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MATERIALS COMPATIBILITY AND LUBRICANTS RESEARCH ON CFC-REFRIGERANT SUBSTITUTES

Quarterly MCLR Program
Technical Progress Report

1 January 1994 - 31 March 1994

Steven R. Szymurski
Michael Hawley
Glenn C. Hourahan
David S. Godwin

Air-Conditioning and Refrigeration Technology Institute, Inc.
4301 North Fairfax Drive, Suite 425
Arlington, Virginia 22203

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MATERIALS COMPATIBILITY AND LUBRICANT RESEARCH ON CFC-REFRIGERANT SUBSTITUTES

ABSTRACT

The Materials Compatibility and Lubricants Research (MCLR) program supports critical research to accelerate the introduction of CFC and HCFC refrigerant substitutes. The MCLR program addresses refrigerant and lubricant properties and materials compatibility. The primary elements of the work include data collection and dissemination, materials compatibility testing, and methods development. The work is guided by an Advisory Committee consisting of technical experts from the refrigeration and air-conditioning industry and government agencies. The Air-Conditioning and Refrigeration Technology Institute, Inc., (ARTI) manages and contracts multiple research projects and a data collection and dissemination effort. Detailed results from these projects are reported in technical reports prepared by each subcontractor.

SCOPE

The Materials Compatibility and Lubricant Research (MCLR) program is a multi-year research grant administered by the Air-Conditioning and Refrigeration Technology Institute (ARTI), a not-for-profit organization for scientific research in the public interest. The program was implemented on 30 September 1991 and, as currently funded, will run through 30 September 1995. The MCLR program consists of a number of research projects grouped in phases. The first phase encompasses seven research projects and a data collection and dissemination project. Phase I projects began in January 1992 and were scheduled for completion in March 1993. However, several of these projects have subsequently been extended due to delays or added work within the scope of the project. Phase II consists of seven research projects and a data collection and dissemination project. Phase II projects began in October 1992 and will run through September 1994. Phase III projects began in November 1993 and will run through September 1995. This report summarizes the research conducted during the 1st quarter of calendar year 1994. This report supersedes report numbers DOE/CE/23810-33, DOE/CE/23810-22, DOE/CE/23810-20, DOE/CE/23810-11, DOE/CE/23810-8, DOE/CE/23810-4, DOE/CE/23810-3, DOE/CE/23810-2 and DOE/CE/23810-1.

SIGNIFICANT RESULTS
ON-GOING PROJECTS

THERMOPHYSICAL PROPERTIES OF HFC-143a AND HFC-152a

Objective:

To provide highly accurate, selected thermophysical properties data for refrigerants HFC-143a (CH_3CF_3) and HFC-152a (CH_3CHF_2); and to fit these data to simple, theoretically-based equations of state, as well as complex equations of state and detailed transport property models.

Results:

The Thermophysics Division of the National Institute of Standards and Technology (NIST) at Boulder, CO, is currently conducting measurements and correlations of HFC-143a and HFC-152a. The new data will fill the gaps in existing data sets and resolve the problems and uncertainties that exist in and between those data sets. Measurements and determinations of thermodynamic properties will include vapor and liquid pressure-volume-temperature (PVT) behavior, saturation and critical points, vapor speed of sound, ideal gas heat capacity, and isochoric heat capacity. The data will then be fitted to the Carnahan-Starling-DeSantis-Morrison (CSDM) and the modified Benedict-Webb-Rubin (MBWR) equations of state. Measurements and correlations of transport properties will include thermal conductivity and viscosity. Preliminary results are contained in the quarterly technical progress report, DOE/CE-23810-38E, *Thermophysical Properties of HFC-143a and HFC-152a*, 1 January 1994 - 31 March 1994, by W. M. Haynes, PhD. These results are summarized below.

HFC-143a

MBWR Equation of State

NIST has analyzed thermophysical properties measurements from this project and data from existing literature to develop a 32-term modified Benedict-Webb-Rubin equation of state for HFC-143a. Table 1 provides the coefficients to the MBWR equation of state. The MBWR equation of state is reported to be valid at temperatures from 180 to 400 K (-136 to 260°F) and for pressures up to 40 MPa (5800 psia). The equation may be reasonably extrapolated from the triple point temperature of 162 K up to 500 K (-168 to 440°F) and for pressures up to 100 MPa (14500 psia).

Table 1. Coefficients to the MBWR Equation of State for HFC-143a (units are K, bar, L, mol)

$$p = \sum_{n=1}^{9} a_n \rho^n + \exp(-\rho^2/\rho_c^2) \sum_{n=10}^{15} a_n \rho^{2n-17}$$

$$\begin{aligned}
a_1 &= RT \\
a_2 &= b_1 T + b_2 T^{0.5} + b_3 + b_4 / T + b_5 / T^2 \\
a_3 &= b_6 T + b_7 + b_8 T + b_9 / T^2 \\
a_4 &= b_{10} T + b_{11} + b_{12} / T \\
a_5 &= b_{13} \\
a_6 &= b_{14} / T + b_{15} / T^2 \\
a_7 &= b_{16} / T \\
a_8 &= b_{17} / T + b_{18} / T^2 \\
a_9 &= b_{19} / T^2 \\
a_{10} &= b_{20} / T^2 + b_{21} / T^3 \\
a_{11} &= b_{22} / T^2 + b_{23} / T^4 \\
a_{12} &= b_{24} / T^2 + b_{25} / T^3 \\
a_{13} &= b_{26} / T^2 + b_{27} / T^4 \\
a_{14} &= b_{28} / T^2 + b_{29} / T^3 \\
a_{15} &= b_{30} / T^2 + b_{31} / T^3 + b_{32} / T^4
\end{aligned}$$

i	b_i	i	b_i
1	$0.326053658322 \times 10^{-1}$	17	$-0.927939144228 \times 10^{-3}$
2	$-0.846331139371 \times 10^{-1}$	18	0.250947031242×10
3	$-0.305253599792 \times 10^{2}$	19	$-0.755054824294 \times 10^{-1}$
4	$0.917478595120 \times 10^{4}$	20	$-0.171719132604 \times 10^{6}$
5	$-0.165632008187 \times 10^{7}$	21	$-0.404322973367 \times 10^{8}$
6	$-0.474205931664 \times 10^{-2}$	22	$-0.119371454920 \times 10^{5}$
7	0.568175751594×10	23	$0.238466476268 \times 10^{9}$
8	$-0.232029232656 \times 10^{4}$	24	$-0.819911376240 \times 10^{2}$
9	$0.728436638001 \times 10^{6}$	25	$-0.686895987123 \times 10^{4}$
10	$0.214685469778 \times 10^{-3}$	26	$-0.134398312504 \times 10$
11	$0.132142017636 \times 10^{-1}$	27	$-0.107791878226 \times 10^{6}$
12	$-0.421876231759 \times 10^{2}$	28	$-0.161289900259 \times 10^{-1}$
13	$-0.128899645225 \times 10^{-1}$	29	0.705806081763×10
14	0.115735615336×10	30	$0.942860255089 \times 10^{-5}$
15	$-0.483926814735 \times 10^{3}$	31	$-0.562324749115 \times 10^{-1}$
16	$-0.222296460032 \times 10^{-1}$	32	0.499692107366×10

The following critical parameters for HFC-143a were used in determining the MBWR equation of state:

T_c	346.751 K
P_c	38.32 bar
ω_c	5.14868 mol/L

Speed of Sound Measurements

NIST measured the speed of sound in HFC-143a using a cylindrical acoustic resonator. Measurements were conducted along isotherms ranging from 235.0 to 400.0 K (-36.7 to 260.3°F) and at pressures from 40 to 1000 kPa (6 to 145.0 psia). The measurement data [tabulated in DOE/CE/23810-38E, Table 2] were analyzed and fitted to the following equation to determine the ideal gas heat capacity, C_p^o:

$$C_p^o/R = a_0 + a_1T + a_2T^2 + a_3T^3$$

where: SI UNITS

a_0	=	8.77910 ± 0.0081
a_1 (°C^{-1})	=	0.021896 ± 0.00014
a_2 (°C^{-2})	=	$9.681 \times 10^{-6} \pm 6.6 \times 10^{-6}$
a_3 (°C^{-3})	=	$-2.357 \times 10^{-7} \pm 5.0 \times 10^{-8}$
R (gas constant)	=	8.314471 J/(mol·K)

PI UNITS

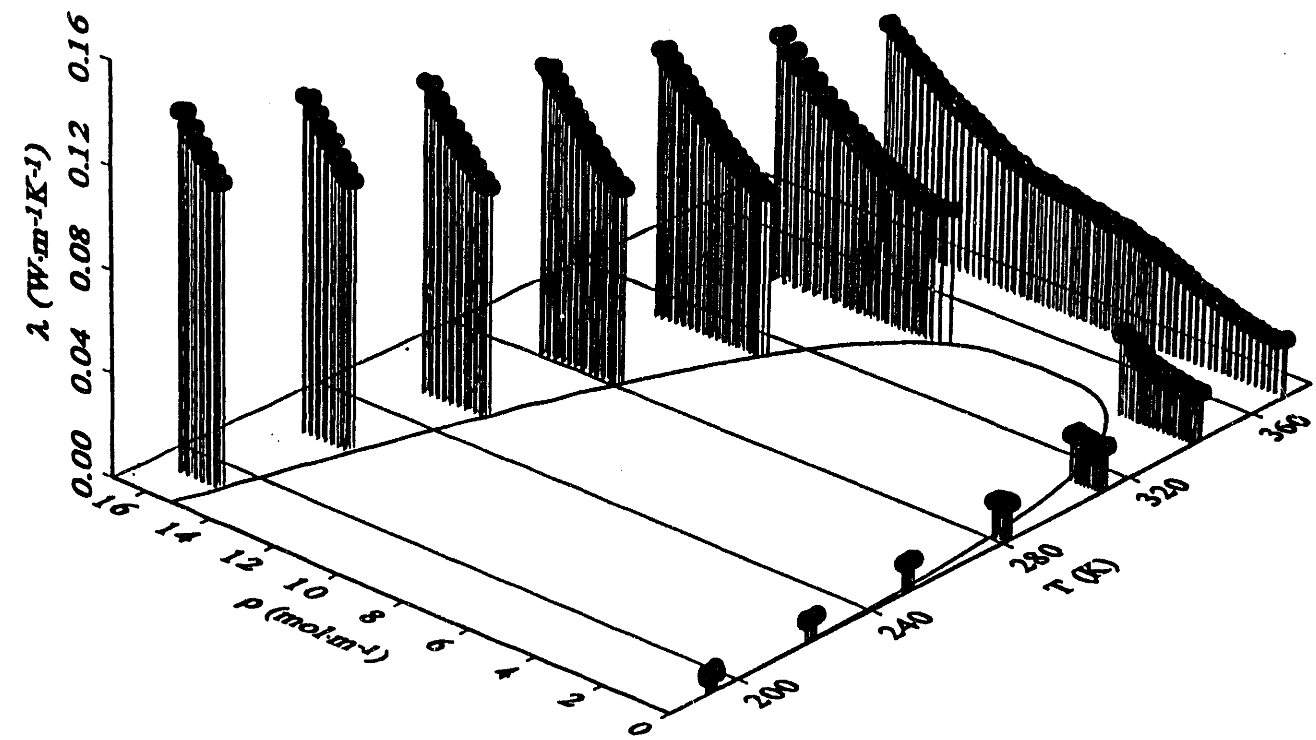
a_0	=	8.39422 ± 0.0087
a_1 (°F^{-1})	=	0.011849 ± 0.00015
a_2 (°F^{-2})	=	$6.868 \times 10^{-6} \pm 2.2 \times 10^{-6}$
a_3 (°F^{-3})	=	$-4.041 \times 10^{-8} \pm 8.6 \times 10^{-9}$
R (gas constant)	=	0.01419457 Btu/(mol·°F)

NIST obtained the second, third and fourth acoustic virial coefficients by analyzing the pressure dependence of the speed of sound. [Results are reported in DOE/CE/23810-38E, Table 3].

Thermal Conductivity Measurements

Thermal conductivity was measured at 1111 points. [Results are tabulated in DOE/CE/23810-38E, Table 8]. Figure 1 depicts a plot of the thermal conductive surface for HFC-143a.

Figure 1. Thermal Conductivity Surface for HFC-143a.



