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# MEASUREMENT OF VISCOSITY, DENSITY, AND GAS SOLUBILITY OF REFRIGERANT BLENDS IN SELECTED SYNTHETIC LUBRICANTS

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# ABSTRACT

Liquid/liquid miscibilities of four different 32 ISO VG polyolesters and one alkylbenzene at three concentrations have been determined with five refrigerant blends, including HC-290. A vapor lubricant equilibrium (VLE) viscosity reduction of 32 ISO VG mineral oil with HCFC-22 has been completed. Composite viscosity reduction information by the fractionate components from R-502 in 32 ISO VG mineral oil has been obtained from -10° C (14°F) to 125°C (257°F) isotherms. Vapor lubricant equilibrium (VLE) viscosity reduction for 32 ISO VG mixed acid polyolester with HFC-134a and HFC-143a has also been completed. Data is also presented for the viscosity reduction of 32 ISO VG branched acid polyolester by these same refrigerants.

# CONTENTS

# LIST OF FIGURES

## LIST OF TABLES

# 1. SCOPE

This study will measure the viscosity, density and solubility of refrigerant/lubricant mixtures using various blended refrigerants. The two lubricants chosen for this study are a fully and partially miscible 32 ISO VG branched acid polyolester and a mixed branched acid 32 ISO VG polyolester. The refrigerant mixtures to be tested are labeled blends A through F; the components of these blends are listed in Table 1 as percentages by weight. The refrigerant gas equilibrium solubility information shows the fractionation of the individual gases in the lubricants. Mixtures of lubricants with the individual gases that make up the refrigerant mixtures (HFC-32, HFC-125, HFC-134a, HFC-143a) will also be studied.

**Table 1. Blends with Refrigerant Proportions in Percentages by Weight**

| Blend | HFC-32 % | HFC-125 % | HFC-134a % | HFC-143a % | HFC-290 % |
|---|---|---|---|---|---|
| A | 60 | 40 | | | |
| B | 30 | | 70 | | |
| C | 30 | 10 | 60 | | |
| D | | 44 | 2 | 54 | |
| E | 20 | 55 | 20 | | 5 |
| F | | 45 | | 55 | |

The miscibilities of these refrigerant mixtures with five different lubricants were determined so that the two lubricants (a 32 ISO VG branched acid polyolester and a mixed branched acid 32 ISO VG polyolester) used for further testing could be selected. Viscosity determinations were conducted only with mixtures C, D, and F. In order to provide a basis for comparing viscosity, gas solubility, and density, evaluations of HCFC-22 and R-502 with a 32 ISO VG mineral oil are included.

**Table 2. Lubricants**

| Fluid | Name | Manufacturer | Type | Trademark? |
|---|---|---|---|---|
| A | Icematic SW32 | Castrol | Branched Acid Polyolester | Registered Trademark |
| B | Emery 2927a | Henkel, Emery Group | Branched Acid Polyolester | Registered Trademark |
| C | RL-32S | ICI Chemicals and Polymers, Ltd | Mixed Acid Polyolester | Registered Trademark |
| D | Artic EAL 224R | Mobil | Mixed Acid Polyolester | Registered Trademark |
| E | Shrieve Zerol 150 | Shrieve Chemical Company | Alkylbenzene | Registered Trademark |
| F | Suniso 3GS | Witco Corporation | Naphthenic Mineral Oil | Registered Trademark |

## 1.1 Statement and Chemical Properties of Lubricants

The viscosity and liquid/liquid miscibility of lubricants with refrigerants depend on the composition of the lubricants. However, because the lubricants and pentarerythritol poloylesters used in this study are proprietary formulations, information about their specific structural properties, including alcohol type and the stochiometry of the carboxylic acids used in synthesis, remains with the manufacturer. As a result, only the miscibility and viscosity differences between the polyolesters are reported.

# 2. METHODS

## 2.1 Viscosity Determinations

The method used in this study is similar to that by Albright (1956-59), Little (1956) and Parmelee (1964.) These authors use the gas equilibrium concept -- the saturation of the liquid with vapor -- to study the viscosity reduction of hydrocarbon refrigeration oils in refrigerant gases. In conjunction with the gas equilibrium approach, this study uses temperature and pressure limitations to determine refrigerant gas concentrations.

Viscosity and density are determined accurately by a fourth generation viscometer (Figure 1), which was taken from a report by Nissen. This viscometer system consists of an oscillating body device enclosed in a low volume pressure tube. The active part of this system is a solid oscillating cylinder made of highly polished stainless steel; this is connected to a precisely thermostatted spring inside a stainless steel pipe. An external electromagnet causes the cylindrical bob to oscillate. The decrement of any solution in the viscometer can be determined by measuring the rate of sinusoidal decay. A quick decay represents a high viscosity; a slow decay, a low one. The viscosity of the solution can be determined from the decrement and density.

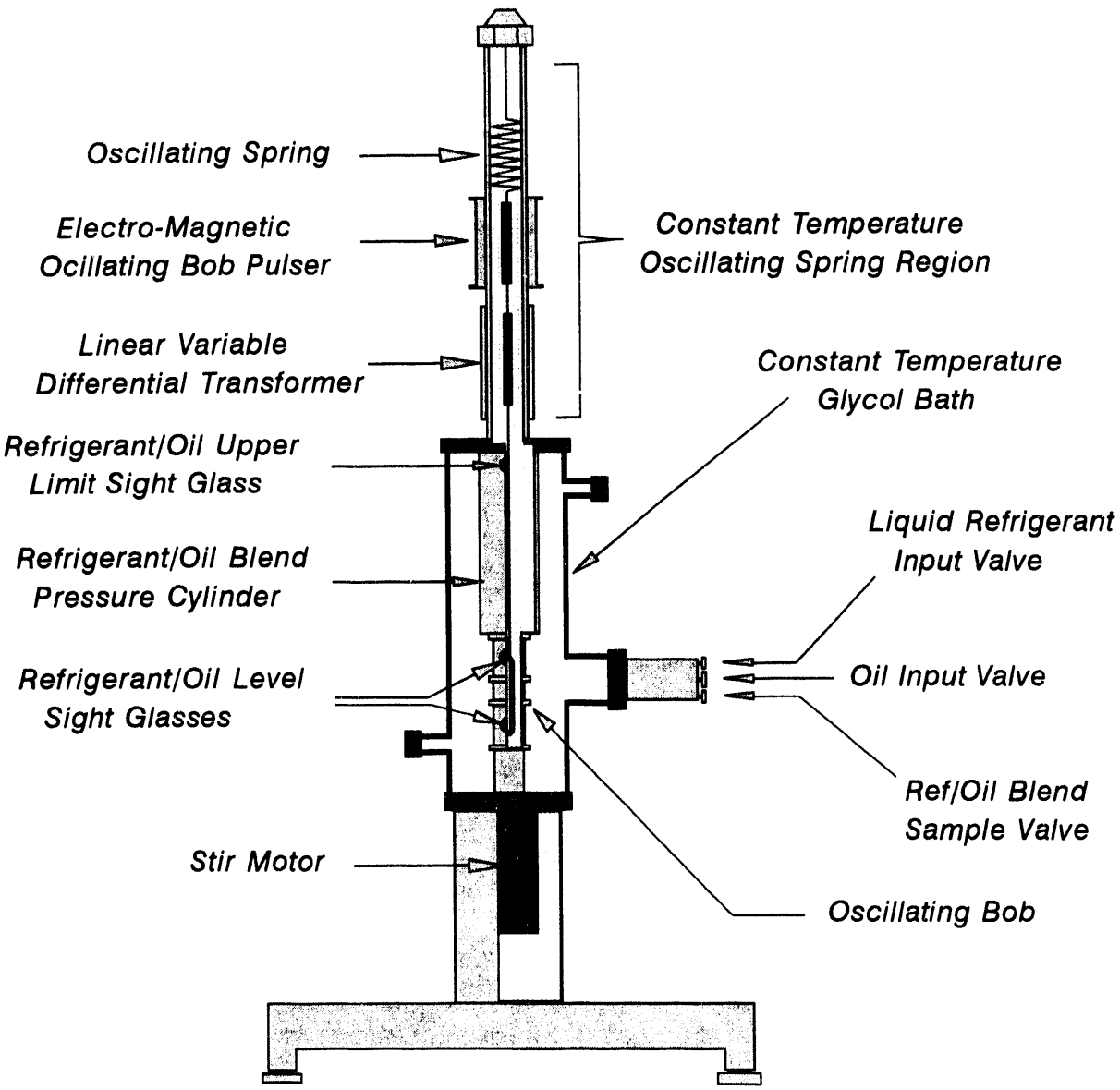
This viscometer allows a wide range of viscosity determinations (.10 to 1800 cP) to be made with a single oscillating bob. The viscosity of polyolester blends B and C, as well as 32 ISO VG mineral oil were measured; the standards used were water and certified standard test fluids (NIST traceable). These standards are calibrated from -25°C to 125°C and are reported in both cP and cSt values. The readability of the viscometer is 0.06 cP. The density of the oils is also reported. The wide temperature range of various calibration oils results in a significant overlap that serves as an internal standard and self check. For low viscosity solutions, the difference between standards is ±0.1% for low viscosity solutions; this increases to ±1.5% for high viscosity solutions.

The bob used to determine viscosity can be used to determine density as well.. By observing the position changes of the bob, density can be determined to within 0.0005 g/ml. Determining consistent density at constant temperature and constant pressure is a very accurate method of measuirng fluid consistency. Accurate density measurements allow the calculation of centistokes (cSt) from centipoise (cP). The density range of the instrument is calibrated with known, readily available pure fluids that are dried over a

molecular sieve prior to use; this provides a straight calibration line for density at specified temperatures. The precision of this determination is ±0.3%

The fluid refrigerant mixture is pumped from the bottom of the viscometer and sprayed into the refrigerant vapor space at specific pressures and temperatures. Consequently, density may be monitored for equilibrium conditions, the decrement may be measured, and the viscosity may be calculated. Before the fluid is sampled, it is visually examined several times to determine that true solution conditions are present. The fluid sample is then drawn through a very low volume capillary line (380μl) into a deeply evacuated, lightweight glass sampling bulb where a total charge is retained. The ratio of gas to liquid oil (percentage by weight) may then be calculated. The concentration measurement is reproducible within ±0.5% by weight at a given isothermal pressure test point. Sampling the refrigerant lubricant mixture at each isothermal pressure test point is essential to the measurement technique used in this study.

**Figure 1. Oscillating Body Viscometer**



The solubility ranges of refrigerant/lubricant combinations may be inconsistent. For example, the viscometer does not allow the kind of immiscibility conditions that could occur in a low temperature pressure cell containing liquid refrigerant and a partially immisible lubricant. According to the principles of gas equilibrium, forced saturation with liquefied gas is required to produce immiscible layers. Oil may be kept saturated with gas at a specific pressure and temperature by accurately monitoring the gas pressure and keeping it at or below the saturation pressure. For oils that are nearly infinitely miscible, liquid refrigerant can be added to the viscometer under pressure, and fluid properties can be measured for viscosity, density, pressure and refrigerant concentration. Measurements are taken when the oil is saturated with refrigerant gas.

Unless there is a zero void space in a pressurized viscometer cell, the refrigerant-oil pair combinations will change. For example, a fluid with 6.6% refrigerant by weight at 100°C (212°F) will have a refrigerant concentration almost three times greater (22.0%) when it is cooled to 10°C(50°F) inside a closed system (like a viscometer) which has available gas space. When refrigerant blends are used, the composition of the gas in the vapor space of the viscometer is maintained equal to that of the pure refrigerant blend. The fractionation of the mixed gases is determined at every temperature and pressure. Samples of the fluid/refrigerant mixture are collected to determine the percent refrigerant by weight in the fluid. The ratio of gases is determined by gas chromatography, as stated in Section 2.2.

The fluid measurement portion of the viscometer is equipped with two high temperature and pressure sight glasses directly adjacent to the suspended stainless steel solid cylinder. Through the upper sight glass, the solution is continually monitored for the formation of any immiscible particulates or haze of the fluid and refrigerant. The observer can ensure that the viscometer is charged with enough fluid to completely cover the bob. The lower sight glass is adjacent to the gas introduction port and to the oil sampling port. The third sight glass, located at the top of the vapor space directly adjacent to the pump exit, allows observation of the foaming qualities of the lubricant and lets the observer guarantee that the mixed system is always at the stated measurement temperature.

For the best reproducible method, pressure is measured with a Bourdon tube gauge with a 660-degree double-helix display . This temperature-compensated gauge is calibrated with both gas and liquid, is accurate to ±0.2 psia and is traceable to NIST standards. Vapor pressure is measured at equilibrium, when the soluble gases are responsible for the fluid

properties. Since the gas content of the fluid is measured, the amount of gas contained in the Bourdon tube is irrelevant.

Density, viscosity, and vapor pressure are always measured under isothermal conditions. The viscometer temperature is maintained by a circulating constant temperature glycol bath controlled by a Platinum RTD (±0.1°C) microprocessor. The RTD probe is mounted at the surface of the viscometer tube inside the liquid bath. The other temperature zones are controlled by electric heaters, using a microprocessor controller (±0.1°C) with type "J" thermocouples.

Oil is pumped into the viscometer by a magnetically coupled impeller located in the pump body and sprayed into a soluble gas vapor space at the top of the viscometer. The pressure and temperature in the instrument can be varied to simulate the lubricant/refrigerant pair conditions that exist in operating compressor systems. Test fluids are degassed at 60°C (140°F) to 20 millitorr for 24 hours and are generally dried to 50 ppm. Similarly, the viscometer is evacuated to 20 millitorr for several hours, purged with the refrigerant gas several times, and evacuated. The test oil is then drawn through the oil charging valve and re-evacuated to 20 millitorr. The oil is purged with refrigerant gas and evacuated again. Non-condensable gas content is not allowed to exceed 10 ppm or equivalent to the refrigerant used.

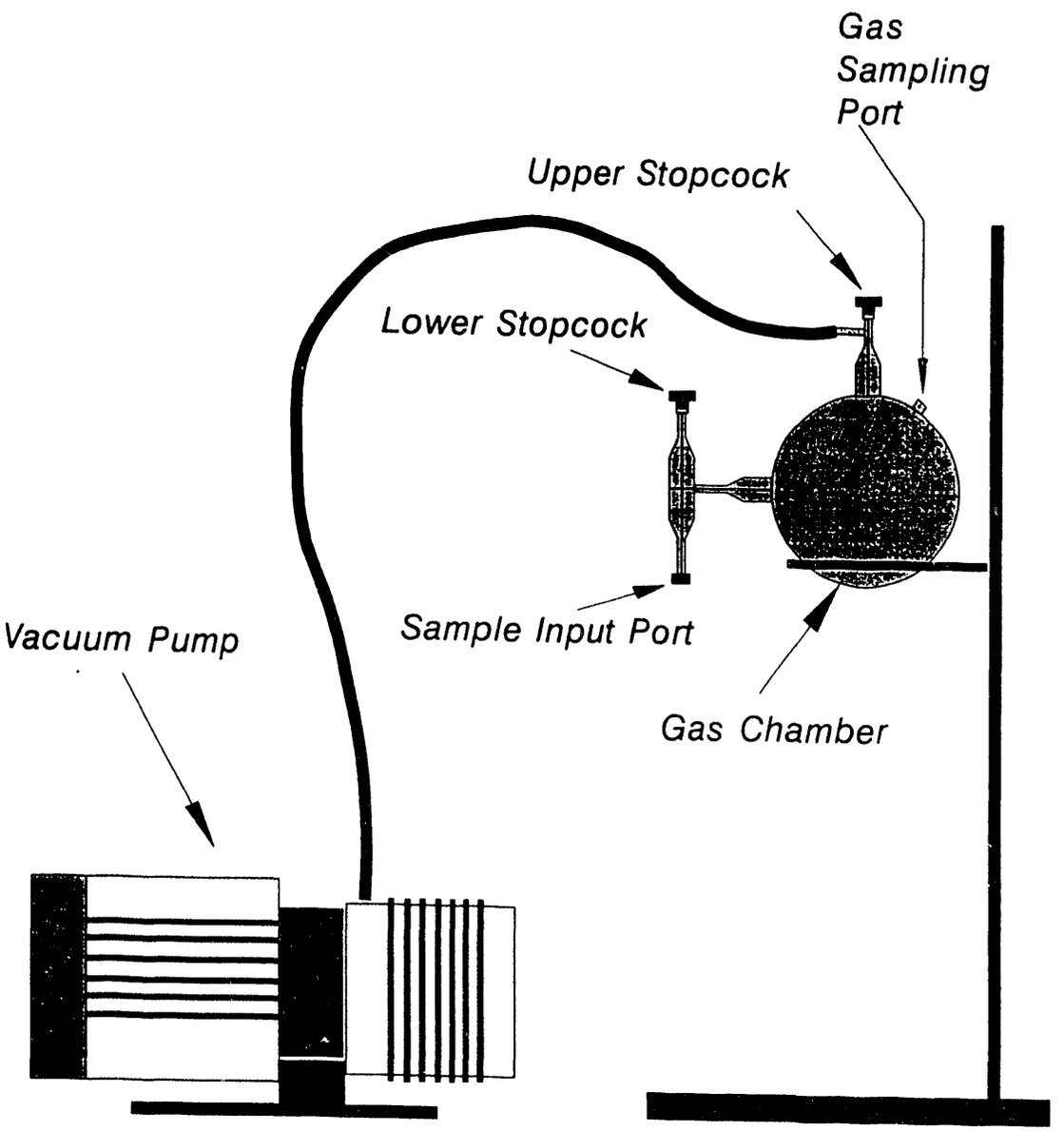
## 2.2 Refrigerant Blend Sampling

After refrigerant/lubricant samples are obtained from the viscometer, the glass container and its rubber stopper are weighed. The glass bulb is placed on the sample input port of the apparatus (Figure 2) with the lower stopcock closed. The upper stopcock is opened and attached to the vacuum pump. The upper stopcock remains open until a sufficient vacuum (30-50 millitorr) has been pulled on the gas chamber. When the upper stopcock is closed, the lower stopcock is opened. The lower pressure in the gas chamber pulls the refrigerant out of the sample in the glass bulb. To separate the refrigerant from the lubricant, the glass bulb is heated carefully with a propane torch. The lower stopcock is closed within 30 seconds after heating. One minute after the lower stopcock is closed, equilibrium is established.

The ratio of the gases can be determined from the sample of gases drawn off the top oil. A second gas sample is obtained to determine if equilibrium has been established and

whether the ratio of gases has changed. Gas chromatography is used to analyze the refrigerant sample. Separate measurement studies indicate that more than 80% of the refrigerant contained in the liquid sampling bulb has been removed. Finally, all remaining traces of refrigerant are removed by heating the bulb to constant weight under vacuum. This was then used for the final measurements of net percentage by weight.

**Figure 2. Refrigerant Blend Sampling Apparatus**



# 3. RESULTS OF PRELIMINARY MEASUREMENTS

In order to select the lubricants to be used in this project, the miscibilities of four different polyolesters and one alkylbenzene with six refrigerant blends have been evaluated. In addition, the density and viscosity of mixtures of pure refrigerant with pure lubricant have been tested; this provides data about the repeatability and accuracy of the viscometer.

## 3.1 Miscibility Determinations

The fluids to be tested for this project were selected based on data about the miscibility of four different polyolesters and one alkylbenzene with six refrigerant blends (Appendix A.)at three different refrigerant/lubricant concentrations. Alkylbenzene is used to determine the miscibility of aromatics. Surprisingly, blend D appears partially miscible, perhaps as a result of lower temperature. This suggests a possibility for good oil return and inverse miscibility at higher temperatures, which indicates undiluted hydrocarbon lubrication.

Levels of immiscibility may significantly effect the fractionation of individual gases at different temperatures and pressures. For example, Lubricant B is a 32 ISO VG branched acid polyolester, believed to be the most miscible type; its very high liquid/liquid miscibility suggests that it will have very little influence on the fractionation of the various gases that compose refrigerant blends. Lubricant C has been determined to be the least miscible lubricant tested, although its viscosity is close to that of Lubricant B. Consequently, Lubricant C was used in this study to verify the impact of partial liquid miscibility on the gas solubility of various gases in refrigerant blends. Lubricants A and D, which are in the intermediate range of miscibility, could also be used for this.

## 3.2 Measurements with Mineral Oil

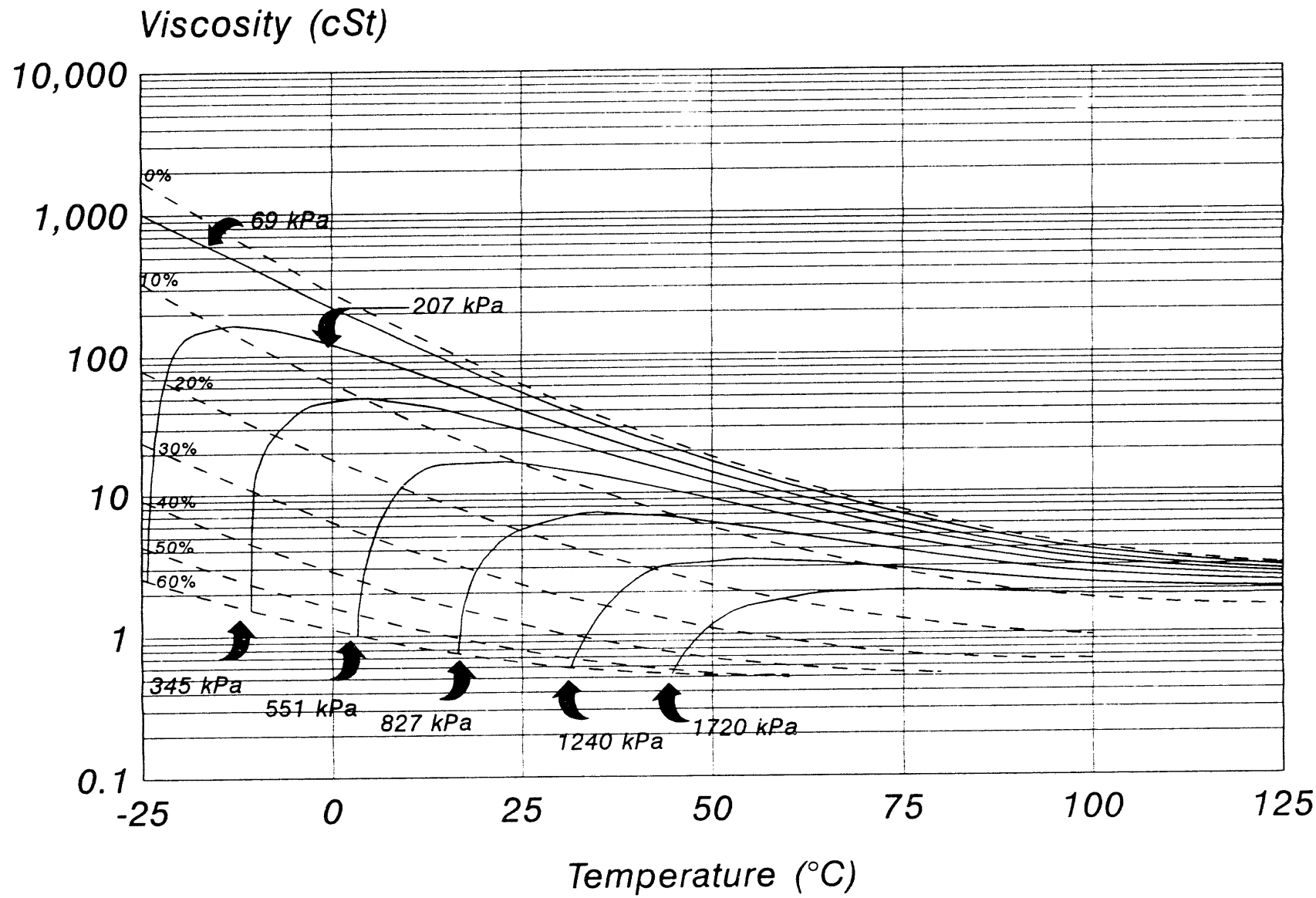
### 3.2.1 Viscosity of 32 ISO VG Mineral Oil and HCFC-22

Appendix B illustrates the isothermal viscosity, density and solubility of HCFC-22 in 32 ISO VG mineral oil. This oil was purchased locally at Grainger Industrial Supply. Isothermal determination provides a snapshot view of refrigerant/lubricant solubility knees, which are unique to each refrigerant/lubricant combination. Solubility knees become apparent as the concentration of refrigerants approaches the critical phase of refrigerant/refrigerant gas solutions. The lowest temperature for which viscosities were determined is -20°C. Viscosity measurements at -40°C were attempted without success; when refrigerant concentrations exceeded 9%, the fluid became immiscible. Figure 3 presents viscosity as a function of temperature, and includes isobaric pressure lines. Figure 4 presents a modified "Daniel Plot" that shows viscosity and pressure at constant concentration as a function of temperature. Figure 5 shows density as a function of temperature at constant concentration. The raw data tables in Appendix B (Table B.1) present density values.

