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# Research and Development

## MISCIBILITY, SOLUBILITY, VISCOSITY, AND DENSITY MEASUREMENTS FOR R-236ea WITH FOUR DIFFERENT EXXON LUBRICANTS

## Prepared for

Strategic Environmental Research and
Development Program

## Prepared by

National Risk Management
Research Laboratory
Research Triangle Park, NC 27711

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The report discusses miscibility, solubility, viscosity, and density data for the refrigerant hydrofluorocarbon (HFC)-236ea (or R-236ea) and four lubricants supplied by Exxon Corporation. Such data are needed to determine the suitability of refrigerant/lubricant combinations for use in refrigeration systems. The miscibility tests were performed in a test facility consisting of a series of miniature test cells submerged in a constant temperature bath, precisely controlled over a range of –50 to 90 C. The test cells were constructed to allow for complete visibility of refrigerant/lubricant mixtures under all test conditions. Critical solution temperatures obtained from the miscibility data are presented for each refrigerant/lubricant combination. Data for the R-236ea in each of the test lubricants have been collected for refrigerant concentrations of 10-90%. The raw data have been presented, and the results have been summarized. Two of the oils (Exxon-03 and –04) were found to be completely miscible over the temperature and concentration ranges tested, while the other two (Exxon-01 and –02) were found to be immiscible over most of the temperature range tested. Solubility, viscosity, and density data were also obtained for R-236a mixed with the same four oils for a refrigerant concentration range of 0-40 wt % refrigerant over a temperature range of 30-100 C.

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A Partnership to Improve the Environment

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# MISCIBILITY, SOLUBILITY, VISCOSITY, AND DENSITY MEASUREMENTS FOR R-236ea WITH FOUR DIFFERENT EXXON LUBRICANTS

by

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## ABSTRACT

Miscibility, solubility, viscosity, and density data are needed to determine the suitability of refrigerant/lubricant combinations for use in refrigeration systems. These property data have been obtained for the refrigerant hydrofluorocarbon (HFC)-236ea (or R-236ea) and four lubricants supplied by EXXON Corporation.

The miscibility tests were performed in a test facility consisting of a series of miniature test cells submerged in a constant temperature bath. The bath temperature was precisely controlled over a temperature range of -50 to 90°C (-58 to 194°F). The test cells were constructed to allow for complete visibility of refrigerant/lubricant mixtures under all test conditions. Critical solution temperatures obtained from the miscibility data are presented for each refrigerant/lubricant combination.

Data for the HFC-236ea in each of the test lubricants have been collected for refrigerant concentrations of 10 to 90%. The raw data have been presented, and the results have been summarized. Two of the EXXON oils, namely EXXON-03 and EXXON-04, were found to be completely miscible over the temperature and concentration ranges tested; while the other two EXXON oils, namely EXXON-01 and EXXON-02, were found to be immiscible over most of the temperature range tested.

Solubility, viscosity, and density data were also obtained for HFC-236ea mixed with the same four EXXON oils for a refrigerant concentration range of 0 to 40 weight percentage refrigerant over a temperature range of 30 to 100°C (86 to 212°F). This range of conditions represents the area of interest necessary for the proper design of compressors. This research shows that the solubility, viscosity, and density each are a function of temperature and concentration. Specifically, this research also shows that (1) the solubility increases with increasing temperature and with increasing refrigerant concentration (i.e., mass fraction of refrigerant), (2) the viscosity decreases with increasing temperature and with increasing refrigerant concentration, and (3) the density decreases with increasing temperature but increases with increasing refrigerant concentration.

This report was submitted in fulfillment of CR 820755-01-4 by Iowa State University under the sponsorship of the U.S. Environmental Protection Agency with funding from the Department of Defense's Strategic Environmental Research and Development Program. This report covers a period from March 1995 to March 1997.

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# CHAPTER 1

# INTRODUCTION

## 1-1. MISCIBILITY OF REFRIGERANT/LUBRICANT MIXTURES

The development of acceptable refrigerants requires the identification of compatible lubricants so that refrigeration systems with mechanical compressors will operate properly. The first requirement of a compatible lubricant is that it be miscible with the refrigerant over the operating temperatures of the system. Refrigeration systems require a miscible refrigerant/lubricant mixture for compressor lubrication, for maximum heat transfer performance in the evaporator, and for proper lubricant return to the compressor.

To obtain miscibility data, the visual observation and careful interpretation of the physical conditions of a refrigerant/ lubricant mixture at specific temperatures are necessary. The procedure is repeated for the desired ranges of temperatures and refrigerant concentrations. Visual inspection of the mixture allows for determination of whether the mixture showed signs of cloudiness, floc or precipitate formation, and/or the formation of a second liquid phase.

Miscibility data were measured for HFC-236ea, hereafter designated as R-236ea, mixed with four different EXXON oils, hereafter designated as EXXON-01, EXXON-02, EXXON-03 and EXXON-04.

Miscibility tests were performed on R-236ea/lubricant mixtures for refrigerant concentrations of 10 to 90% by weight. These tests were performed by keeping the refrigerant/lubricant mixture visible at all times, while controlling temperatures to ±1°C (±1.8°F) and shaking the test cells to mix the contents. Each refrigerant/lubricant combination was tested for miscibility in 10°C (18°F) increments over the test temperature range of -40 to +90°C (-40 to +194°F).

## 1-2. SOLUBILITY, VISCOSITY, AND DENSITY OF REFRIGERANT/LUBRICANT MIXTURES

When introducing a new refrigerant, the choice of lubricant is important in that the role of the lubricant in the refrigeration system is to lubricate the compressor. The acceptability of many alternative refrigerants (i.e., HFCs) and their respective lubricants has been designed around duplicating the solubility and viscosity characteristics of the present CFCs (chlorofluorocarbons)/HCFCs (hydrochlorofluorocarbons) and mineral oil mixtures. The degree of solubility and viscosity required has become a point of discussion in the R & HVAC (refrigerating and heating, ventilating, and air conditioning) industry.

Having decided on the lubricant to be used, the design engineer needs data in order to understand what is happening in the system. For example, a design engineer needs to know what the pressure and temperature relationship is for the refrigerant and lubricant mixture as the concentration of each component changes. The above relationship between pressure, temperature, and concentration is known as solubility. These data should be useful to design engineers who will be evaluating and selecting new refrigerant/lubricant systems in the future. The solubility and viscosity data needed for design using R-114 replacements, such as R-236ea, were unknown before this work was conducted.

The main types of lubricants recently being proposed for use with the new refrigerants are PAGs (poly alkyl glycols), modified PAGs, and POEs (polyol esters). This research presents property data consisting of solubility, viscosity, and density data for R-236ea with four different lubricants. As noted earlier, these lubricants represent typical POE lubricants with and without additives and with different viscosities and are designated as EXXON-01, EXXON-02, EXXON-03, and EXXON-04.

The objectives of this research are to obtain solubility, viscosity, and density data for R-236ea with four different lubricants. These data will be useful for the design of non-chlorofluorocarbon (CFC) refrigerant compressors of the type presently used with R-114 aboard ships. The solubility, viscosity, and density data were obtained for the following conditions:

- Composition: 0 to 40 weight percent refrigerant
- Temperature: 30 to 100 °C (86 to 212°F)
- Pressure: 0 to 3.5 MPa (0 to 500 psia)

The following chapters describe the test facility and the methodology used to measure the properties of miscibility, solubility, viscosity, and density. The property results for the refrigerant/lubricant pairs studied were presented in the form of graphs and empirical correlations. The data points were also tabulated.

# CHAPTER 2

# CONCLUSIONS

## 2-1. MISCIBILITY OF REFRIGERANT/LUBRICANT MIXTURES

Critically needed miscibility data have been obtained for R-236ea with four lubricants. The test facility incorporates test cells with sight windows for viewing the refrigerant/lubricant mixture inside. The cells were charged with variable amounts of refrigerant and lubricant to facilitate refrigerant compositions from 0 to 100% by refrigerant mass fraction. After charging, the test cells were submerged in either the low temperature or high temperature baths which could be set to any described temperature. Operating temperature and pressure ranges for the facility are -50 to 90°C (-58 to 194°F) and 0 to 3.5 MPa (0 to 500 psia), respectively.

Data for the R-236ea in each of the test lubricants have been collected for refrigerant concentrations of 10 to 90%. The raw data have been presented, and the results have been summarized. Two of the EXXON oils, namely EXXON-03 and EXXON-04, were found to be completely miscible over the temperature and concentration ranges tested. The other two EXXON oils, namely EXXON-01 and EXXON-02, were found to be immiscible over most of the temperature range tested.

## 2-2. SOLUBILITY, VISCOSITY, AND DENSITY OF REFRIGERANT/LUBRICANT MIXTURES

In this study, a test facility developed by Van Gaalen et al. (1991a,b) was used to provide critically needed refrigerant/lubricant mixture properties. Specifically, solubility, viscosity, and density data have been obtained and correlated at various ranges of pressure and temperature for four different EXXON lubricant/refrigerant mixtures. Data were obtained using the test facility with operating temperature and pressure ranges of 30 to 100°C (86 to 212°F) and 0 to 3.5 MPa (0 to 500 psia), respectively.

Experimental procedures for the operation of the test facility are described here. Also, the data reduction techniques, including correlating equations, are presented. The measured data showed that the instrumentation was accurate and the results were repeatable. The test facility has been successfully employed to obtain experimental results for refrigerant/lubricant mixtures of R-236ea in four different lubricants, EXXON-01, EXXON-02, EXXON-03, and EXXON-04.

This research shows that the solubility, viscosity, and density each are a function of temperature and concentration. Specifically, this research also shows that (1) the solubility increases with increasing temperature and with increasing refrigerant concentration (i.e., mass fraction of refrigerant), (2) the viscosity decreases with increasing temperature and with increasing refrigerant concentration, and (3) the density decreases with increasing temperature but increases with increasing refrigerant concentration.

The results are also presented in charts where the solubility, dynamic viscosity, kinematic viscosity, and density are plotted as functions of temperature and refrigerant concentration. Empirical correlating equations were developed using multilinear regression analysis. These equations allow convenient interpolation of the data at specific property conditions.

# CHAPTER 3.

# LUBRICANT/REFRIGERANT TEST FACILITY

## 3-1. MISCIBILITY TEST FACILITY

The test facility for measuring miscibility includes test cells capable of withstanding the high pressures and the extreme temperatures encountered in the study of refrigerant/lubricant mixtures. Two constant temperature baths maintained a constant temperature in the test cell. The facility was designed for the purpose of determining the miscibility characteristics of refrigerant/lubricant mixtures over the temperature range of -40 to 90°C (-40 to 194°F) and for pressures up to 3.5 MPa (500 psia). The test cells have glass viewports and are submerged in one of two constant temperature baths so that the miscibility characteristics of the mixture can be observed and recorded. The test facility is described in detail in previous publications (Zoz, 1994 and Zoz and Pate, 1993). Figure 3.1 provides the photograph of miscibility test facility.

The precise temperature of each bath fluid was measured by a platinum resistance temperature detector (RTD) that is connected to a signal conditioner/current transmitter. The RTD had an accuracy of $\pm$0.1°C ($\pm$0.18°F). Since the miscibility characteristics of mixtures in each cell were noted at 10°C (18°F) intervals in this study, the uncertainty in the temperature where a change in the miscibility characteristics occurred was ±5°C (±9°F). Due to the magnitude of this uncertainty, the uncertainty in the actual temperature measurements using the RTD is insignificant.

### 3-1-1. TEST CELLS

The test cells are constructed to allow for complete visibility of the lubricant/refrigerant mixture at all test conditions. Each test cell consists of a double-port seal-cap type liquid indicator, which is essentially a 3.17-cm (1.25-in.) pipe cross with sight windows screwed into opposing ports. Valves for charging the refrigerant into the cell are screwed into the other two ports. A temperature sensor can be inserted in each cell or in an adjoining reference cell exposed to the same heating or cooling conditions.

The overall volume of each test cell was measured to be 65-ml. (3.963--$in.^3$). During charging, each cell can be filled so that the vapor space is less than 15% of the total volume. In addition, if

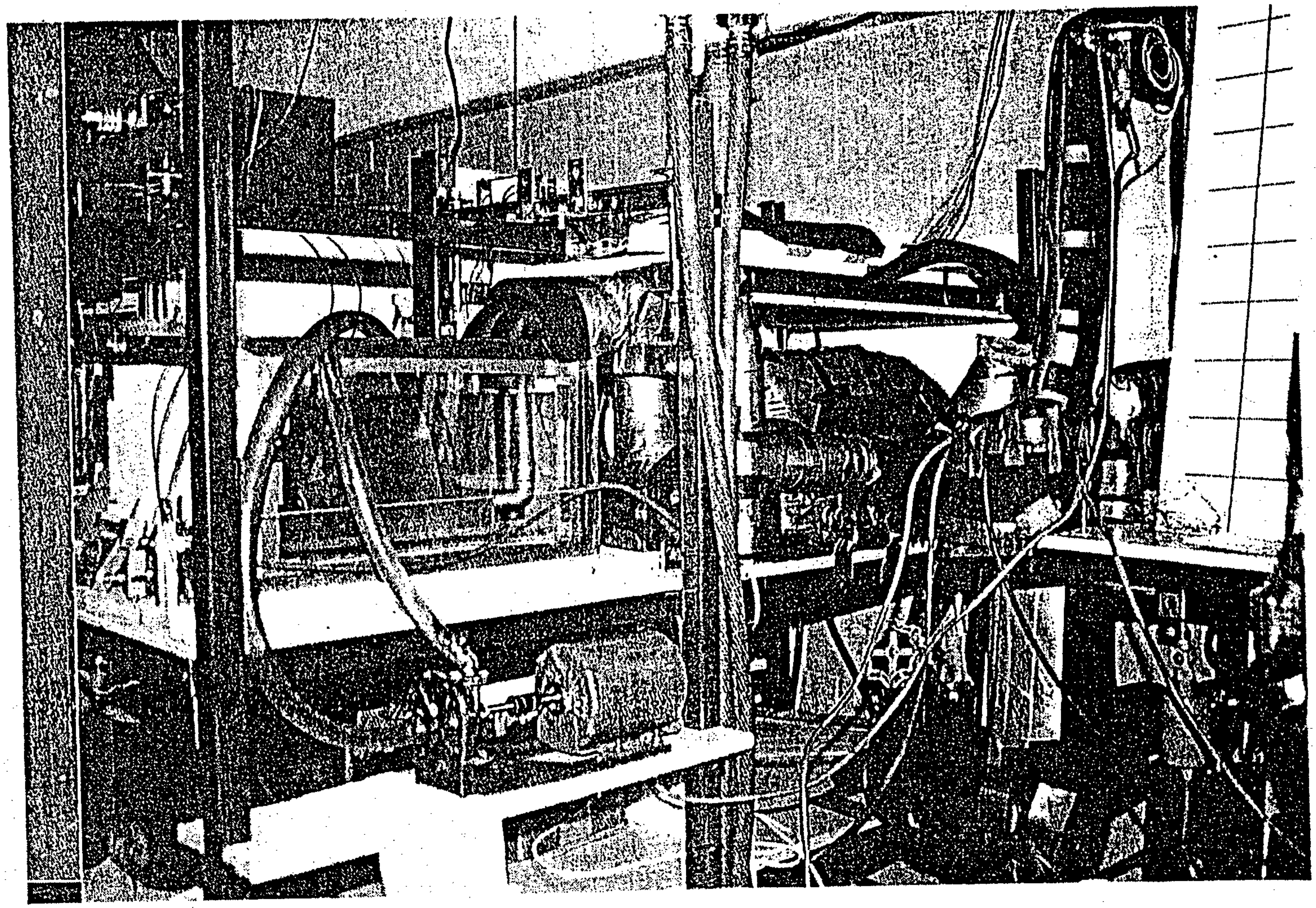

Figure 3.1. Photograph of the miscibility test facility

temperature and pressure data are available, changes in the liquid concentration due to vapor space refrigerant can be calculated.

Three charged cells can be placed in a specially designed Plexiglas™ holder, and two such holders can be placed in the constant temperature bath to permit the testing of six test cells simultaneously.

### 3-1-2. CONSTANT TEMPERATURE BATHS

The temperature of the cells is fixed by placing them in one of two constant temperature baths. The hot bath is used to maintain temperatures from 10 to 95°C (50 to 204°F), while the cold bath is used for temperatures in the range of 10 to -50°C (50 to -58°F).

The baths are constructed of glass which allows complete visibility of the test cell and, therefore, the lubricant/refrigerant mixtures throughout the test. Movable fluorescent lights are located behind a bath to help increase visibility.

#### 3-1-2-1. COLD BATH

The cold bath fluid is composed of 65% pure ethylene glycol and 35% water. Pure ethylene glycol is used so that the bath fluid will be transparent. The bath is cooled with the use of an R-502 refrigeration system. A temperature controller and a heater are installed to regulate the bath temperature.

The bath is insulated on all sides to ensure a uniform temperature. The insulation on the front and back of the bath consists of a double-paned Plexiglas™ window mounted on the glass bath. Condensation is prevented by using a nitrogen purge of the dead air spaces. Insulation on the other sides is provided by 0.0508 m (2 in.) of Styrofoam™.

#### 3-1-2-2. HOT BATH

The hot bath fluid is water with a rust inhibitor added. 0.0508 m (2 in.) of Styrofoam™ provides the insulation on the ends of the bath, while the insulation on the front and back of the bath is provided by a single Plexiglas™ window mounted on the glass leaving a 0.0127 m (1/2-in.) air space.

### 3-1-3. INSTRUMENTATION

The precise temperature of the bath fluid is measured by two internal resistance temperature detectors (RTDs). These primary temperature probes consist of a platinum RTD connected to a signal conditioner/current transmitter that provides a linear response over the temperature range of -51 to 149°C

(-60 to 300°F). The RTD's have an accuracy of ±0.1°C. A microcomputer and data acquisition hardware under the direction of a data acquisition program monitor receive and record signals from all instruments.

One cell in each bath is assembled with an internal RTD to determine equilibrium (i. e., steady state) conditions. The cell is charged with pure lubricant to provide a "worst case" heat transfer situation. The temperature difference between the internal RTD and the bath temperature indicates when thermal equilibrium between the cell and the bath has been achieved. Steady-state conditions are typically achieved about 30 minutes after a change (e.g., 5 to 10°C) in the circulating bath temperature.

### 3-1-4. EXPERIMENTAL PROCEDURE

Experimental procedures have been developed for measuring refrigerant/lubricant miscibility by using the test facility described previously. The cells are first cleaned with the front and back windows removed for cleaning. After cleaning, the back window is installed and tightened. The prescribed amount of lubricant is injected with a syringe through the front window space. The front window is then replaced and tightened. A vacuum pump is hooked up to a port housing one of the valves, and a vacuum is pulled to remove any dissolved moisture or air. Fittings are retightened if a failure to hold either a vacuum or a set pressure indicates that this is necessary.

Liquid refrigerant is injected into the cell from the refrigerant canister by using a manifold that allows for the evacuation of the connecting lines. The cells are weighed on a scale before and after the injection of the lubricant and the refrigerant. The typical weight of cells is approximately 1459.5 grams. The scale has an uncertainty of ±0.01gram. The concentration of the liquid in each cell is calculated from the masses of refrigerant and lubricant injected. The uncertainty in the concentration measurements is ± 0.5%. It is important to note that since the refrigerant vapor density changes as the temperature and pressure change, then the refrigerant vapor mass also varies. As a result, the liquid concentration varies slightly as the temperature and pressure change. For the experimental approach presented here, the vapor volumes are kept small, less than 10% of the total space is vapor. Therefore, the overall variations in refrigerant concentration as temperature and pressure are changed during any particular test are small. Once the desired amounts of lubricant and refrigerant have been injected into the cell, it is ready for testing.

The cells are then placed in the bath and heated or cooled to the desired temperature. The desired temperatures are in 10°C increments for heating from 10 to 90°C or cooling from 10 to -50°C. Steady-state conditions are assumed when two conditions are met: first, the bath temperature is within ±0.5°C of the set point temperature and second, the difference between the instrumented cell and the bath temperature is within 0.5°C. At this point, the characteristics of the fluid in each cell are noted.

After testing the cells through the temperature range, the cells are removed from the bath. The refrigerant/lubricant mixture is drained through one of the valves, and the cell is rinsed three times with solvent. The final cleaning of the cell is accomplished by removing the front and back window and rinsing with solvent to remove traces of lubricant. The windows and seals are then cleaned and visually examined for defects.

### 3-1-5. MISCIBLITY CHARACTERISTICS

When a refrigerant/lubricant mixture is miscible, it appears as a homogeneous transparent solution. However, when a refrigerant/lubricant mixture is immiscible, there is either cloudiness, evidence of particles dispersed throughout the mixture, or there are two liquid phases present in the cell. Throughout all testing, visual inspections were made for these signs of immiscibility. The presence of two liquid phases was the only form of immiscibility observed in this study.

### 3-1-6. REFRIGERANT CONCENTRATION

The refrigerant concentration of each test cell was calculated from the total masses of refrigerant and lubricant charged into the cell. The uncertainty in the concentration measurements depends on the concentration that is being considered; however, the maximum uncertainty in concentration is ±0.005 (0.5%). The uncertainty was calculated by using a propagation-of-error method discussed by Beckwith et al. (1982).

It is important to note that the concentration of the liquid phase in the test cell changed as the temperature of the cell was varied. This occurred because a vapor space was required above the liquid mixture so that the thermal expansion of the liquid mixture did not cause cell failure due to extremely high pressures internal to the cell. Changes in concentrations were less than 1% over a typical range of temperature tested.

### 3-1-7. CRITICAL SOLUTION TEMPERATURES

The critical solution temperature, as defined in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Refrigeration Handbook (1994), is the temperature above which a refrigerant/lubricant combination is miscible for all refrigerant concentrations. Since some of the new refrigerant/lubricant combinations have regions of immiscibility that occur with increasing temperature (sometimes referred to as a high temperature immiscibility), an additional definition must be used. The lower critical solution temperatures presented here are based on the ASHRAE definition, while the upper critical solution temperature is defined as the temperature below which a refrigerant/lubricant combination is miscible for all refrigerant concentrations.

Some refrigerant/lubricant combinations were found to be immiscible in a certain test temperature range for certain concentrations. Other refrigerant/lubricant combinations never became immiscible (i.e., they were always miscible) regardless of the test temperature and concentration. For these cases, a critical solution temperature is not defined. Therefore, when presenting critical solution temperatures, these cases will be identified as two-phase (immiscible) and clear (miscible), respectively. Critical solution temperatures were not presented even for conditions where two-phase behavior occurred. Data show approximately these temperatures. For example for EXXON-01 at a mass fraction of 0.307, the critical solution temperature is between -9.86 and -20.40°C. Perhaps, it should be stated that the critical solution temperature is -14.86 ± 5°C. For any particular combination of the tested combinations, it was less than -40°C.

## 3-2. SUMMARY OF MISCIBILITY TEST FACILITY

A versatile lubricant/refrigerant miscibility test facility has been described to provide critically needed miscibility data for a variety of lubricant/refrigerant mixtures over a range of temperatures and concentrations. Incorporating a commercially available test cell, as well as windows for observation of the test cell's contents, the test facility can be used for determination of the miscibility of these mixtures. Precise, convenient charging of mixtures with refrigerant compositions ranging from 10 to 90% by weight is achievable. These tests were performed with the refrigerant/lubricant mixture visible at all times while controlling temperatures to ±1°C (±1.8°F) and moving the test cells to mix the contents. Each refrigerant/lubricant combination was tested for miscibility in 10°C (18°F) increments over the test temperature ranges of -40 to +90°C (-40 to +194°F).

The following sections outline the solubility, viscosity, and density test facility used for mixtures of R-236ea with four EXXON oils.

## 3-3. SOLUBILITY, VISCOSITY, AND DENSITY TEST FACILITY

The method used in this study to measure the properties of solubility, viscosity, and density for refrigerant/lubricant mixtures was described in detail by Van Gaalen et al. (1991a,b). The apparatus consists of pressure vessels (hereafter referred to as the test cells) charged with known refrigerant/lubricant mixtures and a support system capable of controlling the temperature of the test cells. The test cells, support system, and data acquisition system were designed to measure solubility, viscosity, and density for any lubricant/refrigerant mixture over a normal operating temperature range of 30 to 100°C (86 to 212°F) and for pressures up to 3.5 MPa (500 psia).

The test facility, including instrumentation and data acquisition, and procedure for injecting fluids into the test cell are described in the following sections. The test facility, including the test cell, major components, instrumentation and methods of injecting fluids were described previously by Van Gaalen et al. (1991a,b).

