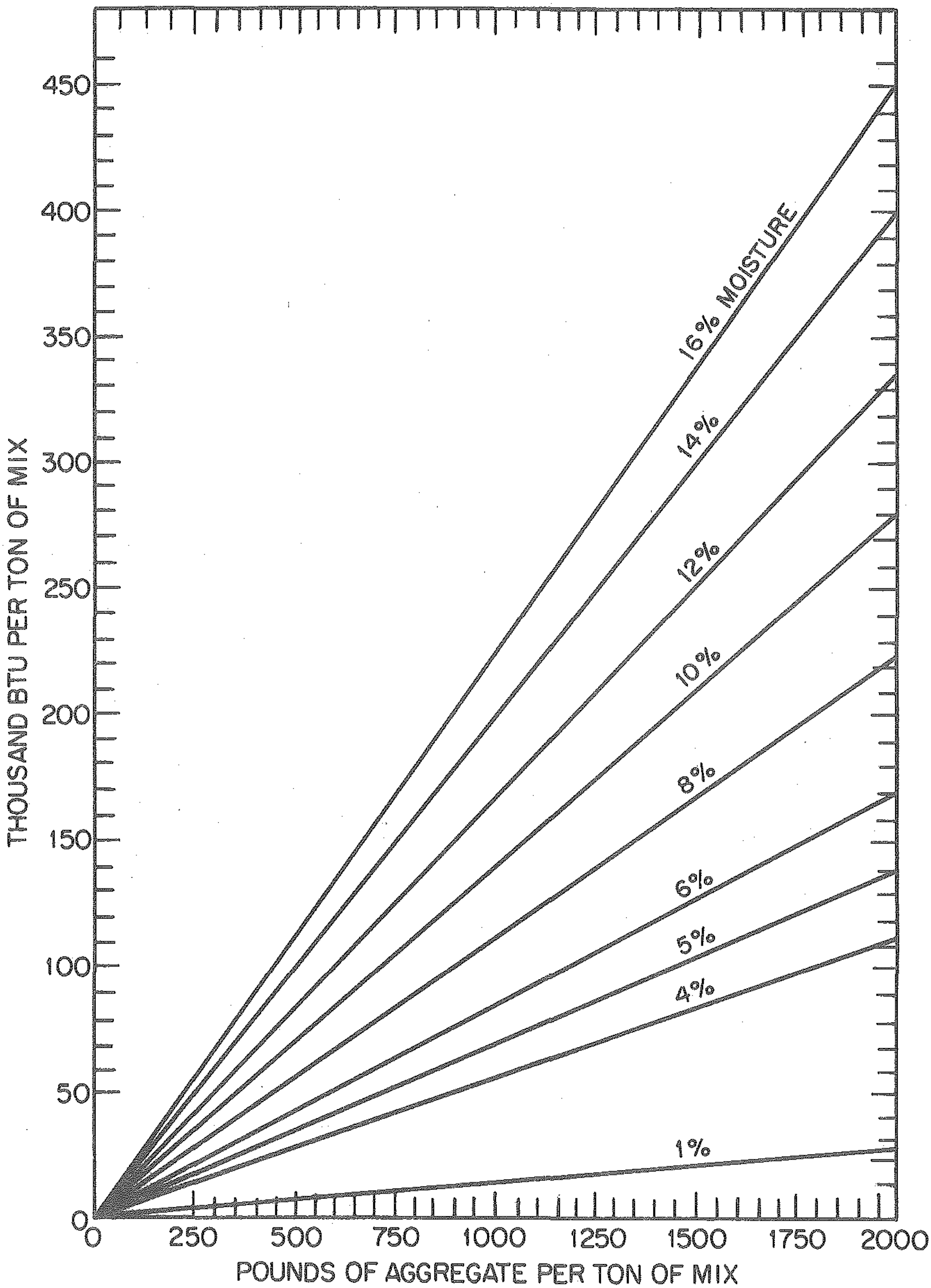

Figure 3. Aggregate drying energy.

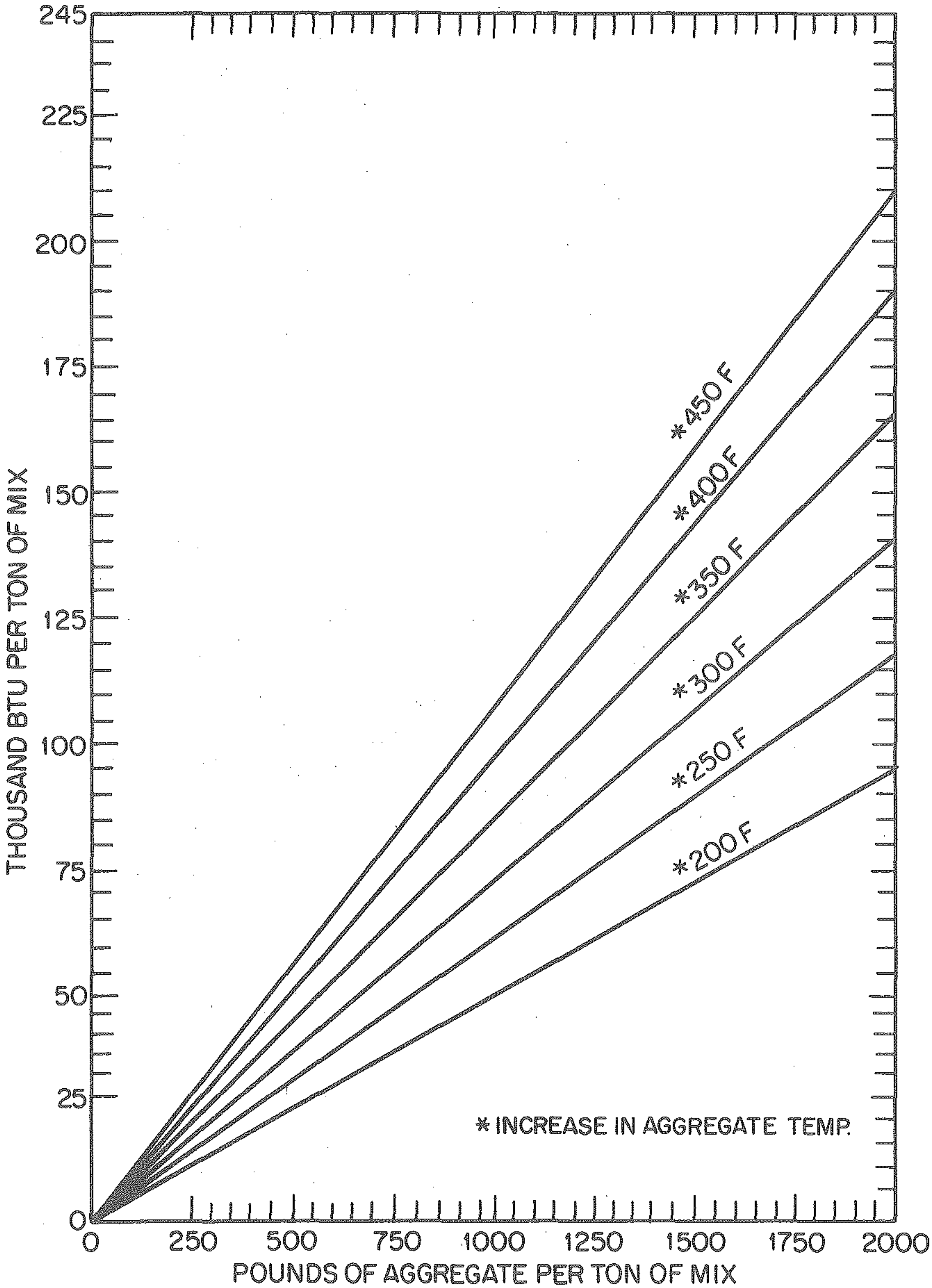

Figure 4. Aggregate heating energy.

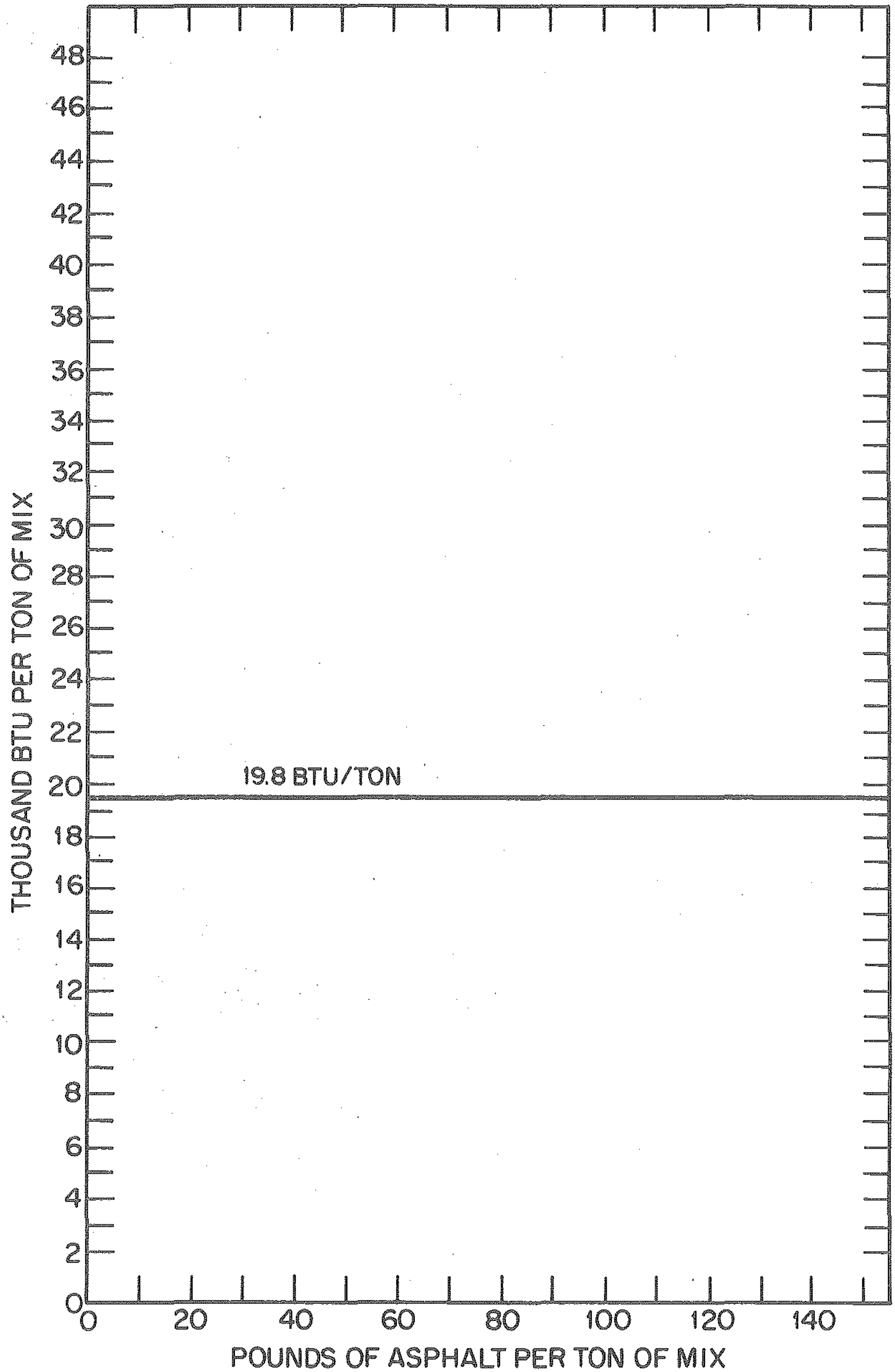

Figure 5. Mixing and miscellaneous plant operations

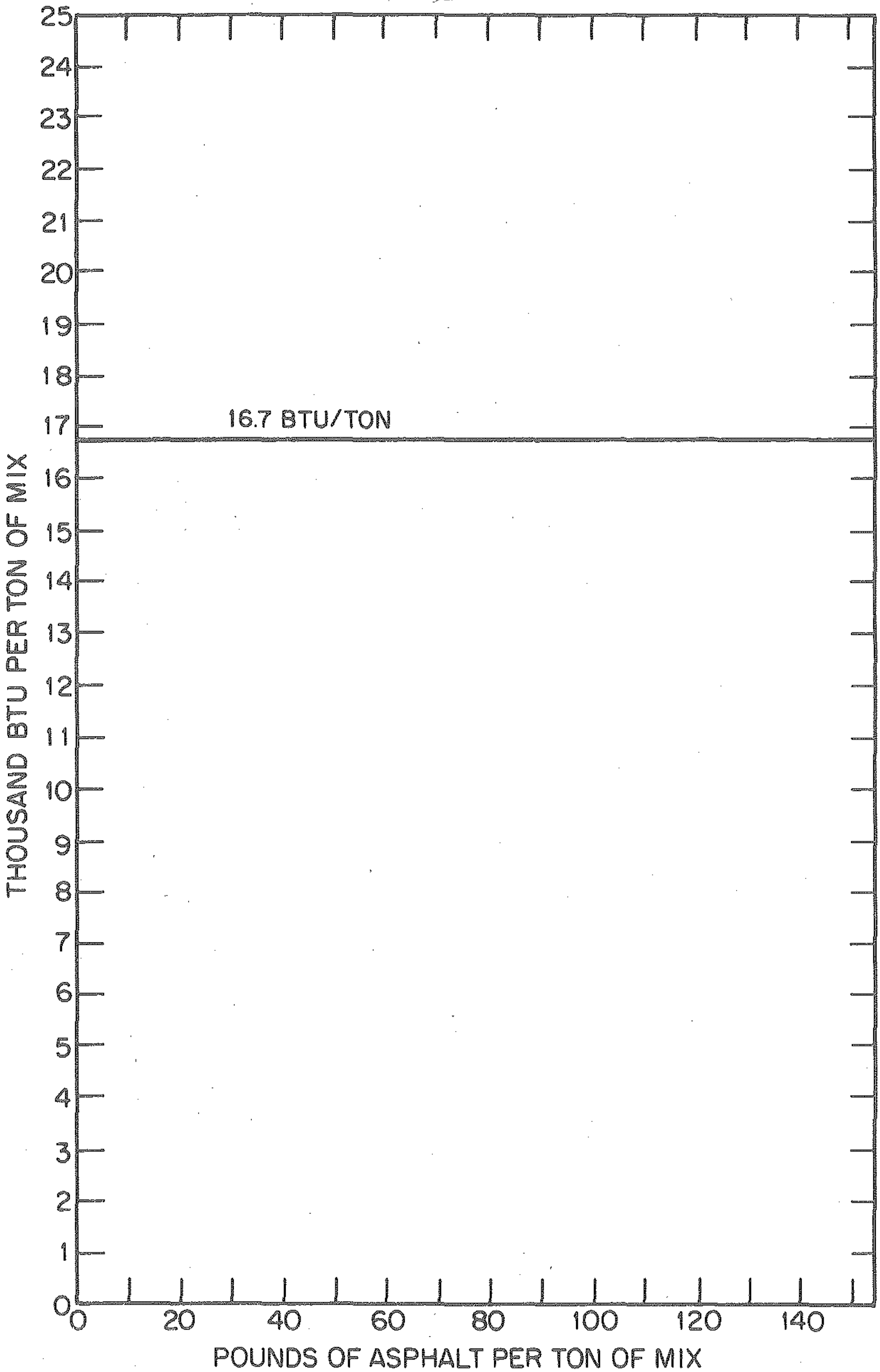

Figure 5A. Placement energy, bituminous mix.

