THERMAL CAPACITOR DESIGN RATIONALE

PART I

THERMAL AND MECHANICAL PROPERTY DATA FOR SELECTED MATERIALS POTENTIALLY USEFUL IN THERMAL CAPACITOR DESIGN AND CONSTRUCTION

FINAL REPORT TO NASA, COOPERATIVE AGREEMENT WITH
NORTH CAROLINA STATE UNIVERSITY CONTRACT NCA8-52

JOHN A. BAILEY, B.S., Ph.D., F.I.M.
and
CHONG-KWANG LIAO, B.S., M.S., Ph.D.

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
NORTH CAROLINA STATE UNIVERSITY

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North Carolina State University

To

Dr. W. R. Humphries, Astronautics Laboratory
Propulsion and Thermodynamic Division
Life Support and Environmental Branch
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

From

John A. Bailey, B.S., Ph.D., F.I.M.

and

Chong-Kwang Liao, B.S., M.S., Ph.D.

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PART I

SELECTED PROPERTY DATA OF MATERIALS POTENTIALLY USEFUL FOR THERMAL CAPACITOR DESIGN AND CONSTRUCTION

1. INTRODUCTION

This part of the report is primarily concerned with a presentation of selected property data of materials potentially useful for thermal capacitor design and construction. Major emphasis is placed on the thermal properties of paraffin hydrocarbons and hydrocarbon mixtures which may be used as the phase change material (PCM) in thermal capacitors. The paraffin hydrocarbons selected for consideration are those in the range from $C_{11}H_{24}$ (n-Undecane) to $C_{20}H_{42}$ (n-Eicosane). However, a limited amount of data is included concerning other properties of paraffin hydrocarbons and the thermal and mechanical properties of several aluminum alloys which may find application as constructional materials.

Data concerning the melting temperature, transition temperature, latent heat of fusion, heat of transition, specific heat, and thermal conductivity of pure and commercial grades of paraffin hydrocarbons is given in Section 2. An index of companies capable of producing paraffin hydrocarbons and information concerning the availability of various grades (purity levels) is given in Sections 3 and 4, respectively. Selected cost data is given in Section 5. Miscellaneous physical and mechanical property data of probable limited use, including tensile strength, dynamic viscosity, density, heat of combustion and flashpoint is given in Section 6. Data concerning equilibrium phase diagrams and latent heats of fusion for various binary paraffin hydrocarbon systems is given in Section 7.

Selected thermal and mechanical property data for a number of aluminum alloys is given in Section 8. Finally, references are given in Section 9.

It is important to mention here that a review of the literature showed the existance of a considerable volume of data concerning the thermal properties of paraffin hydrocarbons. However, for much of the data examined it was found that the purity level of the materials investigated was not given. Such data are, therefore, of limited use.

2. THERMAL PROPERTY DATA FOR PURE AND COMMERCIAL GRADES OF SELECTED PARAFFIN HYDROCARBONS

2.1 Introduction

This section contains the most recent information concerning the melting temperature, transition temperature, latent heat of fusion, heat of transition, specific heat and thermal conductivity of ultra pure and commercial grades of selected paraffin hydrocarbons.

The approach adopted here is to present the most recent available data from the American Petroleum Institute (API) for ultra high purity paraffin hydrocarbons, and that generated by the authors for commercially available materials of various grades provided by two manufacturers. In this way comparisons can be made between the properties of ultra pure and commercial grades of material. The thermal property data generated for the latter materials was obtained using a Perkin-Elmer Differential Scanning Calorimeter, model DSC-1B. The experimental procedures used for the various thermal property determinations was that recommended by the manufacturer. In addition, a limited amount of data derived from other sources is included.

Table 1 shows the purity of selected materials available from the American Petroleum Institute and two manufacturers, namely; Phillips Petroleum Company and Humphrey Chemical Company. Tables 2 and 3 summarize data relating to the temperatures of solid - liquid and solid - solid phase transitions, respectively.

Tables 4 and 5 summarize data relating to the heats of transition for solid ⇌ liquid and solid ⇌ solid phase transitions, respectively. Tables 6 and 7 summarize data relating to the specific heats for the liquid and solid phases, respectively. Data for both heating and cooling cycles are included where appropriate. Table 8 summarizes a limited amount of thermal conductivity data

2.2 Discussion of Results

2.2.1 Transition Temperatures

Very accurate determination of phase transition temperatures for commercial grades of normal paraffin hydrocarbons is difficult because of the presence of impurities. In the work conducted by the authors transition temperature data could be reproduced to ± 0.5 K.

It can be seen from Table 2, with the exception of data for n-Eicosane (90%) and n-Hexadecane (Technical) that the determined solid ⇌ liquid transition temperatures are close to those for the pure materials although data for the commercially available materials appears in general to indicate lower transition temperatures when compared with the ultra pure materials. In addition, there is little difference between the melting and freezing temperatures. This is interpreted as indicating that the impurities are of such a nature and at such a level that the depression of freezing point is small. Further, it was found that there was an absence of super cooling. However, very low rates of heating and cooling of approximately 1 K/min were used. It is, perhaps, important to note that the usual impurities in n-paraffin hydrocarbons are other hydrocarbons of similar chain length. If the impurities are also isomorphic with the major component then the phase behavior of the major component is not drastically altered. For the present materials data seems to suggest that, indeed, the impurities are of a similar chain length and isomorphic with the major component. The two possible exceptions are n-Eicosane (90%) and n-Hexadecane (Technical).

It can be seen from Table 3 that transition changes occur in the solid state for certain paraffin hydrocarbons. The paraffin hydrocarbons showing solid ⇌ solid phase changes are those with an odd number of carbon atoms in the [illegible]. Again, there is little difference in the data derived from heating and cooling cycles. In addition, data for the commercially available materials is not significantly different from that for the pure materials.

Figures 1, 2, and 3 show a graphical presentation of the data contained in Tables 2 and 3. Figure 4 shows a limited amount of similar data derived from other sources. It can be seen that the freezing point temperature increases in a non-linear manner with increasing carbon chain length over the range of molecular weights used in the present investigation; a result which may be anticipated.

2.2.2 Latent Heats of Phase Transition

It can be seen from Table 4 that the determined latent heats of fusion for the commercial grade materials are close to those for the ultra high purity materials. It is interesting to note that the latent heat of fusion for n-Eicosane (90%) and n-Hexadecane (Technical) are close to those for the ultra high purity materials although their melting points are approximately 4K and 7K lower, respectively. There is little difference also between latent heats of fusion for melting and freezing cycles as would be anticipated.

Phase changes in the solid state also were observed for certain of the paraffin hydrocarbons. This data is presented in Table 5. It can be seen that the solid ⇌ solid phase transitions exist only for paraffin hydrocarbons with an odd number of carbon atoms in the chain. Again, data is similar to that given for the ultra pure materials with little difference between heating and cooling cycles. It is evident that the heats of transition for solid ⇌ solid phase changes are considerably lower than those for solid ⇌ liquid phase changes for a material of a given carbon chain length.

Figures 5, 6, and 7 show the variation of the latent heat of fusion and transition with carbon chain length for the materials tested, and derived from data presented in Tables 4 and 5. Figure 8 shows similar data derived from other sources. It can be seen that the paraffin hydrocarbons can be separated into two distinct groups, manely, those with an even number of carbon atoms in the chain and those with an odd number of carbon atoms in the chain. However, for both groups the variation of latent heat of fusion and transition with increasing carbon chain length can be represented by a straight line over the range of molecular weights used in the investigation.

2.2.3 Specific Heat

Tables 6 and 7 show experimentally determined values for the specific heats in the liquid and solid state for the materials given in Table 1 Figure 9, 10, and 11 show the variation of specific heat with temperature for the materials used in the investigation and derived from data presented in Tables 6 and 7. Figure 12 shows a limited amount of data derived from other sources. It can be seen for the materials provided by Humphrey Chemical Company that the hydrocarbons can be divided into two groups; namely, those where the specific heat was determined in the solid state and those where the specific heat was determined in the liquid state. However, for both groups the variation of specific heat with temperature can be represented to a first approximation by a straight line with little scatter in data. The general observation is that an increase in temperature produces an increase in specific heat.

Data for materials provided by the Phillips Petroleum Company can also be represented in a similar manner to the data provided by Humphrey Chemical Company. However, for this latter data there is considerably more scatter particularly for materials of technical purity. Since identical procedures were used for all the determinations of specific heats it is concluded that the scatter of certain of the data presented in Figure 10 arises because of the presence of

unknown quantities or impurities. Apparently, specific heat determinations are more sensitive to the presence of impurities than determinations of latent heats of fusion.

3. POTENTIAL SUPPLIERS OF SELECTED PARAFFIN HYDROCARBONS

A survey was conducted of petroleum product manufacturers in the United States. A selection of the Companies and Laboratories capable of providing the selected paraffin hydrocarbons in quantities sufficiently large to be used in thermal capacitors is given in Table 9. More detailed information is given in "Thermal Capacitor Design Rationale", NASA Cooperative Agreement with North Carolina State University Interim Report No. 2a. January 1973.

4. CAPABILITIES OF SUPPLIERS

A review of the products produced by the various Companies and Laboratories given in Table 9 was undertaken to determine the types of grade of paraffin hydrocarbon available and whether or not thermal and physical property data could be provided. The results of the review are summarized in Table 10. It is to be noted that the American Petroleum Institute (Standard Reference Materials) is the only source of compounds of high certified purity. More detailed information is given in "Thermal Capacitor Design Rationale", NASA Cooperative Agreement with North Carolina State University Interim Report No. 2a. January 1973.

5. COST INFORMATION

An extensive review of the cost of the various products produced by the Companies and Laboratories given in Table 9 was undertaken. Data concerning the cost of paraffin hydrocarbons of various grades produced by the Phillips Petroleum Company and the Humphrey Chemical Company is given in Tables 11 and 12, respectively. Only data from these companies were selected because material from these companies was used for the generation of thermal property data. It is

pointed out that at the time of writing there is considerable variation in the price of paraffin hydrocarbons obtained from different sources. In addition, the cost of paraffin hydrocarbons depends greatly on purity. For example, the ultra high purity standard reference materials available from the American Petroleum Institute cost $95.00 for a 5 ml unit. More detailed information is given in "Thermal Capacitor Design Rationale". NASA Cooperative Agreement with North Carolina State University Interim Report No. 2a. January 1973.

6. ADDITIONAL PHYSICAL AND MECHANICAL PROPERTY DATA

6.1 Physical Properties

Physical properties such as melting point, latent of fusion, heat of transition and specific heat are of great importance in the design of thermal capacitors and a major effort has been made to generate such property data for a number of commercially available materials. The results of these efforts have been presented in a previous section. However, it is recognized that other physical properties not examined in the previous section may assume importance. Such properties include heat of combustion, coefficient of expansion, surface tension, density, absolute viscosity and flash point.

It was not possible to carry out the experimental determination of the aforementioned properties because of insufficient financial resources. Therefore, the approach adopted was to review the literature and collect previously published data. It was found that the only reliable data was that published by the American Petroleum Institute for materials of ultra high purity. This data has been assembled and is presented in Tables 13 to 18. The purity of the materials is given in Table 1.

6.2 Mechanical Properties

During the thermal cycling of capacitors through the phase change regime large changes in the volume of the paraffin hydrocarbon can occur. In the

capacitor the change in volume is accommodated through the provision of sufficient ullage space. However, it is recognized that conditions of highly localized or improper melting (or freezing) could lead to the generation of high stresses within the paraffin hydrocarbon which may ultimately lead to permanent deformation. Knowledge of the strength characteristics of paraffin hydrocarbons may, therefore, be useful.

A review of the literature revealed a surprising lack of information concerning the mechanical properties of paraffin hydrocarbons at various temperatures. It was, therefore, decided to generate such data by experiment using the tensile test to obtain a measure of strength. The basic test procedure used was that described under the American Society for Testing and Materials, Standard Designation D 1320-67 (Reapproved 1971) entitled "Standard Method of Test for Tensile Strength of Paraffin Wax". Details of the procedure will not be given here as they are adequately described in the Standard.

Tests were conducted for each material at five selected temperatures using an Instron Universal Testing Machine to pull the specimens. The testing speed used was 0.25 cm/min. A total of six specimens were used for each temperature and the average ultimate tensile strength used to characterize the material. All materials showed almost negligible ductility except at temperatures close to the melting point temperature.

The results are shown in Figure 13 as a plot of Ultimate Tensile Strength versus Homologous Temperature. The Homologous Temperature is the ratio of the testing temperature to the melting point temperature of the material. It can be seen from the results that over the homologous temperature range investigated the ultimate tensile strength increases with increasing test temperature to a maximum, then decreases with a further increase in test temperature becoming negligible at the melting point temperature of the material. It can be seen also that tensile strength values are extremely low as may be anticipated. In

addition, there was considerable scatter in data to the point where it became impossible to differentiate between the strengths of the various paraffin hydrocarbons at a given homologous temperature. A single curve was, therefore, drawn through all the data points and the width of the scatter band indicated.

The data generated for the paraffin hydrocarbons investigated is quite different from that produced for metallic materials which usually show, in the absence of strain aging, a progressive decrease in strength with increasing temperature. Microscopic examination of test samples showed the presence of many microcracks and fine scale porosity throughout the test section. It is believed that during tests at low temperatures these act as stress raisers which, in the absence of appreciable ductility leads to rapid failure at low nominal stresses. At higher temperatures some viscous flow can occur thereby reducing the effectiveness of the microcracks so that higher nominal stresses are required to produce failure.

7. SELECTED THERMAL PROPERTY DATA FOR VARIOUS PARAFFIN HYDROCARBON BINARY SYSTEMS

7.1 Introduction

This section contains information concerning the temperature-composition equilibrium phase diagrams and variation with composition of the latent heats of fusion and transition for various binary hydrocarbon systems. The data was generated using a Perkin-Elmer Differential Scanning Calorimeter, model DSC-1B. The experimental procedure used for the determination of the temperatures and latent heats associated with phase transitions was that recommended by the manufacturer. The binary systems studied were n-Undecane/n-Dodecane, n-Undecane/n-Hexadecane, n-Dodecane/n-Tridecane, n-Dodecane/n-Nonadecane, n-Dodecane/n-Eicosane, n-Tridecane/n-Octadecane, n-Hexadecane/n-Octadecane, n-Octadecane/n-Nonadecane, n-Nonadecane/n-Eicosane. All tests were conducted at atmospheric pressure.

For each of the aforementioned systems the two pure materials and nine binary compositions at increments of approximately ten weight percent solute were selected for thermal analysis. Each of the selected compositions was melted and mixed thoroughly before determinations were made. Test samples were examined in the approximate temperature range from 73K to 340K. In order to avoid excessively long thermal cycles comparatively high rates of heating and cooling in the range from 10K to 20K per minute were used. With these conditions it was estimated that transition temperatures could be determined to $\pm$ 1.5K.

Figures 14 to 22 show the binary phase diagrams of the selected systems derived from data generated by differential scanning colorimetry. Figures 23 to 31 and Tables 19 to 27 summarize the experimentally determined values for the latent heats of fusion and transition.

7.2 Discussion of Results

7.2.1 Phase Diagrams

It is apparent from the data generated and presented in Figures 14 to 22 that thermal analyses of additional compositions close to the composition extremities of the phase diagrams is required in order to determine accurately the location of the phase boundaries in these regions. Unfortunately, lack of sufficient resources prevented the completion of these additional determinations. It is, therefore, suggested that the areas of the phase diagrams in the vicinity of the composition extremities be treated with some caution; although they do appear reasonable. It is apparent also that several different solid phases can exist simultaneously at a given temperature in all of the phase diagrams. These solid phases have been marked simply with a suffix notation (S_1, S_2, S_3, S_4) to denote differences. No attempt is made here to characterize the structure or nature of these phases. Extensive, carefully controlled X-Ray analysis would, of course, be required to make such structural characterizations. Similarly, no attempt is made to offer a detailed thermodynamic rationale to account

for the forms of the various phase diagrams because of this lack of structural information.

It can be seen from Figures 14 to 22 that three different types of phase diagrams exist. For a binary system formed by paraffin hydrocarbons adjacent in the homologous series (odd-even) a wide range of solid solutions appear to be formed with a single peritectic reaction in that region of the phase diagram high in concentration of the hydrocarbon with an even number of carbon atoms in the chain (Figures 14, 16, 21 and 22). The duplex solid phase region is caused apparently by the presence of a solid $\rightleftharpoons$ solid phase transformation in the hydrocarbon containing an odd number of carbon atoms in the chain. For a binary system formed by paraffin hydrocarbons which are next but one neighbors possessing an even number of carbon atoms in the chain a wide range of solid solutions are again formed. However, two peritectic reaction close, both to the composition extremities of the phase diagram and melting point temperature of the pure hydrocarbons now exist. In addition, a complex eutectoid reaction is present at low temperatures (Figure 20). For a binary system formed by paraffin hydrocarbons where there is a significant difference in carbon chain length eutectic systems form. The major constituents appear to be insoluable in each other in the solid state forming a mechanical mixture: a result which may be anticipated. However, it is believed that these diagrams may be more complex in the high temperature regime than is indicated. Dashed lines have been drawn to denote regions of uncertainty. (Figures 15, 17, 18 and 19).

7.2.2 Latent Heats of Fusion and Transition

Figures 23 to 31 and Tables 19 to 27 summarize data concerning the effect of composition on the latent heats of fusion and transition for the nine binary systems selected for study. It can be seen from Figures 23 to 31 that the addition of solute to the solvent in all instances produces a decrease in the latent heat of fusion so that a minimum is produced in the latent heat of fusion versus

composition curve. For the binary paraffin hydrocarbon systems which form extended solid solution (Figures 14, 16, 20, 21 and 22) the minimum occurs at approximately 50 weight percent solute. For the binary paraffin hydrocarbon systems which form eutectics the minimum appears to occur close to the eutectic composition. Again, no attempt will be made to offer a detailed thermodynamic rationale to account for the forms of the various diagrams given in Figures 23 to 31.

The latent heat of transition appear also to depend upon composition but to a less marked degree than the latent heats of fusion. Determination of the latent heats of transition was extremely difficult and results should be treated with some caution.

8. MECHANICAL AND PHYSICAL PROPERTY DATA OF SELECTED ALUMINUM ALLOYS

Tables 28 to 31 show important mechanical and physical property data for several aluminum alloys of potential use in the construction of thermal capacitors. Data was taken from Metals Handbook Vol. 1, American Society for Metals.

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APPENDIX IA

QUANTITATIVE DATA (TABULATED)

Table 1. GRADES OF MATERIALS INVESTIGATED

	MATERIAL	FORMULA	GRADE*
AMERICAN PETROLEUM INSTITUTE	n-Undecane	$C_{11}H_{24}$	99.96 ± 0.03
	n-Dodecane	$C_{12}H_{26}$	99.969 ± 0.025
	n-Tridecane	$C_{13}H_{28}$	99.91 ± 0.06
	n-Hexadecane	$C_{16}H_{34}$	99.90 ± 0.06
	n-Octadecane	$C_{18}H_{38}$	99.90 ± 0.08
	n-Nonadecane	$C_{19}H_{40}$	99.90 ± 0.08
	n-Eicosane	$C_{20}H_{42}$	99.90 ± 0.08
HUMPHREY CHEMICAL COMPANY	n-Undecane	$C_{11}H_{24}$	99%
	n-Dodecane	$C_{12}H_{26}$	99%
	n-Tridecane	$C_{13}H_{28}$	99%
	n-Hexadecane	$C_{16}H_{34}$	99%
	n-Octadecane	$C_{18}H_{38}$	99%
	n-Nonadecane	$C_{19}H_{40}$	99%
	n-Eicosane	$C_{20}H_{42}$	99%
PHILLIPS PETROLEUM COMPANY	n-Undecane	$C_{11}H_{24}$	Research
	n-Dodecane	$C_{12}H_{26}$	Pure
	n-Tridecane	$C_{13}H_{28}$	Pure
	n-Hexadecane	$C_{16}H_{34}$	Pure
	n-Hexadecane	$C_{16}H_{34}$	Technical
	n-Octadecane	$C_{18}H_{38}$	Technical
	n-Nonadecane	$C_{19}H_{40}$	Technical
	n-Eicosane	$C_{20}H_{42}$	Technical
	n-Eicosane	$C_{20}H_{42}$	(90%)

*Purity, Mole Percent

Table 2. TEMPERATURE OF FUSION

		HEATING CYCLE (solid → liquid)		COOLING CYCLE (liquid → solid)	
	MATERIAL	K	°F	K	°F
AMERICAN PETROLEUM INSTITUTE	n-Undecane	247.41	-14.05	NO DIFFERENCES GIVEN FOR HEATING AND COOLING CYCLES	
	n-Dodecane	263.41	14.74		
	n-Tridecane	267.61	22.30		
	n-Hexadecane	291.17	64.70		
	n-Octadecane	301.18	82.70		
	n-Nonadecane	305.10	89.80		
	n-Eicosane	309.80	98.20		
HUMPHREY CHEMICAL COMPANY	n-Undecane	246.5	-15.7	247.0	-14.8
	n-Dodecane	261.5	11.3	262.5	13.1
	n-Tridecane	267.0	21.2	267.2	21.6
	n-Hexadecane	292.0	66.2	291.5	65.3
	n-Octadecane	300.1	80.8	300.2	81.0
	n-Nonadecane	302.5	85.1	302.5	85.2
	n-Eicosane	308.8	96.5	308.2	95.5
PHILLIPS PETROLEUM COMPANY	n-Undecane	244.6	-19.2	247.0	-14.8
	n-Dodecane	261.8	11.8	262.0	12.2
	n-Tridecane	265.8	19.0	266.0	19.4
	n-Hexadecane	292.0	66.2	291.7	65.7
	n-Hexadecane	284.1	52.0	286.0	55.4
	n-Octadecane	299.7	80.1	299.5	79.7
	n-Nonadecane	304.5	88.7	305.5	90.5
	n-Eicosane	308.0	95.0	308.0	95.0
	n-Eicosane	305.5	90.5	306.0	91.5

Table 3. TEMPERATURE OF TRANSITION

	MATERIAL	HEATING CYCLE (solid - solid) K	HEATING CYCLE (solid - solid) °F	COOLING CYCLE (solid - solid) K	COOLING CYCLE (solid - solid) °F
AMERICAN PETROLEUM INSTITUTE	n-Undecane	236.6	-33.5	NO DIFFERENCES GIVEN FOR HEATING AND COOLING CYCLES	
	n-Dodecane	-			
	n-Tridecane	255.0	- 0.4		
	n-Hexadecane	-			
	n-Octadecane	-			
	n-Nonadecane	295.9	73.2		
	n-Eicosane	-			
HUMPHREY CHEMICAL COMPANY	n-Undecane	237.0	-32.8	236.6	-33.5
	n-Dodecane	-		-	
	n-Tridecane	254.1	2.0	255.0	- 0.4
	n-Hexadecane	-		-	
	n-Octadecane	-		-	
	n-Nonadecane	294.8	71.2	294.0	69.8
	n-Eicosane	-		-	
PHILLIPS PETROLEUM COMPANY	n-Undecane	236.2	-34.3	237.0	-32.8
	n-Dodecane	-		-	
	n-Tridecane	252.1	- 5.65	254.0	- 2.2
	n-Hexadecane	-		-	
	n-Hexadecane	-		-	
	n-Octadecane	-		-	
	n-Nondecane	293.6	69.0	294.0	69.8
	n-Eicosane	-		-	
	n-Eicosane	-		-	