### 3-3-1. TEST CELL

The test cell is a cylinder constructed of Schedule 120 Type 304 stainless steel pipe, with an outside diameter of 141.3 mm (5.563 in.), a wall thickness of 12.7 mm (0.500 in), and a corresponding inside diameter of 115.9 mm (4.563 in.). The length of the pipe internal volume is 457.5 mm (18 in.). The test cell stands upright on one end. Two diametrically opposite slots, 317.5 mm (12.5 in.) in width, were machined through the cylinder wall. Windows bolted into position over these slots allowed visual inspection of the contents at all times and under all test conditions. A schematic drawing of the test cell is provided in Figure 3.2.

Machined end plates 25.4 mm (1 in.) thick were bolted onto flanges welded to the pipe section at each end. An O-ring at each end, seated in machined grooves in the wall of the pipe section, provided the pressure (and vacuum) seals. Because none of the weld joints were exposed to the contents of the test cell, this method of construction obviated the need for inspection of welds for leakage that would be required by other designs. The height of the test cell is sufficient to accommodate the addition of 40 % (by mass) refrigerant to the liquid oil charge, while still reserving a minimum vapor space at all expected densities and at maximum charge conditions.

Entering the test cell through the top end plate are three temperature probes and a heating/cooling coil, as depicted in Figure 3.2. Also provided in the top plate are ports for pressure measurement and pressure relief, as well as for filling and evacuation of the test cell. Two ports machined into the bottom plate allowed for the exit and return of fluid to/from the external viscometer and sampling loops, as shown in Figure 3.1. The actual volume of the test cell and associated loops were determined and scales on the windows calibrated by injecting precise amounts of solvent from the charging system, which had been previously calibrated. With both windows mounted on the test cell and with the viscometer and sample loops full, the overall volume was measured as 5190 mL $\pm$ 20 mL (317-in$^3$ $\pm$ 1.22-in$^3$). Liquid and vapor volume were correlated with liquid level height as measured on the scales.

The temperature, and hence pressure, of the solution under test is controlled by a temperature control flow loop having coils soldered on the exterior of the test cell and by a portion of the loop immersed in the test cell. A heating fluid is supplied to this loop by a circulating bath. Uniform heating of a large surface area minimizes the thermal gradients in the oil/refrigerant mixture. Fiberglass insulation, 50 mm (2 in.) thick around the test cell, minimizes heat loss to the environment. A walled enclosure, described elsewhere, also reduces heat losses.

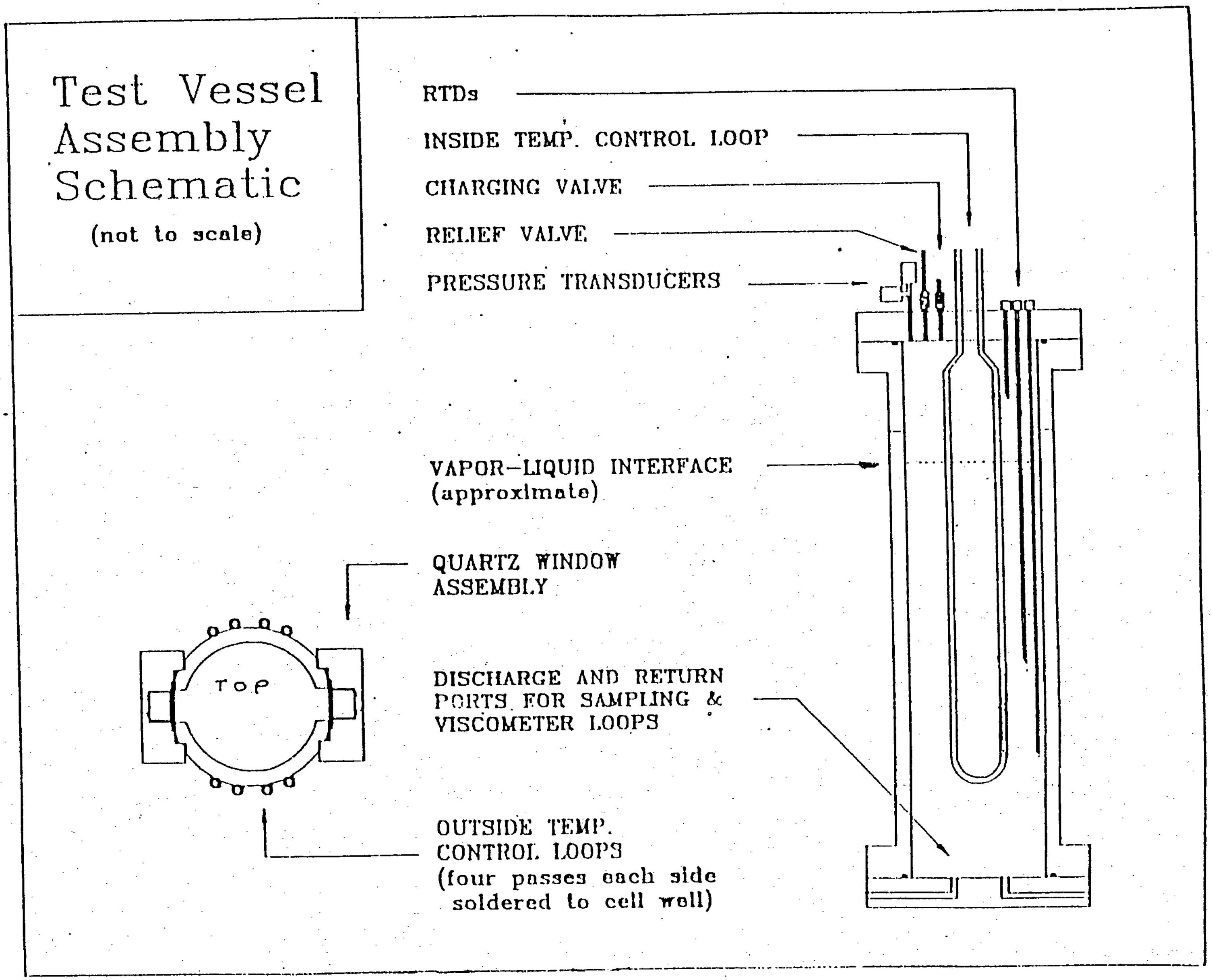


Figure 3.2. Schematic drawing of the test cell

### 3-3-2. WINDOWS

In order to view the contents of the test cell for the purposes of detecting the presence of more than one phase and for density determinations, as well as aiding the charging of the test cell, two diametrically opposite vertical windows were provided in the test cell wall. The viewing slots are 304.8 mm (12 in.) long and 12.7 mm (0.50 in.) wide. Calibrated scales fastened to the retainer plates adjacent to the viewing slots enable measurement of the height of the liquid-vapor interface to within ± 0.794 mm (± 0.03 inch.). This permits determination of the volumes of liquid and vapor present to within ± 9 mL (±0.549 $in^3$), or less than 0.2 % of the total cell volume. Quartz pieces set on O-rings and held in place by retainer plates provide the pressure seal. A stainless steel backing plate holds the quartz against the O-ring in the slot. The whole assembly is then bolted onto the test cell and sealed by another (larger) O-ring compressed between the test cell wall and the window assembly. The O-ring material must be compatible with the lubricant/refrigerant mixtures to which it will be exposed. Neoprene O-rings were used with the R-236ea/lubricant mixtures. Viton O-rings have also proven satisfactory in later work with the same combination of refrigerant/lubricant mixtures. After installation, a hydrostatic test to 3.5 MPa (500 psia) conducted at ambient temperature proved that the windows were leak-tight. Additional pressure tests with nitrogen gas at 3.5 MPa (500 psia) also showed no leaks.

### 3-3-3. TEMPERATURE CONTROL FLOW LOOP

A flow loop for controlling the temperature of the test cell is installed. Figure 3.3 shows a schematic diagram of this loop. The loop has two coils of 9.525 mm (0.375 in.) OD Type 304 stainless steel tubing in parallel, one soldered in place around the test cell wall and the other immersed in the test cell through the top plate. The exterior portion of this loop is further divided into two parts, with each part heating one side of the test cell. The interior portion also bifurcates to provide more thermal contact area. The routing of these internal loop portions was arranged so that they did not obstruct the view through the windows.

A circulating bath maintains the desired temperature of the heating fluid by controlling a 3-kW heating element. The heating fluid is a poly-alpha-olefin (PAO), used from -30 to 380°C (-22 to 716°F). While the viscosity of PAO at the lower end of this temperature range, -30°C (-22F), is high for achieving turbulent flow in the loop with the circulating bath pump, it performs well at higher temperatures in an open system because of its decreasing viscosity and extremely low volatility. The steady-state temperature of the contents of the test cell is indirectly controlled by setting the temperature of the heating fluid in the flow loop. Operating experience has shown that adequate heating of the test cell is provided by this arrangement. Steady-state conditions are typically achieved from 2 to 3 hours after a 10°C (18°F) change in the circulating bath temperature set point. The temperature of the liquid phase of the refrigerant and

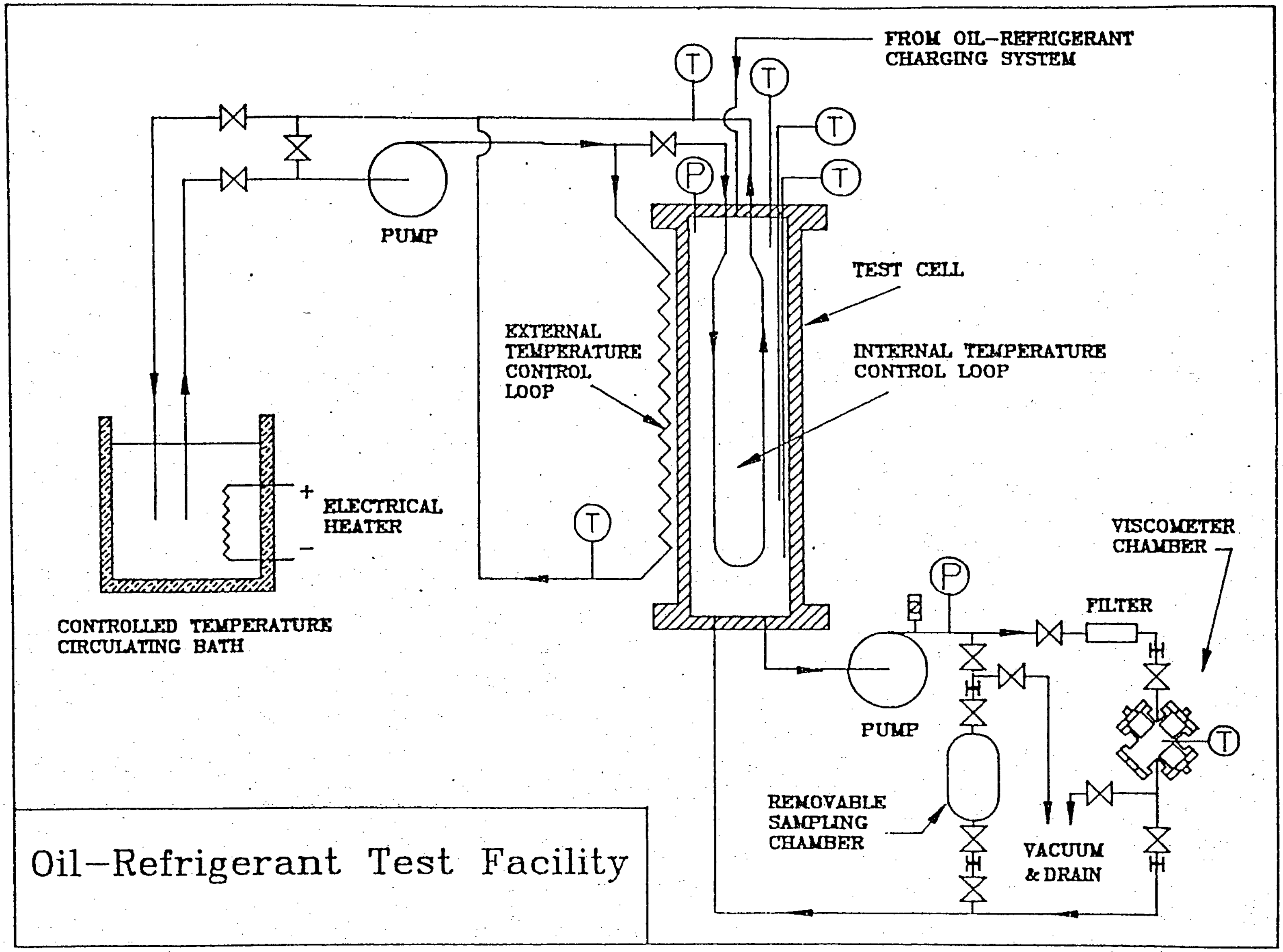


Figure 3.3. Schematic diagram of the flow loop

lubricant mixture inside of the cell is measured by the three internal resistance temperature detectors (RTDs). However, these three RTD's show that the cell contents are at a uniform temperature especially since the liquid phase is well stirred. An average of these liquid temperatures in the cell is used in the reporting of the liquid density data.

### 3-3-4. VISCOMETER

Two commercially available viscosity sensors were installed in the auxiliary viscosity loop [Cambridge Applied Systems (CAS 1989)]. The viscosity sensor operation is based on a movable piston drawn through the fluid in the internal cavity by an applied electromagnetic field. The time elapsed as the piston travels through a known distance is a measure of the viscosity of the fluid. The associated circuit card provides electronics for control and sensing, giving a 0 to 2 volt D.C. signal correlated to viscosity. The uncertainty of the viscosity data is ±2.0% of the reading. Each sensor also contains an RTD for measurement of the local temperature, which is used in the reporting of the viscosity data. Because of internal self-heating in the viscometer that arises from the dissipation of electrical energy in the drive coils of the sensor, this RTD reading is somewhat higher than the temperatures indicated by the RTDs in the test, 2% of the reading. Each sensor also contains an RTD for measurement of the local temperature, which is used in the reporting of the viscosity data. Because of internal self-heating in the viscometer that arises from the dissipation of electrical energy in the drive coils of the sensor, this RTD reading is somewhat higher than the temperatures indicated by the RTDs in the test cell during steady-state operation. This is especially true at the lower end of the investigated temperature range. For example, at 40°C the difference is about 3 - 4°C, depending on the particular viscosity sensor. This difference decreases to about zero at temperatures of 90°C and above.

The two viscosity sensors that are installed in the viscometer chamber have viscosity ranges of 1 to 20 cP (centipoise) and 10 to 200 cP, respectively. Because these ranges overlap, some limited redundant measurements of viscosity are possible, thus increasing the confidence in the validity of the calibrations of each sensor. The viscosity sensors were calibrated by using standard viscosity fluids provided by the Cannon Instrument Company. Use of multiple sensors reduces the downtime that would otherwise be required to change the internal piston of a single sensor to the desired measurement range. Note that pistons are available from the manufacturer for viscosities up to 5000 cP, should they be necessary for measurements at low temperatures where the lubricant/refrigerant solutions may be very viscous.

Internal self-heating in the drive coils of the viscometer tends to cause vapor to flash from the equilibrium mixture. This vapor formation disrupted stable and accurate viscometer operation in early testing. For this reason, it was necessary to construct an external flow loop through which the liquid mixture was compressed before being pumped to the viscometer for measurement and then returned to the test cell. In this manner, stable and repeatable viscosity readings were achieved. Taking liquid from the test cell, a pump in the loop raises the pressure of the liquid without noticeably affecting the temperature. Since a small increase in pressure has a negligible effect on liquid viscosity, this pressurization provides an acceptable means of preventing vapor formation in the viscometer.

Figure 3.4 shows a schematic diagram of viscometer. As shown in Figure 3.4, a magnetically driven positive-displacement gear pump with a variable-speed motor moves the fluid through this loop to the viscometer chamber and back to the test cell. Variable-speed control allows for adjustment of flow from almost zero to about 0.095 L/s (1.5 gpm), which provides for sufficient pressurization of the liquid in the loop while limiting uncontrolled heating of the fluid due to the addition of pumping power. A valve between the viscometer chamber and the discharge to the test cell can be adjusted, along with the flow rate, to produce the required pump discharge pressure at a reasonable flow rate. A pressure gauge is installed at the pump discharge to monitor the pressure increase. A pressure relief valve set to open at 3.5MPa (500psig) is installed just downstream of the pump discharge to provide a safe release of fluid if the downstream flow is inadvertently blocked by the closing of a valve or other restriction.

The chamber that holds the viscometer is constructed from a 31.75 mm NPT (1.25 in.) stainless steel pipe cross. Each of the viscosity sensors thread into a branch of the pipe cross. The fourth branch is plugged for possible future use. Passing over an in-line thermocouple, which provides a rough check of the temperature, fluid enters the chamber through a fitting in the side of the pipe cross, flowing around the active portion of the viscosity sensors before returning to the test cell through the 6.35 mm (0.25 in.) diameter return line.

The inlet and outlet lines contain valves to isolate the chamber for removal or disassembly. A vacuum/drain port is connected to the return line to allow removal of fluid after isolation of the chamber from the test cell before disassembly and to enable the necessary evacuation of the chamber after reinstallation into the loop. The total volume of the liquid contained in this loop is 57.5 mL (3.51 in.$^3$), 1.2% of the total system volume.

### 3-3-5. SAMPLING LOOP

A 75 mL (4.6 in.$^3$) sampling cylinder is connected in parallel with the viscometer and may be independently isolated and removed from the system for measurements of the liquid composition. The sampling loop was assembled with this cylinder and two union bonnet valves on each side. The outer valves may be closed to isolate the chamber from the rest of the system, and the inner valves are closed to ensure that no fluid escapes from the sampling cylinder when it is removed. A vacuum/drain port is also provided. The total volume of the sampling loop is 79 mL (4.8 in.$^3$). Since this is 1.6% of the total system volume, disturbances of test cell conditions are minimized during sampling.

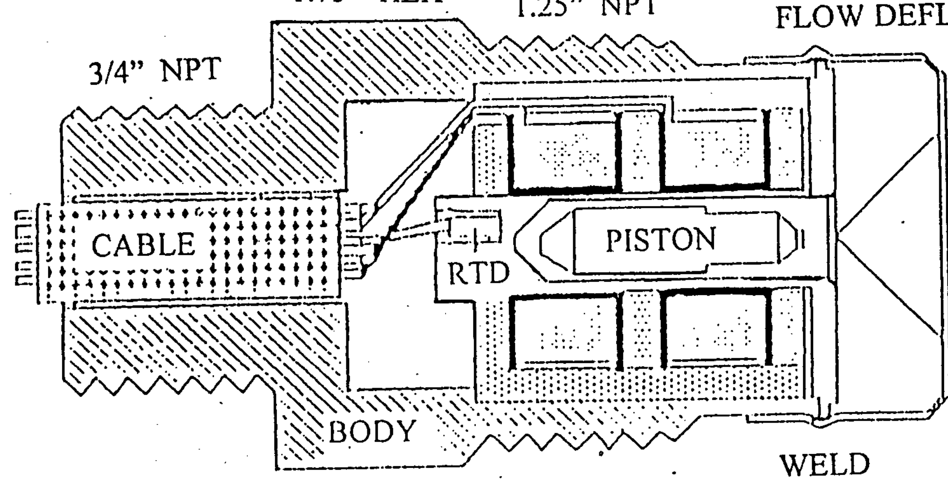


Figure 3.4 Viscosity-Temperature sensor body

## 3-3-6. EQUIPMENT ENCLOSURE

Although all components of the facility are insulated, a frame and panel enclosure consisting primarily of steel framing, plywood, fiberglass ductboard, and Plexiglas™ viewports was constructed to provide additional isolation from the room environment. This provides greater thermal uniformity and stability as well as affording a measure of protection to operators in the event of a high-pressure leak of the hot lubricant/refrigerant mixture. At the same time, the enclosure was designed to allow accessibility and visibility for proper operation and monitoring.

## 3-3-7. DATA ACQUISITION

Viscosities, temperatures, and pressures are recorded by computerized data acquisition methods. A microcomputer controls a digital multimeter and a switching unit that provides a sufficient number of channels to monitor all signals generated by the installed sensors. Table 3.1 gives a summary of the range and precision of the sensors.

A bonded strain gauge pressure transducer is in contact with the test cell contents via a port machined into the top plate. A second pressure transducer employs a capacitance-sensing element. The calibrations of these pressure transducers were checked with the use of a dead-weight pressure tester. These calibration checks indicated that the output signals of both transducers were linear with pressure, matching the factory-supplied calibrations. The uncertainty in the pressure data is ± 5.2 kPa (± 0.75 psia).

Three platinum RTDs independently track the temperature of the liquid contained in the test cell, and another RTD monitors the vapor space temperature. A fifth RTD is inserted into the pipe cross containing the viscometers. Three RTDs were calibrated after connection with current transmitters, the required load resistors, and a power supply.

Table 3.1. Summary of the range and precision of the sensors

| Instrument | Range | Precision* |
|---|---|---|
| Bonded Strain Pressure Transducer | 0 - 3.5 MPa (0 - 500 psia) | ± 5.1 kPa (± 0.75 psia) |
| Variable Capacitance Pressure Transducer | 0 - 3.5 MPa (0 - 500 psia) | ± 3.8 kPa (± 0.55 psia) |
| Viscometer | 1.0 - 200 cP | ± 2 % rdg. |
| Platinum RTD and Signal Conditioner | -50°C - +150°C (-58°F - +302°F) | ± 0.1°C (± 0.2°F) |
| Concentration Measurements | 0 - 100 % | ± 1 % |

*Precision of the instrument was provided by its manufacturer.

The signal conditioners used with the RTDs linealize the response, providing a 4 to 20 mA signal that is linear over the temperature range -50 to 150°C (- 58 to 302°F). This signal produces a 1 to 5 volt output when measured across a 250-ohm load resistor, which is monitored by the data acquisition equipment. The calibration of output voltage versus temperature showed that all RTDs provided a linear response. The uncertainty of these temperature measurement was ±0.2°F (0.1°C).

## 3-3-8. DESCRIPTION OF THE REFRIGERANT/LUBRICANT CHARGING

A charging station was designed to inject a precise amount of refrigerant into the test cell. The refrigerant is injected by a separate, parallel system. The refrigerant side employed a stainless steel cylinder of 617.8 mL (37.7 in.$^3$) having a 50.8 mm (2 in.) bore with a 304.8 mm (12 in.) stroke. The cylinder displacements were calibrated with the use of known solvent, and they agree with the above values to within ± 2 mL (0.1 in.$^3$). The commercially available cylinder allowed injection of refrigerant in suitable quantities to give the desired concentration increments.

A commercial supply can is connected with the lower end of the cylinder. The cylinder is then further pressurized with nitrogen to ensure that only liquid refrigerant is contained in the cylinder. This pressure is also used to force refrigerant into the test cell.

The presence of a "slug" charge of subcooled liquid in the injection cylinder is checked by applying nitrogen pressure well above the vapor pressure of the refrigerant and ensuring no piston rod movement. The cylinder contents are then discharged to the test cell through 9.525 mm (3/8 in.) diameter copper tube and a connecting refrigeration hose by application of pressurized nitrogen gas to the rod side of the cylinder as the charging valve on the test cell is opened. A partial injection of a given volume can be made by determining in advance the required displacement and then moving the rod to the appropriate position on a scale mounted directly behind the rod.

For the lubricant charging, the lubricant contents can be heated as a vacuum is applied in order to liberate dissolved air and water vapor. The removal of air and water from the lubricant is especially important prior to injection for testing. After disconnecting the vacuum pump from the test cell, the lubricant is injected into the test cell used by the outlet valve in the lower loop which is located outside of test cell.

## 3-3-9 EXPERIMENTAL PROCEDURES AND DATA REDUCTION

In addition to the description of the test facility, procedures were described for accurate and convenient measurement of the solubility, viscosity, and density of a wide range of lubricant/refrigerant solutions. This section provides a discussion of the experimental procedures that were employed to collect the data discussed in later chapters.

### 3-3-9-1 GENERAL EXPERIMENTAL PROCEDURES

The methods used to charge and operate the test facility vary, depending on the range of compositions and conditions desired in a particular test. A typical operating procedure for collecting viscosity, solubility and density data over a range of liquid-phase compositions and temperatures involves several operations. These operations, which are described in more detail later in this section, include evacuation of the test cell and auxiliary flow loops, injecting of the necessary oil and refrigerant quantities, operating the gear pump to provide good mixing, heating the test cell and contents to the desired temperature, checking to ensure steady-state conditions, and taking the data. Prior to injecting another incremental charge to change the liquid concentration, cooling of the vessel contents to room temperature is required.

All measurements of pressure, temperature, and viscosity are done under programmed control of the data acquisition system described earlier. Careful recording of liquid level as the temperature changes allows the calculation of liquid density at each test condition. As explained more fully below, this also permits a calculation of the actual liquid composition, which varies slightly with temperature because of variation in the vapor and liquid densities.