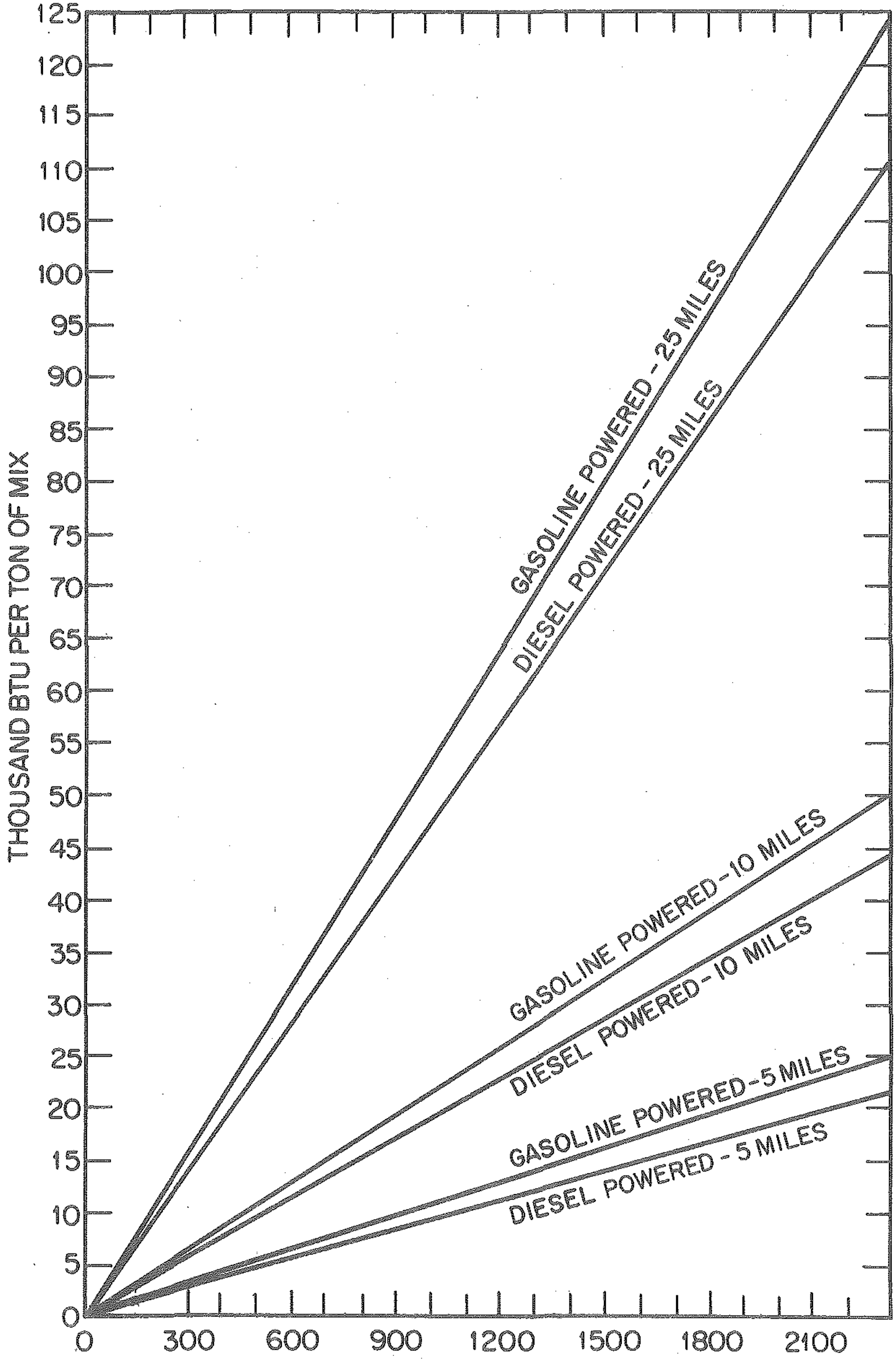

Figure 6A. Transportation energy for mix components, 3 axle single units

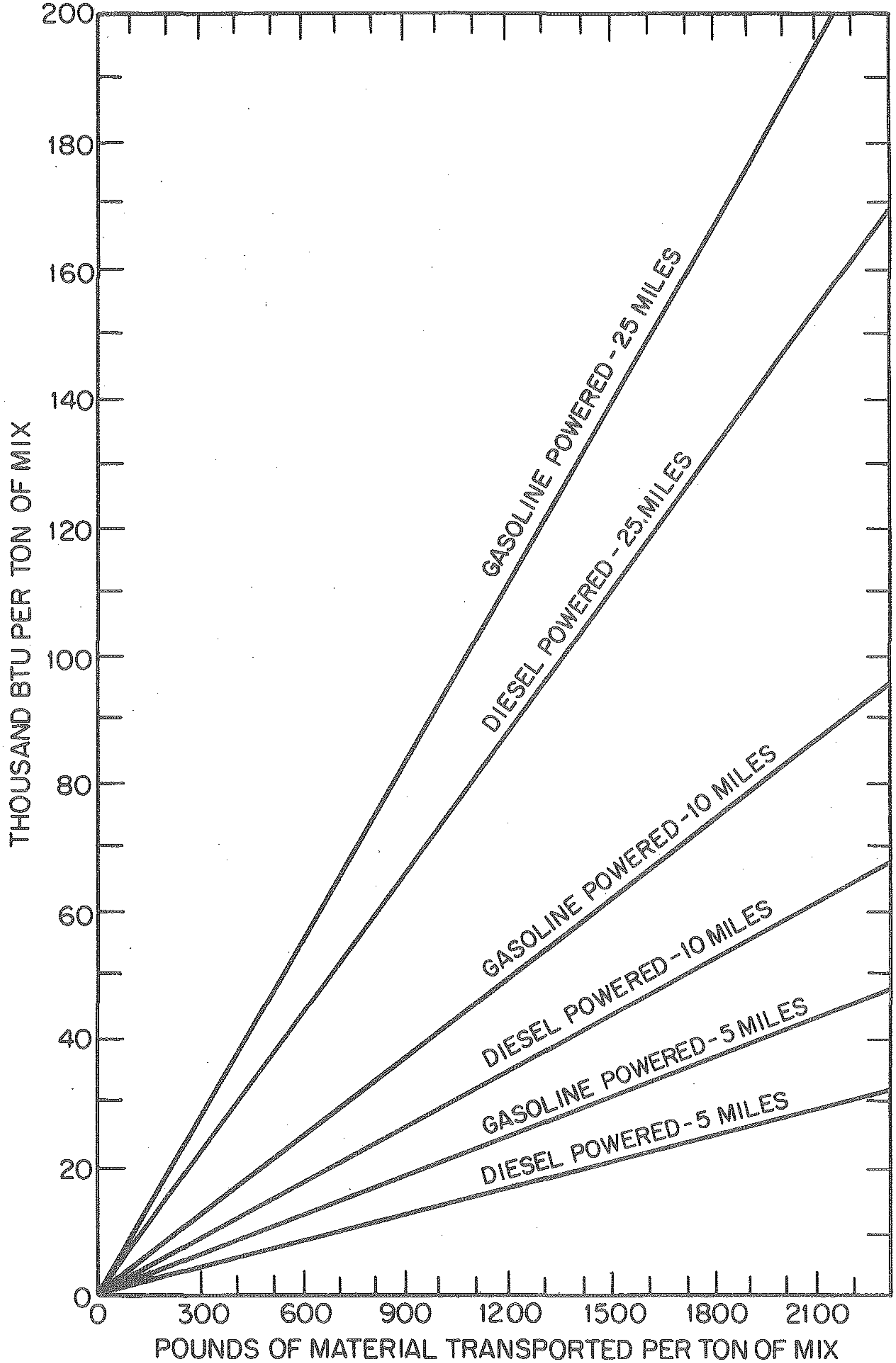

Figure 6B. Transportation energy - 3 axle Comb.

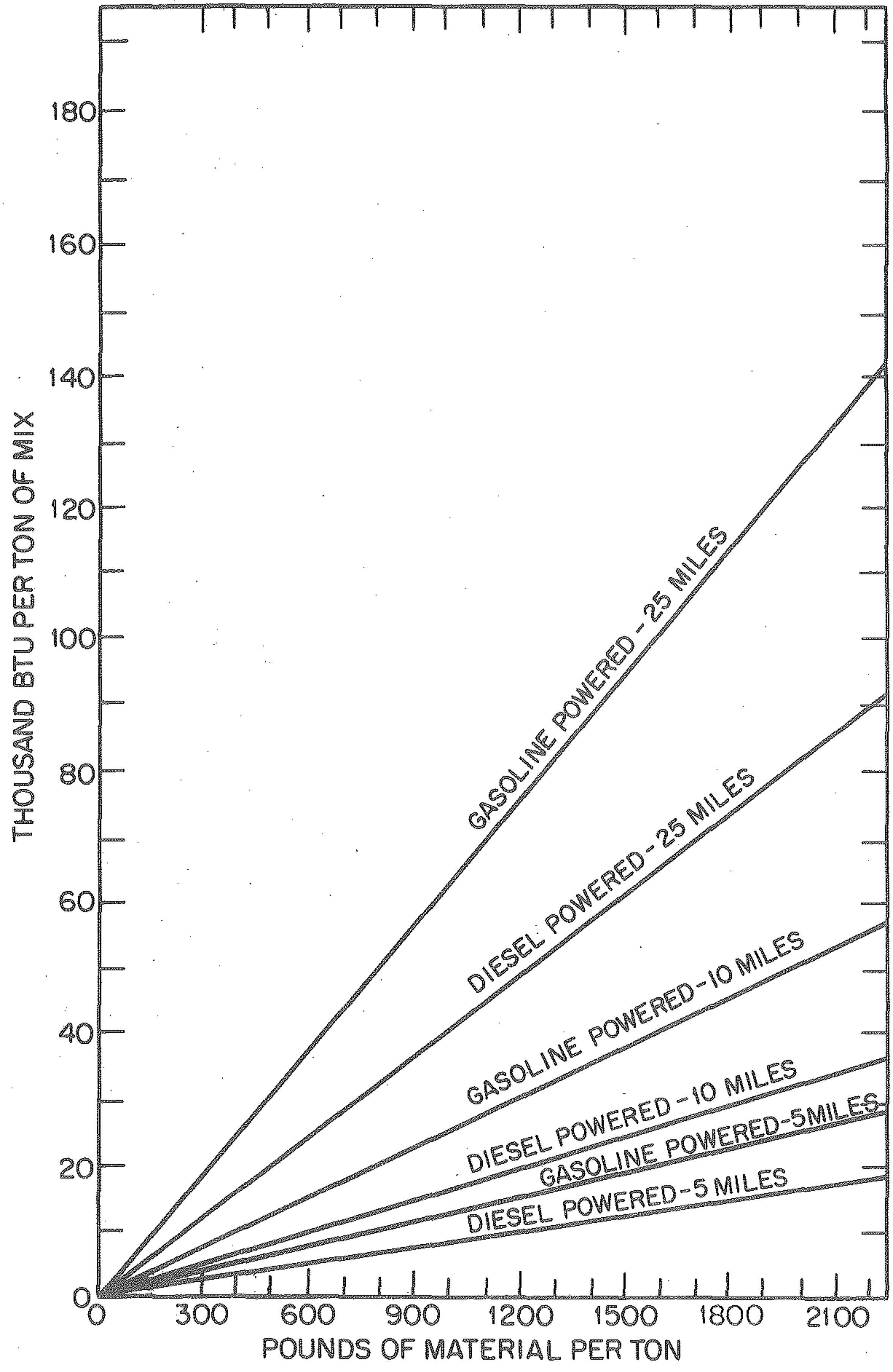

Figure 6C. Transportation energy - 4 axle comb.