# Viscosity vs Temperature

## HCFC-22 in 32 ISO VG Mineral Oil

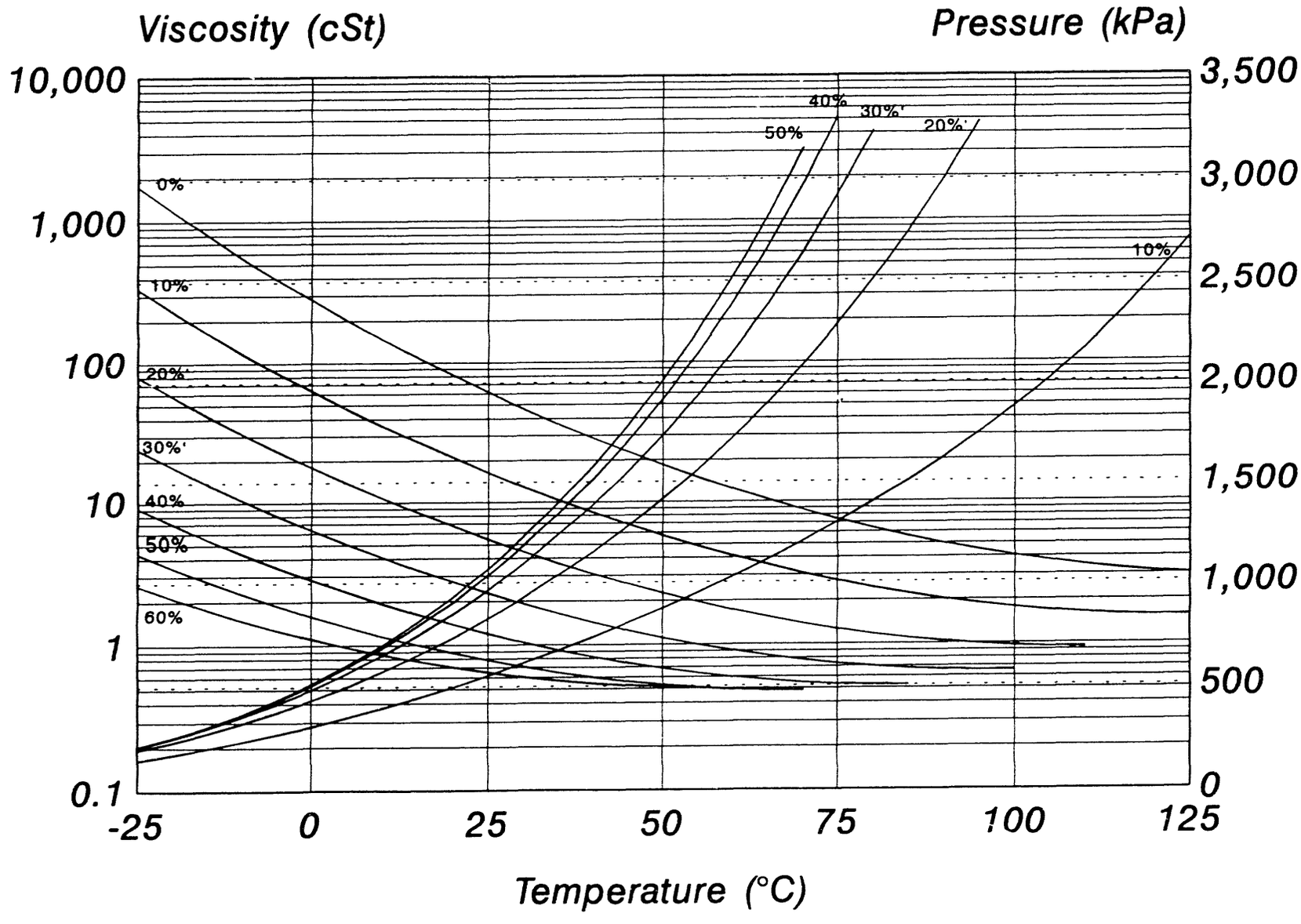
*Figure 3*



# Viscosity and Pressure at Constant Concentrations

## HCFC-22 in 32 ISO VG Mineral Oil

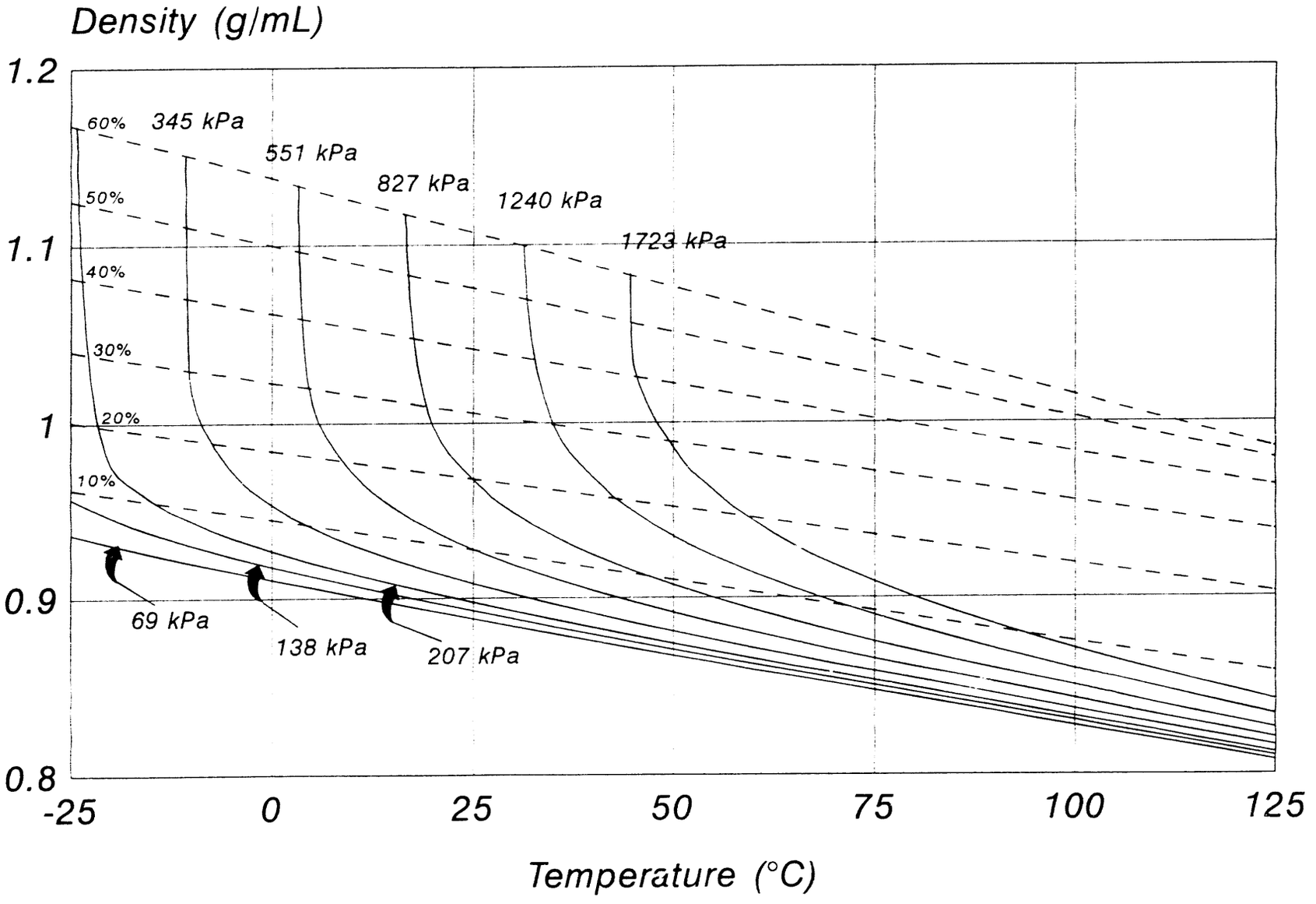
*Figure 4*



# Density vs Temperature

## HCFC-22 in 32 ISO VG Mineral Oil

Figure 5



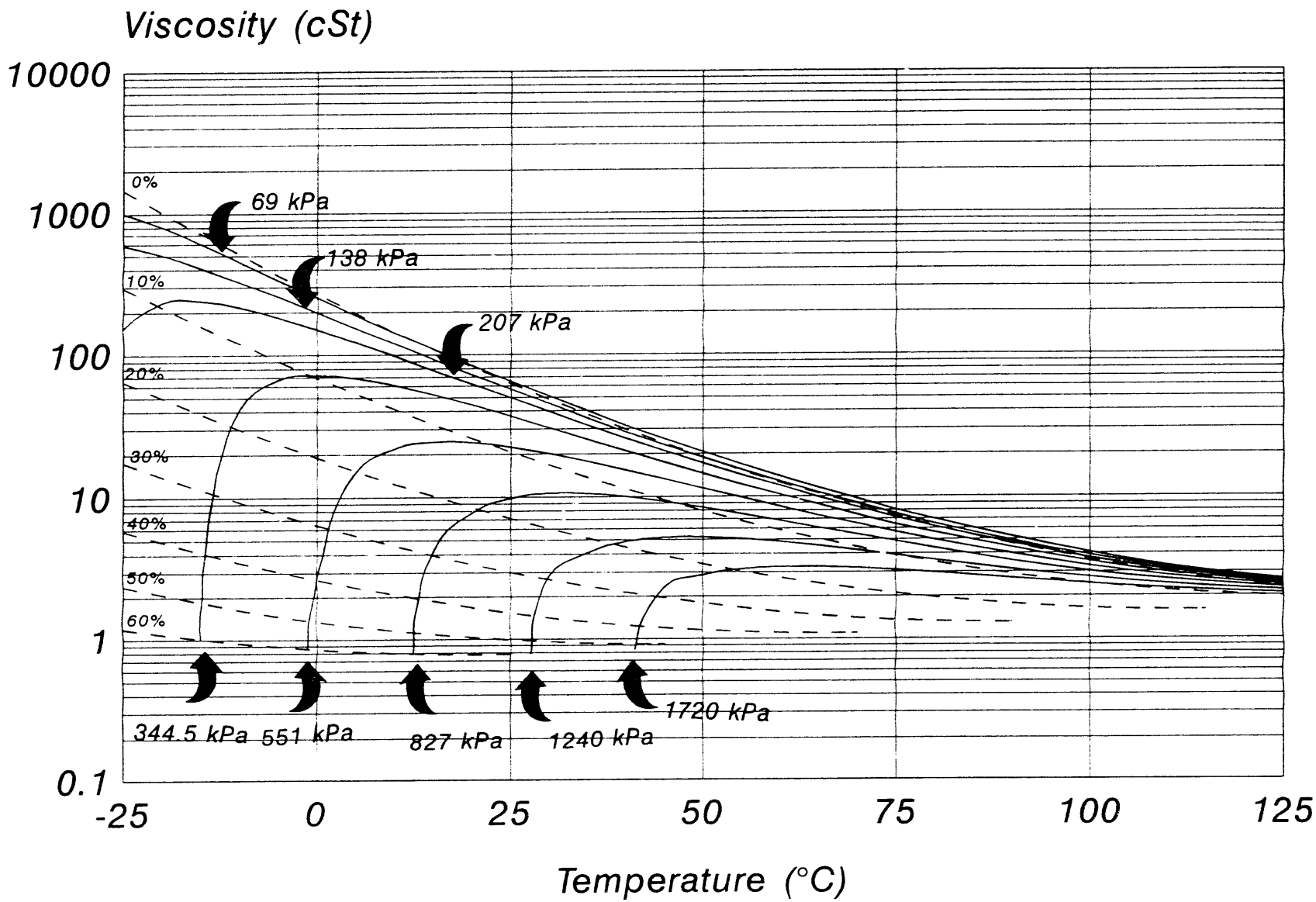
### 3.2.2 Viscosity of 32 ISO VG Mineral Oil with R-502

Appendix C shows the isothermal viscosity, density, and solubility of R-502 in 32 ISO VG mineral oil. Each isothermal plot shows the fractionation of R-502 as percentage R-22 of the total gas in solution. The lowest temperature at which viscosity was determined is -10°C: the highest is 125°C and 500 psia. At each test temperature and pressure, mixed refrigerant gas is purged through the lubricant until the fractionated components reach equilibrium. The equilibrium is maintained by making the refrigerant gas above the lubricant equal to the proportion of the mixed lubricant and refrigerant. The percent concentration of the total refrigerant represents the total of both gases that are soluble in the fluid at that pressure and temperature. Figure 6 presents viscosity as a function of temperature and includes isobaric pressure lines. Figure 7 presents a modified "Daniel Plot" that shows viscosity and pressure at constant concentration as a function of temperature. Figure 8 shows density as a function of temperature at constant concentration.

# Viscosity vs Temperature

## R-502 in 32 ISO VG Mineral Oil

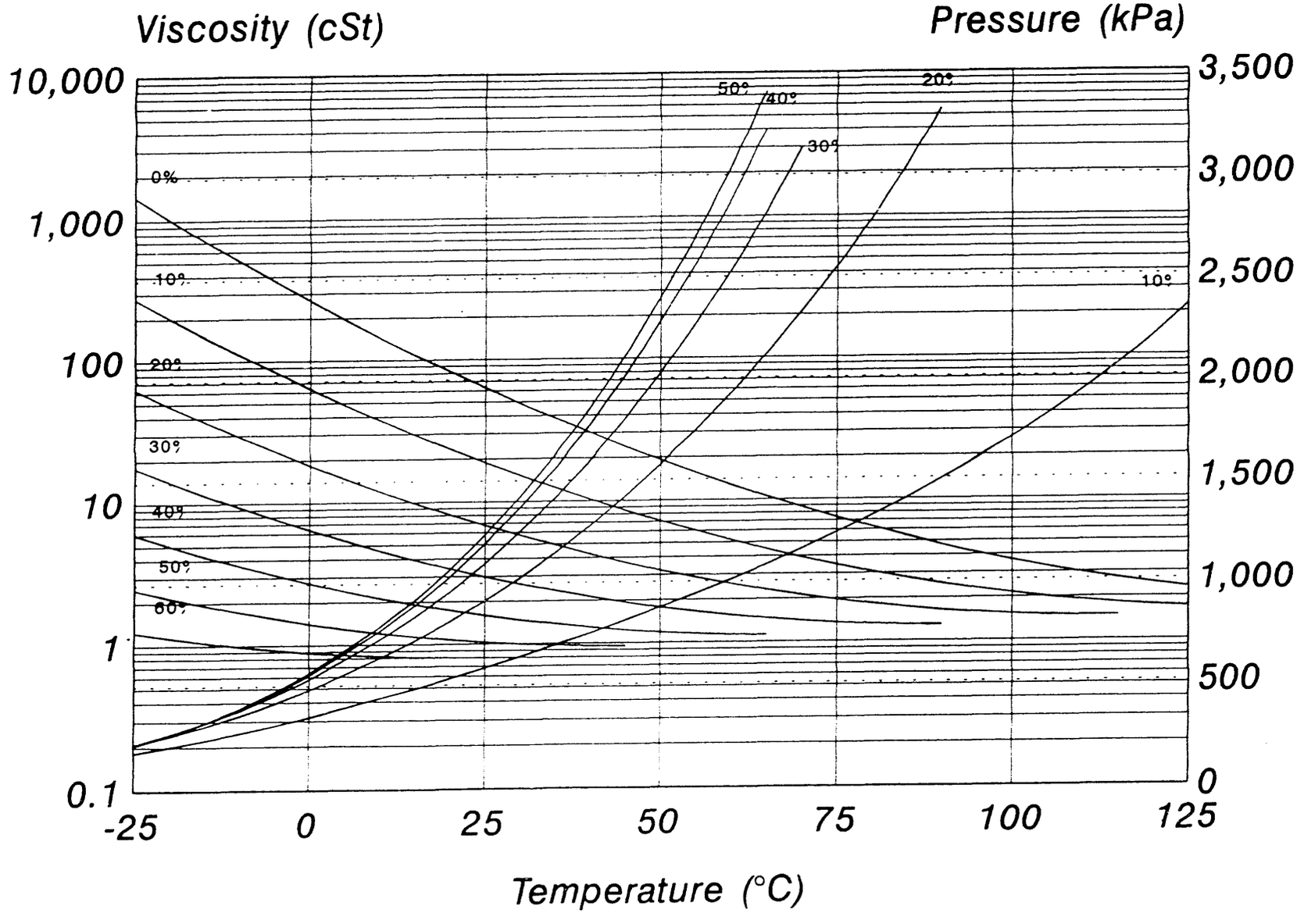
Figure 6



# Viscosity and Pressure at Constant Concentrations

## R-502 in 32 ISO VG Mineral Oil

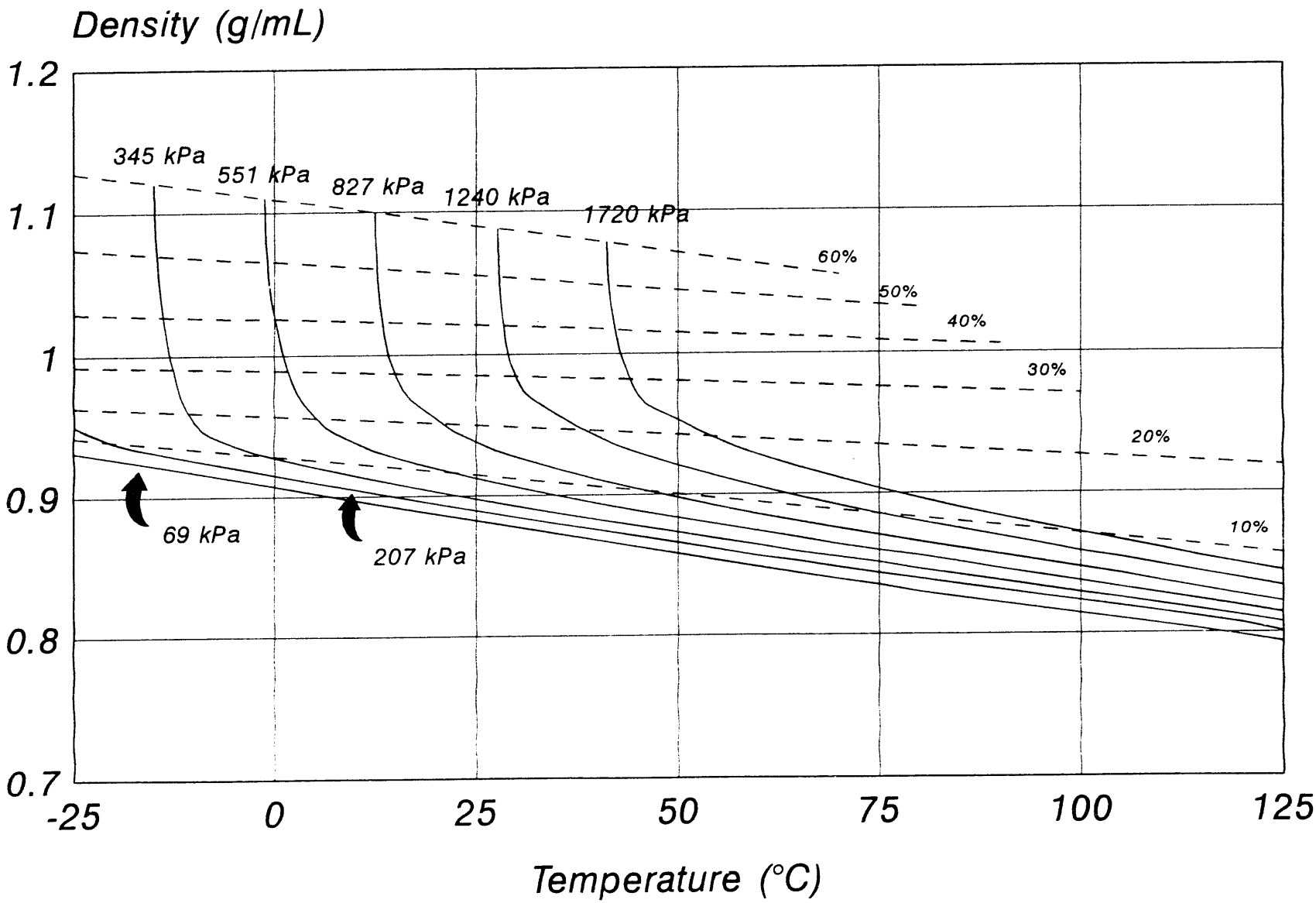
*Figure 7*



# Density vs. Temperature

## R-502 in 32 ISO VG Mineral Oil

## Figure 8



### 3.3 Measurements with Polyolesters

#### 3.3.1 Viscosity of 32 ISO VG Mixed Acid Polyester with HFC-134a

Appendix D presents, in Table D.1, the isothermal viscosity, density, and solubility of gaseous HFC-134a in a 32 ISO VG mixed acid polyolester with good miscibility characteristics. Some isothermal curves illustrate reasonably straight viscosity reduction with increasing refrigerant dilution, while some show a characteristic solubility knee. Several viscosity data points were taken; the lowest temperature at which viscosity was measured was -30°C. Figure 9 presents viscosity as a function of temperature and includes isobaric pressure lines. Figure 10 presents a modified "Daniel plot" showing viscosity and pressure at constant concentrations as a function of temperature. Figure 11 shows density as a function of temperature at constant concentrations.

#### 3.3.2 Viscosity of 32 ISO VG Branched Acid Polyester with HFC-134a

Appendix E presents, in Table E.1, the isothermal viscosity, density, and solubility of gaseous HFC-134a in a 32 ISO VG branched acid polyolester with good miscibility characteristics. Figure 12 presents viscosity as a function of temperature and includes isobaric pressure lines. Figure 13 presents a modified "Daniel plot" showing viscosity and pressure at constant concentrations as a function of temperature. Figure 14 shows density as a function of temperature at constant concentrations.

#### 3.3.3 Viscosity of 32 ISO VG Branched Acid Polyester with HFC-143a

Appendix F presents, in Table F.1, the isothermal viscosity, density, and solubility of gaseous HFC-143a in a 32 ISO VG branched acid polyolester. Five viscosity data points were taken for each temperature. Figure 15 presents viscosity as a function of temperature and includes isobaric pressure lines. Figure 16 presents a modified "Daniel plot" showing viscosity and pressure at constant concentrations as a function of temperature. The 10% and 20% concentration lines flatten as the temperature increases. The characteristics of HFC-143a may cause this effect, which is confirmed by the isothermal test points. However, it is not seen with mixed-acid polyolester (see figure 19). Figure 17 shows density as a function of temperature at constant concentrations.

#### 3.3.4 Viscosity of 32 ISO VG Mixed Acid Polyester with HFC-143a

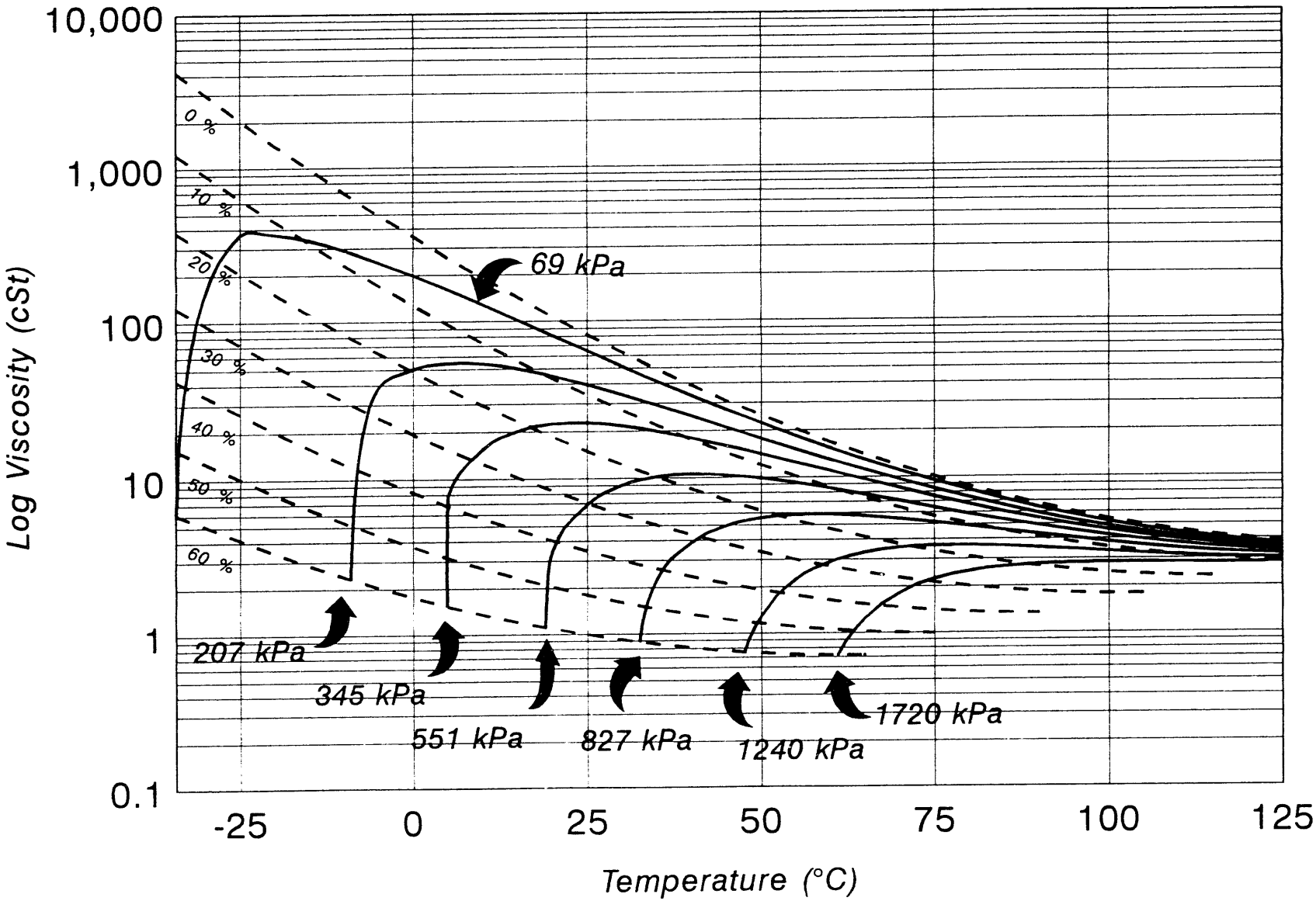
Appendix G presents, in Table G.1, the isothermal viscosity, density, and solubility of gaseous HFC-143a in a 32 ISO VG mixed acid polyolester with good miscibility characteristics. Five viscosity data points were taken for each temperature. Figure 18 presents viscosity as a function of temperature and includes isobaric pressure lines. Figure

19 presents a modified "Daniel plot" showing viscosity and pressure at constant concentrations as a function of temperature. Figure 20 shows density as a function of temperature at constant concentrations.