#### 3-3-9-1-1. RIG CLEANSING

Prior to the injection of any fluid for testing, the test cell and auxiliary loops are rinsed and cleaned with a sufficient amount of known solvent (which is compatible with the 0-ring material in the cell) to remove traces of any oil that had been previously tested. The 0-rings that seal the windows may also be replaced at this time if a failure to hold a vacuum or set pressure indicates that this is necessary.

#### 3-3-9-1-2. DATA MEASUREMENT

The cell and auxiliary loops are then evacuated, and the connecting hoses from the charging station are attached to a valve on the test cell. Measured amounts of refrigerant and oil are injected to provide the desired volume and concentration of liquid. The circulating pump aids mixing of the two fluids as they are charged. The contents are then heated to desired temperatures and pressures. Temperatures, viscosity, and height of the liquid-vapor interface are read after checking to ensure steady-state operation. The reported pressure is the average of the pressures indicated by the two pressure transducers. The solubility pressure is reported at a liquid-vapor interface temperature taken to be the average of the temperature of the RTD in contact with vapor only and the average liquid temperature. The average liquid temperature is the mean of the temperature of the RTDs immersed in the liquid in the test cell and the RTD in the flow loop pipe cross containing the viscometers. The liquid density is reported at the temperature measured by an RTD inside the viscometer, which is generally slightly higher than the average liquid temperature due to the internal self-heating of the viscometer as discussed before. At each measurement point, 20 consecutive viscosity readings are recorded and the mean and standard deviation are computed. When an acceptable scatter of 1% or less is obtained, the mean of 20 viscosity reading is recorded as a viscosity data point for the specified condition. The acceptable percent scatter is defined as the standard deviation divided by the mean of 20 readings. It should be noted that even though the acceptable scatter of 1% was selected for recording data, the uncertainty of each data point is the same as the precision of the measuring instrument, which is 2% (see Table 3.1) as supplied by the manufacturer. When immiscible, the refrigerant-rich phase which occurs at the bottom is measured for viscosity. However, due to unstable conditions when immiscible, the results obtained in this region show much more scatter. Once the limiting pressure of 3.5 MPa (500 psia) is approached, the contents are allowed to cool. More data are then collected at several steady-state test points during the cooldown phase.

### 3-3-9-1-3. REFRIGERANT/LUBRICANT SAMPLE EVALUATION

After the solubility and viscosity data for a given mixture have been collected over the desired temperature range, the sample cylinder is isolated and removed so that the mass fraction of refrigerant in the liquid can be determined. The procedure for determining the composition of an oil/refrigerant mixture by sampling is as follows:

- The full sample cylinder is weighed and recorded.
- One valve is slightly opened to carefully vent off the refrigerant vapor.
- The cylinder is heated to drive off the remaining refrigerant.
- The cylinder is continually weighed as the refrigerant is removed.
- Heating is continued until the cylinder weight is constant signifying the presence of oil only.
- The cylinder with only oil is then weighed and recorded.
- Using a suitable solvent, the oil is removed.
- The empty chamber is weighed and recorded.
- The net weights of the refrigerant and the mixture, as well as the oil, are found by differences, and the mixture composition is calculated (to an estimated uncertainty of $\pm 1\%$).

The temperature, pressure, and liquid level at which the sample was removed are also noted. At this point oil may be injected into the test cell or refrigerant may be added (or vented) to alter the concentration for another set of data.

### 3-3-9-1-4. MIXTURE CONCENTRATION AND DENSITY DETERMINATION

The actual concentration and the density of the liquid is calculated as follows for each test condition. Since the vapor mass varies along with slight variations in the volume as the temperature and pressure change, this also means that the liquid concentration varies slightly as the temperature and pressure change. Generally, the overall variation in liquid refrigerant concentration as temperature and pressure were changed during any particular test was less than 3%. The vapor density is calculated from known temperature and vapor pressure by a computerized property routine based on work by the National Institute of Standards and Technology [NIST (1993)]. However, it should be noted that any accurate property relation or table could also have been used. With this density and the vapor volume determined from the level of the vapor-liquid interface, the mass of refrigerant in the vapor is calculated. Since the total mass of oil and refrigerant charged is known, the mass of refrigerant in the liquid is calculated by subtracting the mass of the vapor from the total mass of refrigerant in the cell. A ratio of the mass of refrigerant in the liquid to the total liquid mass determines the resulting liquid composition at each test condition. As noted earlier, the liquid is also sampled at one temperature during each run to check the composition at that test condition. Table 3.2 show results of calculated concentration and sampling concentration.

With the known masses of oil and refrigerant and the observed level of the liquid, the liquid densities are calculated for each test point. It should be noted that these densities are determined from test data and are not calculated using the ideal mixing assumption. As a point of comparison, the liquid density at the sampling temperature is also determined from the net mass of the liquid sample and the known volume of the sampling chamber.

Table 3.2 Comparison of calculated concentrations and sampled concentrations

| R-236ea/EXXON-01 | | R-236ea/EXXON-02 | | R-236ea/EXXON-03 | | R-236ea/EXXON-04 | |
|---|---|---|---|---|---|---|---|
| Concentration (%) | | Concentration (%) | | Concentration (%) | | Concentration (%) | |
| Calculated | Sample | Calculated | Sample | Calculated | Sample | Calculated | Sample |
| 10 | 11 | 10 | 10 | 10 | 13 | 10 | 10 |
| 25 | 25 | 25 | 25 | 25 | 26 | 25 | 25 |
| 45 | 48 | 45 | 48 | 45 | 46 | 45 | 48 |

### 3-3-9-2. EXPERIMENTAL PROCEDURES

Once the basic components of temperature, composition, pressure, liquid viscosity, and density are determined for each data point, a useful and convenient presentation of the results follows from the development of the correlating equations. The following section presents a discussion of the techniques which were used to derive coefficients for the empirical correlating equations used to represent the data.

### 3-3-9-2-1. DATA REDUCTION

Calculations required to determine the liquid density and composition from observed data at each test condition have been discussed in general terms in a previous section which outlined experimental procedures. A more detailed discussion of these calculations and the associated uncertainties, illustrated by using an example test condition, is provided in a publication by Van Gaalen et al. (1991a).

### 3-3-9-2-2. DATA CORRELATION EQUATIONS

After all the data have been compiled into one file, a nonlinear regression analysis is performed to determine the best set of coefficients for each of the following empirical equations. These equations can be used to reproduce the data or to interpolate results at intermediate states for which data were not directly obtained. It should be noted that these equations are empirical fits of the data and are not based on theoretical considerations.

$$\log_{10}\mu = A_0 + A_1C + A_2\theta + A_3C\theta + A_4C^2 + A_5C^2\theta + A_6C\theta^2 + A_7\theta^2 + A_8C^2\theta^2 \tag{1}$$

$$P = B_0 + B_1C + B_2\theta + B_3C\theta + B_4C^2 + B_5C^2\theta + B_6C\theta^2 + B_7\theta^2 + B_8C^2\theta^2 \tag{2}$$

$$\rho L = D_0 + D_1C + D_2\theta + D_3C\theta + D_4C^2 + D_5C^2\theta + D_6C\theta^2 + D_7\theta^2 + D_8C^2\theta^2 \tag{3}$$

where

$A_0, A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8$ = set of coefficients in Equation 1 (units vary depending on term)

$B_0, B_1, B_2, B_3, B_4, B_5, B_6, B_7, B_8$ = set of coefficients in Equation 2 (units vary depending on term)

$D_0, D_1, D_2, D_3, D_4, D_5, D_6, D_7, D_8$ = set of coefficients in Equation 3 (units vary depending on term)

$C$ = the mass fraction of refrigerant in the liquid (%)

$\theta$ = nondimensional (temperature in K divided by the reference temperature of 293.15K)

$\mu$ = nondimensional viscosity in cP (viscosity in cP divided by 1 cP)

$P$ = the absolute pressure, MPa

$\rho L$ = the density of the liquid, g/cm^3

Although the above equations are nonlinear, they are linearized using the following variable substitutions in order to make use of a general-purpose multivariate linear regression algorithm to determine the coefficients:

$$X_1 = C; \quad X_2 = \theta; \quad X_3 = C\theta; \quad X_4 = C^2;$$
$$X_5 = C^2\theta; \quad X_6 = C\theta^2; \quad X_7 = \theta^2; \quad X_8 = C^2\theta^2$$

The resulting equations are linear in the eight variables $X_1$ through $X_8$. For example,

$$\log_{10}\mu = A_0 + A_1X_1 + A_2X_2 + A_3X_3 + A_4X_4 + A_5X_5 + A_6X_6 + A_7X_7 + A_8X_8 \quad (4)$$

The linear regression algorithm is performed using Statistical Analysis System [SAS (1993)] software. SAS provides statistical information about the significance of each of the coefficients in the above equations. It also used to calculate regression coefficients as an indication of the overall goodness of fit of each equation. Tables 4.6, 4.11, 4.16, and 4.21 listing the coefficients obtained from the Statistical Analysis System are to be presented later. Those tables also list the standard error and the probability (Prob > |T| ). This probability provides an indication of empirical significance level (P-value) of the coefficients. It is important to note that the resulting equations are empirical fits of data and are not based on theoretical considerations. Also, some of the coefficients which do not significantly contribute to the correlation are omitted to provide a more useful and simpler equation.

## 3-4. SUMMARY OF SOLUBILITY, VISCOSITY, AND DENSITY TEST FACILITY

A lubricant/refrigerant test facility has been described, which can provide critically needed viscosity, solubility, and density data for a variety of lubricant/refrigerant mixtures over a range of pressures and temperatures. The facility used instrument test cells for observation of the contents. This test facility could be used for determination of the solubility, viscosity and density of lubricant/refrigerant mixtures with refrigerant compositions ranging from 0 % to 40 %. The operating temperatures of the test facility ranged from 30 to 100°C (86 to 212°F). The operating pressure ranged from 0 to 3.5 MPa (0 to 500 psia).

Experimental procedures and data reduction techniques, including the correlating equations, have been outlined. Data obtained with this test facility for the mixtures of R-236ea with four different EXXON lubricants are presented in the following chapter.

# CHAPTER 4.

# R-236ea/LUBRICANT (EXXON OILS) PROPERTY RESULTS

## 4-1. MISCIBILITY RESULTS FOR R-236ea/EXXON OIL MIXTURES

This section presents results of miscibility measurements for each of four different lubricants with R-236ea. The raw data are presented and also summarized. Results of the measurements of R-236ea in each lubricant are presented below. For every refrigerant/lubricant combination investigated, the data set consists of the concentration, temperature, and visual characteristics of the contents of the cell. Table 4.1 and 4.2 provide the test results for each R-236ea/lubricant pair. For comparison purposes, results of R-236ea mixed with other lubricants taken in previous studies are shown in the following tables. The EXXON-03 and EXXON-04 lubricants were found to be completely miscible over the temperature and concentration ranges tested, while the EXXON-01 and EXXON-02 lubricants were found to be immiscible over the portions of temperature range tested.

TABLE 4.1: Miscibility raw data for R-236ea/EXXON-01 and R-236ea/EXXON-02 mixtures

| Oil name | Refrigerant mass fraction | | | | | |
|---|---|---|---|---|---|---|
| | EXXON-01 | | | EXXON-02 | | |
| Temp(°C) | 0.307 | 0.57 | 0.759 | 0.265 | 0.509 | 0.723 |
| 89.69 | clear | clear | clear | two-phase | two-phase | two-phase |
| 80.08 | clear | clear | clear | two-phase | two-phase | two-phase |
| 69.13 | clear | clear | two-phase | clear | two-phase | two-phase |
| 59.87 | clear | clear | two-phase | clear | two-phase | two-phase |
| 49.14 | clear | clear | two-phase | clear | clear | two-phase |
| 40.76 | clear | clear | two-phase | clear | clear | two-phase |
| 29.69 | clear | clear | two-phase | clear | clear | two-phase |
| 20.84 | clear | clear | two-phase | clear | clear | two-phase |
| 10.22 | clear | clear | two-phase | clear | clear | two-phase |
| 0.52 | clear | clear | two-phase | clear | clear | clear |
| -9.86 | clear | clear | two-phase | clear | clear | clear |
| -20.40 | two-phase | two-phase | two-phase | clear | clear | clear |
| -30.32 | two-phase | two-phase | two-phase | clear | clear | clear |
| -42.32 | two-phase | two-phase | two-phase | clear | clear | clear |

**Notes:** (1) Mass fraction is the mass of refrigerant divided by total mass of mixture.
(2) Clear refers to the presence of a single phase only and that the mixture is miscible.
(3) Two-phase means that the mixture is immiscible.

TABLE 4.2: Miscibility raw data for R-236ea/EXXON-03 and R-236ea/EXXON-04 mixtures

| Oil name | Refrigerant mass fraction | | | | | |
|---|---|---|---|---|---|---|
| | EXXON-03 | | | EXXON-04 | | |
| Temp(°C) | 0.245 | 0.524 | 0.69 | 0.323 | 0.526 | 0.662 |
| 90.63 | clear | clear | clear | clear | clear | clear |
| 80.34 | clear | clear | clear | clear | clear | clear |
| 70.57 | clear | clear | clear | clear | clear | clear |
| 59.90 | clear | clear | clear | clear | clear | clear |
| 21.34 | clear | clear | clear | clear | clear | clear |
| 40.24 | clear | clear | clear | clear | clear | clear |
| 30.18 | clear | clear | clear | clear | clear | clear |
| 20.63 | clear | clear | clear | clear | clear | clear |
| 11.06 | clear | clear | clear | clear | clear | clear |
| 0.02 | clear | clear | clear | clear | clear | clear |
| -9.51 | clear | clear | clear | clear | clear | clear |
| -20.42 | clear | clear | clear | clear | clear | clear |
| -30.29 | clear | clear | clear | clear | clear | clear |
| -39.27 | clear | clear | clear | clear | clear | clear |

**Notes:** (1) Mass fraction is the mass of lubricant divided by total mass.
(2) Clear refers to the presence of a single phase only and that the mixture is miscible.

## 4-2. SOLUBILITY, VISCOSITY, AND DENSITY RESULTS FOR R-236ea/EXXON OIL MIXTURES

For every refrigerant/lubricant mixture tested, the data set at each nominal liquid composition consists of temperature, pressure, and concentration, absolute viscosity, and density values for a series of test points. The data for each nominal concentration tested is then correlated into a complete data set for each lubricant/refrigerant mixture pair. A non-linear multi-regression analysis is performed on a data set to find the best set of coefficients of the correlating equation. It is important to note that the correlating equations are empirical fits of the data and are not based on theoretical considerations. The results of the regression are then presented graphically as well as in the form of the empirical correlations. The correlations for the solubility, viscosity, and density of R-236ea with EXXON-oil mixtures generally fit the test data within ±5%. This value of 5% was obtained by comparing the raw data and predicted tables as presented in this report.

The results of viscosity, solubility, and density measurements for R-236ea with four different EXXON lubricants are presented in the following order:

- Sample experimental raw data.
- Results of the multi-regression analysis are given in the forms of coefficients for empirical equations.
- Correlations used to develop solubility, viscosity, and density charts and tables.

- Complete sets of experimental data.

### 4-2-1. R-236ea WITH EXXON-01

#### 4-2-1-1. RAW DATA

Table 4.3 through Table 4.5 provide complete listings of the experimental data for solubility, viscosity, and density for R-236ea with lubricant EXXON-01 solutions. These tables show that for mixtures of R-236ea with lubricant EXXON-01 the solubility, viscosity, and density each is a function of temperature and concentration. For the R-236ea with lubricant EXXON-01 mixtures, (1) the solubility increases with increasing temperature and with increasing refrigerant concentration (i.e., mass fraction of refrigerant), (2) the viscosity decreases with increasing temperature and with increasing refrigerant concentration, and (3) the density decreases with increasing temperature but increases with increasing refrigerant concentration.

The solubility table is tabulated with saturated vapor pressure and temperature for various concentrations of R-236ea in the liquid mixture. The viscosity table is tabulated with dynamic viscosity and temperature for various concentrations of R-236ea in the liquid mixture. Also, the density table is tabulated with liquid density and vapor density versus temperature for various concentrations of liquid mixture.

Table 4.3 shows that for a nominal concentration the vapor pressure increases with increasing temperature and with increasing refrigerant concentration. Table 4.4 shows that for a nominal concentration the dynamic viscosity decreases with increasing temperature and with increasing refrigerant concentration. Table 4.5 shows that for a nominal concentration the density decreases with increasing temperature and increases with increasing refrigerant concentration.

#### 4-2-1-2. CORRELATING EQUATION

The coefficients for the correlating equations (Equations 1 to 3 in Section 3-3-9-2-2) as derived for R-236ea with lubricant Exxon-01 are given in Table 4.6.

It is important to note that when using the correlations in lieu of the graphs that special care must be taken to avoid extrapolation beyond the limits of applicability. These limits of applicability are given, along with the correlating coefficients, in Table 4.6.

Table 4.3. Experimental solubility data for R-236ea and Exxon-01 lubricant solutions

| Temperature (°C) | Saturated vapor pressure (kPa) | Refrigerant concentration (mass fraction) |
|---|---|---|
| 104.9 | 0.0 | 0.000 |
| 95.6 | 0.0 | 0.000 |
| 84.7 | 0.0 | 0.000 |
| 74.8 | 0.0 | 0.000 |
| 64.5 | 0.0 | 0.000 |
| 55.6 | 0.0 | 0.000 |
| 46.0 | 0.0 | 0.000 |
| 24.2 | 0.0 | 0.000 |
| 33.7 | 0.0 | 0.000 |
| | | |
| 106.2 | 393.1 | 0.095 |
| 96.2 | 350.7 | 0.097 |
| 85.6 | 297.2 | 0.100 |
| 75.7 | 258.6 | 0.102 |
| 64.7 | 218.2 | 0.104 |
| 55.7 | 188.5 | 0.106 |
| 45.2 | 158.2 | 0.108 |
| 23.1 | 113.8 | 0.111 |
| 34.4 | 128.4 | 0.110 |
| | | |
| 107.7 | 1029.0 | 0.250 |
| 97.6 | 881.6 | 0.256 |
| 87.1 | 731.9 | 0.263 |
| 76.5 | 600.8 | 0.268 |
| 65.5 | 479.9 | 0.274 |
| 55.4 | 391.2 | 0.278 |
| 45.6 | 316.6 | 0.281 |
| 20.3 | 180.4 | 0.287 |
| 26.4 | 201.7 | 0.286 |
| | | |
| 108.1 | 1443.8 | 0.483 |
| 97.7 | 1206.1 | 0.487 |
| 87.1 | 986.0 | 0.491 |
| 76.2 | 791.2 | 0.494 |
| 65.6 | 633.8 | 0.497 |
| 55.3 | 505.8 | 0.499 |
| 44.5 | 394.4 | 0.501 |
| 23.4 | 218.9 | 0.504 |
| 28.2 | 251.2 | 0.504 |

Table 4.4. Experimental dynamic viscosity data for R-236ea and Exxon-01 lubricant solutions

| Temperature (°C) | Dynamic viscosity (cP) | Refrigerant concentration (mass fraction) |
|---|---|---|
| 93.7 | 9.0 | 0.000 |
| 89.2 | 10.5 | 0.000 |
| 80.0 | 13.6 | 0.000 |
| 71.6 | 17.6 | 0.000 |
| 63.4 | 23.8 | 0.000 |
| 56.4 | 35.8 | 0.000 |
| 49.2 | 51.4 | 0.000 |
| 34.9 | 107.4 | 0.000 |
| 40.0 | 80.9 | 0.000 |
| | | |
| 98.0 | 5.3 | 0.095 |
| 90.1 | 6.4 | 0.097 |
| 80.8 | 8.2 | 0.100 |
| 73.3 | 10.1 | 0.102 |
| 64.7 | 13.3 | 0.104 |
| 57.8 | 16.8 | 0.106 |
| 49.3 | 23.2 | 0.108 |
| 31.8 | 60.3 | 0.111 |
| 39.3 | 40.8 | 0.110 |
| | | |
| 101.4 | 2.0 | 0.250 |
| 93.01 | 2.4 | 0.256 |
| 84.0 | 2.9 | 0.263 |
| 75.1 | 3.5 | 0.268 |
| 65.4 | 4.3 | 0.274 |
| 57.0 | 5.4 | 0.278 |
| 48.9 | 6.8 | 0.281 |
| 27.4 | 14.2 | 0.287 |
| 32.1 | 11.8 | 0.286 |
| | | |
| 102.6 | 0.9 | 0.483 |
| 93.6 | 1.0 | 0.487 |
| 84.4 | 1.2 | 0.491 |
| 74.8 | 1.5 | 0.494 |
| 65.6 | 1.9 | 0.497 |
| 56.9 | 2.3 | 0.499 |
| 47.2 | 3.4 | 0.501 |
| 25.2 | 5.4 | 0.504 |
| 29.8 | 4.7 | 0.504 |

Table 4.5. Experimental density data for R-236ea and Exxon-01 lubricant solutions

| Temperature (°C) | Density (g/cm^3) | R-236ea concentration. (mass fraction) | Vapor Density (g/cm^3) |
|---|---|---|---|
| 99.1 | 0.844 | 0.000 | 0.000 |
| 91.1 | 0.851 | 0.000 | 0.000 |
| 80.8 | 0.857 | 0.000 | 0.000 |
| 71.8 | 0.864 | 0.000 | 0.000 |
| 62.6 | 0.868 | 0.000 | 0.000 |
| 54.6 | 0.875 | 0.000 | 0.000 |
| 46.5 | 0.886 | 0.000 | 0.000 |
| 29.1 | 0.900 | 0.000 | 0.000 |
| 37.5 | 0.897 | 0.000 | 0.000 |
| | | | |
| 100.0 | 0.905 | 0.095 | 0.020 |
| 91.2 | 0.914 | 0.097 | 0.018 |
| 82.3 | 0.925 | 0.100 | 0.016 |
| 72.5 | 0.934 | 0.102 | 0.014 |
| 62.8 | 0.945 | 0.104 | 0.012 |
| 54.4 | 0.954 | 0.106 | 0.011 |
| 45.1 | 0.964 | 0.108 | 0.009 |
| 26.6 | 0.983 | 0.111 | 0.007 |
| 36.3 | 0.978 | 0.110 | 0.008 |
| | | | |
| 102.9 | 0.902 | 0.250 | 0.057 |
| 93.7 | 0.915 | 0.256 | 0.050 |
| 83.9 | 0.926 | 0.263 | 0.042 |
| 74.0 | 0.936 | 0.268 | 0.036 |
| 63.8 | 0.947 | 0.274 | 0.029 |
| 54.5 | 0.955 | 0.278 | 0.024 |
| 45.4 | 0.963 | 0.281 | 0.020 |
| 21.8 | 0.975 | 0.287 | 0.012 |
| 27.9 | 0.971 | 0.286 | 0.013 |
| | | | |
| 103.8 | 1.015 | 0.483 | 0.088 |
| 94.1 | 1.031 | 0.487 | 0.074 |
| 84.1 | 1.047 | 0.491 | 0.061 |
| 73.8 | 1.063 | 0.494 | 0.049 |
| 63.8 | 1.079 | 0.497 | 0.040 |
| 54.2 | 1.091 | 0.499 | 0.032 |
| 43.8 | 1.117 | 0.501 | 0.025 |
| 20.0 | 1.143 | 0.504 | 0.014 |
| 25.5 | 1.136 | 0.504 | 0.016 |

Table 4.6. Coefficients for empirical correlations of property data for R-236ea/Exxon-01 mixtures

Note: The limits of applicability of the correlations are
Composition (X): 0 to 45 weight percent refrigerant
Temperature: 30 to 100 °C (86 to 212°F)
Pressure: 0 to 3.5 MPa (0 to 500 psia)

| Solubility (kPa) | | | |
|---|---|---|---|
| Term | Coefficient | Standard Error | Prob. > \|T\| |
| Intercept | $B_0$= 0.0 | | |
| C | $B_1$= 32.582914 | 5.03797269 | 0.0001 |
| $\theta$ | $B_2$= 0.0 | | |
| $C^2$ | $B_3$= -31.141127 | 11.40093303 | 0.0105 |
| $C\theta$ | $B_4$= -66.579792 | 8.81655991 | 0.0001 |
| $\theta^2$ | $B_5$= 0.0 | | |
| $C^2\theta$ | $B_6$= 61.684298 | 19.95265609 | 0.0043 |
| $C\theta^2$ | $B_7$= 34.986020 | 3.83607134 | 0.0001 |
| $C^2\theta^2$ | $B_8$= -31.691474 | 8.68187431 | 0.0010 |

| Viscosity (cP) | | | |
|---|---|---|---|
| Term | Coefficient | Standard Error | Prob. > \|T\| |
| Intercept | $A_0$= 23.109807 | 2.85725540 | 0.0001 |
| C | $A_1$= -41.625437 | 8.62494862 | 0.0001 |
| $\theta$ | $A_2$= -32.245543 | 4.96324957 | 0.0001 |
| $C^2$ | $A_3$= 10.789867 | 3.47647847 | 0.0043 |
| $C\theta$ | $A_4$= 58.320753 | 14.65768574 | 0.0004 |
| $\theta^2$ | $A_5$=11.631786 | 2.15045023 | 0.0001 |
| $C^2\theta$ | $A_6$= -7.661814 | 3.01997053 | 0.0170 |
| $C\theta^2$ | $A_7$= -21.67139 | 6.28863646 | 0.0018 |
| $C^2\theta^2$ | $A_8$= 0.0 | | |

| Density (g/cm³) | | | |
|---|---|---|---|
| Term | Coefficient | Standard Error | Prob. > \|T\| |
| Intercept | $D_0$= 1.060209 | 0.02890442 | 0.0001 |
| C | $D_1$= 0.172301 | 0.08241708 | 0.0446 |
| $\theta$ | $D_2$= 0.0 | | |
| $C^2$ | $D_3$= 0.410527 | 0.15713971 | 0.0136 |
| $C\theta$ | $D_4$= 0.0 | | |
| $\theta^2$ | $D_5$= -0.129728 | 0.02098156 | 0.0001 |
| $C^2\theta$ | $D_6$= 0.0 | | |
| $C\theta^2$ | $D_7$= 0.0 | | |
| $C^2\theta^2$ | $D_8$= 0.0 | | |

### 4-2-1-3. TABULAR RESULTS

Values for solubility, dynamic viscosity, kinematic viscosity, and density can be obtained by using the correlating equations described earlier. These "correlated (smoothed) data" are sometimes (such as when using a computer) more useful than picking numbers off of a graph. Table 4.7 provides "smoothed data" for R-236ea/EXXON-01 mixtures.