Critical Properties

NIST used an optical cell to measure the refractive index and capillary rise of HFC-143a to determine the critical temperature. The refractive index data and liquid density data were used to deduce the Lorentz-Lorenz constant. and the refractive index data and the Lorentz-Lorenz constant to determine the critical density. Results were reported as follows:

T_c	=	346.75 ± 0.02 K	(164.48 ± 0.04°F)
Lorentz-Lorenz constant	=	0.1347 cm^3/g	
ρ_c	=	432.7 ± 6.9 kg/m^3	(27.01 ± 0.43 lb/ft^3)

HFC-152a

MBWR Equation of State

NIST has revised the 32-term modified Benedict-Webb-Rubin equation of state for HFC-152a, which was reported in the last quarterly report [DOE/CE/23810-33 and DOE/CE/23810-33A]. This revised equation of state will be incorporated into future version of the REFPROP computer program. Table 2 provides the revised coefficients to the equation of state.

NIST reports the equation to be valid at temperatures from 155 to 450 K (-181 to 350°F) and pressures up to 40 MPa (5800 psia). The equation may be reasonably extrapolated up to 500 K (440°F) and pressures up to 100 MPa (14500 psia).

The following critical parameters for HFC-152a were used in determining the MBWR equation of state:

Table	T_c	=	386.441 K
	P_c	=	45.167 bar
	ρ_c	=	5.57145 mol/L

Thermal Conductivity Measurements

NIST has used high-temperature transient hot-wire thermal conductivity instruments to measure the thermal conductivity of HFC-152a at 1470 points. [Results are presented in DOE/CE/23810-38E, Table 13]. Figure 2 depicts the thermal conductivity surface for HFC-152a.

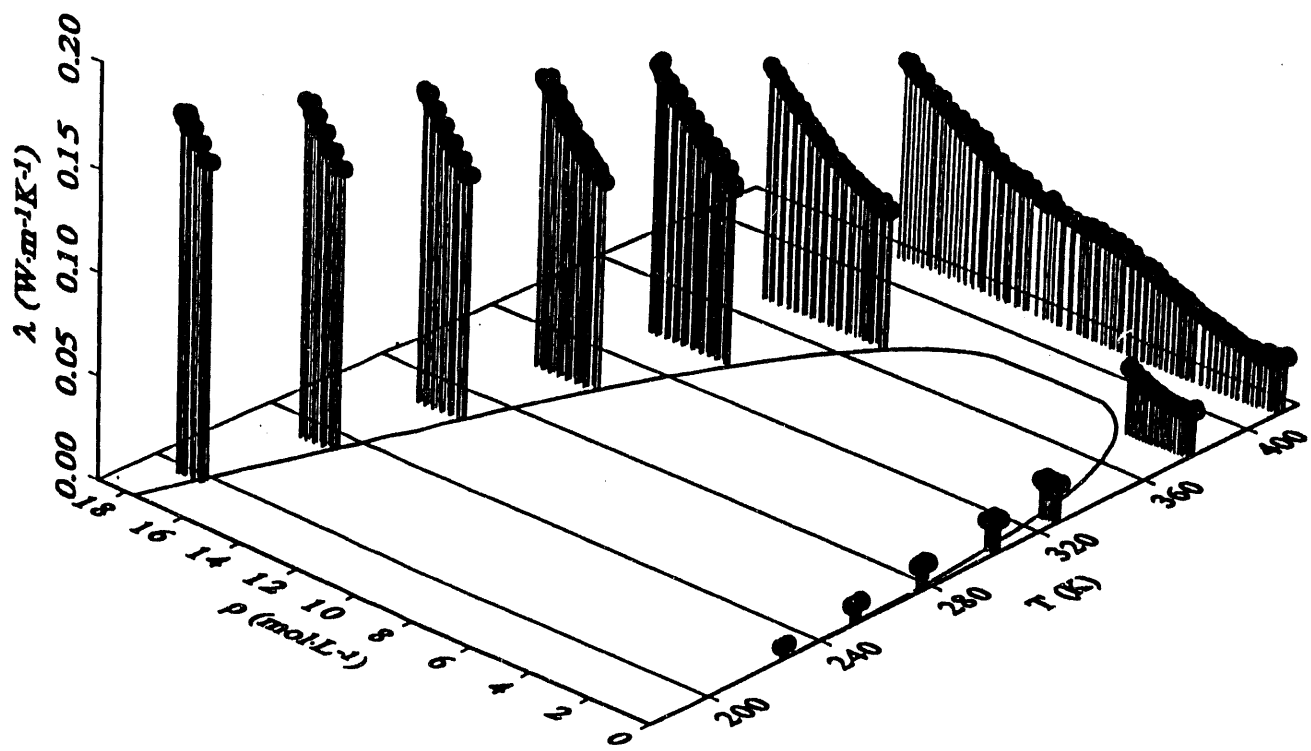
Table 2. Revised Coefficients to the MBWR Equation of State for HFC-152a. (units are K, bar, L, mol)

$$p = \sum_{n=1}^{9} a_n \rho^n + \exp(-\rho^2/\rho_c^2) \sum_{n=10}^{15} a_n \rho^{2n-17}$$

$$\begin{aligned}
a_1 &= RT \\
a_2 &= b_1 T + b_2 T^{0.5} + b_3 + b_4 / T + b_5 / T^2 \\
a_3 &= b_6 T + b_7 + b_8 T + b_9 / T^2 \\
a_4 &= b_{10} T + b_{11} + b_{12} / T \\
a_5 &= b_{13} \\
a_6 &= b_{14} / T + b_{15} / T^2 \\
a_7 &= b_{16} / T \\
a_8 &= b_{17} / T + b_{18} / T^2 \\
a_9 &= b_{19} / T^2 \\
a_{10} &= b_{20} / T^2 + b_{21} / T^3 \\
a_{11} &= b_{22} / T^2 + b_{23} / T^4 \\
a_{12} &= b_{24} / T^2 + b_{25} / T^3 \\
a_{13} &= b_{26} / T^2 + b_{27} / T^4 \\
a_{14} &= b_{28} / T^2 + b_{29} / T^3 \\
a_{15} &= b_{30} / T^2 + b_{31} / T^3 + b_{32} / T^4
\end{aligned}$$

i	b_i	i	b_i
1	$-0.228045823361 \times 10^{-1}$	17	$0.214099003128 \times 10^{-2}$
2	0.303431958631×10	18	0.763280410204
3	$-0.823958103384 \times 10^{2}$	19	$-0.186248644783 \times 10^{-1}$
4	$0.148702974065 \times 10^{5}$	20	$-0.449227267620 \times 10^{6}$
5	$-0.230283972846 \times 10^{7}$	21	$-0.414386750878 \times 10^{8}$
6	$-0.598555815027 \times 10^{-3}$	22	$-0.180824754701 \times 10^{5}$
7	-0.652180504112	23	$0.526311932608 \times 10^{9}$
8	$0.414998934602 \times 10^{3}$	24	$-0.158631034911 \times 10^{3}$
9	$0.682705599404 \times 10^{6}$	25	$0.520191028698 \times 10^{4}$
10	$-0.105074858872 \times 10^{-3}$	26	$-0.151001104140 \times 10$
11	0.524630953619	27	$-0.690665865062 \times 10^{5}$
12	$-0.215263826140 \times 10^{3}$	28	$-0.905780922499 \times 10^{-2}$
13	$-0.143801177834 \times 10^{-1}$	29	0.361488775375×10
14	-0.200517809387	30	$-0.216252082796 \times 10^{-4}$
15	$-0.223863020885 \times 10^{3}$	31	$-0.147563864078 \times 10^{-1}$
16	$0.706005017250 \times 10^{-1}$	32	$-0.108162704937 \times 10$

Figure 2. Thermal Conductivity Surface of HFC-152a.



Speed of Sound Measurements

NIST also measured the speed of sound in HFC-152a using a cylindrical acoustic resonator. Measurements were conducted along isotherms ranging from 242.8 to 400.0 K (-22.7 to 260.3°F) at pressures from 35 to 1030 kPa (5 to 149.4 psia). [The measurements were previously tabulated in Table 8, DOE/CE/23810-33A]. NIST obtained the ideal-gas heat capacity, $C_p°$, by analyzing this data and fitting it to the following equation:

$$C_p°/R = a_0 + a_1T + a_2T^2 + a_3T^3$$

where: SI UNITS

a_0	=	7.6253 ± 0.0041
a_1 (°C^{-1})	=	0.02021 ± 0.00018
a_2 (°C^{-2})	=	$-2.626 \times 10^{-5} \pm 4.6 \times 10^{-6}$
a_3 (°C^{-3})	=	$1.035 \times 10^{-7} \pm 2.8 \times 10^{-8}$
R	=	8.314471 J/(mol·K)

or PI UNITS

a_0	=	7.251 ± 0.0054
a_1 (°F^{-1})	=	0.01180 ± 0.00014
a_2 (°F^{-2})	=	$-9.809 \times 10^{-6} \pm 1.5 \times 10^{-6}$
a_3 (°F^{-3})	=	$1.775 \times 10^{-8} \pm 4.8 \times 10^{-8}$
R	=	0.01419457 Btu/(mol·°F)

MEASUREMENT OF VISCOSITY, DENSITY, AND GAS SOLUBILITY OF REFRIGERANT AZEOTROPES AND BLENDS

Objective:

To measure the viscosity, density, and solubility of three refrigerant mixtures that may potentially replace HCFC-22 or R-502.

Results:

Imagination Resources, Inc., is performing this research under contract with ARTI. A detailed report of its progress is contained in the quarterly technical progress report, DOE/CE/23810-38B, *Measurement of Viscosity, Density, and Gas Solubility of Refrigerant Blends*, 1 January 1994 - 31 March 1994, by Richard C. Cavestri, PhD.

Viscosity, solubility, and density data are reported for the following refrigerant-lubricant pairs:

Baseline pairs:

- HCFC-22 and Suniso® 3GS mineral oil
- R-502 and Suniso® 3GS mineral oil

Single-component refrigerant pairs:

- HFC-134a and 32 ISO mixed-acid polyolester
- HFC-134a and 32 ISO branched-acid polyolester
- HFC-143a and 32 ISO mixed-acid polyolester
- HFC-143a and 32 ISO branched-acid polyolester

Refrigerant-blend pairs:

- HFC-32/HFC-125 (50/50%) and 32 ISO mixed-acid polyolester
- HFC-32/HFC-125 (50/50%) and 32 ISO branched-acid polyolester
- HFC-125/HFC-143a/HFC-134a (44/52/4%) and 32 ISO mixed-acid polyolester
- HFC-125/HFC-143a/HFC-134a (44/52/4%) and 32 ISO branched-acid polyolester

For each refrigerant-lubricant pair, the report graphically presents data from -20 or 0°C to 125°C (-4 or 32°C to 257°F) for a pressure range of 69 to 1,724 kPa (10 to 250 psia):

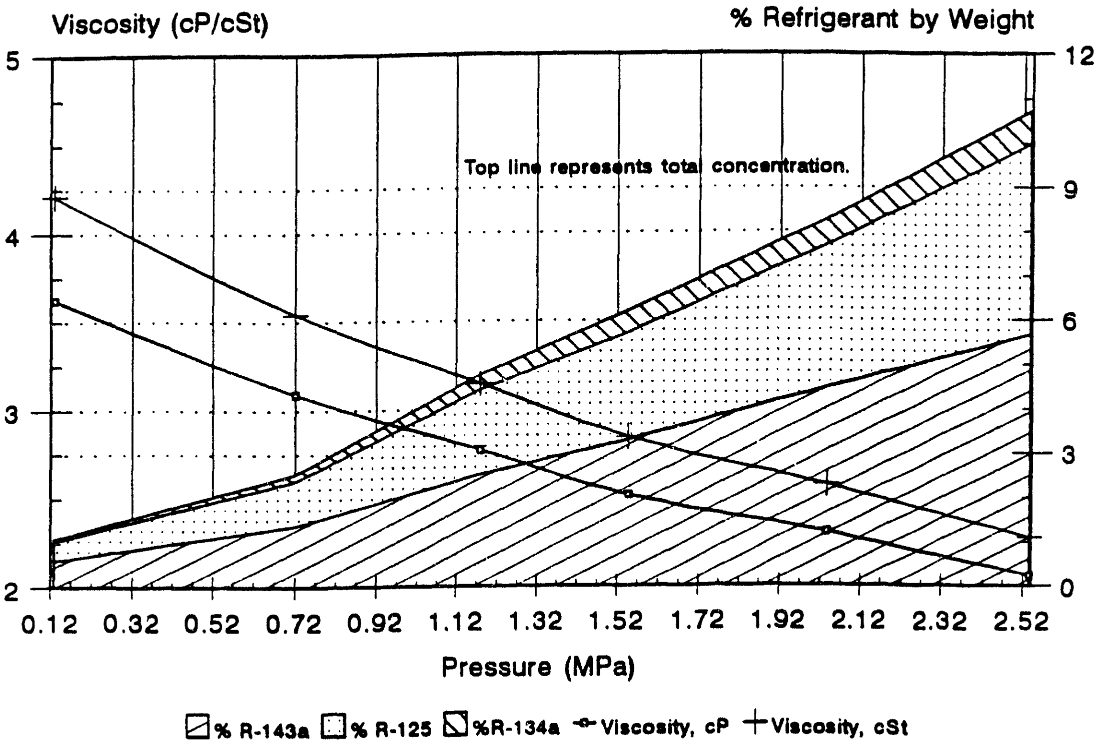
- viscosity vs. pressure at constant refrigerant concentrations (0, 10, 20, 30, 40, 50, and 60%)
- density vs. temperature
- viscosity vs. temperature
- viscosity vs. gas solubility (at temperature intervals of 0, 20, 40, 60, 80, 100, and 125°C)

Figure 3 is an example of the presentation plot for viscosity vs. gas solubility of HFC-125/HFC-143a/HFC-134a (44/52/4%) at 125°C (257°F). It depicts the relationship between reduction in refrigerant-lubricant viscosity with increasing concentration of refrigerant. Gas fractionation of the individual constituents within the refrigerant blend are also indicated.