# Viscosity vs. Temperature

## HFC-134a in 32 ISO VG Mixed Acid Polyolester

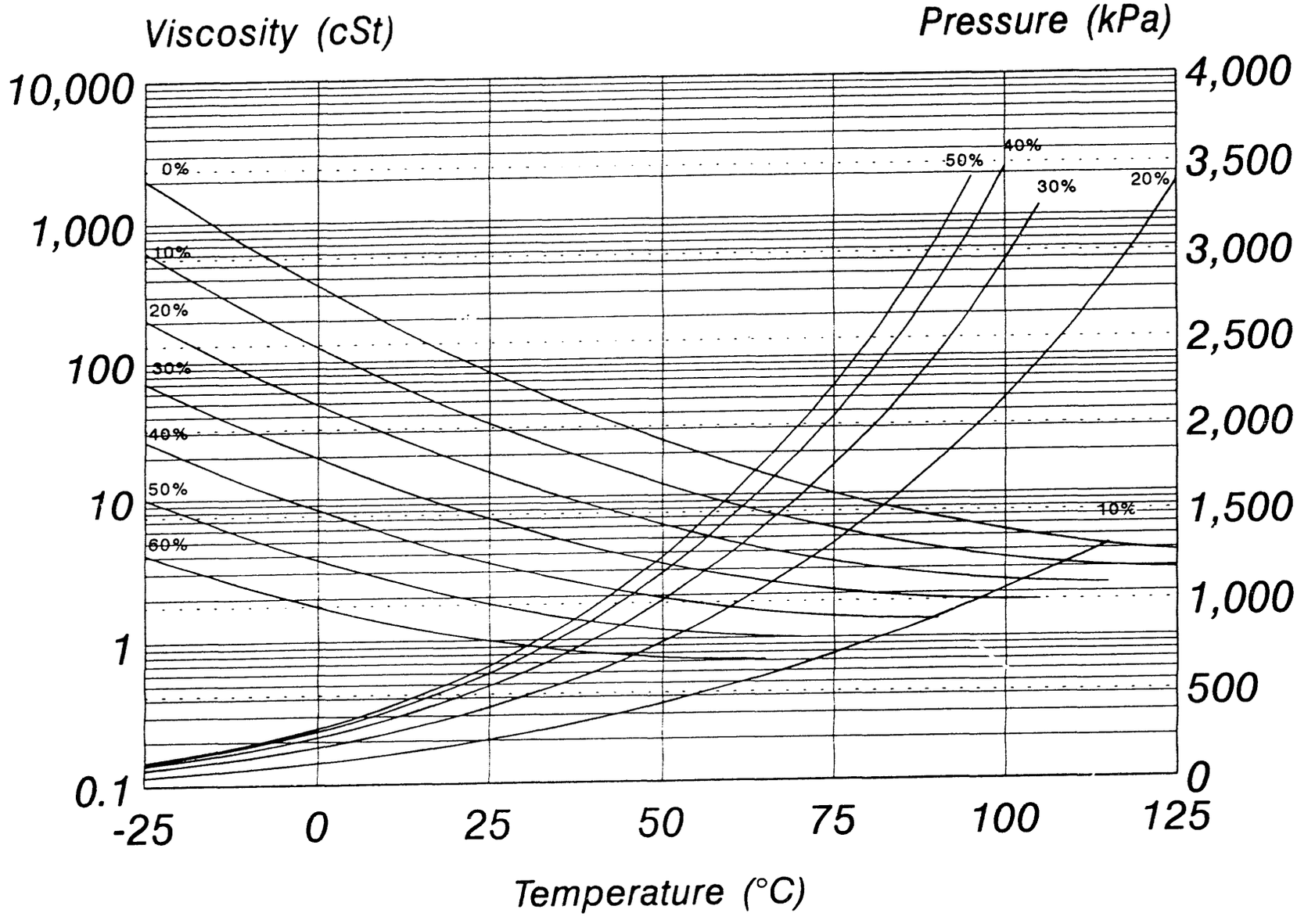
*Figure 9*



# Viscosity and Pressure at Constant Concentrations

## R-134a in 32 ISO VG Mixed Acid Polyolester

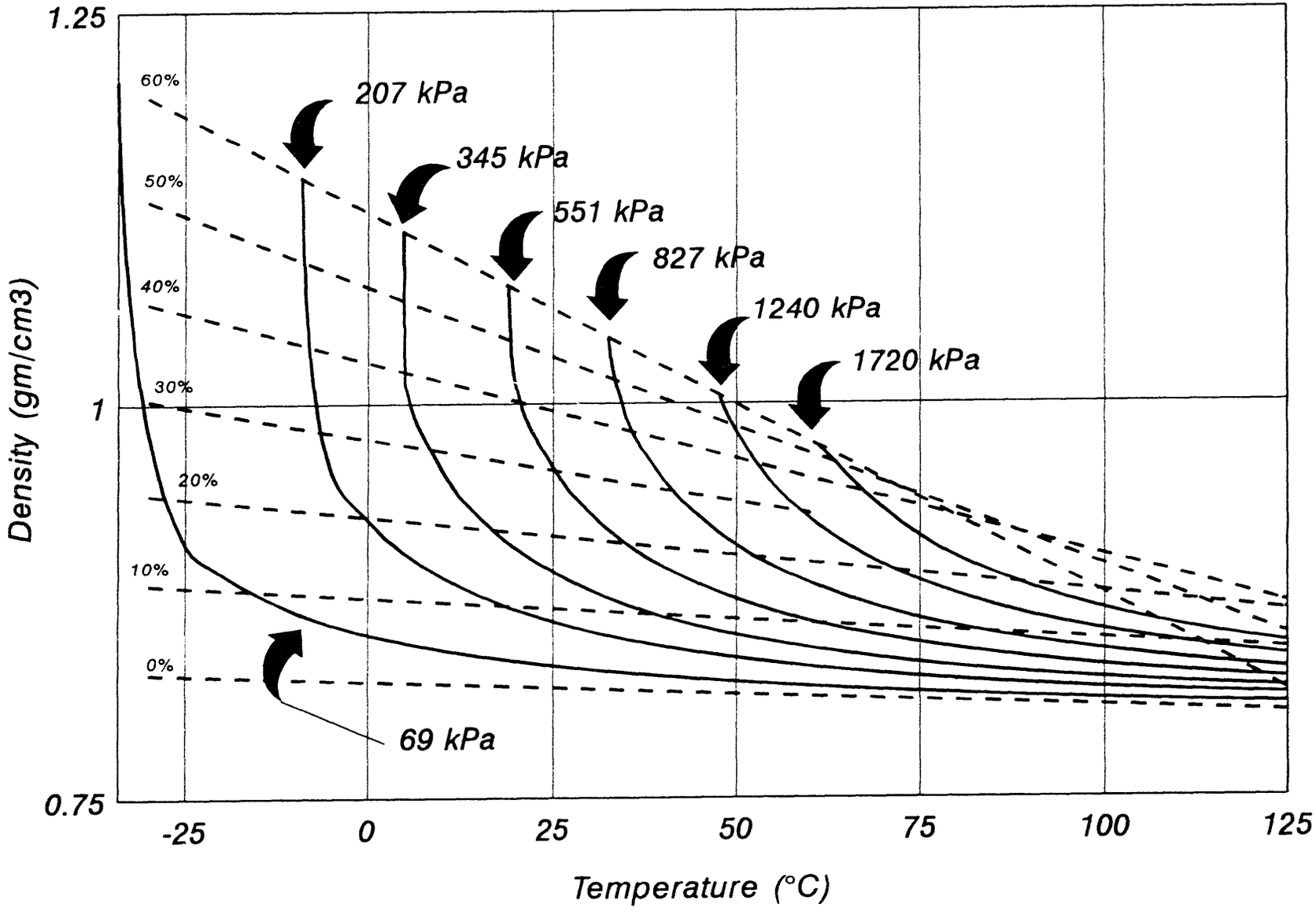
Figure 10



# Density vs. Temperature

## HFC-134a in 32 ISO VG Mixed Acid Polyolester

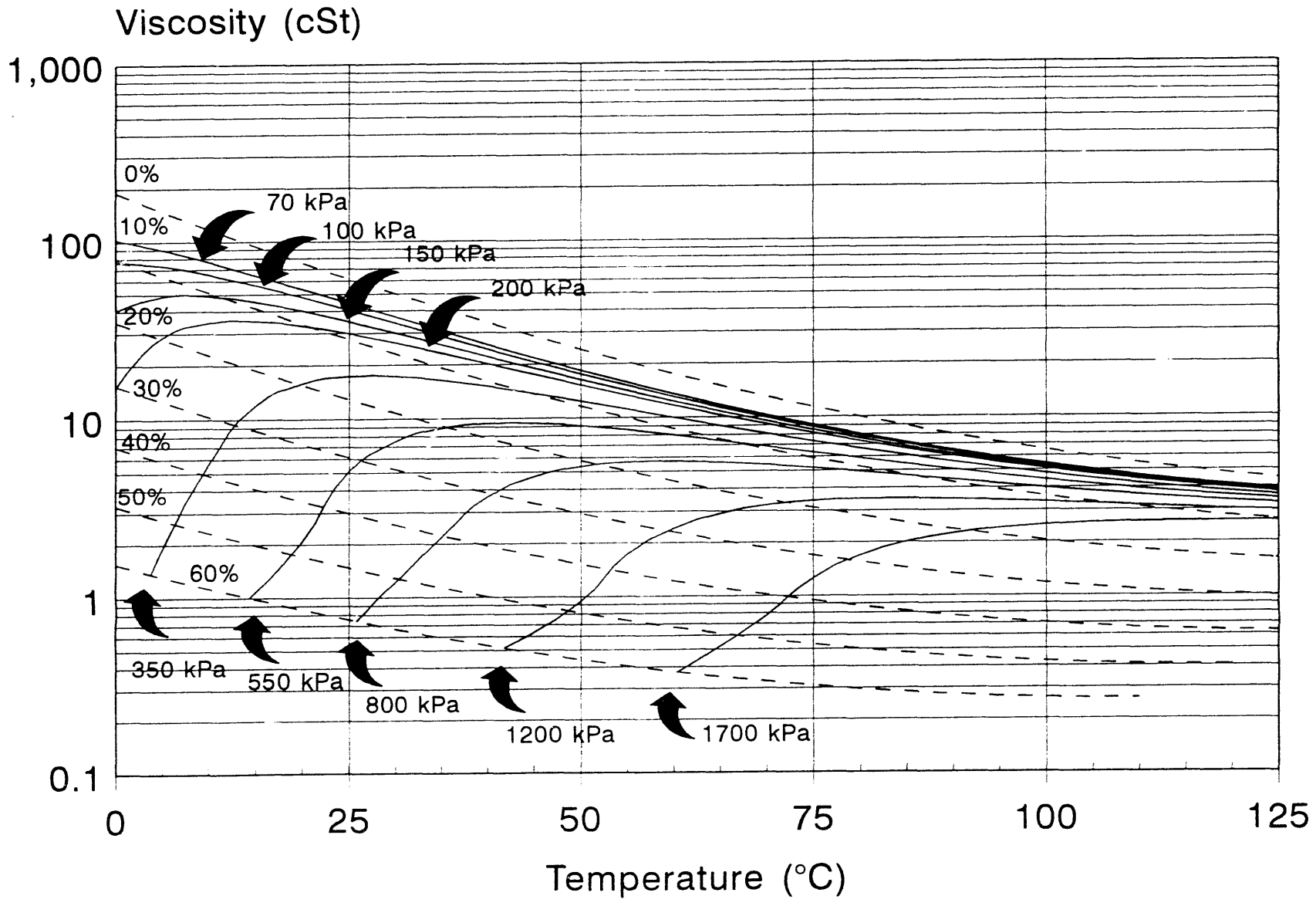
## Figure 11



# *Viscosity vs. Temperature*

## *HFC-134a in 32 ISO VG Branched Acid Polyolester*

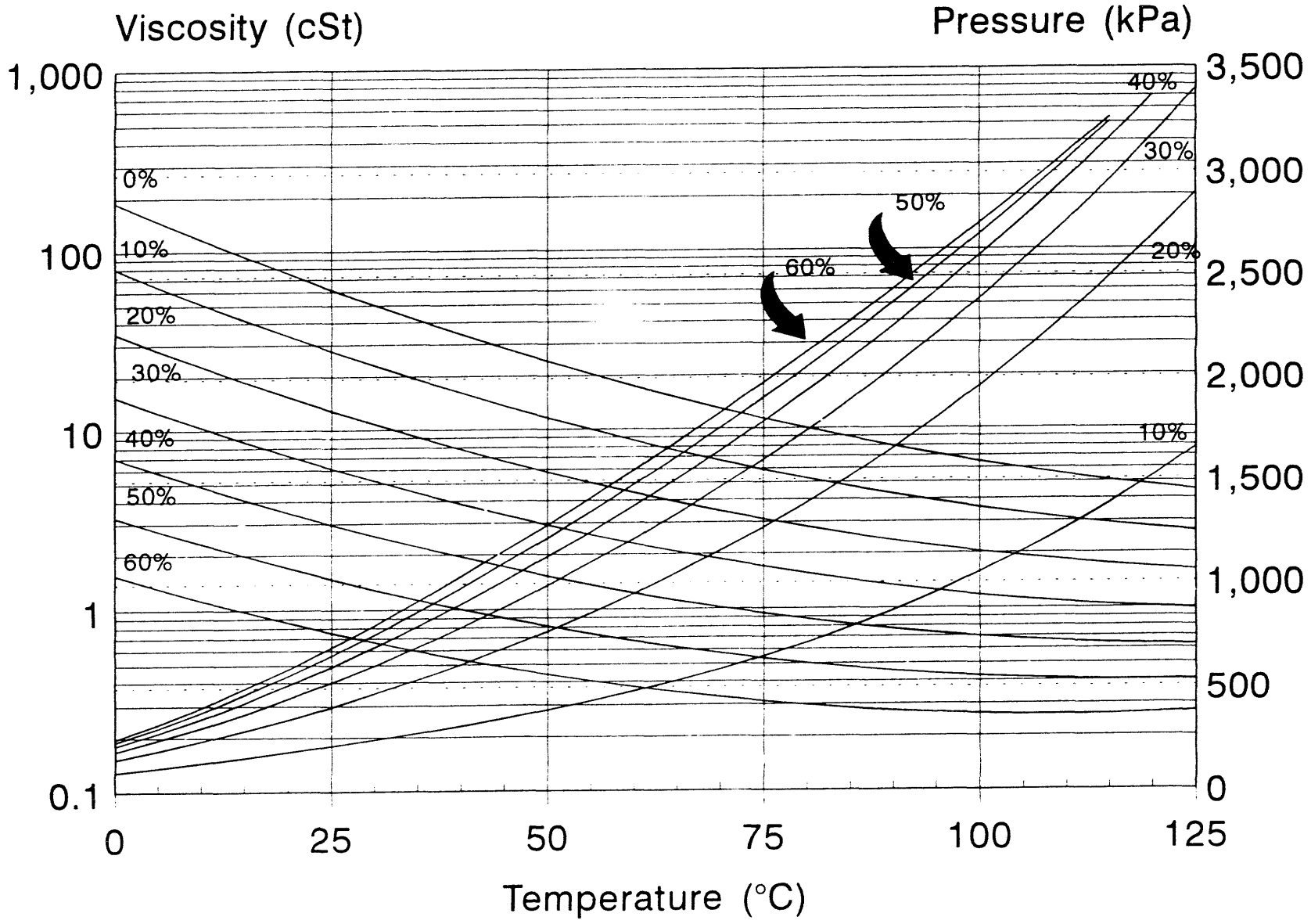
*Figure 12*



# *Viscosity and Pressure at Constant Concentrations*

*HFC-134a in 32 ISO VG Branched Acid Polyolester*

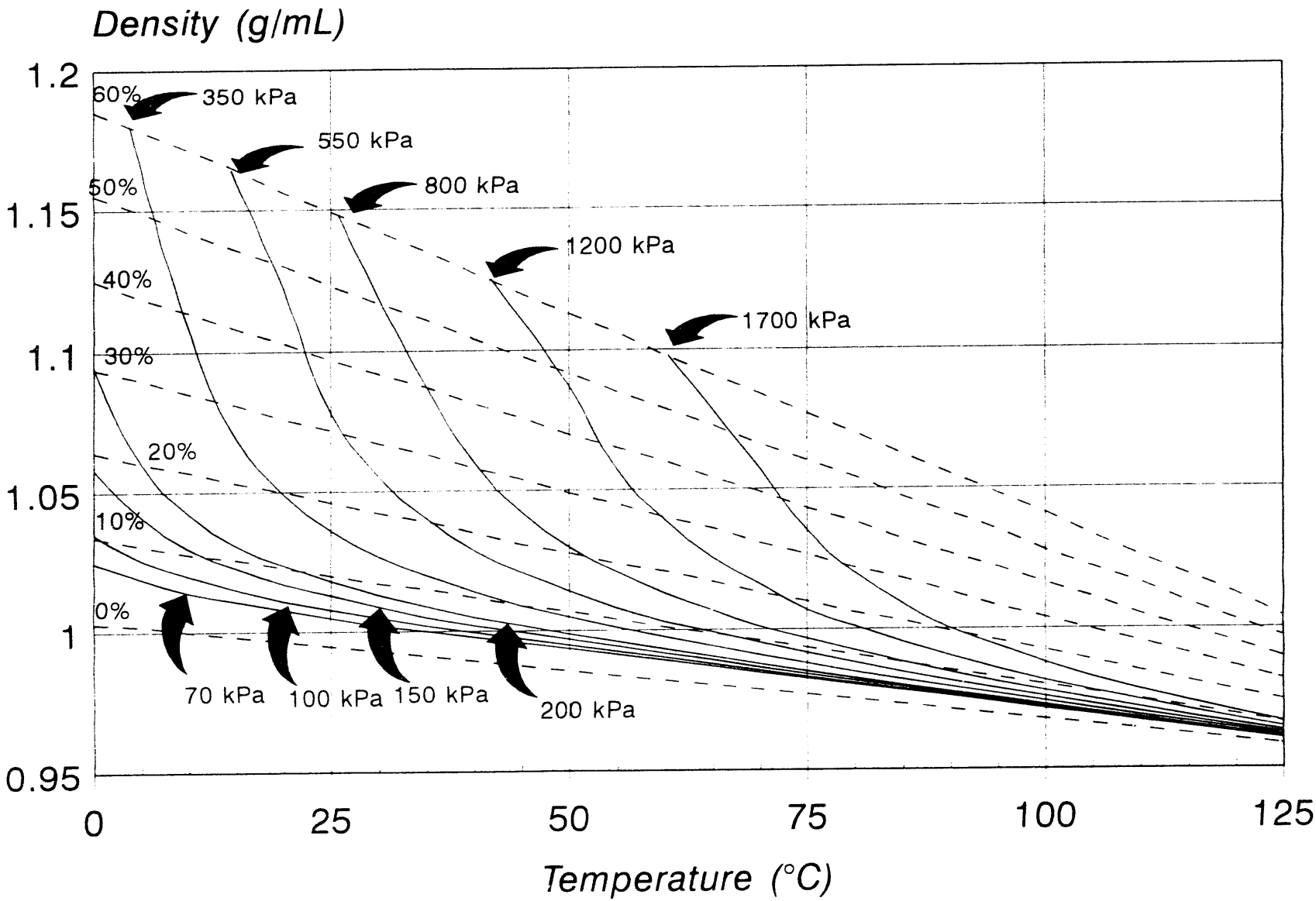
*Figure 13*



# Density vs. Temperature

## HFC-134a in 32 ISO VG Branched Acid Polyolester

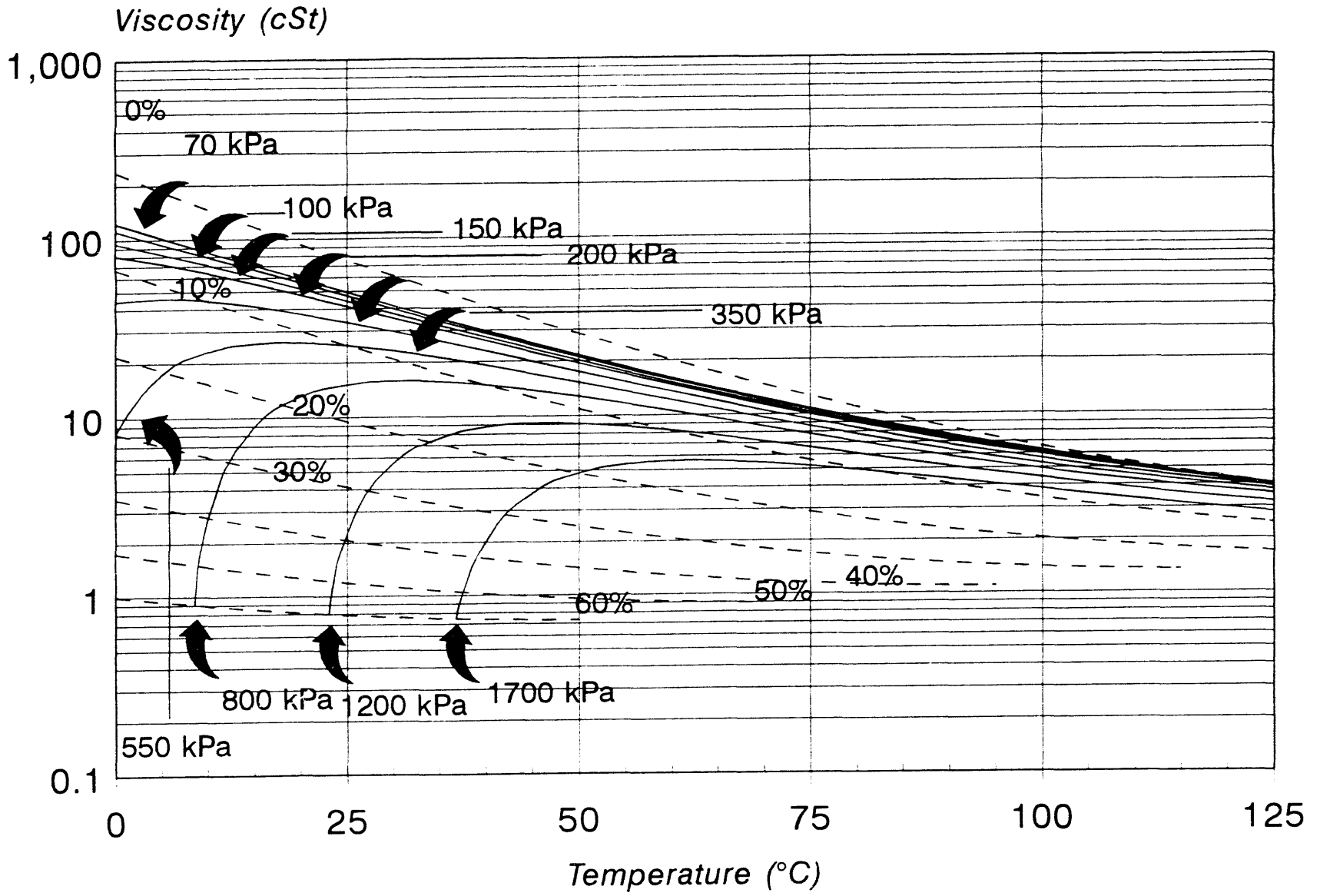
*Figure 14*



# *Viscosity vs. Temperature*

## *HFC-143a in 32 ISO Branched Acid Polyolester*

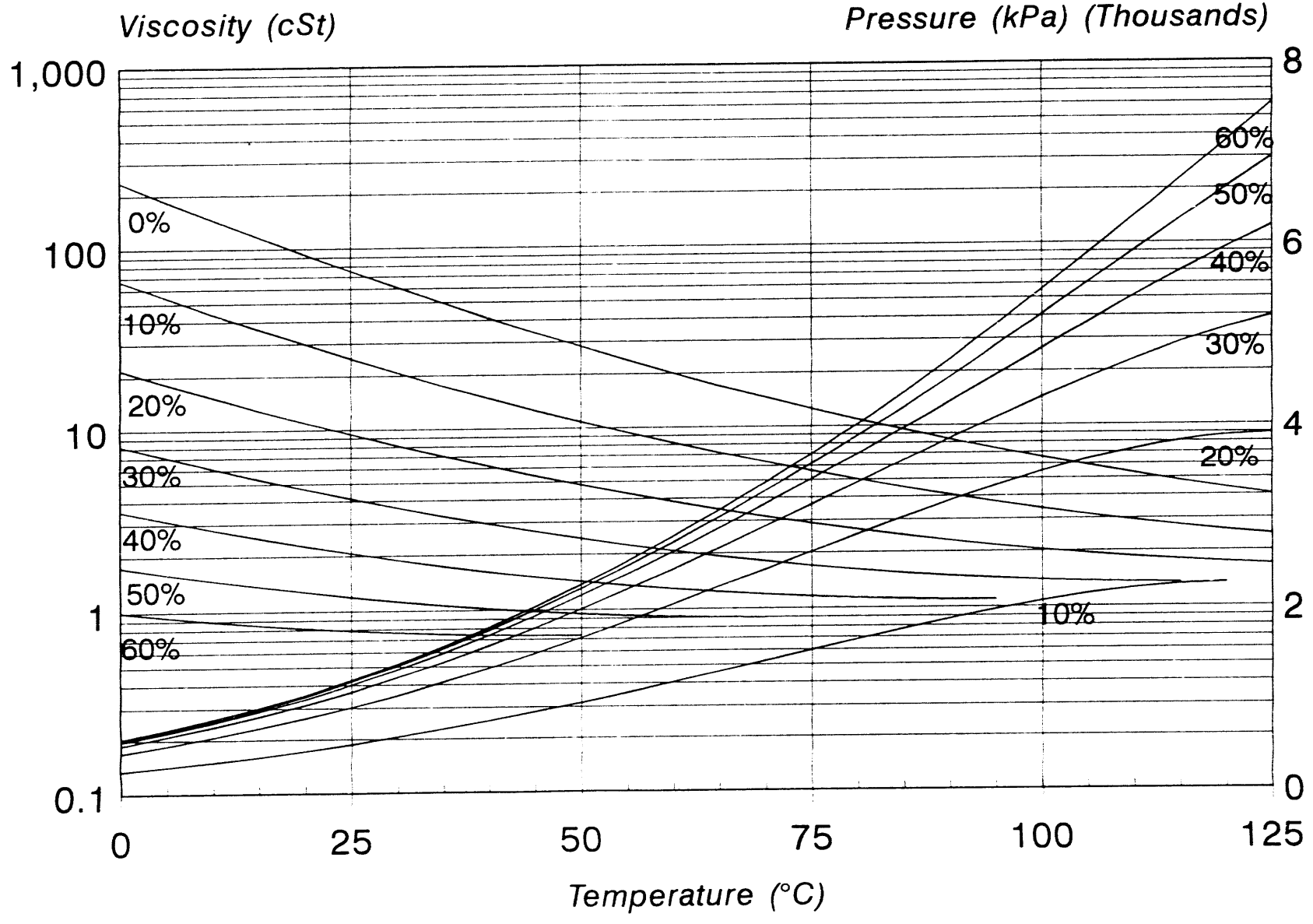
## *Figure 15*



# Viscosity and Pressure at Constant Concentrations

## HFC-143a in 32 ISO VG Branched Acid Polyolester

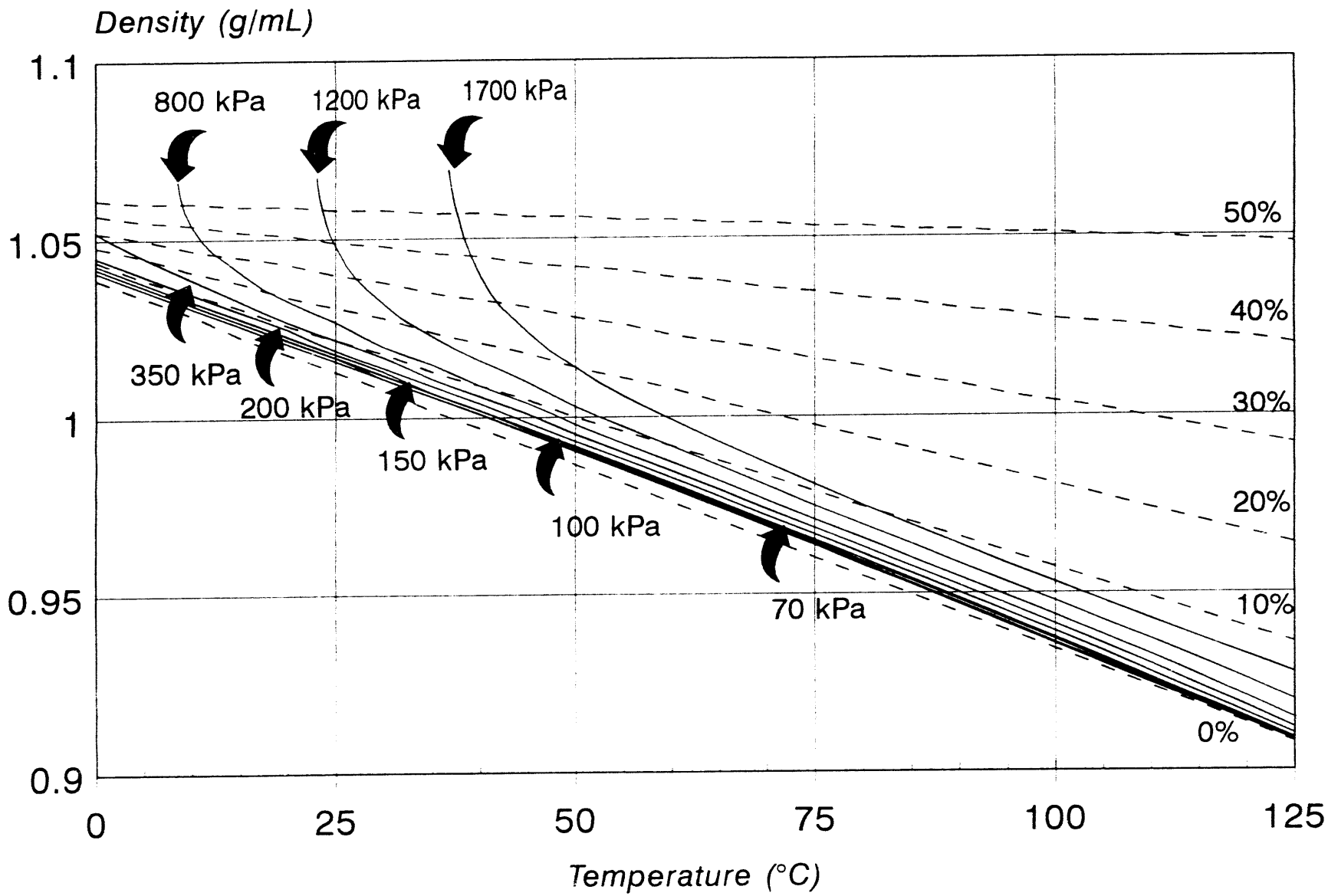
*Figure 16*



# *Density vs. Temperature for Constant Concentrations*

*HFC-143a with 32 ISO VG Branched Acid Polyolester*

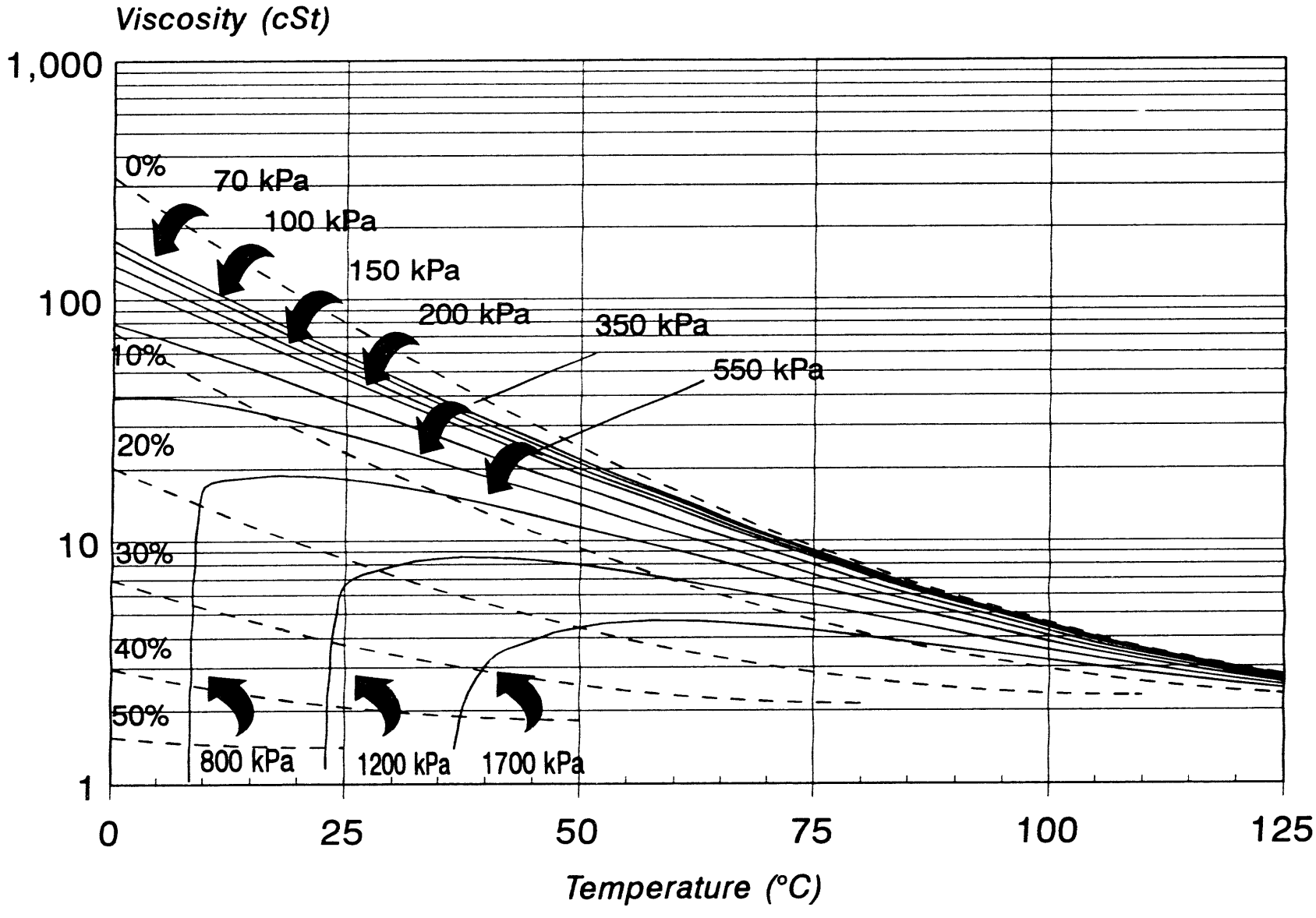
*Figure 17*



# *Viscosity vs. Temperature*

## *HFC-143a in 32 ISO Mixed Acid Polyolester*

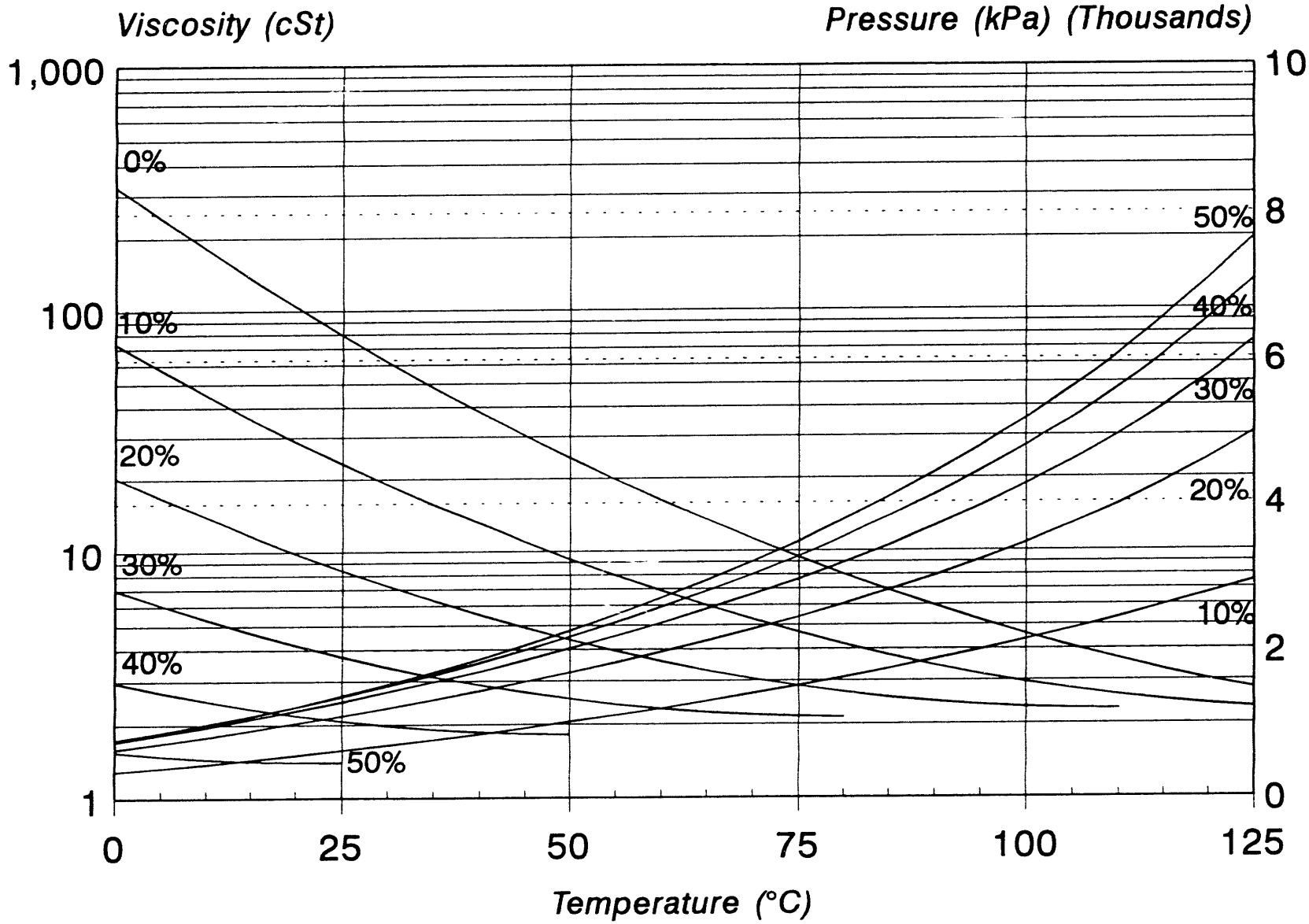
## *Figure 18*



# Viscosity and Pressure at Constant Concentrations

## HFC-143a in 32 ISO VG Mixed Acid Polyolester

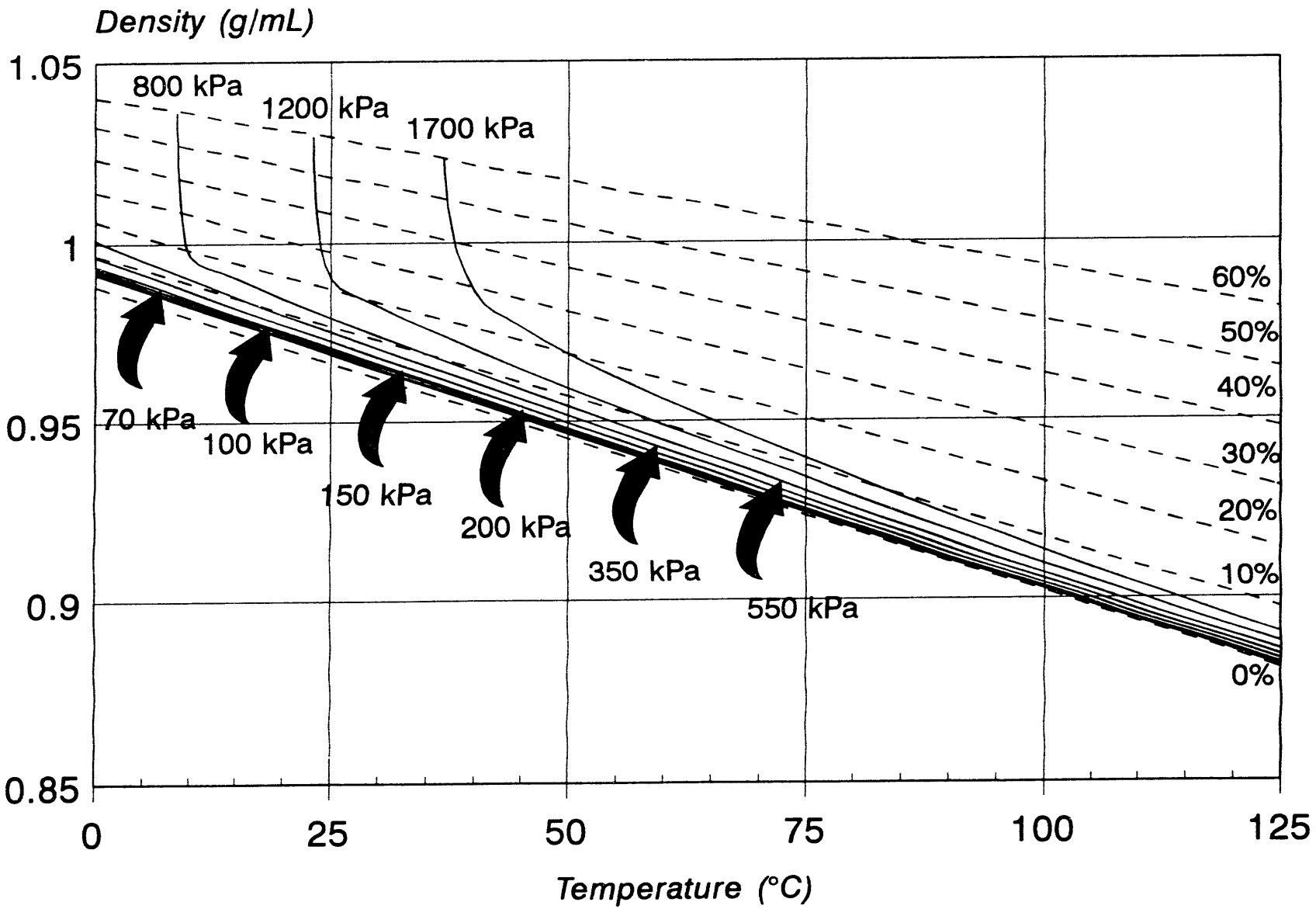
*Figure 19*



# *Density vs. Temperature*

## *HFC-143a in 32 ISO VG Mixed Acid Polyolester*

## *Figure 20*



## 4. Compliance with Agreement

Imagination Resources, Inc. is in compliance with the contract agreement.