### 4-2-1-4. GRAPHICAL RESULTS

Property plots for solubility, dynamic viscosity, kinematic viscosity, and density can be developed by using the correlating equations described earlier. Graphical results for the solubility, dynamic viscosity, kinematic viscosity, and density of R-236ea and Exxon-01 mixtures are given in Figures 4.1 through 4.4, respectively. The plot of pressure versus refrigerant concentration for a range of temperatures shows that the pressure increases with increasing refrigerant concentration and temperature. The plot of dynamic viscosity versus temperature for a range of refrigerant concentrations shows that the dynamic viscosity decreases with increasing refrigerant concentration and temperature. The plot of kinematic viscosity versus temperature for a range of refrigerant concentrations shows that the kinematic viscosity decreases with increasing refrigerant concentration and temperature. The plot of density versus temperature for a range of refrigerant concentrations shows that the density increases with increasing refrigerant concentration and decreases with increasing temperature.

### 4-2-2. R-236ea WITH EXXON-02

### 4-2-2-1. RAW DATA

Table 4.8 through Table 4.10 provide complete listings of the experimental data for solubility, viscosity, and density for R-236ea with Exxon-02 solutions. These tables show that for mixtures of R-236ea with Exxon-02 the solubility, viscosity, and density each is a function of temperature and concentration. For the R-236ea/ Exxon-02 mixtures (1) the solubility increases with increasing temperature and with increasing refrigerant concentration (i.e., mass fraction of refrigerant), (2) the viscosity decreases with increasing temperature and with increasing refrigerant concentration, and (3) the density decreases with increasing temperature but increases with increasing refrigerant concentration.

The solubility table is tabulated with saturated vapor pressure and temperature for various concentrations of R-236ea in the liquid mixture. The viscosity table is tabulated with dynamic viscosity and temperature for various concentrations of R-236ea in the liquid mixture. Also, the density table is tabulated with liquid density and vapor density versus temperature for various concentrations of R-236ea in

Table 4.7 Smoothed data for R-236ea/EXXON-01 mixture

| Temp. (°C) | Refrigerant Concentration (mass fraction) | Density (g/cm^3) | Viscosity Dynamic (cP) | Viscosity Kinematic (cSt) | Viscosity Saybolt (SUS) | Pressure (kPa) | Pressure (psia) |
|---|---|---|---|---|---|---|---|
| 30 | 0.00 | 0.921 | 159.65 | 173.25 | 802.0 | 0.0 | 0.00 |
| 40 | 0.00 | 0.912 | 86.57 | 94.91 | 440.0 | 0.0 | 0.00 |
| 50 | 0.00 | 0.903 | 49.96 | 55.36 | 257.5 | 0.0 | 0.00 |
| 60 | 0.00 | 0.893 | 30.69 | 34.38 | 161.6 | 0.0 | 0.00 |
| 70 | 0.00 | 0.882 | 20.06 | 22.74 | 109.9 | 0.0 | 0.00 |
| 80 | 0.00 | 0.872 | 13.96 | 16.01 | 81.8 | 0.0 | 0.00 |
| 90 | 0.00 | 0.861 | 10.34 | 12.01 | 66.4 | 0.0 | 0.00 |
| 100 | 0.00 | 0.850 | 8.15 | 9.59 | 57.8 | 0.0 | 0.00 |
| | | | | | | | |
| 30 | 0.10 | 0.943 | 60.64 | 64.32 | 298.3 | 102.1 | 14.81 |
| 40 | 0.10 | 0.934 | 36.13 | 38.71 | 180.9 | 124.2 | 18.02 |
| 50 | 0.10 | 0.924 | 22.65 | 24.52 | 117.4 | 153.7 | 22.30 |
| 60 | 0.10 | 0.914 | 14.94 | 16.34 | 82.9 | 190.6 | 27.65 |
| 70 | 0.10 | 0.904 | 10.36 | 11.47 | 64.3 | 235.0 | 34.08 |
| 80 | 0.10 | 0.893 | 7.56 | 8.47 | 53.9 | 286.7 | 41.58 |
| 90 | 0.10 | 0.882 | 5.81 | 6.58 | 47.7 | 345.8 | 50.15 |
| 100 | 0.10 | 0.871 | 4.69 | 5.38 | 43.9 | 412.3 | 59.80 |
| | | | | | | | |
| 30 | 0.20 | 0.972 | 26.29 | 27.04 | 128.2 | 179.4 | 26.02 |
| 40 | 0.20 | 0.963 | 17.00 | 17.66 | 88.1 | 220.2 | 31.94 |
| 50 | 0.20 | 0.953 | 11.44 | 12.00 | 66.1 | 274.4 | 39.80 |
| 60 | 0.20 | 0.944 | 8.00 | 8.48 | 53.8 | 341.9 | 49.58 |
| 70 | 0.20 | 0.933 | 5.82 | 6.24 | 46.5 | 422.7 | 61.31 |
| 80 | 0.20 | 0.923 | 4.40 | 4.77 | 41.9 | 516.9 | 74.97 |
| 90 | 0.20 | 0.912 | 3.46 | 3.80 | 38.8 | 624.4 | 90.56 |
| 100 | 0.20 | 0.901 | 2.83 | 3.14 | 36.7 | 745.2 | 108.08 |
| | | | | | | | |
| 30 | 0.30 | 1.010 | 13.00 | 12.87 | 69.2 | 231.8 | 33.62 |
| 40 | 0.30 | 1.001 | 9.02 | 9.02 | 55.5 | 288.0 | 41.77 |
| 50 | 0.30 | 0.991 | 6.43 | 6.49 | 47.2 | 361.9 | 52.50 |
| 60 | 0.30 | 0.981 | 4.72 | 4.81 | 41.9 | 453.7 | 65.80 |
| 70 | 0.30 | 0.971 | 3.55 | 3.66 | 38.2 | 563.3 | 81.69 |
| 80 | 0.30 | 0.961 | 2.75 | 2.87 | 35.7 | 690.6 | 100.16 |
| 90 | 0.30 | 0.950 | 2.19 | 2.31 | 33.8 | 835.7 | 121.21 |
| 100 | 0.30 | 0.939 | 1.79 | 1.91 | 32.5 | 998.6 | 144.84 |
| | | | | | | | |
| 30 | 0.40 | 1.056 | 7.34 | 6.95 | 48.6 | 259.3 | 37.61 |
| 40 | 0.40 | 1.047 | 5.40 | 5.16 | 42.9 | 327.5 | 47.50 |
| 50 | 0.40 | 1.037 | 4.03 | 3.89 | 38.9 | 416.4 | 60.40 |
| 60 | 0.40 | 1.027 | 3.06 | 2.98 | 36.0 | 526.1 | 76.31 |
| 70 | 0.40 | 1.017 | 2.36 | 2.32 | 33.8 | 656.6 | 95.23 |
| 80 | 0.40 | 1.007 | 1.85 | 1.84 | 32.2 | 807.8 | 117.17 |
| 90 | 0.40 | 0.996 | 1.47 | 1.48 | 31.0 | 979.9 | 142.12 |
| 100 | 0.40 | 0.985 | 1.19 | 1.21 | 30.1 | 1172.6 | 170.08 |

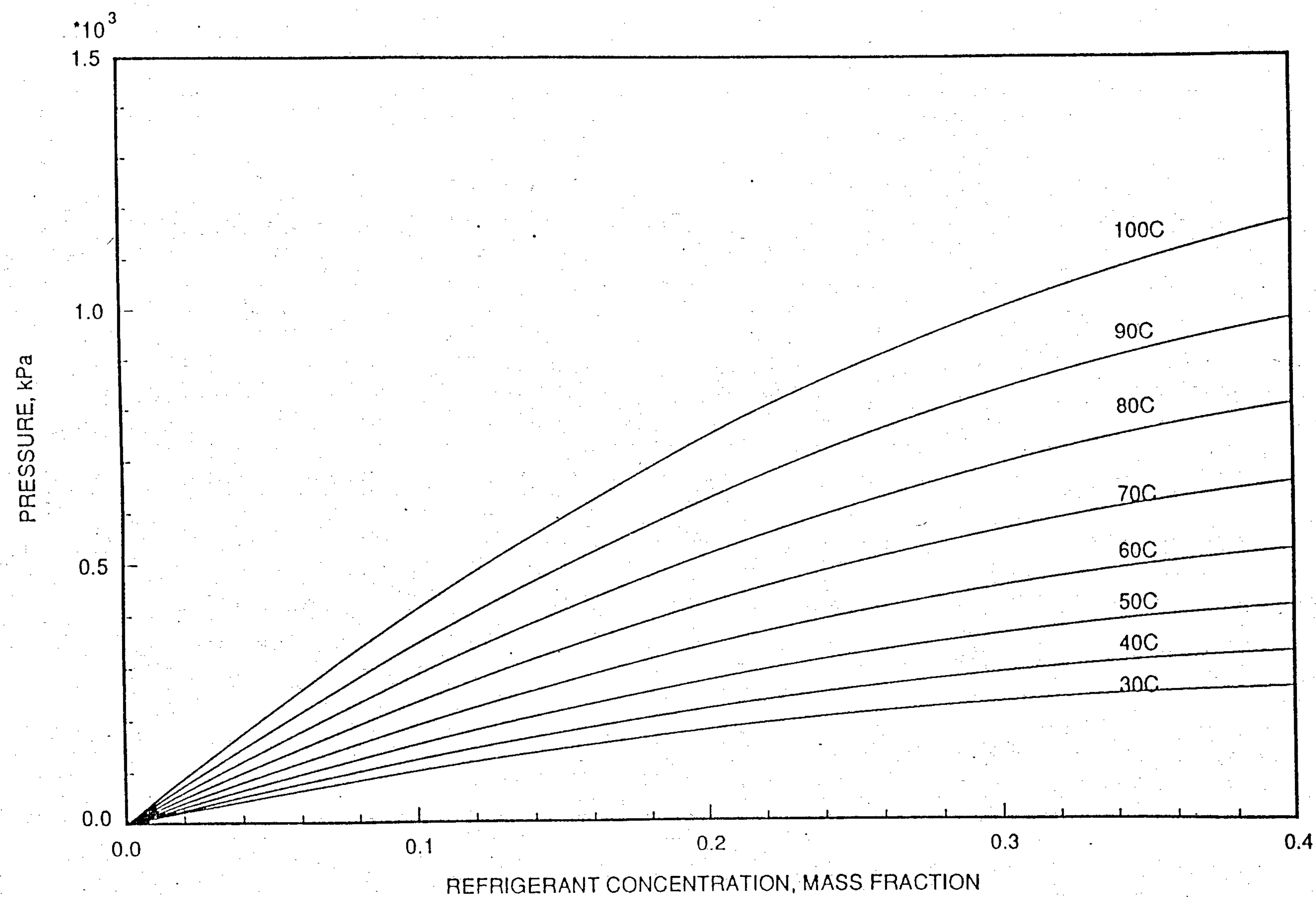


Figure 4.1 Solubility of EXXON-01 with R-236ea mixtures

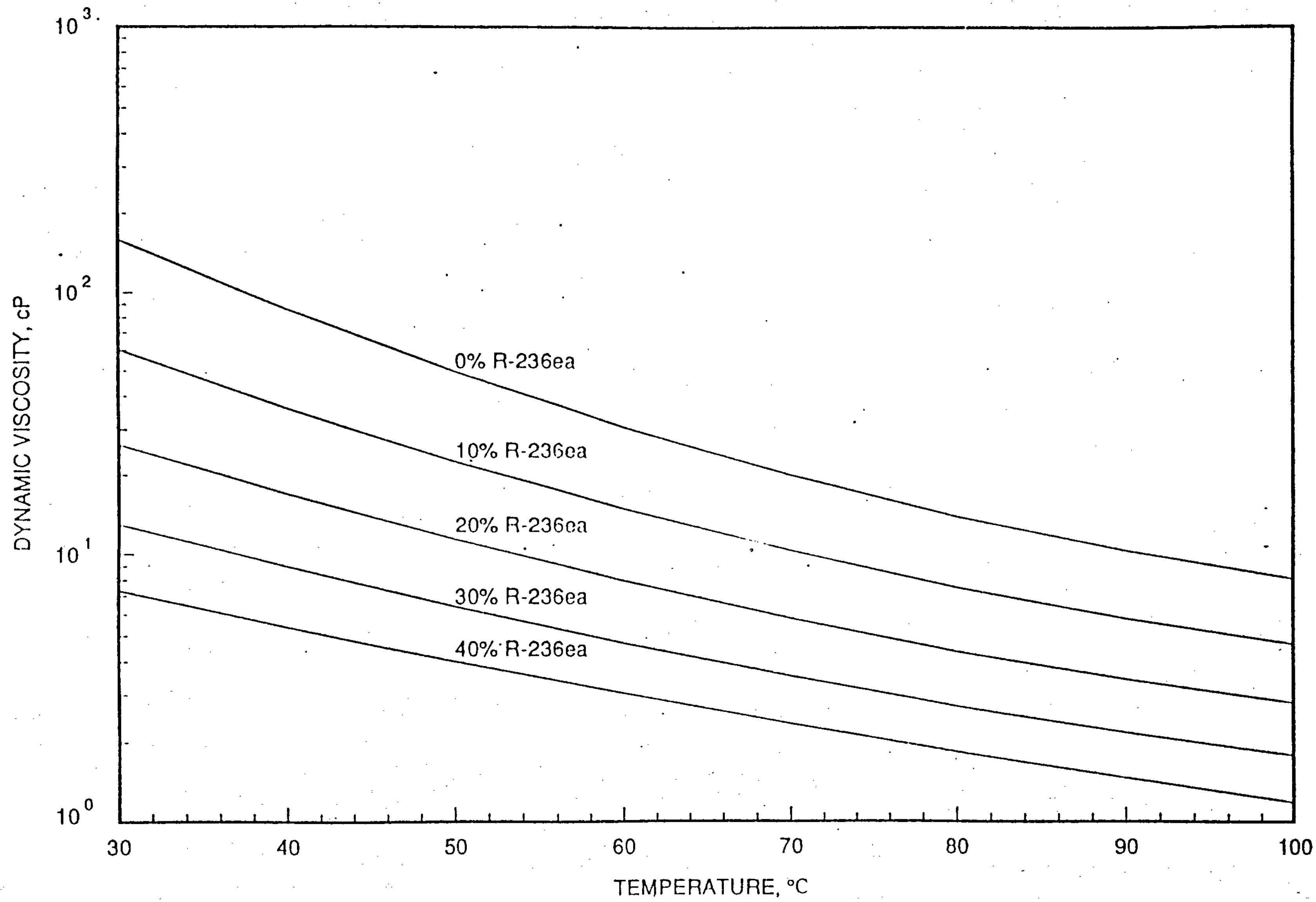


Figure 4.2 Dynamic viscosity of EXXON-01 with R-236ea mixtures

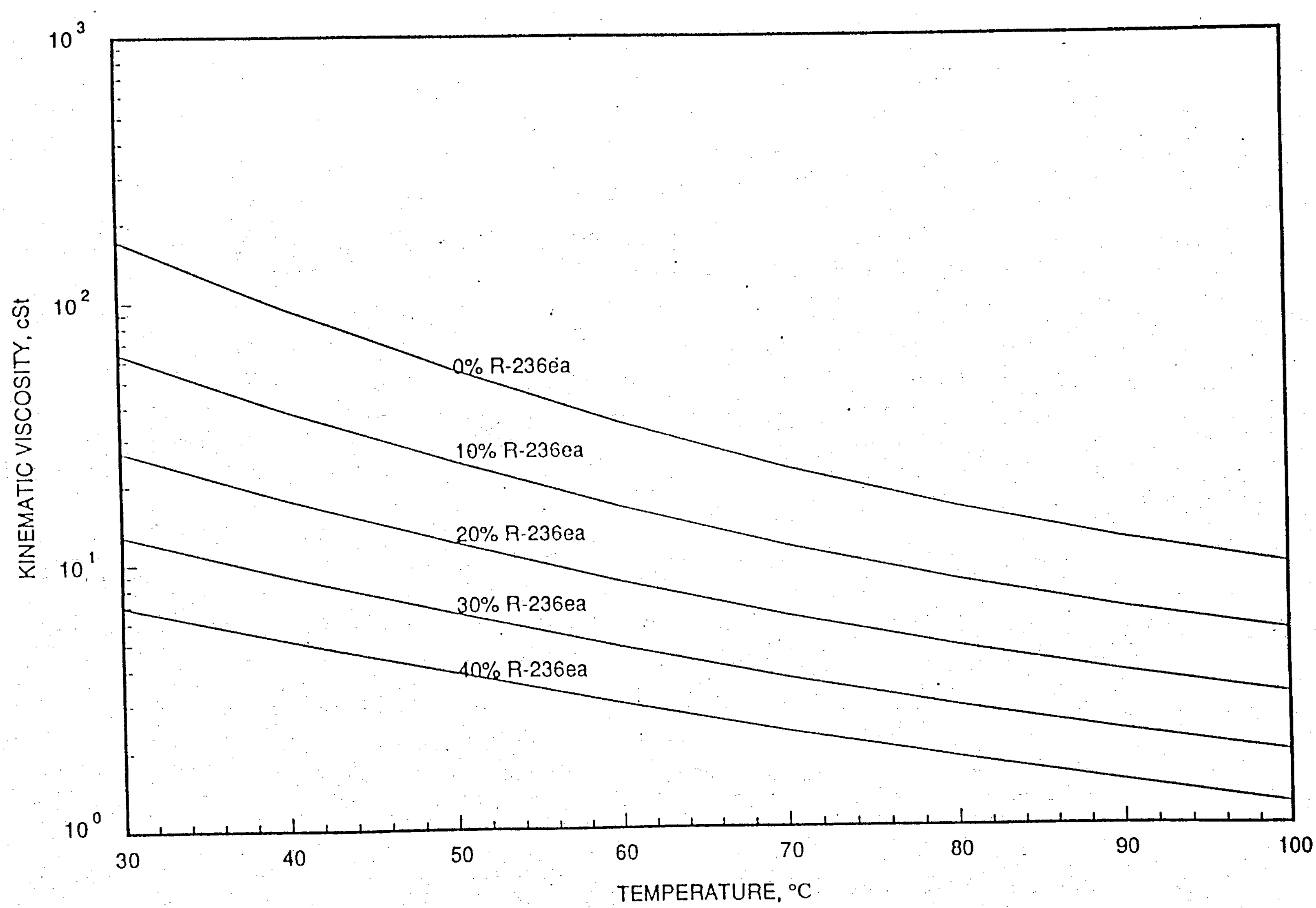


Figure 4.3 Kinematic viscosity of EXXON-01 with R-236ea mixtures

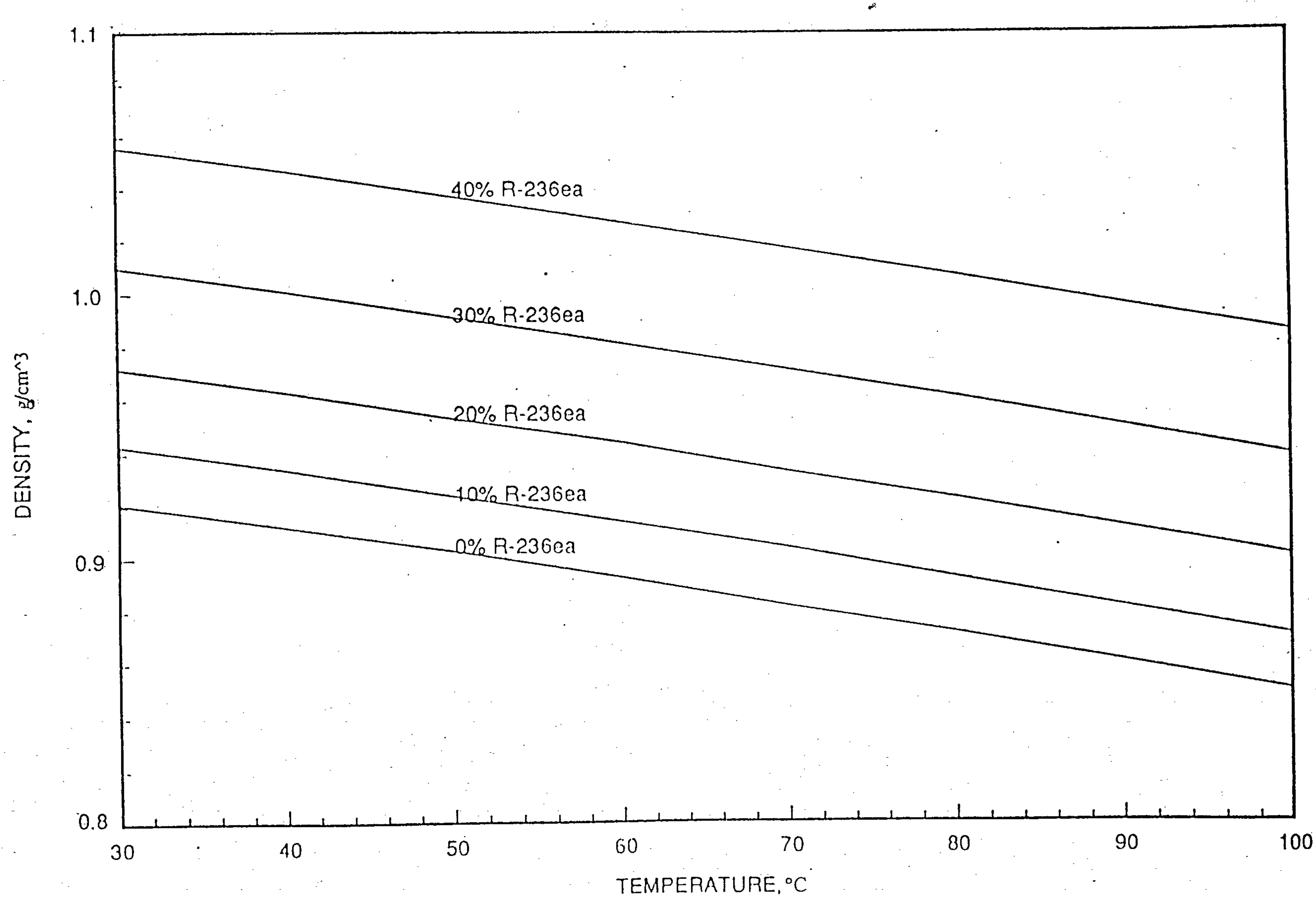


Figure 4.4 Density of EXXON-01 with R-236ea mixtures

the liquid mixture.

Table 4.8 shows that for a nominal concentration the vapor pressure increases with increasing temperature and with increasing refrigerant concentration. Table 4.9 shows that for a nominal concentration the dynamic viscosity decreases with increasing temperature and with increasing refrigerant concentration. Table 4.10 shows that for a nominal concentration the density decreases with increasing temperature and increases with increasing refrigerant concentration.