Table 4. HEAT OF FUSION

	MATERIAL	HEATING CYCLE (solid → liquid) Joule/Kg	Btu/lb	COOLING CYCLE (liquid → solid) Joule/Kg	Btu/lb
AMERICAN PETROLEUM INSTITUTE	n-Undecane	14.2×10^4	61.2	NO DIFFERENCES GIVEN FOR HEATING AND COOLING CYCLES	
	n-Dodecane	21.6×10^4	93.2		
	n-Tridecane	15.4×10^4	66.5		
	n-Hexadecane	23.5×10^4	101.5		
	n-Octadecane	24.4×10^4	105.0		
	n-Nonadecane	18.7×10^4	80.6		
	n-Eicosane	24.8×10^4	107.0		
HUMPHREY CHEMICAL COMPANY	n-Undecane	14.0×10^4	60.4	14.3×10^4	61.7
	n-Dodecane	21.8×10^4	94.0	22.0×10^4	94.9
	n-Tridecane	14.5×10^4	62.5	15.9×10^4	68.5
	n-Hexadecane	23.7×10^4	102.0	23.5×10^4	101.5
	n-Octadecane	24.8×10^4	107.0	24.5×10^4	105.6
	n-Nonadecane	18.0×10^4	77.5	18.0×10^4	77.5
	n-Eicosane	24.9×10^4	107.5	24.5×10^4	105.5
PHILLIPS PETROLEUM COMPANY	n-Undecane	14.2×10^4	61.4	14.1×10^4	61.0
	n-Dodecane	21.8×10^4	94.0	21.2×10^4	91.5
	n-Tridecane	15.4×10^4	66.2	15.0×10^4	64.8
	n-Hexadecane	23.9×10^4	103.0	23.5×10^4	101.5
	n-Hexadecane	24.4×10^4	105.0	23.7×10^4	102.0
	n-Octadecane	24.3×10^4	104.6	24.2×10^4	104.5
	n-Nonadecane	18.2×10^4	78.3	17.9×10^4	77.2
	n-Eicosane	25.5×10^4	110.0	24.3×10^4	104.8
	n-Eicosane	24.1×10^4	104.0	23.4×10^4	101.0

Table 5. HEAT OF TRANSITION

		HEATING CYCLE (solid → solid)		COOLING CYCLE (solid → solid)	
	MATERIAL	Joule/Kg	Btu/lb	Joule/Kg	Btu/lb
AMERICAN PETROLEUM INSTITUTE	n-Undecane	4.39×10^4	18.9	NO DIFFERENCES GIVEN FOR HEATING AND COOLING CYCLES	
	n-Dodecane	-			
	n-Tridecane	4.16×10^4	17.9		
	n-Hexadecane	-			
	n-Octadecane	-			
	n-Nonadecane	5.14×10^4	22.2		
	n-Eicosane	-			
HUMPHREY CHEMICAL COMPANY	n-Undecane	4.09×10^4	17.6	4.05×10^4	17.4
	n-Dodecane	-		-	
	n-Tridecane	4.33×10^4	18.7	4.7×10^4	20.3
	n-Hexadecane	-		-	
	n-Octadecane	-		-	
	n-Nonadecane	5.13×10^4	22.1	5.16×10^4	22.3
	n-Eicosane	-		-	
PHILLIPS PETROLEUM COMPANY	n-Undecane	4.03×10^4	17.4	4.22×10^4	18.2
	n-Dodecane	-		-	
	n-Tridecane	4.03×10^4	17.4	4.06×10^4	17.5
	n-Hexadecane	-		-	
	n-Hexadecane	-		-	
	n-Octadecane	-		-	
	n-Nonadecane	4.95×10^4	21.4	4.99×10^4	21.5
	n-Eicosane	-		-	
	n-Eicosane	-		-	

Table 6. SPECIFIC HEAT (LIQUID PHASE)

	MATERIAL	Btu/lb°F	Joule/Kg.K	TEMPERATURE K	TEMPERATURE °F
AMERICAN PETROLEUM INSTITUTE	n-Undecane	0.366	1.53×10^3	273	32.0
	n-Dodecane	0.366	1.53×10^3	273	32.0
	n-Tridecane	0.366	1.53×10^3	273	32.0
	n-Hexadecane	0.406	1.70×10^3	311	100.0
	n-Octadecane	0.406	1.70×10^3	311	100.0
	n-Nonadecane	0.405	1.69×10^3	311	100.0
	n-Eicosane	0.464	1.94×10^3	366	200.0
HUMPHREY CHEMICAL COMPANY	n-Undecane	0.451	1.89×10^3	270	26.6
	n-Dodecane	0.513	2.15×10^3	290	62.6
	n-Tridecane	0.516	2.16×10^3	300	80.2
	n-Hexadecane	0.551	2.31×10^3	330	134.5
	n-Octadecane	0.556	2.33×10^3	330	134.5
	n-Nonad-cane	0.549	2.30×10^3	340	153.5
	n-Eicosane	0.587	2.46×10^3	350	171.0
PHILLIPS PETROLEUM COMPANY	n-Undecane	0.509	2.13×10^3	270	26.6
	n-Dodecane	0.540	2.26×10^3	290	62.6
	n-Tridecane	0.526	2.20×10^3	300	80.6
	n-Hexadecane	0.552	2.31×10^3	330	134.5
	n-Hexadecane	0.578	2.42×10^3	330	134.5
	n-Octadecane	0.536	2.24×10^3	330	134.5
	n-Nonadecane	0.536	2.24×10^3	340	153.5
	n-Eicosane	0.536	2.24×10^3	340	153.5
	n-Eicosane	0.559	2.34×10^3	340	153.5

Table 7. SPECIFIC HEAT (SOLID PHASE)

	MATERIAL	Btu/lb°F	Joule/Kg.K	TEMPERATURE K	TEMPERATURE °F
AMERICAN PETROLEUM INSTITUTE	n-Undecane	-	-	-	-
	n-Dodecane	0.347	1.42×10^3	255	0
	n-Tridecane	0.346	1.42×10^3	255	0
	n-Hexadecane	0.346	1.42×10^3	255	0
	n-Octadecane	0.346	1.42×10^3	255	0
	n-Nonadecane	0.346	1.42×10^3	255	0
	n-Eicosane	0.345	1.41×10^3	255	0
HUMPHREY CHEMICAL COMPANY	n-Undecane	0.320	1.34×10^3	220	-63.5
	n-Dodecane	0.405	1.69×10^3	250	- 9.4
	n-Tridecane	0.380	1.59×10^3	240	-27.5
	n-Hexadecane	0.430	1.80×10^3	280	44.6
	n-Octadecane	0.450	1.88×10^3	280	44.6
	n-Nonadecane	0.430	1.80×10^3	270	26.6
	n-Eicosane	0.460	1.92×10^3	300	80.6
PHILLIPS PETROLEUM COMPANY	n-Undecane	0.301	1.26×10^3	220	-63.5
	n-Dodecane	0.420	1.76×10^3	250	- 9.4
	n-Tridecane	0.380	1.59×10^3	240	27.5
	n-Hexadecane	0.401	1.68×10^3	270	26.6
	n-Hexadecane	0.402	1.68×10^3	270	26.6
	n-Octadecane	0.470	1.97×10^3	280	44.6
	n-Nonadecane	0.452	1.89×10^3	280	44.6
	n-Eicosane	0.426	1.78×10^3	290	62.6
	n-Eicosane	0.569	2.38×10^3	290	62.6

Table 8 THERMAL CONDUCTIVITY (AT PHASE CHANGE TEMPERATURE)

	MATERIAL	Btu/hr-ft-°F	Watt/m-K
AMERICAN PETROLEUM INSTITUTE	n-Undecane	0.0865	0.1496
	n-Dodecane	0.0860	0.1488
	n-Tridecane	0.0865	0.1496
	n-Hexadecane	0.0870	0.1505
	n-Octadecane	0.0870	0.1505
	n-Nonadecane	----	----
	n-Eicosane	0.0870	0.1505

Table 9 POTENTIAL SUPPLIERS OF SELECTED PARAFFIN HYDROCARBONS

COMPANY	ADDRESS	PHONE NUMBER	CONTACT	POSITION
American Petroleum Institute Standard Reference Materials	Carnegie-Mellon University Schenley Park Pittsburgh, Pennsylvania 15213	[412] 621-2600	A. J. Streiff	Director
Aldrich Chemical Company Inc.	940 West Saint Paul Avenue Milwaukee, Wisconsin 53233	[414] 273-3850	D. W. Griffiths	Manager Technical Services
Analabs Incorporated	80 Republic Drive North Haven, Connecticut 06473	[203] 288-3400	G. W. Critzer	Production Manager
Chemical Sample Company	4692 Kenny Road Columbus, Ohio 43221	[614] 451-3322	K. W. Greenlee	President
Eastman (Kodak) Organic Chemicals	2400 Mt. Read Boulevard Rochester, New York 14650	[716] 458-4080	R. J. Leicht	Supervisor of Customer Relations
Gallard - Schlesinger Chemical Manufacturing Corporation	584 Mineola Avenue Carle Place, New York 11514	[516] 333-5600	R. Rosenburg	Sales Manager
The Humphrey Chemical Company	Devine Street North Haven, Connecticut 06473	[203] 288-3883	L. R. Buerger	Vice President
Lachat Chemicals Incorporated	20200 Ashland Avenue Chicago Heights, Illinois 60411	[312] 754-5151	L. Lachat	President
Phillips Petroleum Company	Bartlesville, Oklahoma 74004	[918] 661-6600	H. Frantz	Marketing Manager
Polysciences Inc.	Paul Valley Industrial Park Warrington, Pennsylvania 18976	[215] 343-6484	B. D. Halpern	President

Table 10. CAPABILITIES OF POTENTIAL SUPPLIERS

COMPANY	ABILITY TO SUPPLY PARAFFIN HYDROCARBONS	GRADES OF PARAFFIN HYDROCARBON AVAILABLE	ABILITY TO SUPPLY THERMAL AND PHYSICAL PROPERTY DATA
American Petroleum Institute	can be supplied	Ultra high purity	can be supplied
Aldrich Chemical Company	can be supplied	Only one grade available, unspecified purity	cannot be supplied
Analabs Incorporated	can be supplied	Only one grade available, purity specified greater than 99%	cannot be supplied
Chemical Sample Company	can be supplied	Several grades available	limited amount of data available*
Eastman Organic Chemicals	can be supplied	Only one grade available, unspecified purity	cannot be supplied
Gallard-Schlesinger Chemical Manufacturing Corporation	do not manufacture paraffin hydrocarbons but can obtain them on request from other sources	Only one grade available, unspecified purity	cannot be supplied
Humphrey Chemical Company	can be supplied	Only one grade available, specified purity 99%	limited amount of data available*
Lachat Chemical Incorporated	can be supplied	Only one grade available, specified purity 99%	limited amount of data available*
Phillips Petroleum Company	can be supplied	Several grades available	can be supplied*
Polysciences Incorporated	can be supplied as specialized items	can provide materials at any purity level	cannot be supplied

*Data probably obtained from American Petroleum Institute (Standard Reference Materials)

Table 11 PHILLIPS PETROLEUM COMPANY*

MATERIAL	FORMULA	PURITY	COST
n-Nonane	C_9H_{20}	99.67% (Research)	200gm-$59.40, 400gm-$95.00
n-Nonane	C_9H_{20}	99.0% (Pure)	0.7lb-$10.80, 1.4lb-$19.40
n-Nonane	C_9H_{20}	95.0% (Technical)	1.4lb-$15.10, 6.0lb-$38.85
n-Decane	$C_{10}H_{22}$	99.7% (Research)	200gm-$59.40, 400gm-$95.00
n-Decane	$C_{10}H_{22}$	99.0% (Pure)	0.7lb-$16.20, 1.4lb-$29.15
n-Decane	$C_{10}H_{22}$	95.0% (Technical)	1.4lb-$12.95, 6.1lb-$35.60
n-Undecane	$C_{11}H_{24}$	99.75% (Research)	200gm-$59.40, 400gm-$95.00
n-Undecane	$C_{11}H_{24}$	99.0% (Pure)	1.5lb-$23.75, 6.2lb-$70.20
n-Undecane	$C_{11}H_{24}$	95% (Technical)	1.5lb-$16.20, 6.2lb-$39.95
n-Dodecane	$C_{12}H_{26}$	99.74% (Research)	200gm-$59.40, 400gm-$95.00
n-Dodecane	$C_{12}H_{26}$	99.0% (Pure)	0.7lb-$10.80, 1.5lb-$18.35
n-Dodecane	$C_{12}H_{26}$	95.0% (Technical)	1.5lb-$12.95, 6.2lb-$35.60
n-Tridecane	$C_{13}H_{28}$	99.82% (Research)	200gm-$59.40, 400gm-$95.00
n-Tridecane	$C_{13}H_{28}$	99.0% (Pure)	0.7lb-$18.35, 1.5lb-$33.45
n-Tridecane	$C_{13}H_{28}$	95% (Technical)	1.5lb-$22.65, 6.3lb-$63.70
n-Tetradecane	$C_{14}H_{30}$	99% (Pure)	1.5lb-$20.50, 6.4lb-$66.95
n-Tetradecane	$C_{14}H_{30}$	95% (Technical)	1.5lb-$12.95, 6.4lb-$45.35
n-Pentadecane	$C_{15}H_{32}$	95% (Technical)	0.7lb-$11.85, 1.5lb-$20.50

Table 11. PHILLIPS PETROLEUM COMPANY (cont)

MATERIAL	FORMULA	PURITY	COST
n-Hexadecane	$C_{16}H_{34}$	99.0% (Pure)	0.71b-$15.00, 1.51b-$24.00
n-Hexadecane	$C_{16}H_{34}$	95% (Technical)	1.51b-$21.50, 6.41b-$58.30
n-Heptadecane	$C_{17}H_{36}$	95% (Technical)	0.71b-$11.85, 1.51b-$20.50
n-Octadecane	$C_{18}H_{38}$	95% (Technical)	0.71b-$11.85, 1.51b-$20.50
n-Nonadecane	$C_{19}H_{40}$	95% (Technical)	0.71b-$11.00, 1.51b-$19.00
n-Eicosane	$C_{20}H_{42}$	95% (Technical)	0.71b-$16.00, 1.51b-$28.00
n-Eicosane	$C_{20}H_{42}$	90%	1.51b-$20.50, 6.41b-$58.30

*Information obtained from Hydrocarbons and Petrosulfur compounds, price list number 17. Phillips Petroleum Company. Similar information available for many other compounds from same source.

Table 12 HUMPHREY CHEMICAL COMPANY*

MATERIAL	FORMULA	CATALOG NUMBER	PURITY	COST
n-Nonane	C_9H_{20}	A9	99%	0.25gal-$20.00, 1.0gal-$72.00 1 gal 6.0 lbs
n-Decane	$C_{10}H_{22}$	A10	99%	0.25gal-$11.00, 1.0gal-$45.00 1 gal 6.1 lbs
n-Undecane	$C_{11}H_{24}$	A11	99%	0.25gal-$29.00, 1.0gal-$66.00 1 gal 6.2 lbs
n-Dodecane	$C_{12}H_{26}$	A12	99%	0.25gal-$12.00, 1.0gal-$47.00 1 gal 6.3 lbs
n-Tridecane	$C_{13}H_{28}$	A13	99%	0.25gal-$29.00, 1.0gal-$100.00 1 gal 6.3 lbs
n-Tetradecane	$C_{14}H_{30}$	A14	99%	0.25gal-$14.00, 1.0gal-$55.00 1 gal 6.4 lbs
n-Pentadecane	$C_{15}H_{32}$	A15	99%	0.25gal-$30.00, 1.0gal-$120.00 1 gal 6.4 lbs
n-Hexadecane	$C_{16}H_{34}$	A16	99%	0.25gal-$12.50, 1.0gal-$48.00 1 gal 6.4 lbs
n-Heptadecane	$C_{17}H_{36}$	A17	99%	0.25gal-$33.00, 1.0gal-$110.00 1 gal 6.4 lbs
n-Octadecane	$C_{18}H_{38}$	A18	99%	0.25gal-$14.00, 1.0gal-$55.00 1 gal 6.5 lbs
n-Nonadecane	$C_{19}H_{40}$	A19	99%	0.25gal-$36.00, 1.0gal-$120.00 1 gal 6.5 lbs
n-Eicosane	$C_{20}H_{42}$	A20	99%	0.25gal-$20.00, 1.0gal-$78.00 1 gal 6.6 lbs

*Information obtained from Humphrey Chemical Company Catalog. Similar information available for other compounds from same source.

Table 13. DENSITY (LIQUID PHASE)

	MATERIAL	lbm/ft^3 (30° F)	kg/m^3 (272 K)	lbm/ft^3 (60° F)	kg/m^3 (289 K)
AMERICAN PETROLEUM INSTITUTE	n-Undecane	47.2	756.1	46.4	743.6
	n-Dodecane	47.7	764.6	47.0	752.1
	n-Tridecane	48.2	771.6	47.4	759.3
	n-Hexadecane	--	--	48.5*	776.4*
	n-Octadecane	--	--	49.0*	784.7*
	n-Nonadecane	--	--	49.2*	788.4*
	n-Eicosane	--	--	49.4*	791.3*

	MATERIAL	lbm/ft^3 (68° F)	kg/m^3 (293 K)	lbm/ft^3 (77° F)	kg/m^3 (298 K)
AMERICAN PETROLEUM INSTITUTE	n-Undecane	46.2	740.2	46.0	736.5
	n-Dodecane	46.7	748.7	46.5	745.2
	n-Tridecane	47.2	756.2	47.0	752.7
	n-Hexadecane	48.3	773.4	48.1	770.1
	n-Octadecane	48.8*	781.9*	48.6*	778.3*
	n-Nonadecane	49.0*	785.4*	48.8*	782.0*
	n-Eicosane	49.2*	788.6*	49.0*	785.2*

Table 13 DENSITY (LIQUID PHASE) continued

	MATERIAL	lbm/ft^3 (100° F)	kg/m^3 (311 K)
AMERICAN PETROLEUM INSTITUTE	n-Undecane	45.4	727.1
	n-Dodecane	46.0	736.1
	n-Tridecane	46.4	743.1
	n-Hexadecane	47.5	761.2
	n-Octadecane	48.1	769.9
	n-Nonadecane	46.5	773.5
	n-Eicosane	48.5	776.9

* Undercooled liquid below normal freezing point.

Table 14 SURFACE TENSION

	MATERIAL	lbf/in (68° F)	N/M (293 K)	lbf/in (104° F)	N/M (313 K)
AMERICAN PETROLEUM INSTITUTE	n-Undecane	14.1×10^{-5}	24.7×10^{-3}	13.1×10^{-5}	22.9×10^{-3}
	n-Dodecane	14.5×10^{-5}	25.4×10^{-3}	$\times 10^{-5}$	23.6×10^{-3}
	n-Tridecane	14.8×10^{-5}	26.0×10^{-3}	13.9×10^{-5}	24.2×10^{-3}
	n-Hexadecane	15.7×10^{-5}	27.5×10^{-3}	14.7×10^{-5}	25.8×10^{-3}
	n-Octadecane	$16.2^* \times 10^{-5}$	$28.3^* \times 10^{-3}$	15.2×10^{-5}	26.6×10^{-3}
	n-Nonadecane	$16.3^* \times 10^{-5}$	$28.6^* \times 10^{-3}$	15.4×10^{-5}	26.9×10^{-3}
	n-Eicosane	16.5* x 10-5	$28.9^* \times 10^{-3}$	15.5×10^{-5}	27.2×10^{-3}

	MATERIAL	lbf/in (140° F)	N/M (333 K)	lbf/in (176° F)	N/M (353 K)
AMERICAN PETROLEUM INSTITUTE	n-Undecane	12.0×10^{-5}	21.1×10^{-3}	11.0×10^{-5}	19.3×10^{-3}
	n-Dodecane	12.5×10^{-5}	21.8×10^{-3}	11.5×10^{-5}	20.1×10^{-3}
	n-Tridecane	12.9×10^{-5}	22.5×10^{-3}	11.9×10^{-5}	20.8×10^{-3}
	n-Hexadecane	13.7×10^{-5}	24.1×10^{-3}	12.8×10^{-5}	22.4×10^{-3}
	n-Octadecane	14.2×10^{-5}	24.9×10^{-3}	13.3×10^{-5}	23.2×10^{-3}
	n-Nonadecane	14.4×10^{-5}	25.2×10^{-3}	13.5×10^{-5}	23.6×10^{-3}
	n-Eicosane	14.5×10^{-5}	25.5×10^{-3}	13.6×10^{-5}	23.9×10^{-3}

* Undercooled liquid below normal freezing point.

Table 15 ABSOLUTE VISCOSITY

	MATERIAL	$lbf\text{-}sec/ft^2$ (50° F)	$N\text{-}sec/m^2$ (283 K)	$lbf\text{-}sec/ft^2$ (68° F)	$N\text{-}sec/m^2$ (293 K)
AMERICAN PETROLEUM INSTITUTE	n-Undecane	2.96×10^{-5}	1.42×10^{-3}	2.48×10^{-5}	1.19×10^{-3}
	n-Dodecane	3.82×10^{-5}	1.83×10^{-3}	3.14×10^{-5}	1.50×10^{-3}
	n-Tridecane	4.80×10^{-5}	2.30×10^{-3}	3.93×10^{-5}	1.88×10^{-3}
	n-Hexadecane	----	----	7.26×10^{-5}	3.47×10^{-3}
	n-Octadecane	----	----	----	----
	n-Nonadecane	----	----	----	----
	n-Eicosane	----	----	----	----

	MATERIAL	$lbf\text{-}sec/ft^2$ (86° F)	$N\text{-}sec/m^2$ (303 K)	$lbf\text{-}sec/ft^2$ (104° F)	$N\text{-}sec/m^2$ (313 K)
AMERICAN PETROLEUM INSTITUTE	n-Undecane	2.11×10^{-5}	1.01×10^{-3}	1.82×10^{-5}	0.87×10^{-3}
	n-Dodecane	2.63×10^{-5}	1.26×10^{-3}	2.25×10^{-5}	1.08×10^{-3}
	n-Tridecane	3.25×10^{-5}	1.56×10^{-3}	2.74×10^{-5}	1.31×10^{-3}
	n-Hexadecane	5.76×10^{-5}	2.76×10^{-3}	4.69×10^{-5}	2.24×10^{-3}
	n-Octadecane	8.10×10^{-5}	3.88×10^{-3}	6.44×10^{-5}	3.08×10^{-3}
	n-Nonadecane	----	----	7.47×10^{-5}	3.58×10^{-3}
	n-Eicosane	----	----	8.66×10^{-5}	4.14×10^{-3}

Table 15 ABSOLUTE VISCOSITY (continued)

	MATERIAL	lbf-sec/ft^2 (122° F)	N-sec/m^2 (323 K)	lbf-sec/ft^2 (140° F)	N-sec/m^2 (333 K)
AMERICAN PETROLEUM INSTITUTE	n-Undecane	1.59×10^{-5}	0.76×10^{-3}	1.40×10^{-5}	0.67×10^{-3}
	n-Dodecane	1.94×10^{-5}	0.93×10^{-3}	1.70×10^{-5}	0.81×10^{-3}
	n-Tridecane	2.34×10^{-5}	1.12×10^{-3}	2.03×10^{-5}	0.97×10^{-3}
	n-Hexadecane	3.89×10^{-5}	1.86×10^{-3}	3.28×10^{-5}	1.57×10^{-3}
	n-Octadecane	5.24×10^{-5}	2.51×10^{-3}	4.35×10^{-5}	2.08×10^{-3}
	n-Nonadecane	6.02×10^{-5}	2.88×10^{-3}	4.95×10^{-5}	2.37×10^{-3}
	n-Eicosane	6.91×10^{-5}	3.31×10^{-3}	5.64×10^{-5}	2.70×10^{-3}

Table 16 HEAT OF COMBUSTION (77° F/298 K)

	MATERIAL	STATE	H_2O (liquid) Btu/lb	CO_2 (gas) Joule/Kg	H_2O (gas) Btu/lb	CO_2 (gas) Joule/Kg
AMERICAN PETROLEUM INSTITUTE	n-Undecane	gas	20.6×10^3	47.9×10^6	19.1×10^3	44.5×10^6
		liquid	20.4×10^3	47.5×10^6	19.0×10^3	44.1×10^6
	n-Dodecane	gas	20.6×10^3	47.8×10^6	19.1×10^3	44.4×10^6
		liquid	20.4×10^3	47.4×10^6	19.0×10^3	44.1×10^6
	n-Tridecane	gas	20.5×10^3	47.7×10^6	19.1×10^3	44.4×10^6
		liquid	20.4×10^3	47.4×10^6	18.9×10^3	44.0×10^6
	n-Hexadecane	gas	20.5×10^3	47.6×10^6	19.1×10^3	44.3×10^6
		liquid	20.3×10^3	47.2×10^6	19.0×10^3	43.9×10^6
	n-Octadecane	gas	20.4×10^3	47.5×10^6	19.0×10^3	44.2×10^6
		liquid*	20.3×10^3	47.2×10^6	19.0×10^3	43.9×10^6
	n-Nonadecane	gas	20.4×10^3	47.5×10^6	18.9×10^3	42.2×10^6
		liquid*	20.3×10^3	47.1×10^6	19.0×10^3	44.2×10^6
	n-Eicosane	gas	20.4×10^3	47.5×10^6	19.0×10^3	44.2×10^6
		liquid*	20.3×10^3	47.1×10^6	18.9×10^3	43.8×10^6

* Undercooled liquid below normal freezing point temperature.