## 5. Principal Investigator Effort

The principal investigators have devoted 1750 hours toward the completion of this contract. Activities include reporting early refrigerant miscibility information to the Technical Oversight Group, and measuring viscosity, density, and solubility.

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## APPENDICES

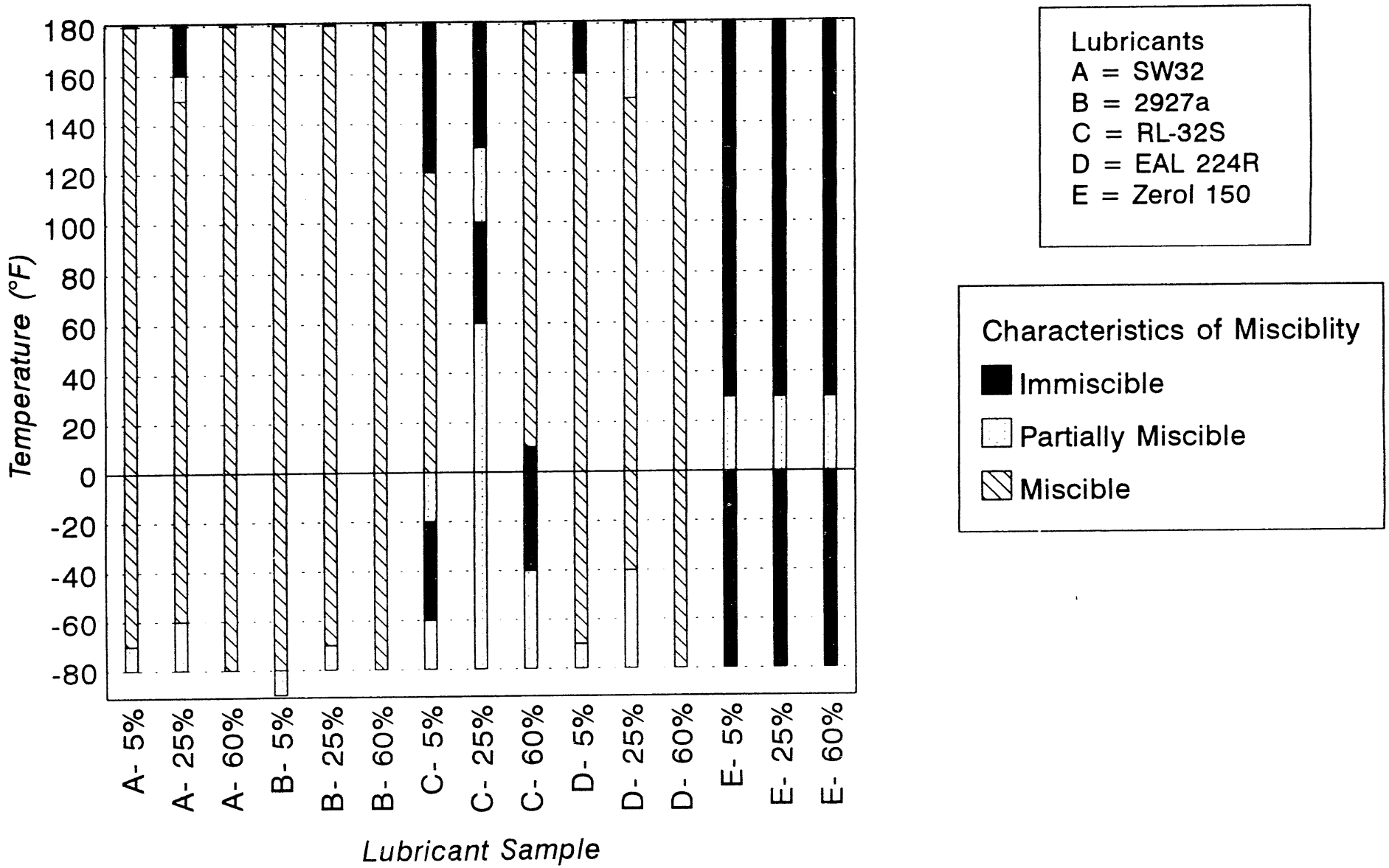
## APPENDIX A
## Miscibilities of Refrigerant Blends A-F

The following graphs present data about the miscibility of four different polyolesters and one alkylbenzene with six refrigerant blends at three different refrigerant/lubricant concentrations. This information was used to select the lubricants tested in this study.

# *Miscibility of Refrigerant Blend A*

*HFC-32 (60%) and HFC-125 (40%)*

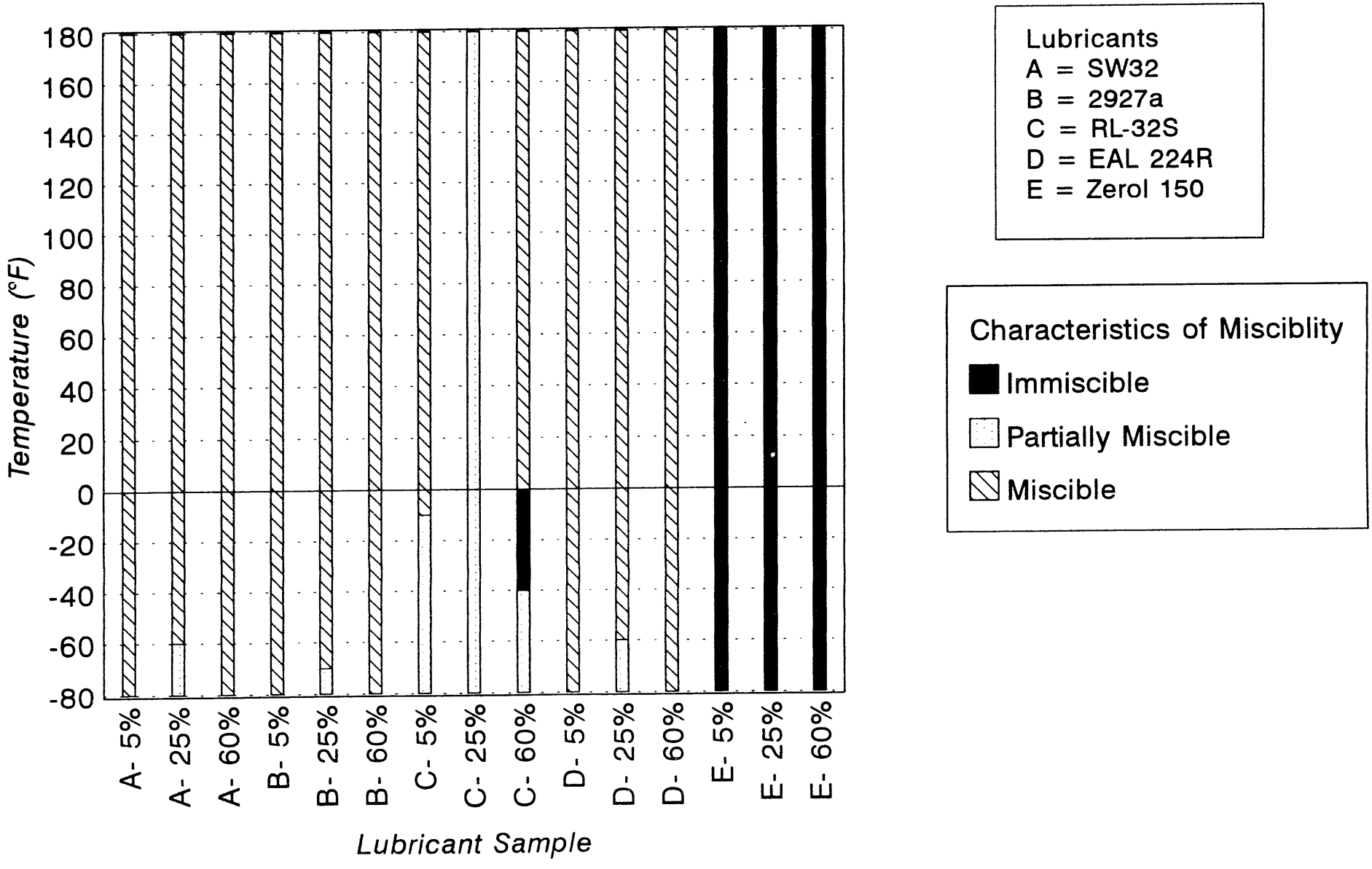
*Figure A.1*



# *Miscibility of Refrigerant Blend B*

## *HFC-32 (30%) and HFC-134a (70%)*

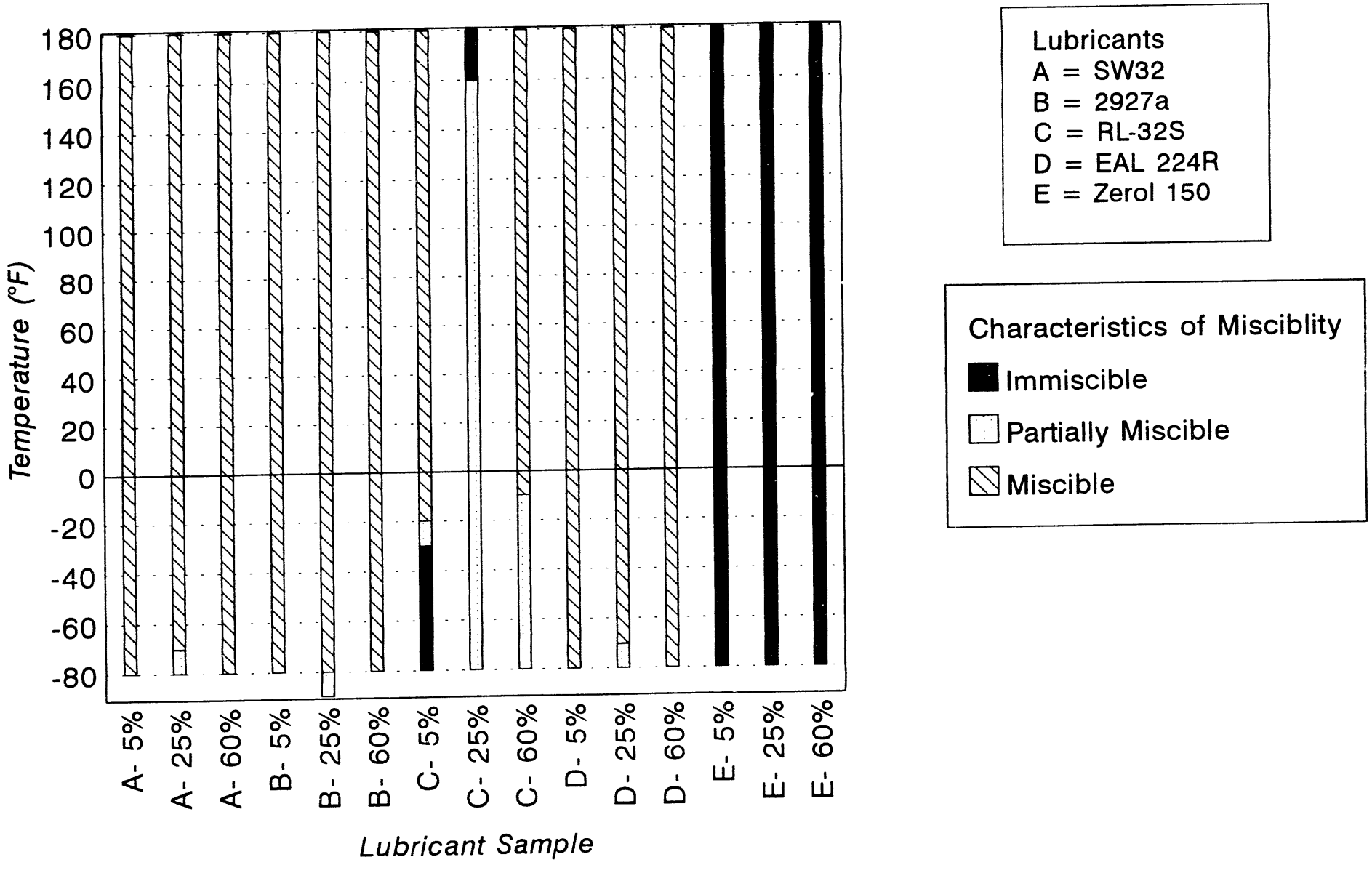
## *Figure A.2*



# *Miscibility of Refrigerant Blend C*

## *HFC-32 (30%), HFC-125 (10%), and HFC-134a (60%)*

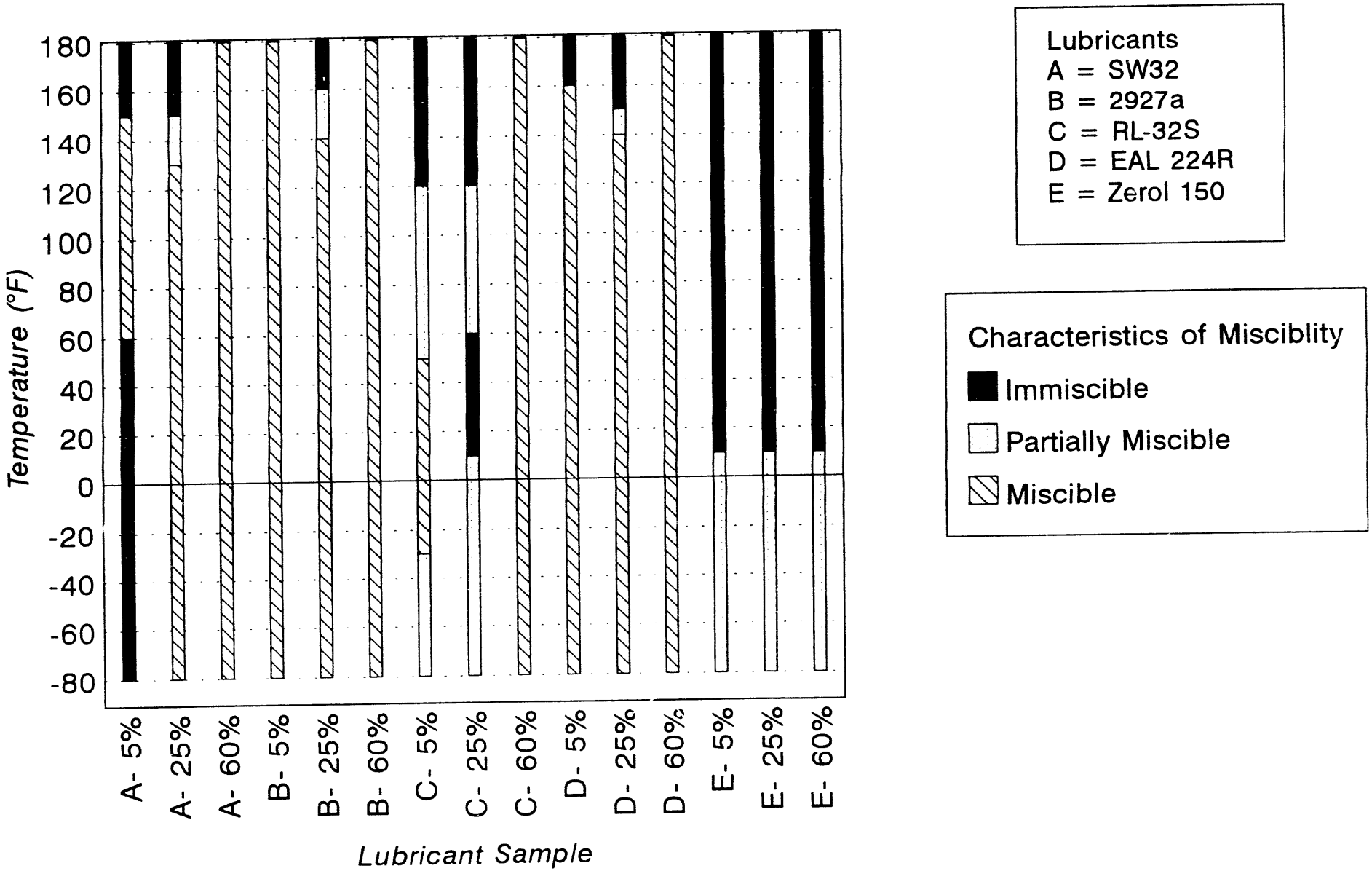
*Figure A.3*



# *Miscibility of Refrigerant Blend D*

## *HFC-125 (44%), HFC-143a (52%) and HFC-134a (4%)*

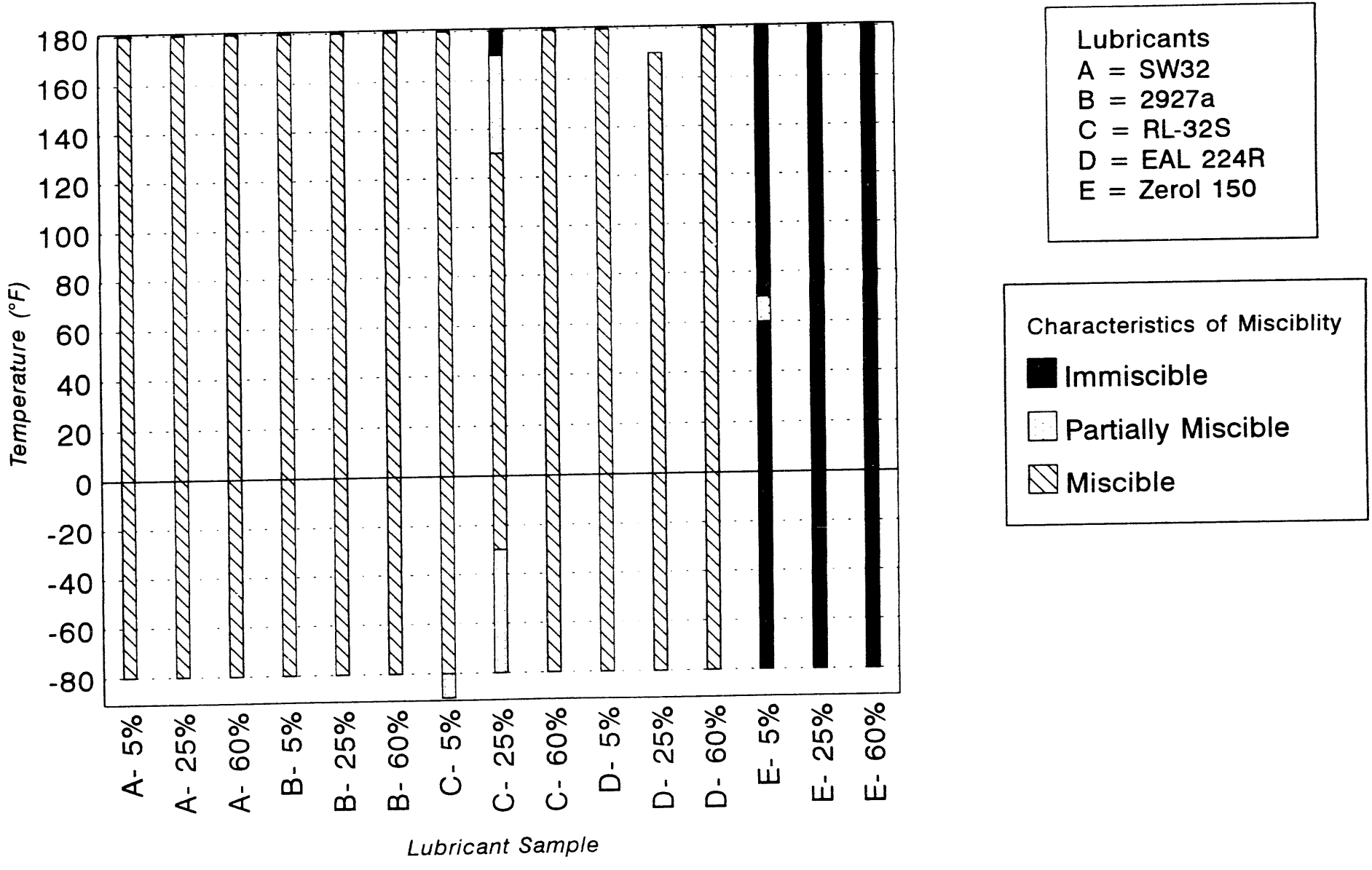
*Figure A.4*



# *Miscibility of Refrigerant Blend E*

## *HFC-32 (30%), HFC-125 (55%), HFC-134a (20%), and HC-290 (5%)*

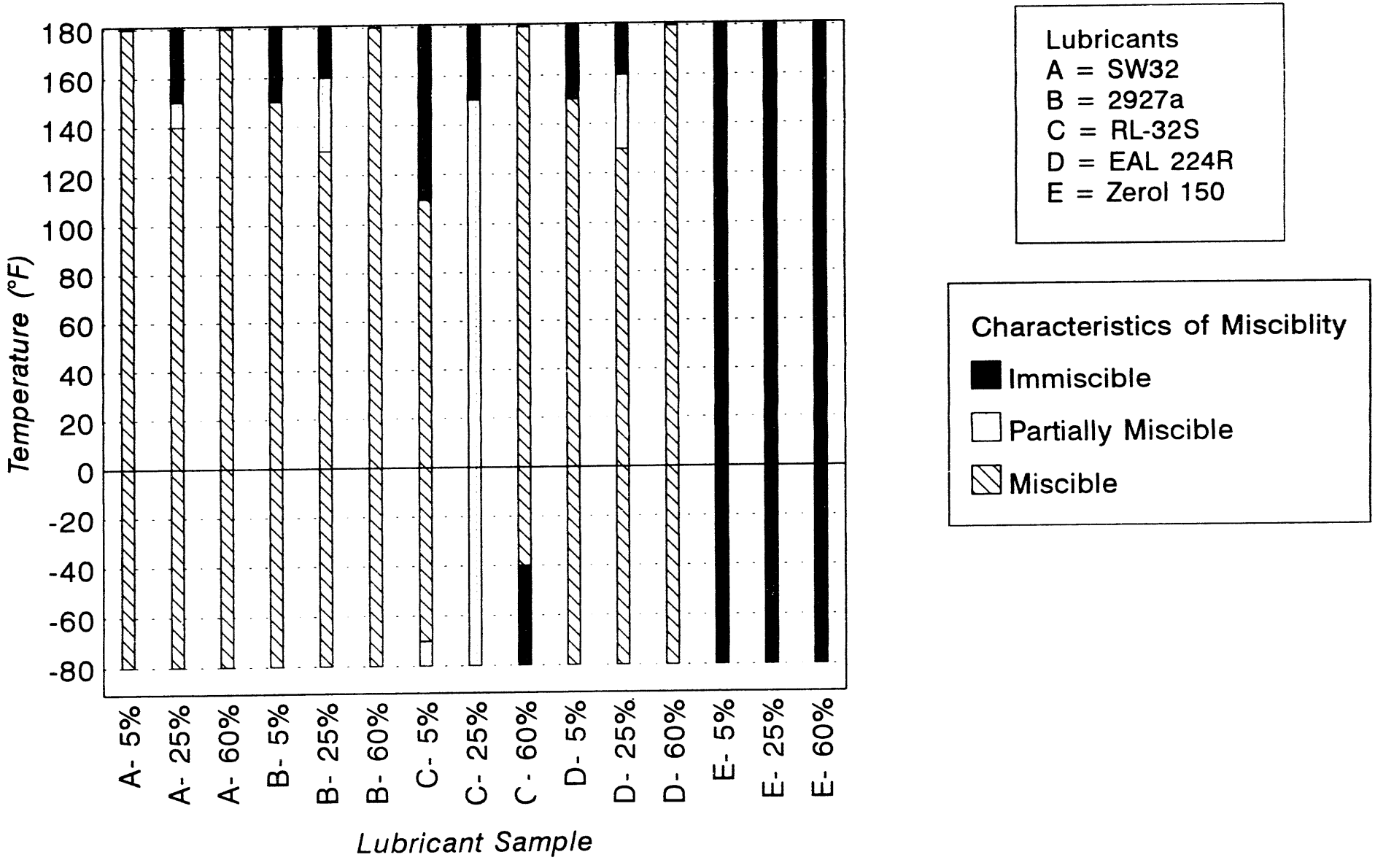
*Figure A.5*



# *Miscibility of Refrigerant Blend F*

## *HFC-125 (45%) and HFC-143a (55%)*

## *Figure A.6*



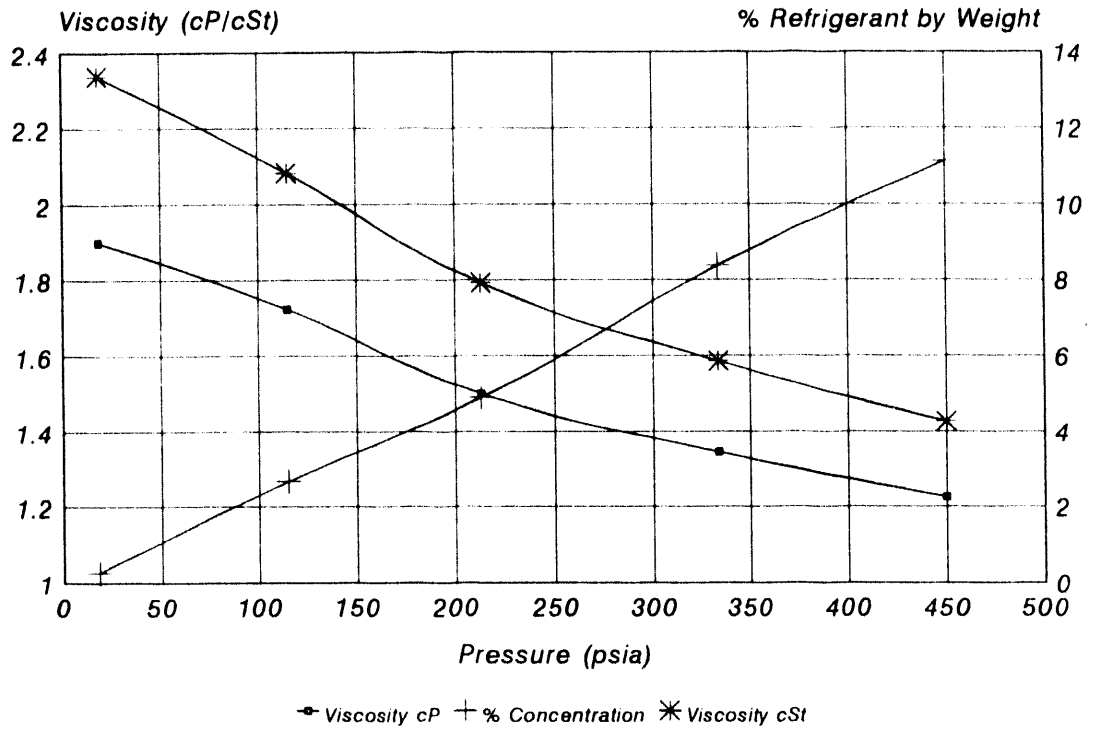
**APPENDIX B:**

**Viscosity and Gas Solubility of 32 ISO VG Mineral Oil at Various Temperatures with HCFC-22**

## *Viscosity and Gas Solubility*

*32 ISO VG Mineral Oil with HCFC-22 at 125°C*

*Figure B.1*

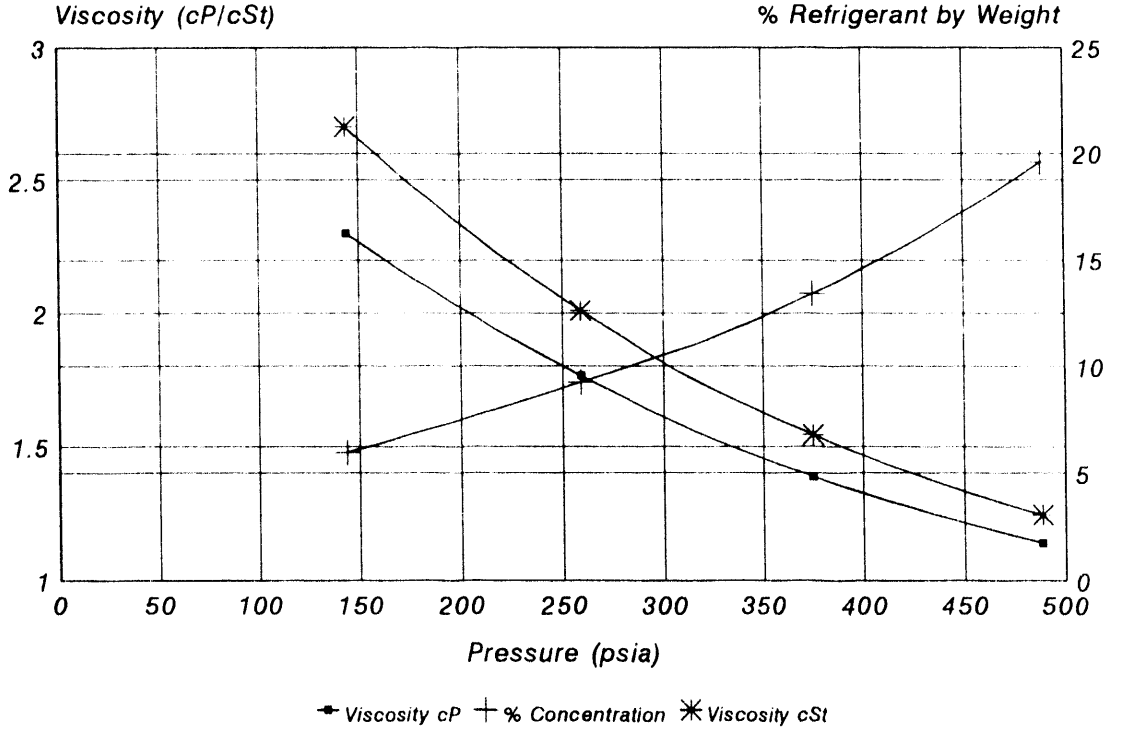



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mineral Oil with HCFC-22 at 100°C*