The draft final report is anticipated in August 1994 and will include viscosity, gas solubility, and density data on HFC-32, HFC-125, and HFC-32/HFC-125/HFC-134a (32/25/52%) with mixed-acid and branched-acid pentaerythritol ester lubricants (ISO 32 cSt).

Figure 3. Viscosity, Solubility and Gas Fractionation

32 ISO VG Mixed Acid Polyolester with Blend 125/143a/134a (44/52/4%) at 125°C



Viscosity via Gas Solubility Equilibrium
Oil degassed to 20 Millitorr

VISCOSITY, SOLUBILITY AND DENSITY MEASUREMENTS OF REFRIGERANT-LUBRICANT MIXTURES

Objective:

To measure the viscosity, solubility, and density of alternative refrigerant-lubricant mixtures

Results:

Spauschus Associates, Inc., is performing this research under contract with ARTI. A detailed report of result is contained in the final report, DOE/CE/23810-34, *Solubility, Viscosity and Density of Refrigerant/Lubricant Mixtures*, by David R. Henderson, PE.

This research involves viscosity, solubility, and density measurements of thirty-eight refrigerant-lubricant mixtures listed below at seven different concentrations (0, 10, 20, 30, 80, 90, and 100% refrigerant by weight):

Baseline Mixtures:

CFC-12/mineral oil (ISO 32 cSt)
CFC-12/mineral oil (ISO 100 cSt)
HCFC-22/mineral oil (ISO 32 cSt)

Test Mixtures:

HFC-134a/polypropylene glycol butyl monoether (ISO 68 cSt)
HFC-134a/pentaerythritol ester - mixed acid (ISO 22 cSt)
HFC-134a/pentaerythritol ester - mixed acid (ISO 32 cSt)
HFC-134a/pentaerythritol ester - mixed acid (ISO 68 cSt)
HFC-134a/pentaerythritol ester - mixed acid (ISO 100 cSt)
HFC-134a/pentaerythritol ester - branched acid (ISO 22 cSt)
HFC-134a/pentaerythritol ester - branched acid (ISO 32 cSt)
HFC-134a/pentaerythritol ester - branched acid (ISO 68 cSt)
HFC-134a/pentaerythritol ester - branched acid (ISO 100 cSt)
HCFC-123/mineral oil (ISO 32 cSt)
HCFC-123/mineral oil (ISO 100 cSt)
HCFC-123/alkylbenzene (ISO 32 cSt)
HCFC-123/alkylbenzene (ISO 68 cSt)

Test Mixtures (Continued):

HFC-32/pentaerythritol ester - mixed acid (ISO 22 cSt)
HFC-32/pentaerythritol ester - mixed acid (ISO 68 cSt)
HFC-32/pentaerythritol ester - branched acid (ISO 32 cSt)
HFC-32/pentaerythritol ester - branched acid (ISO 100 cSt)
HFC-125/pentaerythritol ester - mixed acid (ISO 22 cSt)
HFC-125/pentaerythritol ester - mixed acid (ISO 68 cSt)
HFC-125/pentaerythritol ester - branched acid (ISO 32 cSt)
HFC-125/pentaerythritol ester - branched acid (ISO 100 cSt)
HFC-152a/alkylbenzene (ISO 32 cSt)
HFC-152a/alkylbenzene (ISO 68 cSt)
HFC-152a/pentaerythritol ester - mixed acid (ISO 22 cSt)
HFC-152a/pentaerythritol ester - mixed acid (ISO 68 cSt)
HFC-143a/pentaerythritol ester - mixed acid (ISO 22 cSt)
HFC-143a/pentaerythritol ester - mixed acid (ISO 68 cSt)
HFC-143a/pentaerythritol ester - branched acid (ISO 32 cSt)
HFC-143a/pentaerythritol ester - branched acid (ISO 100 cSt)
HCFC-124/alkylbenzene (ISO 32 cSt)
HCFC-124/alkylbenzene (ISO 68 cSt)
HCFC-142b/alkylbenzene (ISO 32 cSt)

Mr. Henderson presents experimental data for each refrigerant-lubricant mixture in the form of curve fitted mathematical models and two charts. One chart presents the density as a function of temperature and concentration. The other presents viscosity and solubility as functions of temperature for given concentrations (Daniel chart).

Low Refrigerant Concentrations

An oscillating piston viscometer was used to measure viscosities at low refrigerant concentrations. For low refrigerant concentrations viscosity, solubility, and density measurements were fitted to the equations (1) through (4):

High Concentration Refrigerants

The experimental technique used to measure viscosity for the low refrigerant concentration mixtures was unsuitable for measurement of high refrigerant concentration mixtures for a number or reasons. For the high concentration refrigerant mixture viscosity measurements Mr. Henderson used glass capillary viscometers and differential pressure transducers to measure the pressure differences between a reference bomb containing the 100% concentration (neat) refrigerant and the two other bombs containing the 90% and 80% refrigerant concentration mixtures. The viscometers and pressure bombs were thermally controlled in a programmable air bath.

For refrigerant-lubricant mixtures containing HFC-125 or HFC-152a, the refrigerant density is close to the lubricant density which results in data that is not modelled well by the many polynomial equations (cross overs occur near the temperatures where the refrigerant and lubricant densities are equal). For these mixtures containing either of these two refrigerants data was fitted to curves for each concentration.

High refrigerant concentration data (other than HFC-125 and HFC-152a) were fitted to equations (5) through (8). For mixtures containing HFC-125 or HFC-152a, high refrigerant concentration data was fitted to equations (9) through (11).

Multivariate correlation coefficients, σ, have been calculated to measure the fit of the regression equation to the data. The coefficients are derived from the following expression:

$$\sigma = \sqrt{\frac{\Sigma(y_i - y_{av})^2 - \Sigma(y_i - y_c)^2}{\Sigma(y_i - y_{av})^2}}$$

where

y_i = experimental data point

y_c = calculated data point

y_{av} = average of experimental data points

Equations for Low Refrigerant Concentrations

Dynamic viscosity is represented by a modified Walther equation:

$$(1) \quad \log\{\log(\mu + 0.7)\} = \{a_1 + a_2\log(T) + a_3\log^2(T)\} + \omega\{a_4 + a_5\log(T) + a_6\log^2(T)\} + \omega^2\{a_7 + a_8\log(T) + a_9\log^2(T)\}$$

Vapor pressure is represented by:

$$(2) \quad P = \{a_1 + a_2T + a_3T^2\} + \omega\{a_4 + a_5T + a_6T^2\} + \omega^2\{a_7 + a_8T + a_9T^2\}$$

Density is represented by:

$$(3) \quad \rho = \{a_1 + a_2T + a_3T^2\} + \omega\{a_4 + a_5T + a_6T^2\} + \omega^2\{a_7 + a_8T + a_9T^2\}$$

Kinematic viscosity is represented by:

$$(4) \quad \log\{\log(\nu + 0.7)\} = \{a_1 + a_2\log(T) + a_3\log^2(T)\} + \omega\{a_4 + a_5\log(T) + a_6\log^2(T)\} + \omega^2\{a_7 + a_8\log(T) + a_9\log^2(T)\}$$

where:

μ	dynamic (absolute) viscosity, centipoise
P	pressure, kilopascals
ρ	density, gram/cubic centimeter
ν	kinematic viscosity, centistoke
T	temperature, Kelvin
ω	mass fraction refrigerant
$a_1 \ldots a_9$	constants

Equations for High Concentration Refrigerants
(other than HFC-125 and HFC-152a)

Dynamic viscosity is represented by a modified Walther equation:

$$(5)\quad \log(\mu + 0.7) = \{a_1 + a_2/T + a_3/T^2\} + \omega\{a_4 + a_5/T + a_6/T^2\} + \omega^2\{a_7 + a_8/T + a_9/T^2\}$$

Vapor pressure is represented by:

$$(6)\quad \log(P) = \{a_1 + a_2/T + a_3/T^2\} + \omega\{a_4 + a_5/T + a_6/T^2\} + \omega^2\{a_7 + a_8/T + a_9/T^2\}$$

Density is represented by:

$$(7)\quad \rho = \{a_1 + a_2T_r + a_3T_r^2\} + \omega\{a_4 + a_5T_r + a_6T_r^2\} + \omega^2\{a_7 + a_8T_r + a_9T_r^2\}$$

Kinematic viscosity is represented by:

$$(8)\quad \log(\nu + 0.7) = \{a_1 + a_2/T + a_3/T^2\} + \omega\{a_4 + a_5/T + a_6/T^2\} + \omega^2\{a_7 + a_8/T + a_9/T^2\}$$

where:

μ	dynamic (absolute) viscosity, centipoise
P	pressure, kilopascals
ρ	density, gram/cubic centimeter
ν	kinematic viscosity, centistoke
T	temperature, Kelvin
T_c	critical temperature, Kelvin
T_r	$1 - T/T_c$
ω	mass fraction refrigerant
log	logarithm to the base 10
$a_1 \ldots a_9$	constants

Equations for High Refrigerant Concentrations
of HFC-125 and HFC-152a

Kinematic viscosity is represented by:

(9)
$$\log(\nu_{100}) = a_1 + a_2/T + a_3/T^2$$
$$\log(\nu_{90}) = a_4 + a_5/T + a_6/T^2$$
$$\log(\nu_{80}) = a_7 + a_8/T + a_9/T^2$$

Vapor pressure is given by:

(10)
$$\log(P_{100}) = a_1 + a_2/T + a_3/T^2$$
$$\log(P_{90}) = a_4 + a_5/T + a_6/T^2$$
$$\log(P_{80}) = a_7 + a_8/T + a_9/T^2$$

Density is given by:

(11)
$$\omega_{100} = a_1 + a_2T = a_3T^2$$
$$\omega_{90} = a_4 + a_5T = a_6T^2$$
$$\omega_{80} = a_7 + a_8T = a_9T^2$$

where

ν	kinematic viscosity, centistokes
P	kinematic viscosity, centistokes
ω	density, g/cc
log	logarithm to the base 10
T	temperature, Kelvin
$a_1 \ldots a_9$	constants
the subscripts	100, 90, and 80 refer to the mass fraction refrigerant

Mr. Henderson's report contains tables with viscosity, solubility and density parameters density charts and Daniel charts for each of the refrigerant lubricant mixtures measured. Tables 3 and 4 and Figures 4 through 7 are samples of the summaries for HFC-134a and ISO 68 cSt pentaerythritol ester mixed-acid mixtures.