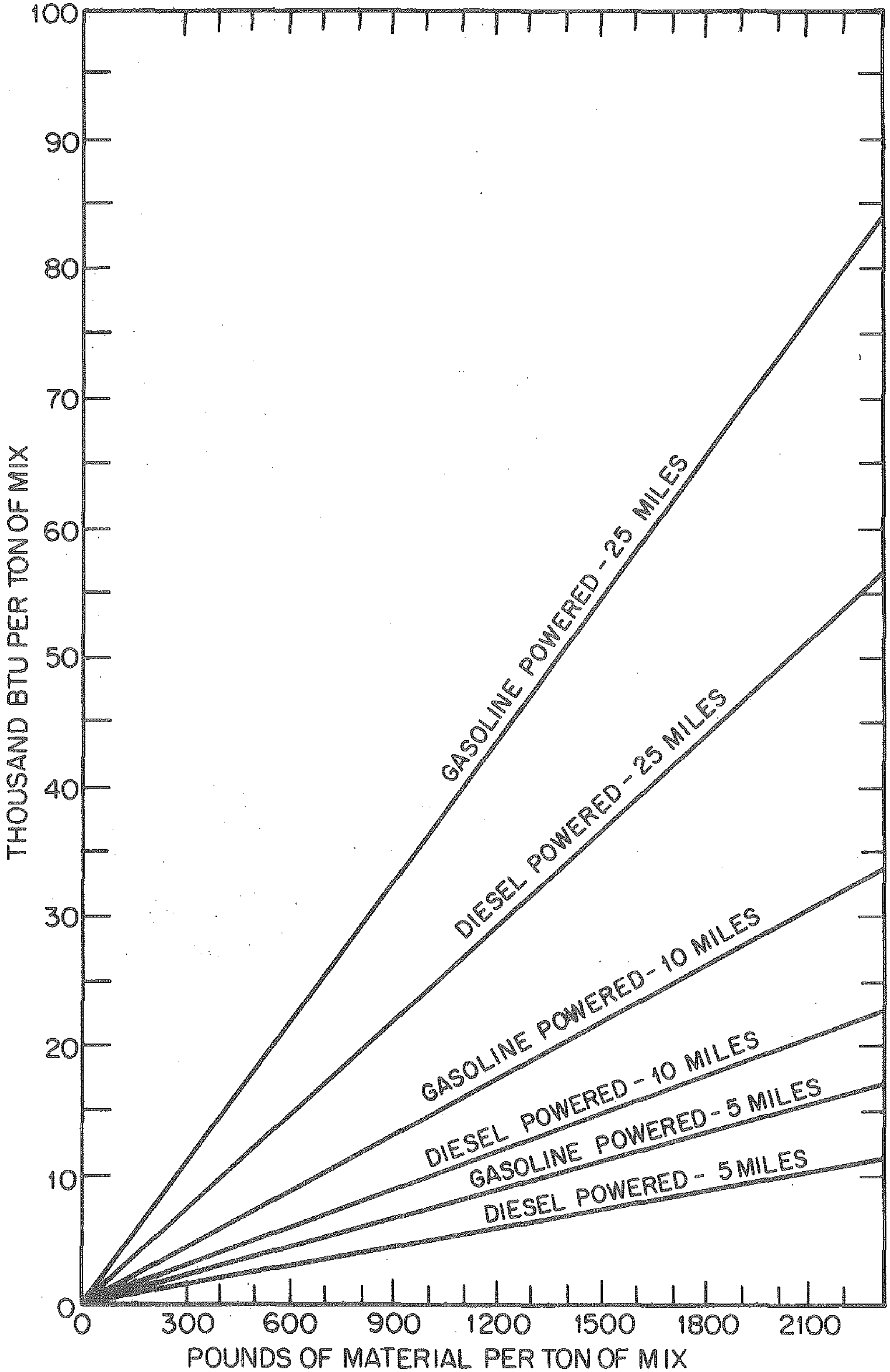

Figure 6D. Transportation energy - 5 axle comb.

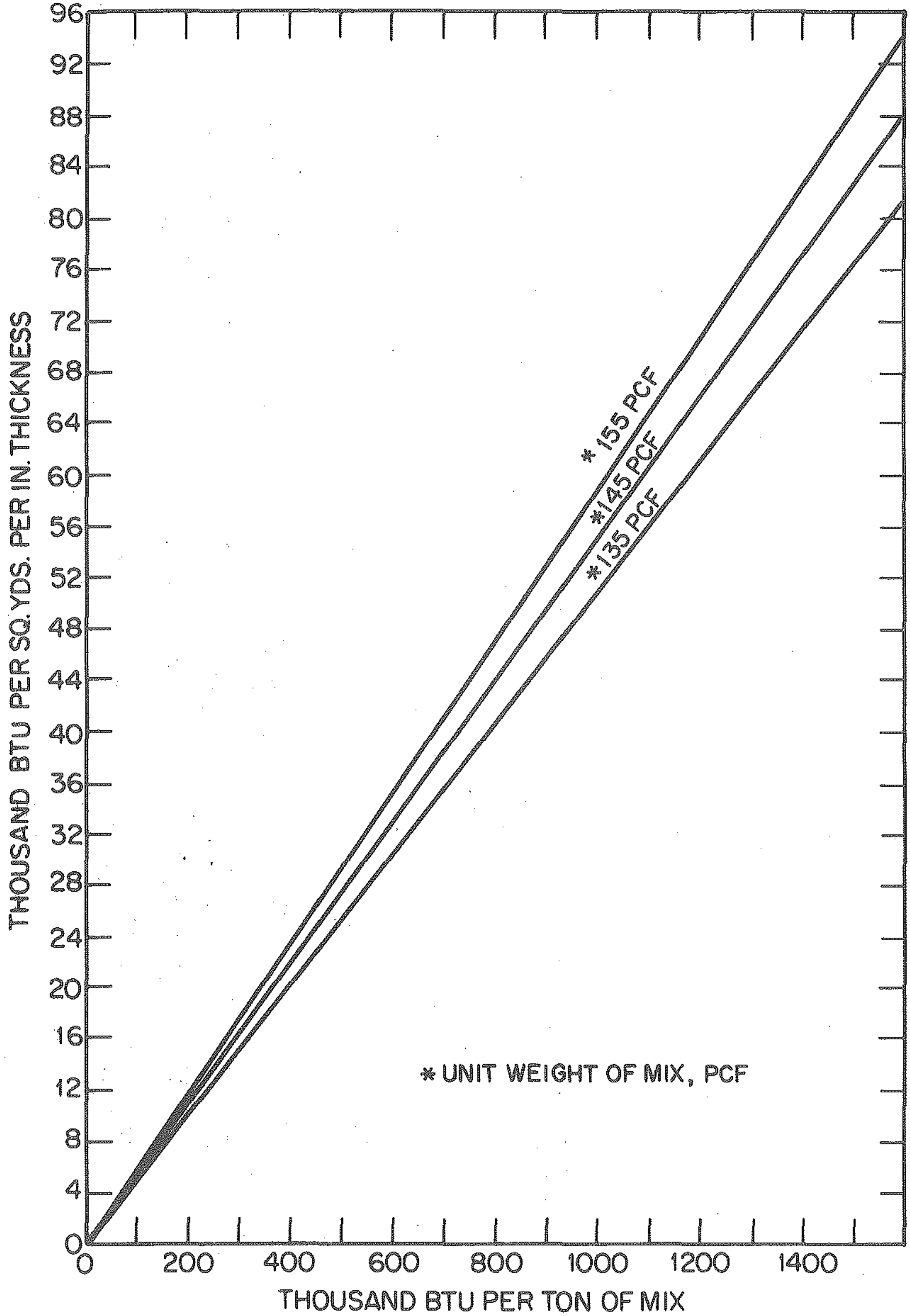

Figure 7. Conversion chart to BTU's per sq.yd per inch.

PORTLAND CEMENT CONCRETE

FIGURES

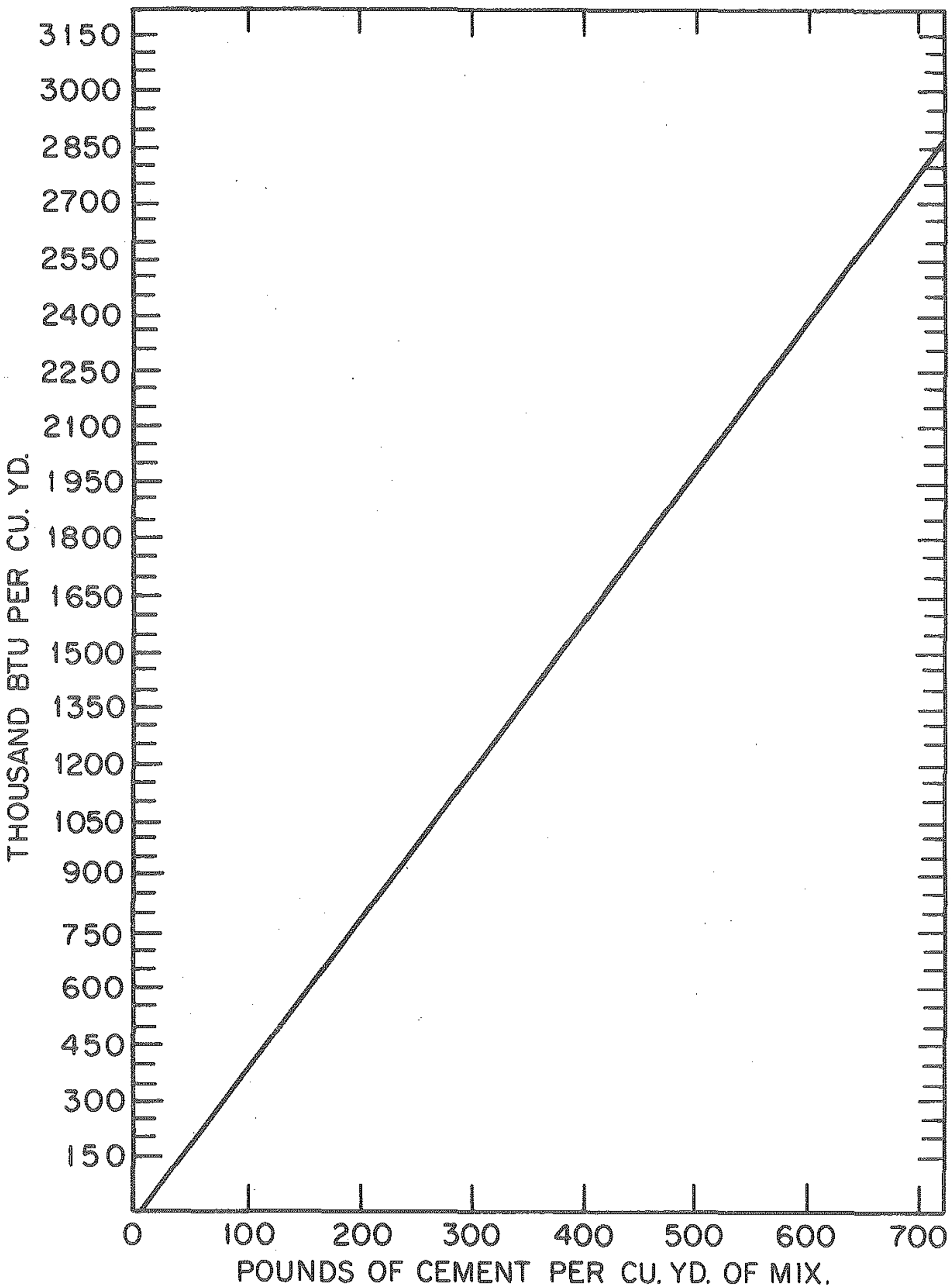

Figure A. Energy for manufacture - Portland Cement

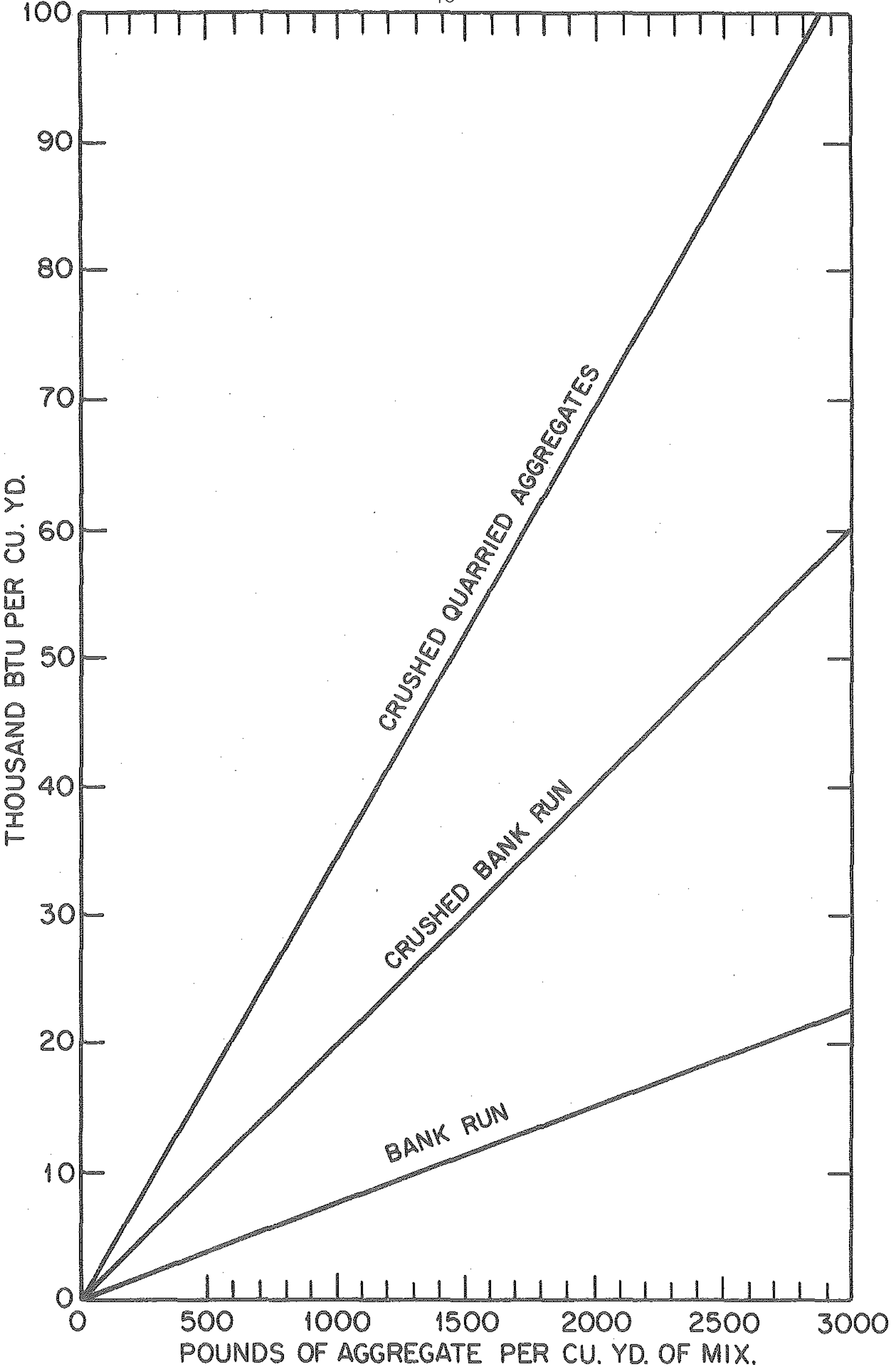

Figure B. Aggregate production energy.