Table 17 FLASH POINT

	MATERIAL	TEMPERATURE °F	K
AMERICAN PETROLEUM INSTITUTE	n-Undecane	149	338
	n-Dodecane	160	344
	n-Tridecane	175	352
	n-Hexadecane	-	-
	n-Octadecane	-	-
	n-Nonadecane	-	-
	n-Eicosane	-	-

Table 18 COEFFICIENT OF EXPANSION (60° F/289 K)

	MATERIAL	1/°F	1/K
AMERICAN PETROLEUM INSTITUTE	n-Undecane	5.6×10^{-4}	10.1×10^{-4}
	n-Dodecane	5.5×10^{-4}	9.9×10^{-4}
	n-Tridecane	5.2×10^{-4}	9.4×10^{-4}
	n-Hexadecane	----	----
	n-Octadecane	----	----
	n-Nonadecane	----	----
	n-Eicosane	4.7×10^{-4}	8.5×10^{-4}

Table 19. HEAT OF FUSION AND TRANSITION

UNDECANE - DODECANE SYSTEM				
Weight Percent Dodecane	Heat of Fusion		Heat of Transition	
	Joule/Kg	Btu/lb	Joule/Kg	Btu/lb
0	14.0×10^4	60.4	4.39×10^4	18.9
10	10.0×10^4	43.1	---	-
20	5.0×10^4	21.6	---	-
30	4.5×10^4	19.4	---	-
40	3.5×10^4	15.1	---	-
50	0.5×10^4	2.2	---	-
60	3.0×10^4	12.9	---	-
70	6.0×10^4	25.8	---	-
80	10.0×10^4	43.1	---	-
90	15.0×10^4	64.7	---	-
100	21.8×10^4	94.0	---	-

Table 20. HEAT OF FUSION AND TRANSITION

UNDECANE - HEXADECANE SYSTEM				
Weight Percent Hexadecane	Heat of Fusion		Heat of Transition	
	Joule/Kg	Btu/lb	Joule/Kg	Btu/lb
0	14.0×10^4	60.4	4.05×10^4	17.5
10	10.0×10^4	43.1	2.5×10^4	10.8
20	4.0×10^4	17.2	---	-
30	5.0×10^4	21.6	2.5×10^4	10.8
40	5.0×10^4	21.6	---	-
50	4.5×10^4	19.4	---	-
60	6.5×10^4	28.0	3.0×10^4	12.9
70	10.0×10^4	43.1	3.0×10^4	12.9
80	11.5×10^4	49.6	3.0×10^4	12.9
90	17.5×10^4	75.4	3.0×10^4	12.9
100	23.7×10^4	102.0	---	-

Table 21. HEAT OF FUSION AND TRANSITION

DODECANE - TRIDECANE SYSTEM				
Weight Percent Tridecane	Heat of Fusion		Heat of Transition	
	Joule/Kg	Btu/lb	Joule/Kg	Btu/lb
0	21.8×10^4	94.0	---	-
10	17.0×10^4	73.3	2.5×10^4	10.8
20	13.5×10^4	58.2	2.0×10^4	8.6
30	10.5×10^4	45.3	1.7×10^4	7.3
40	8.5×10^4	36.6	1.6×10^4	6.9
50	6.7×10^4	28.7	0.5×10^4	2.2
60	7.7×10^4	33.2	1.2×10^4	5.2
70	9.4×10^4	40.5	1.7×10^4	7.3
80	11.5×10^4	49.6	2.0×10^4	8.6
90	13.7×10^4	59.0	3.0×10^4	12.9
100	14.5×10^4	62.5	4.33×10^4	18.7

Table 22. HEAT OF FUSION AND TRANSITION

DODECANE - NONADECANE SYSTEM				
Weight Percent Nonadecane	Heat of Fusion		Heat of Transition	
	Joule/Kg	Btu/lb	Joule/Kg	Btu/lb
0	21.8×10^4	94.0	---	-
10	12.0×10^4	51.7	---	-
20	10.0×10^4	43.1	---	-
30	6.5×10^4	28.0	---	-
40	5.2×10^4	22.4	---	-
50	5.9×10^4	25.4	4.0×10^4	17.2
60	10.0×10^4	43.1	4.0×10^4	17.2
70	8.7×10^4	37.5	5.0×10^4	21.6
80	12.3×10^4	53.0	4.0×10^4	17.2
90	15.2×10^4	65.5	---	-
100	18.0×10^4	107.5	5.13×10^4	22.1

Table 23. HEAT OF FUSION AND TRANSITION

DODECANE - EICOSANE SYSTEM				
Weight Percent Eicosane	Heat of Fusion		Heat of Transition	
	Joule/Kg	Btu/lb	Joule/Kg	Btu/lb
0	21.8×10^4	94	---	---
10	12.5×10^4	53.9	---	---
20	8.5×10^4	36.6	---	---
30	6.3×10^4	27.2	---	---
40	7.7×10^4	33.2	---	---
50	7.8×10^4	33.6	---	---
60	8.8×10^4	37.9	---	---
70	9.4×10^4	40.5	---	---
80	12.3×10^4	53.0	---	---
90	16.7×10^4	72.0	---	---
100	24.9×10^4	107	---	---

Table 24. HEAT OF FUSION AND TRANSITION

TRIDECANE - OCTADECANE SYSTEM				
Weight Percent Octadecane	Heat of Fusion		Heat of Transition	
	Joule/Kg	Btu/lb	Joule/Kg	Btu/lb
0	14.5×10^4	62.5	4.33×10^4	18.7
10	10.2×10^4	44.0		
20	9.6×10^4	41.4	4.5×10^4	19.4
30	4.2×10^4	18.1	4.0×10^4	17.2
40	5.2×10^4	22.4	---	---
50	5.6×10^4	24.1	5.0×10^4	21.6
60	9.0×10^4	38.8	5.0×10^4	21.6
70	12.6×10^4	54.3	5.0×10^4	21.6
80	17.5×10^4	75.4	---	---
90	22.5×10^4	97.0	5.0×10^4	21.6
100	24.9×10^4	107.5	---	---

Table 25. HEAT OF FUSION AND TRANSITION

HEXADECANE - OCTADECANE SYSTEM				
Weight Percent Octadecane	Heat of Fusion		Heat of Transition	
	Joule/Kg	Btu/lb	Joule/Kg	Btu/lb
0	23.7×10^4	102.0	---	--
10	18.0×10^4	77.6	---	--
20	13.7×10^4	59.0	2.0×10^4	8.62
30	10.2×10^4	43.9	2.0×10^4	8.62
40	9.2×10^4	39.6	1.5×10^4	6.46
50	9.2×10^4	39.6	1.5×10^4	6.46
60	11.1×10^4	47.8	2.0×10^4	8.62
70	13.6×10^4	58.6	2.5×10^4	10.85
80	16.6×10^4	71.5	---	--
90	19.5×10^4	84.0	---	--
100	24.8×10^4	107.0	---	--

Table 26. HEAT OF FUSION AND TRANSITION

OCTADECANE - NONADECANE SYSTEM				
Weight Percent Nonadecane	Heat of Fusion		Heat of Transition	
	Joule/Kg	Btu/lb	Joule/Kg	Btu/lb
0	24.8×10^4	107	---	--
10	16.0×10^4	68.9	4.0×10^4	17.2
20	13.4×10^4	57.7	3.0×10^4	12.9
30	10.5×10^4	45.3	2.8×10^4	12.1
40	10.1×10^4	43.5	2.5×10^4	10.8
50	9.3×10^4	40.1	2.0×10^4	8.62
60	10.5×10^4	45.3	2.5×10^4	10.8
70	11.2×10^4	48.3	3.0×10^4	12.9
80	14.2×10^4	61.2	3.3×10^4	14.2
90	15.6×10^4	67.2	4.0×10^4	17.24
100	18.0×10^4	77.5	5.13×10^4	22.1

Table 27. HEAT OF FUSION AND TRANSITION

NONADECANE - EICOSANE SYSTEM				
Weight Percent Eicosane	Heat of Fusion		Heat of Transition	
	Joule/Kg	Btu/lb	Joule/Kg	Btu/lb
0	18.0×10^4	77.5	4.95×10^4	21.4
10	15.0×10^4	64.7	3.3×10^4	14.2
20	12.7×10^4	54.7	2.8×10^4	12.1
30	10.1×10^4	43.5	2.6×10^4	11.2
40	10.0×10^4	43.1	2.6×10^4	11.2
50	10.1×10^4	43.5	1.5×10^4	6.5
60	11.7×10^4	50.9	2.1×10^4	9.1
70	13.4×10^4	57.7	2.6×10^4	11.2
80	16.5×10^4	71.1	3.7×10^4	15.9
90	20.0×10^4	86.2	5.0×10^4	21.6
100	24.9×10^4	107.5	---	--

Table 28. MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

ALLOY	TEMPER	TENSILE STRENGTH psi	TENSILE STRENGTH N/m^2	YIELD STRENGTH psi	YIELD STRENGTH N/m^2	SHEAR STRENGTH psi	SHEAR STRENGTH N/m^2	HARDNESS Bhn	FATIGUE LIMIT* psi	FATIGUE LIMIT* N/m^2
1100	0	13.0×10^3	8.96×10^7	5.0×10^3	3.45×10^7	9.0×10^3	6.20×10^7	23	5.0×10^3	3.45×10^7
	H12	16.0×10^3	11.03×10^7	15.0×10^3	10.34×10^7	10.0×10^3	6.89×10^7	28	6.0×10^3	4.13×10^7
	H14	18.0×10^3	12.4×10^7	17.0×10^3	11.71×10^7	11.0×10^3	7.58×10^7	32	7.0×10^3	4.82×10^7
	H16	21.0×10^3	14.74×10^7	20.0×10^3	13.79×10^7	12.0×10^3	8.27×10^7	38	9.0×10^3	6.20×10^7
	H18	24.0×10^3	16.54×10^7	22.0×10^3	15.17×10^7	13.0×10^3	8.96×10^7	44	9.0×10^3	6.20×10^7
2014	0	27.0×10^3	18.61×10^7	14.0×10^3	9.65×10^7	18.0×10^3	12.40×10^7	45	13.0×10^3	8.96×10^7
	T4	62.0×10^3	42.74×10^7	42.0×10^3	28.95×10^7	38.0×10^3	26.19×10^7	105	20.0×10^3	13.79×10^7
	T6	70.0×10^3	48.26×10^7	60.0×10^3	41.36×10^7	42.0×10^3	28.94×10^7	135	18.0×10^3	12.40×10^7
2024	0	27.0×10^3	18.61×10^7	11.0×10^3	75.83×10^7	18.0×10^3	12.40×10^7	47	13.0×10^3	8.96×10^7
	T3	70.0×10^3	48.26×10^7	50.0×10^3	34.47×10^7	41.0×10^3	28.26×10^7	120	20.0×10^3	13.79×10^7
	T4	68.0×10^3	46.88×10^7	47.0×10^3	32.4×10^7	41.0×10^3	28.26×10^7	120	20.0×10^3	13.79×10^7
	T36	72.0×10^3	49.64×10^7	57.0×10^3	39.30×10^7	42.0×10^3	28.94×10^7	130	18.0×10^3	12.40×10^7

*Based on 5×10^8 cycles R. R. Moore Test

Table 29. MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

ALLOY	TEMPER	TENSILE STRENGTH psi	TENSILE STRENGTH N/m^2	YIELD STRENGTH psi	YIELD STRENGTH N/m^2	SHEAR STRENGTH psi	SHEAR STRENGTH N/m^2	HARDNESS Bhn	FATIGUE LIMIT* psi	FATIGUE LIMIT* N/m^2
3003	0	16.0×10^3	11.03×10^7	6.0×10^3	4.13×10^7	11.0×10^3	7.58×10^7	28	7.0×10^3	4.82×10^7
	H12	19.0×10^3	13.09×10^7	18.0×10^3	12.40×10^7	12.0×10^3	8.27×10^7	35	8.0×10^3	5.51×10^7
	H14	22.0×10^3	15.17×10^7	21.0×10^3	14.47×10^7	14.0×10^3	9.65×10^7	40	9.0×10^3	6.20×10^7
	H16	26.0×10^3	17.92×10^7	25.0×10^3	17.23×10^7	15.0×10^3	10.34×10^7	47	10.0×10^3	6.89×10^7
	H18	29.0×10^3	19.99×10^7	27.0×10^3	18.61×10^7	16.0×10^3	11.03×10^7	55	10.0×10^3	6.89×10^7
5052	0	28.0×10^3	19.30×10^7	13.0×10^3	8.96×10^7	18.0×10^3	12.40×10^7	47	16.0×10^3	11.03×10^7
	H32	33.0×10^3	22.70×10^7	28.0×10^3	19.30×10^7	20.0×10^3	13.78×10^7	60	17.0×10^3	11.71×10^7
	H34	38.0×10^3	26.19×10^7	31.0×10^3	21.37×10^7	21.0×10^3	14.47×10^7	68	18.0×10^3	12.40×10^7
	H36	40.0×10^3	27.57×10^7	35.0×10^3	24.13×10^7	23.0×10^3	15.85×10^7	73	19.0×10^3	13.09×10^7
	H38	42.0×10^3	28.95×10^7	37.0×10^3	25.50×10^7	24.0×10^3	16.54×10^7	77	20.0×10^3	13.78×10^7
6061	0	18.0×10^3	12.40×10^7	8.0×10^3	5.51×10^7	12.0×10^3	8.27×10^7	30	9.0×10^3	6.20×10^7
	T4	35.0×10^3	24.12×10^7	21.0×10^3	14.47×10^7	24.0×10^3	16.54×10^7	65	14.0×10^3	9.65×10^7
	T6	45.0×10^3	31.02×10^7	40.0×10^3	27.57×10^7	30.0×10^3	20.68×10^7	95	14.0×10^3	9.65×10^7
7075	0	33.0×10^3	22.75×10^7	15.0×10^3	10.34×10^7	22.0×10^3	15.16×10^7	60	-	-
	T6	83.0×10^3	57.22×10^7	73.0×10^3	50.32×10^7	48.0×10^3	33.09×10^7	150	23.0×10^3	15.85×10^7

*Based on 5.0×10^8 cycles R. R. Moore Test

Table 30. MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

ALLOY	TEMPER	MODULUS OF ELASTICITY psi	MODULUS OF ELASTICITY N/m^2	MODULUS OF RIGIDITY psi	MODULUS OF RIGIDITY N/m^2	POISSON'S RATIO
1100	All	10.0×10^6	6.89×10^{10}	3.75×10^6	2.59×10^{10}	0.33
2014	All	10.0×10^6	6.89×10^{10}	4.0×10^6	2.75×10^{10}	0.33
2024	All	10.1×10^6	6.96×10^{10}	4.0×10^6	2.75×10^{10}	0.33
3003	All	10.0×10^6	6.89×10^{10}	3.75×10^6	2.59×10^{10}	0.33
5052	All	10.2×10^6	7.03×10^{10}	3.75×10^6	2.59×10^{10}	0.33
6061	All	10.0×10^6	6.89×10^{10}	3.75×10^6	2.59×10^{10}	0.33
7075	All	10.4×10^6	7.16×10^{10}	3.90×10^6	2.68×10^{10}	0.33

Table 31. PHYSICAL PROPERTIES OF ALUMINUM ALLOYS

ALLOY	TEMPER	DENSITY 68°F-293k		SPECIFIC HEAT 212°F-373K		THERMAL CONDUCTIVITY		THERMAL EXPANSION 68°F-293k	
		lb_m/ft^3	kg/m^3	Joule/kgK	Btu/lb°F	Btu/hr ft °F	Watt/mK	1/°F	1/°K
1100	All	1.69×10^2	2.71×10^4	962.32	0.23	128.2	221	12.2×10^{-6}	22.0×10^{-6}
2014	All	1.75×10^2	2.80×10^4	962.32	0.23	111.3	192.5	11.8×10^{-6}	21.4×10^{-6}
2024	All	1.73×10^2	2.77×10^4	962.32	0.23	108.9	188.4	11.8×10^{-6}	21.4×10^{-6}
3003	All	1.71×10^2	2.73×10^4	962.32	0.23	111.3	192.5	11.8×10^{-6}	21.4×10^{-6}
5052	All	1.67×10^2	2.68×10^4	962.32	0.23	79.8	138.0	13.0×10^{-6}	23.4×10^{-6}
6061	All	1.69×10^2	2.70×10^4	962.32	0.23	99.2	171.6	12.9×10^{-6}	23.2×10^{-6}
7075	All	1.74×10^2	2.80×10^4	962.32	0.23	70.2	121.4	12.9×10^{-6}	23.2×10^{-6}

APPENDIX IB

QUANTITATIVE DATA (GRAPHICAL)