#### 4-2-2-2. CORRELATING EQUATION

The coefficients for the correlating equations (Equations 1 to 3 in Section 3-3-9-2-2) as derived for R-236ea with lubricant Exxon-02 are given in Table 4.11.

It is important to note that when using the correlations in lieu of the graphs that special care must be taken to avoid extrapolation beyond the limits of applicability. These limits of applicability are given, along with the correlating coefficients, in Table 4.11.

#### 4-2-2-3. TABULAR RESULTS

Values for solubility, dynamic viscosity, kinematic viscosity, and density can be obtained by using the correlating equations described earlier. These "correlated (smoothed) data" are sometimes (such as when using a computer) more useful than picking numbers off of a graph. Table 4.12 provides "smoothed data" for R-236ea/EXXON-02 mixtures.

#### 4-2-2-4. GRAPHICAL RESULTS

Property plots for solubility, dynamic viscosity, kinematic viscosity, and density can be developed by using the correlating equations described earlier. Graphical results for the solubility, dynamic viscosity, kinematic viscosity, and density of R-236ea and Exxon-02 mixtures are given in Figures 4.5 through 4.8, respectively. The plot of pressure versus refrigerant concentration for a range of temperatures shows that the pressure increases with increasing refrigerant concentration and temperature. The plot of dynamic viscosity versus temperature for a range of refrigerant concentrations shows that the dynamic viscosity decreases with increasing refrigerant concentration and temperature. The plot of kinematic viscosity versus temperature for a range of refrigerant concentrations shows that the kinematic viscosity decreases with increasing refrigerant concentration and temperature. The plot of density versus temperature for a range of refrigerant concentrations shows that the density increases with increasing refrigerant concentration and decreases with increasing temperature.

Table 4.8. Experimental solubility data for R-236ea and Exxon-02 lubricant solutions

| Temperature (°C) | Saturated vapor pressure (kPa) | Refrigerant concentration (mass fraction) |
|---|---|---|
| 99.2 | 0.0 | 0.000 |
| 93.6 | 0.0 | 0.000 |
| 84.7 | 0.0 | 0.000 |
| 75.9 | 0.0 | 0.000 |
| 64.8 | 0.0 | 0.000 |
| 58.0 | 0.0 | 0.000 |
| 51.2 | 0.0 | 0.000 |
| 44.9 | 0.0 | 0.000 |
| 30.9 | 0.0 | 0.000 |
| | | |
| 99.3 | 283.1 | 0.100 |
| 91.6 | 258.6 | 0.101 |
| 79.2 | 201.0 | 0.104 |
| 68.6 | 162.0 | 0.106 |
| 59.4 | 132.9 | 0.107 |
| 51.8 | 111.9 | 0.108 |
| 44.6 | 95.2 | 0.109 |
| 27.7 | 63.0 | 0.111 |
| 33.1 | 69.8 | 0.111 |
| | | |
| 99.8 | 641.0 | 0.239 |
| 91.5 | 559.9 | 0.242 |
| 81.8 | 464.9 | 0.245 |
| 70.1 | 360.9 | 0.249 |
| 60.4 | 292.2 | 0.252 |
| 47.9 | 210.8 | 0.255 |
| 43.1 | 192.0 | 0.256 |
| 28.3 | 126.8 | 0.258 |
| 34.3 | 148.6 | 0.257 |
| | | |
| 101.0 | 1086.1 | 0.448 |
| 92.8 | 942.1 | 0.450 |
| 83.3 | 777.4 | 0.453 |
| 60.8 | 465.8 | 0.458 |
| 51.6 | 370.7 | 0.460 |
| 43.9 | 306.5 | 0.461 |
| 25.2 | 179.0 | 0.463 |
| 28.0 | 196.2 | 0.463 |

Table 4.9. Experimental dynamic viscosity data for R-236ea and Exxon-02 lubricant solutions

| Temperature (°C) | Dynamic viscosity (cP) | Refrigerant concentration (mass fraction) |
|---|---|---|
| 90.2 | 9.7 | 0.000 |
| 85.9 | 11.0 | 0.000 |
| 79.0 | 13.5 | 0.000 |
| 72.3 | 17.1 | 0.000 |
| 62.2 | 28.7 | 0.000 |
| 56.7 | 35.9 | 0.000 |
| 52.2 | 44.1 | 0.000 |
| 47.7 | 54.4 | 0.000 |
| 39.0 | 85.2 | 0.000 |
| | | |
| 90.8 | 6.2 | 0.100 |
| 85.6 | 7.0 | 0.101 |
| 74.9 | 9.4 | 0.104 |
| 66.9 | 12.1 | 0.106 |
| 58.6 | 17.1 | 0.107 |
| 52.7 | 21.8 | 0.108 |
| 47.3 | 27.6 | 0.109 |
| 34.6 | 50.3 | 0.111 |
| 38.1 | 42.0 | 0.111 |
| | | |
| 91.9 | 3.2 | 0.239 |
| 86.1 | 3.6 | 0.242 |
| 78.2 | 4.3 | 0.245 |
| 68.4 | 5.5 | 0.249 |
| 60.5 | 6.8 | 0.252 |
| 49.7 | 9.5 | 0.255 |
| 46.9 | 10.3 | 0.256 |
| 35.2 | 16.5 | 0.258 |
| 39.6 | 13.9 | 0.257 |
| | | |
| 93.9 | 1.2 | 0.448 |
| 87.8 | 1.4 | 0.450 |
| 79.9 | 1.6 | 0.453 |
| 65.5 | 2.2 | 0.457 |
| 60.8 | 2.4 | 0.458 |
| 53.3 | 3.0 | 0.460 |
| 46.9 | 3.5 | 0.461 |
| 30.8 | 5.6 | 0.463 |
| 32.8 | 5.1 | 0.463 |

Table 4.10. Experimental density data for R-236ea and Exxon-02 lubricant solutions

| Temperature (°C) | Density (g/cm^3) | R-236ea concentration (mass fraction) | Vapor Density (g/cm^3) |
|---|---|---|---|
| 91.9 | 0.891 | 0.000 | 0.000 |
| 87.3 | 0.896 | 0.000 | 0.000 |
| 79.2 | 0.902 | 0.000 | 0.000 |
| 71.2 | 0.906 | 0.000 | 0.000 |
| 61.4 | 0.909 | 0.000 | 0.000 |
| 55.7 | 0.913 | 0.000 | 0.000 |
| 49.7 | 0.919 | 0.000 | 0.000 |
| 44.4 | 0.924 | 0.000 | 0.000 |
| 32.8 | 0.929 | 0.000 | 0.000 |
| | | | |
| 91.4 | 0.923 | 0.100 | 0.014 |
| 85.1 | 0.926 | 0.101 | 0.013 |
| 73.8 | 0.936 | 0.104 | 0.011 |
| 64.3 | 0.943 | 0.106 | 0.009 |
| 56.2 | 0.950 | 0.107 | 0.007 |
| 50.1 | 0.954 | 0.108 | 0.006 |
| 44.4 | 0.960 | 0.109 | 0.006 |
| 30.5 | 0.970 | 0.111 | 0.004 |
| 35.3 | 0.966 | 0.111 | 0.004 |
| | | | |
| 92.3 | 0.961 | 0.239 | 0.034 |
| 85.4 | 0.971 | 0.242 | 0.030 |
| 76.9 | 0.980 | 0.245 | 0.026 |
| 66.0 | 0.990 | 0.249 | 0.021 |
| 57.9 | 0.998 | 0.252 | 0.017 |
| 46.0 | 1.008 | 0.255 | 0.013 |
| 42.7 | 1.010 | 0.256 | 0.012 |
| 30.1 | 1.026 | 0.258 | 0.008 |
| 35.2 | 1.021 | 0.257 | 0.009 |
| | | | |
| 94.7 | 1.022 | 0.448 | 0.063 |
| 87.7 | 1.034 | 0.450 | 0.055 |
| 79.1 | 1.044 | 0.453 | 0.046 |
| 63.5 | 1.058 | 0.457 | 0.032 |
| 58.4 | 1.068 | 0.458 | 0.028 |
| 49.8 | 1.077 | 0.460 | 0.023 |
| 43.0 | 1.087 | 0.461 | 0.019 |
| 25.6 | 1.116 | 0.463 | 0.012 |
| 28.3 | 1.109 | 0.463 | 0.013 |

Table 4.11. Coefficients for empirical correlations of property data for R-236ea/Exxon-02 mixtures

Note: The limits of applicability of the correlations are
Composition (X): 0 to 45 weight percent refrigerant
Temperature: 30 to 100°C (86 to 212°F)
Pressure: 0 to 3. 5 MPa (0 to 500 psia)

| Solubility (kPa) | | | |
|---|---|---|---|
| Term | Coefficient | Standard Error | Prob. > \|T\| |
| Intercept | $B_0$= 0.0 | | |
| C | $B_1$= 21.749891 | 1.61826509 | 0.0001 |
| $\theta$ | $B_2$= 0.0 | | |
| $C^2$ | $B_3$= -10.084831 | 3.86276705 | 0.0142 |
| $C\theta$ | $B_4$= -45.340066 | 2.83015083 | 0.0001 |
| $\theta^2$ | $B_5$= 0.0 | | |
| $C^2\theta$ | $B_6$= 20.841873 | 6.76334066 | 0.0045 |
| $C\theta^2$ | $B_7$= 24.084018 | 1.23210830 | 0.0001 |
| $C^2\theta^2$ | $B_8$= -11.076996 | 2.94729816 | 0.0008 |

| Viscosity (cP) | | | |
|---|---|---|---|
| Term | Coefficient | Standard Error | Prob. > \|T\| |
| Intercept | $A_0$= 19.963140 | 0.99341870 | 0.0001 |
| C | $A_1$= -7.702753 | 0.36912604 | 0.0001 |
| $\theta$ | $A_2$= -26.668974 | 1.72411958 | 0.0001 |
| $C^2$ | $A_3$= -42.295731 | 7.17413149 | 0.0001 |
| $C\theta$ | $A_4$= 0.0 | | |
| $\theta^2$ | $A_5$= 9.157992 | 0.74706334 | 0.0001 |
| $C^2\theta$ | $A_6$= 82.540113 | 12.70375017 | 0.0001 |
| $C\theta^2$ | $A_7$= 3.831020 | 0.27777640 | 0.0001 |
| $C^2\theta^2$ | $A_8$= -39.223475 | 5.64927702 | 0.0001 |

| Density (g/cm³) | | | |
|---|---|---|---|
| Term | Coefficient | Standard Error | Prob. > \|T\| |
| Intercept | $D_0$= 1.119877 | 0.00890100 | 0.0001 |
| C | $D_1$= 0.0 | | |
| $\theta$ | $D_2$= -0.182798 | 0.00774245 | 0.0001 |
| $C^2$ | $D_3$= 4.062685 | 0.59698709 | 0.0001 |
| $C\theta$ | $D_4$= 0.821127 | 0.08501064 | 0.0001 |
| $\theta^2$ | $D_5$= 0.0 | | |
| $C^2\theta$ | $D_6$= -6.830902 | 1.08868376 | 0.0001 |
| $C\theta^2$ | $D_7$= -0.469887 | 0.07391573 | 0.0001 |
| $C^2\theta^2$ | $D_8$= 2.876510 | 0.50334547 | 0.0001 |

Table 4.12 Smoothed data for R-236ea/EXXON-02 mixture

| Temp. (°C) | Refrigerant Concentration (mass fraction) | Density (g/cm^3) | Viscosity | | | Pressure | |
|---|---|---|---|---|---|---|---|
| | | | Dynamic (cP) | Kinematic (cSt) | Saybolt (SUS) | (kPa) | (psia) |
| 30 | 0.00 | 0.931 | 150.62 | 161.81 | 749.0 | 0.0 | 0.00 |
| 40 | 0.00 | 0.925 | 84.12 | 90.98 | 421.8 | 0.0 | 0.00 |
| 50 | 0.00 | 0.918 | 49.35 | 53.73 | 250.0 | 0.0 | 0.00 |
| 60 | 0.00 | 0.912 | 30.40 | 33.33 | 156.9 | 0.0 | 0.00 |
| 70 | 0.00 | 0.906 | 19.67 | 21.72 | 105.5 | 0.0 | 0.00 |
| 80 | 0.00 | 0.900 | 13.37 | 14.86 | 77.2 | 0.0 | 0.00 |
| 90 | 0.00 | 0.893 | 9.54 | 10.68 | 61.6 | 0.0 | 0.00 |
| 100 | 0.00 | 0.887 | 7.16 | 8.07 | 52.6 | 0.0 | 0.00 |
| | | | | | | | |
| 30 | 0.10 | 0.966 | 67.36 | 69.72 | 323.2 | 58.1 | 8.42 |
| 40 | 0.10 | 0.959 | 40.08 | 41.79 | 195.0 | 75.3 | 10.92 |
| 50 | 0.10 | 0.952 | 25.05 | 26.31 | 125.3 | 97.8 | 14.19 |
| 60 | 0.10 | 0.945 | 16.44 | 17.40 | 87.2 | 125.8 | 18.24 |
| 70 | 0.10 | 0.938 | 11.33 | 12.08 | 66.5 | 159.0 | 23.06 |
| 80 | 0.10 | 0.930 | 8.20 | 8.82 | 55.0 | 197.6 | 28.66 |
| 90 | 0.10 | 0.923 | 6.24 | 6.76 | 48.3 | 241.6 | 35.04 |
| 100 | 0.10 | 0.916 | 4.98 | 5.44 | 44.1 | 290.9 | 42.19 |
| | | | | | | | |
| 30 | 0.20 | 1.003 | 31.72 | 31.62 | 148.6 | 108.6 | 15.75 |
| 40 | 0.20 | 0.995 | 20.11 | 20.22 | 98.8 | 141.3 | 20.50 |
| 50 | 0.20 | 0.986 | 13.33 | 13.52 | 71.8 | 184.3 | 26.73 |
| 60 | 0.20 | 0.978 | 9.24 | 9.45 | 57.1 | 237.4 | 34.43 |
| 70 | 0.20 | 0.970 | 6.70 | 6.91 | 48.7 | 300.7 | 43.62 |
| 80 | 0.20 | 0.961 | 5.08 | 5.29 | 43.5 | 374.2 | 54.27 |
| 90 | 0.20 | 0.953 | 4.03 | 4.23 | 40.2 | 457.9 | 66.41 |
| 100 | 0.20 | 0.945 | 3.34 | 3.54 | 38.0 | 551.7 | 80.02 |
| | | | | | | | |
| 30 | 0.30 | 1.042 | 15.72 | 15.09 | 77.7 | 151.5 | 21.98 |
| 40 | 0.30 | 1.031 | 10.62 | 10.30 | 59.9 | 198.2 | 28.74 |
| 50 | 0.30 | 1.021 | 7.44 | 7.29 | 49.8 | 259.3 | 37.61 |
| 60 | 0.30 | 1.011 | 5.41 | 5.34 | 43.6 | 335.0 | 48.58 |
| 70 | 0.30 | 1.002 | 4.07 | 4.07 | 39.5 | 425.1 | 61.66 |
| 80 | 0.30 | 0.993 | 3.18 | 3.21 | 36.8 | 529.7 | 76.83 |
| 90 | 0.30 | 0.984 | 2.58 | 2.62 | 34.9 | 648.9 | 94.11 |
| 100 | 0.30 | 0.975 | 2.17 | 2.22 | 33.6 | 782.5 | 113.49 |
| | | | | | | | |
| 30 | 0.40 | 1.081 | 8.20 | 7.58 | 50.6 | 186.9 | 27.11 |
| 40 | 0.40 | 1.069 | 5.91 | 5.53 | 44.1 | 245.8 | 35.65 |
| 50 | 0.40 | 1.057 | 4.35 | 4.12 | 39.6 | 323.0 | 46.84 |
| 60 | 0.40 | 1.045 | 3.29 | 3.15 | 36.5 | 418.4 | 60.69 |
| 70 | 0.40 | 1.034 | 2.54 | 2.46 | 34.3 | 532.2 | 77.18 |
| 80 | 0.40 | 1.024 | 2.01 | 1.96 | 32.6 | 664.2 | 96.34 |
| 90 | 0.40 | 1.014 | 1.63 | 1.61 | 31.4 | 814.6 | 118.14 |
| 100 | 0.40 | 1.005 | 1.35 | 1.35 | 30.5 | 983.2 | 142.60 |