Table 3. Viscosity, Solubility and Density Parameters HFC-134a/ISO 68 Pentaerythritol Ester Mixed-Acid. (Low Refrigerant Concentrations)

Coefficient	Dynamic Viscosity (eq. 1)	Vapor Pressure (eq. 2)	Density (eq. 3)	Kinematic Viscosity (eq. 4)
a_1	1.05204E+1	1.16900E+3	1.20668	1.02380E+1
a_2	-4.11222	-7.39656	-9.16226E-4	-3.99658
a_3	0	1.16084E-2	3.28702E-7	0
a_4	-1.17928E+1	-5.87454E+3	3.67221E-1	-1.20459E+1
a_5	4.18034	-5.09869E+1	4.48469E-5	4.27634
a_6	0	2.65209E-1	-1.13568E-6	0
a_7	2.55320E+1	1.79697E+5	8.22484E-1	2.57746E+1
a_8	-9.93423	-1.02803E+3	-4.69511E-3	-1.00588E+1
a_9	0	1.39473	5.95292E-6	0
σ	0.9993	0.9998	0.9999	0.9993

Figure 4. Density of HFC-134a/ISO 68 Pentaerythritol Ester Mixed-Acid. (Low Refrigerant Concentrations)

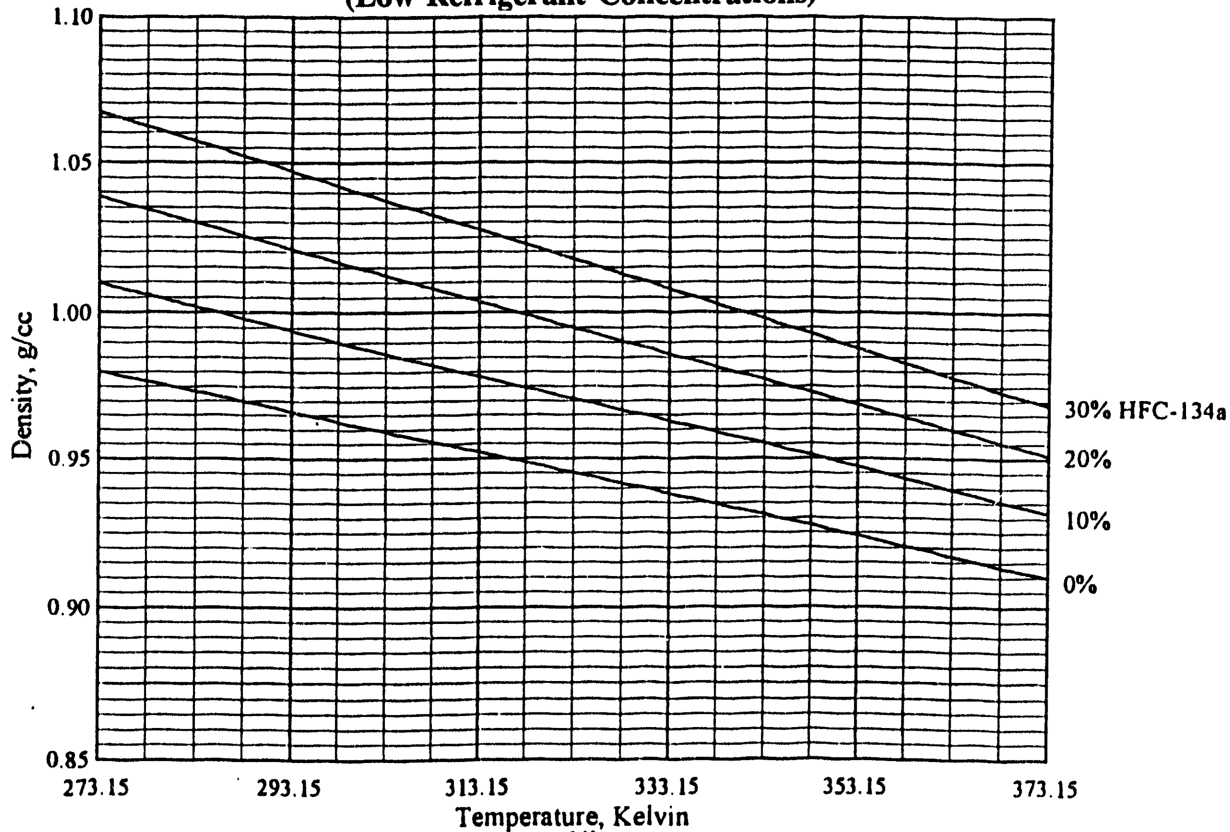


Figure 5. Viscosity and Solubility of HFC-134a/ISO 68 Pentaerythritol Ester Mixed-Acid. (Low Refrigerant Concentrations)

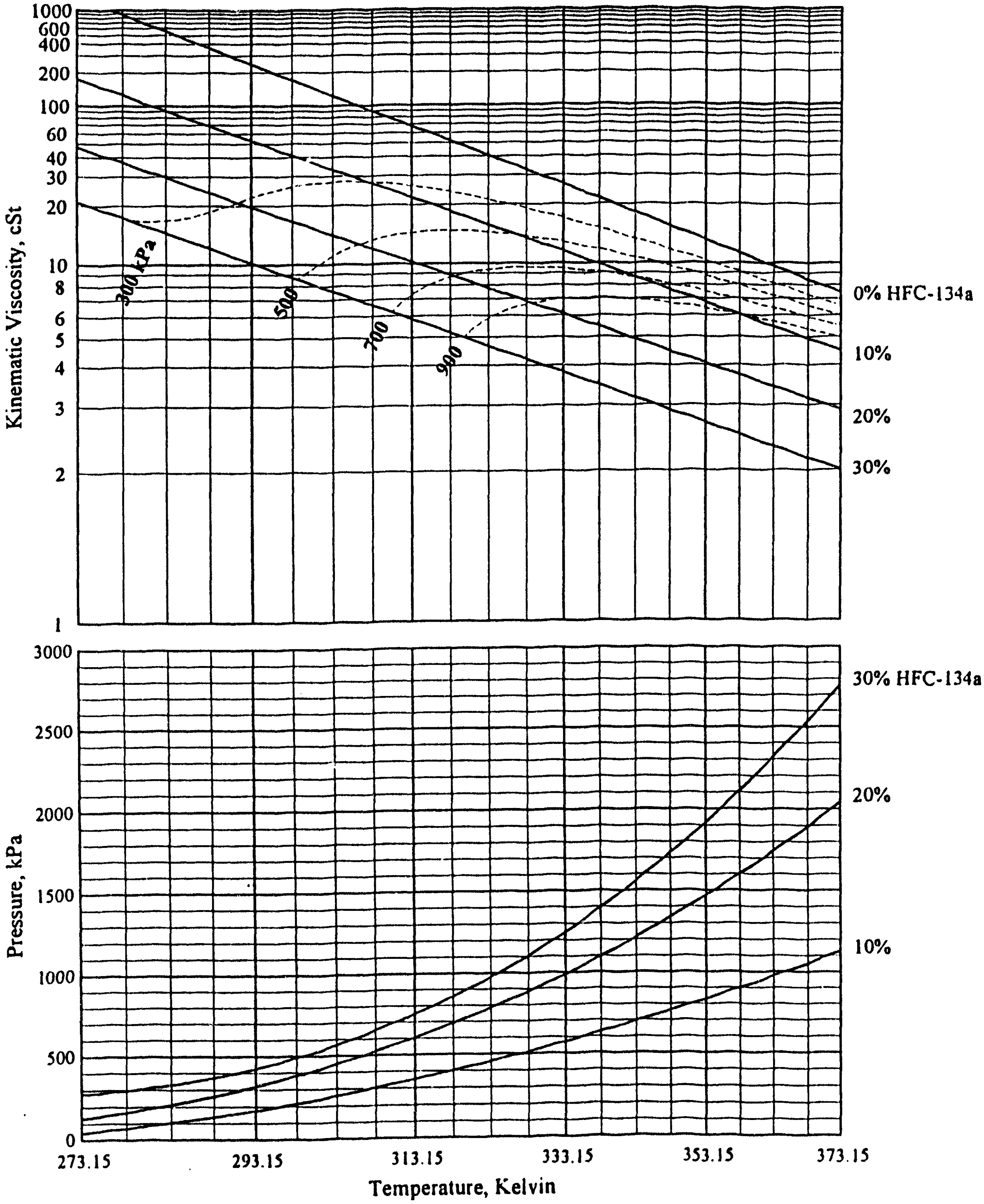


Table 4. Viscosity, Solubility and Density Parameters HFC-134a/ISO 68 Pentaerythritol Ester Mixed-Acid. (High Refrigerant Concentrations)

Coefficient	Dynamic Viscosity (eq. 5)	Vapor Pressure (eq. 6)	Density (eq. 7)	Kinematic Viscosity (eq. 8)
a_1	-1.54267E-1	4.93501	-6.03916E-2	6.70804E-1
a_2	-1.30839E+2	-3.90373E+2	-2.50554	-1.13257E+2
a_3	1.89773E+5	-9.75213E+4	1.66826	1.90778E+5
a_4	-1.35162	1.98743	1.30515	-2.54713
a_5	-1.84121E+2	-6.29632E+2	5.39346	-2.84865E+2
a_6	-9.66564E+4	5.83317E+4	-4.46156	-9.66465E+4
a_7	-7.89904E-1	9.65170E-1	-3.42380E-1	3.26527E-1
a_8	8.13268E+2	-7.75785E+2	-1.35909	5.19287E+2
a_9	-1.03939E+5	1.23434E+5	2.26507	-6.55262E+4
σ	0.9999	0.9999	0.9999	0.9999

Figure 6. Density of HFC-134a/ISO 68 Pentaerythritol Ester Mixed-Acid. (High Refrigerant Concentrations)