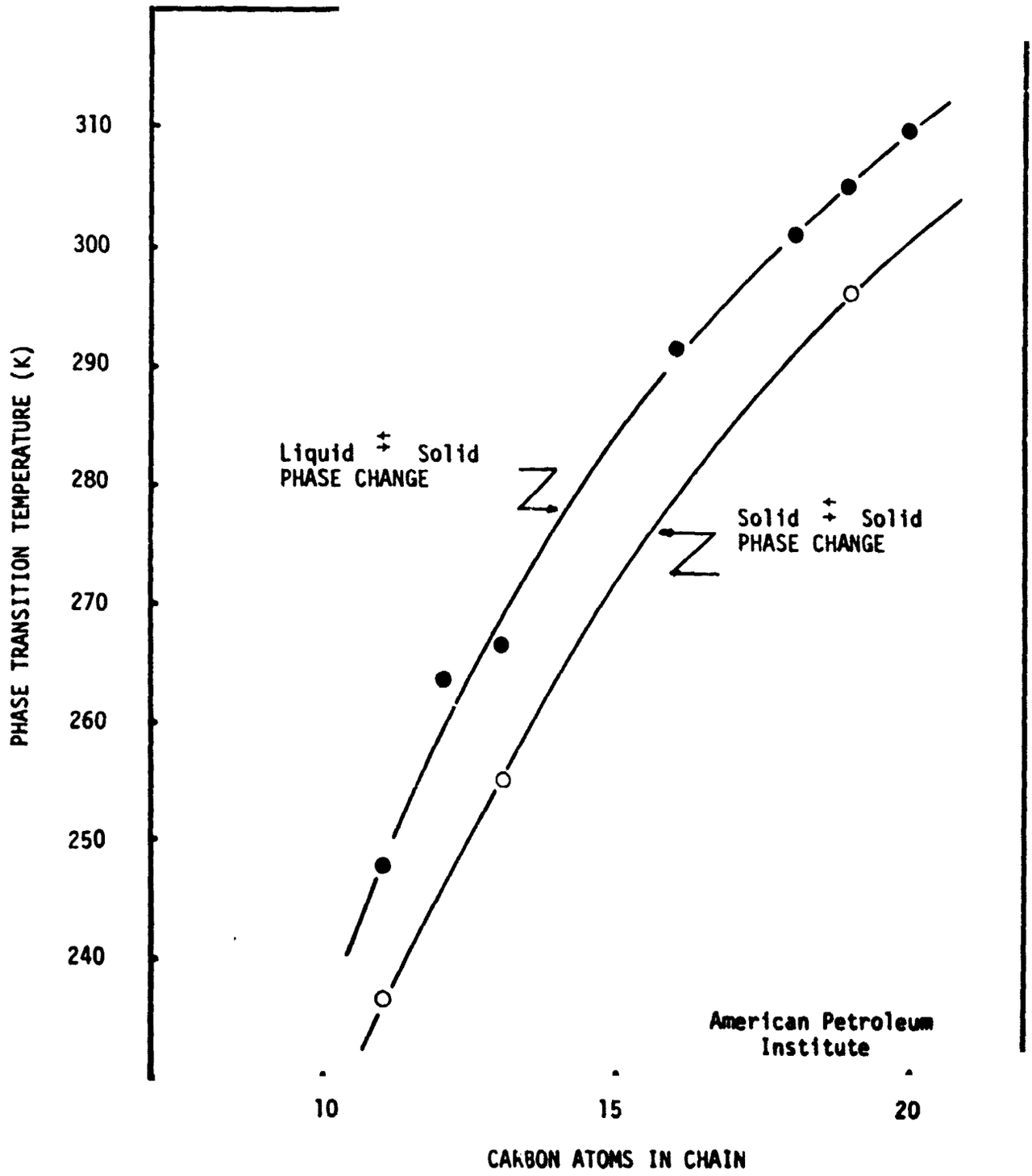

Figure 1. Effect of Carbon Chain Length on Phase Transition Temperature

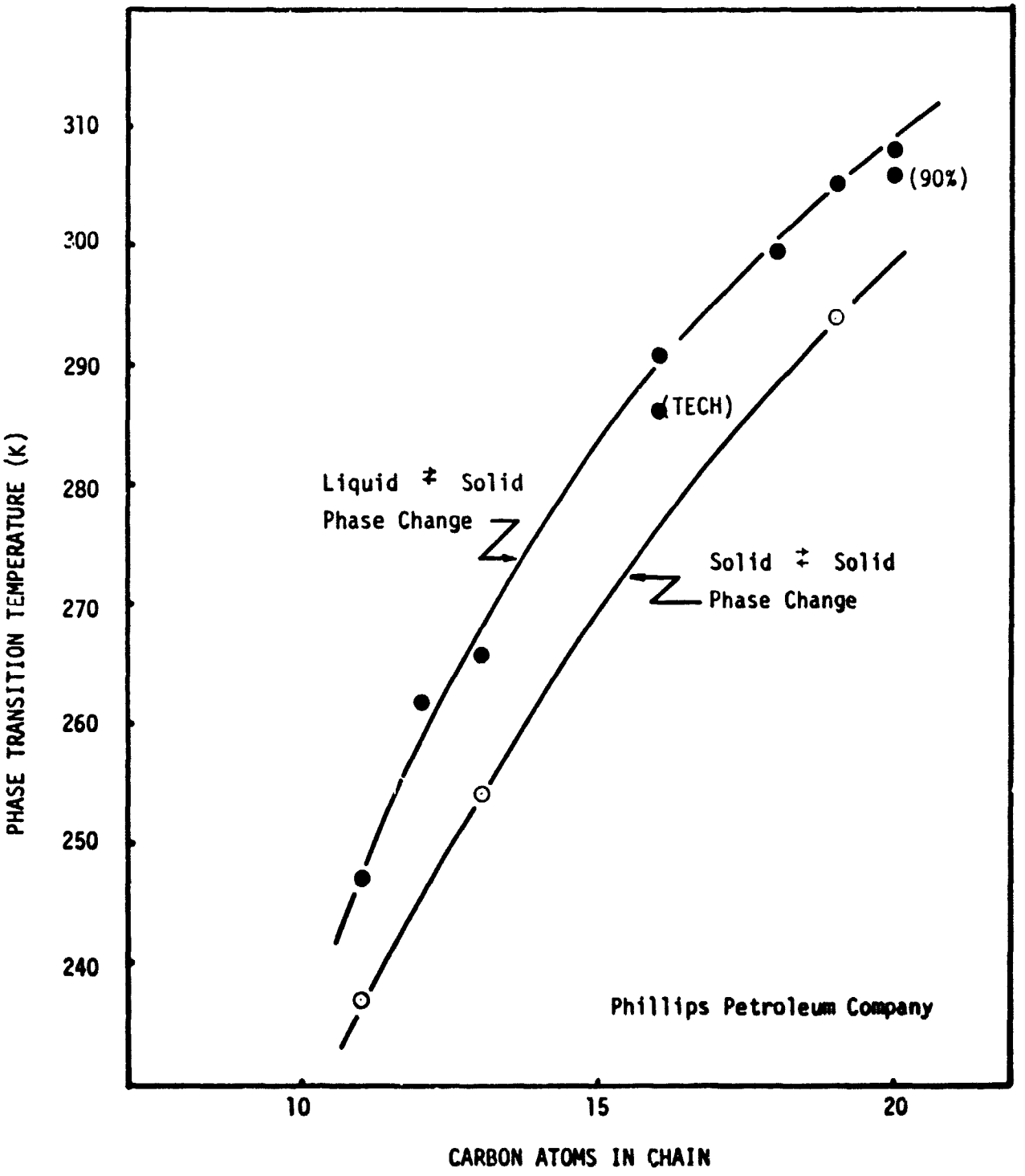

Figure 2. Effect of Carbon Chain Length on Phase Transition Temperature

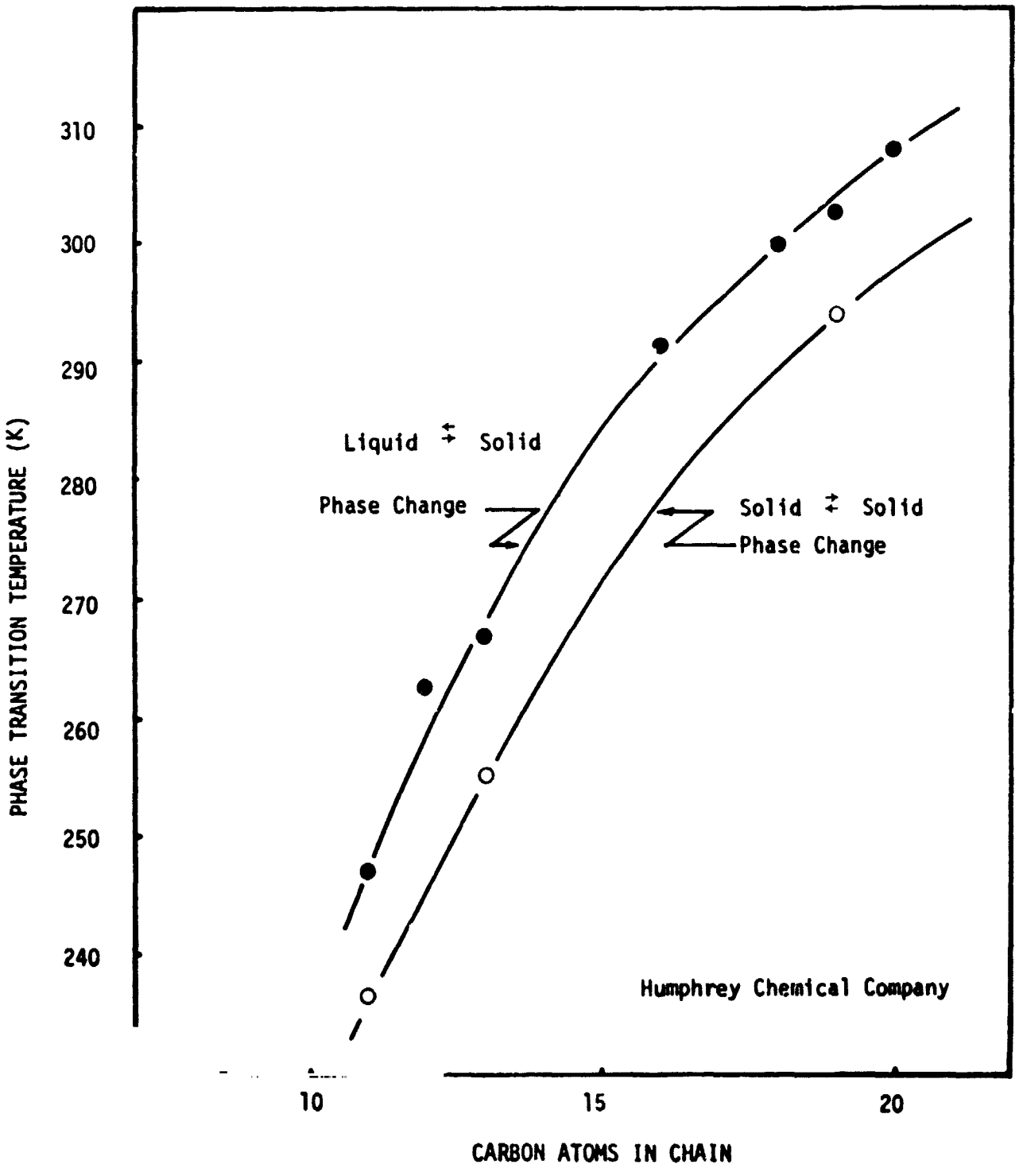

Figure 3. Effect of Carbon Chain Length on Phase Transition Temperature

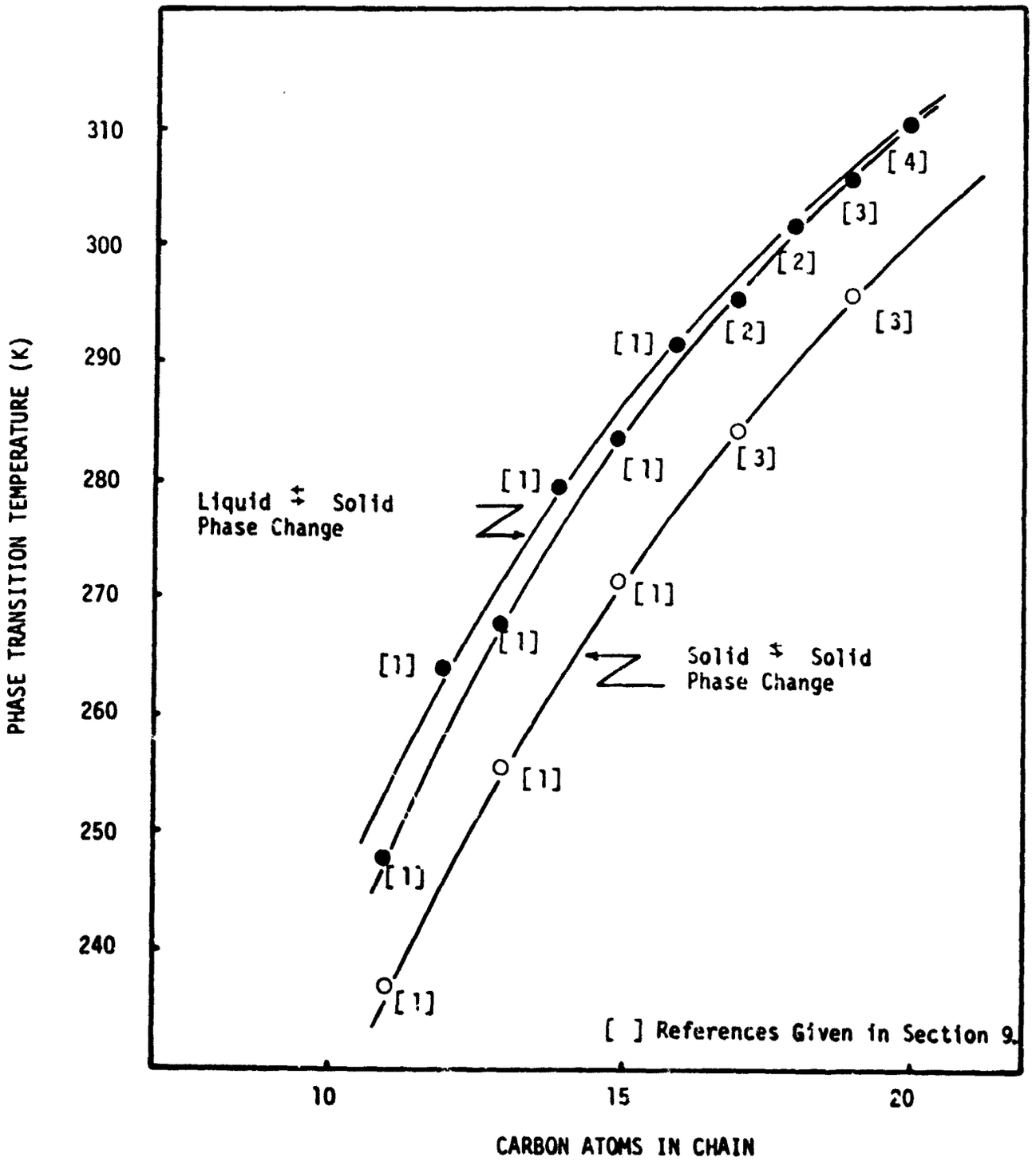

Figure 4. Effect of Carbon Chain Length on Phase Transition Temperature

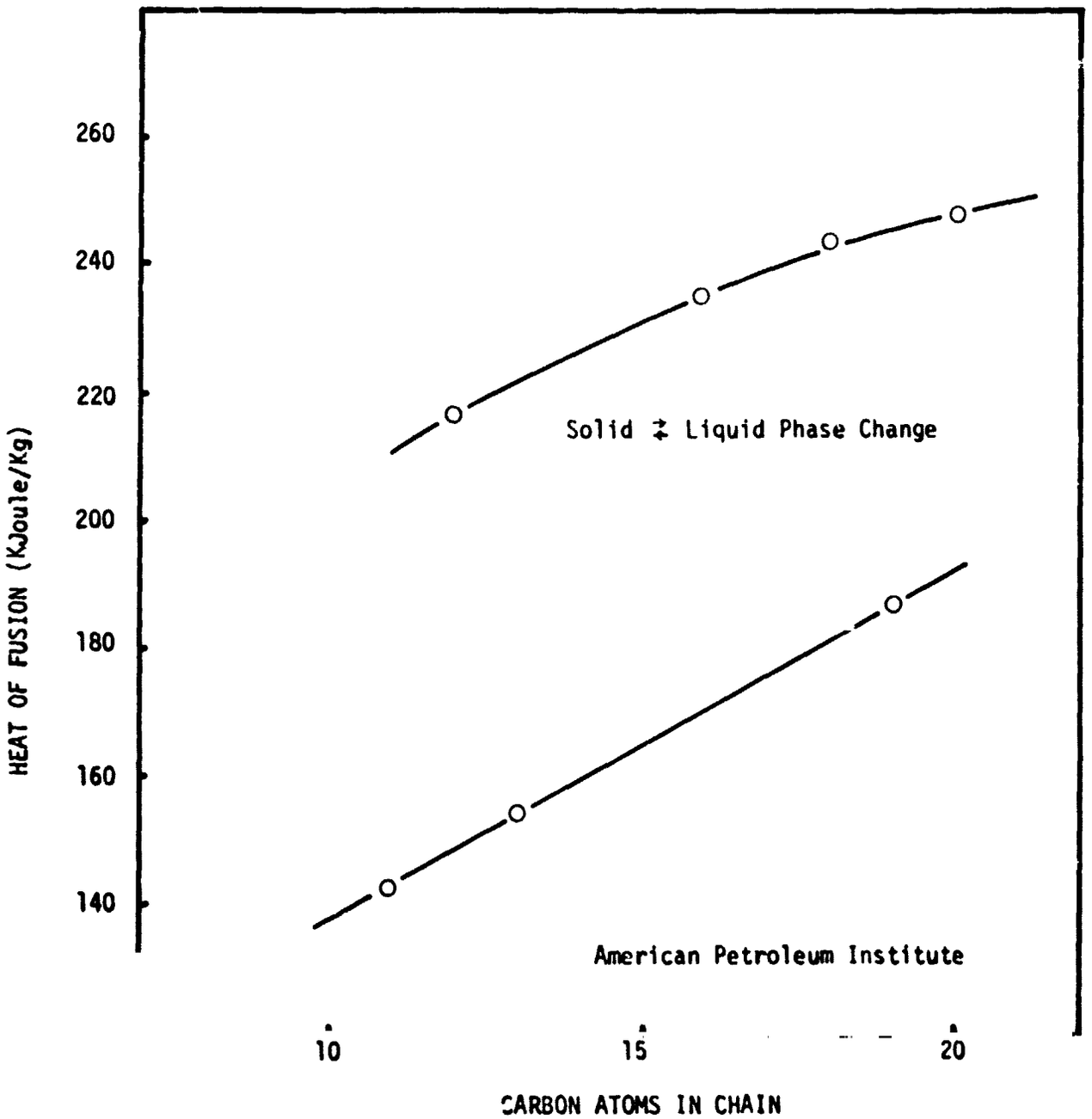

Figure 5(a) Effect of Carbon Chain Length on Heat of Fusion

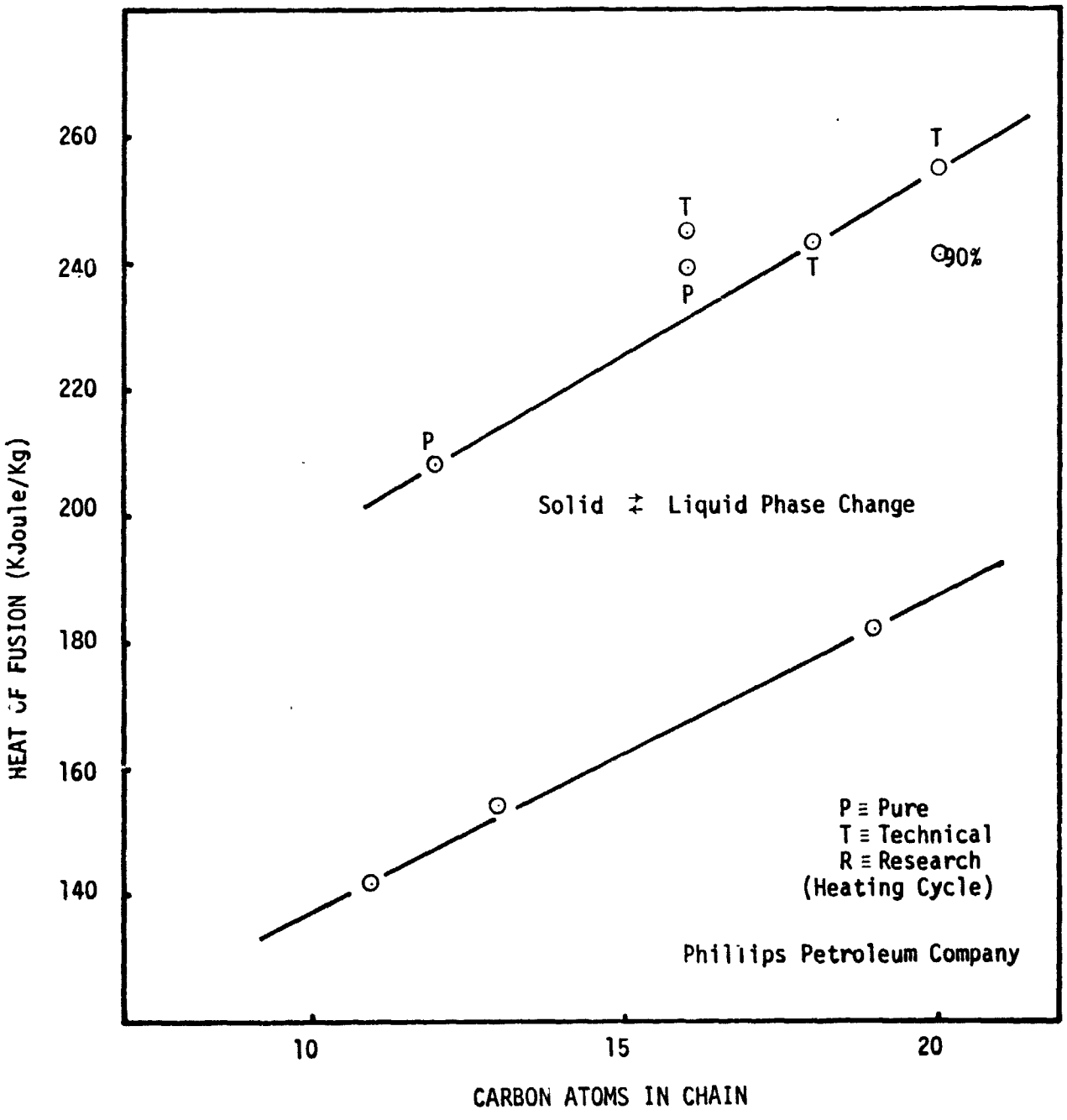

Figure 6(a) Effect of Carbon Chain Length on Heat of Fusion

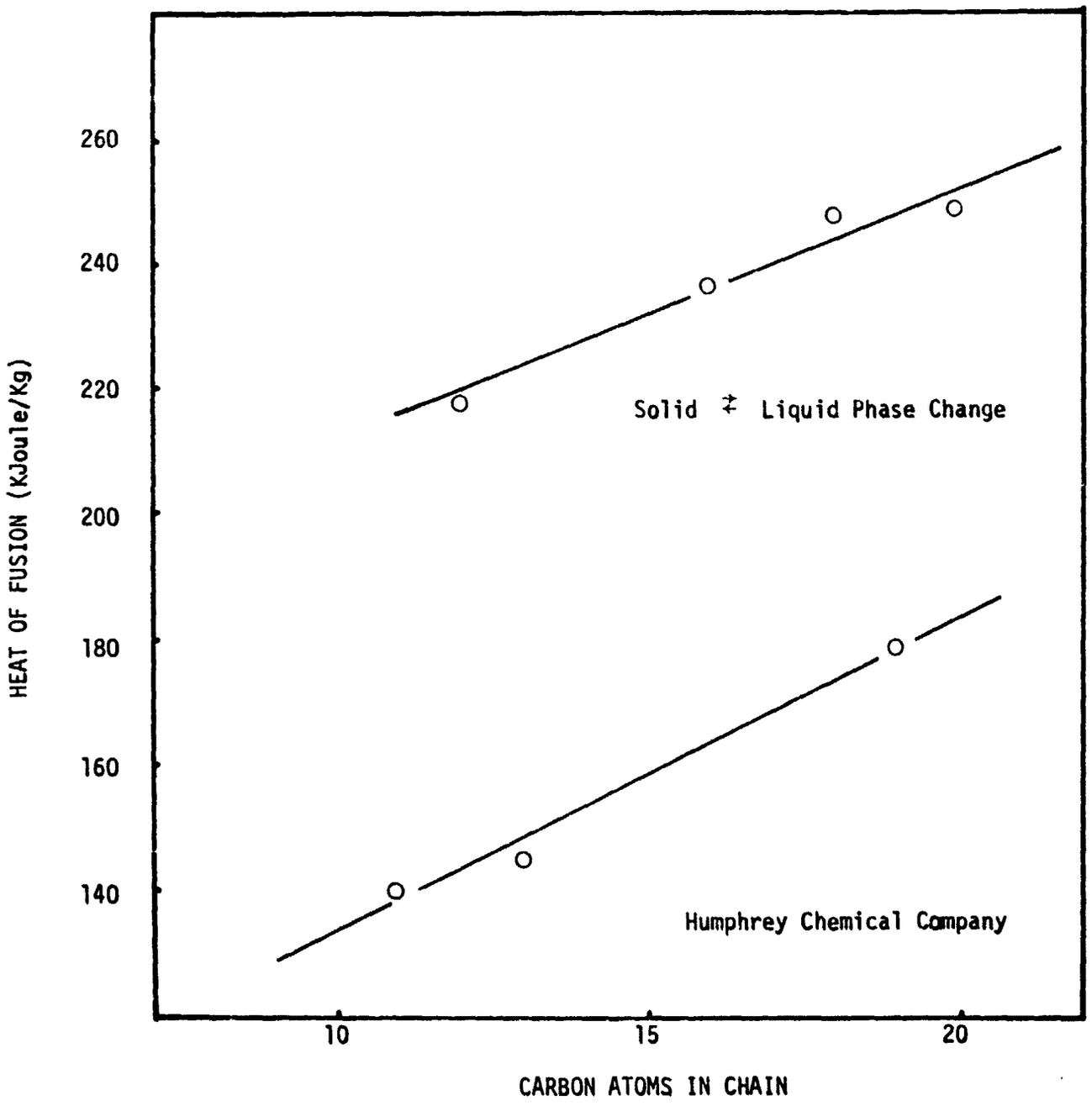

Figure 7(a) Effect of Carbon Chain Length on Heat of Fusion

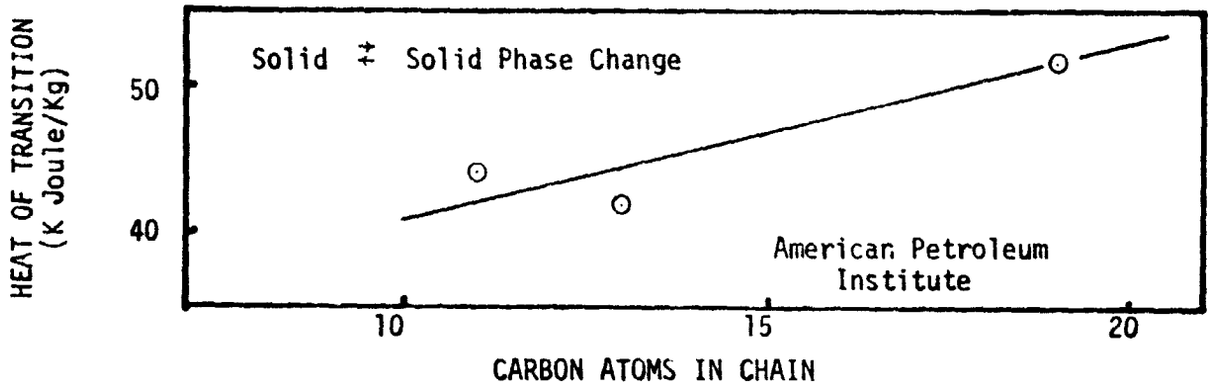

Figure 5(b). Effect of Carbon Chain Length on Heat of Transition