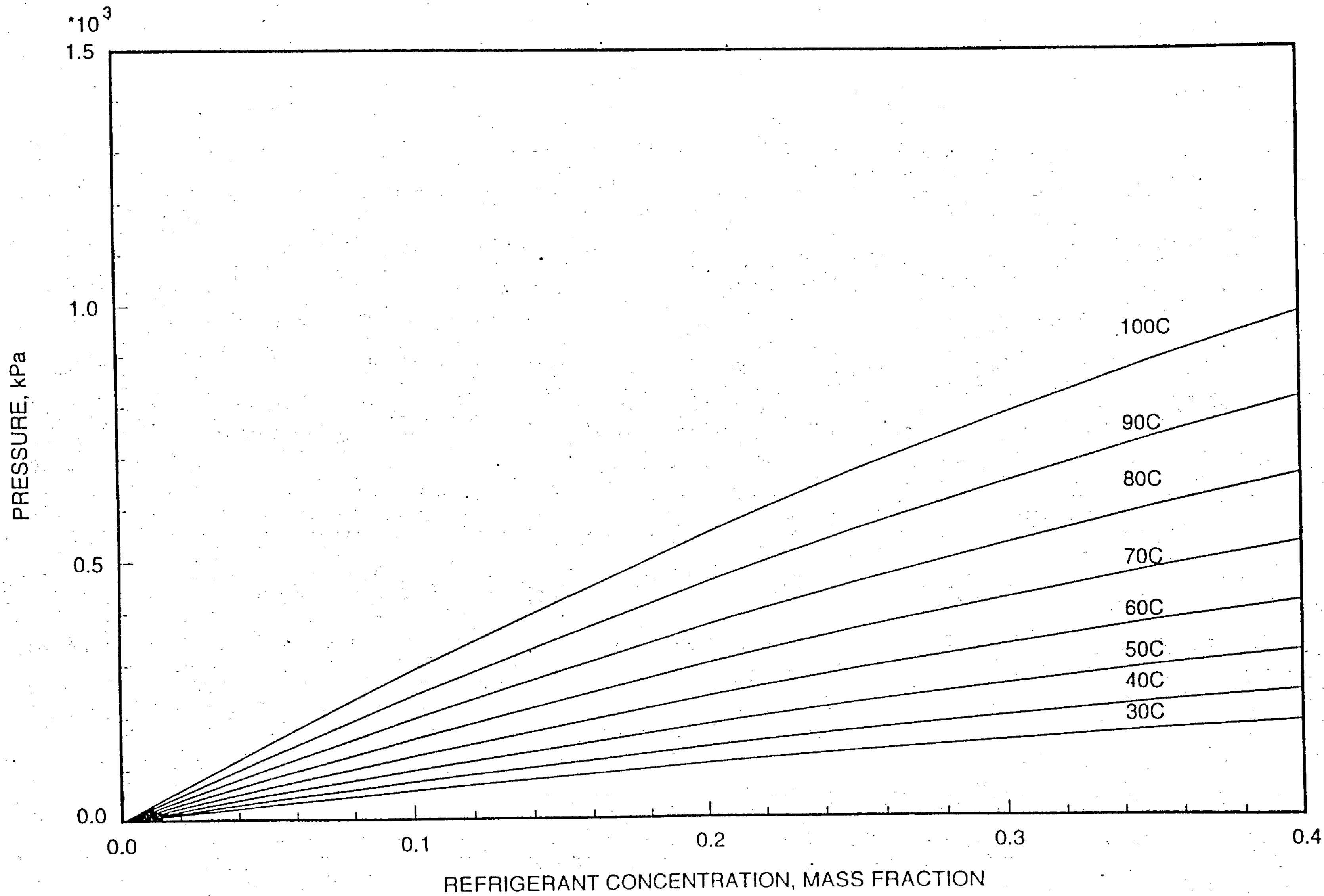


Figure 4.5 Solubility of EXXON-02 with R-236ea mixtures

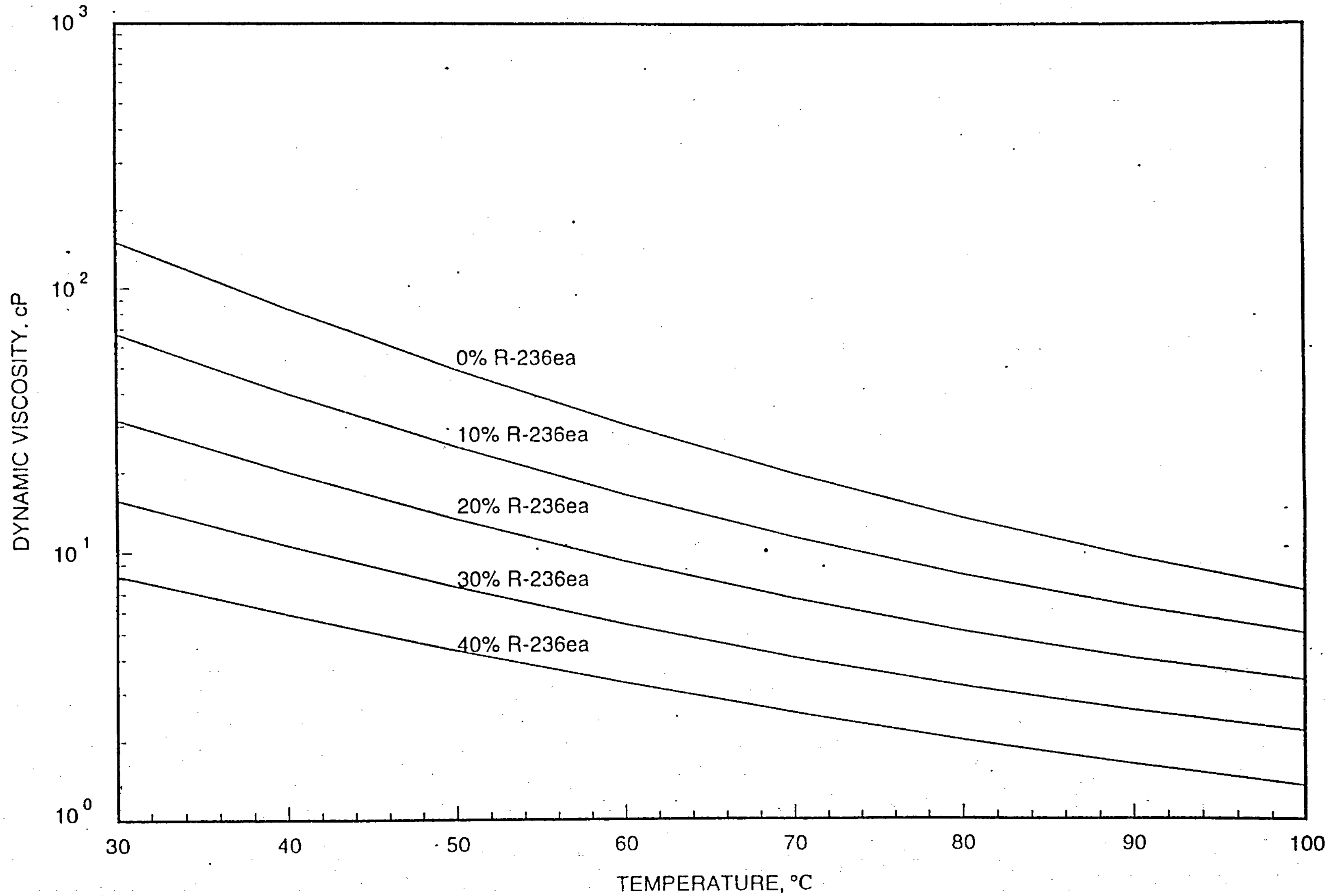


Figure 4.6 Dynamic viscosity of EXXON-02 with R-236ea mixtures

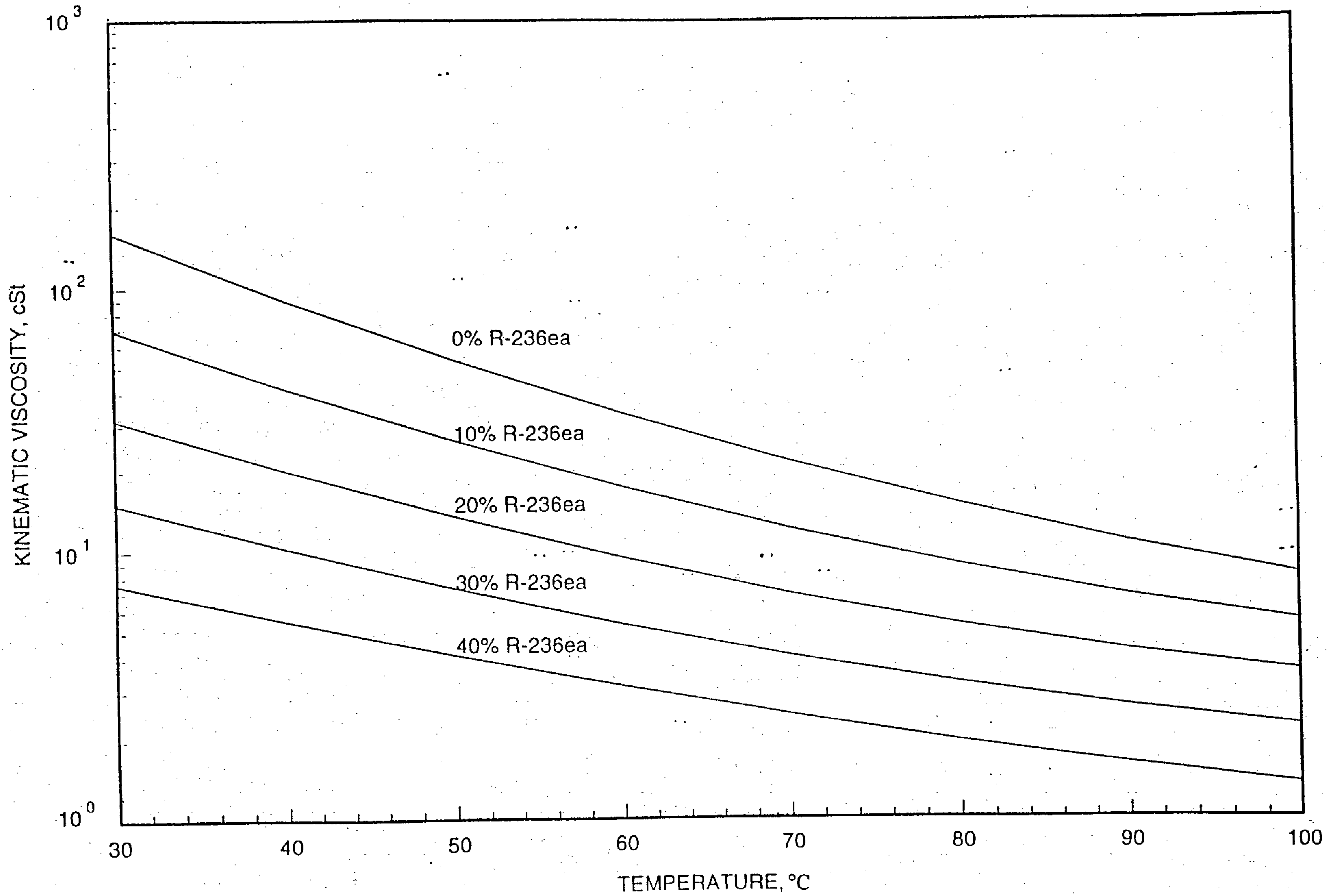


Figure 4.7 Kinematic viscosity of EXXON-02 with R-236ea mixtures

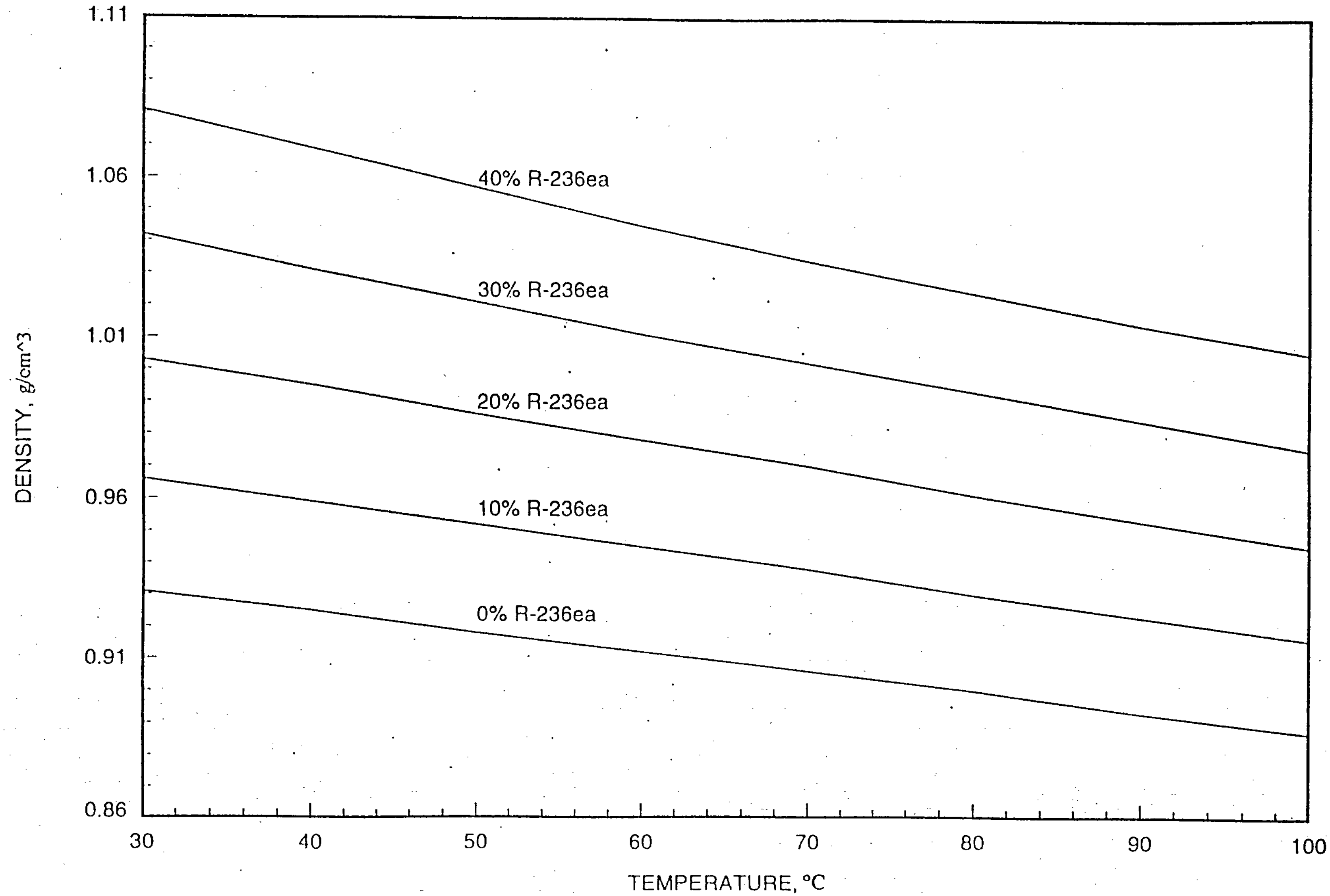


Figure 4.8 Density of EXXON-02 with R-236ea mixtures

## 4-2-3. R-236ea WITH EXXON-03

### 4-2-3-1. RAW DATA

Table 4.13 through Table 4.15 provide complete listings of the experimental data for solubility, viscosity, and density for R-236ea with lubricant Exxon-03 solutions. These tables show that for mixtures of R-236ea with Exxon-03 the solubility, viscosity, and density each is a function of temperature and concentration. For the R-236ea/ Exxon-03 mixtures, (1) the solubility increases with increasing temperature and with increasing refrigerant concentration (i.e., mass fraction of refrigerant), (2) the viscosity decreases with increasing temperature and with increasing refrigerant concentration, and (3) the density decreases with increasing temperature but increases with increasing refrigerant concentration.

The solubility table is tabulated with saturated vapor pressure and temperature for various concentrations of R-236ea in the liquid mixture. The viscosity table is tabulated with dynamic viscosity and temperature for various concentrations of R-236ea in the liquid mixture. Also, the density table is tabulated with liquid density and vapor density versus temperature for various concentration of liquid mixture.

Table 4.13 shows that for a nominal concentration the vapor pressure increases with increasing temperature and with increasing refrigerant concentration. Table 4.14 shows that for a nominal concentration the dynamic viscosity decreases with increasing temperature and with increasing refrigerant concentration. Table 4.15 shows that for a nominal concentration the density decreases with increasing temperature and increases with increasing refrigerant concentration.

### 4-2-3-2. CORRELATING EQUATION

The coefficients for the correlating equations (Equations 1 to 3 in Section 3-3-9-2-2) as derived for R-236ea with lubricant Exxon-03 are given in Table 4.16. It is important to note that when using the correlations in lieu of the graphs that special care must be taken to avoid extrapolation beyond the limits of applicability. These limits of applicability are given, along with the correlating coefficients, in Table 4.16.

### 4-2-3-3. TABULAR RESULTS

Values for solubility, dynamic viscosity, kinematic viscosity, and density can be obtained by using the correlating equations described earlier. These "correlated (smoothed) data" are sometimes (such as when using a computer) more useful than picking numbers off of a graph. Table 4.17 provides "smoothed data" for R-236ea/EXXON-03 mixtures.

Table 4.13. Experimental solubility data for R-236ea and Exxon-03 lubricant solutions

| Temperature (°C) | Saturated vapor pressure (kPa) | Refrigerant concentration (mass fraction) |
|---|---|---|
| 97.2 | 0.0 | 0.000 |
| 89.4 | 0.0 | 0.000 |
| 80.2 | 0.0 | 0.000 |
| 70.6 | 0.0 | 0.000 |
| 61.9 | 0.0 | 0.000 |
| 54.2 | 0.0 | 0.000 |
| 44.6 | 0.0 | 0.000 |
| 29.3 | 0.0 | 0.000 |
| 33.0 | 0.0 | 0.000 |
| | | |
| 80.0 | 224.4 | 0.100 |
| 70.8 | 223.0 | 0.101 |
| 62.2 | 192.0 | 0.103 |
| 52.2 | 157.6 | 0.105 |
| 44.9 | 137.6 | 0.106 |
| 30.5 | 105.6 | 0.108 |
| 37.5 | 118.2 | 0.107 |
| | | |
| 98.8 | 684.4 | 0.239 |
| 90.8 | 610.9 | 0.241 |
| 80.5 | 506.6 | 0.245 |
| 70.5 | 418.7 | 0.28 |
| 56.3 | 301.9 | 0.253 |
| 50.5 | 274.8 | 0.254 |
| 42.2 | 223.0 | 0.256 |
| 27.3 | 159.4 | 0.29 |
| 29.5 | 166.2 | 0.258 |
| | | |
| 90.8 | 985.7 | 0.452 |
| 82.4 | 816.8 | 0.455 |
| 71.3 | 644.5 | 0.458 |
| 62.4 | 532.1 | 0.460 |
| 51.7 | 416.9 | 0.462 |
| 44.3 | 351.6 | 0.463 |
| 27.0 | 222.8 | 0.465 |
| 29.1 | 234.9 | 0.465 |

Table 4.14. Experimental dynamic viscosity data for R-236ea and Exxon-03 lubricant solutions

| Temperature (°C) | Dynamic viscosity (cP) | Refrigerant concentration (mass fraction) |
|---|---|---|
| 86.2 | 11.0 | 0.000 |
| 80.9 | 13.5 | 0.000 |
| 73.9 | 17.7 | 0.000 |
| 66.9 | 23.6 | 0.000 |
| 59.9 | 31.6 | 0.000 |
| 55.2 | 38.7 | 0.000 |
| 47.7 | 54.8 | 0.000 |
| 37.8 | 92.4 | 0.000 |
| 38.7 | 87.1 | 0.000 |
| | | |
| 84.6 | 7.1 | 0.095 |
| 80.4 | 7.9 | 0.097 |
| 71.8 | 10.1 | 0.100 |
| 66.0 | 12.3 | 0.101 |
| 60.3 | 15.4 | 0.103 |
| 48.0 | 25.2 | 0.106 |
| 41.8 | 33.5 | 0.107 |
| | | |
| 84.7 | 3.7 | 0.239 |
| 81.2 | 4.0 | 0.241 |
| 73.5 | 4.8 | 0.245 |
| 67.4 | 5.6 | 0.248 |
| 55.3 | 7.8 | 0.253 |
| 52.1 | 8.6 | 0.254 |
| 45.9 | 10.4 | 0.256 |
| 35.0 | 15.7 | 0.259 |
| | | |
| 89.2 | 1.5 | 0.447 |
| 82.8 | 1.5 | 0.452 |
| 77.4 | 1.7 | 0.455 |
| 68.6 | 2.0 | 0.458 |
| 62.2 | 2.3 | 0.460 |
| 53.4 | 3.1 | 0.462 |
| 48.0 | 3.4 | 0.463 |
| 32.4 | 5.1 | 0.465 |
| 34.5 | 4.7 | 0.465 |

Table 4.15. Experimental density data for R-236ea and Exxon-03 lubricant solutions

| Temperature (°C) | Density (g/cm^3) | R-236ea concentration (mass fraction) | Vapor Density (g/cm^3) |
|---|---|---|---|
| 90.5 | 0.891 | 0.000 | 0.000 |
| 83.7 | 0.895 | 0.000 | 0.000 |
| 75.5 | 0.900 | 0.000 | 0.000 |
| 67.1 | 0.905 | 0.000 | 0.000 |
| 60.1 | 0.909 | 0.000 | 0.000 |
| 53.5 | 0.913 | 0.000 | 0.000 |
| 45.9 | 0.919 | 0.000 | 0.000 |
| 31.4 | 0.926 | 0.000 | 0.000 |
| 35.2 | 0.922 | 0.000 | 0.000 |
| | | | |
| 90.6 | 0.917 | 0.095 | 0.018 |
| 83.6 | 0.925 | 0.097 | 0.016 |
| 74.4 | 0.931 | 0.100 | 0.014 |
| 66.5 | 0.938 | 0.101 | 0.012 |
| 59.5 | 0.945 | 0.103 | 0.011 |
| 50.8 | 0.951 | 0.105 | 0.009 |
| 45.0 | 0.956 | 0.106 | 0.008 |
| 33.1 | 0.965 | 0.108 | 0.007 |
| 39.1 | 0.960 | 0.107 | 0.007 |
| | | | |
| 90.4 | 0.959 | 0.239 | 0.037 |
| 84.0 | 0.966 | 0.241 | 0.033 |
| 75.0 | 0.975 | 0.245 | 0.028 |
| 66.2 | 0.986 | 0.248 | 0.024 |
| 52.8 | 1.000 | 0.253 | 0.108 |
| 48.6 | 1.003 | 0.254 | 0.107 |
| 41.0 | 1.010 | 0.256 | 0.014 |
| 27.9 | 1.022 | 0.259 | 0.010 |
| 29.9 | 1.018 | 0.258 | 0.011 |
| | | | |
| 92.0 | 1.029 | 0.447 | 0.075 |
| 84.7 | 1.045 | 0.452 | 0.059 |
| 77.6 | 1.055 | 0.455 | 0.049 |
| 67.7 | 1.067 | 0.458 | 0.039 |
| 59.9 | 1.077 | 0.460 | 0.033 |
| 50.2 | 1.087 | 0.462 | 0.026 |
| 43.5 | 1.095 | 0.463 | 0.022 |
| 26.6 | 1.110 | 0.465 | 0.015 |
| 29.3 | 1.106 | 0.465 | 0.015 |

Table 4.16. Coefficients for empirical correlations of property data for R-236ea/Exxon-03 mixtures

Note: The limits of applicability of the correlations are
Composition (X): 0 to 45 weight percent refrigerant
Temperature: 30 to 100°C (86 to 212°F)
Pressure: 0 to 3.5 MPa (0 to 500 psia)

| Solubility (kPa) | | | |
|---|---|---|---|
| Term | Coefficient | Standard Error | Prob. > \|T\| |
| Intercept | $B_0$= 0.0 | | |
| C | $B_1$= 0.0 | | |
| $\theta$ | $B_2$= 0.0 | | |
| $C^2$ | $B_3$= 45.512450 | 5.25172383 | 0.0001 |
| $C\theta$ | $B_4$= -6.856959 | 0.41908051 | 0.0001 |
| $\theta^2$ | $B_5$= 0.0 | | |
| $C^2\theta$ | $B_6$= -77.920158 | 9.53719328 | 0.0001 |
| $C\theta^2$ | $B_7$= 7.429186 | 0.36679427 | 0.0001 |
| $C^2\theta^2$ | $B_8$= 32.116462 | 4.35597316 | 0.0001 |

| Viscosity (cP) | | | |
|---|---|---|---|
| Term | Coefficient | Standard Error | Prob. > \|T\| |
| Intercept | $A_0$= 16.914811 | 1.34557441 | 0.0001 |
| C | $A_1$= 0.0 | | |
| $\theta$ | $A_2$= -21.461500 | 2.36046385 | 0.0001 |
| $C^2$ | $A_3$= -40.569395 | 9.78401071 | 0.0003 |
| $C\theta$ | $A_4$= -13.415663 | 0.73757895 | 0.0001 |
| $\theta^2$ | $A_5$= 6.943585. | 1.03359902 | 0.0001 |
| $C^2\theta$ | $A_6$= 79.250107 | 17.42936865 | 0.0001 |
| $C\theta^2$ | $A_7$= 9.494222 | 0.64554653 | 0.0001 |
| $C^2\theta^2$ | $A_8$= -37.303797 | 7.79084884 | 0.0001 |

| Density (g/cm³) | | | |
|---|---|---|---|
| Term | Coefficient | Standard Error | Prob. > \|T\| |
| Intercept | $D_0$= 1.008017 | 0.00344674 | 0.0001 |
| C | $D_1$= -0.490913 | 0.26945013 | 0.0785 |
| $\theta$ | $D_2$= 0.0 | | |
| $C^2$ | $D_3$= 0.0 | | |
| $C\theta$ | $D_4$= 1.818371 | 0.47870436 | 0.0007 |
| $\theta^2$ | $D_5$= -0.075748 | 0.00263603 | 0.0001 |
| $C^2\theta$ | $D_6$= 0.0 | | |
| $C\theta^2$ | $D_7$= -0.988589 | 0.21219273 | 0.0001 |
| $C^2\theta^2$ | $D_8$= 0.106224 | 0.00887782 | 0.0001 |

Table 4.17 Smoothed data for R-236ea/EXXON-03 mixture

| Temp. (°C) | Refrigerant Concentration (mass fraction) | Density (g/cm^3) | Viscosity | | | Pressure | |
|---|---|---|---|---|---|---|---|
| | | | Dynamic (cP) | Kinematic (cSt) | Saybolt (SUS) | (kPa) | (psia) |
| 30 | 0.00 | 0.930 | 138.59 | 149.02 | 689.8 | 0.0 | 0.00 |
| 40 | 0.00 | 0.923 | 81.89 | 88.70 | 411.3 | 0.0 | 0.00 |
| 50 | 0.00 | 0.916 | 50.02 | 54.59 | 254.0 | 0.0 | 0.00 |
| 60 | 0.00 | 0.909 | 31.58 | 34.74 | 163.3 | 0.0 | 0.00 |
| 70 | 0.00 | 0.902 | 20.62 | 22.87 | 110.5 | 0.0 | 0.00 |
| 80 | 0.00 | 0.894 | 13.91 | 15.56 | 80.0 | 0.0 | 0.00 |
| 90 | 0.00 | 0.886 | 9.71 | 10.95 | 62.6 | 0.0 | 0.00 |
| 100 | 0.00 | 0.878 | 7.00 | 7.97 | 52.3 | 0.0 | 0.00 |
| | | | | | | | |
| 30 | 0.10 | 0.964 | 69.07 | 71.62 | 332.0 | 54.9 | 7.96 |
| 40 | 0.10 | 0.957 | 41.22 | 43.05 | 200.7 | 72.4 | 10.50 |
| 50 | 0.10 | 0.950 | 25.75 | 27.10 | 128.8 | 95.8 | 13.90 |
| 60 | 0.10 | 0.943 | 16.84 | 17.86 | 89.1 | 125.2 | 18.15 |
| 70 | 0.10 | 0.935 | 11.52 | 12.32 | 67.4 | 160.5 | 23.27 |
| 80 | 0.10 | 0.928 | 8.26 | 8.90 | 55.3 | 201.7 | 29.25 |
| 90 | 0.10 | 0.920 | 6.19 | 6.73 | 48.2 | 248.8 | 36.09 |
| 100 | 0.10 | 0.911 | 4.86 | 5.33 | 43.8 | 301.9 | 43.79 |
| | | | | | | | |
| 30 | 0.20 | 1.002 | 34.29 | 34.23 | 160.4 | 102.2 | 14.83 |
| 40 | 0.20 | 0.994 | 21.22 | 21.34 | 103.5 | 135.1 | 19.59 |
| 50 | 0.20 | 0.987 | 13.77 | 13.96 | 73.5 | 179.8 | 26.07 |
| 60 | 0.20 | 0.979 | 9.38 | 9.58 | 57.5 | 236.3 | 34.28 |
| 70 | 0.20 | 0.971 | 6.70 | 6.90 | 48.6 | 304.8 | 44.21 |
| 80 | 0.20 | 0.963 | 5.02 | 5.22 | 43.3 | 385.1 | 55.85 |
| 90 | 0.20 | 0.954 | 3.95 | 4.14 | 39.9 | 477.3 | 69.22 |
| 100 | 0.20 | 0.945 | 3.26 | 3.45 | 37.7 | 581.3 | 84.32 |
| | | | | | | | |
| 30 | 0.30 | 1.042 | 16.96 | 16.27 | 82.4 | 142.0 | 20.59 |
| 40 | 0.30 | 1.034 | 11.17 | 10.80 | 61.7 | 188.0 | 27.27 |
| | 0.30 | 1.025 | 7.66 | 7.47 | 50.4 | 251.9 | 36.53 |
| 60 | 0.30 | 1.017 | 5.46 | 5.37 | 43.7 | 333.5 | 48.37 |
| 70 | 0.30 | 1.008 | 4.05 | 4.02 | 39.4 | 433.0 | 62.80 |
| 80 | 0.30 | 0.999 | 3.13 | 3.14 | 36.6 | 550.2 | 79.80 |
| 90 | 0.30 | 0.990 | 2.52 | 2.55 | 34.6 | 685.3 | 99.39 |
| 100 | 0.30 | 0.980 | 2.11 | 2.15 | 33.3 | 838.2 | 121.57 |
| | | | | | | | |
| 30 | 0.40 | 1.085 | 8.35 | 7.69 | 51.0 | 174.2 | 25.26 |
| 40 | 0.40 | 1.076 | 6.01 | 5.59 | 44.3 | 231.3 | 33.54 |
| 50 | 0.40 | 1.067 | 4.42 | 4.15 | 39.7 | 312.1 | 45.27 |
| 60 | 0.40 | 1.057 | 3.32 | 3.15 | 36.5 | 416.7 | 60.44 |
| 70 | 0.40 | 1.047 | 2.55 | 2.44 | 34.2 | 545.0 | 79.05 |
| 80 | 0.40 | 1.037 | 2.00 | 1.93 | 32.5 | 697.1 | 101.10 |
| 90 | 0.40 | 1.026 | 1.61 | 1.56 | 31.3 | 872.9 | 126.60 |
| 100 | 0.40 | 1.016 | 1.32 | 1.30 | 30.4 | 1072.4 | 155.54 |

### 4-2-3-4. GRAPHICAL RESULTS

Property plots for solubility, dynamic viscosity, kinematic viscosity, and density can be obtained by using the correlating equations described earlier. Graphical results for the solubility, dynamic viscosity, kinematic viscosity, and density of R-236ea in Exxon-03 mixtures are given in Figures 4.9 through 4.12, respectively. The plot of pressure versus refrigerant concentration for a range of temperatures shows that the pressure increases with increasing refrigerant concentration and temperature. The plot of dynamic viscosity versus temperature for a range of refrigerant concentrations shows that the dynamic viscosity decreases with increasing refrigerant concentration and temperature. The plot of kinematic viscosity versus temperature for a range of refrigerant concentrations shows that the kinematic viscosity decreases with increasing refrigerant concentration and temperature. The plot of density versus temperature for a range of refrigerant concentrations shows that the density increases with increasing refrigerant concentration and decreases with increasing temperature.

## 4-2-4. R-236ea WITH EXXON-04

### 4-2-4-1. RAW DATA

Table 4.18 through Table 4.20 provide complete listings of the experimental data for solubility, viscosity, and density for R-236ea with lubricant Exxon-04 solutions. These tables show that for mixtures of R-236ea with Exxon-04 the solubility, viscosity, and density each is a function of temperature and concentration. For the R-236ea/ Exxon-04 mixtures, (1) the solubility increases with increasing temperature and with increasing refrigerant concentration (i.e., mass fraction of refrigerant), (2) the viscosity decreases with increasing temperature and with increasing refrigerant concentration, and (3) the density decreases with increasing temperature but increases with increasing refrigerant concentration.