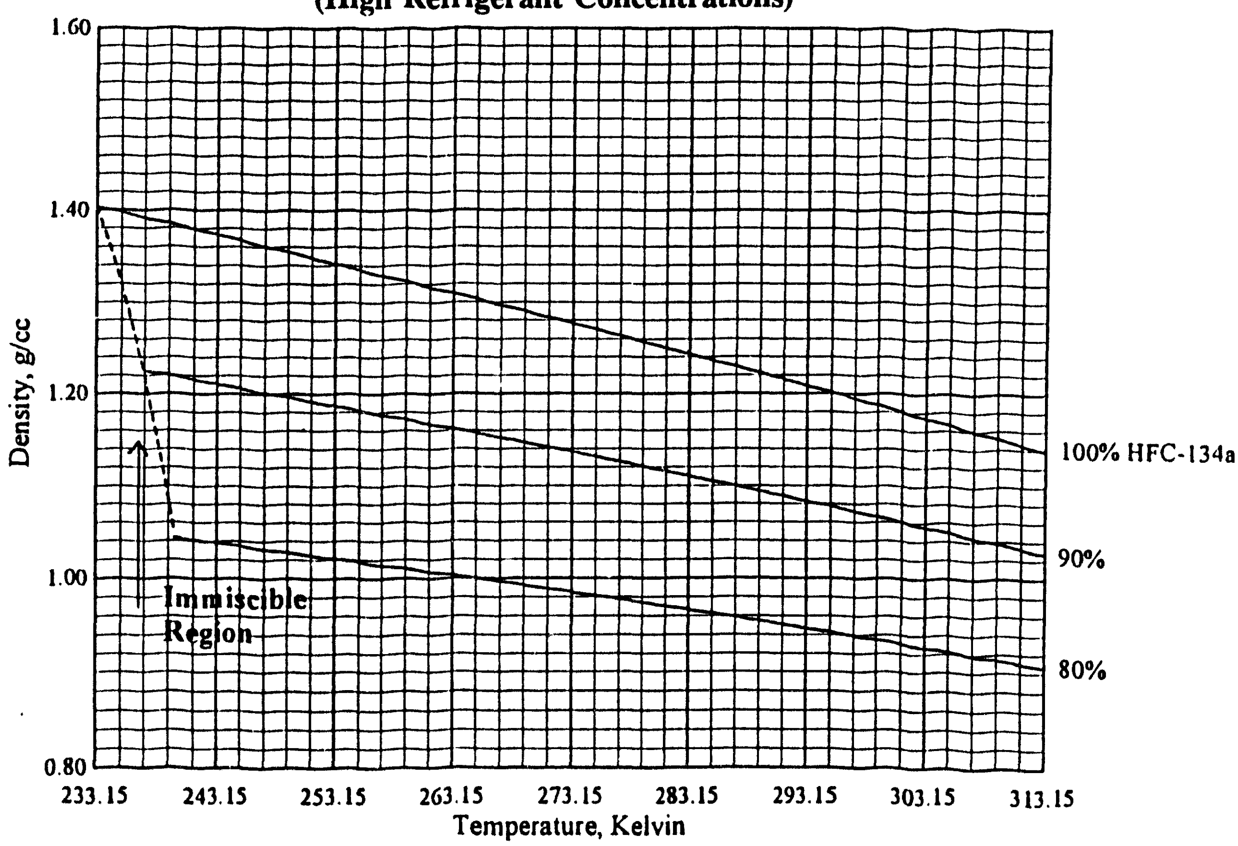
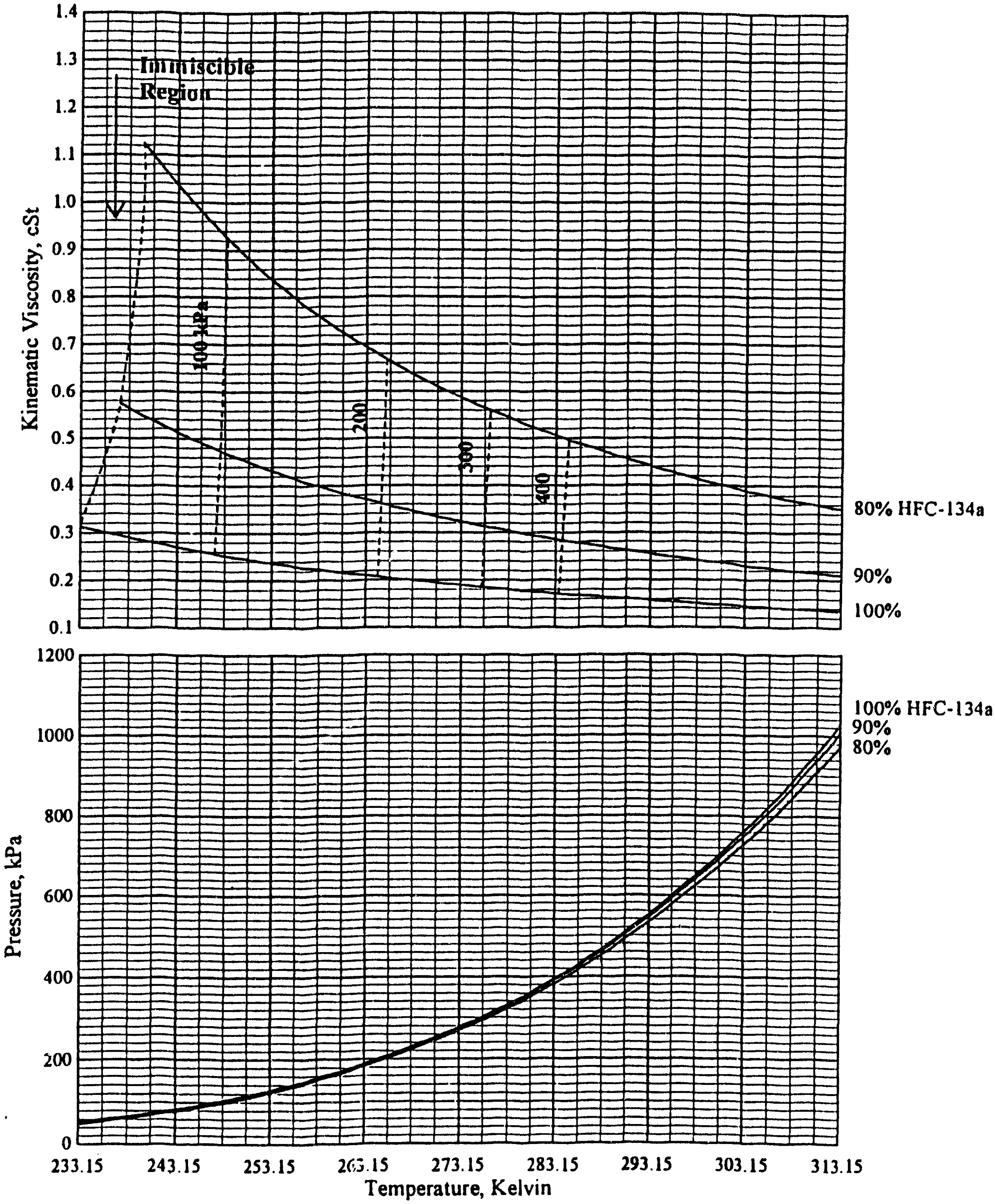


Figure 7. Viscosity and Solubility of HFC-134a/ISO 68 Pentaerythritol Ester Mixed-Acid. (High Refrigerant Concentrations)



SEALED TUBE COMPARISONS OF THE COMPATIBILITY OF DESICCANTS WITH REFRIGERANTS AND LUBRICANTS

Objectives:

To provide compatibility information for desiccants with potential substitutes for CFC refrigerants and suitable lubricants.

To obtain data on chemical and thermal stability of desiccants exposed to refrigerant-lubricant mixtures under anticipated operating conditions.

Results:

Spauschus Associates, Inc., is performing this research under contract with ARTI. A detailed report of progress in contained in the quarterly technical progress report, DOE/CE/23810-38A, *Sealed Tube Comparisons of the Compatibility of Desiccants with Refrigerants and Lubricants*, 1 January 1994 - 31 March 1994, by Jay E. Field, PhD.

This project will determine the compatibility of sixteen desiccants in thirteen refrigerant-lubricant mixtures using bench-scale sealed tube tests. Samples will be obtained from two manufacturers for the following eight categories of desiccants:

1. 4A molecular sieve
2. 3A molecular sieve
3. alumina
4. silica gel
5. core type with carbon
    - 10 to 25% molecular sieve type 3A
    - alumina
    - 5 to 15% carbon
    - 10 to 20% phosphate binder
6. core type with carbon
    - 10 to 25% molecular sieve type 4A
    - alumina
    - 5 to 15% carbon
    - 10 to 20% phosphate binder
7. core type without carbon
    - 15 to 30% molecular sieve type 3A
    - alumina
    - 10 to 20% phosphate binder

8. core type without carbon
   15 to 30% molecular sieve type 4A
   Alumina
   10 to 20% phosphate binder

Refrigerant-Lubricant Mixtures Under Study:

1. CFC-11 with naphthenic mineral oil
2. CFC-12 with naphthenic mineral oil
3. HCFC-22 with naphthenic mineral oil
4. HCFC-123 with naphthenic mineral oil
5. HFC-134a with pentaerythritol mixed-acid polyolester lubricant
6. HFC-134a with pentaerythritol branched-acid polyolester lubricant
7. HFC-152a with alkylbenzene lubricant (or with pentaerythritol mixed-acid polyolester lubricant.
8. HFC-32 with pentaerythritol mixed-acid polyolester lubricant
9. HFC-32 with pentaerythritol branched-acid polyolester lubricant
10. HCFC-124 with alkylbenzene lubricant
11. HFC-125 with pentaerythritol mixed-acid polyolester lubricant
12. HFC-125 with pentaerythritol branched-acid polyolester lubricant
13. HFC-143a with pentaerythritol branched-acid polyolester lubricant

The following tests will be conducted on unexposed desiccant, refrigerant and lubricant samples and compared with samples exposed for 28 days at 149°C:

Visual Inspection
Desiccant Crush Strength
GC Refrigerant Decomposition
Lubricant Total Acid Number
Liquid Phase Halide Ion/Acid Anion
Desiccant Halide Ion/Acid Anion

Dr. Starr has begun analyzing results of desiccant compatibility with several of the refrigerant-lubricant combinations. Current data is provided in Tables 5 through 10.

Code Key For Summary Test Results Tables

Liquid Color
Colors follow ASTM Standard D1500. However, 8 mm internal diameter is much less than that specified. Therefore, colors "0" through "2" appear the same. The first number listed is the color before aging and the second number is the color after aging.

- 2.0 Water clear
- 2.5 Very Faint Yellow
- 3.0 Pale Yellow
- 3.5 Light Yellow
- 4.0 Yellow
- 4.5 Yellow-Orange
- 5.0 Light Orange
- 5.5 Orange
- 6.0 Orange-Brown
- 6.5 Brown
- 7.0 Dark Brown
- 7.5 Brown-Black
- 8.0 Black

Desiccant Color

- 0 No change
- 1 Darker
- 2 Very Dark
- 3 Black

Copper Plating

- 0 none
- 1 spots on edges
- 2 edges covered
- 3 spots on surface
- 4 Partially coated surface
- 5 Fully coated surface

Solids Formation

- 0 None
- 1 small amount
- 2 medium amount
- 3 heavy amount

Steel Corrosion

- 0 None
- 1 Spot darkening
- 2 Complete darkening
- 3 Pitting or coating

Crush Strength
The value entered is the average Crush Strength in pounds.

GC % Refrigerant Reacted
Based on peak area ratios for largest decomposition product detected.

Total Acid Number
mg of KOH per gram of oil.

F ion in Liquid
The ppm by weight for the concentration of F ion in the liquid phase from the aged tube.

F ion on Desiccant
ppm based on weight of desiccant.

Cl ion in Liquid
The ppm by weight for the concentration of Cl ion in the liquid phase from the aged tube.

Cl ion on Desiccant
ppm based on weight of desiccant.

Organic Acid in Liquid
Sum of the ppm results for all organic anions found in the liquid phase from the aged tube

Organic Acid on Desiccant
Sum of the ppm results for all organic anions found based on the desiccant weight.

Table 5. Desiccant A - 4A Molecular Sieve.

Summary Test Results

Code	System Fluids	Liquid Color (2-8)	Desic Color (0-3)	Copper Plating (0-6)	Solids Formation (0-3)	Steel Corrosion (0-3)	Crush Strength (lbs)	GC % Ref Reacted (wt %)	Total Acid Number (mg KOH)	F Ion in Liquid (ppm)	F Ion on Desiccant (ppm)	Cl Ion in Liquid (ppm)	Cl Ion on Desiccant (ppm)	Org Acid in Liquid (ppm)	Org Acid on Desic (ppm)
A-New	None	2.5	0	-	-		17.3	-	-	0	190	0	15	0	1,740
	50 ppm Moisture														
A-11	R11/mineral oil														
A-12	R12/mineral oil	4.0	1	0	0	0	13.3	0.0	<0.1	4	670	28	1,560	60	2,600
A-13	R22/mineral oil	3.5	2	0	0	1	17.0	0.7	<0.1	6	1,840	370	2,500	0	3,870
A-14	R123/mineral oil														
A-15	R134a/ mixed ester	2.5	1	0	0	0	14.7	0.0	0.5	0	85	0	0	2,310	7,120
A-16	R134a/branched ester														
A-17	R152a/alkylbenzene	4.0	2	0	0	0			<0.1	2	1,570	0	0	2,210	650
A-18	R32/mixed ester	3.0	2	0	0	1	9.2	3.3	5.6	4	5,340	5	18	11,630	6,070
A-19	R32/branched ester	2.5	0	0	0	0	6.6	2.2	1.2	6	3,480	6	9	4,460	6,890
A-20	R124/alkylbenzene	3.0	0	0	0	0			<0.1	1	80	9	61	6	1,530
A-21	R125/mixed ester	2.5	0	0	0	0			<0.1	1	65	4	7	1,840	5,770
A-22	R125/branched ester	2.5	0	0	0	0			0.1	1	51	3	9	730	4,040
A-23	R143a/branched ester	2.5	0	0	0	0			0.3						
	1000 ppm Moisture														
A-41	R11/mineral oil														
A-42	R12/mineral oil	4.0	1	0	0	0	13.1	0.0	0.1	2	1,240	21	1,390	90	2,970
A-43	R22/mineral oil	3.5	2	0	0	1	20.1	0.6	<0.1	12	1,920	570	25,830	0	3,930
A-44	R123/mineral oil														
A-45	R134a/ mixed ester	2.5	1	0	0	0	11.1	0.0	0.5	0	84	0	11	1,950	8,880
A-46	R134a/branched ester														
A-47	R152a/alkylbenzene	4.0	2	0	0	0			0.2	1	1,210	0	18	2,060	610
A-48	R32/mixed ester	3.0	2	0	0	1	8.8	3.6	4.6	0	5,840	3	18	12,250	6,800
A-49	R32/branched ester	2.5	0	0	0	0			1.4	6		0		3,360	
A-50	R124/alkylbenzene	3.0	0	0	0	0			<0.1	1	140	11	55	18	1,430
A-51	R125/mixed ester	3.0	0	0	0	0			<0.1	1		6		2,760	
A-52	R125/branched ester	2.5	0	0	0	0			0.1	1	57	6	9	1,300	4,500
A-53	R143a/branched ester	2.5	0	0	0	0			0.6	0	47	8	17	2,030	4,960

Table 6. Desiccant E - 4A Molecular Sieve.