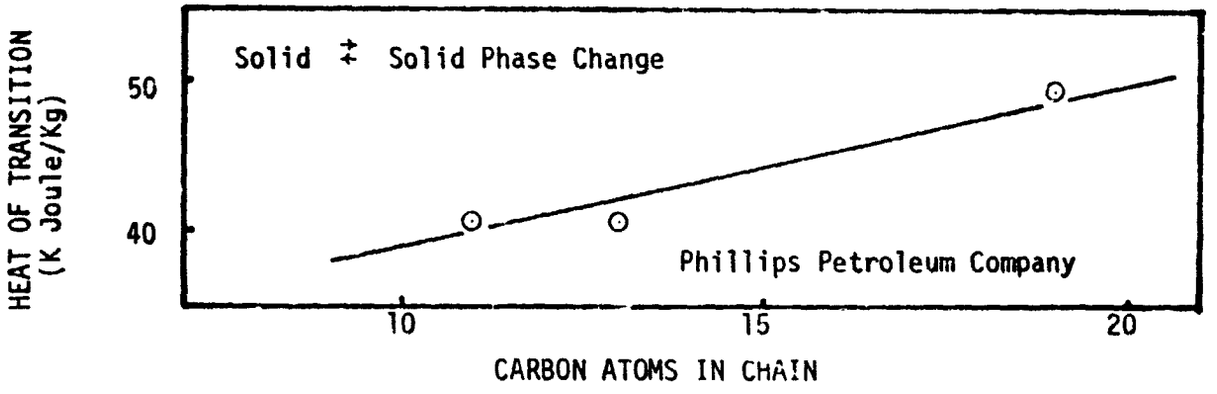

Figure 6(b) Effect of Carbon Chain Length on Heat of Transition

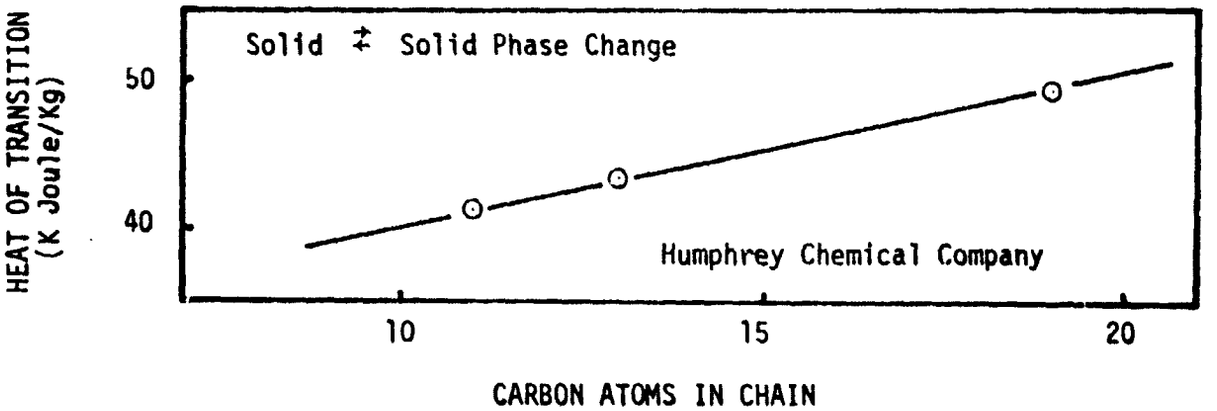

Figure 7(b) Effect of Carbon Chain Length on Heat of Transition

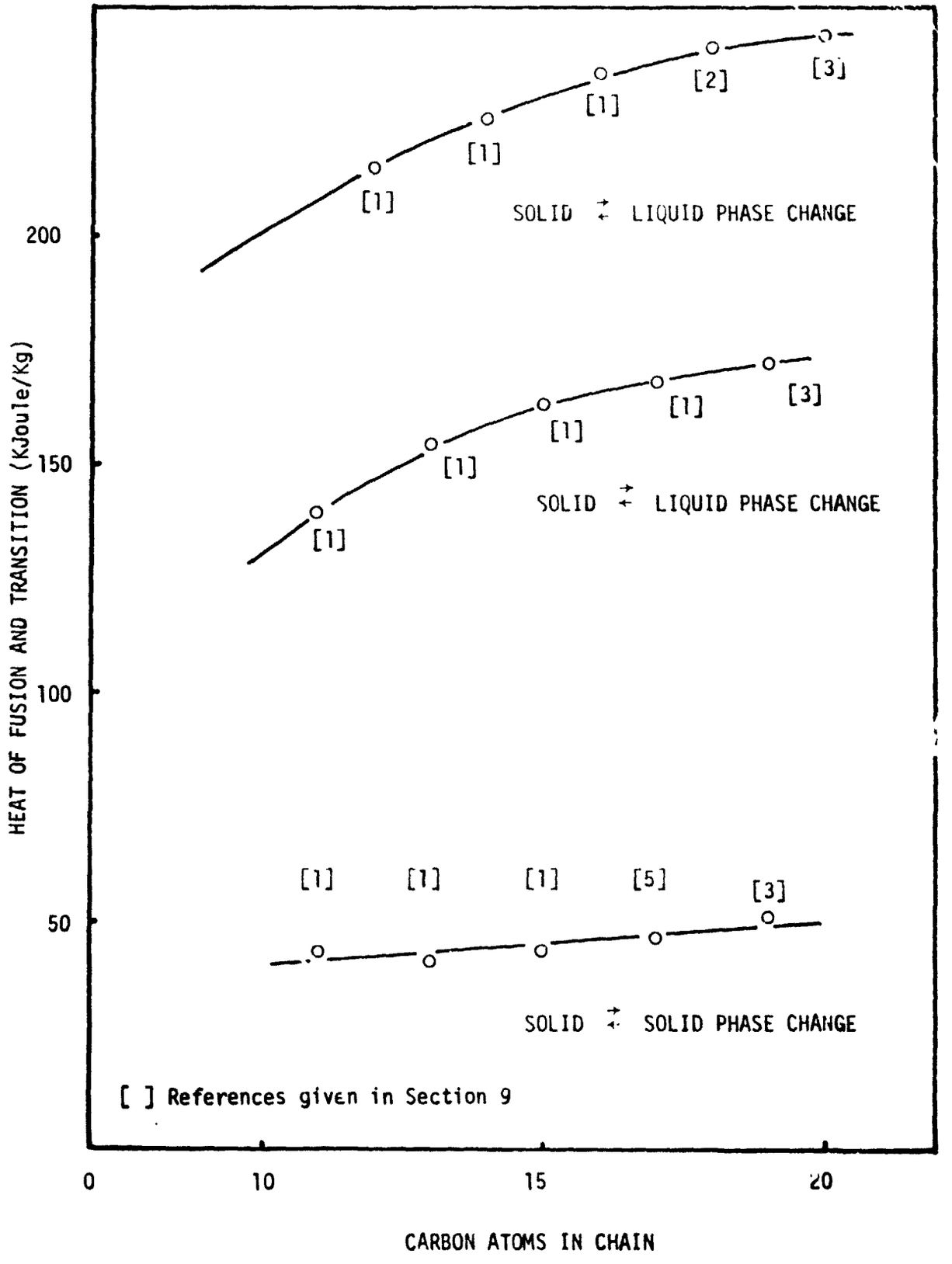

Figure 8. Effect of Carbon Chain Length on Heats of Fusion and Transition

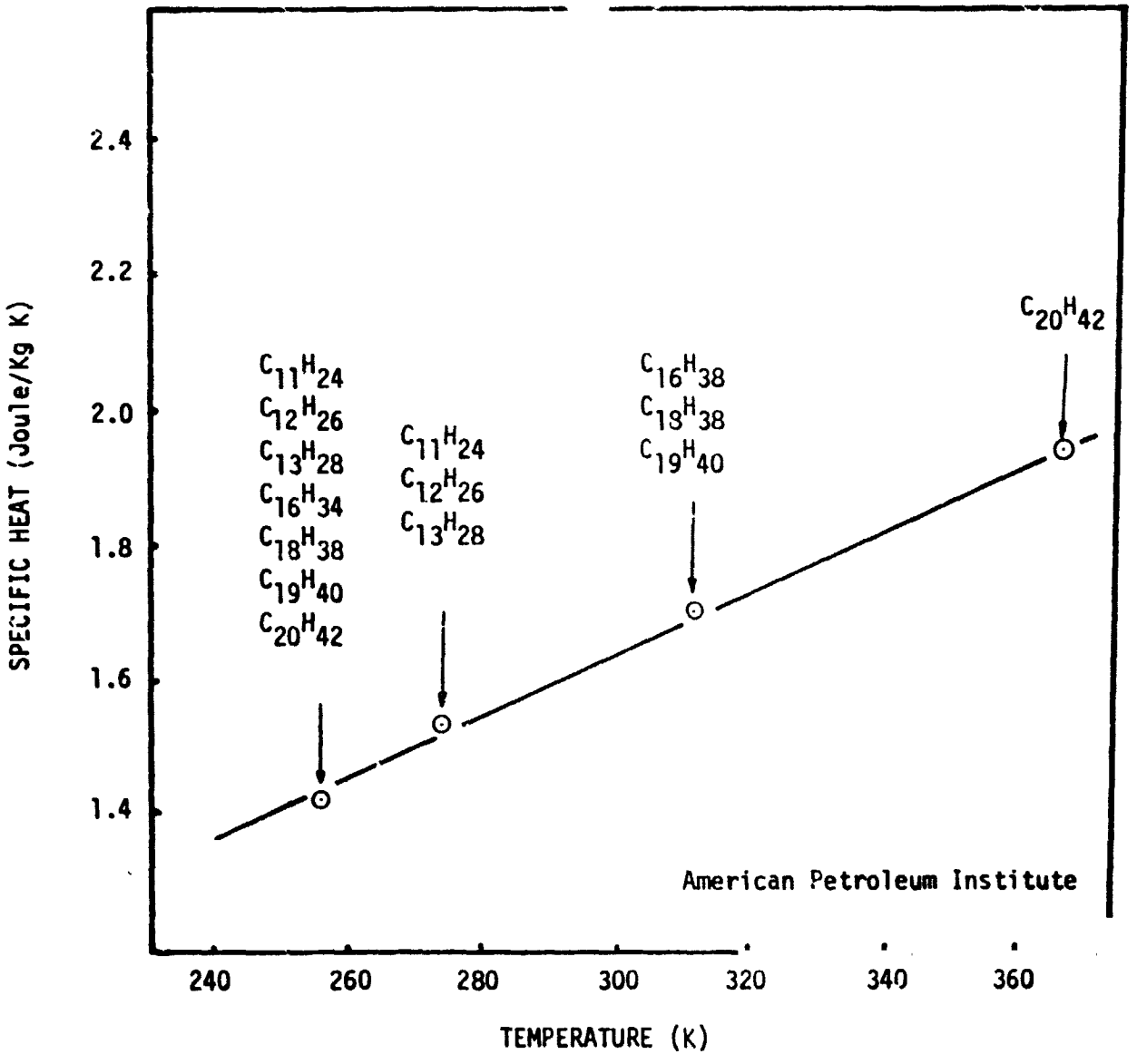

Figure 9. Effect of Temperature on Specific Heat

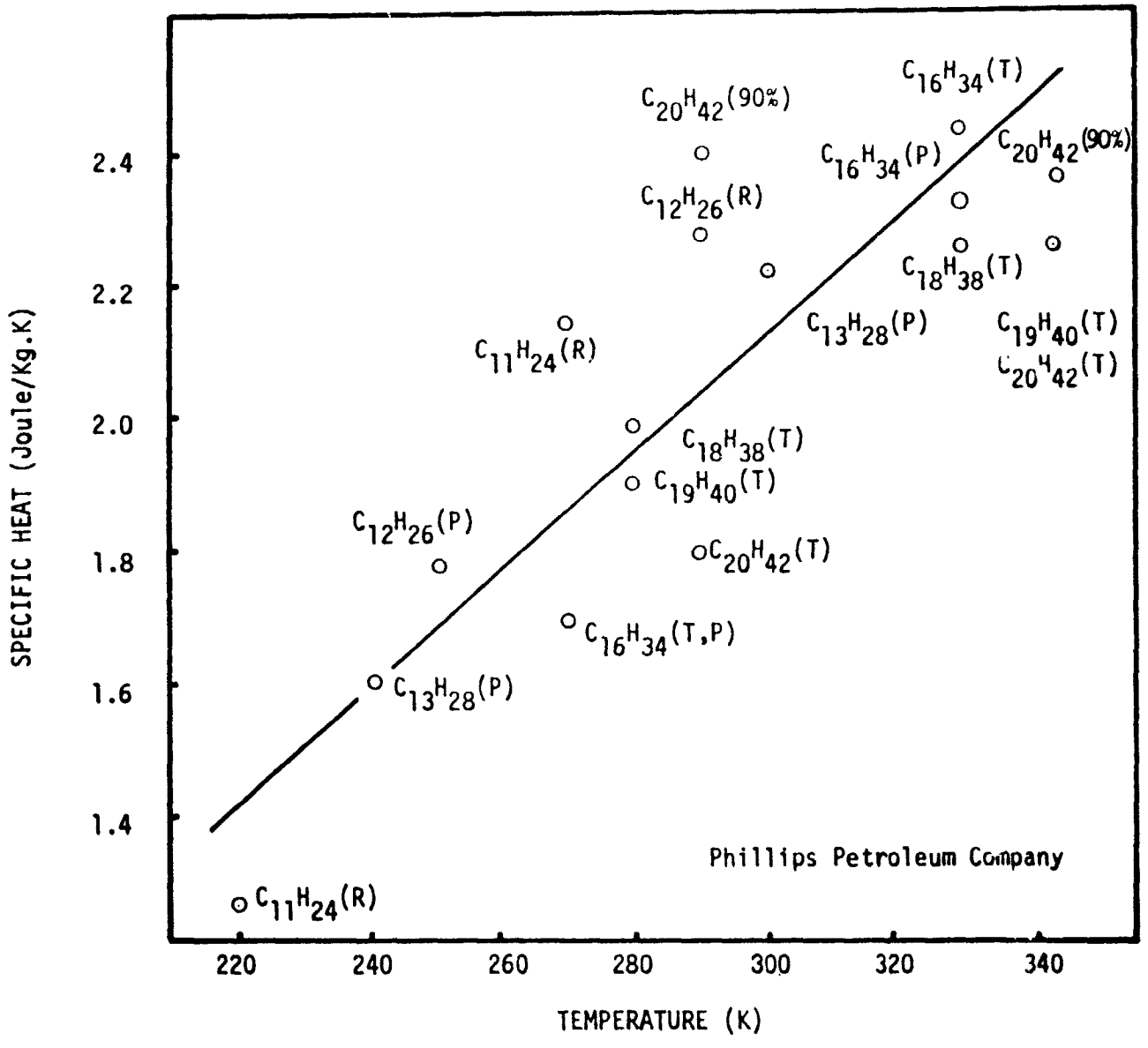

Figure 10. Effect of Temperature on Specific Heat

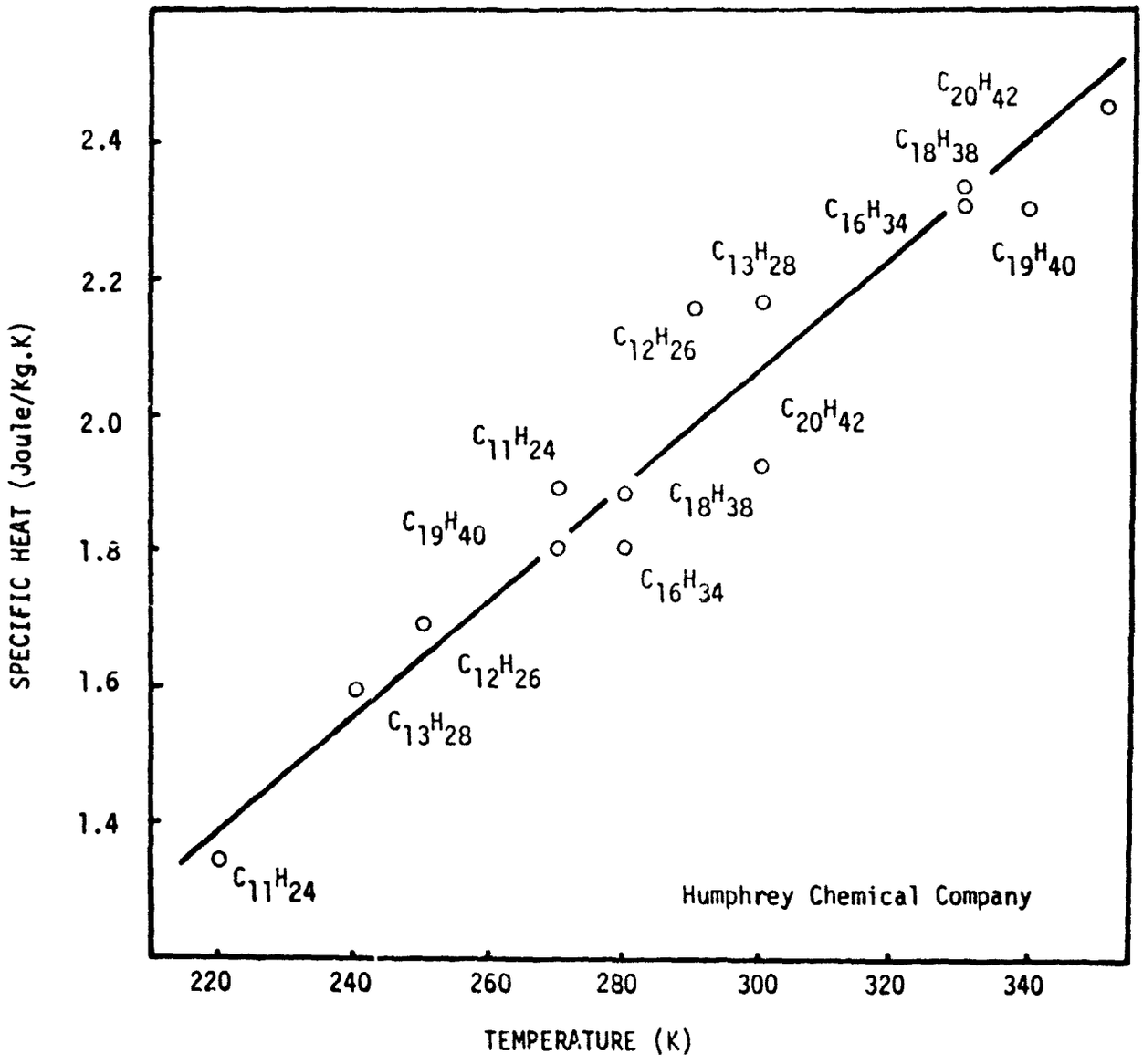

Figure 11. Effect of Temperature on Specific Heat

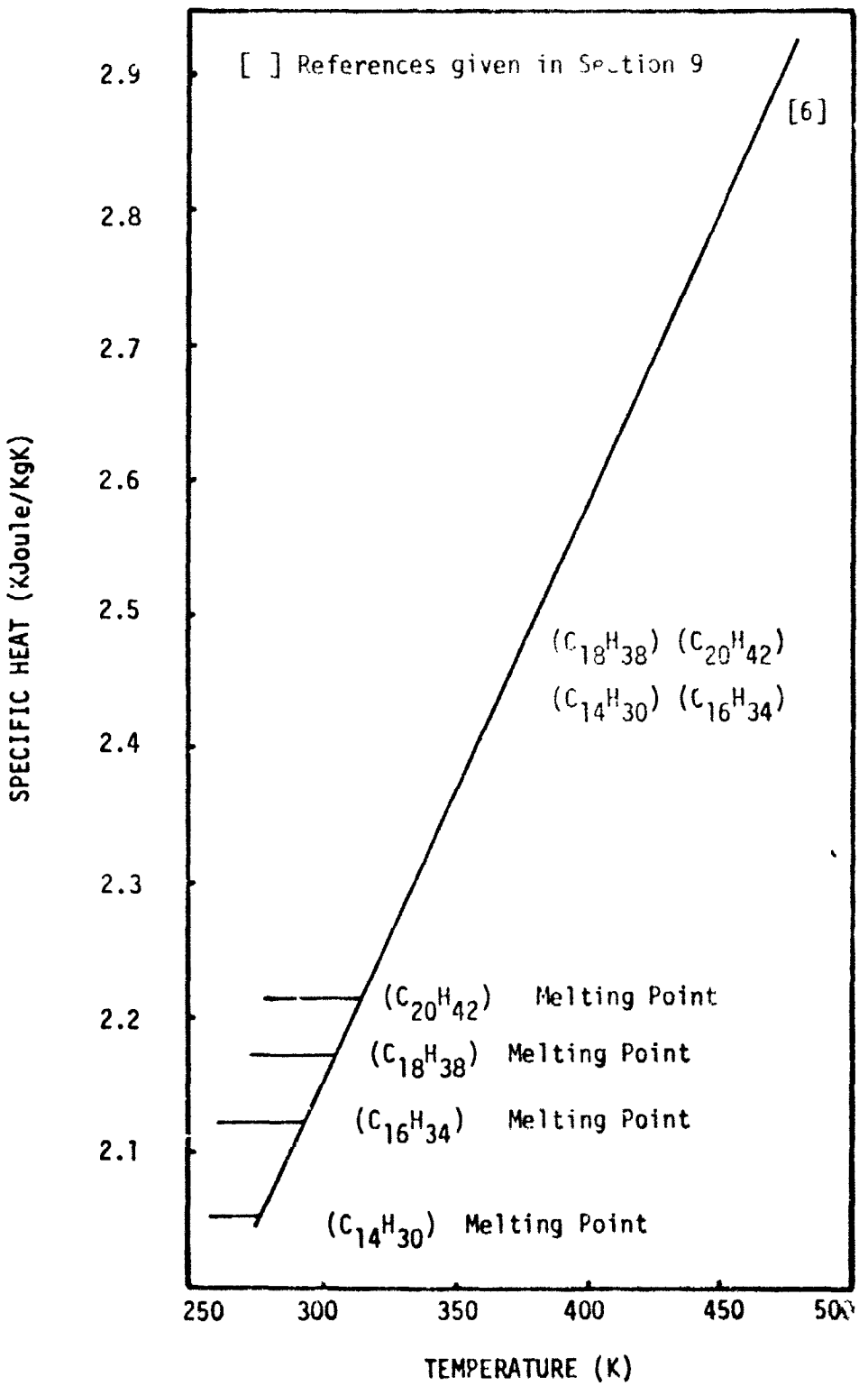

Figure 12. Effect of Temperature on Specific Heat

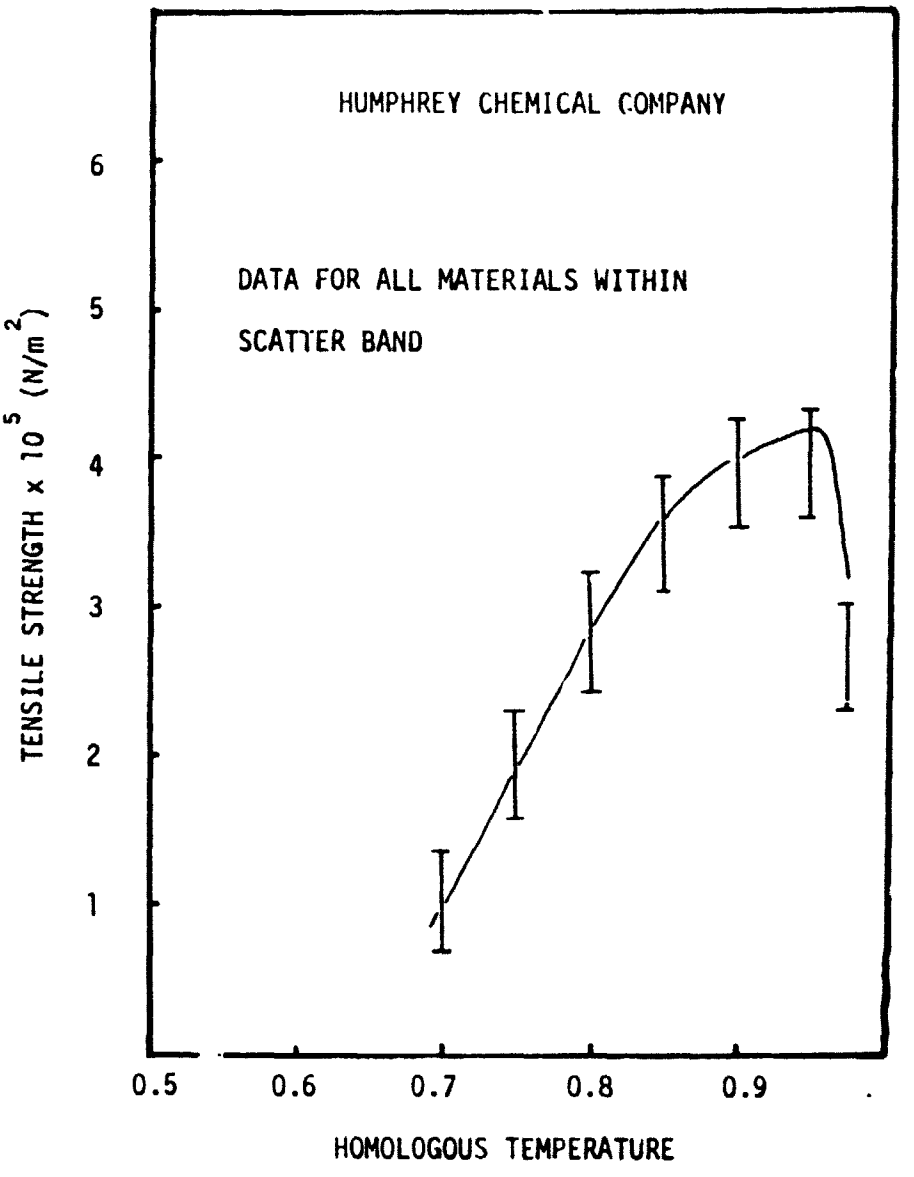

Figure 13. Effect of Homologous Temperature on Tensile Strength of Paraffin Hydrocarbons