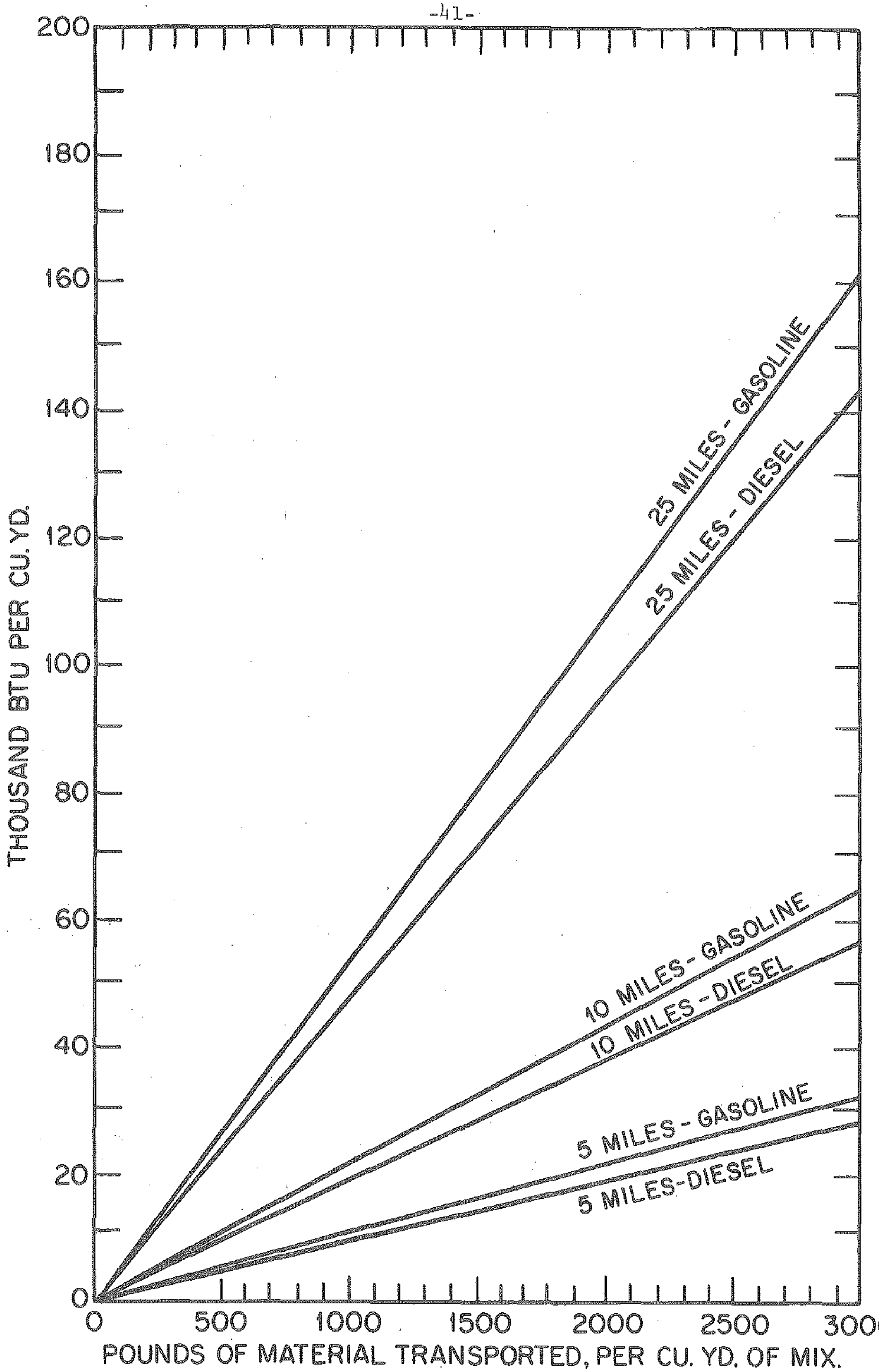

Figure C. Transportation energy for mix components, 3 axle single unit.

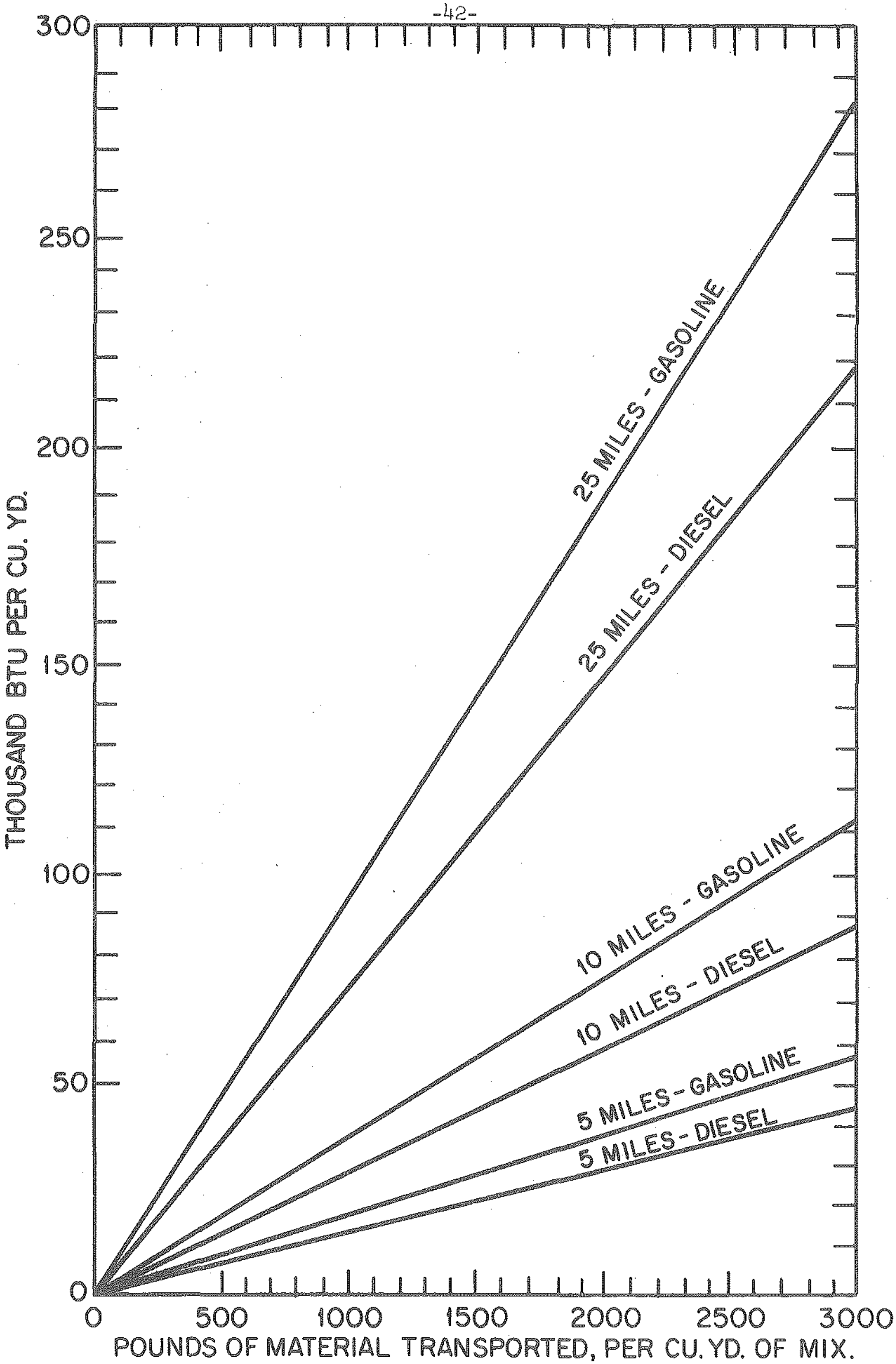

Figure D. Transportation energy for mix. components, 3 axle comb.

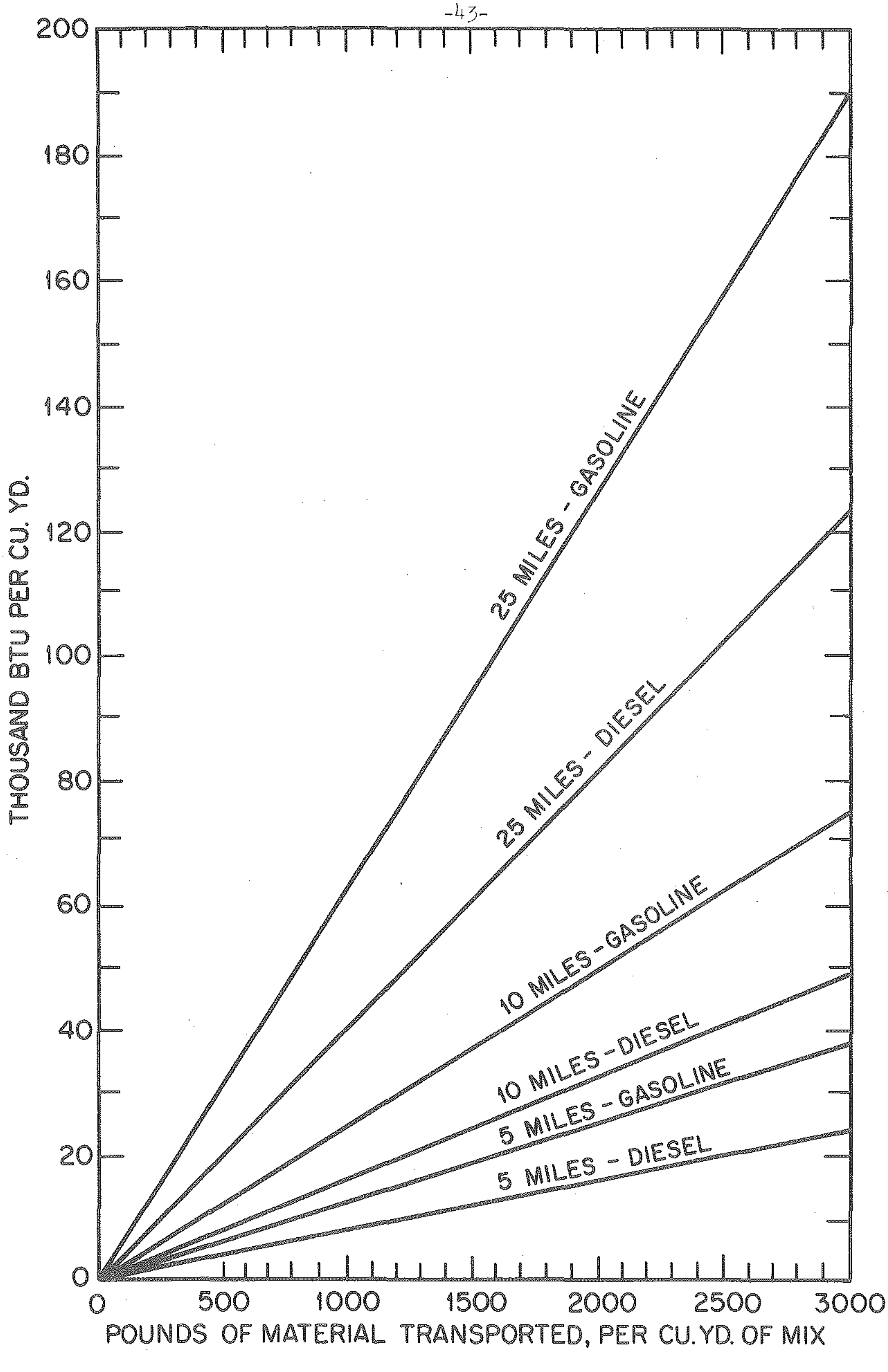

Figure E. Transportation energy for mix components, 4 axle comb.