Summary Test Results

Code	System Fluids	Liquid Color (2-8)	Desic Color (0-3)	Copper Plating (0-5)	Solids Formation (0-3)	Steel Corrosion (0-3)	Crush Strength (lbs)	GC % Ref Reacted (wt %)	Total Acid Number (mg KOH)	F ion in Liquid (ppm)	F ion on Desiccant (ppm)	Cl ion in Liquid (ppm)	Cl ion on Desiccant (ppm)	Org Acid in Liquid (ppm)	Org Acid on Desic (ppm)
E-New	None	2.5		-	-		30.9	-	-	0	10	0	11	0	430
	50 ppm Moisture														
E-11	R11/mineral oil														
E-12	R12/mineral oil	3.5	1	0	0	0	27.0	0.0	<0.1	1	440	18	660	73	610
E-13	R22/mineral oil	4.0	2	0	0	1			<0.1	2	3,110	340	24,940	0	3,460
E-14	R123/mineral oil														
E-15	R134a/ mixed ester	2.5	1	0	0	0	21.9	0.0	<0.1	0	91	0	14	480	2,130
E-16	R134a/branched ester														
E-17	R152a/alkylbenzene	4.5	2	0	0	1			3.0	3	2,790	0	0	3,320	940
E-18	R32/mixed ester	3.0	2	0	0	1	21.0	2.7	4.7	0	5,270	0	0	10,020	5,170
E-19	R32/branched ester	2.5	0	0	0	0	17.7	1.6	1.5	14	3,900	0	0	7,460	9,360
E-20	R124/alkylbenzene	2.5	0	0	0	0			<0.1	2	42	6	21	4	12
E-21	R125/mixed ester	2.5	0	0	0	0			0.1	1		6		2,230	
E-22	R125/branched ester	2.5	0	0	0	0			<0.1	0	1	2	6	110	610
E-23	R143a/branched ester	2.5	0	0	0	0			0.2	0	3	9	6	840	240
	1000 ppm Moisture														
E-41	R11/mineral oil														
E-42	R12/mineral oil	3.0	1	0	0	0	23.6	0.0	<0.1	1	570	18	720	120	720
E-43	R22/mineral oil	2.5	2	0	0	1	30.8	0.7	<0.1	1	2,910	87	25,800	0	4,260
E-44	R123/mineral oil														
E-45	R134a/ mixed ester	2.5	1	0	0	1	25.8	0.0	0.2	0	84	0	0	150	1,690
E-46	R134a/branched ester														
E-47	R152a/alkylbenzene	4.5	2	0	0	2			2.0	8	3,340	0	7	2,770	580
E-48	R32/mixed ester	3.0	2	0	0	1	17.2	2.7	5.1	0	4,970	0	0	14,260	5,130
E-49	R32/branched ester	2.5	0	0	0	0			1.5	18	3,500	0	0	7,330	4,620
E-50	R124/alkylbenzene	2.5	0	0	0	0			<0.1	3	27	9	20	19	100
E-51	R125/mixed ester	3.0	0	0	0	0			<0.1	1		2		230	
E-52	R125/branched ester	2.5	0	0	0	0			0.1	0	1	5	6	510	710
E-53	R143a/branched ester	2.5	0	0	0	0			<0.1	0	200	8	28	170	1,720

Table 7. Desiccant F - 3A Molecular Sieve.

Summary Test Results

Code	System Fluids	Liquid Color (2-8)	Desic Color (0-3)	Copper Plating (0-6)	Solids Formation (0-3)	Steel Corrosion (0-3)	Crush Strength (lbs)	GC % Ref Reacted (wt %)	Total Acid Number (mg KOH)	F Ion in Liquid (ppm)	F Ion on Desiccant (ppm)	Cl Ion in Liquid (ppm)	Cl Ion on Desiccant (ppm)	Org Acid in Liquid (ppm)	Org Acid on Desic (ppm)
F-New	None	2.5		-	-		20.0	-	-	0	160	0	23	0	1260
	50 ppm Moisture														
F-11	R11/mineral oil														
F-12	R12/mineral oil	4.5	1	0	0	0	18.0	0.1	1.3	41	1580	130	6500	140	1900
F-13	R22/mineral oil	2.5	1	0	0	0			0.1	47	1170	220	16710	4	1850
F-14	R123/mineral oil														
F-15	R134a/ mixed ester	2.5	1	0	0	0	18.1	0.0	0.3	0	130	0	19	740	10950
F-16	R134a/branched ester														
F-17	R152a/alkylbenzene	3.0	0	0	0	0			<0.1	3	1300	13	17	300	1000
F-18	R32/mixed ester	3.0	2	0	0	1	9.5	2.0	0.2	14	5670	5	110	6040	8400
F-19	R32/branched ester	2.5	1	0	0	0	11.9	0.9	1.9	17	1730	0	59	1660	1410
F-20	R124/alkylbenzene	2.5	1	0	0	0			<0.1	3	120	8	500	100	1190
F-21	R125/mixed ester	2.5	1	0	0	0			0.3						
F-22	R125/branched ester	2.5	1	0	0	0			<0.1	0	61	2	17	560	4280
F-23	R143a/branched ester	2.5	1	0	0	1			<0.1		77		36		2950
	1000 ppm Moisture														
F-41	R11/mineral oil														
F-42	R12/mineral oil	4.5	0	0	0	0	18.6	0.1	<0.1	52	1390	76	5770	90	2120
F-43	R22/mineral oil	2.5	1	0	0	0	11.6	0.5	<0.1	25	900	92	10500	0	960
F-44	R123/mineral oil														
F-45	R134a/ mixed ester	2.5	1	0	0	1	13.8	0.0	0.2	0	120	0	26	1210	11410
F-46	R134a/branched ester														
F-47	R152a/alkylbenzene	3.0	0	0	0	0			<0.1	12	1190	15	24	710	460
F-48	R32/mixed ester	3.0	2	0	0	1			0.3	70	1960	2	148	2920	3940
F-49	R32/branched ester	2.5	0	0	0	1	13.2	1.1	1	17	1470	0	53	2380	1480
F-50	R124/alkylbenzene	2.5	1	0	0	0			<0.1	4	100	15	370	1	1080
F-51	R125/mixed ester	2.5	1	0	0	1			0.4						
F-52	R125/branched ester	2.5	1	0	0	0			0.1	1	53	8	11	1240	4160
F-53	R143a/branched ester	2.5	1	0	0	1			0.2	0		4		1040	[illegible]

Table 8. Desiccant H - 3A Molecular Sieve.

Summary Test Results

Code	System Fluids	Liquid Color (2-8)	Desic Color (0-3)	Copper Plating (0-8)	Solids Formation (0-3)	Steel Corrosion (0-3)	Crush Strength (lbs)	GC % Ref Reacted (wt %)	Total Acid Number (mg KOH)	F Ion in Liquid (ppm)	Fl Ion on Desiccant (ppm)	Cl Ion in Liquid (ppm)	Cl Ion on Desiccant (ppm)	Org Acid in Liquid (ppm)	Org Acid on Desic (ppm)
H-New	None	2.5		-	-		34.6	-	-	0	18	0	4	0	184
	50 ppm Moisture														
H-11	R11/mineral oil														
H-12	R12/mineral oil	3.5	1	0	0	0	24.4	0	<0.1	4	1010	24	1600	110	820
H-13	R22/mineral oil	3.0	0	0	0	1	24.2	2	<0.1	10	2000	650	22720	0	2640
H-14	R123/mineral oil														
H-15	R134a/ mixed ester	2.5	1	0	0	0	18.8	0	0.8	0	18	0	11	1490	3970
H-16	R134a/branched ester														
H-17	R152a/alkylbenzene	3.5	2	0	0	0			0.2	18	1720	0	0	760	322
H-18	R32/mixed ester	3.0	2	0	0	0	15.6	3	0.4	1280	8530	0	0	11390	9650
H-19	R32/branched ester	2.5	0	0	0	0	16.4	3	0.2	16	4270	0	0	5700	5310
H-20	R124/alkylbenzene	2.5	0	0	0	0			<0.1	2	58	6	86	40	290
H-21	R125/mixed ester	2.5	0	0	0	0			0.6	0		3		1230	
H-22	R125/branched ester	2.5	0	0	0	0			0.4	0	7	5	6	1090	1630
H-23	R143a/branched ester	2.5	0	0	0	0			<0.1		9		13		1030
	1000 ppm Moisture														
H-41	R11/mineral oil														
H-42	R12/mineral oil	3.5	1	0	0	0	24.5	0	<0.1	2	432	21	754	100	750
H-43	R22/mineral oil														
H-44	R123/mineral oil														
H-45	R134a/ mixed ester	2.5	1	0	0	1	20.6	0	0.7	0	12	0	0	1760	3380
H-46	R134a/branched ester														
H-47	R152a/alkylbenzene	3.5	2	0	0	0			<0.1	14	1090	0	5	2130	160
H-48	R32/mixed ester	2.5	2	0	0	1	15.1	3	0.4	10	9570	0	0	12040	12400
H-49	R32/branched ester	2.5	0	0	0	0			<0.1	13	4620	0	0	5390	4670
H-50	R124/alkylbenzene	2.5	0	0	0	0			0.2	4	44	8	72	110	320
H-51	R125/mixed ester	2.5	0	0	0	0			0.9	1		0		2420	
H-52	R125/branched ester	2.5	0	0	0	0			0.6	0	4	0	5	2060	2040
H-53	R143a/branched ester	2.5	0	0	0	0			0.6						

Table 9. Desiccant I - Alumina.

Summary Test Results

Code	System Fluids	Liquid Color (2-8)	Desic Color (0-3)	Copper Plating (0-5)	Solids Formation (0-3)	Steel Corrosion (0-3)	Crush Strength (lbs)	GC % Ref Reacted (wt %)	Total Acid Number (mg KOH)	F Ion in Liquid (ppm)	F Ion on Desiccant (ppm)	Cl Ion in Liquid (ppm)	Cl Ion on Desiccant (ppm)	Org Acid in Liquid (ppm)	Org Acid on Desic (ppm)
I-New	None	2.5		-	-		11.9	-	-	0	2	0	59	0	3900
	50 ppm Moisture														
I-11	R11/mineral oil														
I-12	R12/mineral oil	3.0	1	0	0	0	9.5	0	<0.1	3	10	21	4630	90	1550
I-13	R22/mineral oil	6.0	3	0	2	1	10.2	8.5	<0.1	1	4800	220	10130	7	2900
I-14	R123/mineral oil														
I-15	R134a/ mixed ester	2.5	0	0	0	0	10.7	0.2	3.1	0	0	0	20	4970	33930
I-16	R134a/branched ester														
I-17	R152a/alkylbenzene	4.5	1	0	0	3			4.2						
I-18	R32/mixed ester	7.5	2	0	3	3	14.3	19	>30	29500	10650	100	19	52480	4580
I-19	R32/branched ester	3.5	2	0	0	1			20.9	1250	10600	12	0	42600	31130
I-20	R124/alkylbenzene	2.5	0	0	0	0			<0.1	2	32	7	1830	72	1420
I-21	R125/mixed ester	3.0	0	0	0	1			1.0	0		3		3470	
I-22	R125/branched ester	2.5	0	0	0	1			2.0	0	2	4	20	2320	13530
I-23	R143a/branched ester	2.5	0	0	0	1			2.2	0	0	6	63	2300	9730
	1000 ppm Moisture														
I-41	R11/mineral oil														
I-42	R12/mineral oil	3.0	1	0	0	0	12.3	0	0.1						
I-43	R22/mineral oil									9	3000	740	9640	76	1470
I-44	R123/mineral oil														
I-45	R134a/ mixed ester														
I-46	R134a/branched ester														
I-47	R152a/alkylbenzene														
I-48	R32/mixed ester														
I-49	R32/branched ester														
I-50	R124/alkylbenzene														
I-51	R125/mixed ester														
I-52	R125/branched ester														
I-53	R143a/branched ester														

Table 10. Desiccant K - Silica Gel.