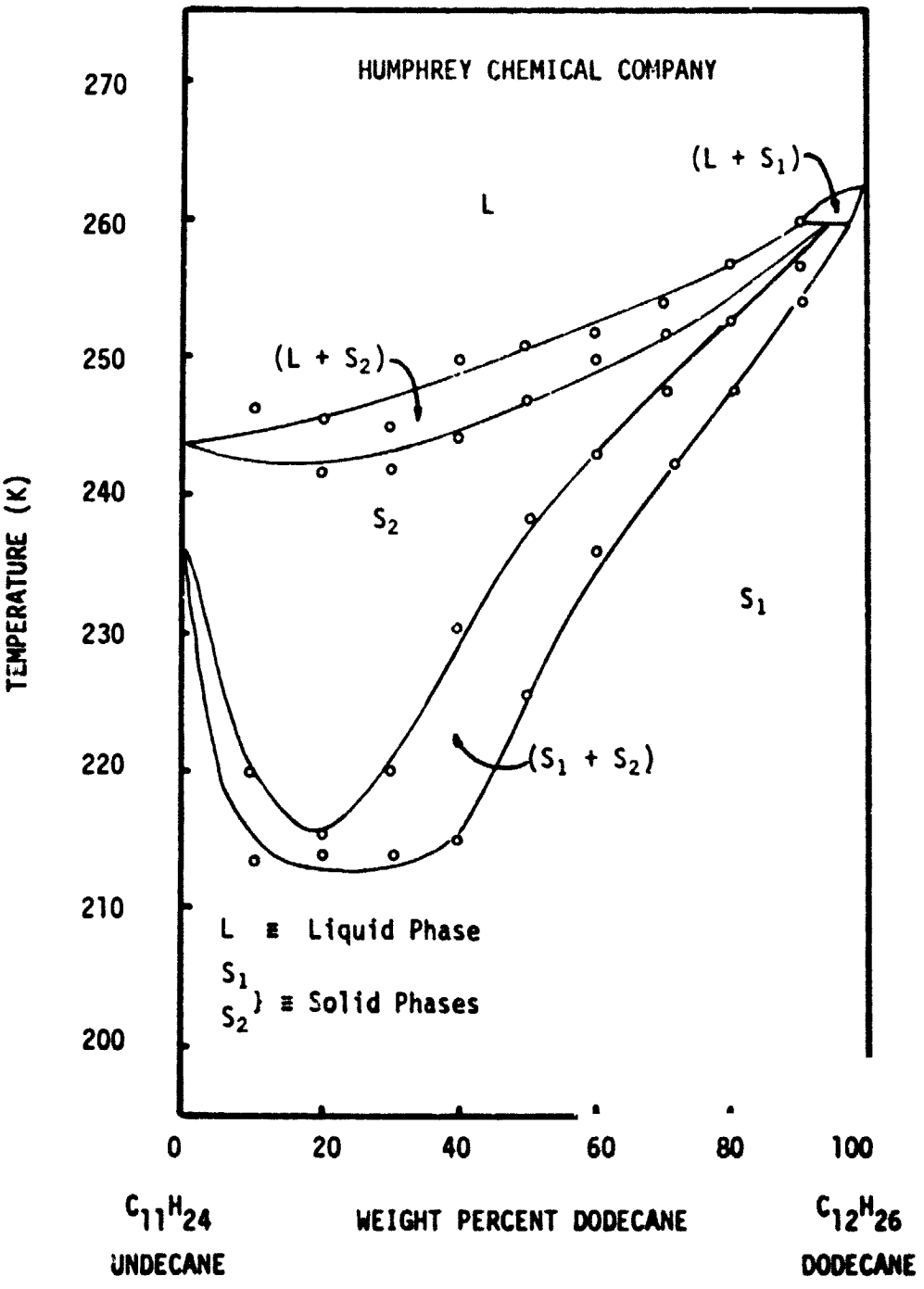

Figure 14. Undecane - Dodecane Binary System

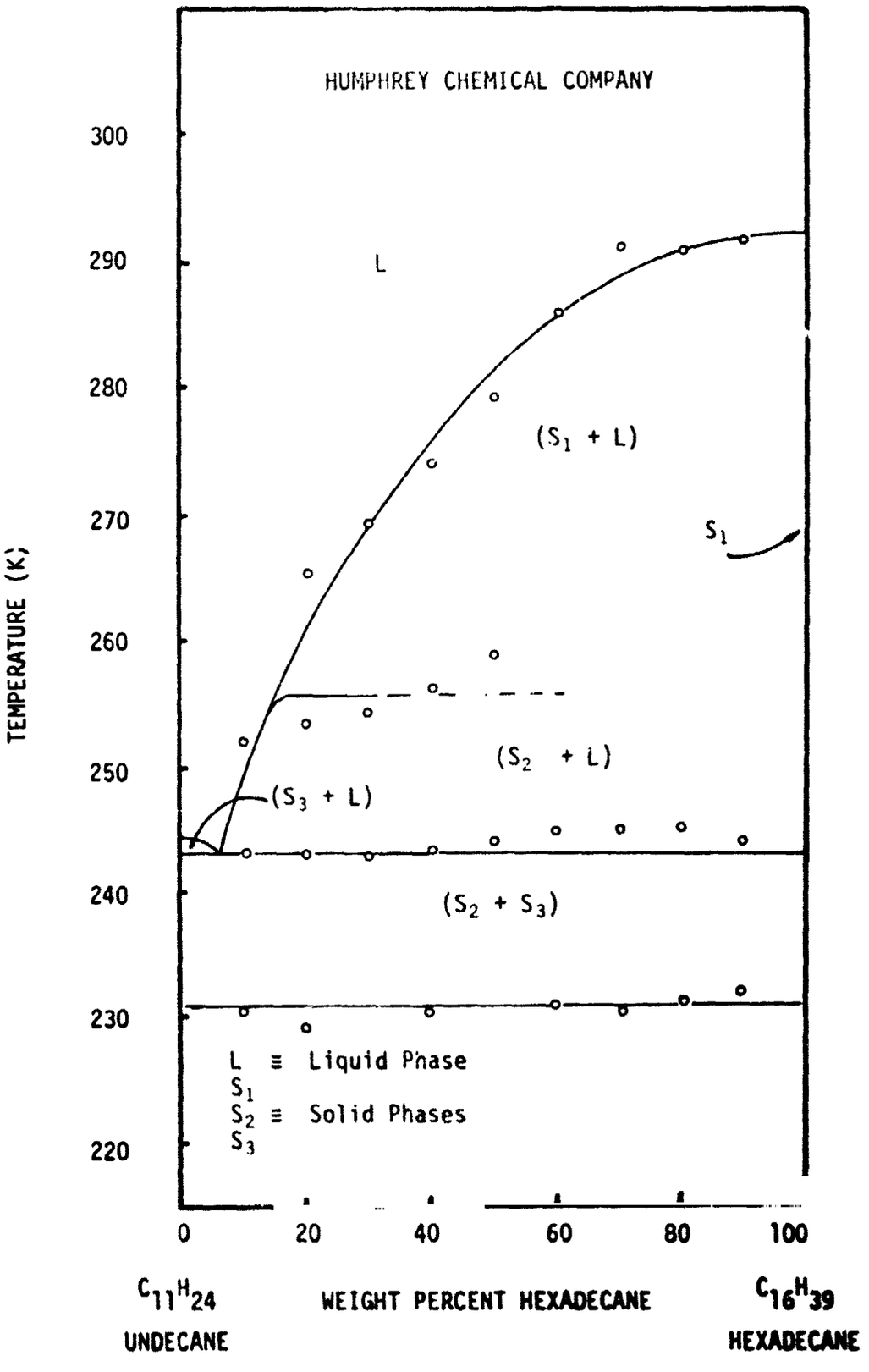

Figure 15. Undecane - Hexadecane Binary System

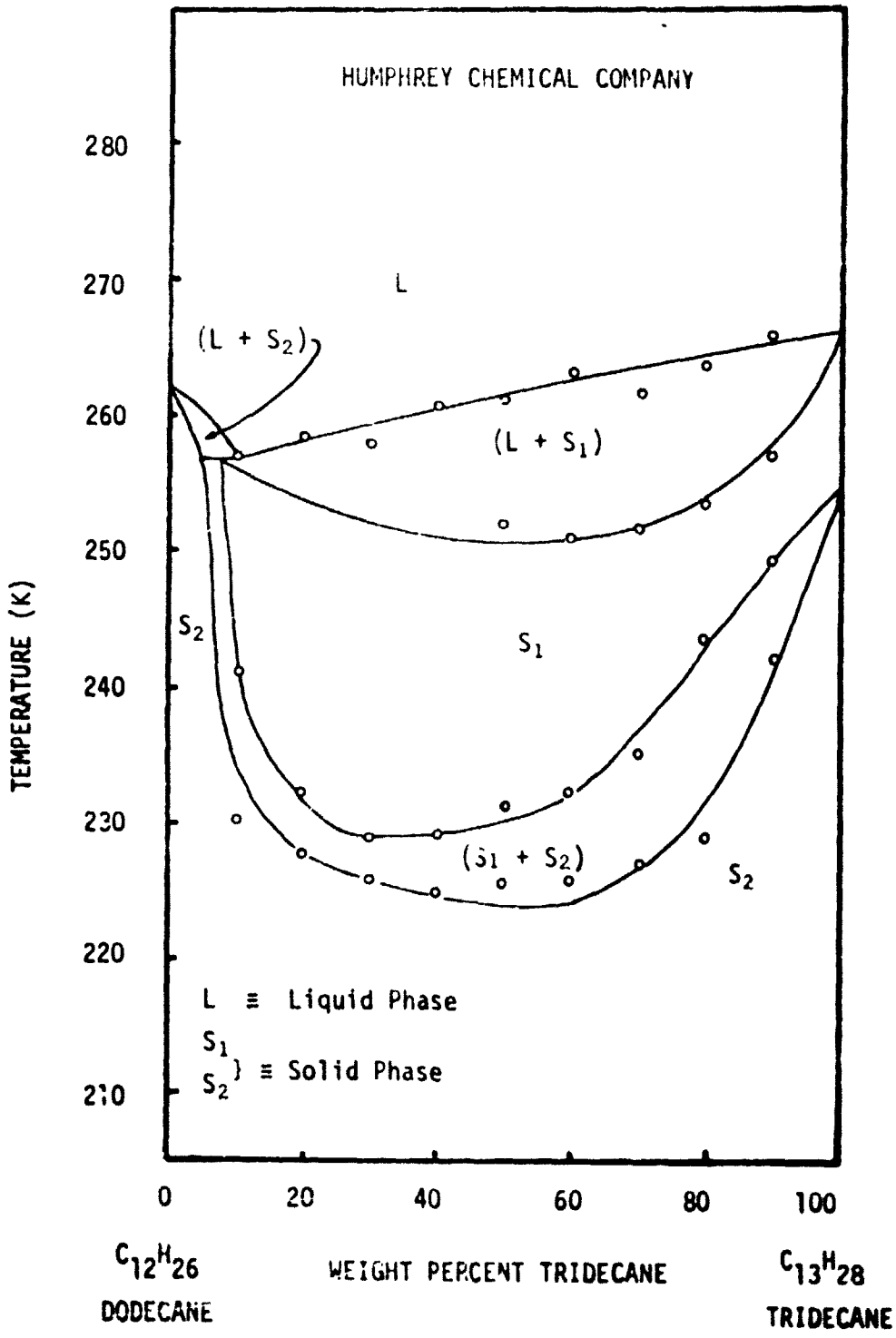

Figure 16. Dodecane - Tridecane Binary System

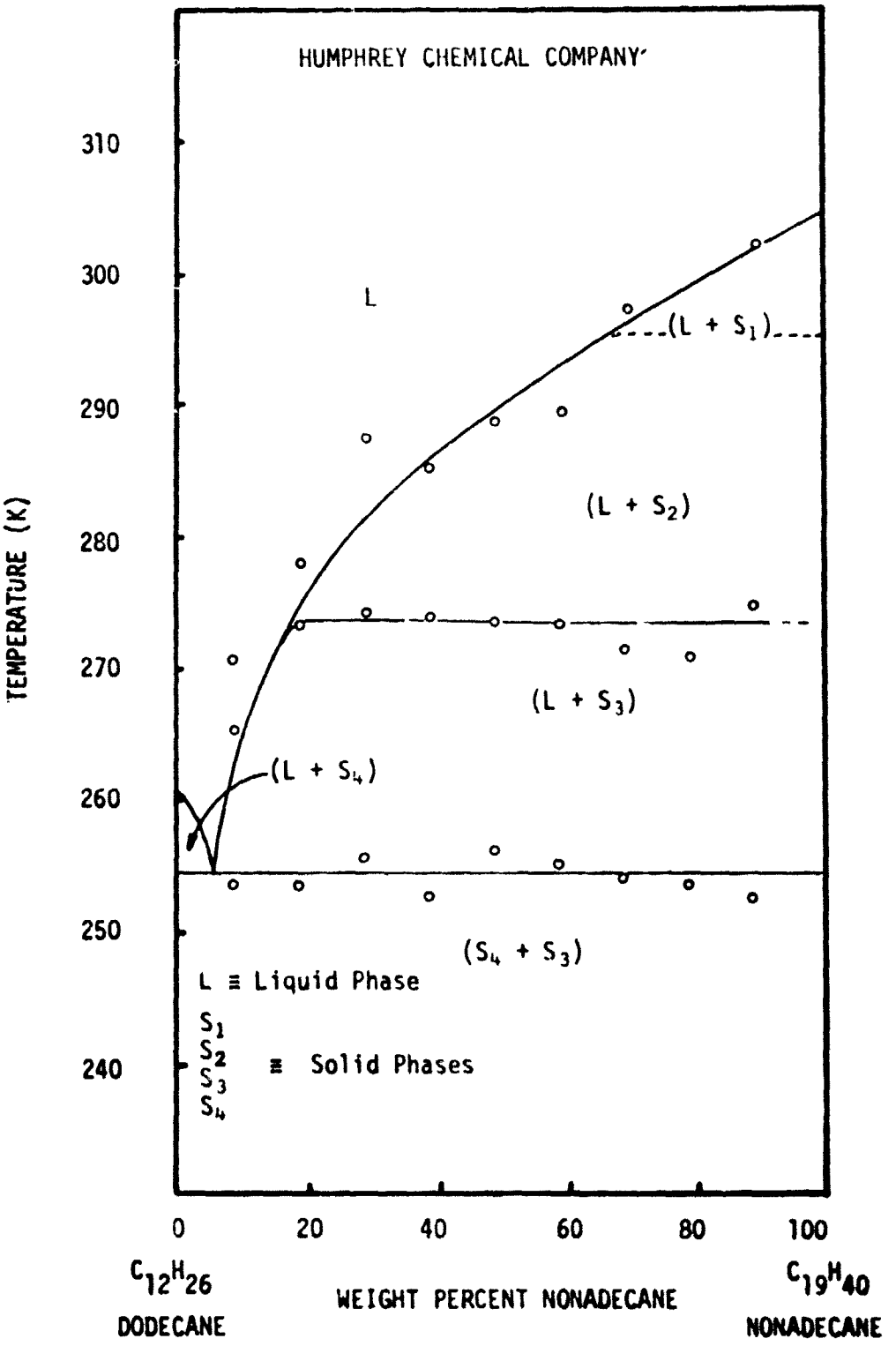

Figure 17. Dodecane - Nonadecane Binary System

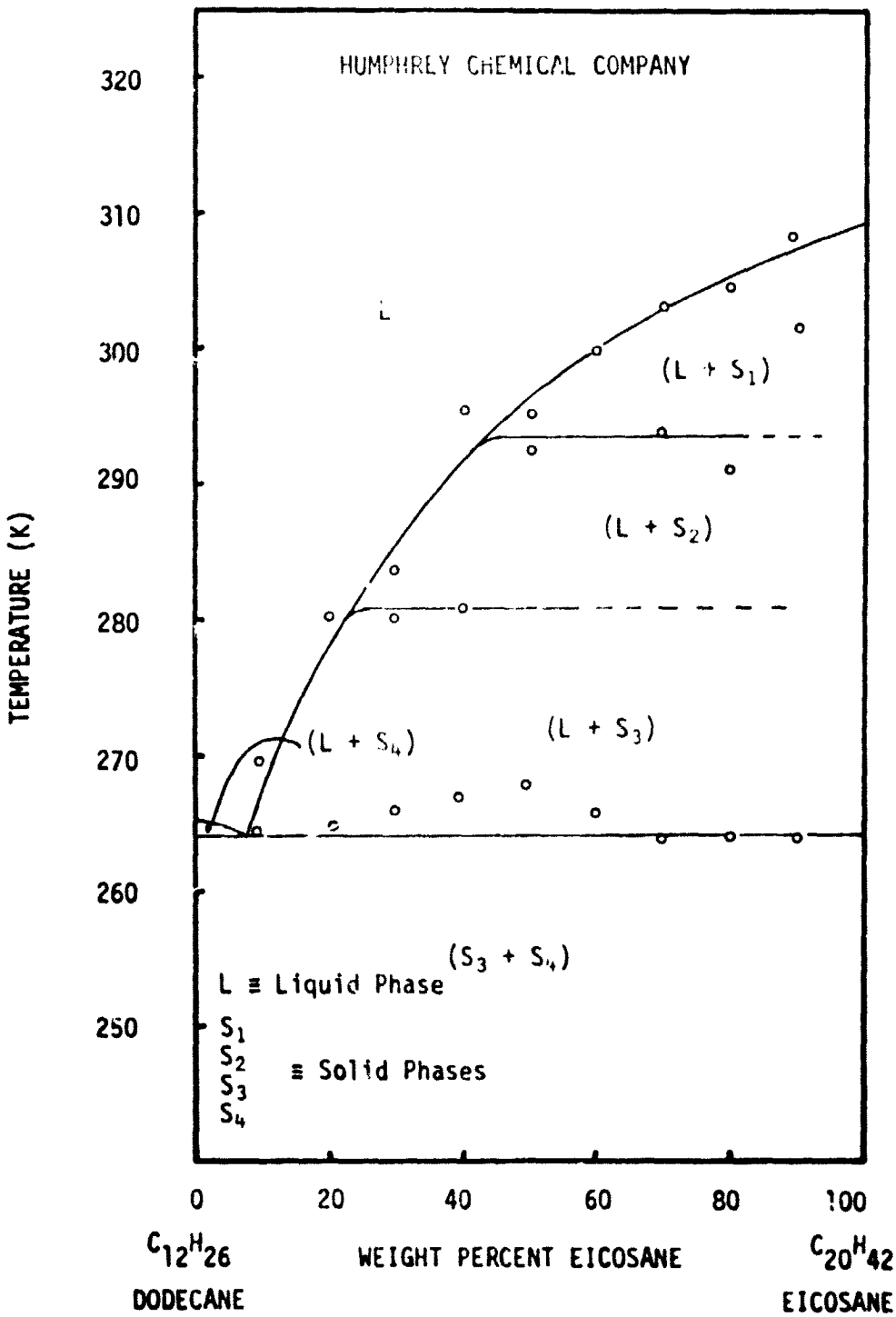

Figure 18. Dodecane - Ficosane Binary System

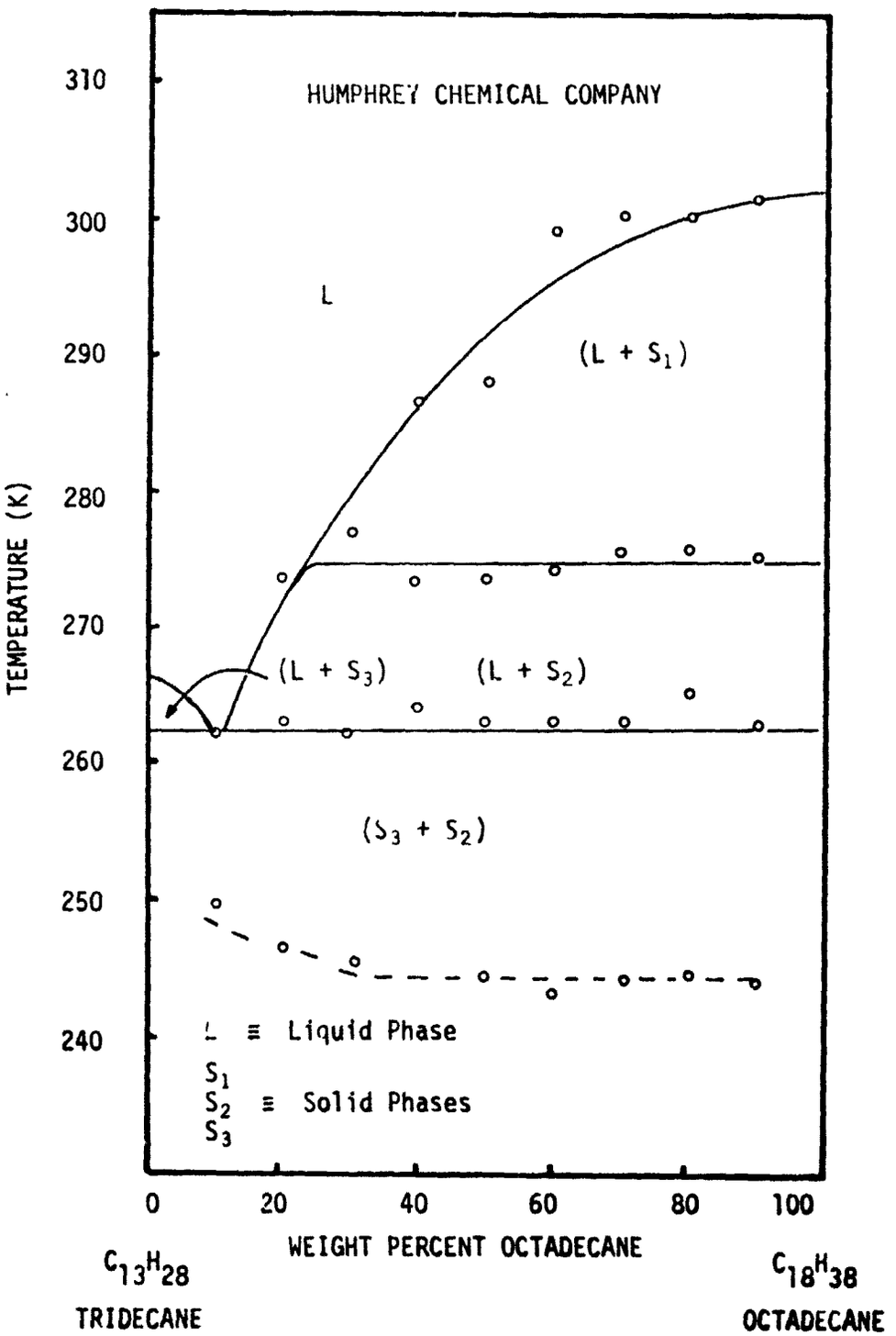

Figure 19. Tridecane - Octadecane Binary System

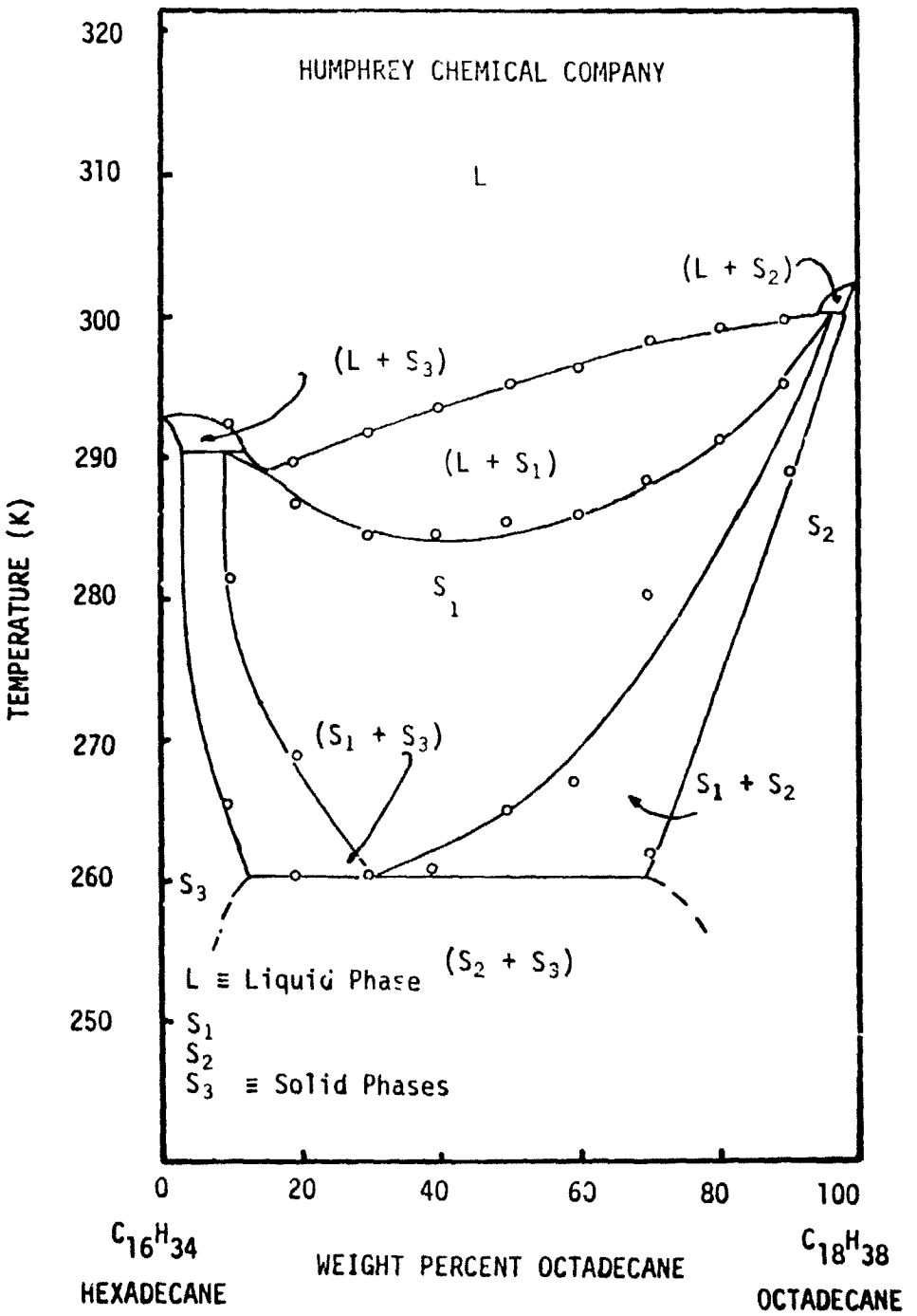

Figure 20. Hexadecane - Octadecane Binary System