*Figure B.2*

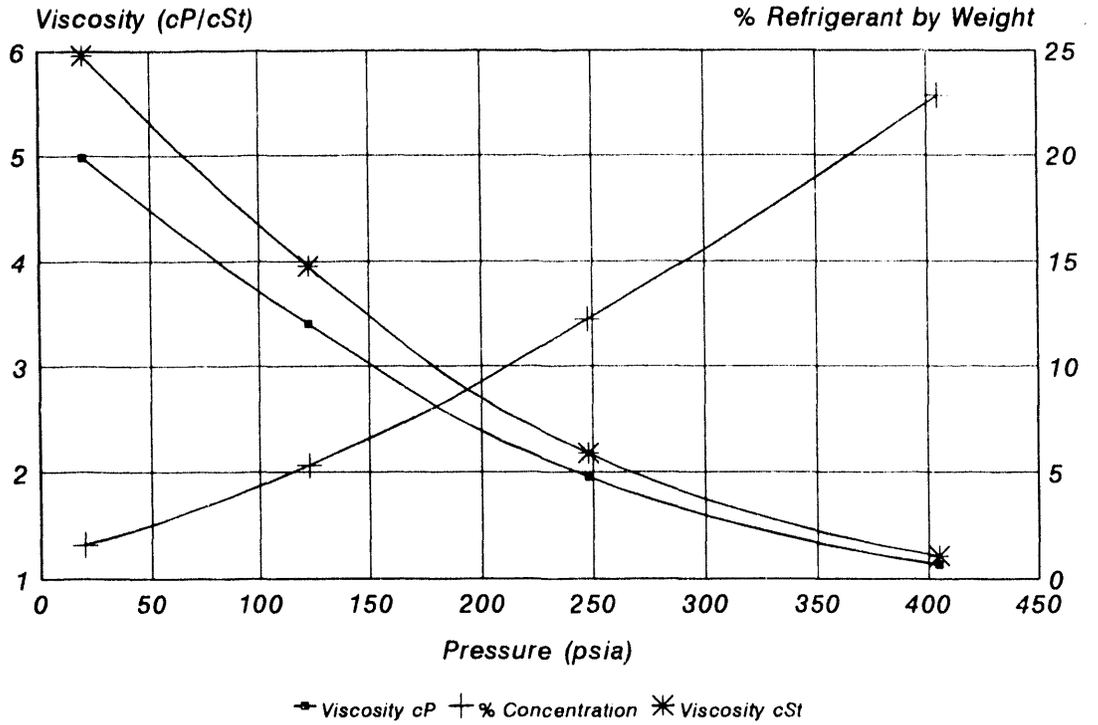



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mineral Oil with HCFC-22 at 80°C*

*Figure B.3*

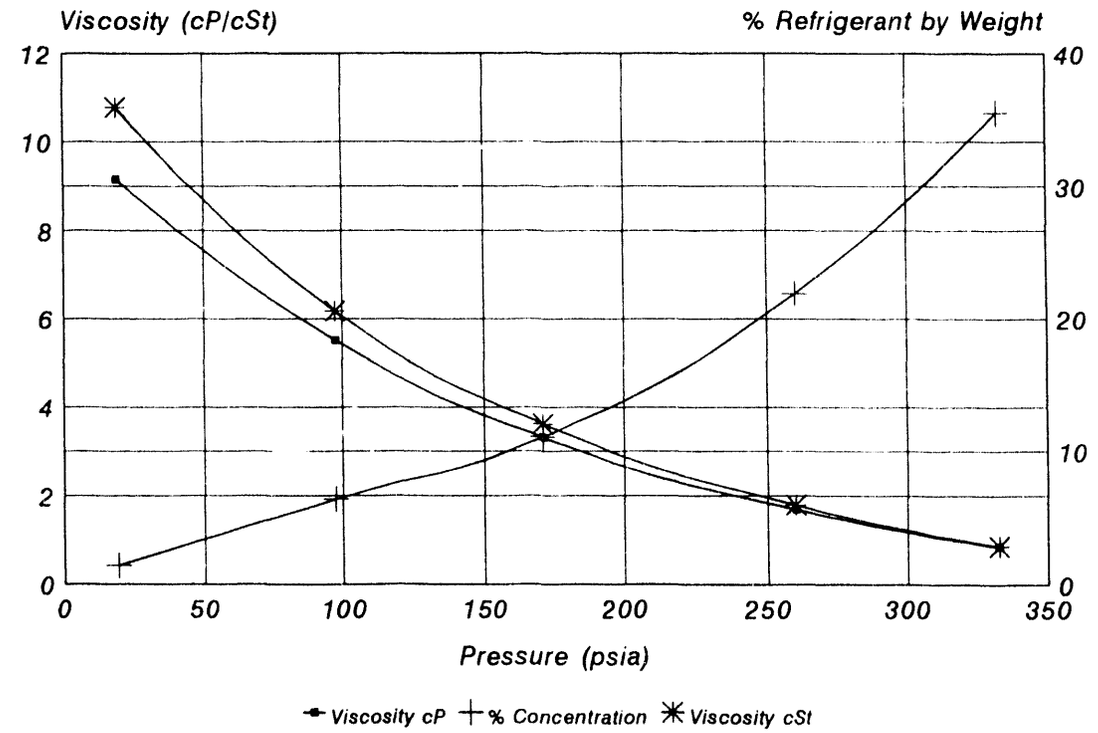



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mineral Oil with HCFC-22 at 60°C*

*Figure B.4*

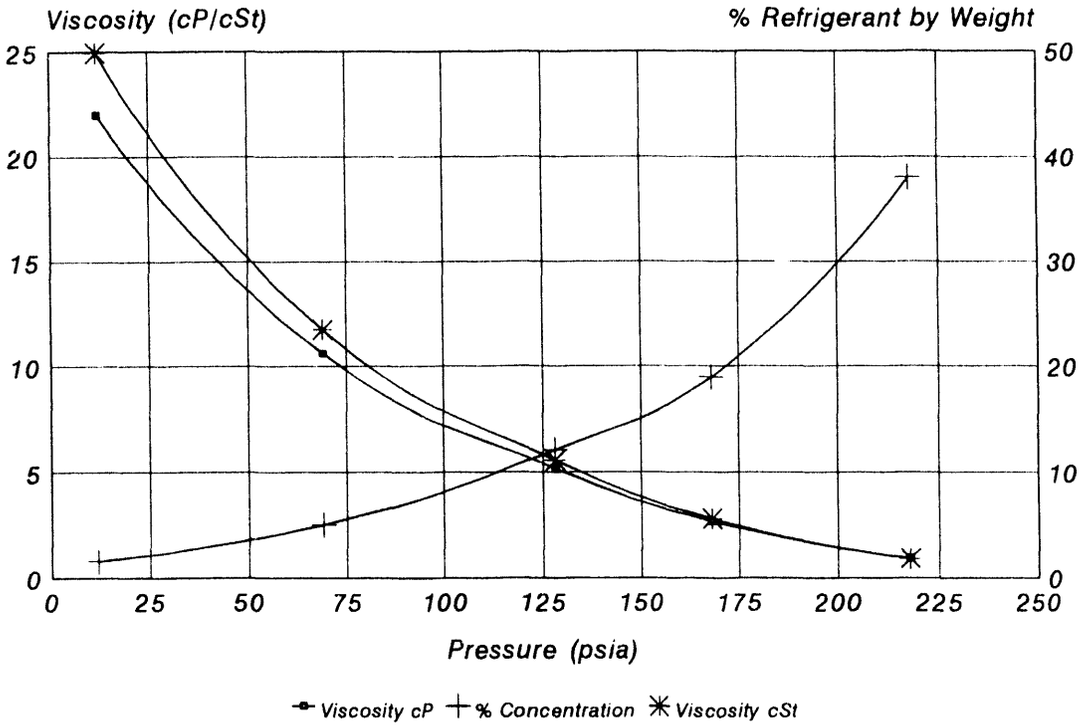



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mineral Oil with HCFC-22 at 40°C*

*Figure B.5*

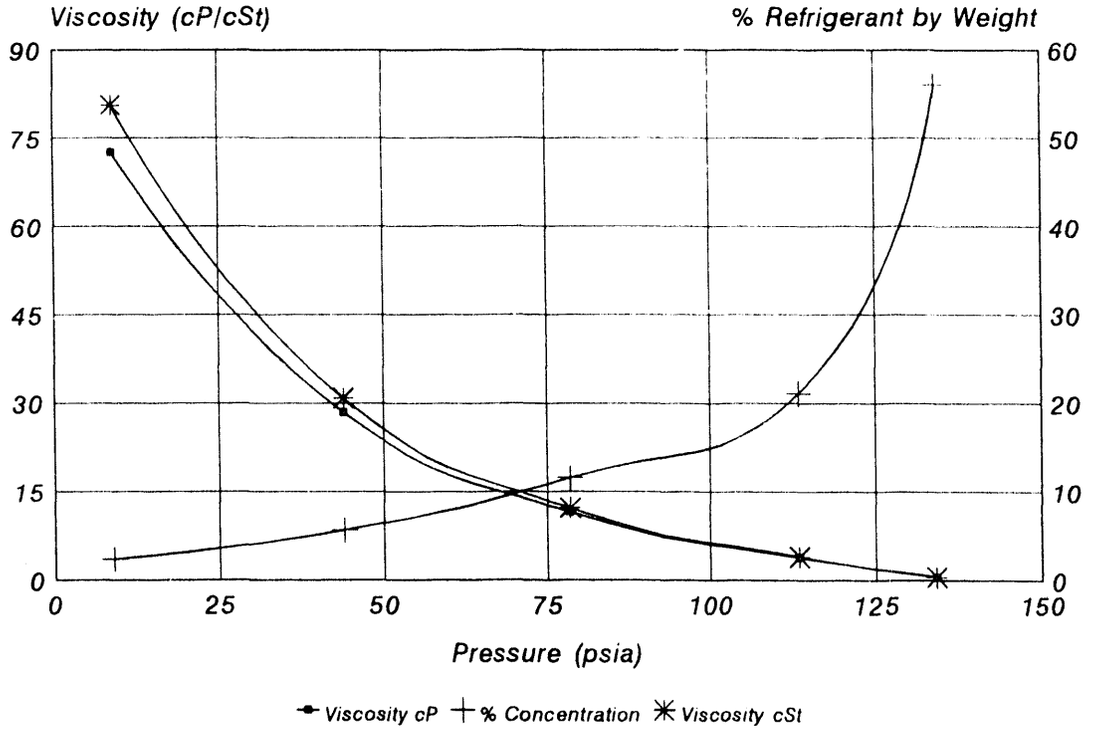



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mineral Oil with HCFC-22 at 20°C*

*Figure B.6*

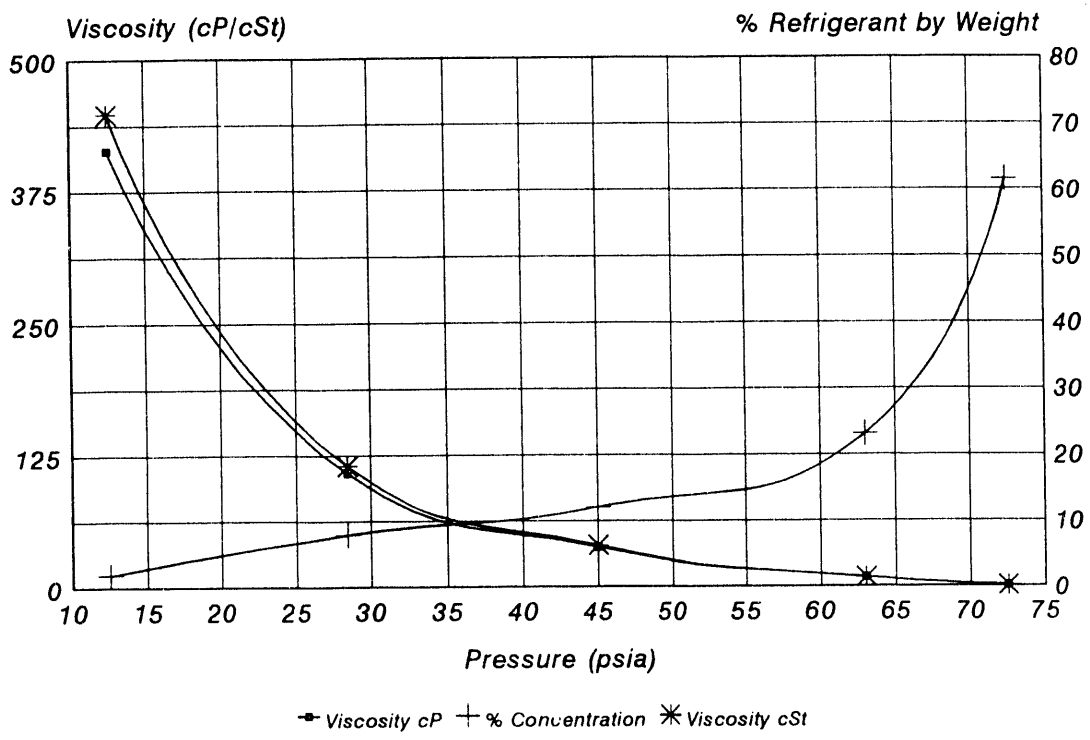



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mineral Oil with HCFC-22 at 0°C*

*Figure B.7*

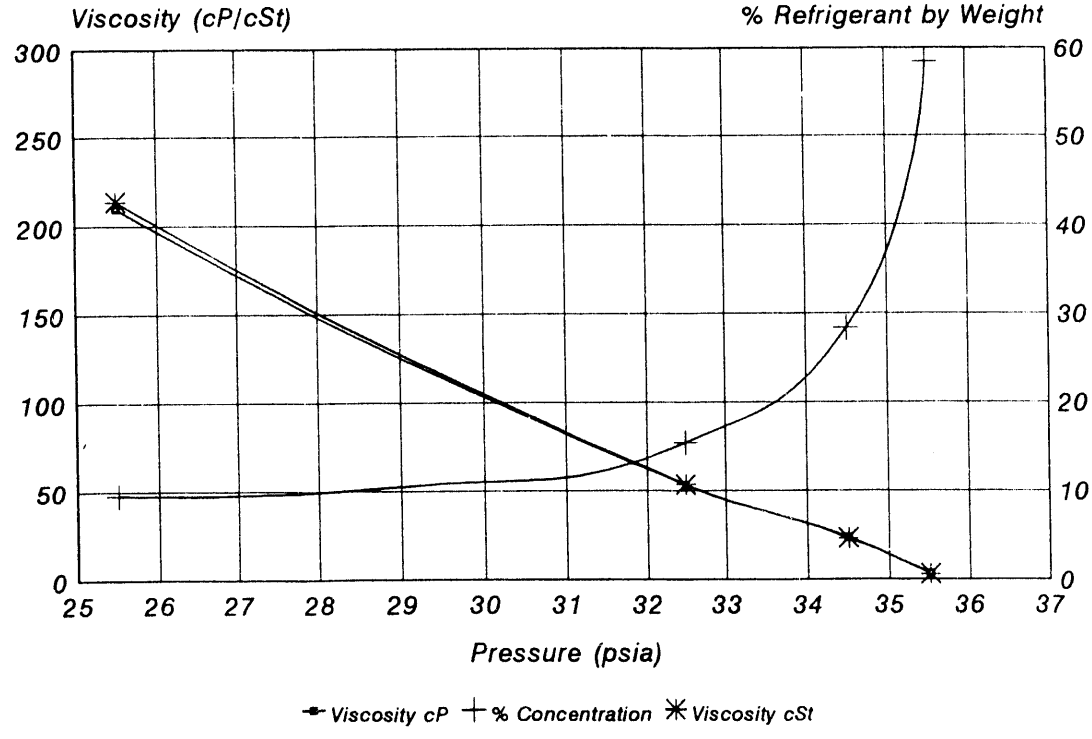



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mineral Oil with HCFC-22 at -20°C*

*Figure B.8*




Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

# Raw Data: Viscosity, Density, and Solubility
# 32 ISO VG Mineral Oil with HCFC−22
# Table B.1

125.0°C Temperature
>500.0 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.8129 | 18.50 | 0.271 | 1.900 | 2.338 |
| 0.8271 | 115.00 | 2.669 | 1.725 | 2.084 |
| 0.8368 | 213.00 | 4.906 | 1.500 | 1.792 |
| 0.8480 | 334.00 | 8.379 | 1.345 | 1.586 |
| 0.8592 | 450.00 | 11.134 | 1.225 | 1.426 |

100 °C Temperature
>500 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.8260 | 10.00 | 1.732 | 3.231 | 3.908 |
| 0.8530 | 144.00 | 5.968 | 2.301 | 2.699 |
| 0.8779 | 259.00 | 9.261 | 1.765 | 2.010 |
| 0.8996 | 375.00 | 13.416 | 1.388 | 1.543 |
| 0.9168 | 489.00 | 19.272 | 1.140 | 1.244 |

80 °C Temperature
>500 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.8360 | 20.00 | 1.590 | 4.982 | 5.959 |
| 0.8610 | 155.20 | 5.336 | 3.403 | 3.954 |
| 0.8980 | 248.00 | 12.237 | 1.958 | 1.279 |
| 0.9330 | 405.00 | 22.825 | 1.133 | 1.215 |

60 °C Temperature
500 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 1.8502 | 18.75 | 1.406 | 9.158 | 10.775 |
| 0.8929 | 97.50 | 6.389 | 5.514 | 6.176 |
| 0.9146 | 171.00 | 11.057 | 3.307 | 3.616 |
| 0.9437 | 260.00 | 21.928 | 1.689 | 1.791 |
| 0.9878 | 332.50 | 35.500 | 0.849 | 0.860 |

40 °C Temperature
222.4 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.8809 | 12.00 | 1.615 | 21.987 | 24.958 |
| 0.9042 | 69.00 | 5.071 | 10.630 | 11.758 |
| 0.9303 | 128.25 | 5.878 | 5.185 | 5.574 |
| 0.9565 | 168.00 | 18.977 | 2.690 | 2.813 |
| 1.0268 | 27.75 | 38.002 | 0.938 | 0.918 |

20 °C Temperature
132.0 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.9004 | 9.00 | 2.346 | 72.070 | 80.603 |
| 0.9221 | 44.00 | 5.619 | 28.453 | 30.856 |
| 0.9445 | 78.00 | 11.573 | 11.495 | 12.171 |
| 0.9811 | 113.00 | 21.107 | 3.839 | 3.913 |
| 1.1060 | 132.00 | 55.534 | 0.608 | 0.550 |

0 °C Temperature
72.2 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.9228 | 12.50 | 1.891 | 413.875 | 448.500 |
| 0.9390 | 28.50 | 7.929 | 107.891 | 114.961 |
| 0.9580 | 45.00 | 12.073 | 37.507 | 39.154 |
| 1.0065 | 63.00 | 23.106 | 8.634 | 8.579 |
| 1.1531 | 72.50 | 61.534 | 0.890 | 0.772 |

−20 °C Temperature
40.3 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.9811 | 25.50 | 9.542 | 209.777 | 213.815 |
| 0.9908 | 32.50 | 15.426 | 52.501 | 53.491 |
| 1.0177 | 34.50 | 33.365 | 23.486 | 23.077 |
| 1.1665 | 35.50 | 58.439 | 3.398 | 2.874 |

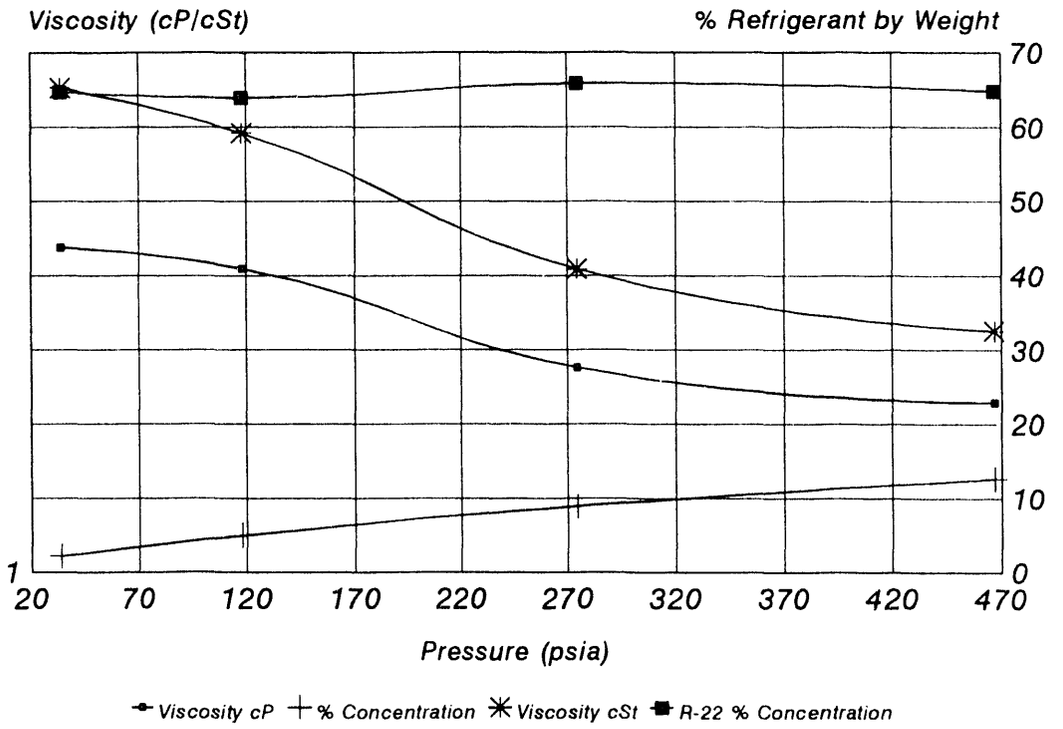
**APPENDIX C:**

**Viscosity, Solubility and Gas Fractionation of 32 ISO VG Mineral Oil at Various Temperatures with R-502**

## *Viscosity, Solubility and Gas Fractionation*

*32 ISO VG Mineral Oil with R-502 at 125°C*

*Figure C.1*

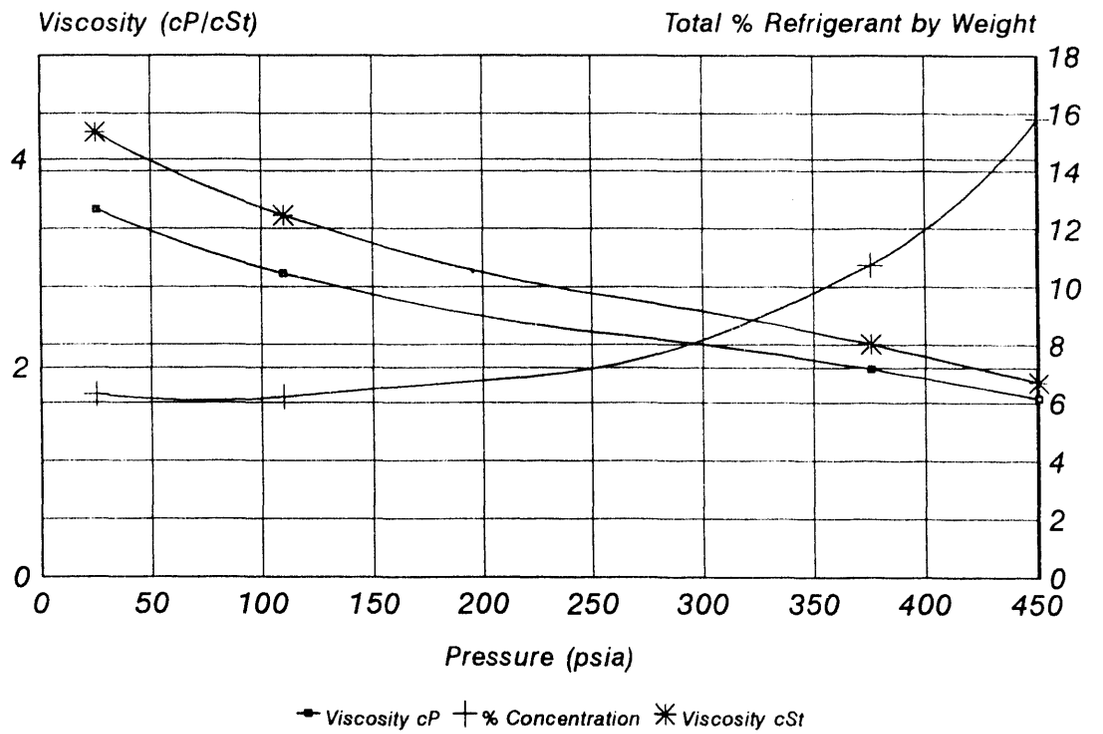



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity, Solubility, and Gas Fractionation*

*32 ISO VG Mineral Oil with R-502 at 100°C*

*Figure C.2*

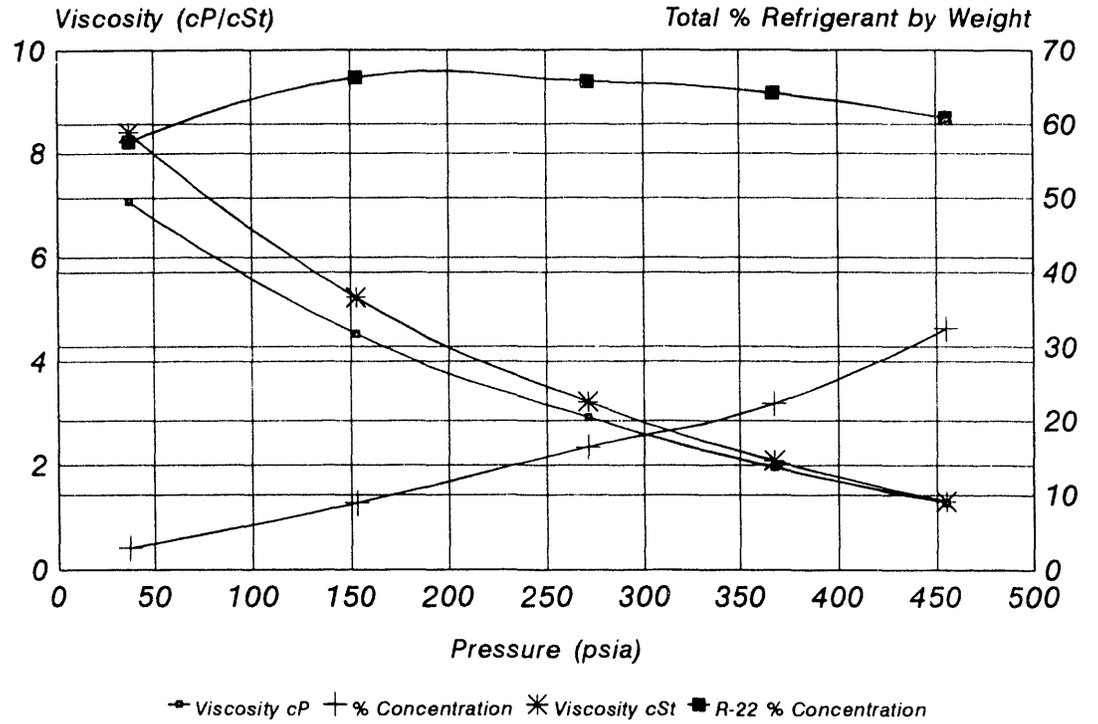



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity, Solubility, and Gas Fractionation*

*32 ISO VG Mineral Oil with R-502 at 70°C*

*Figure C.3*

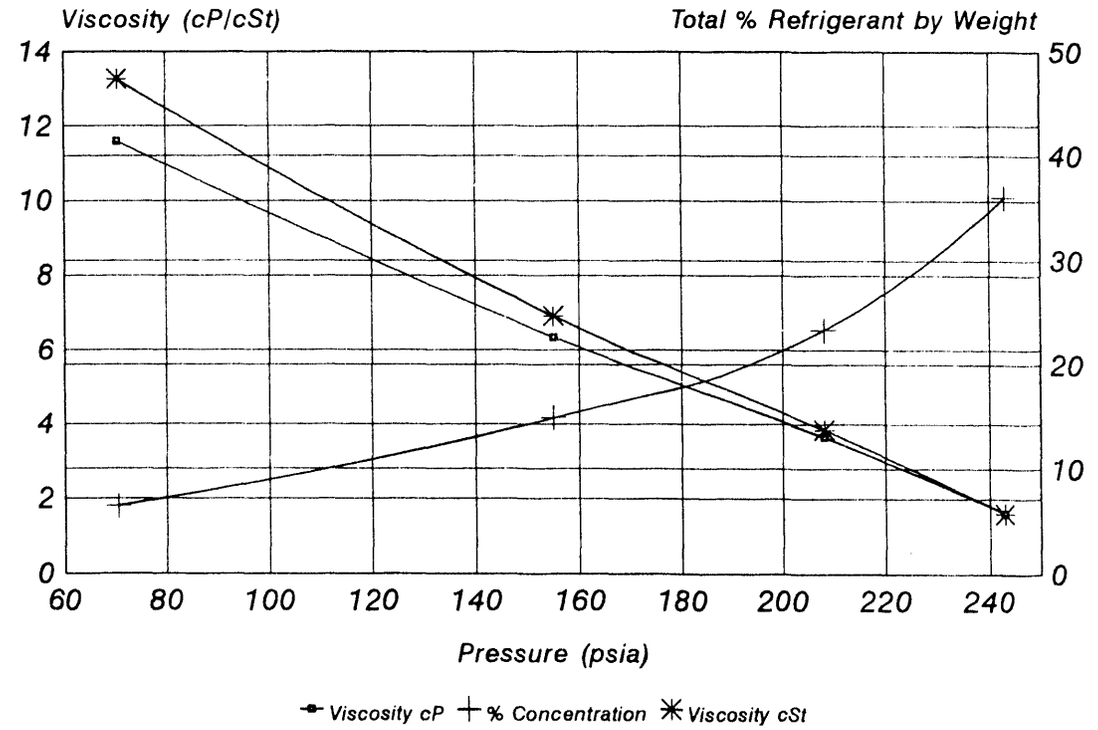



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity, Solubility, and Gas Fractionation*