Summary Test Results

Code	System Fluids	Liquid Color (2-8)	Desic Color (0-3)	Copper Plating (0-8)	Solids Formation (0-3)	Steel Corrosion (0-3)	Crush Strength (lbs)	GC % Ref Reacted (wt %)	Total Acid Number (mg KOH)	F Ion in Liquid (ppm)	F Ion on Desiccant (ppm)	Cl Ion in Liquid (ppm)	Cl Ion on Desiccant (ppm)	Org Acid in Liquid (ppm)	Org Acid on Desic (ppm)
K-New	None	2.5		-	-		76.4	-	-	-	3	-	14	0	0
	50 ppm Moisture														
K-11	R11/mineral oil														
K-12	R12/mineral oil	2.5	0	0	0	0	50.8	0	<0.1	8	330	600	320	150	10
K-13	R22/mineral oil	2.5	1	0	0	2	51.9	0	0.1	2	650	330	330	0	200
K-14	R123/mineral oil														
K-15	R134a/ mixed ester	2.5	1	0	0	2	85.3	0.02	21.1	0	0	0	0	24010	20920
K-16	R134a/branched ester														
K-17	R152a/alkylbenzene	2.5	2	0	0	0			<0.1	66	3630	0	2	760	0
K-18	R32/mixed ester	2.5	0	0	0	3	11.9	0	14.3	4	11	3	0	22120	11070
K-19	R32/branched ester	2.5	1	0	0	2	12.3		17.8	2	22	0	0	18470	6680
K-20	R124/alkylbenzene	2.5	0	1	0	2			<0.1	3	10	17	27	130	43
K-21	R125/mixed ester	3.0	1	0	0	3			2.2	0	0	13	6	18340	12170
K-22	R125/branched ester	2.5	1	0	1	1			13.6	0	11	7	0	19160	7100
K-23	R143a/branched ester	2.5	1	0	0	2			13.3	1	5.4	33	32	12890	8310
	1000 ppm Moisture														
K-41	R11/mineral oil														
K-42	R12/mineral oil	2.5	2	0	0	1	86.1								
K-43	R22/mineral oil								<0.1	45	750	870	170	76	730
K-44	R123/mineral oil														
K-45	R134a/ mixed ester														
K-46	R134a/branched ester														
K-47	R152a/alkylbenzene														
K-48	R32/mixed ester														
K-49	R32/branched ester														
K-50	R124/alkylbenzene														
K-51	R125/mixed ester														
K-52	R125/branched ester														
K-53	R143a/branched ester														

ACCELERATED SCREENING METHODS FOR PREDICTING LUBRICANT PERFORMANCE IN REFRIGERANT COMPRESSORS

Objective:

To propose or devise a bench test device for conducting lubricity tests that simulates conditions in refrigeration and air-conditioning compressors.

Results:

The University of Illinois at Urbana-Champaign is performing this research under contract with ARTI. An interim report detailing Falex® comparisons is available under DOE report number DOE/CE/23810-35, *Accelerated Screening Methods for Predicting Lubricant Performance in Refrigerant Compressors*, January 1994, by C. Cusano, PhD.

Refrigerants and lubricants tested in the program are:

CFC-12 and mineral oil	---	CFC baseline
HCFC-22 and mineral oil	---	HCFC baseline
HFC-134a and pentaerythritol ester lubricants	---	HFC evaluation
R-32/125/134a (30/10/60%) and ester lubricants	---	blend evaluation

Comparison of HPT Results with Falex® Test Results

Qualitative Falex® results provided by three air-conditioning and refrigeration compressor manufacturers were compared against data measured in the University of Illinois' proprietary high pressure tribometer (HPT). The contact geometries, speeds, and refrigerant-lubricant mixtures used by the manufacturers in obtaining the Falex® results were modeled in the HPT. However, whereas the Falex® tests were conducted at room temperature and atmospheric pressure at relatively high contact loads, the HPT tests were performed at temperatures, pressures and load conditions that better approximate critical contacts in scroll and reciprocating compressors. The following contact pairs were evaluated for friction and wear (e.g., wear scars, wear surface, and surface roughness) in unidirectional or oscillating contact tests:

SAE 380 die cast aluminum with carburized 1018 low carbon steel

SAE 356 die cast aluminum with hardened steel drill rod

gray cast iron with SAE 333 die cast aluminum

gray cast iron with carburized 1018 low carbon steel

The report draws the following conclusions on the Falex® and HPT comparisons:

1). For a given refrigerant, varying the speed and the load affects the performance of a given refrigerant-lubricant combination. Hence, what may be acceptable at one condition may not be acceptable at another operation point.
2). The materials utilized in the contact pairs directly affects the ranking of lubricants. A refrigerant-lubricant combination could have excellent wear characteristics with one contact pair and poor wear characteristics with another.
3). In general, for a given contact pair at similar test conditions, the HPT tests ranked lubricant performance in an order different than did the Falex® tests.
4). Generally, no correlation exists between friction and wear. A tribo-contact which yields relatively low friction can experience relatively high wear, and vice-versa.

Comparison of HPT Results with Compressor Wear Data

To ascertain how well the HPT device models actual compressor operation, it is expected that four material contact pairs will be evaluated and the results compared to those observed by compressor manufacturers:

Compressor Application Simulation	Possible Contact Pairs
reciprocating wrist pin in conformal contact	308 die cast aluminum with case hardened low carbon steel
screw male-female rotor interface in a line contact	AISI 1141 steel with itself, and with ductile cast iron
rotary vane-roller line contact	sintered ferrous metal with itself
scroll thrust bearing Oldham-coupling area contact	aluminum with Norplex™

The intent is to determine if the data obtained with the HPT can more accurately predict tribological behavior of critical contacts in compressors than that obtained from simpler Falex® testers. Utilizing this information, a recommendation will be made on the design of a bench-type device that can be utilized by industry in screening lubricants for use with various refrigerants.

A report that compares the HPT results against the wear data obtained from compressor lubricity tests will be available in the fourth quarter 1994.

ACCELERATED TEST METHODS FOR PREDICTING THE LIFE OF MOTOR MATERIALS EXPOSED TO REFRIGERANT-LUBRICANT MIXTURES

Objectives:

- To develop test methods and procedures to predict the life of motor insulating materials and varnishes used in hermetic motors.
- To validate proposed test methods and procedures.

Results:

The Radian Corporation has completed Phase 1 of this research under contract with ARTI. This phase included a literature search and analysis of current test methods, along with the conceptual design for an improved accelerated test method. Results of this study are presented in the report, DOE/CE/23810-21, *Accelerated Test Methods for Predicting the Life of Motor Materials Exposed to Refrigerant/Lubricant Mixtures, Phase 1: Conceptual Design*, by Peter F. Ellis II and Alan Ferguson, 11 June 1993.

As a result of their studies, researchers at Radian found that the majority of hermetic motor insulation failures occur in the stator windings of the motor due to a combination of thermal, chemical, and mechanical interactions. A review of an insurance industry survey [Stouppe and Lau, 1989] indicated that 84.0% of hermetic motor failures were attributed to stator winding failures.

Radian examined several degradation models and investigated the advantages and disadvantages of the following test methods which are used by industry for testing of hermetic motors:

Motorette tests (IEEE Standard 117 & UL Standard 984-1989),
sealed tube aging tests, and
plug-reversal test.

The motorette test uses a simplified simulation of stator windings as the test device. The motorette is stressed with electrical potential, but no current, while exposed to a refrigerant-lubricant mixture in a heated autoclave. The motorette test method provides information on the chemical and thermal degradation of insulation materials. However, it does not provide information of degradation due to the differential thermal expansion or magnetic forces on the windings.

The sealed-tube test developed by General Electric [Spauschus and Sellers, 1969; Spauschus and Field, 1979] used bifilar coils of magnet wire sealed in glass tubes with the refrigerant-lubricant mixtures. Leads of each bifilar coil were sealed through the top of the glass tube, which allowed monitoring of the dielectric properties of the insulation. Although the method was useful for determining the Arrhenius constants of magnet wire varnish insulation degradation, it does not address the degradation of other insulation components and only simulates the thermochemical aging process.

The plug-reversal test uses a hermetic motor-compressor unit as the test device, modifying the compressor so that it can rotate in either direction with equal ease. The unit is placed inside a refrigerant loop. The polarities of two of the three phase wires of the motor are repeatedly reversed, causing the motor to stall and reverse direction with each reversal. Each plug reversal simulates a locked rotor. This test simulates the full range of forces on hermetic motors. However, the overall test apparatus is complex and has two drawbacks. Components of the supporting refrigeration test loop often fail prior to an actual motor failure and purging the entire test loop for subsequent refrigerant-lubricant mixture tests is difficult and costly.

A test method has been proposed that combines the advantages of these test methods into a single practical method. This proposed method uses a stator simulator unit (SSU). The SSU (see Figure 8) consists of a laminated electric steel core, simulating the stator stack of a hermetic motor. The core will contain slot insulation, two coils separated by phase-to-phase insulation and slot wedge insulation.

The test method exposes the SSU to a refrigerant-lubricant mixture in an autoclave equipped with a headspace chiller and syphon cup similar to those used for motorette tests. Plug-reversal in-rush currents are simulated by intermittent 30 Amp AC pulses applied to the lead wires of the SSU.

The SSU and test protocol would emulated the following forces which act on motor stator windings and cause insulation failure:

thermal aging
chemical aging
differential thermal expansion
magnetodynamic forces
transient voltage stresses from simulated starting cycles.

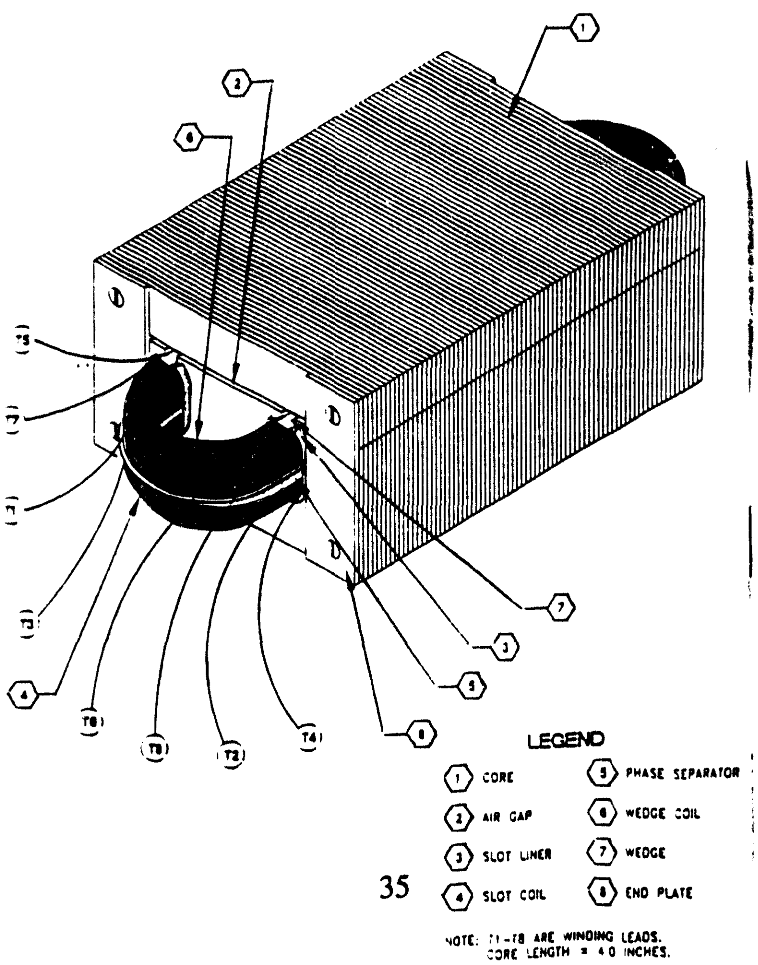
Several parameters will be used to evaluate SSU performance:

- Winding capacitance
- Capacitance (power) dissipation factor
- Surge testing
- DC high potential testing
- Polarization index.