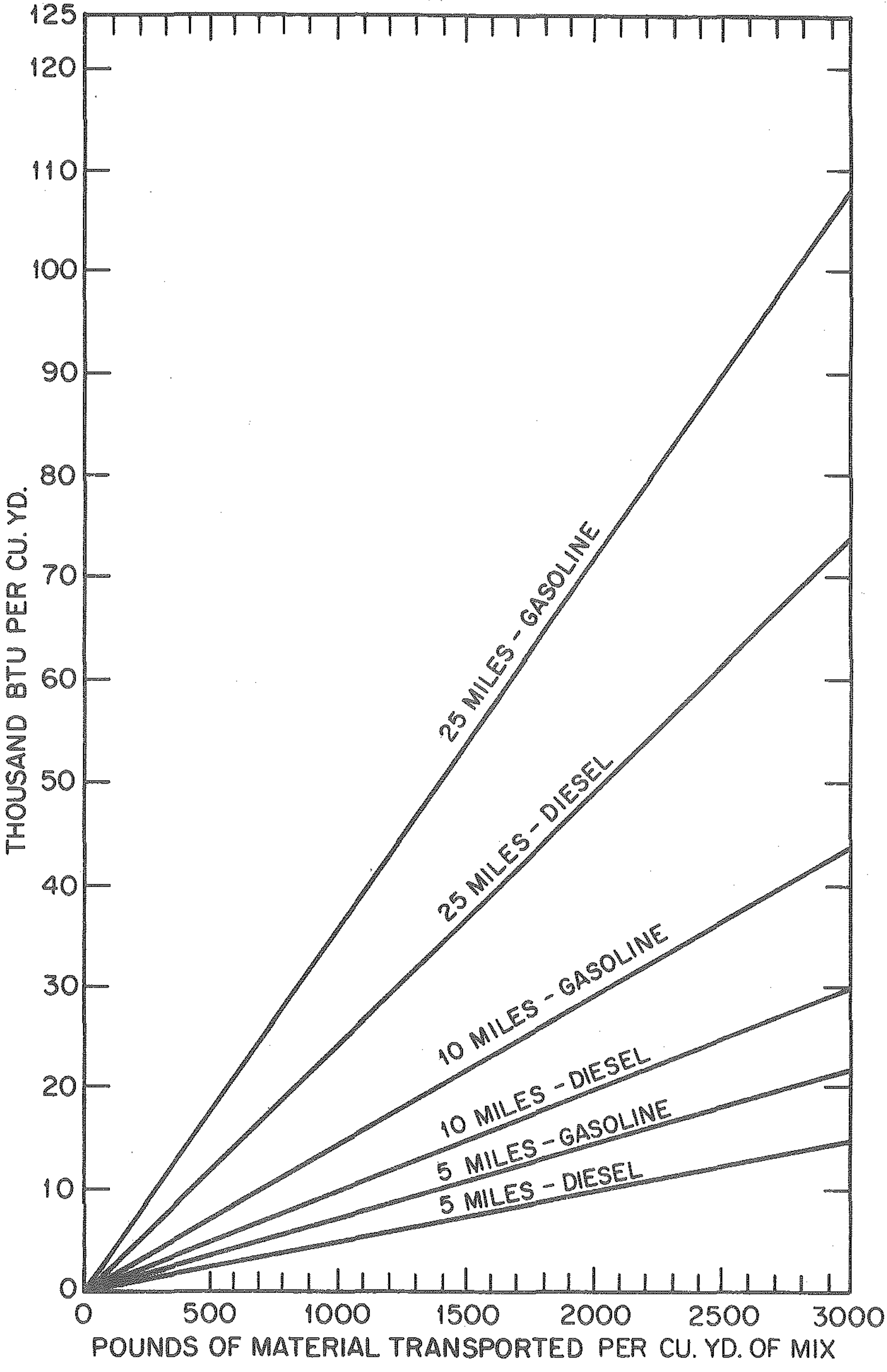

Figure F. Transportation energy for mix components, 5 axle comb.

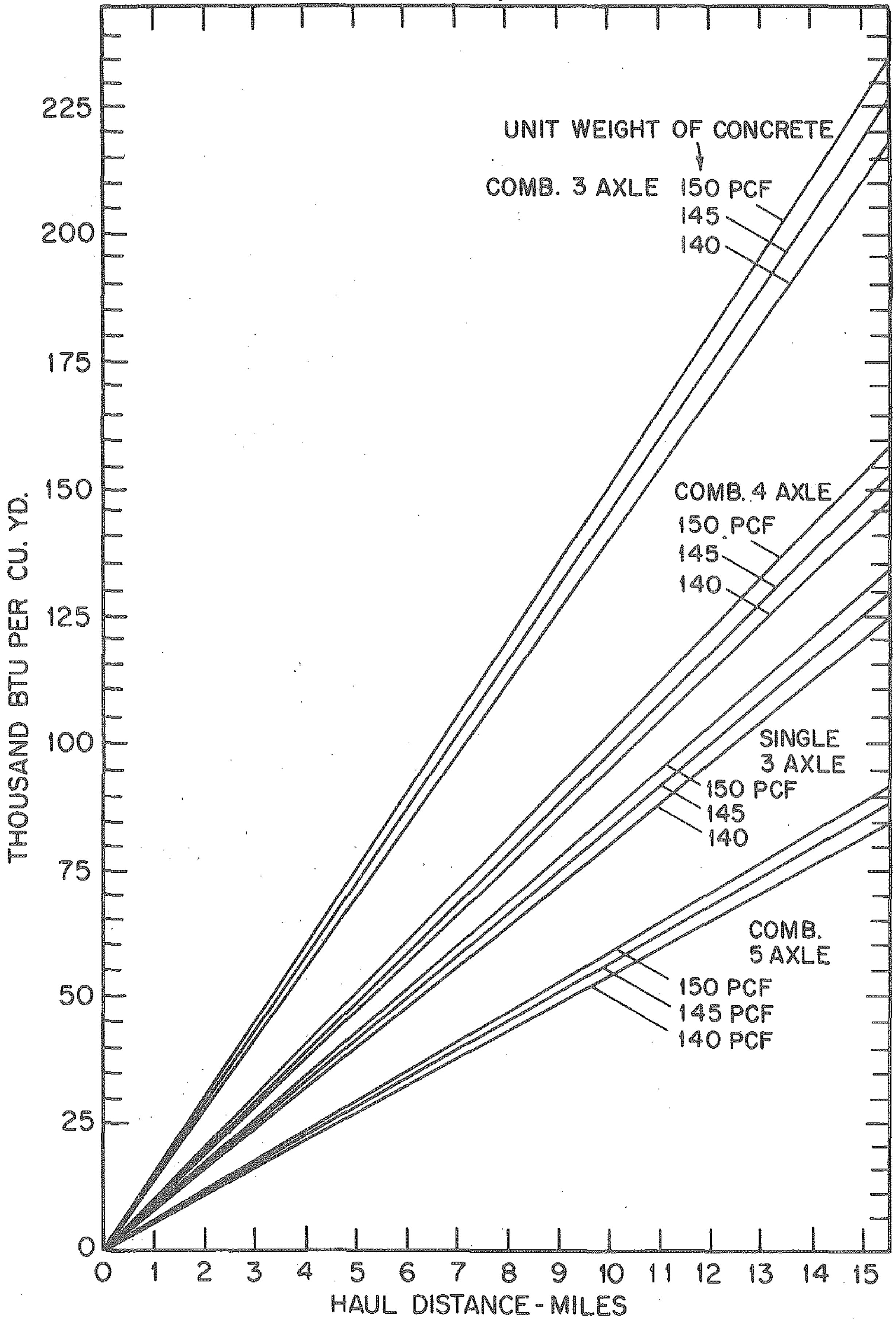

Figure G. Transportation energy for concrete mix, gasoline powered trucks

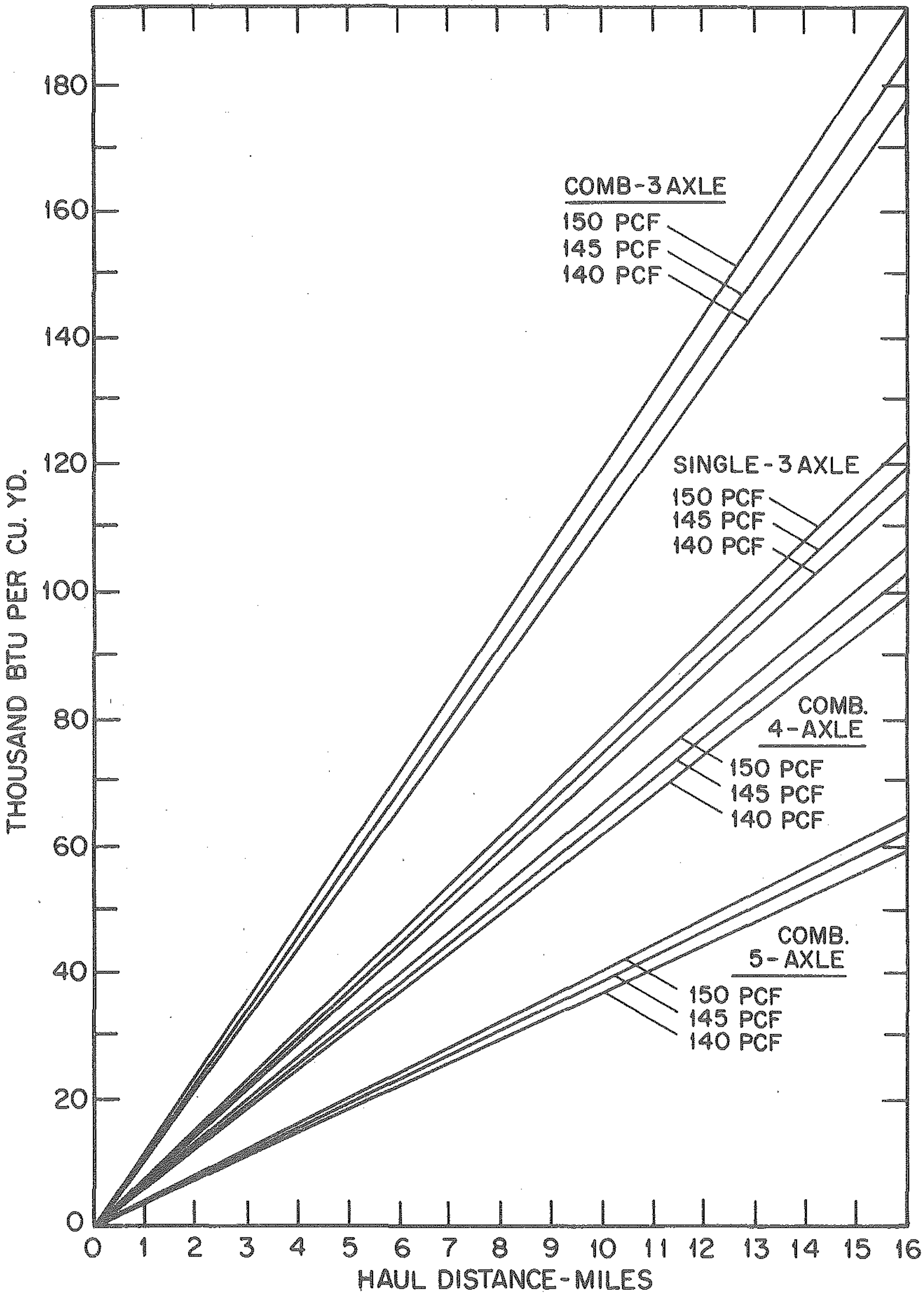

Figure H. Transportation energy for concrete mix, diesel powered trucks.

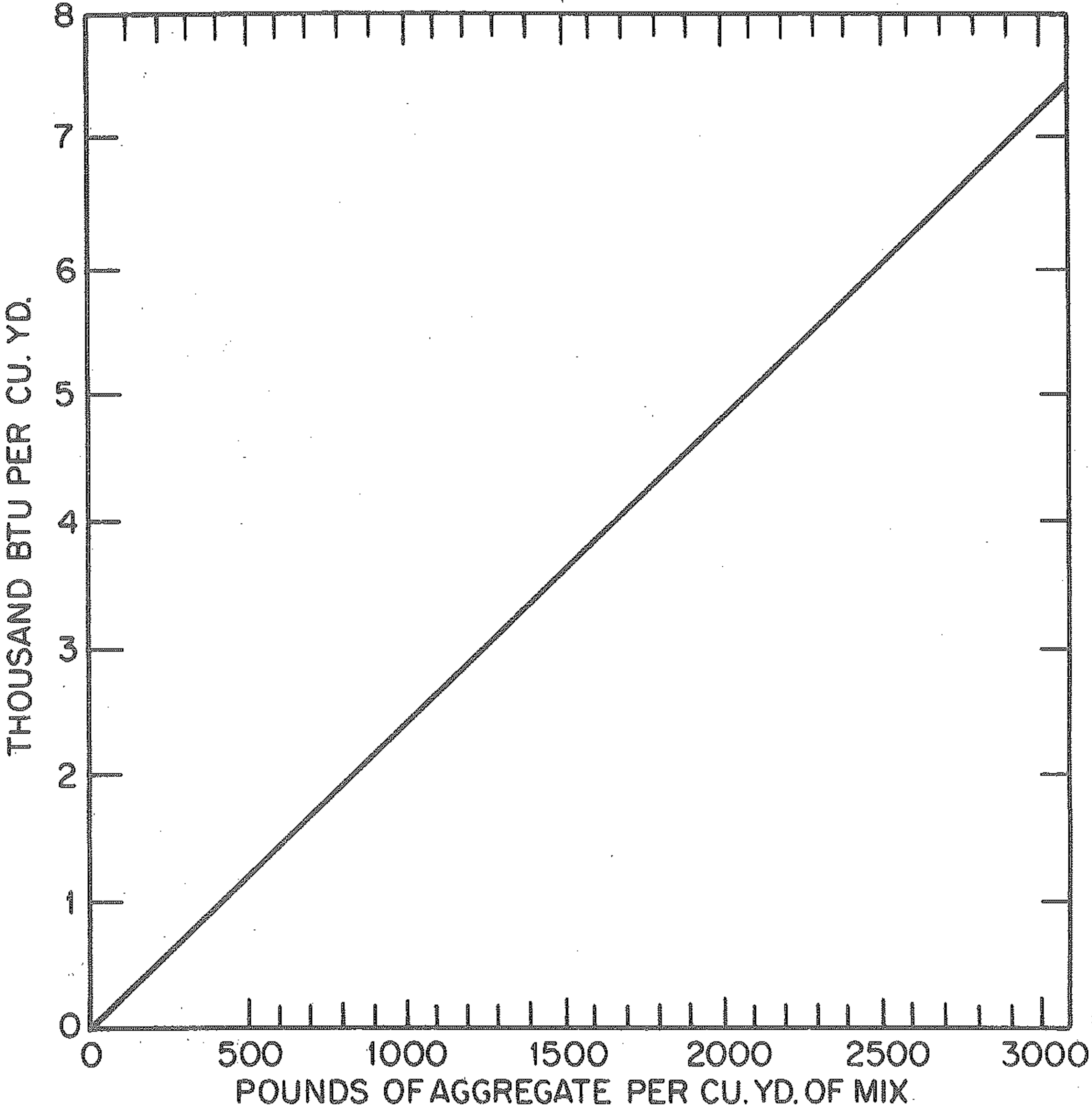

Figure I. Energy for aggregate planning at plant.