*32 ISO VG Mineral Oil with R-502 at 40°C*

*Figure C.4*

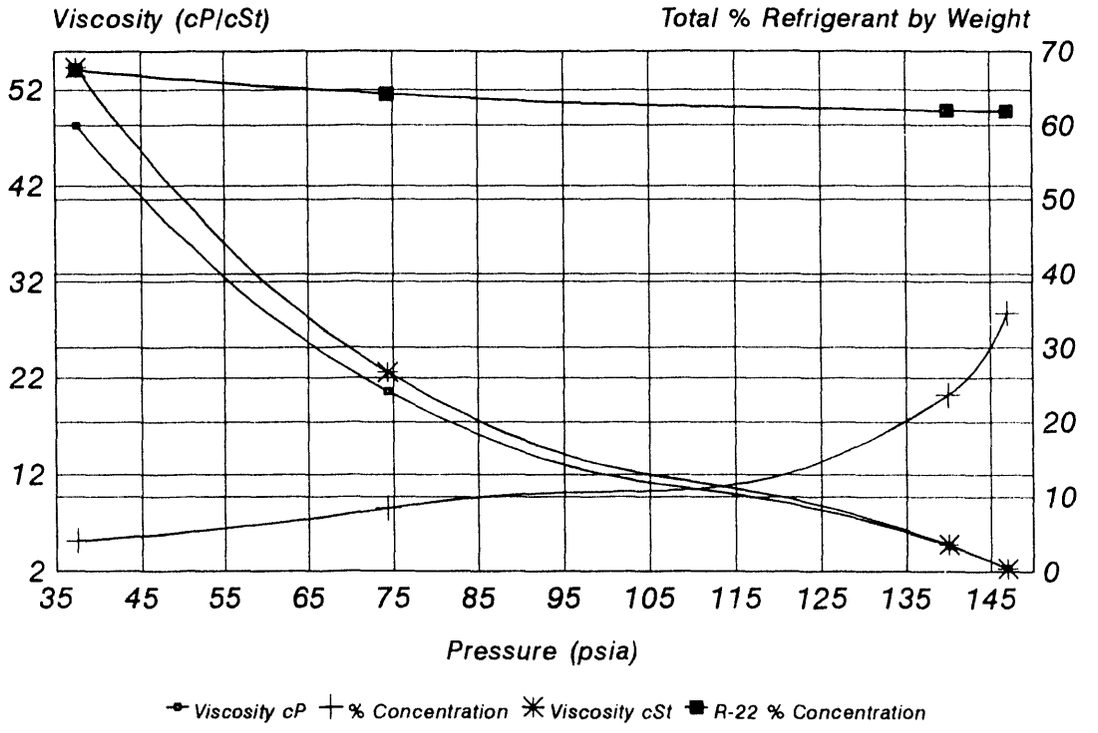



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity, Solubility, and Gas Fractionation*

*32 ISO VG Mineral Oil with R-502 at 20°C*

*Figure C.5*

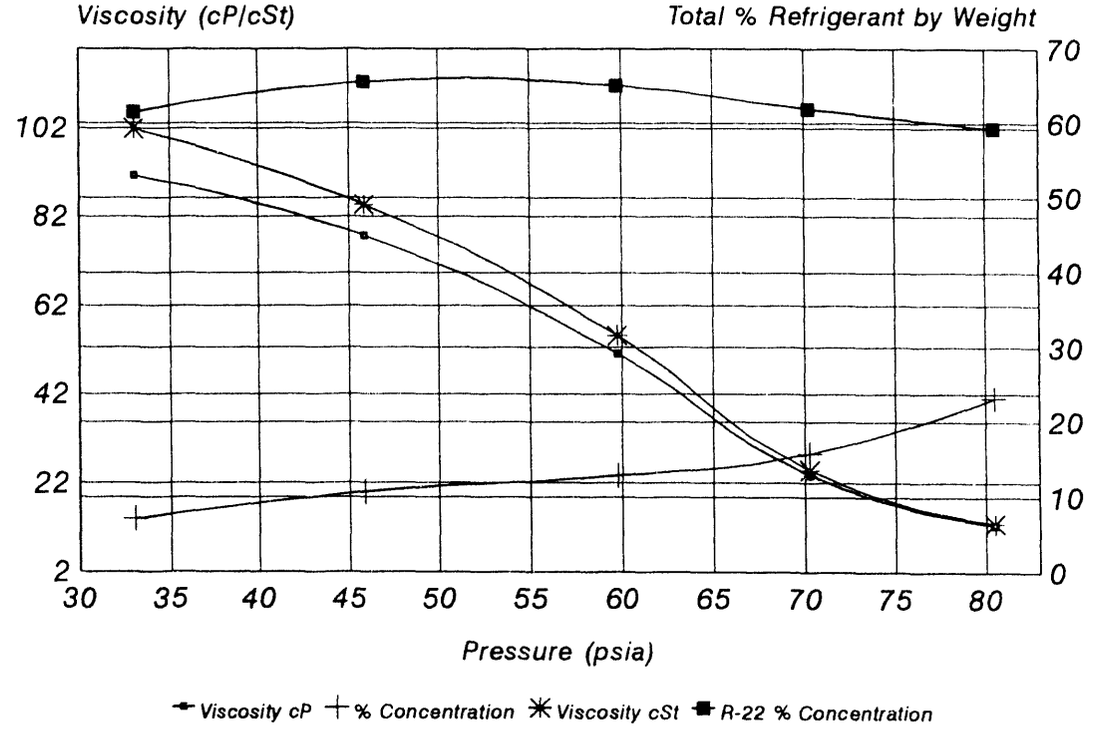



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity, Solubility, and Gas Fractionation*

*32 ISO VG Mineral Oil with R-502 at 0°C*

*Table C.6*

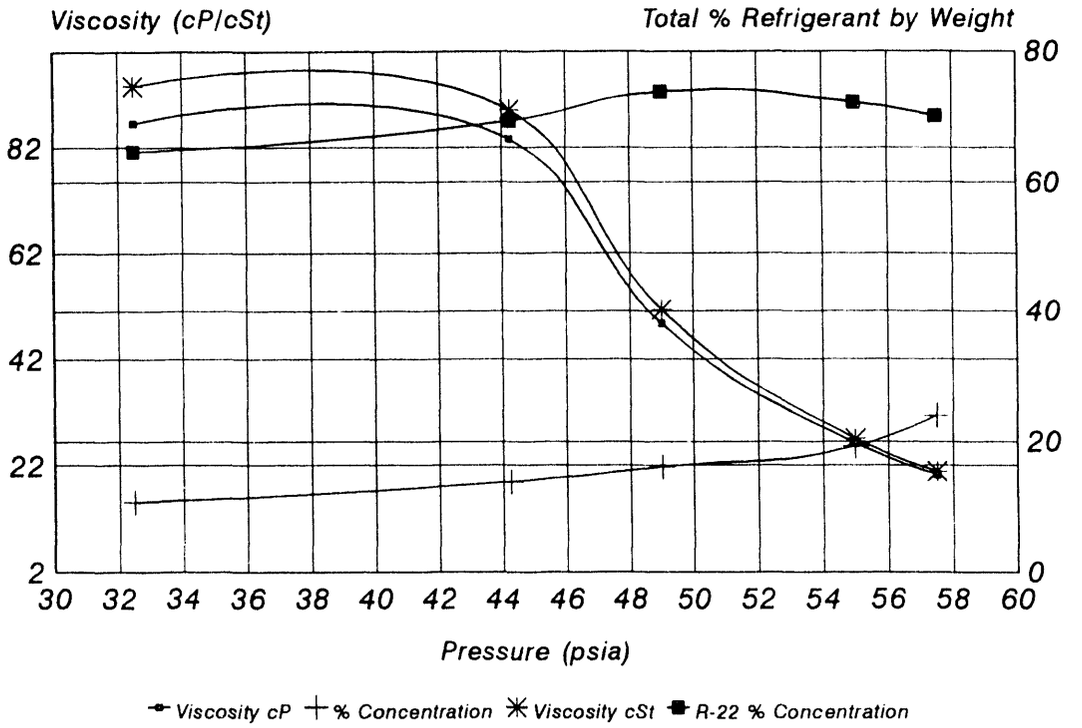



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

# *Viscosity, Solubility, and Gas Fractionation*

*32 ISO VG Mineral Oil with R-502 at -10°C*

*Table C.7*




Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

# Raw Data: Viscosity, Density, Solubility, and Gas Fractionation
# 32 ISO VG Mineral Oil with R−502
# Table C.1

125.0°C Temperature
>500.0 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt | % R−22 |
|---|---|---|---|---|---|
| 0.8073 | 34.75 | 2.175 | 1.938 | 2.400 | 66.100 |
| 0.8273 | 118.00 | 4.930 | 1.877 | 2.269 | 63.900 |
| 0.8488 | 274.50 | 8.926 | 1.593 | 1.876 | 66.400 |
| 0.8785 | 466.75 | 12.671 | 1.492 | 1.733 | 65.900 |

80 °C Temperature
>500 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt | % R−22 |
|---|---|---|---|---|---|
| 0.8259 | 25.00 | 6.295 | 4.263 | 4.263 | 66.100 |
| 0.8399 | 110.00 | 6.189 | 3.460 | 3.460 | 63.900 |
| 0.8925 | 375.50 | 10.755 | 2.232 | 2.232 | 66.400 |
| 0.9176 | 451.00 | 15.819 | 1.863 | 1.863 | 65.900 |

70 °C Temperature
467.67 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt | % R−22 |
|---|---|---|---|---|---|
| 0.8414 | 37.00 | 2.884 | 7.080 | 8.409 | 57.600 |
| 0.8653 | 153.00 | 8.888 | 4.530 | 5.232 | 66.300 |
| 0.9087 | 271.00 | 16.452 | 2.927 | 3.221 | 65.800 |
| 0.9391 | 367.50 | 22.332 | 1.959 | 2.086 | 64.000 |
| 0.9835 | 455.00 | 32.430 | 1.284 | 1.305 | 60.850 |

40 °C Temperature
243.2 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt | % R−22 |
|---|---|---|---|---|---|
| 0.8747 | 70.50 | 6.432 | 11.599 | 13.260 | 59.550 |
| 0.9183 | 155.00 | 14.889 | 6.348 | 6.913 | 56.600 |
| 0.9487 | 208.00 | 23.358 | 36.500 | 3.650 | 60.800 |
| 1.0027 | 243.00 | 36.055 | 1.613 | 1.609 | 59.450 |

20 °C Temperature
147.9 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt | % R−22 |
|---|---|---|---|---|---|
| 0.8889 | 37.50 | 4.083 | 48.295 | 54.331 | 67.50 |
| 0.9124 | 74.50 | 8.436 | 20.602 | 22.579 | 64.25 |
| 0.9827 | 140.00 | 23.638 | 4.706 | 4.789 | 62.00 |
| 1.0286 | 147.00 | 34.676 | 2.536 | 2.293 | 61 8 |

0 °C Temperature
83.1 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt | % R−22 |
|---|---|---|---|---|---|
| 0.8962 | 33.00 | 7.073 | 101.942 | 101.942 | 61.50 |
| 0.9169 | 45.90 | 10.664 | 84.659 | 84.659 | 65.25 |
| 0.9258 | 59.75 | 12.851 | 55.281 | 30.281 | 65.10 |
| 0.9539 | 70.25 | 15.755 | 24.874 | 55.281 | 61.95 |
| 0.9728 | 80.50 | 23.191 | 12.905 | 24.874 | 59.30 |

−10 °C Temperature
60.1 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt | % R−22 |
|---|---|---|---|---|---|
| 0.9255 | 32.50 | 10.708 | 86.521 | 93.536 | 64.60 |
| 0.9265 | 40.75 | 10.544 | 123.132 | 132.903 | 62.85 |
| 0.9384 | 44.25 | 13.822 | 83.596 | 89.091 | 69.9 |
| 0.9494 | 49.00 | 16.106 | 48.671 | 51.264 | 73.85 |
| 0.9687 | 55.00 | 19.303 | 26.584 | 27.021 | 72.30 |
| 0.9708 | 57.50 | 20.286 | 20.286 | 20.895 | 70.20 |

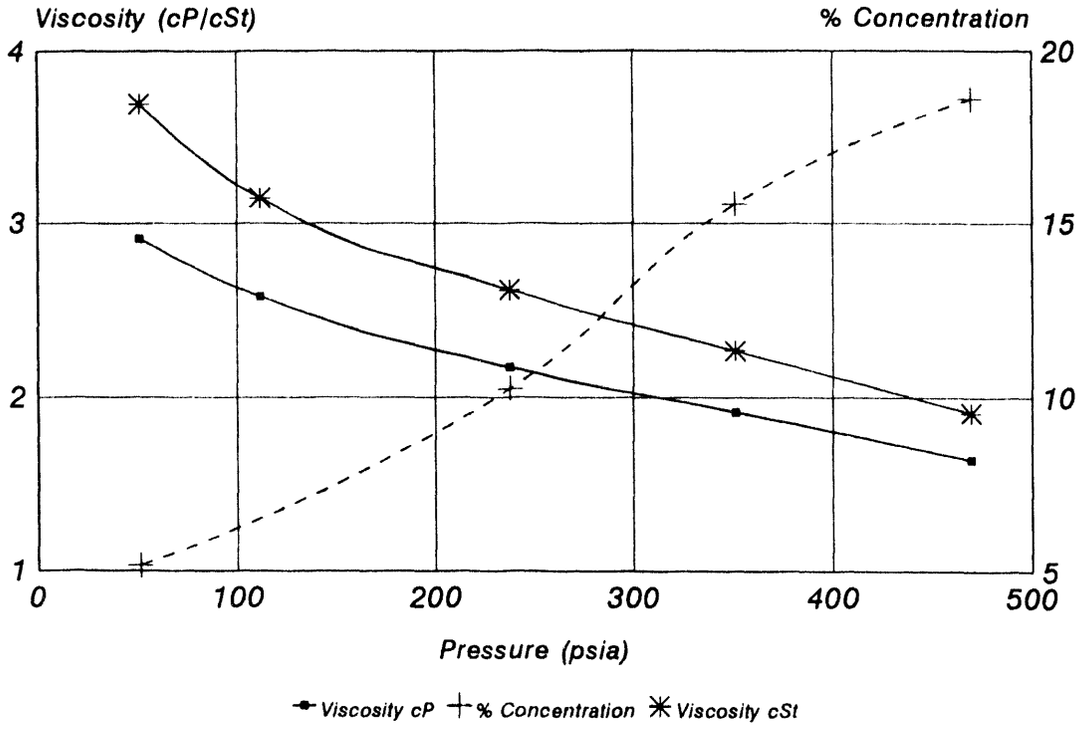
**APPENDIX D:**

**Viscosity, Density and Gas Solubility of 32 ISO VG Mixed Acid Polyolester at Various Temperatures with HFC-134a**

## *Viscosity and Gas Solubility*

*32 ISO VG Mixed Acid Polyolester With R-134a at 125°C*

*Figure D.1*

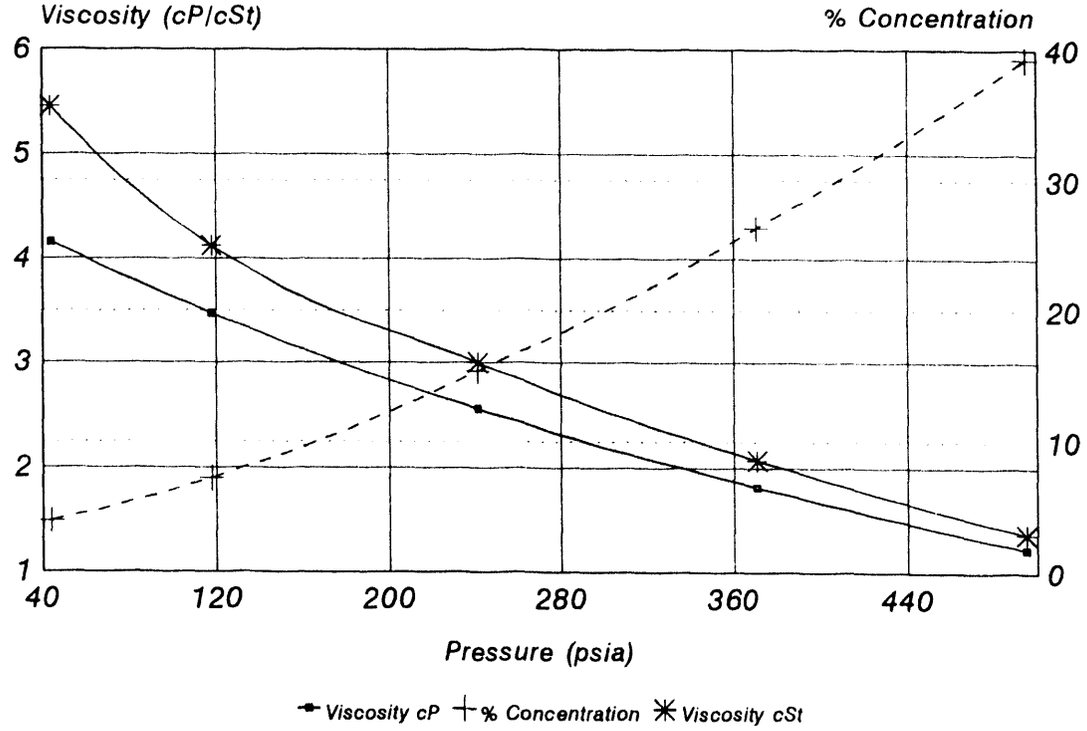



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mixed Acid Polyolester with R-134a at 100°C*

*Figure D.2*

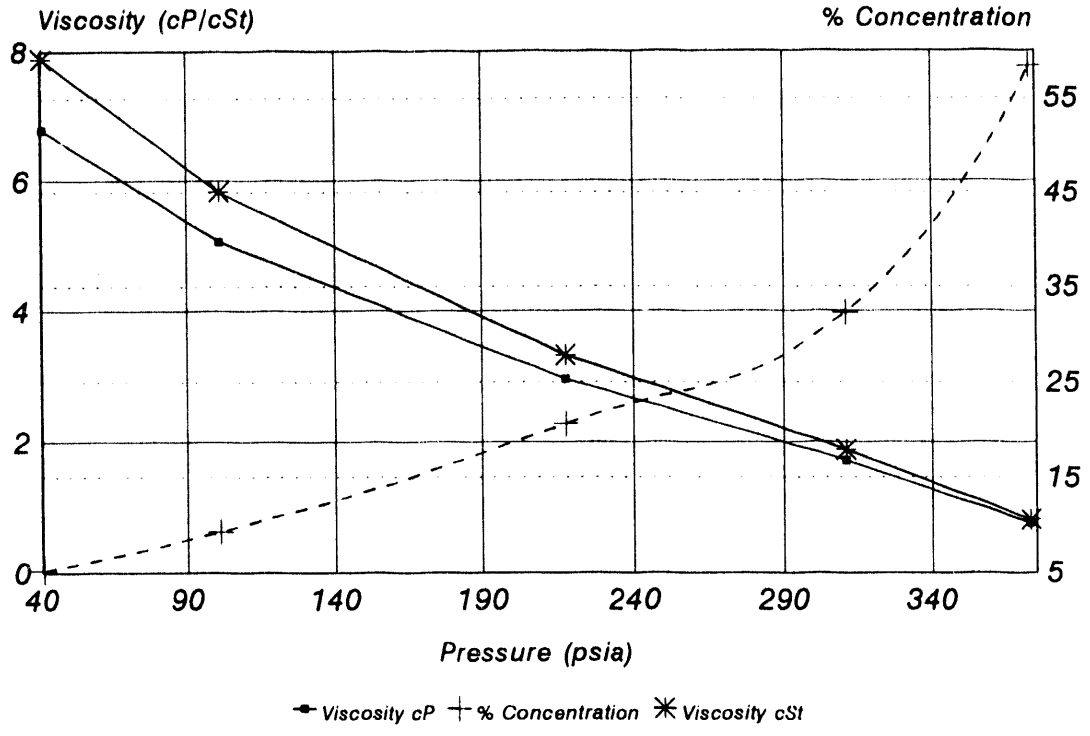



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mixed Acid Polyolester with R-134a at 80°C*

*Figure D.3*

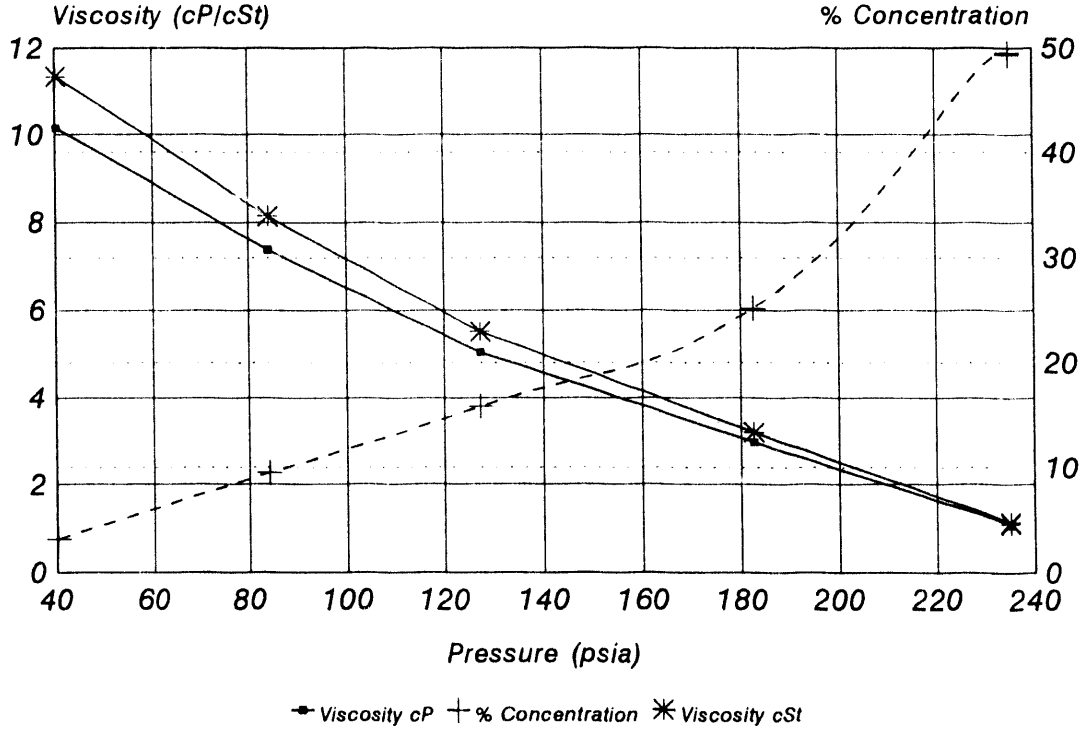



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mixed Acid Polyolester with R-134a at 60°C*

*Figure D.4*

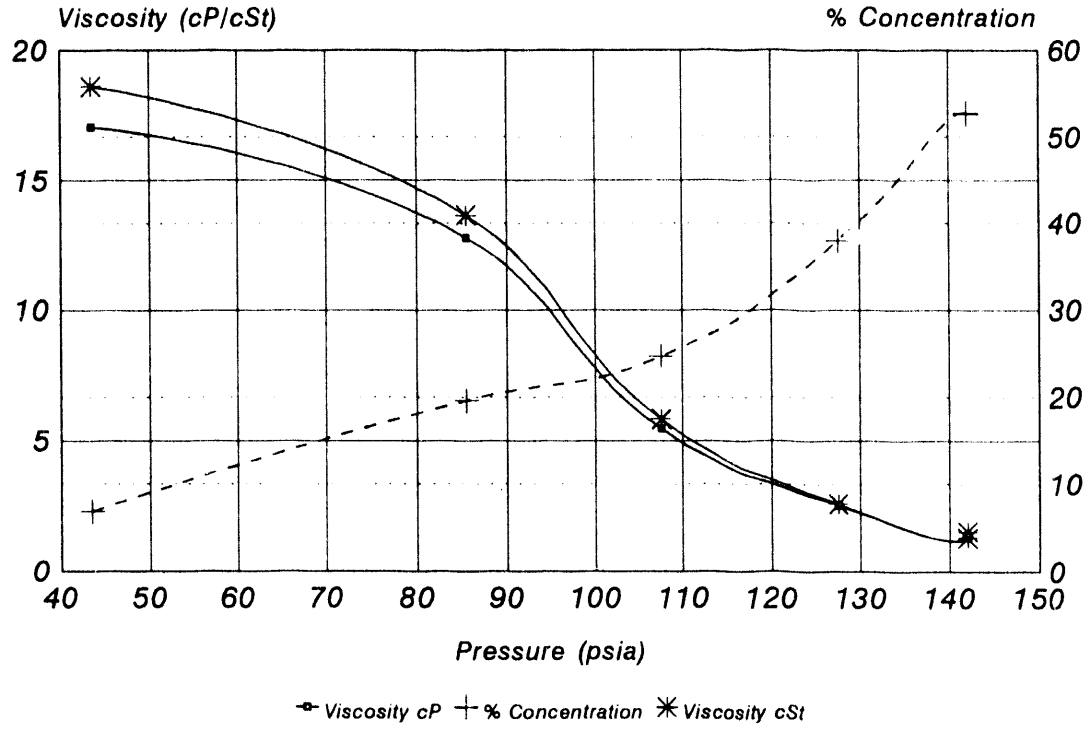



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Solubility*

*32 ISO VG Mixed Acid Polyolester with R-134a at 40°C*

*Figure D.5*

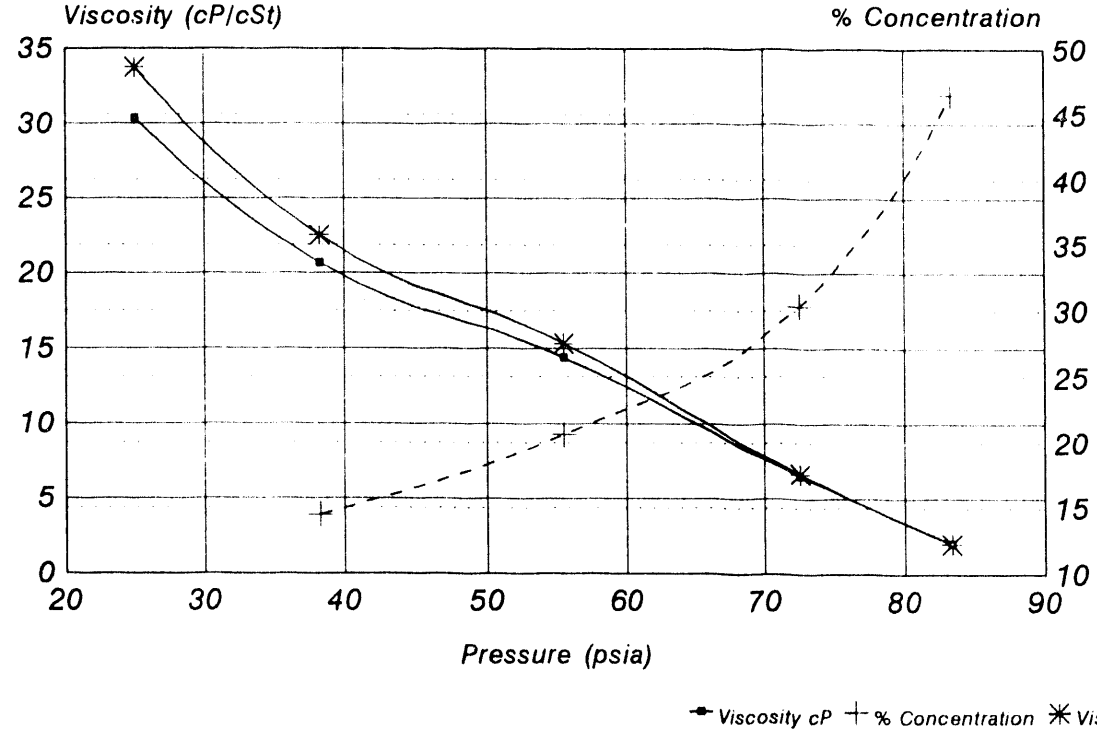



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mixed Acid Polyolester with R-134a at 20°C*

*Figure D.6*

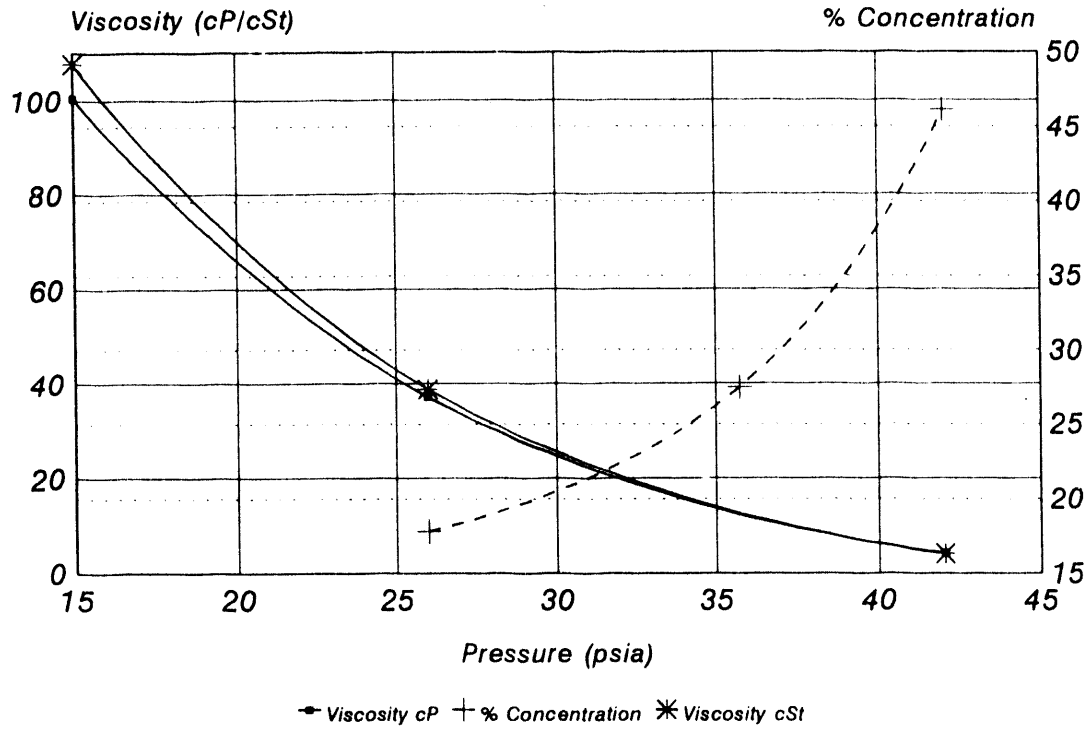



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mixed Acid Polyolester with R-134a at 0°C*

*Figure D.7*

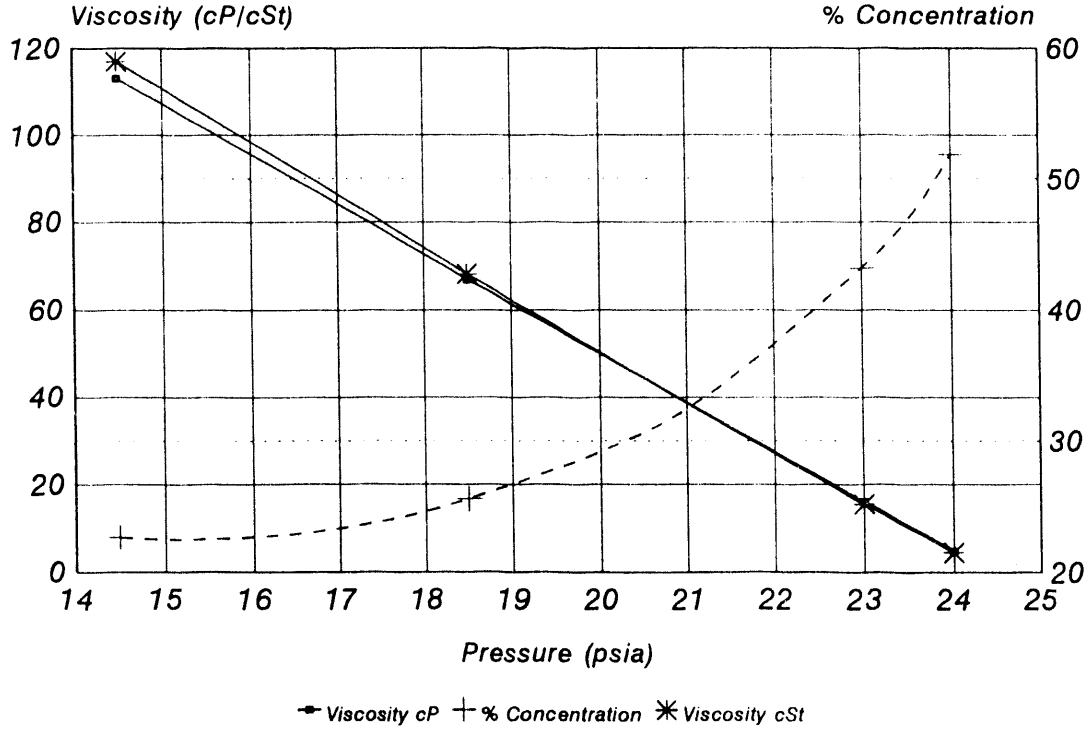



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mixed Acid Polyolester with R-134a at -15.0°C*