The solubility table is tabulated with saturated vapor pressure and temperature for various concentrations of R-236ea in the liquid mixture. The viscosity table is tabulated with dynamic viscosity and temperature for various concentrations of R-236ea in the liquid mixture. Also, the density table is tabulated with liquid density and vapor density versus temperature for various concentration of liquid mixture.

Table 4.18 shows that for a nominal concentration the vapor pressure increases with increasing temperature and with increasing refrigerant concentration. Table 4.19 shows that for a nominal concentration the dynamic viscosity decreases with increasing temperature and with increasing refrigerant concentration. Table 4.20 shows that for a nominal concentration the density decreases with increasing temperature and increases with increasing refrigerant concentration.

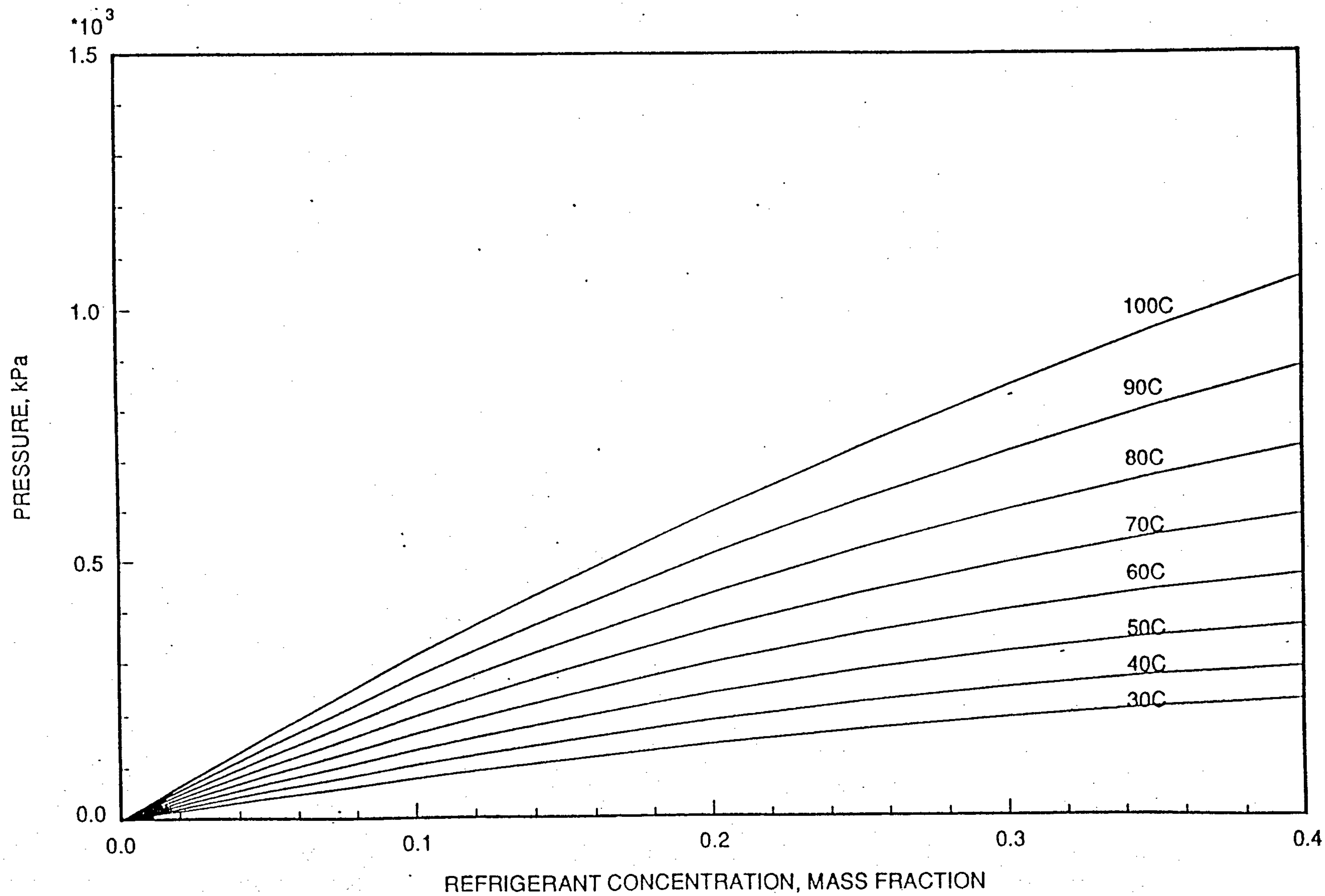


Figure 4.9 Solubility of EXXON-03 with R-236ea mixtures

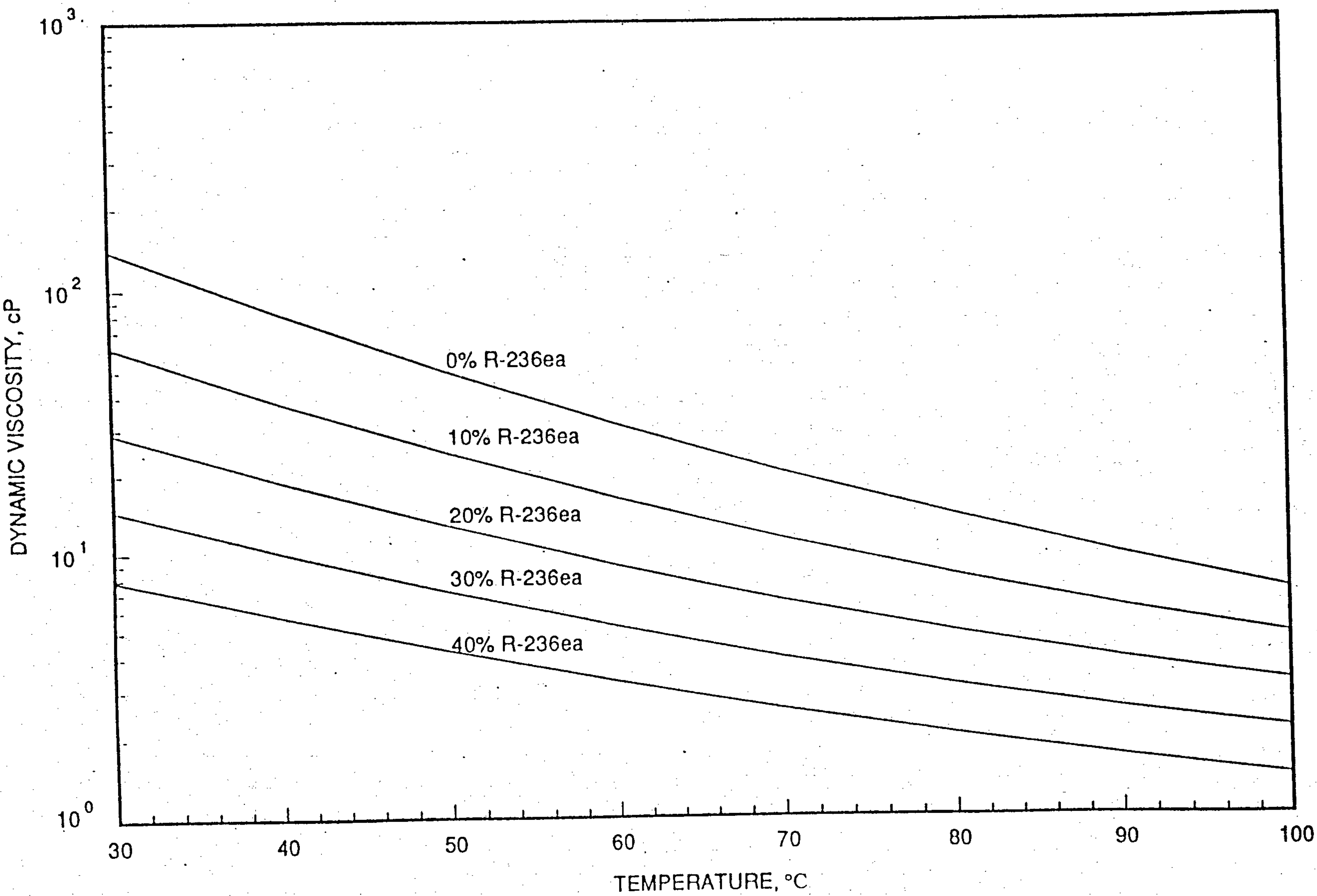


Figure 4.10 Dynamic viscosity of EXXON-03 with R-236ea mixtures

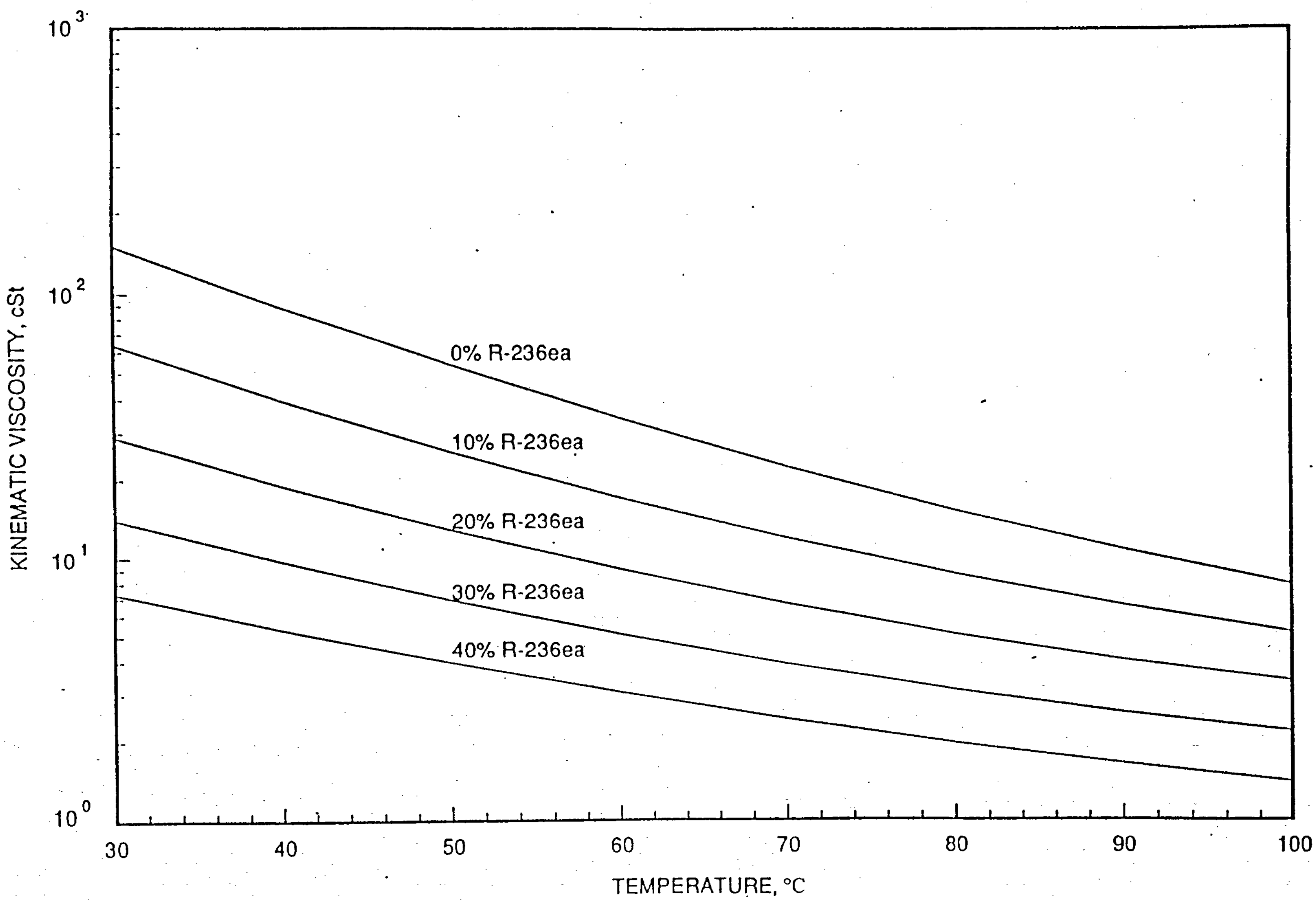


Figure 4.11 Kinematic viscosity of EXXON-03 with R-236ea mixtures

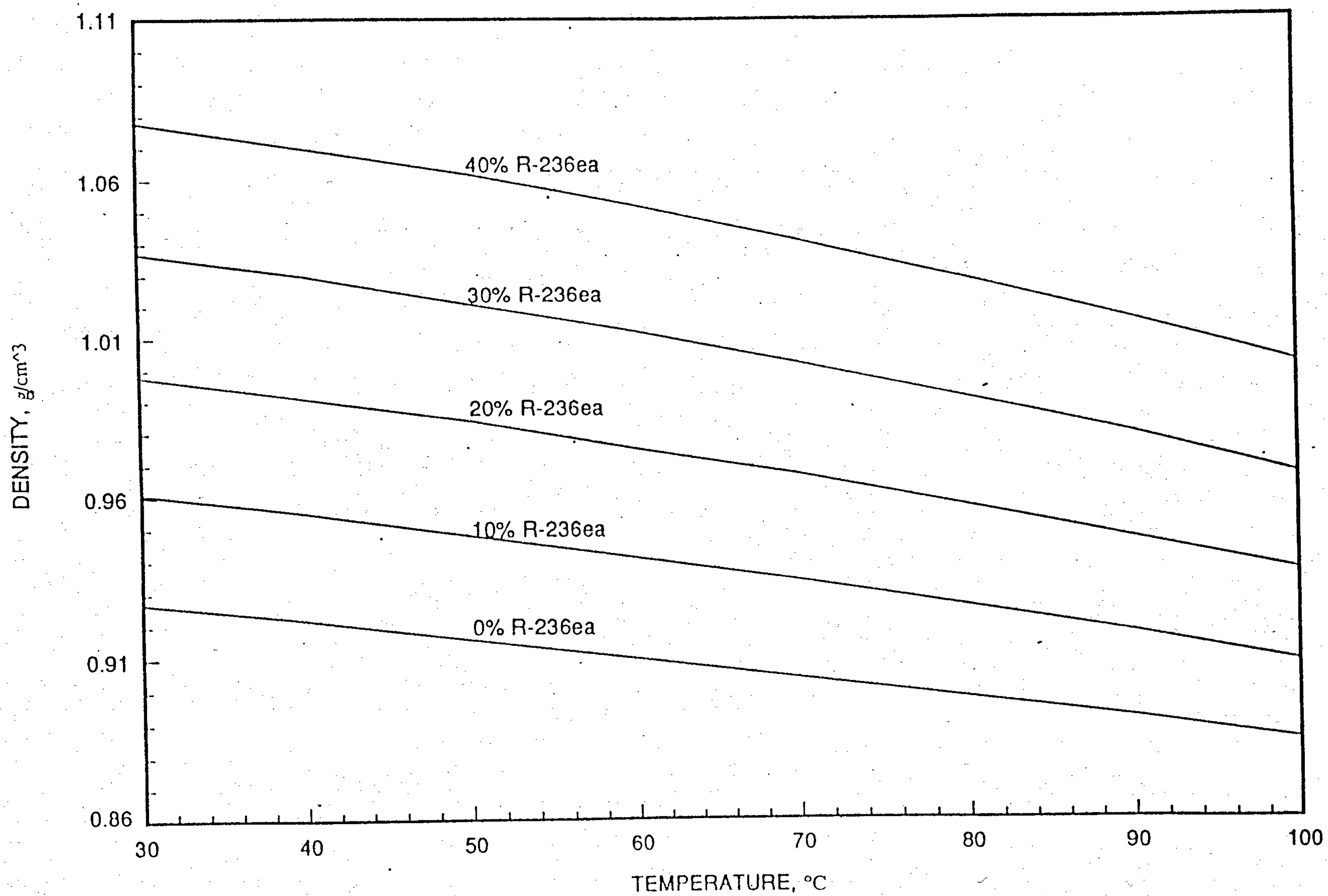


Figure 4.12 Density of EXXON-03 with R-236ea mixtures

Table 4.18. Experimental solubility data for R-236ea and Exxon-04 lubricant solutions

| Temperature (°C) | Saturated vapor pressure (kPa) | Refrigerant concentration (mass fraction) |
|---|---|---|
| 105.3 | 0.0 | 0.000 |
| 95.6 | 0.0 | 0.000 |
| 84.8 | 0.0 | 0.000 |
| 75.1 | 0.0 | 0.000 |
| 51.8 | 0.0 | 0.000 |
| 55.2 | 0.0 | 0.000 |
| 46.1 | 0.0 | 0.000 |
| 26.5 | 0.0 | 0.000 |
| 34.2 | 0.0 | 0.000 |
| | | |
| 106.7 | 358.9 | 0.096 |
| 96.4 | 312.5 | 0.098 |
| 86.4 | 263.1 | 0.100 |
| 75.9 | 212.9 | 0.102 |
| 65.6 | 166.7 | 0.105 |
| 54.7 | 127.9 | 0.107 |
| 45.7 | 103.6 | 0.108 |
| 22.4 | 58.7 | 0.110 |
| 32.7 | 78.7 | 0.110 |
| | | |
| 107.3 | 806.6 | 0.236 |
| 97.3 | 683.3 | 0.240 |
| 86.6 | 555.2 | 0.244 |
| 76.0 | 445.1 | 0.247 |
| 64.9 | 348.4 | 0.251 |
| 55.0 | 270.1 | 0.254 |
| 44.1 | 204.2 | 0.256 |
| 20.5 | 102.4 | 0.260 |
| 28.6 | 129.8 | 0.259 |
| | | |
| 97.6 | 1062.5 | 0.464 |
| 89.0 | 902.0 | 0.466 |
| 80.3 | 750.6 | 0.468 |
| 57.1 | 443.7 | 0.472 |
| 42.4 | 295.2 | 0.474 |
| 28.2 | 194.9 | 0.476 |
| 26.3 | 184.1 | 0.476 |

Table 4.19. Experimental dynamic viscosity data for R-236ea and Exxon-04 lubricant solutions

| Temperature (°C) | Dynamic viscosity (cP) | Refrigerant concentration (mass fraction) |
|---|---|---|
| 98.7 | 7.5 | 0.000 |
| 90.8 | 9.4 | 0.000 |
| 81.2 | 12.3 | 0.000 |
| 73.2 | 16.0 | 0.000 |
| 64.2 | 25.0 | 0.000 |
| 56.1 | 34.9 | 0.000 |
| 49.2 | 47.6 | 0.000 |
| 35.7 | 93.5 | 0.000 |
| 40.2 | 73.8 | |
| | | |
| 100.2 | 4.9 | 0.096 |
| 91.4 | 6.0 | 0.098 |
| 83.0 | 7.5 | 0.100 |
| 74.3 | 9.6 | 0.102 |
| 66.0 | 12.4 | 0.105 |
| 56.8 | 17.0 | 0.107 |
| 49.9 | 21.9 | 0.108 |
| 30.2 | 62.6 | 0.110 |
| 37.6 | 43.2 | 0.110 |
| | | |
| 100.5 | 2.8 | 0.236 |
| 92.4 | 3.3 | 0.240 |
| 83.1 | 4.0 | 0.244 |
| 74.2 | 5.0 | 0.247 |
| 64.2 | 6.5 | 0.251 |
| 56.1 | 8.2 | 0.254 |
| 47.0 | 10.8 | 0.256 |
| 26.8 | 22.3 | 0.260 |
| 32.7 | 21.4 | 0.259 |
| | | |
| 91.8 | 1.3 | 0.464 |
| 84.7 | 1.5 | 0.466 |
| 77.7 | 1.8 | 0.468 |
| 65.7 | 2.4 | 0.471 |
| 57.3 | 2.8 | 0.472 |
| 50.2 | 3.5 | 0.473 |
| 43.3 | 4.2 | 0.474 |
| 33.1 | 6.2 | 0.476 |
| 31.0 | 5.1 | 0.476 |

Table 4.20. Experimental density data for R-236ea and Exxon-04 lubricant solutions

| Temperature (°C) | Density (g/cm^3) | R-236ea concentration (mass fraction) | Vapor Density (g/cm^3) |
|---|---|---|---|
| 100.60 | 0.912 | 0.000 | 0.000 |
| 91.47 | 0.919 | 0.000 | 0.000 |
| 81.44 | 0.926 | 0.000 | 0.000 |
| 72.36 | 0.929 | 0.000 | 0.000 |
| 36.31 | 0.938 | 0.000 | 0.000 |
| 54.32 | 0.943 | 0.000 | 0.000 |
| 46.48 | 0.947 | 0.000 | 0.000 |
| 30.63 | 0.958 | 0.000 | 0.000 |
| 37.74 | 0.954 | 0.000 | 0.000 |
| | | | |
| 101.15 | 0.934 | 0.096 | 0.018 |
| 91.74 | 0.942 | 0.098 | 0.016 |
| 82.53 | 0.951 | 0.100 | 0.014 |
| 72.92 | 0.960 | 0.102 | 0.012 |
| 63.60 | 0.968 | 0.105 | 0.009 |
| 53.37 | 0.975 | 0.107 | 0.007 |
| 45.33 | 0.988 | 0.108 | 0.006 |
| 25.26 | 0.996 | 0.110 | 0.004 |
| 34.60 | 0.988 | 0.110 | 0.004 |
| | | | |
| 102.23 | 0.980 | 0.236 | 0.043 |
| 93.03 | 0.991 | 0.240 | 0.037 |
| 83.05 | 1.003 | 0.244 | 0.031 |
| 73.24 | 1.014 | 0.247 | 0.025 |
| 62.47 | 1.025 | 0.251 | 0.020 |
| 53.35 | 1.033 | 0.254 | 0.016 |
| 42.97 | 1.039 | 0.256 | 0.012 |
| 21.71 | 1.064 | 0.260 | 0.007 |
| 29.10 | 1.056 | 0.259 | 0.008 |
| | | | |
| 92.23 | 1.016 | 0.464 | 0.063 |
| 84.49 | 1.028 | 0.466 | 0.054 |
| 76.58 | 1.037 | 0.468 | 0.045 |
| 63.65 | 1.053 | 0.471 | 0.033 |
| 54.30 | 1.062 | 0.472 | 0.027 |
| 46.77 | 1.069 | 0.473 | 0.023 |
| 39.22 | 1.083 | 0.474 | 0.018 |
| 27.88 | 1.091 | 0.476 | 0.013 |
| 26.18 | 1.096 | 0.476 | 0.012 |

### 4-2-4-2. CORRELATING EQUATION

The coefficients for the correlating equations (Equations 1 to 3 in Section 3-3-9-2-2) as derived for R-236ea with lubricant Exxon-04 are given in Table 4.21.

It is important to note that when using the correlations in lieu of the graphs that special care must be taken to avoid extrapolation beyond the limits of applicability. These limits of applicability are given along with the correlating coefficients in Table 4.21.

### 4-2-4-3. TABULAR RESULTS

Values for solubility, dynamic viscosity, kinematic viscosity, and density can be obtained by using the correlating equations described earlier. These "correlated (smoothed) data" are sometimes (such as when using a computer) more useful than picking numbers off of a graph. Table 4.22 provides "smoothed data" for R-236ea/EXXON-04 mixtures.

### 4-2-4-4. GRAPHICAL RESULTS

Property plots for solubility, dynamic viscosity, kinematic viscosity, and density can be obtained by using the correlating equations described earlier. Graphical results for the solubility, dynamic viscosity, kinematic viscosity, and density of R-236ea in Exxon-04 mixtures are given in Figures 4.13 through 4.16, respectively. The plot of pressure versus refrigerant concentration for a range of temperatures shows that the pressure increases with increasing refrigerant concentration and temperature. The plot of dynamic viscosity versus temperature for a range of refrigerant concentrations shows that the dynamic viscosity decreases with increasing refrigerant concentration and temperature. The plot of kinematic viscosity versus temperature for a range of refrigerant concentrations shows that the kinematic viscosity decreases with increasing refrigerant concentration and temperature. The plot of density versus temperature for a range of refrigerant concentrations shows that the density increases with increasing refrigerant concentration and decreases with increasing temperature.