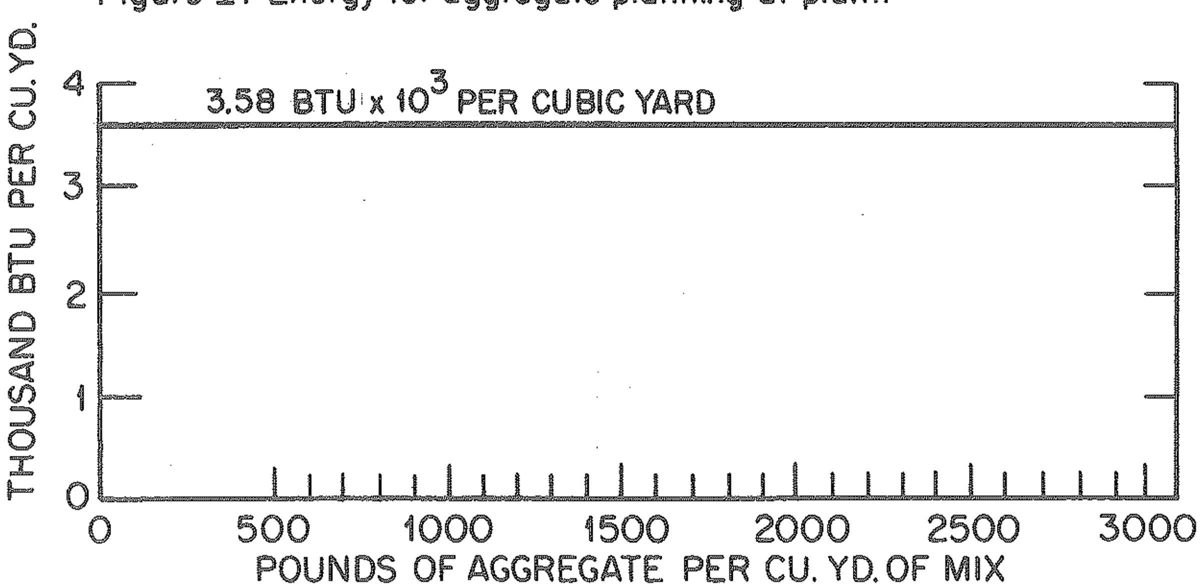

Figure J. Energy for mixing and miscellaneous plant operations.

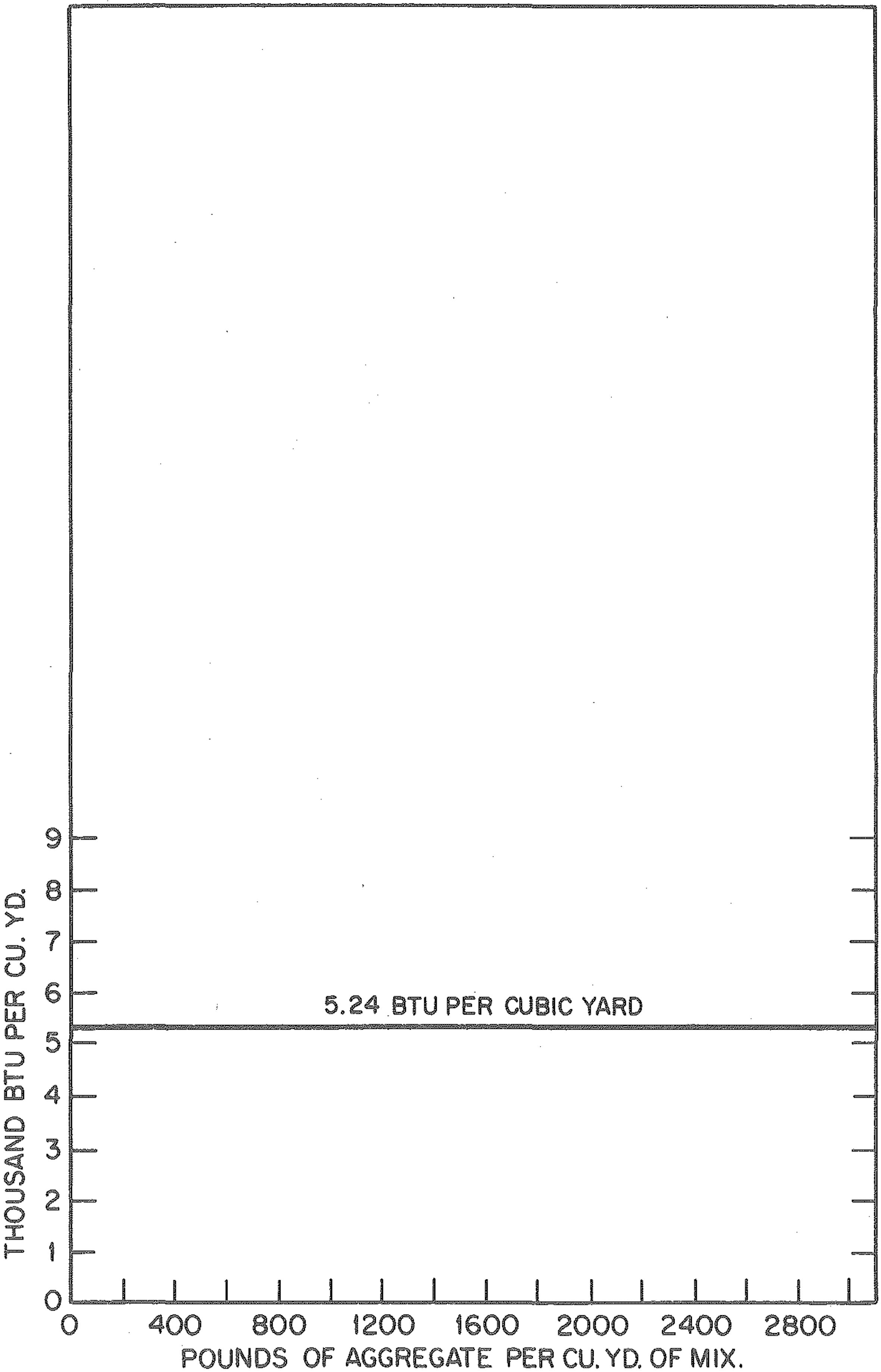

Figure K. Concrete placement energy

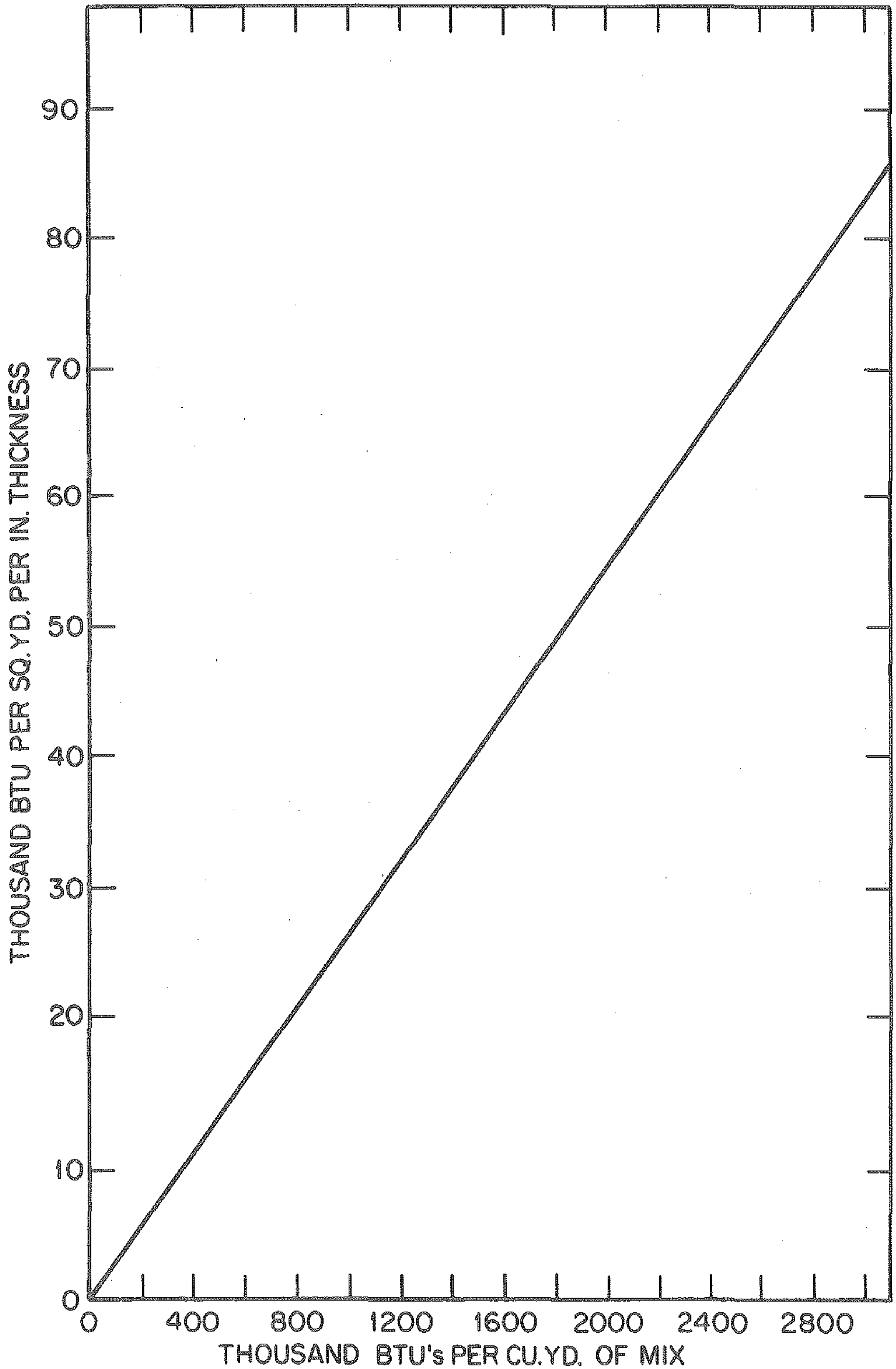

Figure L. Conversion chart to BTU's per sq. yd. per inch.

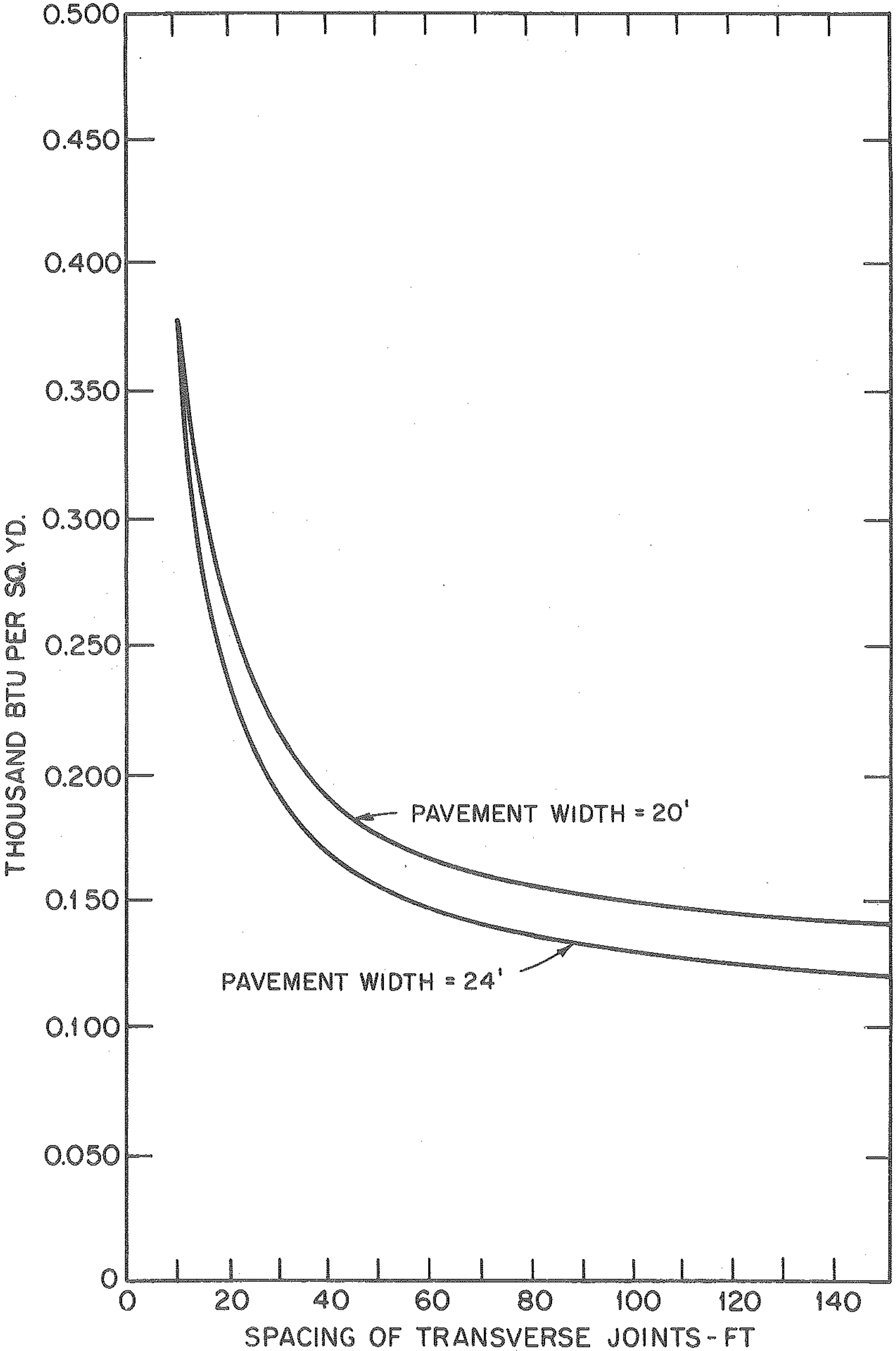

Figure M. Energy for joint sawing, longitudinal and transverse.