*Figure D.8*

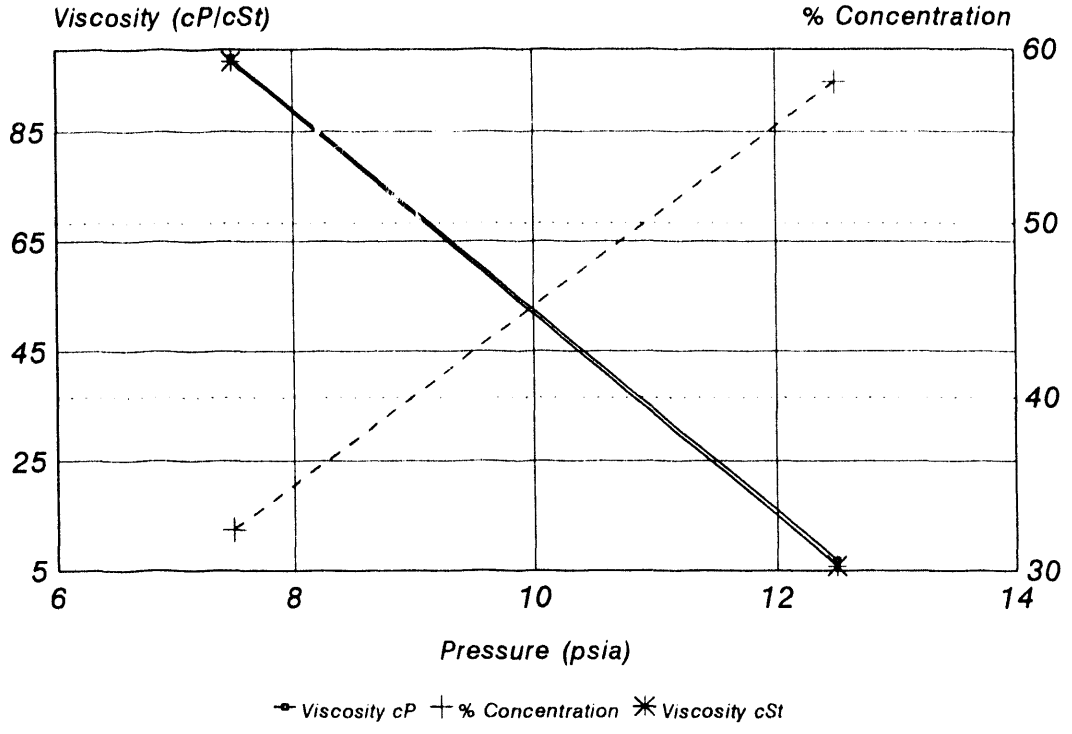



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

# *Viscosity and Gas Solubility*

*32 ISO VG Mixed Acid Polyolester with R-134a at -30.0°C*

*Figure D.9*




Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

# Raw Data: Viscosity, Density, and Gas Solubility
# 32 ISO VG Mixed Acid Polyolester with HFC–134a
# Table D.1

Temperature: 125.0 °C
Max. Pressure: 500.0

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.7906 | 51.00 | 5.16 | 2.91 | 3.69 |
| 0.8198 | 111.25 | 5.40 | 2.58 | 3.15 |
| 0.8298 | 238.00 | 10.25 | 2.17 | 2.62 |
| 0.8455 | 351.25 | 15.57 | 1.92 | 2.27 |
| 0.8598 | 469.00 | 18.02 | 1.64 | 1.91 |

Temperature: 100.0 °C
Max. Pressure: 500.0

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.762 | 44.00 | 3.92 | 4.16 | 5.46 |
| 0.8426 | 117.50 | 7.20 | 3.47 | 4.12 |
| 0.8533 | 241.38 | 15.35 | 2.56 | 3.00 |
| 0.8769 | 371.00 | 26.38 | 1.82 | 2.07 |
| 0.894 | 495.00 | 39.29 | 1.22 | 1.37 |

Temperature: 80° C
Sat. Pressure 382.61 psia

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.8605 | 40.50 | 5.20 | 6.78 | 7.88 |
| 0.8683 | 101.00 | 9.28 | 5.06 | 5.83 |
| 0.8911 | 217.50 | 20.64 | 2.96 | 3.32 |
| 0.8911 | 217.50 | 21.74 | 2.96 | 3.32 |
| 0.9125 | 311.00 | 32.32 | 1.71 | 1.88 |
| 0.9404 | 373.00 | 58.41 | 0.76 | 0.81 |
| 0.9404 | 373.00 | 57.70 | 0.76 | 0.81 |

Temperature: 60.0 °C
Sat. Pressure: 245.24 psia

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.8954 | 40.25 | 3.15 | 10.15 | 11.34 |
| 0.9054 | 84.00 | 9.46 | 7.38 | 8.15 |
| 0.914 | 127.50 | 15.85 | 5.04 | 5.51 |
| 0.9297 | 182.50 | 25.21 | 2.98 | 3.20 |
| 0.9546 | 235.00 | 49.51 | 1.09 | 1.14 |
| 0.9725 | 235.00 | 49.33 | 1.07 | 1.10 |

Temperature: 40.0 °C
Sat. Pressure: 147.47 psia

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.9168 | 43.50 | 6.89 | 17.06 | 18.61 |
| 0.9368 | 85.50 | 19.60 | 12.78 | 13.64 |
| 0.9382 | 107.50 | 24.69 | 5.47 | 5.83 |
| 0.9775 | 127.50 | 38.00 | 2.53 | 2.59 |
| 1.0081 | 142.00 | 52.76 | 1.31 | 1.30 |
| 0.9268 | 142.00 | 52.66 | 1.42 | 1.54 |

Temperature: 20.0 °C
Sat. Pressure: 83.38 psia

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.8997 | 25.00 | 19.82 | 30.36 | 33.75 |
| 0.9183 | 38.25 | 14.47 | 20.65 | 22.49 |
| 0.9397 | 55.50 | 20.61 | 14.41 | 15.33 |
| 0.981 | 72.50 | 30.36 | 6.52 | 6.64 |
| 1.0281 | 83.38 | 46.50 | 2.06 | 2.00 |

Temperature 0.0°C
Sat. Pressure: 41.98 psia

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.9325 | 15.00 | none | 100.42 | 107.69 |
| 0.9568 | 26.00 | 17.81 | 37.17 | 38.85 |
| 0.9753 | 35.75 | 27.49 | 19.17 | 19.66 |
| 1.0388 | 42.00 | 46.15 | 4.27 | 4.11 |

Temperature: –15.0° C
Sat. Pressure: 23.51 psia

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.9668 | 14.50 | 22.64 | 113.07 | 116.95 |
| 0.9825 | 18.50 | 25.61 | 67.08 | 68.27 |
| 1.0402 | 23.00 | 43.20 | 16.19 | 15.56 |
| 1.0802 | 23.70 | 51.86 | 4.83 | 4.47 |

Temperature: –30° C
Sat. Pressure: 12.20 psia

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 1.0053 | 7.50 | 32.33 | 98.36 | 97.84 |
| 1.1779 | 12.50 | 58.15 | 6.83 | 5.80 |

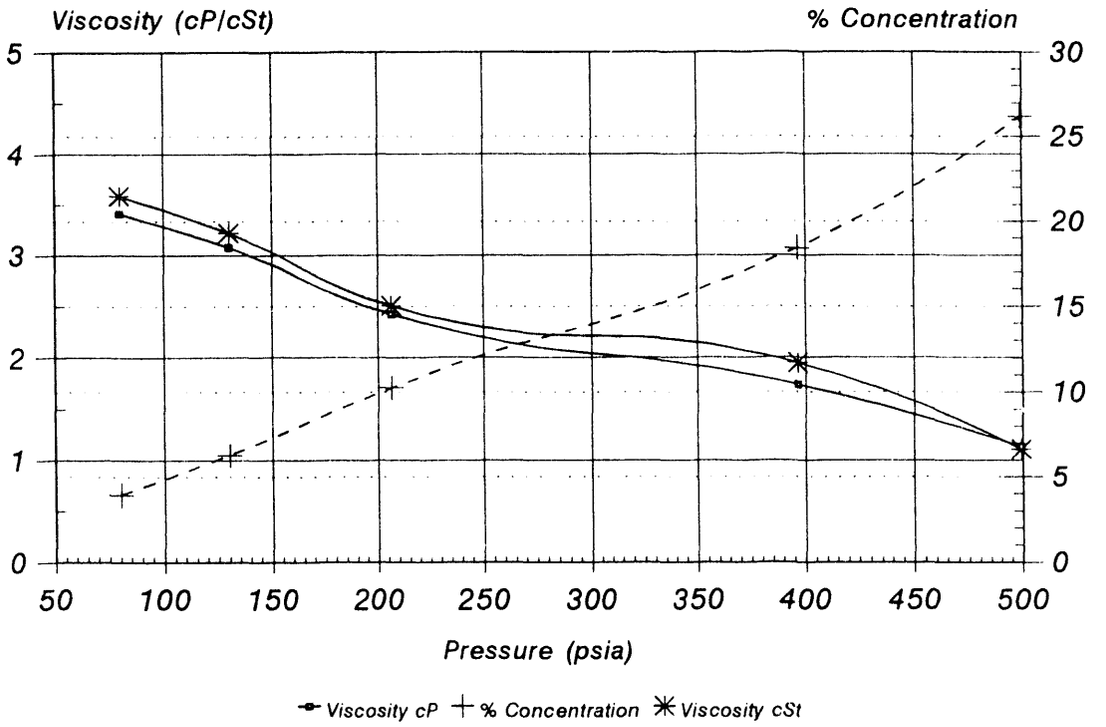
**APPENDIX E:**

**Viscosity, Density and Gas Solubility of 32 ISO VG Branched Acid Polyolester at Various Temperatures with HFC-134a**

## *Viscosity and Gas Solubility*

*32 ISO VG Branched Acid Polyolester With HFC-134a at 125°C*

*Figure E.1*

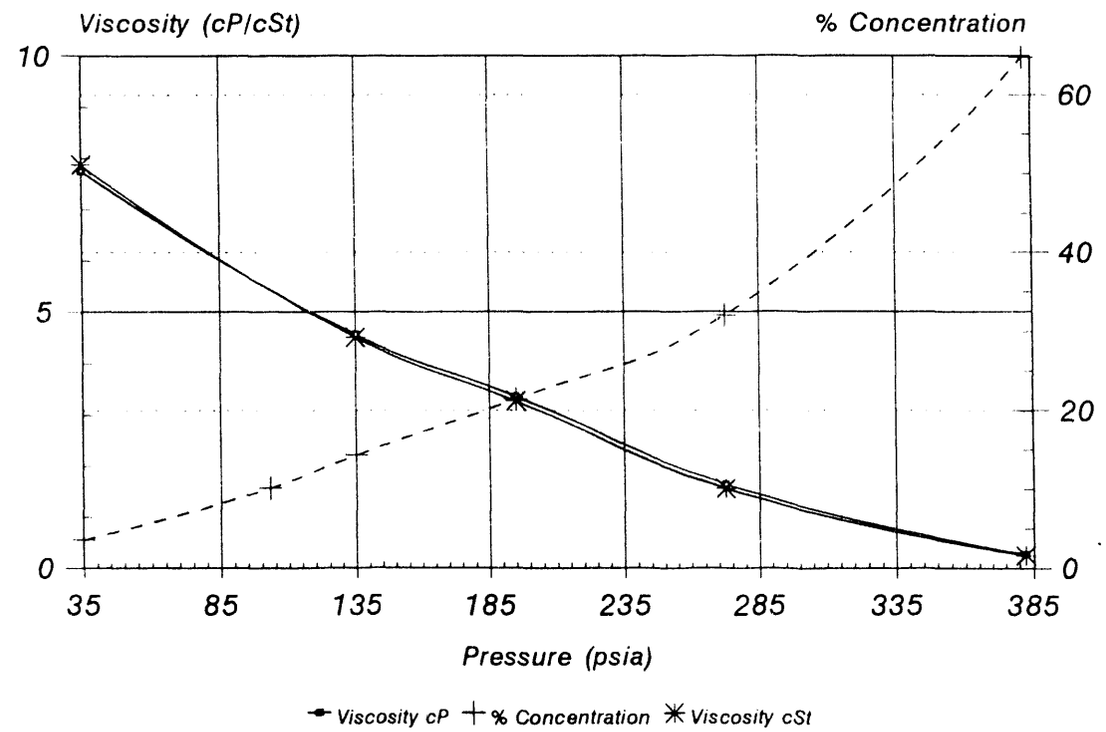



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Branched Acid Polyolester with HFC-134a at 80°C*

*Figure E.2*

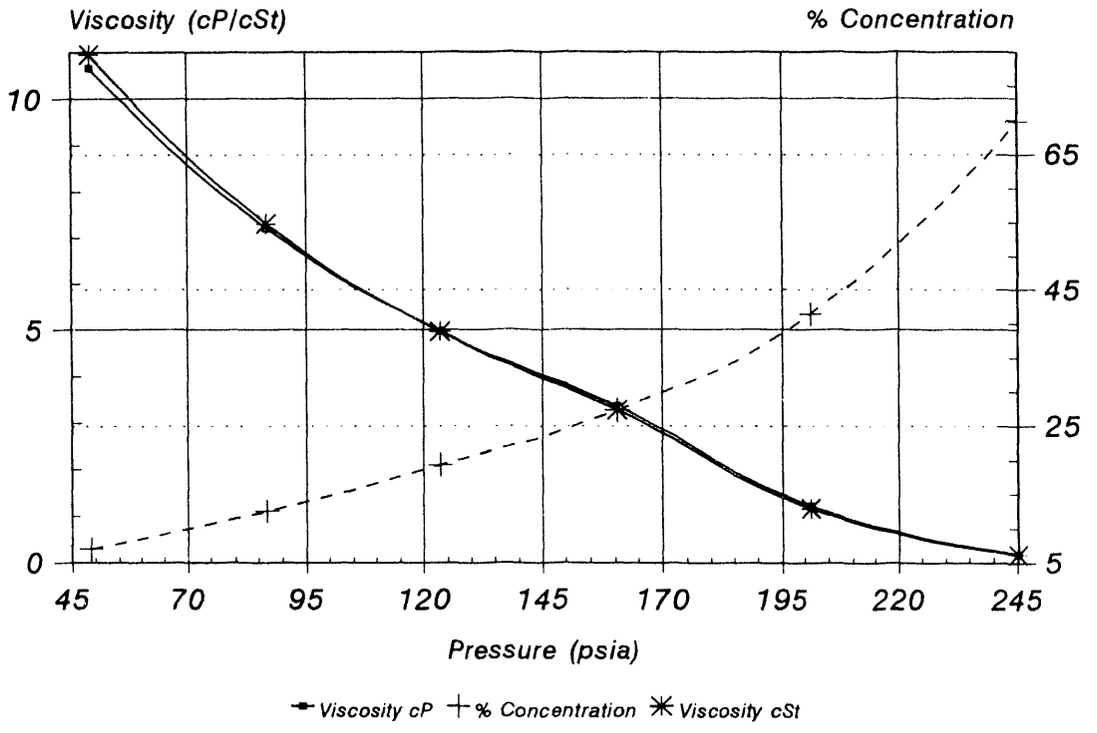



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Branched Acid Polyolester with HFC-134a at 60°C*

*Figure E.3*

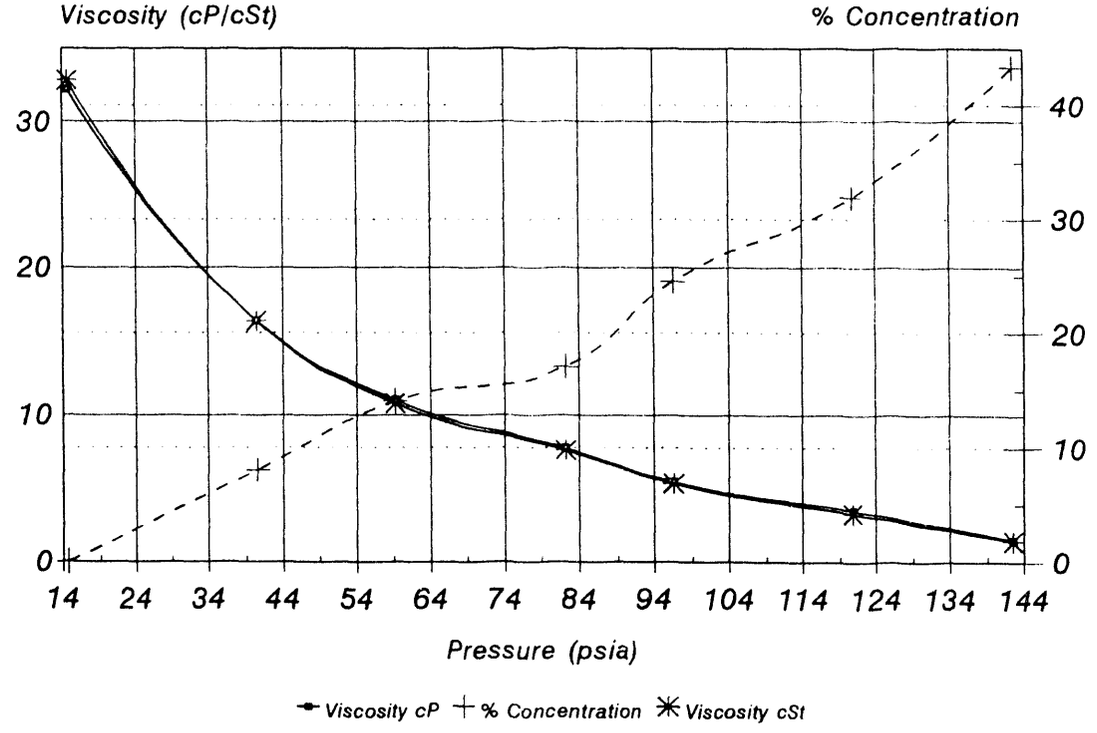



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Branched Acid Polyolester with HFC-134a at 40°C*

*Figure E.4*

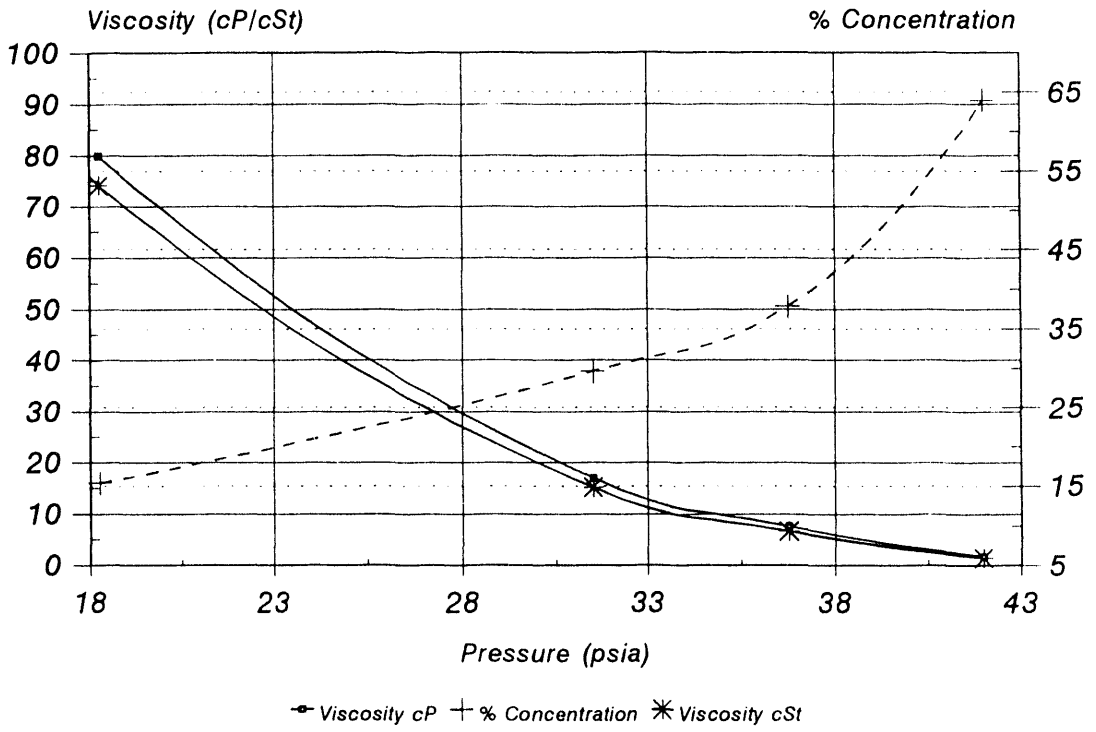



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

# *Viscosity and Gas Solubility*

*32 ISO VG Mixed Acid Polyolester with HFC-134a at 0°C*

*Figure E.5*




Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

# Raw Data: Viscosity, Density, and Solubility
# 32 ISO VG Branched Acid Polyolester with HFC–134a
# Table E.1

125 °C Temperature
500.0 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.951 | 80.00 | 3.95 | 3.41 | 3.58 |
| 0.956 | 130.00 | 6.30 | 3.08 | 3.22 |
| 0.967 | 206.50 | 10.27 | 2.42 | 2.50 |
| 1.003 | 396.50 | 18.42 | 1.74 | 1.95 |
| 1.022 | 499.25 | 26.19 | 1.13 | 1.11 |

40 °C Temperature
147.673 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 1.000 | 40.50 | 8.00 | 16.40 | 16.41 |
| 1.013 | 59.25 | 14.08 | 10.88 | 10.74 |
| 1.025 | 82.25 | 17.08 (not plotted) | 7.56 | 7.37 |
| 1.035 | 96.50 | 24.54 | 5.26 | 5.22 |
| 1.058 | 120.78 | 31.92 | 3.29 | 3.11 |
| 1.066 | 142.50 | 43.39 | 1.47 | 1.38 |

80 °C Temperature
382 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.985 | 35.00 | 3.56 | 7.75 | 7.86 |
| 1.009 | 103.00 | 10.14 | 5.10 | 4.77 |
| 1.013 | 135.00 | 14.35 | 4.56 | 4.50 |
| 1.029 | 195.00 | 21.49 | 3.36 | 3.27 |
| 1.054 | 272.50 | 32.07 | 1.64 | 1.55 |
| 1.086 | 382.00 | 64.83 | 0.28 | 0.25 |

0°C Temperature
41.98 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 1.079 | 18.25 | 15.38 | 79.83 | 73.99 |
| 1.122 | 31.50 | 29.65 | 16.93 | 15.09 |
| 1.145 | 36.75 | 37.85 | 7.60 | 6.63 |
| 1.206 | 41.98 | 63.96 | 1.70 | 1.41 |

60 °C Temperature
245.2 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.973 | 49.00 | 7.01 | 10.66 | 10.95 |
| 0.986 | 86.75 | 12.51 | 7.21 | 7.31 |
| 1.004 | 128.50 | 19.30 | 4.98 | 4.96 |
| 1.025 | 160.50 | 27.35 | 3.36 | 3.28 |
| 1.050 | 201.25 | 41.45 | 1.22 | 1.16 |
| 1.088 | 245.20 | 69.78 | 0.19 | 0.18 |

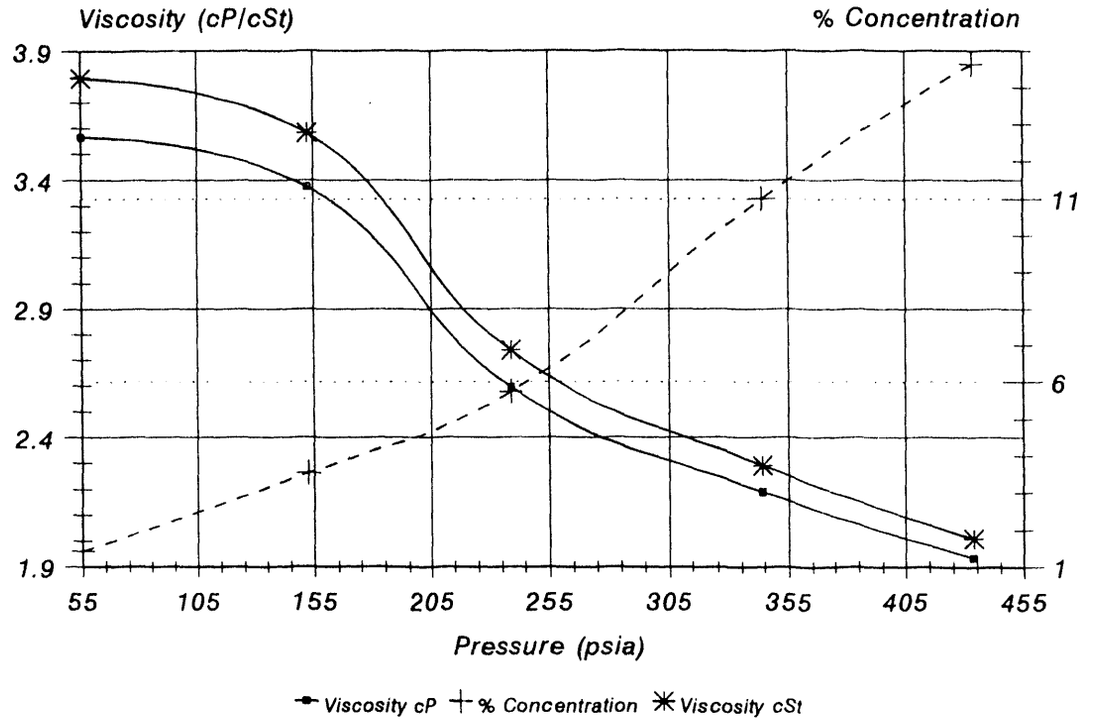
**APPENDIX F:**

**Viscosity, Density and Gas Solubility of 32 ISO VG Branched Acid Polyolester at Various Temperatures with HFC-143a**

## *Viscosity and Gas Solubility*

*32 ISO VG Branched Acid Polyolester with HFC-143a at 125°C*

*Figure F.1*

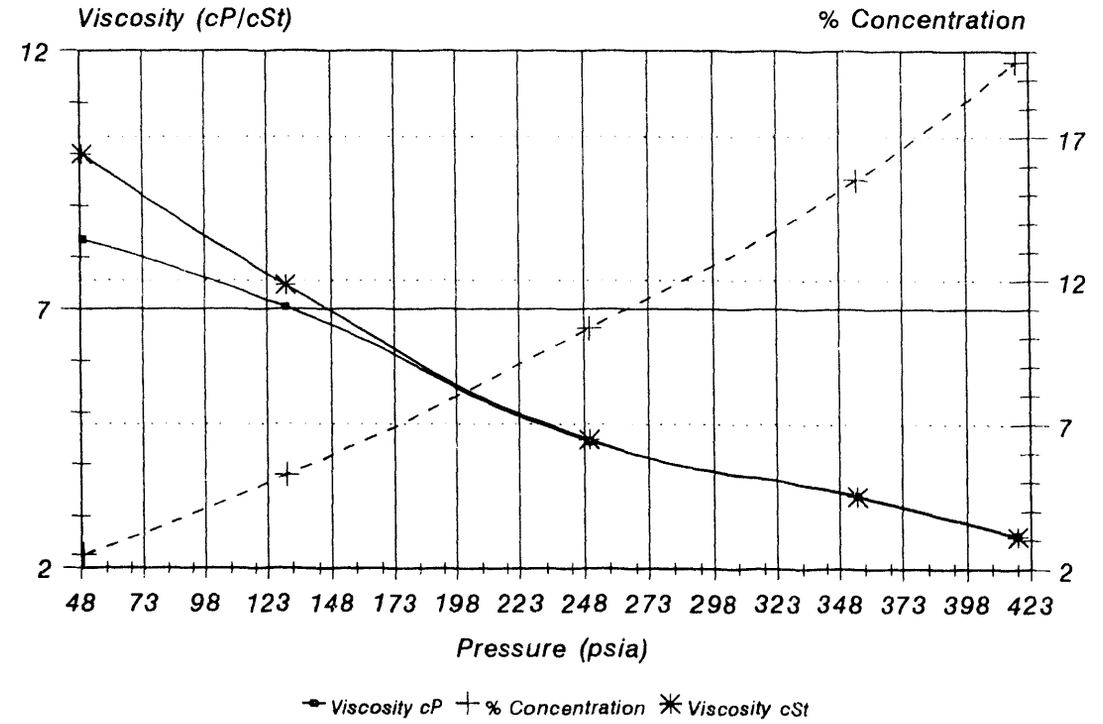



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Branched Acid Polyolester with HFC-143a at 80°C*

*Figure F.2*

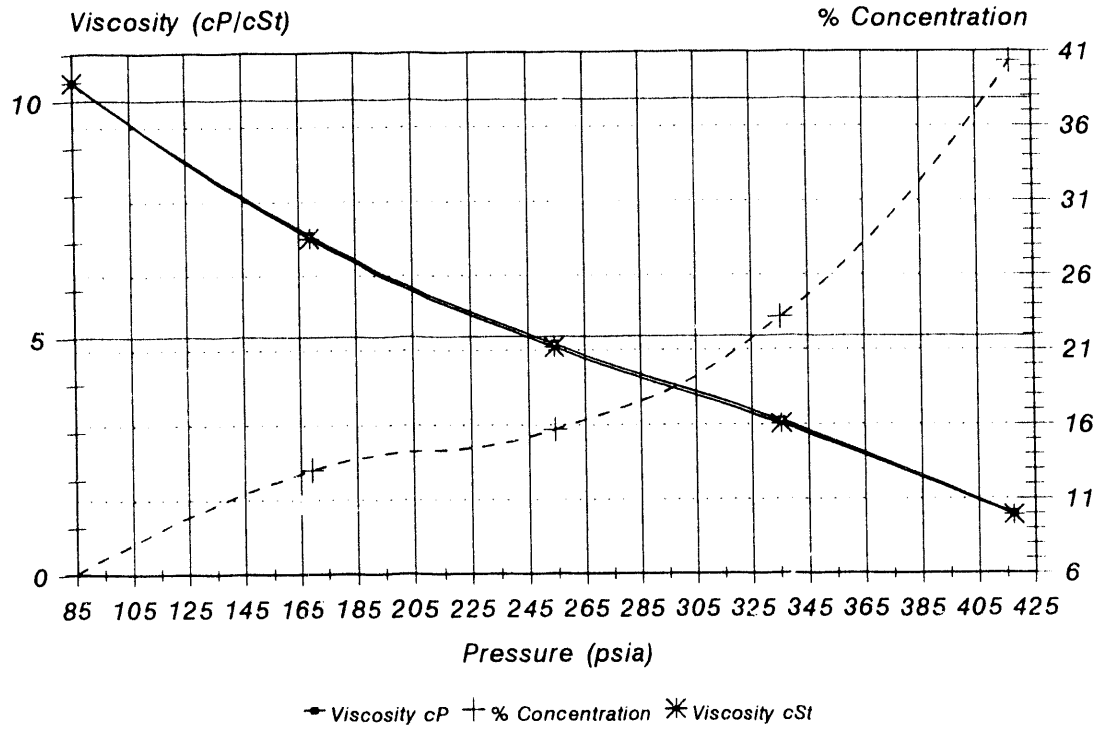



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Branched Acid Polyolester with HFC-143a at 60°C*