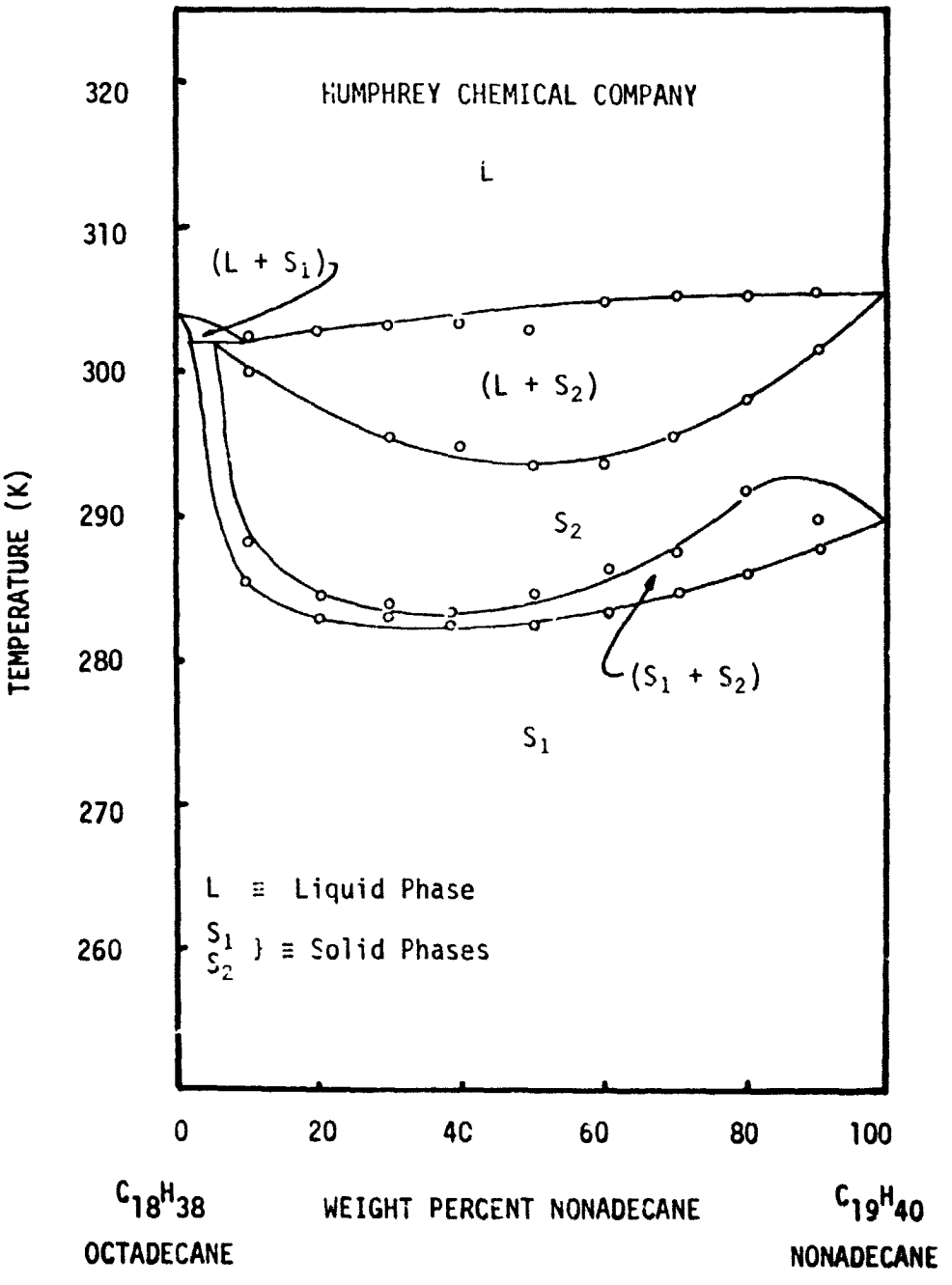

Figure 21. Octadecane - Nonadecane Binary System

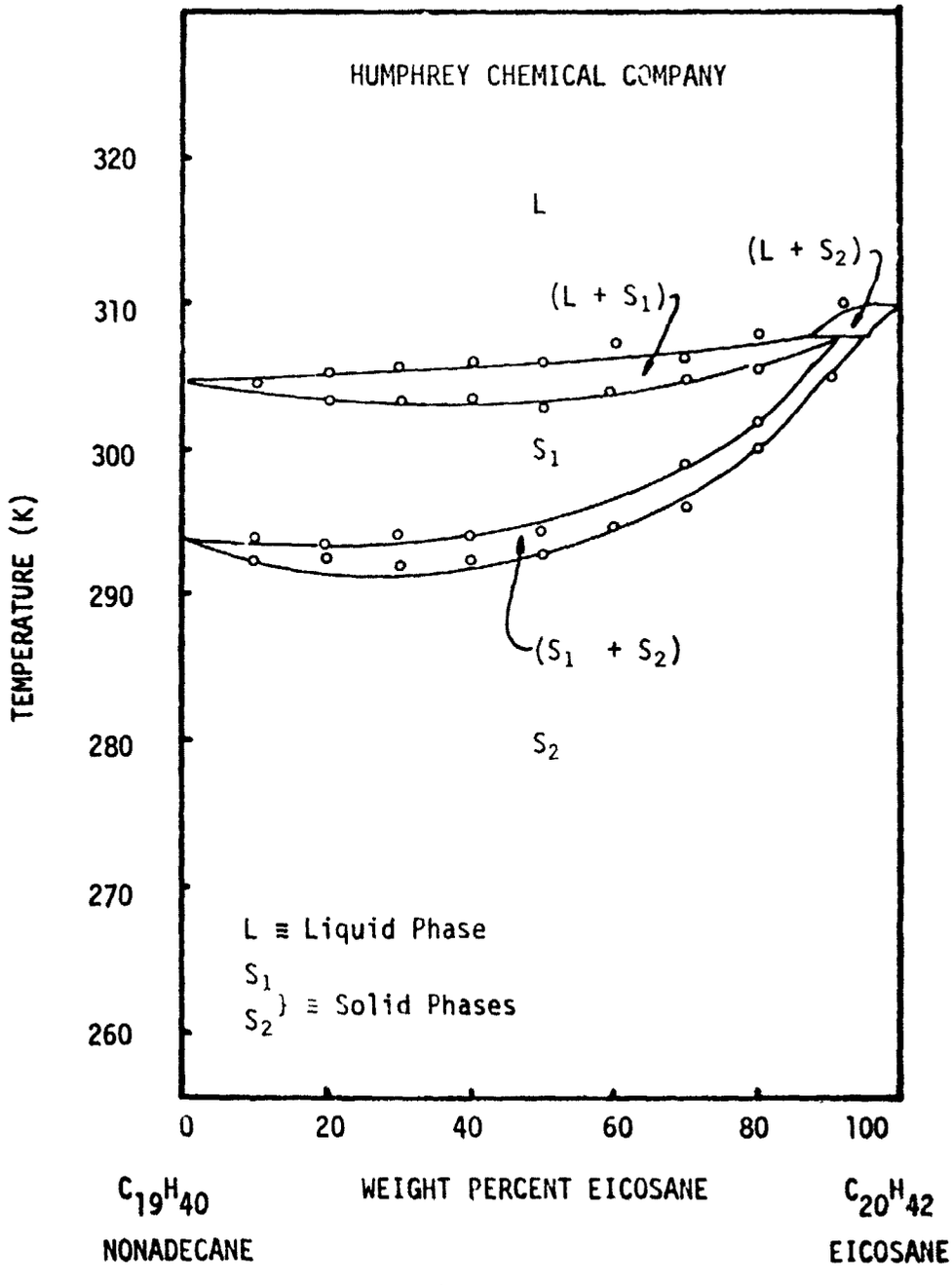

Figure 22. Nonadecane - Eicosane Binary System

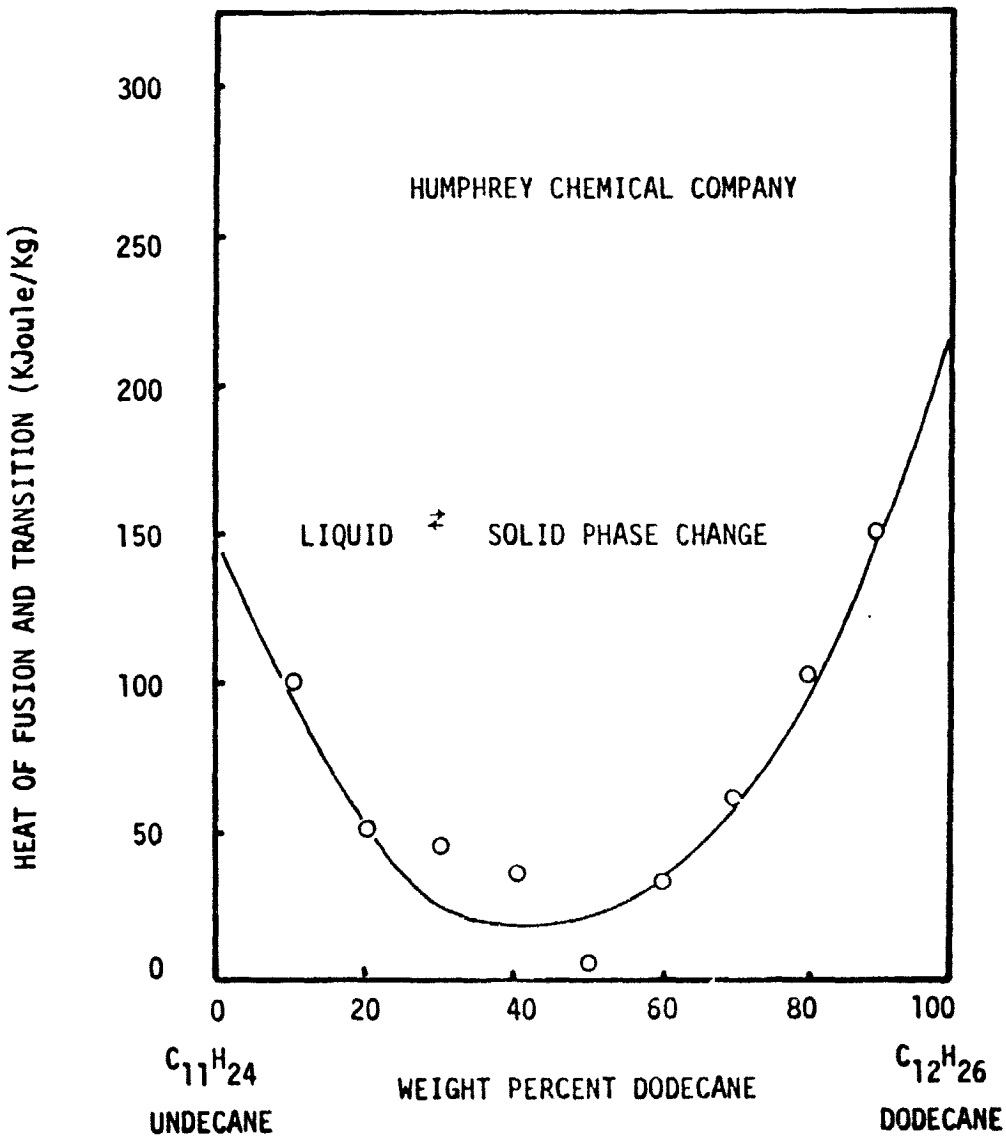

Figure 23. Effect of Composition on Heats of Fusion and Transition for Undecane - Dodecane Binary System

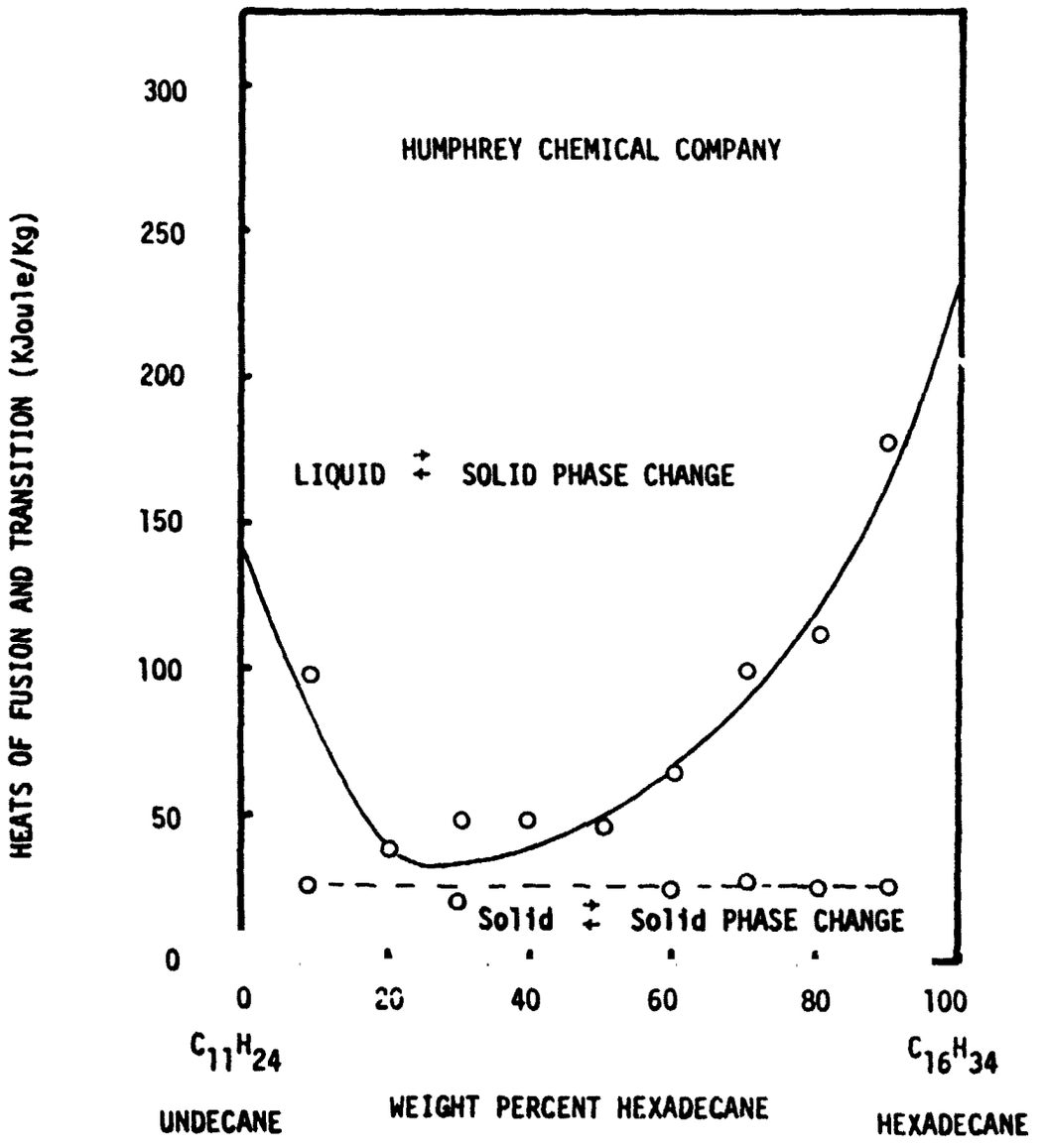

Figure 24. Effect of Composition on Heats of Fusion and Transition for Undecane - Hexadecane Binary System

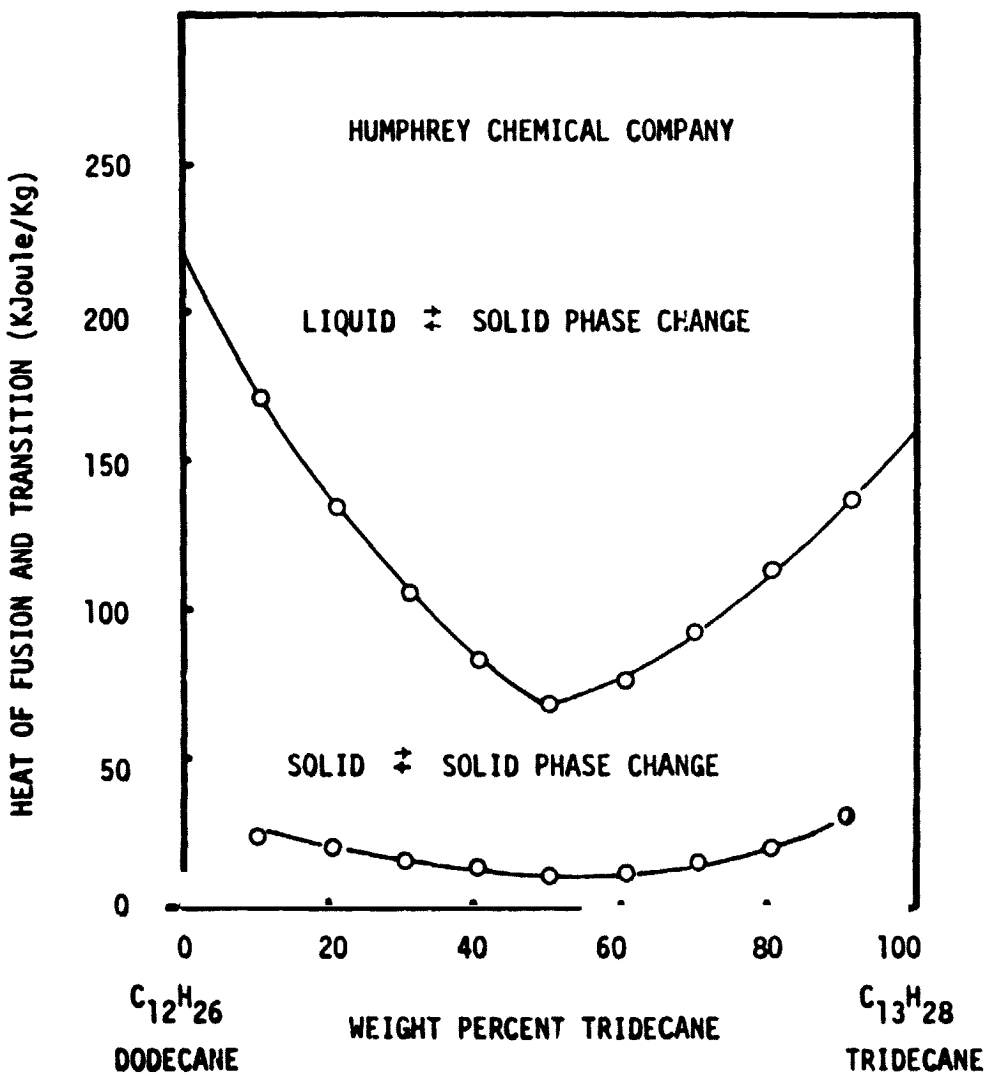

Figure 25. Effect of Composition on Heats of Fusion and Transition for Dodecane - Tridecane Binary System