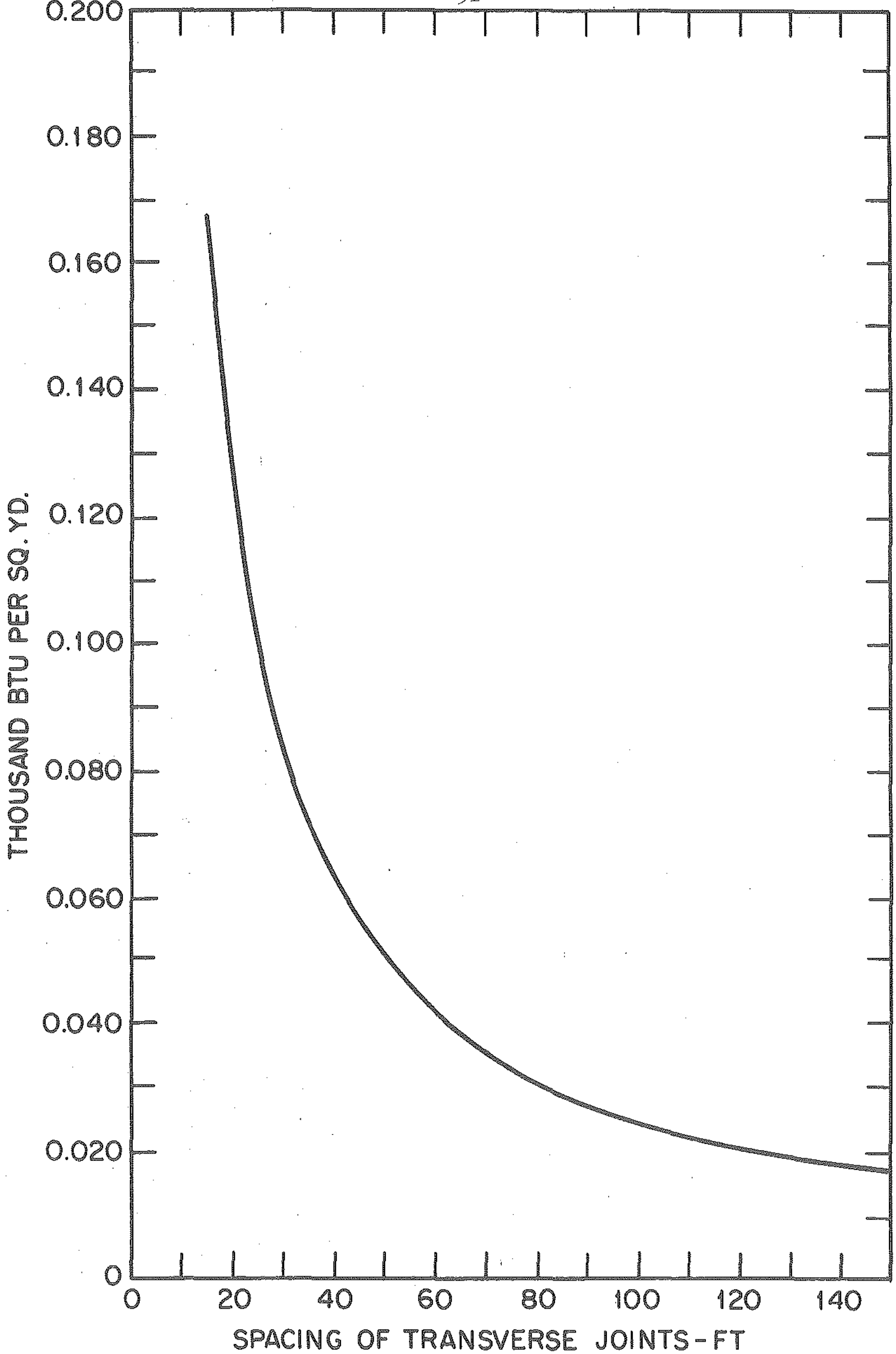

Figure N. Energy of joint sawing-transverse only

GRANULAR BASE

FIGURES

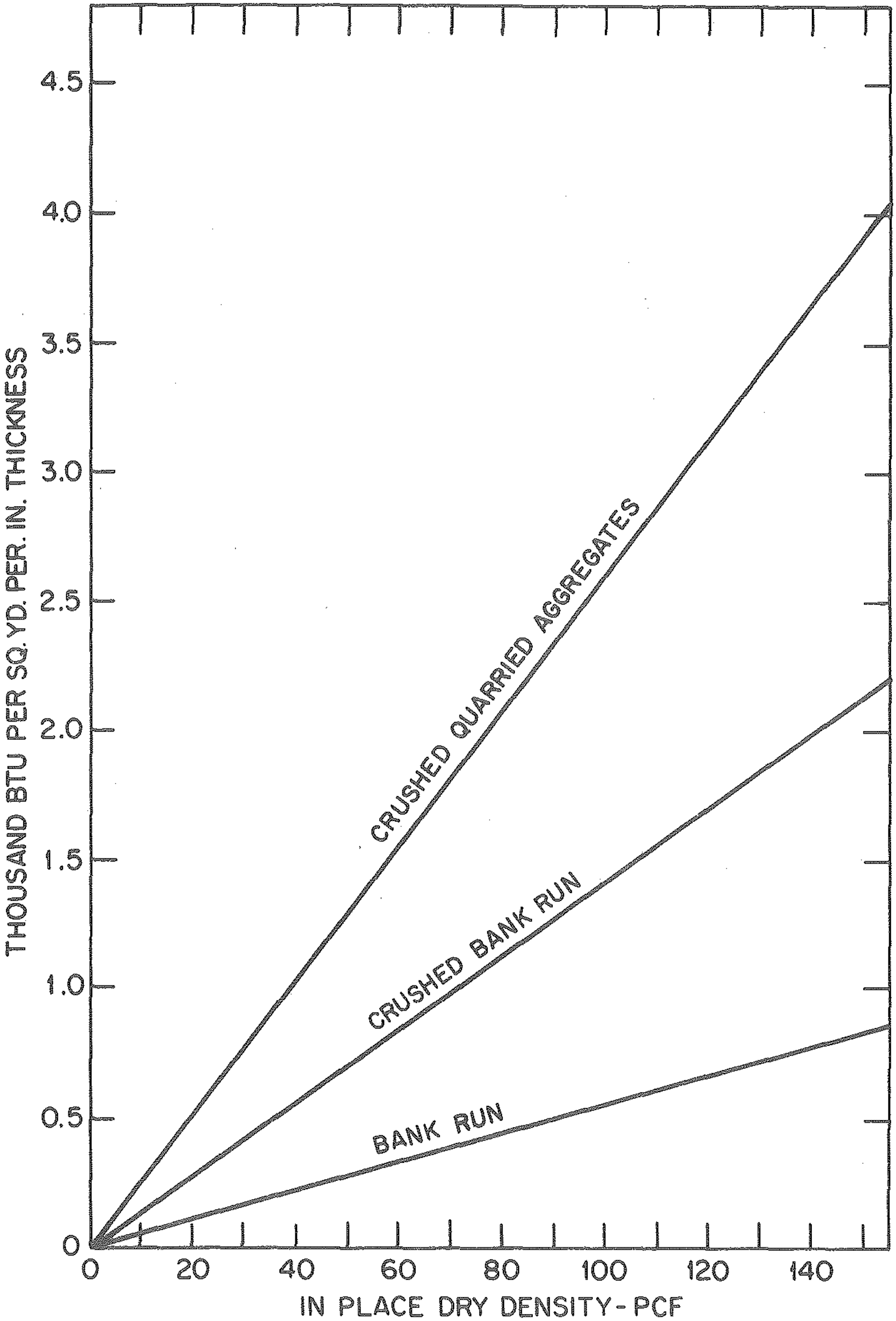

Figure I. Production energy - granular base materials

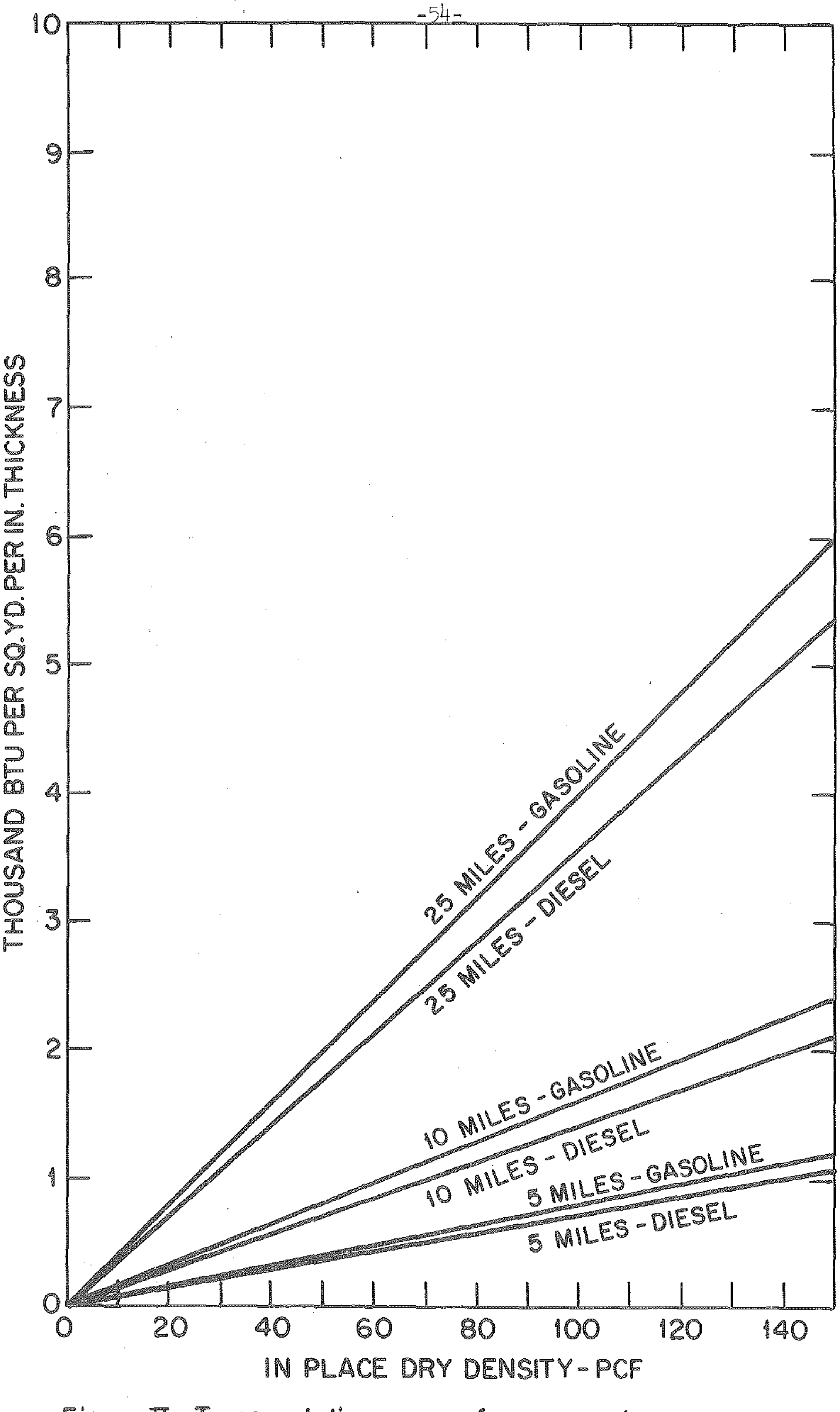

Figure II. Transportation energy for aggregates.
3 axle single unit.