Table 4.21. Coefficients for empirical correlations of property data for R-236ea/Exxon-04 mixtures

Note: The limits of applicability of the correlations are
Composition (X): 0 to 45 weight percent refrigerant
Temperature: 30 to 100°C (86 to 212°F)
Pressure: 0 to 3.5 MPa (0 to 500 psia)

| Solubility (kPa) | | | |
|---|---|---|---|
| Term | Coefficient | Standard Error | Prob. > \|T\| |
| Intercept | $B_0$= 0.0 | | |
| C | $B_1$= 28.923595 | 1.56987243 | 0.0001 |
| θ | $B_2$= 0.0 | | |
| $C^2$ | $B_3$= -28.218758 | 4.09002742 | 0.0001 |
| Cθ | $B_4$= -59.747427 | 2.74882676 | 0.0001 |
| $\theta^2$ | $B_5$= 0.0 | | |
| $C^2\theta$ | $B_6$= 56.376285 | 7.18091853 | 0.0001 |
| $C\theta^2$ | $B_7$= 31.325247 | 1.19669273 | 0.0001 |
| $C^2\theta^2$ | $B_8$= -28.527597 | 3.13472068 | 0.0001 |

| Viscosity (cP) | | | |
|---|---|---|---|
| Term | Coefficient | Standard Error | Prob. > \|T\| |
| Intercept | $A_0$= 19.654542 | 1.31958970 | 0.0001 |
| C | $A_1$= -10.182429 | 1.19447477 | 0.0001 |
| θ | $A_2$= -26.401929 | 2.27664917 | 0.0001 |
| $C^2$ | $A_3$= -40.633640 | 12.76049946 | 0.0035 |
| Cθ | $A_4$= 6.686434 | 1.03558065 | 0.0001 |
| $\theta^2$ | $A_5$= 9.140863 | 0.97997867 | 0.0001 |
| $C^2\theta$ | $A_6$= 76.354218 | 22.44924195 | 0.0020 |
| $C\theta^2$ | $A_7$= 0.0 | | |
| $C^2\theta^2$ | $A_8$= -35.031269 | 9.91628123 | 0.0014 |

| Density (g/cm³) | | | |
|---|---|---|---|
| Term | Coefficient | Standard Error | Prob. > \|T\| |
| Intercept | $D_0$= 1.036619 | 0.00995960 | 0.0001 |
| C | $D_1$= 0.840684 | 0.07807521 | 0.0001 |
| θ | $D_2$= 0.0 | | |
| $C^2$ | $D_3$= -0.386874 | 0.03913176 | 0.0001 |
| Cθ | $D_4$= -0.350597 | 0.06553734 | 0.0001 |
| $\theta^2$ | $D_5$= -0.079033 | 0.00745069 | 0.0001 |
| $C^2\theta$ | $D_6$= 0.0 | | |
| $C\theta^2$ | $D_7$= 0.0 | | |
| $C^2\theta^2$ | $D_8$= 0.0 | | |

Table 4.22 Smoothed data for R-236ea/EXXON-04 mixture

| Temp. (°C) | Refrigerant Concentration (mass fraction) | Density (g/cm^3) | Viscosity Dynamic (cP) | Viscosity Kinematic (cSt) | Viscosity Saybolt (SUS) | Pressure (kPa) | Pressure (psia) |
|---|---|---|---|---|---|---|---|
| 30 | 0.00 | 0.952 | 134.00 | 140.74 | 651.5 | 0.0 | 0.00 |
| 40 | 0.00 | 0.946 | 76.21 | 80.53 | 373.5 | 0.0 | 0.00 |
| 50 | 0.00 | 0.941 | 45.52 | 48.40 | 225.5 | 0.0 | 0.00 |
| 60 | 0.00 | 0.935 | 28.55 | 30.55 | 144.3 | 0.0 | 0.00 |
| 70 | 0.00 | 0.928 | 18.81 | 20.26 | 99.3 | 0.0 | 0.00 |
| 80 | 0.00 | 0.922 | 13.01 | 14.12 | 74.3 | 0.0 | 0.00 |
| 90 | 0.00 | 0.915 | 9.46 | 10.33 | 60.3 | 0.0 | 0.00 |
| 100 | 0.00 | 0.909 | 7.22 | 7.94 | 52.2 | 0.0 | 0.00 |
| | | | | | | | |
| 30 | 0.10 | 0.996 | 64.41 | 64.67 | 299.9 | 59.4 | 8.62 |
| 40 | 0.10 | 0.989 | 38.69 | 39.11 | 182.8 | 79.0 | 11.46 |
| 50 | 0.10 | 0.982 | 24.36 | 24.80 | 118.7 | 105.3 | 15.27 |
| 60 | 0.10 | 0.975 | 16.08 | 16.49 | 83.5 | 138.1 | 20.04 |
| 70 | 0.10 | 0.967 | 11.12 | 11.50 | 64.4 | 177.6 | 25.76 |
| 80 | 0.10 | 0.960 | 8.07 | 8.40 | 53.6 | 223.7 | 32.45 |
| 90 | 0.10 | 0.952 | 6.13 | 6.44 | 47.3 | 276.5 | 40.10 |
| 100 | 0.10 | 0.944 | 4.89 | 5.18 | 43.2 | 335.9 | 48.71 |
| | | | | | | | |
| 30 | 0.20 | 1.032 | 32.22 | 31.21 | 146.8 | 110.3 | 16.00 |
| 40 | 0.20 | 1.024 | 20.52 | 20.04 | 97.0 | 147.1 | 21.33 |
| 50 | 0.20 | 1.016 | 13.63 | 13.42 | 71.4 | 195.8 | 28.40 |
| 60 | 0.20 | 1.008 | 9.44 | 9.37 | 56.8 | 256.4 | 37.19 |
| 70 | 0.20 | 0.999 | 6.81 | 6.82 | 48.4 | 328.9 | 47.71 |
| 80 | 0.20 | 0.990 | 5.12 | 5.17 | 43.1 | 413.4 | 59.96 |
| 90 | 0.20 | 0.981 | 4.01 | 4.09 | 39.7 | 509.8 | 73.94 |
| 100 | 0.20 | 0.972 | 3.28 | 3.37 | 37.4 | 618.1 | 89.65 |
| | | | | | | | |
| 30 | 0.30 | 1.061 | 16.77 | 15.81 | 80.5 | 152.7 | 22.15 |
| 40 | 0.30 | 1.051 | 11.38 | 10.82 | 61.7 | 204.2 | 29.61 |
| 50 | 0.30 | 1.042 | 7.97 | 7.65 | 51.0 | 271.5 | 39.38 |
| 60 | 0.30 | 1.032 | 5.77 | 5.59 | 44.0 | 354.8 | 51.46 |
| 70 | 0.30 | 1.023 | 4.31 | 4.22 | 40.0 | 453.9 | 65.84 |
| 80 | 0.30 | 1.013 | 3.33 | 3.29 | 37.1 | 569.0 | 82.52 |
| 90 | 0.30 | 1.002 | 2.65 | 2.64 | 35.0 | 699.9 | 101.52 |
| 100 | 0.30 | 0.992 | 2.18 | 2.20 | 33.5 | 846.8 | 122.81 |
| | | | | | | | |
| 30 | 0.40 | 1.081 | 9.08 | 8.40 | 53.3 | 186.5 | 27.05 |
| 40 | 0.40 | 1.071 | 6.59 | 6.15 | 46.1 | 250.2 | 36.29 |
| 50 | 0.40 | 1.060 | 4.88 | 4.60 | 41.2 | 332.5 | 48.22 |
| 60 | 0.40 | 1.050 | 3.68 | 3.50 | 37.7 | 433.3 | 62.84 |
| 70 | 0.40 | 1.039 | 2.83 | 2.72 | 35.2 | 552.6 | 80.15 |
| 80 | 0.40 | 1.027 | 2.21 | 2.15 | 33.9 | 690.5 | 100.15 |
| 90 | 0.40 | 1.016 | 1.77 | 1.74 | 31.9 | 846.9 | 122.83 |
| 100 | 0.40 | 1.004 | 1.44 | 1.43 | 30.8 | 1021.8 | 148.21 |

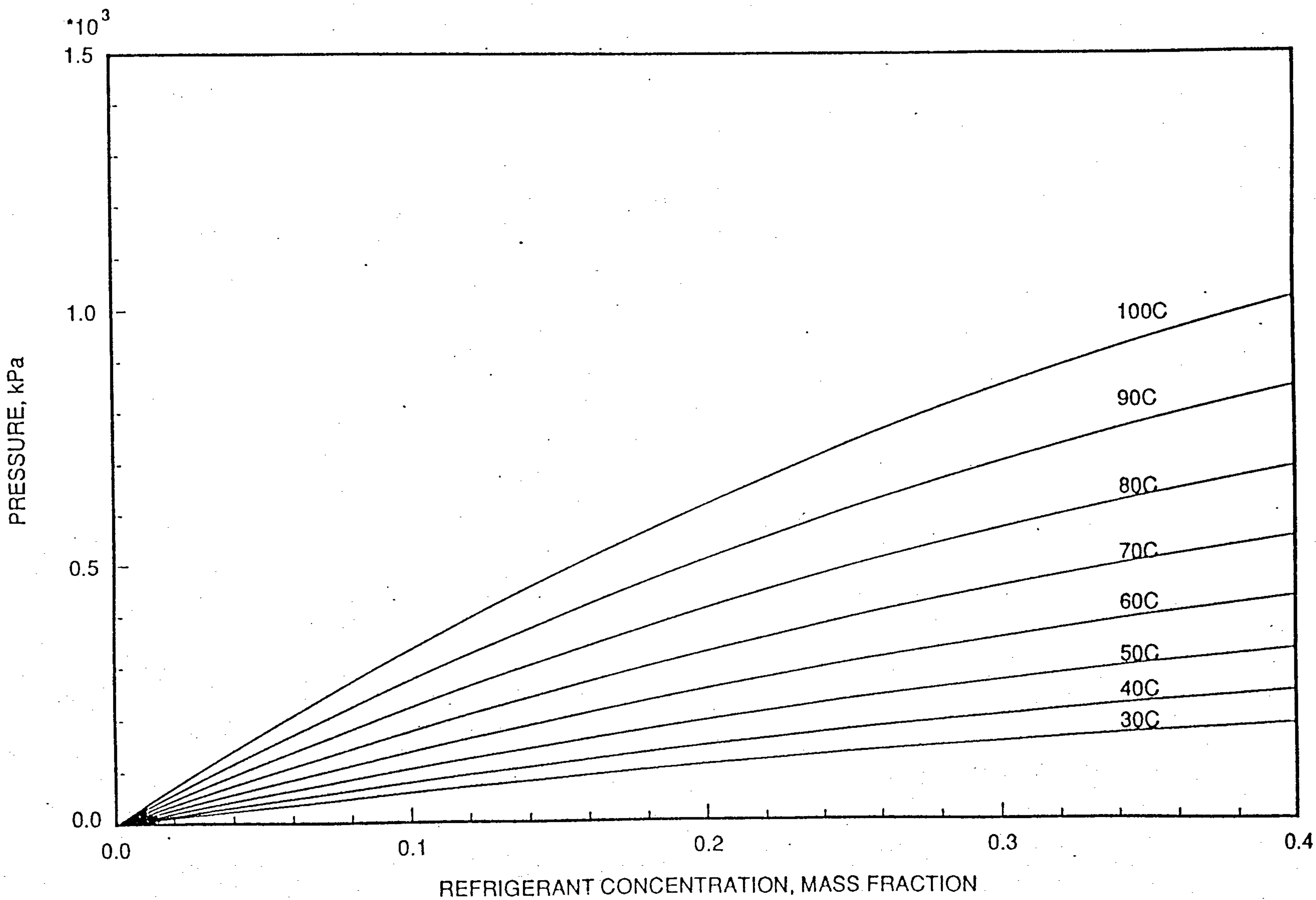


Figure 4.13 Solubility of EXXON-04 with R-236ea mixtures

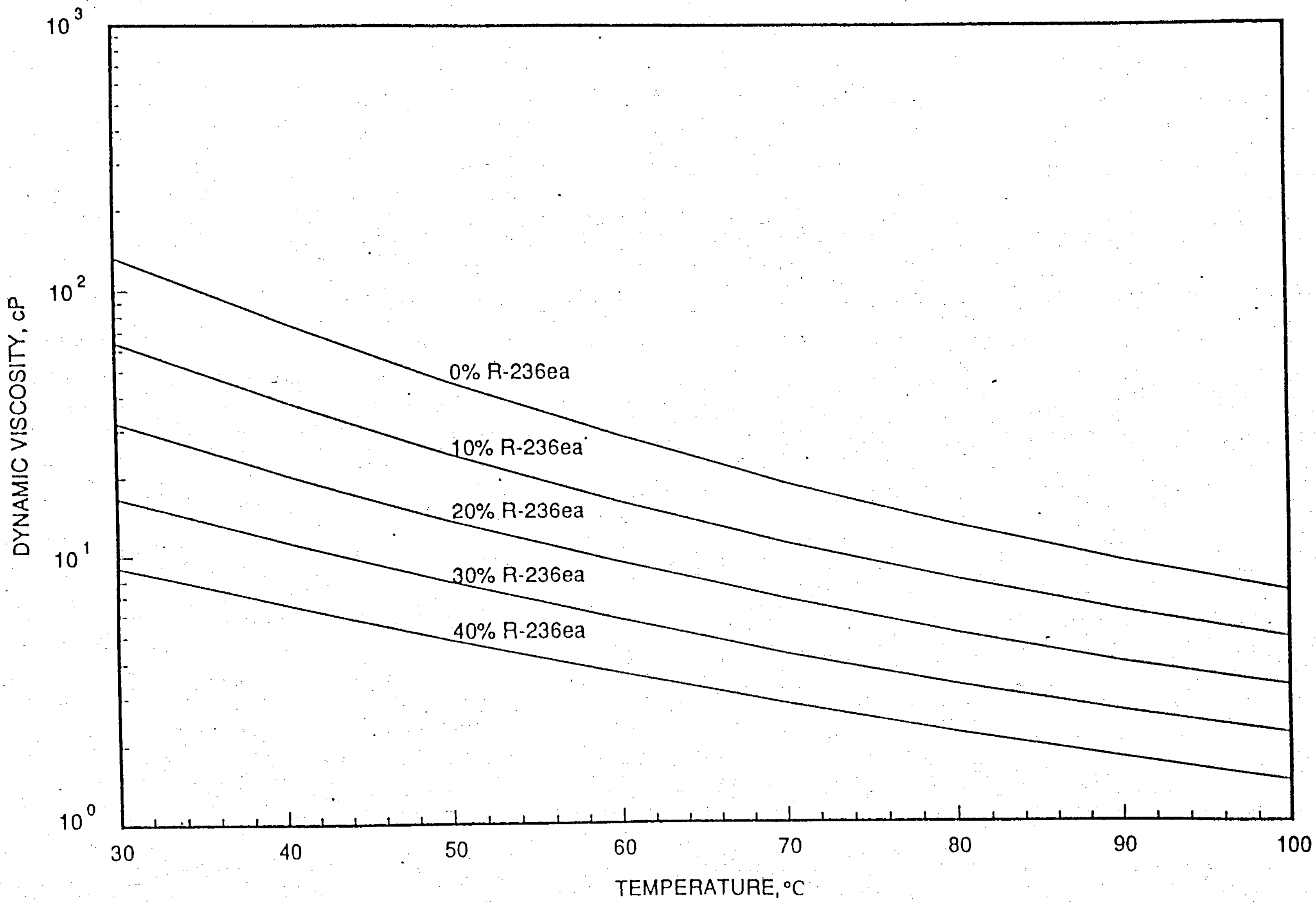


Figure 4.14 Dynamic viscosity of EXXON-041 with R-236ea mixtures

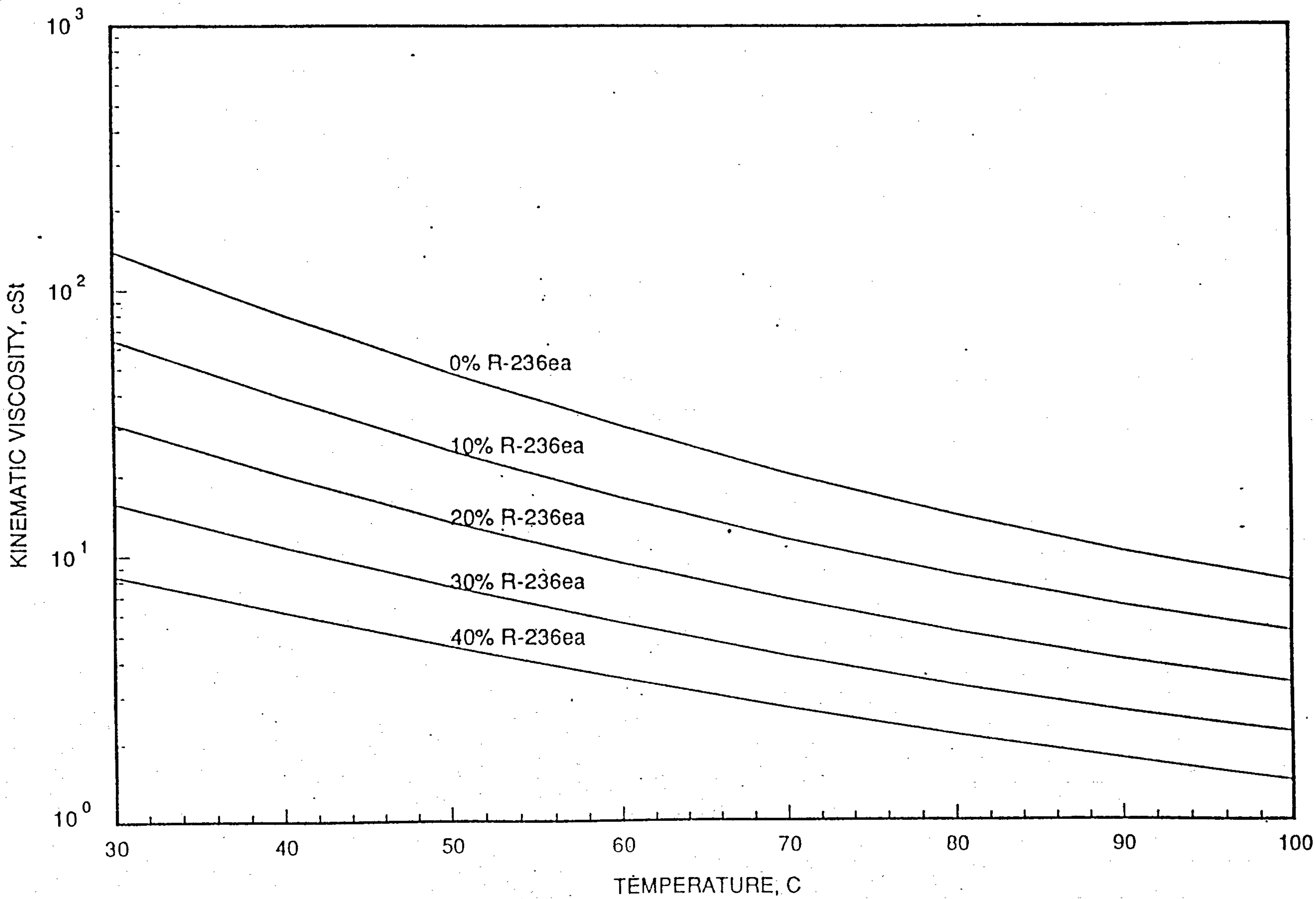


Figure 4.15 Kinematic viscosity of EXXON-04 with R-236ea mixtures

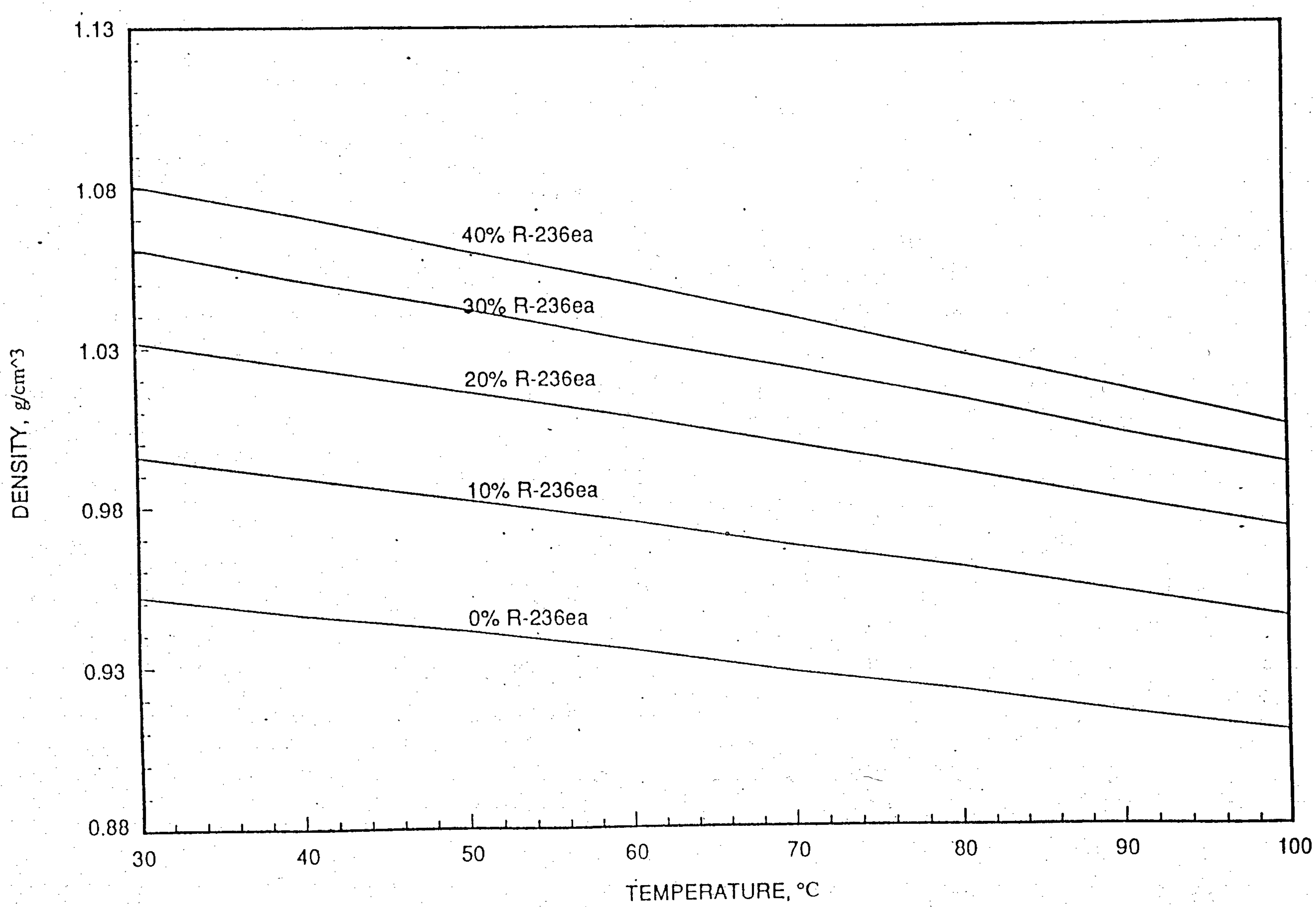


Figure 4.16 Density of EXXON-04 with R-236ea mixtures

## 4-3. SUMMARY

Data have been collected for mixtures of refrigerant R-236ea and four different lubricants, which are designated as Exxon-01, Exxon-02, Exxon-03, and Exxon-04. Miscibility data have been obtained for temperatures from -40 to +90°C (-40 to 194°F) for the variety of refrigerant compositions from 10 to 90% by refrigerant weight. Also property data such as solubility, viscosity, and density have been measured for temperatures as high as 100°C (212°F) and for pressures up to 3.5 MPa (500 psia). The results are also presented as solubility, dynamic viscosity, kinematic viscosity, and density charts, where the properties are plotted as a function of temperature and refrigerant concentration. Empirical correlating equations developed from these data allow convenient interpolation of the data at specific property conditions.

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# TECHNICAL REPORT DATA
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16. ABSTRACT The report discusses miscibility, solubility, viscosity, and density data for the refrigerant hydrofluorocarbon (HFC)-236ea (or R-236ea) and four lubricants supplied by Exxon Corporation. Such data are needed to determine the suitability of refrigerant/lubricant combinations for use in refrigeration systems. The miscibility tests were performed in a test facility consisting of a series of miniature test cells submerged in a constant temperature bath, precisely controlled over a range of -50 to 90 C. The test cells were constructed to allow for complete visibility of refrigerant/lubricant mixtures under all test conditions. Critical solution temperatures obtained from the miscibility data are presented for each refrigerant/lubricant combination. Data for the R-236ea in each of the test lubricants have been collected for refrigerant concentrations of 10-90%. The raw data have been presented, and the results have been summarized. Two of the oils (Exxon-03 and -04) were found to be completely miscible over the temperature and concentration ranges tested, while the other two (Exxon-01 and -02) were found to be immiscible over most of the temperature range tested. Solubility, viscosity, and density data were also obtained for R-236a mixed with the same four oils for a refrigerant concentration range of 0-40 wt % refrigerant over a temperature range of 30-100 C.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| Pollution | Pollution Control | 13B |
| Refrigerants | Stationary Sources | 13A |
| Lubricants | Miscibility | 11G |
| Solubility | | 07D |
| Viscosity | | 20D |
| Density | | 14G |

| | | |
|---|---|---|
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