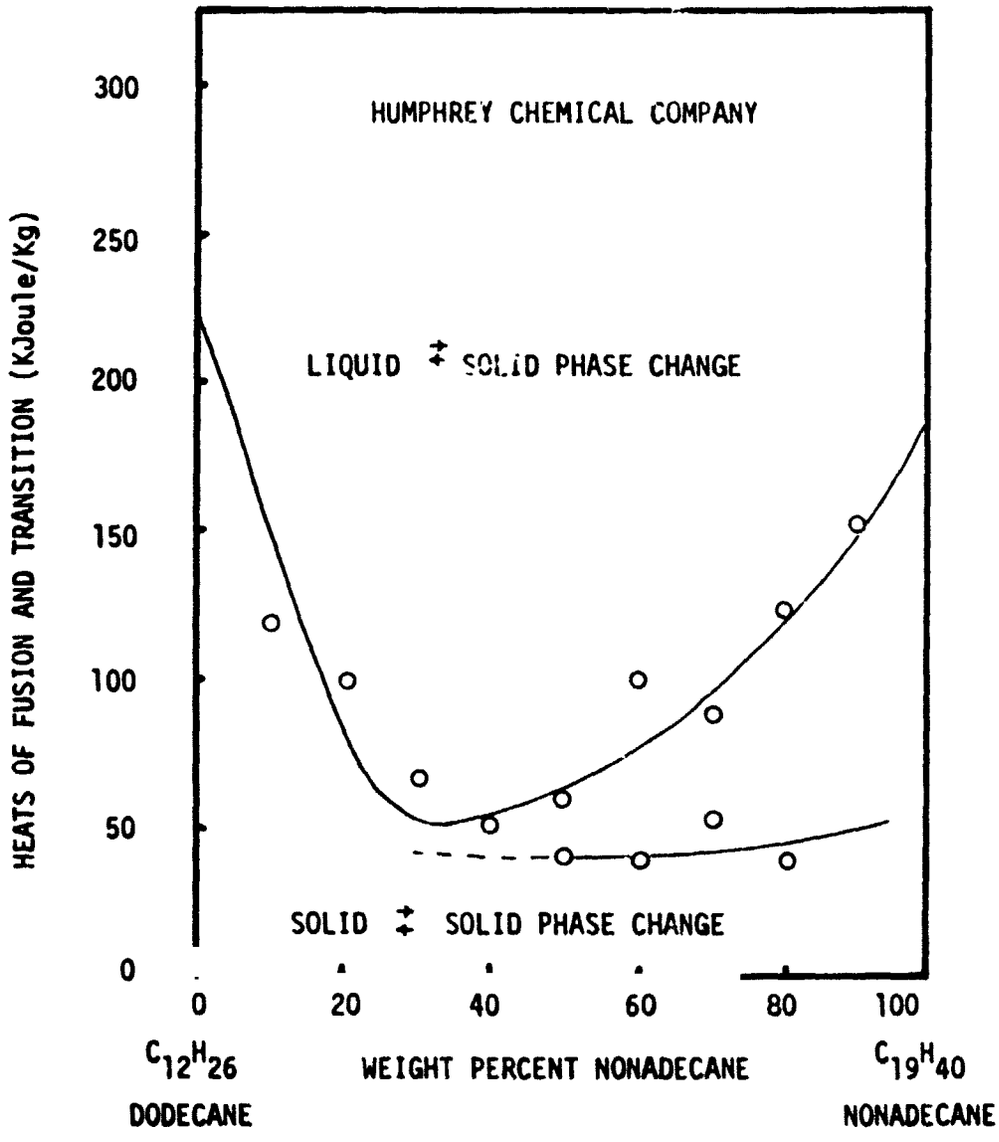

Figure 26. Effect of Composition on Heats of Fusion and Transition for Dodecane - Nonadecane Binary System

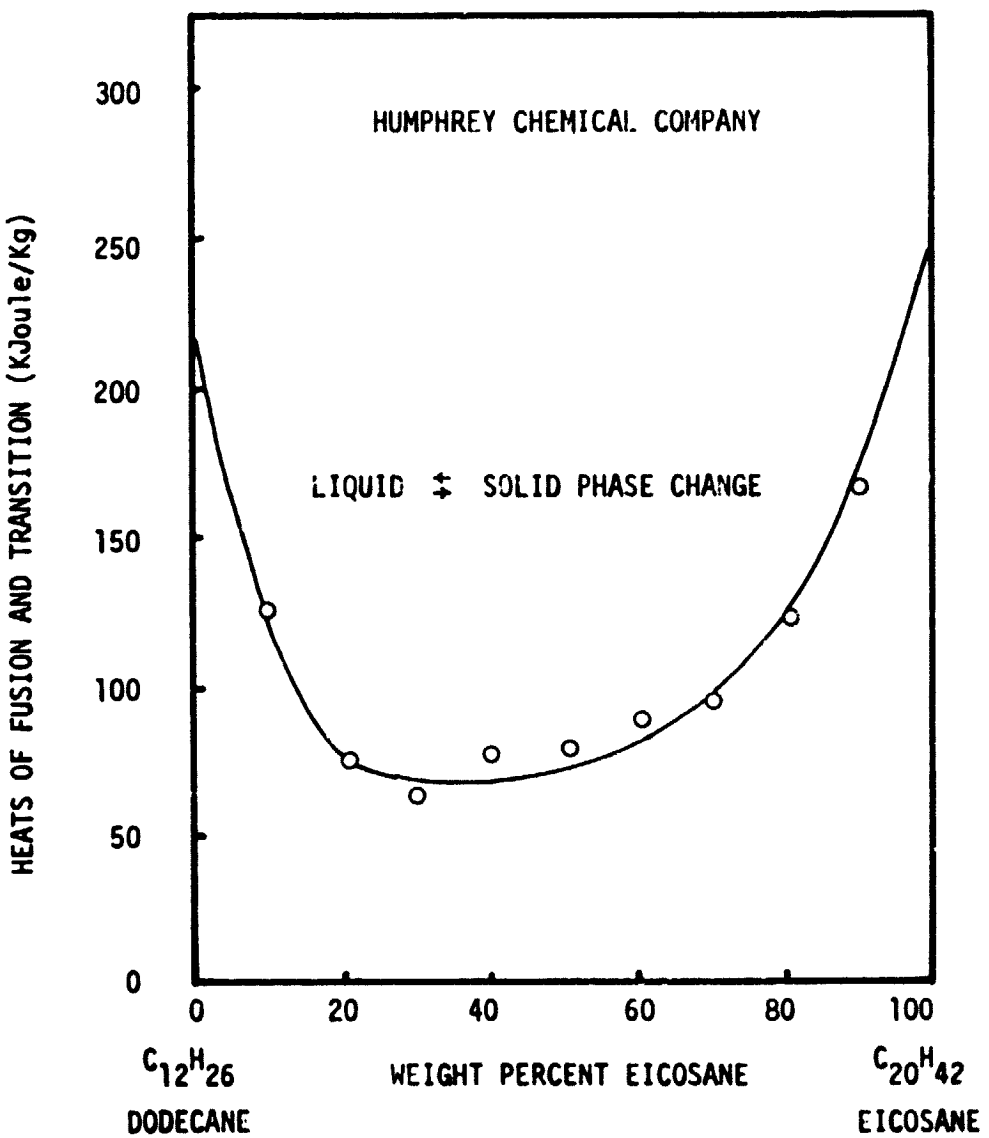

Figure 27. Effect of Composition on Heats of Fusion and Transition for Dodecane - Eicosane Binary System

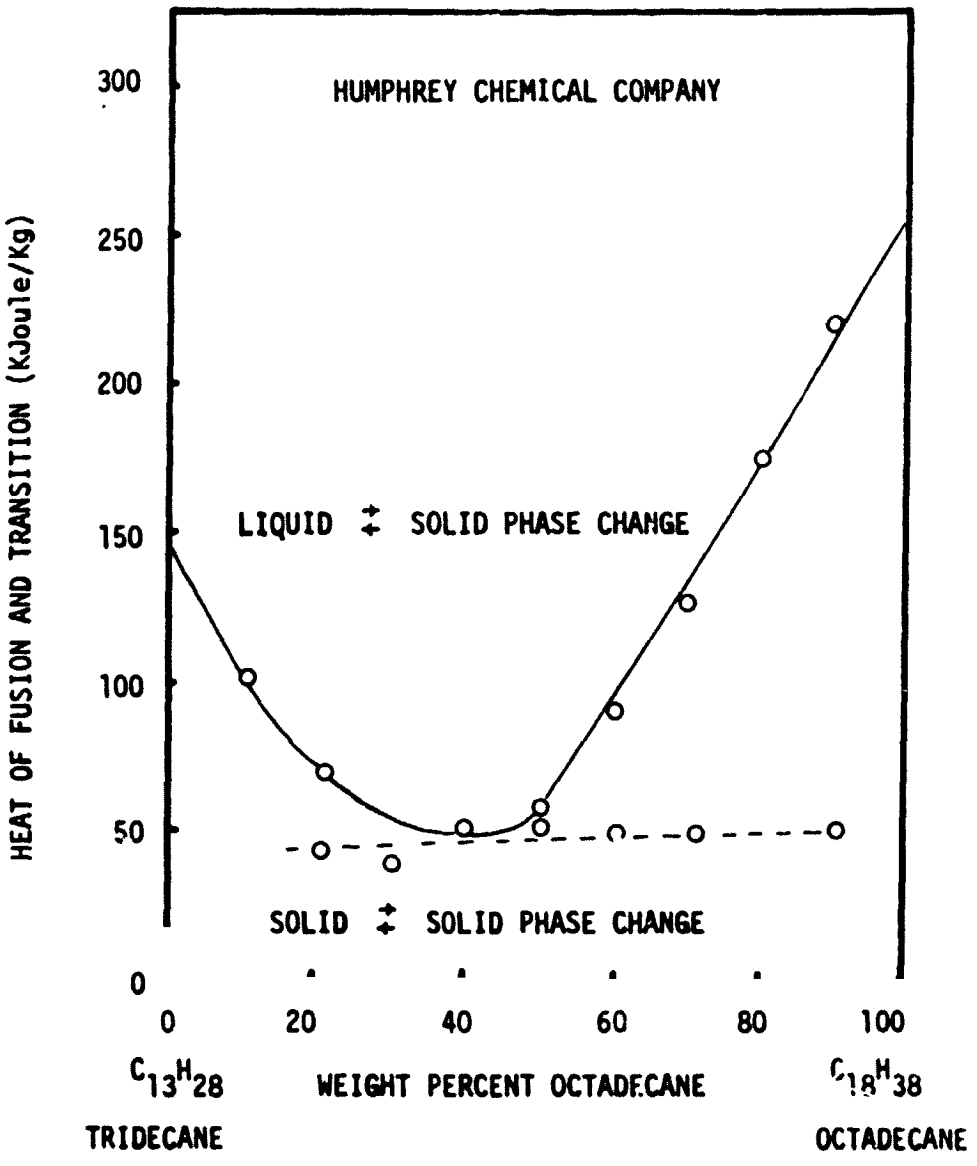

Figure 28. Effect of Composition on Heats of Fusion and Transition for Tridecane - Octadecane Binary System

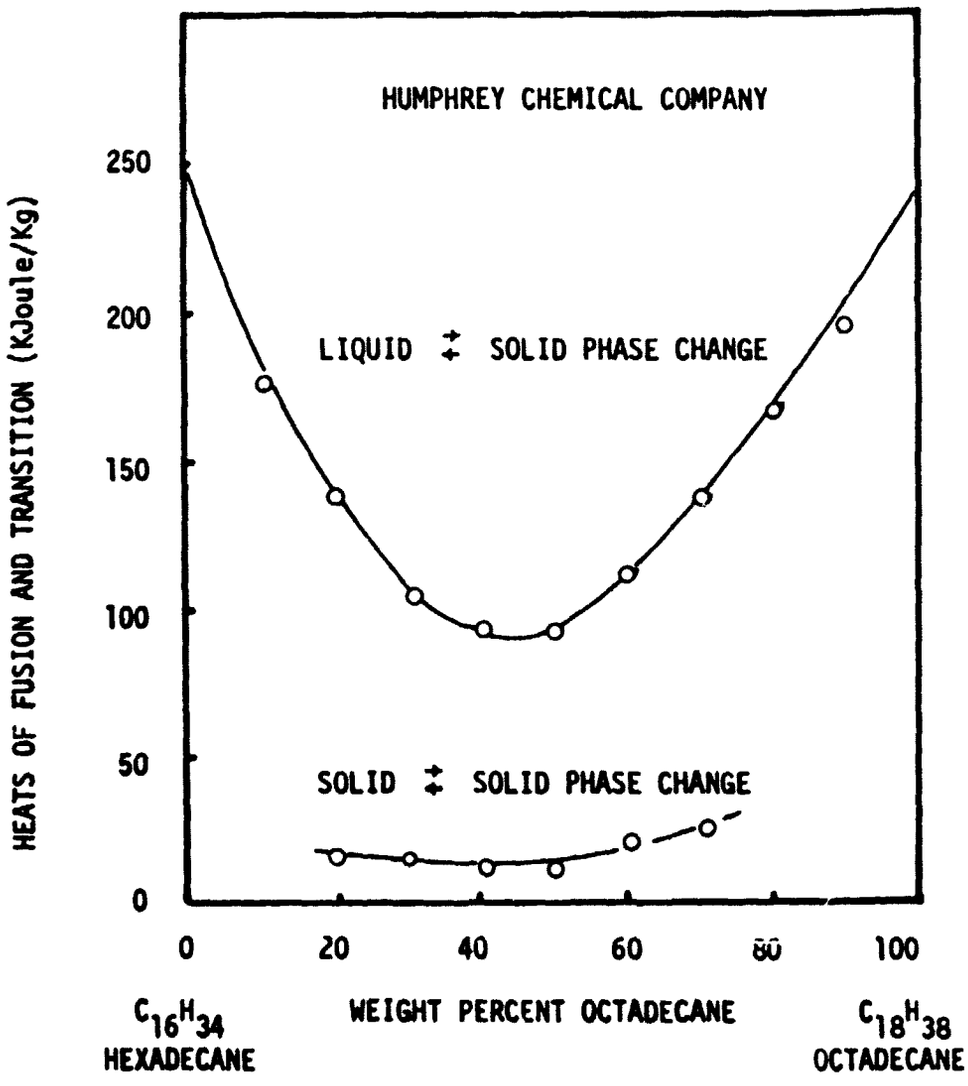

Figure 29. Effect of Composition on Heats of Fusion and Transition for Hexadecane - Octadecane Binary System

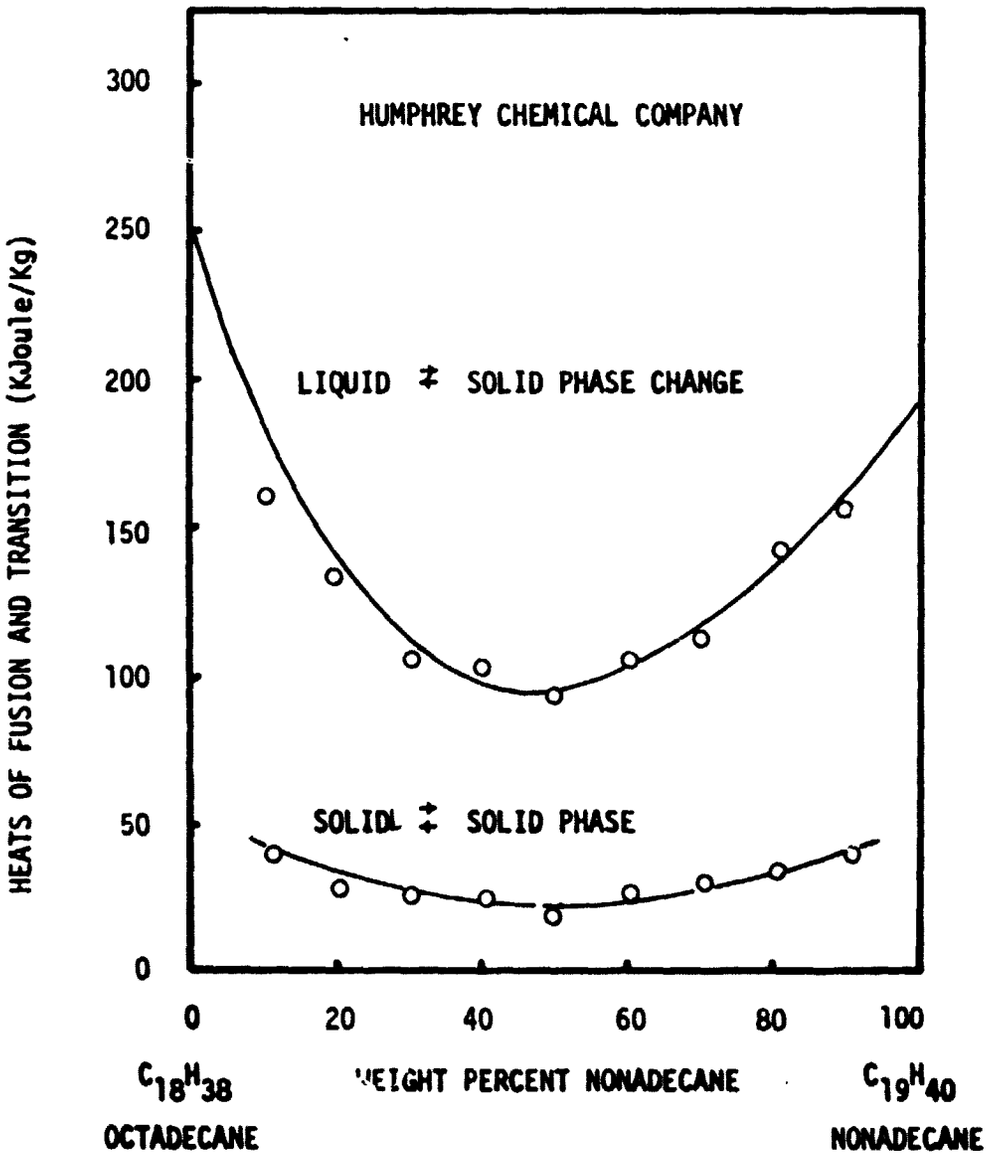

Figure 30. Effect of Composition on Heats of Fusion and Transition for Octadecane - Nonadecane Binary System

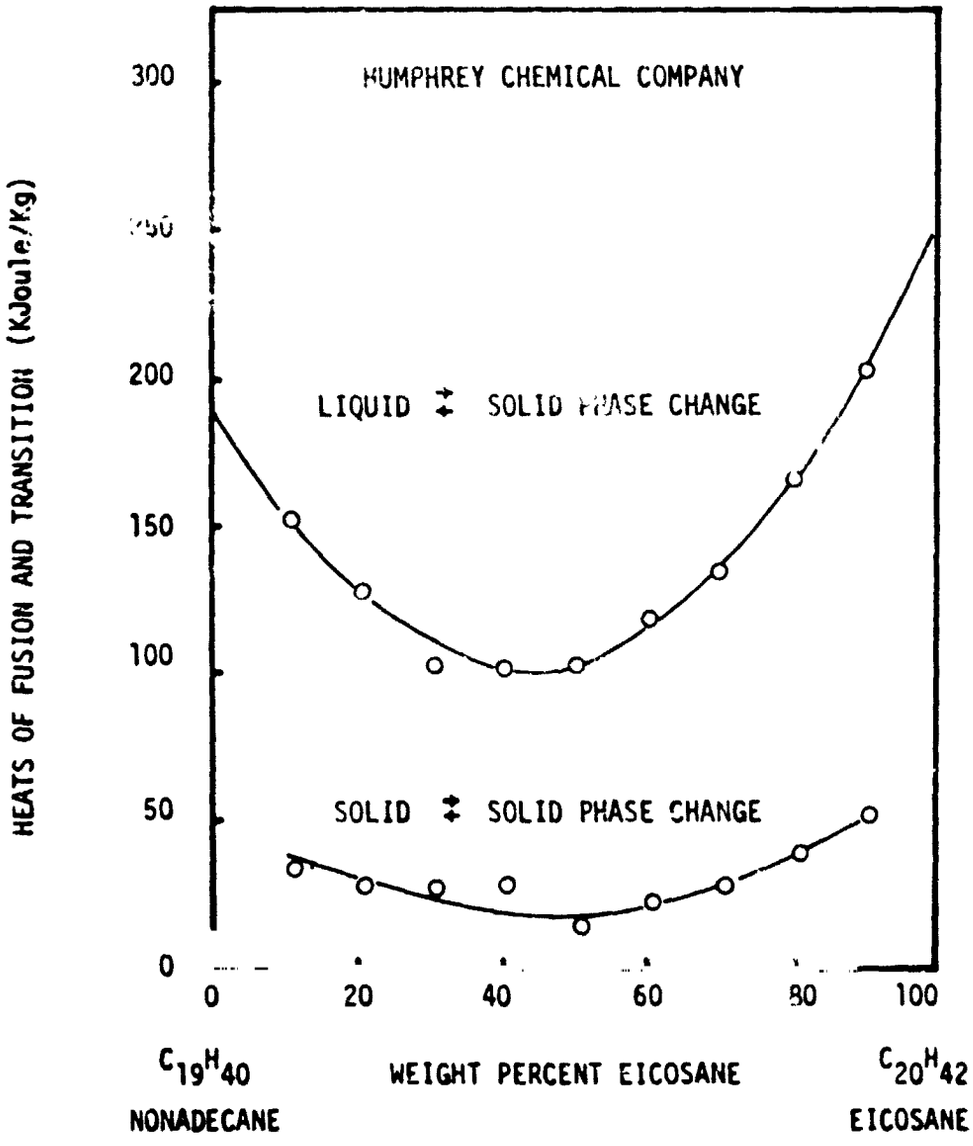

Figure 31. Effect of Composition on Heats of Fusion and Transition for Nonadecane - Eicosane Binary System