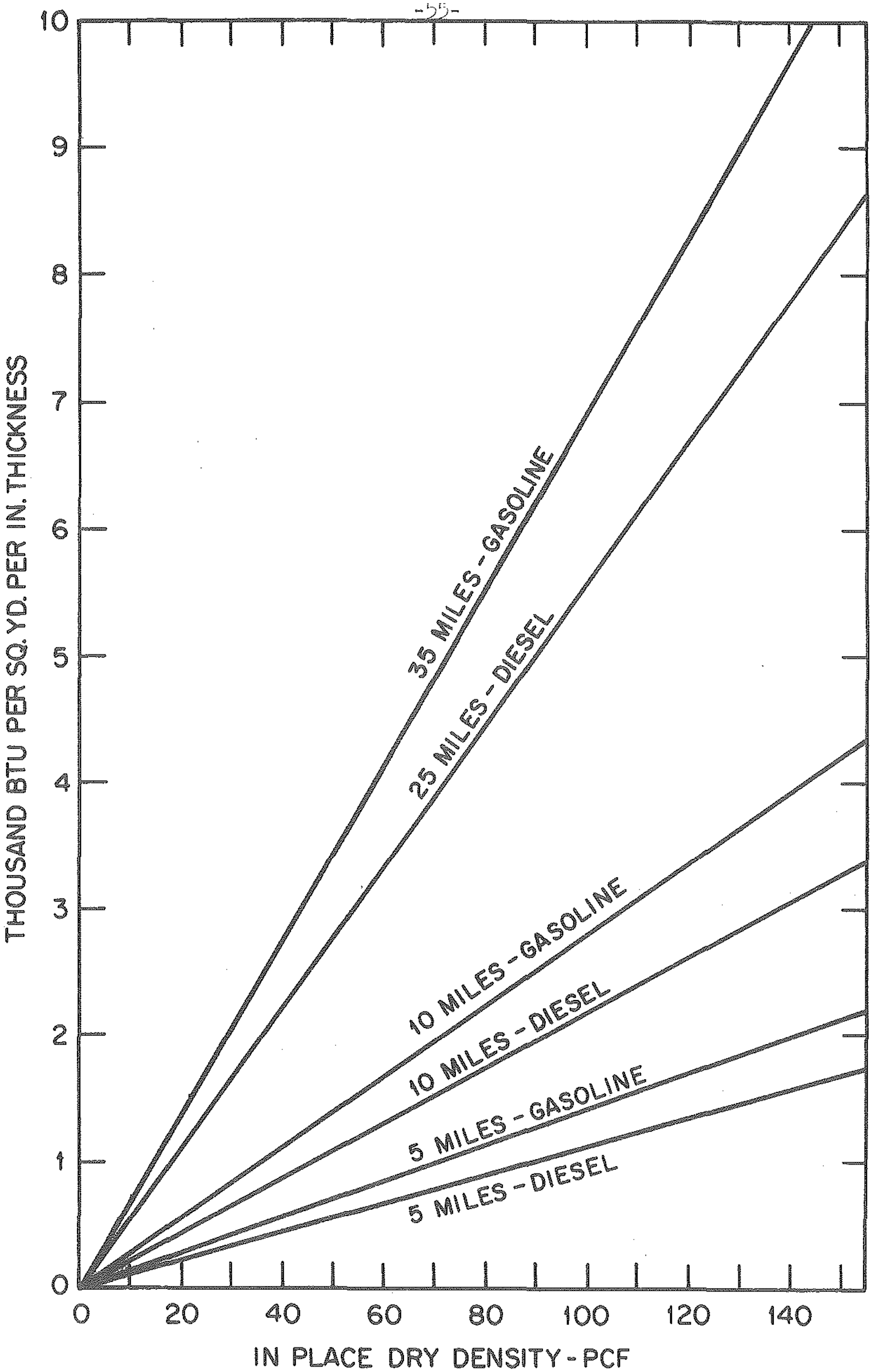

Figure III. Transportation energy for aggregates, 3 axle comb.

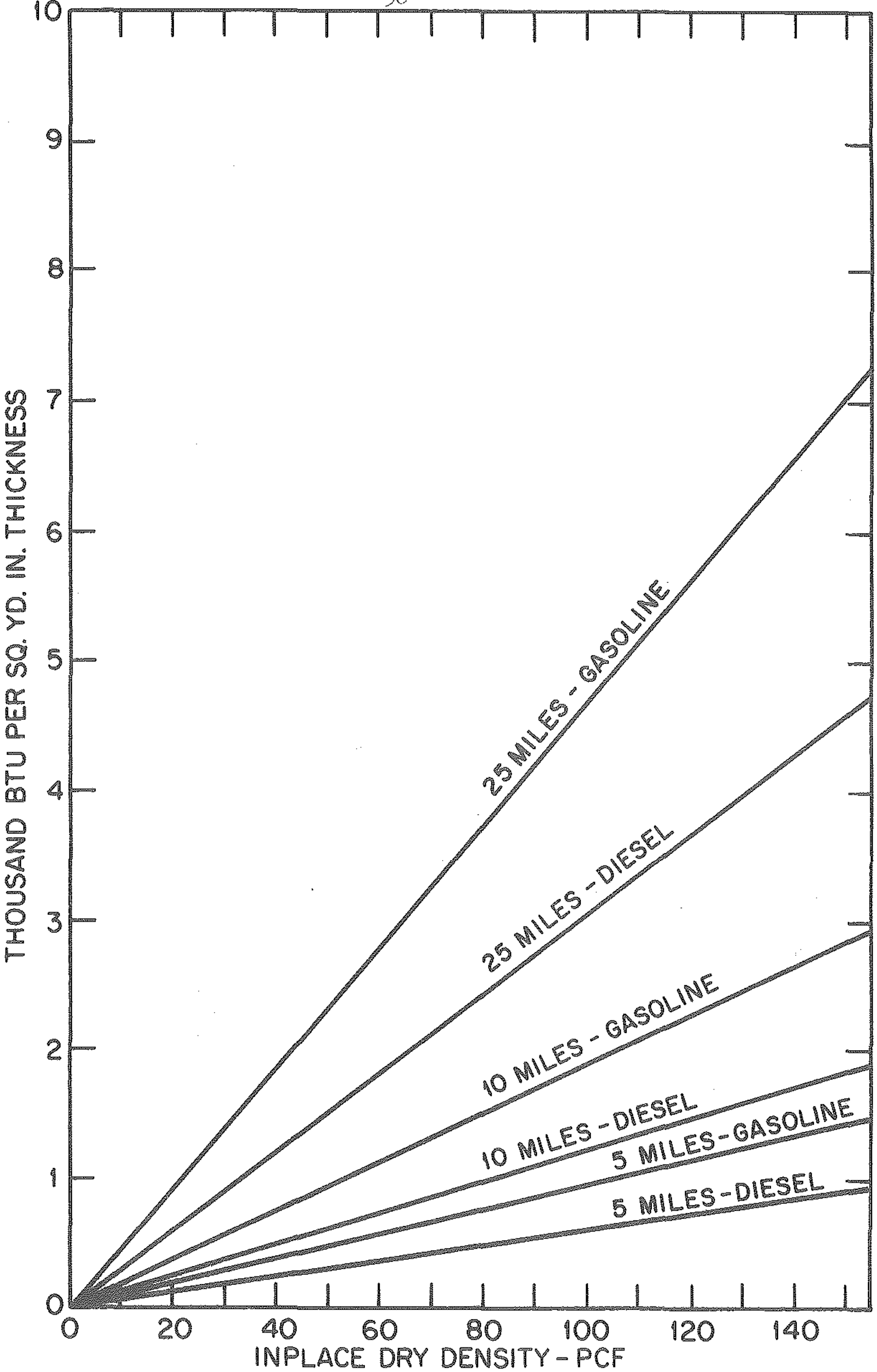

Figure IV. Transportation energy for aggregates, 4 axle comb.

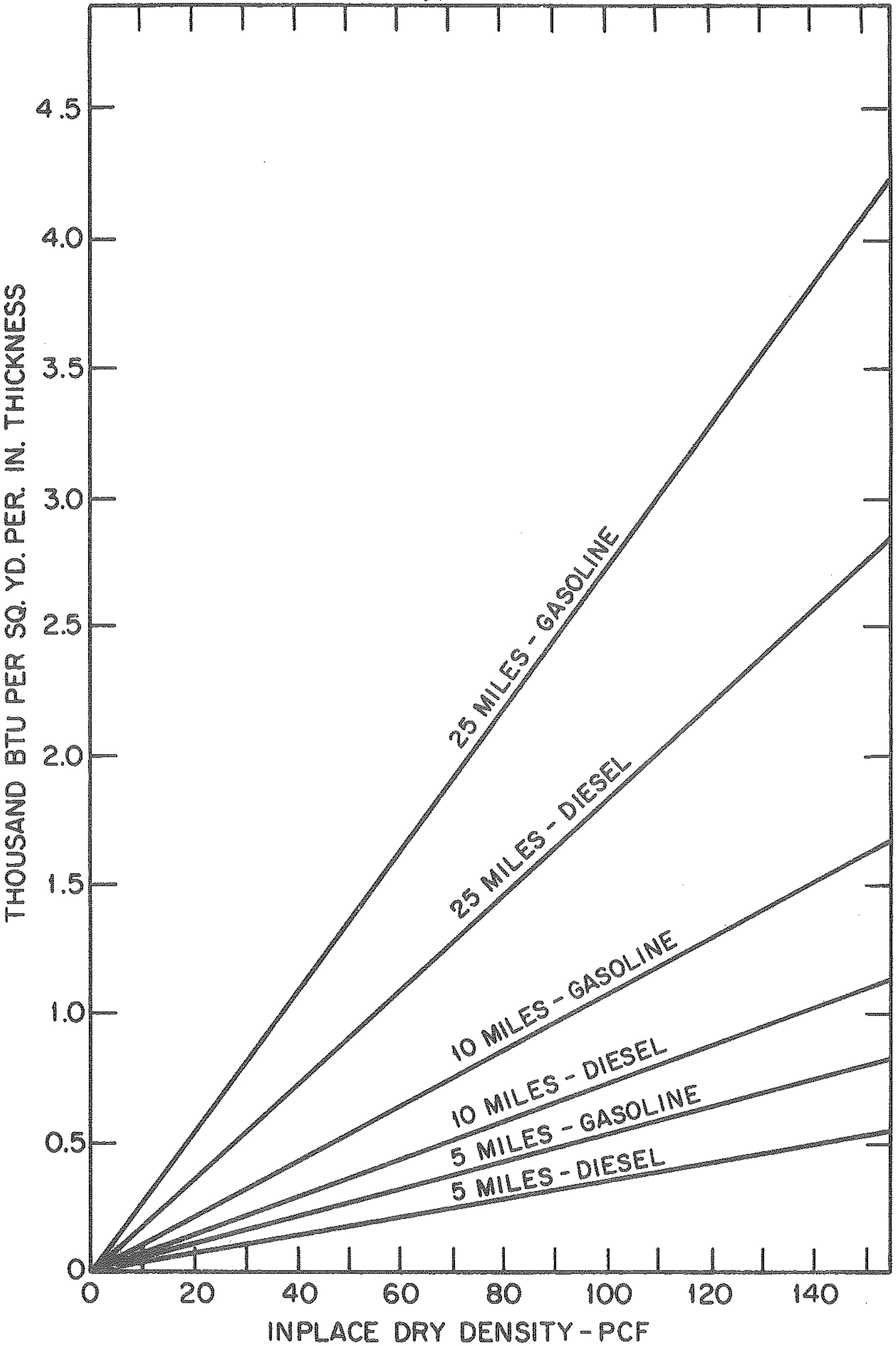

Figure V. Transportation energy for aggregates, 5 axle comb.

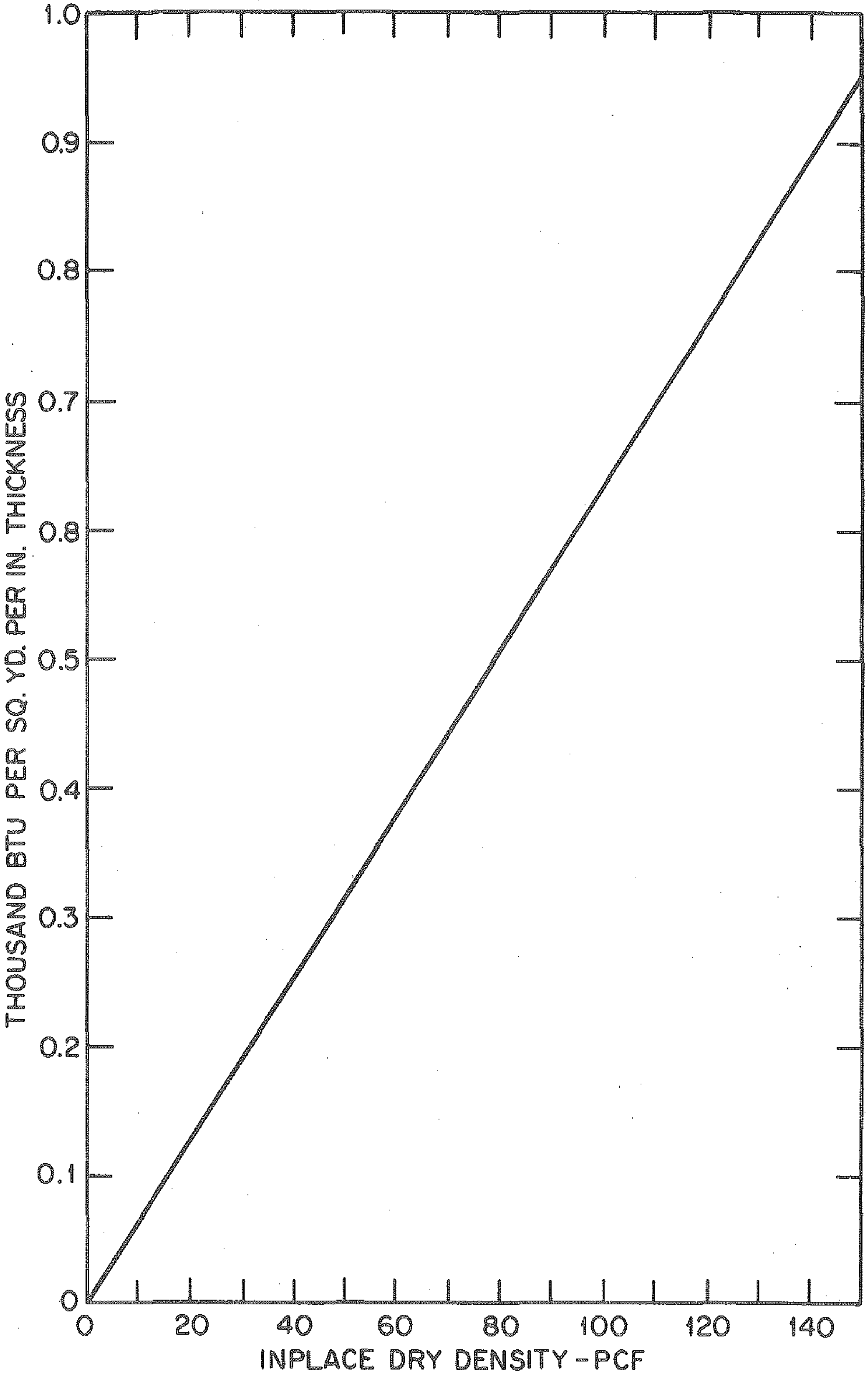

Figure VI. Energy of placement and compaction for granular bases.