*Figure F.3*

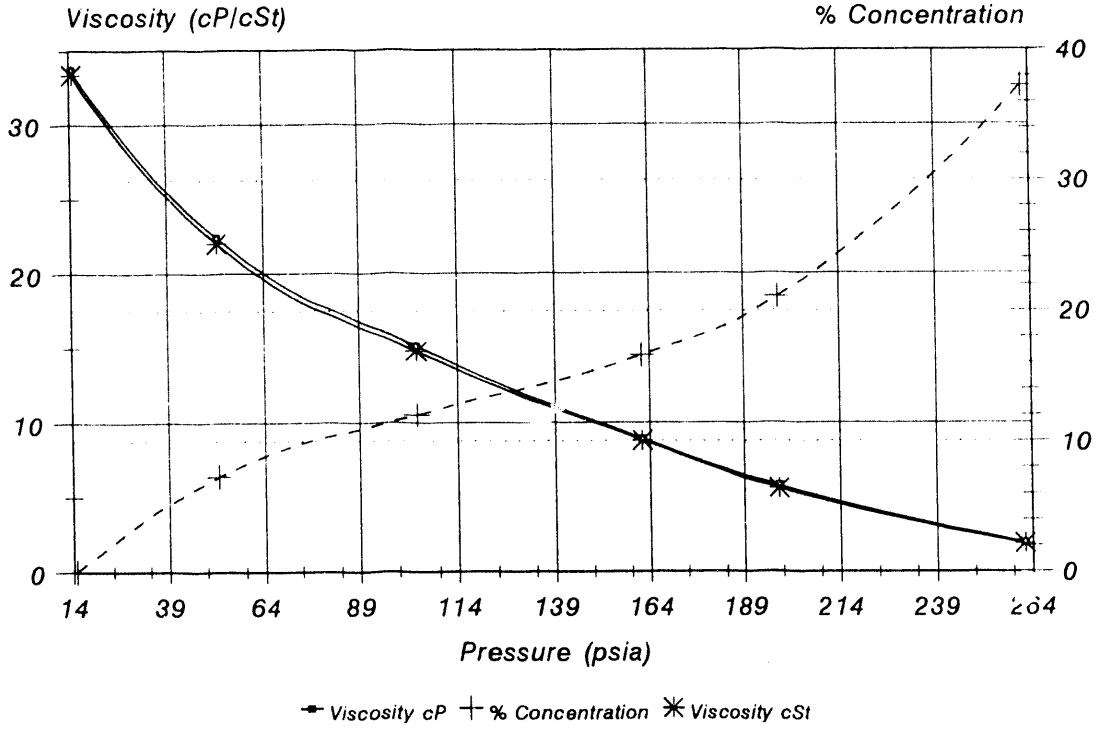



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO Branched Acid Polyolester with HFC-143a at 40°C*

*Figure F.4*

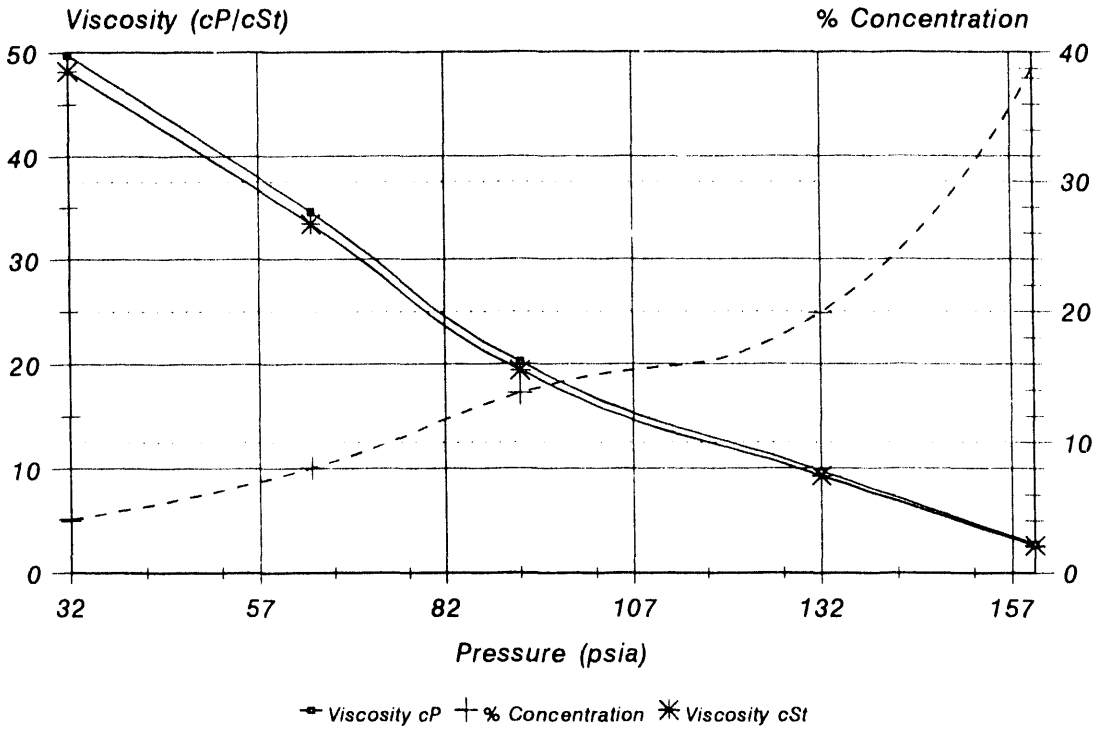



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Branched Acid Polyolester with HFC-143a at 20°C*

*Figure F.5*

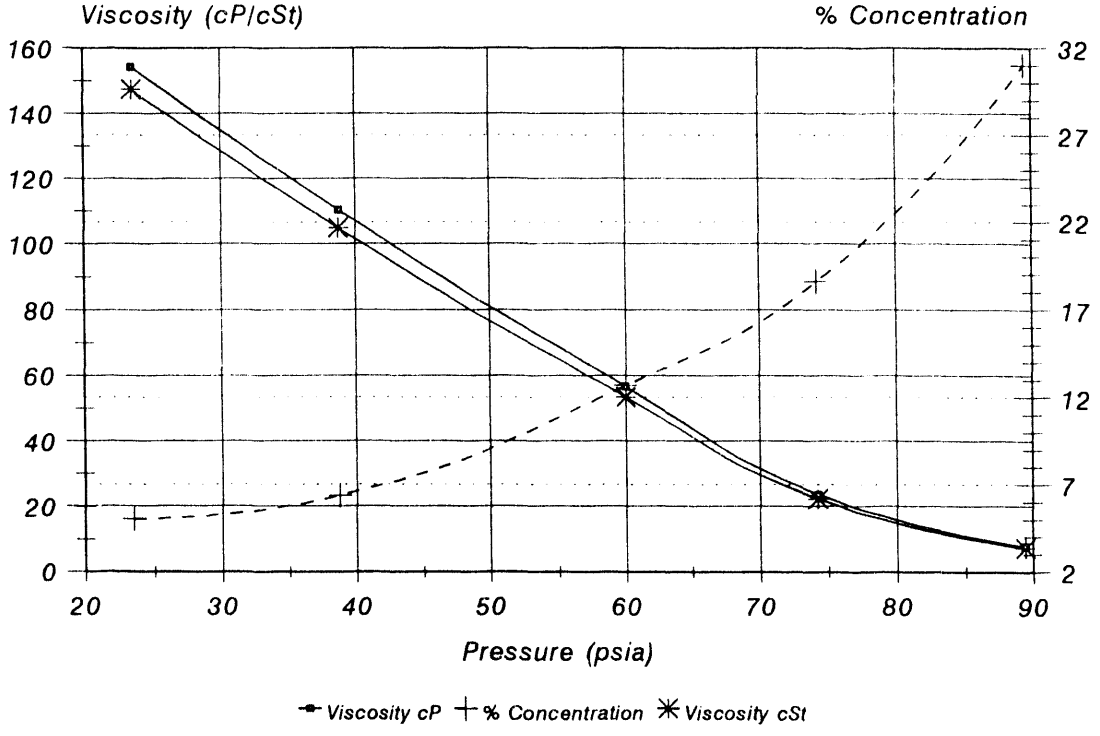



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Branched Acid Polyolester with HFC-143a at 0°C*

*Figure F.6*




Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

# Raw Data: Viscosity, Density, and Solubility
# 32 ISO Branched Acid Polyolester with HFC–143a
# Table F.1

125.0°C Temperature
>500.0 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.939 | 55.00 | 1.41 | 3.56 | 3.79 |
| 0.942 | 152.50 | 3.54 | 3.38 | 3.58 |
| 0.948 | 239.00 | 5.74 | 2.60 | 2.74 |
| 0.956 | 344.00 | 11.01 | 2.19 | 2.29 |
| 0.963 | 433.50 | 14.64 | 1.94 | 2.01 |

80 °C Temperature
>500 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.835 | 49.00 | 2.41 | 8.35 | 10.00 |
| 0.944 | 130.50 | 5.23 | 7.05 | 7.47 |
| 0.992 | 250.00 | 10.33 | 4.45 | 4.48 |
| 1.004 | 355.00 | 15.51 | 3.40 | 3.39 |
| 1.008 | 418.00 | 19.63 | 2.64 | 2.62 |

60 °C Temperature
417.37 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 1.000 | 85.00 | 6.09 | 10.40 | 10.40 |
| 1.008 | 169.00 | 13.02 | 7.14 | 7.08 |
| 1.014 | 254.25 | 15.68 | 4.85 | 4.78 |
| 1.022 | 335.50 | 23.16 | 3.22 | 3.15 |
| 1.022 | 417.37 | 40.34 | 1.26 | 1.23 |

40 °C Temperature
266.69 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 1.010 | 14.70 | 0.00 | 33.71 | 33.38 |
| 1.017 | 52.00 | 7.32 | 22.39 | 22.01 |
| 1.023 | 103.50 | 12.01 | 15.12 | 14.78 |
| 1.029 | 162.00 | 16.60 | 8.90 | 8.64 |
| 1.033 | 198.00 | 21.07 | 5.77 | 5.58 |
| 1.033 | 262.00 | 37.25 | 1.94 | 1.88 |

20 °C Temperature
160.30 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 1.032 | 32.00 | 4.11 | 49.73 | 48.19 |
| 1.035 | 64.00 | 8.07 | 34.59 | 33.43 |
| 1.042 | 92.00 | 13.79 | 20.20 | 19.38 |
| 1.048 | 132.00 | 19.88 | 9.72 | 9.28 |
| 1.054 | 160.00 | 38.75 | 2.73 | 2.59 |

0 °C Temperature
89.43 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 1.047 | 23.50 | 5.02 | 154.26 | 147.28 |
| 1.053 | 38.75 | 6.37 | 110.34 | 104.83 |
| 1.061 | 60.00 | 12.68 | 56.72 | 53.44 |
| 1.064 | 74.25 | 18.59 | 23.73 | 22.30 |
| 1.072 | 89.43 | 31.01 | 7.82 | 7.30 |

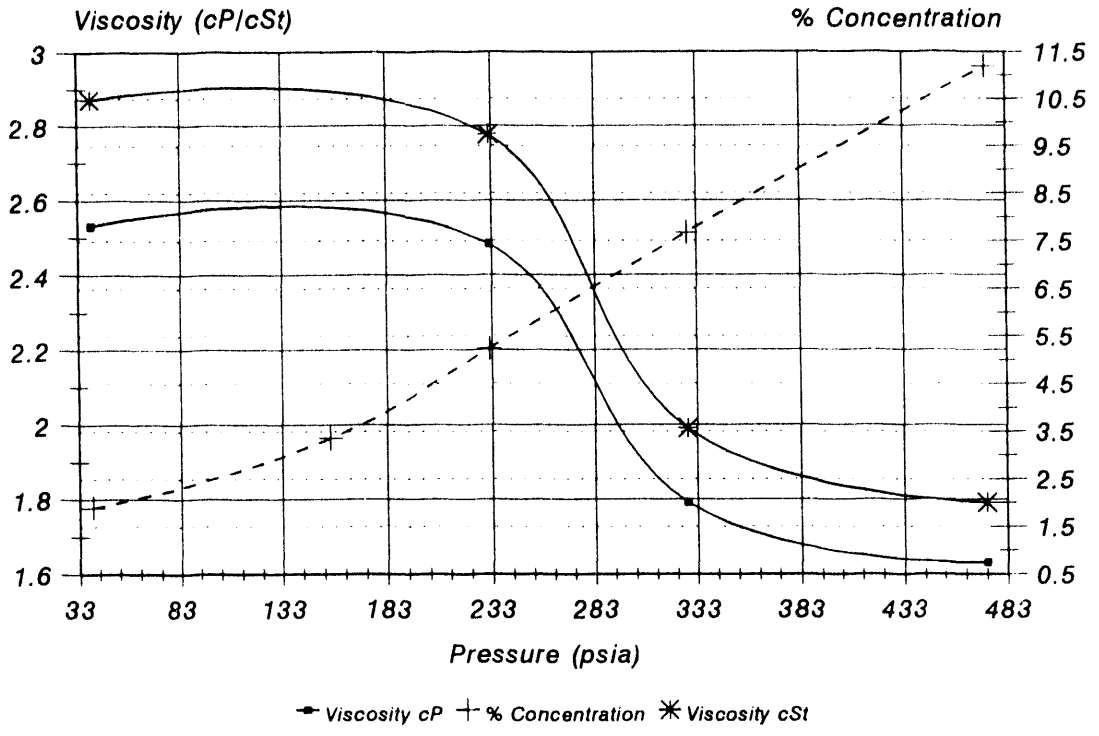
**APPENDIX G:**

**Viscosity, Density and Gas Solubility of 32 ISO VG Mixed Acid Polyolester at Various Temperatures with HFC-143a**

# Viscosity and Gas Solubility

*32 ISO VG Mixed Acid Polyolester with HFC-143a at 125°C*

*Figure G.1*

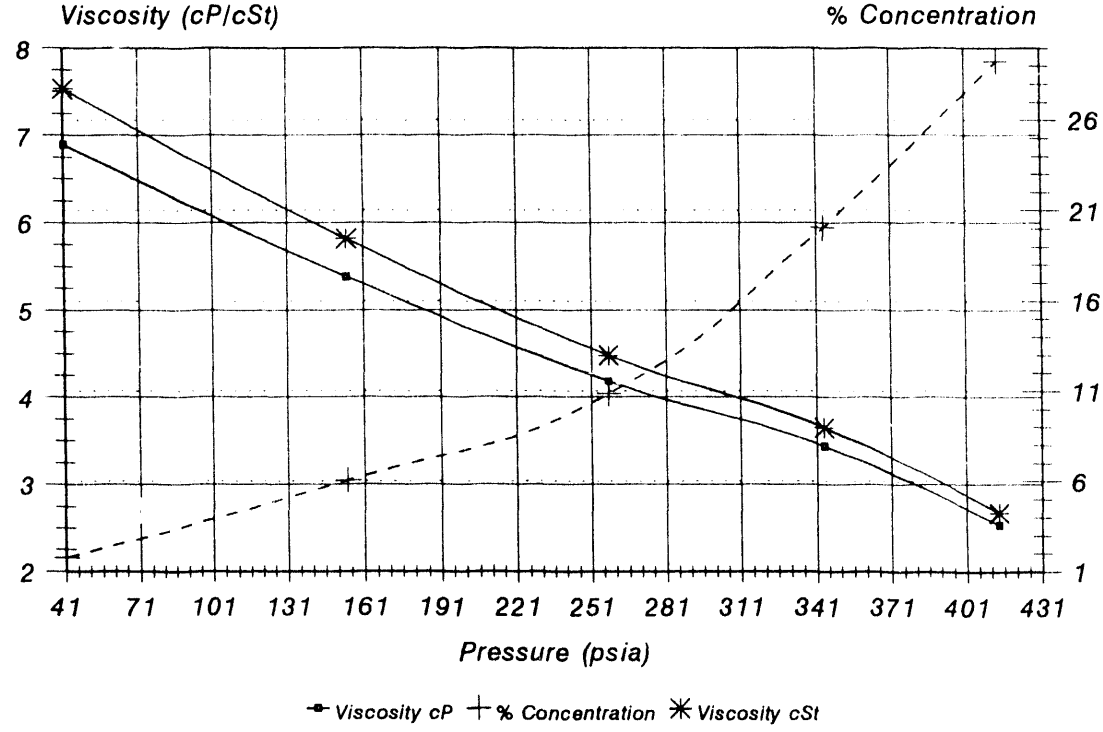



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

# Viscosity and Gas Solubility

*32 ISO VG Mixed Acid Polyolester with HFC-143a at 80°C*

*Figure G.2*

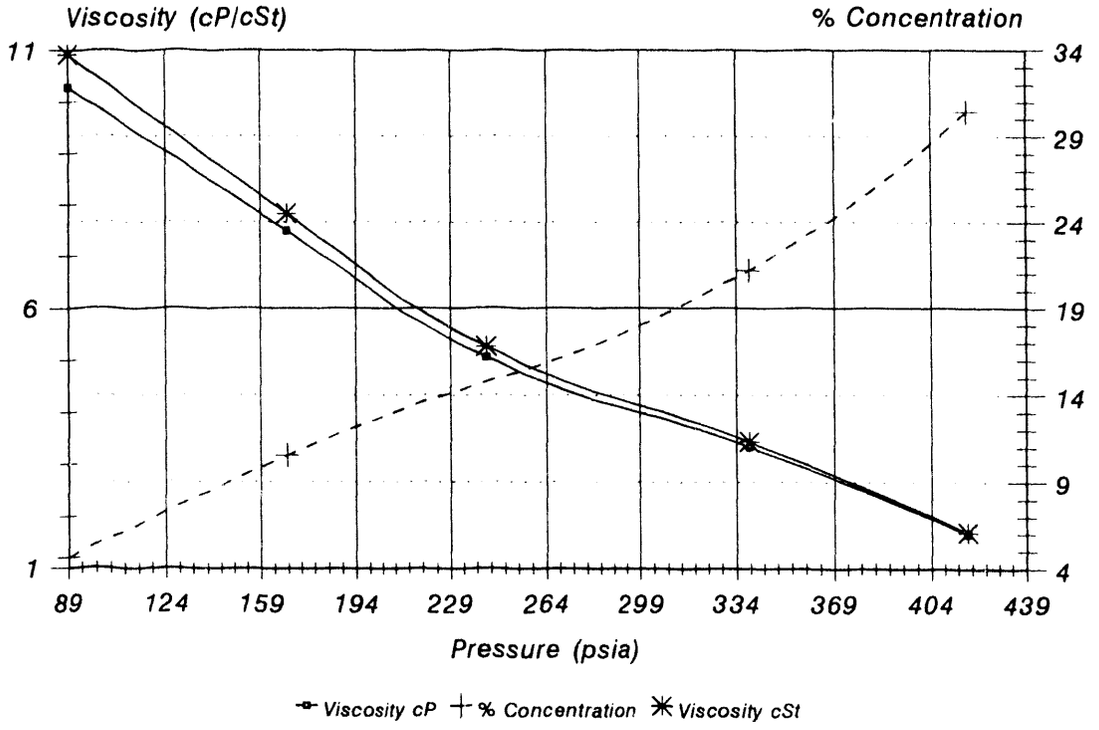



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mixed Acid Polyolester with HFC-143a at 60°C*

*Figure G.3*

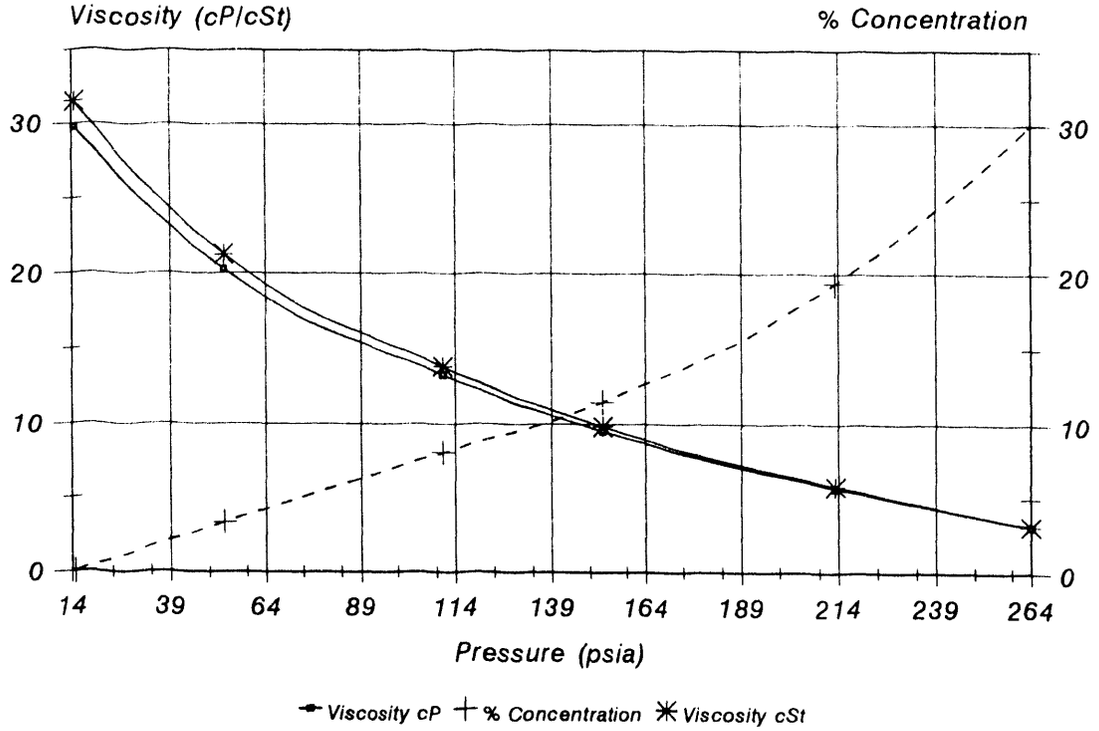



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mixed Acid Polyolester with HFC-143a at 40°C*

*Figure G.4*

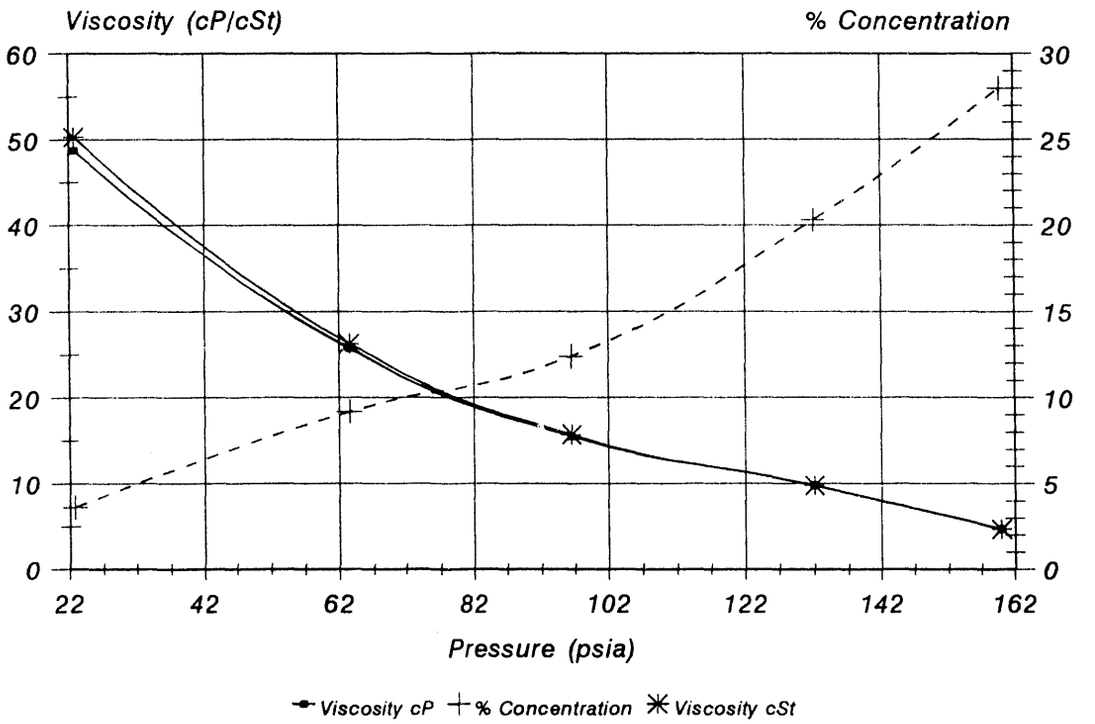



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscosity and Gas Solubility*

*32 ISO VG Mixed Acid Polyolester with HFC-143a at 20°C*

*Figure G.5*

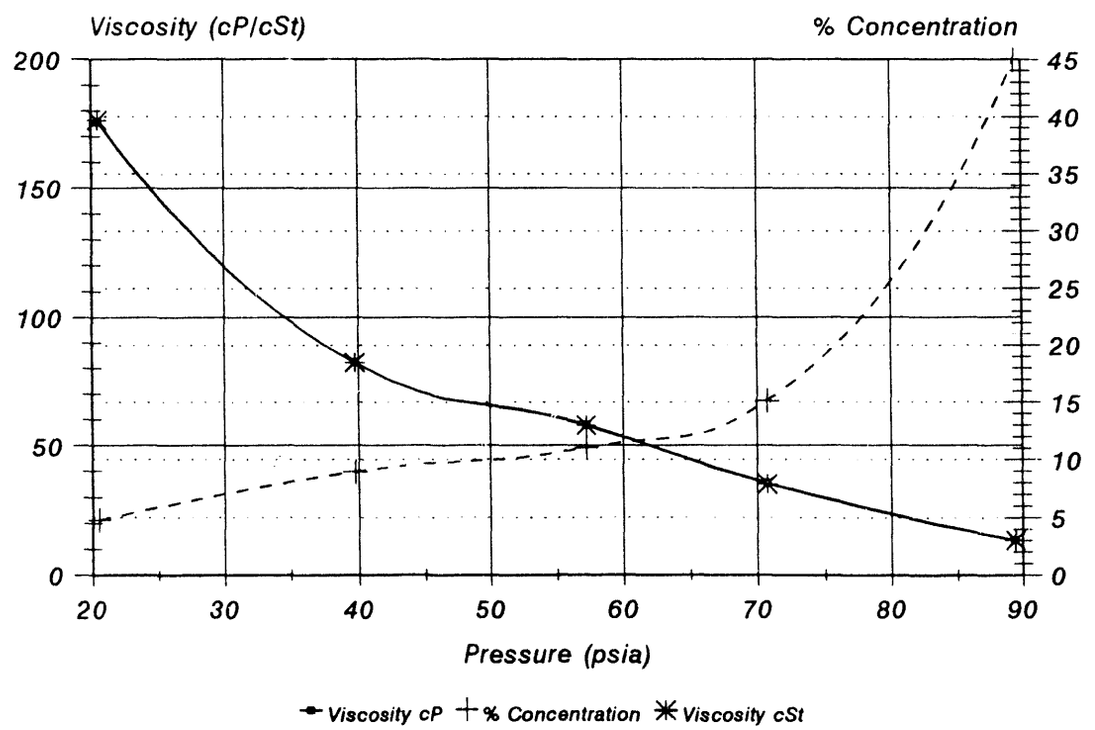



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

## *Viscc nd Gas Solubility*

*32 ISO VG Mixe olyolester with HFC-143a at 0°C*

*igure G.6*




Visc sity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

# Raw Data: Viscosity, Density, and Solubility
# 32 ISO Mixed Acid Polyolester with HFC – 143a
# Table G.1

125.0°C Temperature
>500.0 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.881 | 39.25 | 1.90 | 2.53 | 2.87 |
| 0.889 | 156.00 | 3.36 | 2.58 | 2.91 |
| 0.894 | 231.75 | 5.24 | 2.48 | 2.78 |
| 0.901 | 328.00 | 7.67 | 1.79 | 1.99 |
| 0.910 | 473.00 | 11.20 | 1.63 | 1.79 |

80 °C Temperature
>500 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.915 | 41.25 | 1.76 | 6.89 | 7.53 |
| 0.925 | 154.50 | 6.06 | 5.38 | 5.82 |
| 0.934 | 258.00 | 10.86 | 4.18 | 4.48 |
| 0.942 | 344.00 | 20.06 | 3.44 | 3.65 |
| 0.948 | 414.00 | 29.26 | 2.53 | 2.67 |

60 °C Temperature
417.37 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.941 | 89.00 | 4.58 | 10.28 | 10.92 |
| 0.957 | 168.50 | 10.53 | 7.50 | 7.83 |
| 0.961 | 242.50 | 17.00 | 5.06 | 5.26 |
| 0.972 | 338.50 | 21.19 | 3.35 | 3.45 |
| 0.981 | 417.37 | 30.43 | 1.67 | 1.70 |

40 °C Temperature
266.69 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.945 | 14.70 | 0.00 | 29.79 | 31.51 |
| 0.954 | 53.00 | 3.32 | 20.28 | 21.25 |
| 0.961 | 110.75 | 8.05 | 13.28 | 13.81 |
| 0.969 | 152.50 | 11.49 | 9.53 | 9.84 |
| 0.982 | 213.25 | 19.39 | 5.69 | 5.79 |
| 0.989 | 264.00 | 30.04 | 3.11 | 3.14 |

20 °C Temperature
160.30 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.969 | 22.75 | 3.64 | 48.75 | 50.32 |
| 0.979 | 63.50 | 9.20 | 25.71 | 26.25 |
| 0.989 | 96.50 | 12.39 | 15.55 | 15.72 |
| 1.003 | 132.00 | 20.29 | 9.81 | 9.79 |
| 1.011 | 160.00 | 28.01 | 4.75 | 4.70 |

0 °C Temperature
89.43 psia Saturation Pressure

| Density | Pressure | % Refrig. Conc. | Viscosity cP | Viscosity cSt |
|---|---|---|---|---|
| 0.996 | 20.50 | 4.75 | 175.55 | 176.31 |
| 1.001 | 39.75 | 8.97 | 82.31 | 82.22 |
| 1.006 | 57.25 | 11.06 | 58.02 | 57.70 |
| 1.010 | 70.75 | 15.14 | 35.53 | 35.18 |
| 1.015 | 89.43 | 44.98 | 13.62 | 13.41 |

# END

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