Industry accepted guidelines exist for evaluating each of these parameters which permit determination of logical test endpoints, before actually reaching a SSU burnout. It is postulated that trend analysis results for each of these parameters may allow projection of the time to a set endpoint well before that end-point is reached. That being the case, then the required test period could be shortened.

The proposed test method will produce results that reflect insulation life relative to a reference refrigerant-lubricant mixture. Although Radian concluded that development of an absolute life prediction test is beyond the state of the art, the proposed SSU test method does represent a more economical test method than the battery of methods presently used by the industry.

Figure 8. Stator Simulator Unit (SSU).



DOE/CE/23810-38

ACCELERATED SCREENING METHODS FOR DETERMINING CHEMICAL AND THERMAL STABILITY OF REFRIGERANT-LUBRICANT MIXTURES

Objectives:

- To develop screening methods and procedures to assess the chemical and thermal stability of refrigerants and lubricants, as well as additives, metals, surface treatments, and polymers, used in hermetic systems.

- To validate these screening methods and procedures.

Results:

This research is being performed by the University of Dayton Research Institute under contract to ARTI.

A literature search has been completed and several analytical techniques that might be developed into accelerated stability screening tests were identified. These methods employ one or more of the following techniques:

- Incorporation of thermocouple wells into sample vessels for temperature monitoring,
- *In situ* monitoring of temperature, conductivity, and/or voltage production,
- *In situ* monitoring of viscosity using surface acoustic wavelength devices,
- Employing differential thermal analysis (DTA) techniques during sample aging,
- Use of flat bottom, four millimeter diameter glass tubes for sample analysis,
- Use of miniature metal bombs for sample analysis.

The report, DOE/CE/23810-10, *Accelerated Screening Methods for Determining Chemical and Thermal Stability of Refrigerant-Lubricant Mixtures; Part I: Method Assessment*, by Robert Kauffman, April 1993, gives more details on the results of this literature search and the candidate screening methods. This report is currently available from the ARTI Refrigerant Database (RDB3501, 42 pages).

Part II concentrates on evaluating various techniques for development into an accelerated screening method. Details of the contractor's progress are contained in the quarterly technical progress reports, DOE/CE/23810-20D (1 March 1993 - 30 June 1993), DOE/CE/23810-22D (1 July 1993 - 30 September 1993), and DOE/CE/23810-33D (1 October 1993 - 31 December 1993), *Accelerated Screening Methods for Determining*

Chemical and Thermal Stability of Refrigerant-Lubricant Mixtures; Part II: Experimental Comparison and Verification of Methods, by Mr. Robert Kauffman. The latter report is still undergoing technical review and will be available when approved.

Tests employing DTA techniques, using thermocouples or thermistors inside or outside the sample vessels, have been conducted. Initial results indicate that these techniques are only slightly sensitive to CFC-12/mineral oil reactions. It is hypothesized that these techniques will be less sensitive to HCFC/lubricant and HFC/lubricant reactions.

Use of ferric fluoride as a degradation catalyst was tested. Initial results show that at temperatures above 175°C (347°F), the catalyzed reactions appear to be more dependent on lubricant degradation than on refrigerant degradation. It is concluded that the use of ferric fluoride as a catalyst may have the potential for development into an accelerated screening method for lubricant stability.

In situ color (light transmission) measurements were tested as a potential stability screening method. It was found that transmission depended on temperature and light source output, as well as color change of the refrigerant-lubricant mixture, and therefore may not be as promising as other screening techniques reviewed.

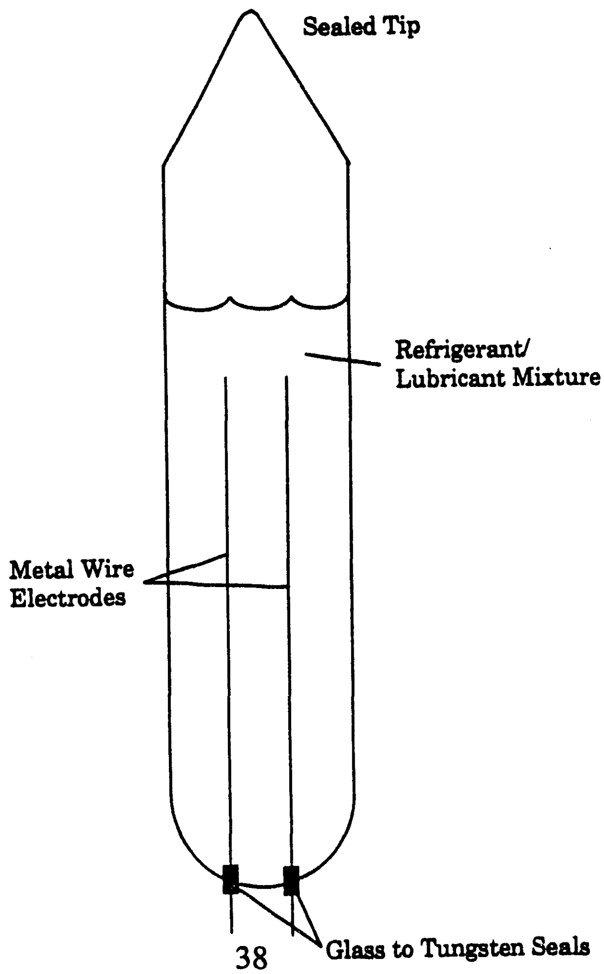
Tests involving *in situ* conductivity monitoring have also been performed. These techniques involve measuring current between two metal electrodes, sealed into the sample vessel, with a known applied voltage. Evaluations were made using combinations of: ac or dc voltage; tungsten, copper, and/or iron metal electrodes; steel, copper or no metal coupons as catalysts; and continuous or non-continuous conductivity monitoring. Initial results indicate that the *in situ* conductivity measurements correlate with refrigerant-lubricant stability as reported in the literature and as determined by other analytical techniques (color and gas chromatography measurements). Initial results also show that continuous measurement of conductivity (i.e., maintaining the applied voltage throughout the aging process) accelerates as well as monitors the degradation of refrigerant-lubricant mixtures.

Tests were conducted using HFC-134a and four polyolester lubricants, heated in modified glass tubes (see Figure 9) for two days at 175°C (347°F). Conductivity was monitored continuously by application of a triangular voltage wave-form across two tungsten leads sealed into the tubes. Dramatic changes in the first twelve hours of measurements are hypothesized to be related to interactions between the metal (tungsten) surface and the refrigerant-lubricant mixture. Conductivity changes thereafter (between 12 and 48 hours) were seen to correspond to chemical/thermal stability as determined by ASTM color tests:

Table 11. Analytical Results for Aged HFC-134a/Lubricant Mixtures

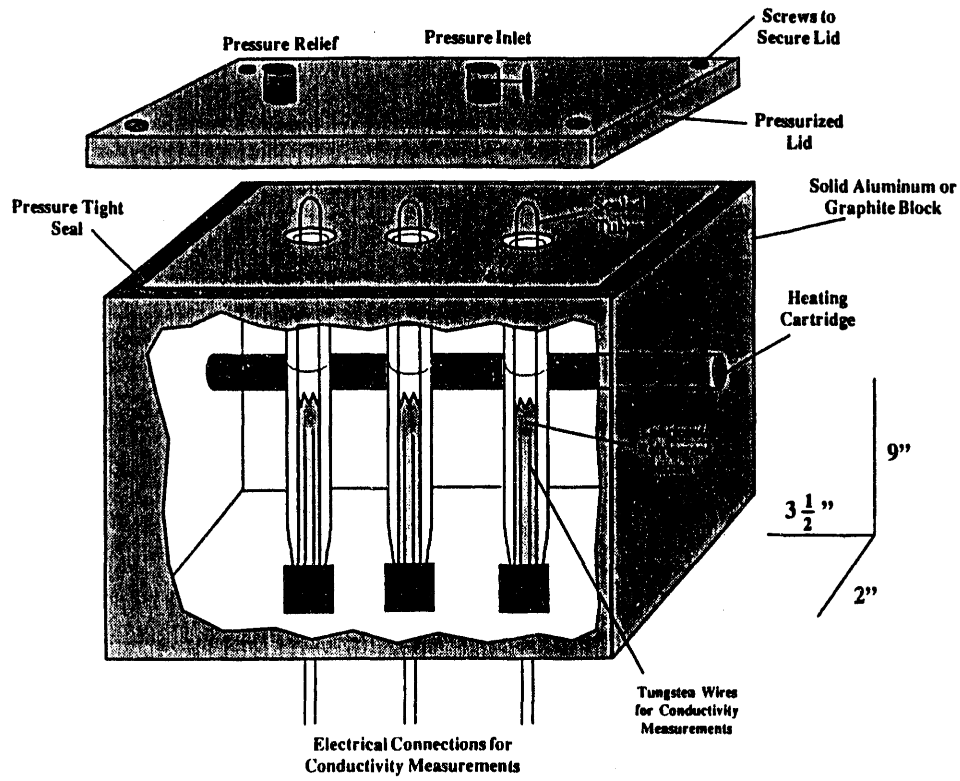
Lubricant	ASTM Color		Conductivity (absolute units)		Percent Change
	Before	After	T=12 hours	T=48 hours	absolute
Pentaerythritol Branched-Acid 2	<0.5	<0.5	828.36	921.31	11.2
Pentaerythritol Mixed-Acid 2	<0.5	0.5	186.67	116.36	37.7
Pentaerythritol Branched-Acid 1, "fresh"	<0.5	<1.0	438	268	38.8
Pentaerythritol Branched-Acid 1, "exposed"	0.5	3.5	707	1033	46.1

Figure 9. Modified Sealed Glass Tube.



Two aluminum heating blocks have been constructed with built-in cartridge heaters and electrical connections for monitoring the conductivity of the fluids inside the modified sealed tubes. A programmable temperature controller will be used to subject refrigerant/lubricant mixtures to both isothermal and ramped temperature tests. Figure 10, below, is a schematic of a three-well aluminum block heating system.

Figure 10. Three-Well Aluminum Block Heating System.



REFRIGERANT DATABASE

Objectives:

- To develop a database for materials compatibility and lubricant research (MCLR) information on substitutes for chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants for applied refrigeration cycles.

- To assemble physical properties, materials compatibility, and related test data for these refrigerants and lubricants, along with comparative data for currently-used refrigerants.

- To make the data readily accessible for rapid screening and identification of pertinent source documents based on user-defined search criteria.

Results:

James M. Calm, Engineering Consultant, is performing this research under contract to ARTI. The database is available on a subscription basis (for a nominal charge to recover distribution costs) in either a computerized or printed format.

The core of the database consists of bibliographic citations and synopses for publications that may be useful in research and design of air-conditioning and refrigeration equipment. The bibliographic citations provide information to facilitate ordering of source documents from the author or the publisher. Approximately 40% of the documents are available from the database contractor. Detailed synopses have been prepared for many of the entries. These detailed synopses describe the data, tests, evaluations, and the materials noted in the documents. The synopses permit searching of information by refrigerant or refrigerant-lubricant combination, topic, author, material (by generic or commercial name), specific refrigerant property, or just about any other combination of search criteria.

The computerized version of the database includes summaries for over 200 refrigerants, both single-component and blends. Refrigerants are identified by ASHRAE Standard 34 designations, chemical names and formulae, common names, refrigerant groups, blend compositions, and familiar chemical abstract numbers. Summary property data (with dimensional quantities in dual IP and SI units) are provided for molecular mass, atmospheric boiling point, melting or freezing point, and critical-point parameters (temperature, pressure, specific volume, and density). The lower and upper flammability limits (LFL and UFL), ASHRAE Standard 34 safety classification, ozone depletion potential (ODP), global warming potential (GWP), halocarbon global warming potential

(HGWP), and common uses are indicated if known. Specific sources are referenced for the data to enable verification, obtaining further information, and examining underlying limitations.

The February 1994 release of the ARTI Refrigerant Database will contain in excess of 1,350 entries related to:

- refrigerant properties
- performance with new refrigerants
- materials compatibility
- lubricants for new refrigerants
- environmental and safety data
- related research programs

DOE/CE/23810-38

COMPATIBILITY OF MANUFACTURING PROCESS FLUIDS WITH HFC REFRIGERANTS AND ESTER LUBRICANTS

Objective:

- To provide information that will enable manufacturers of components of air-conditioning and refrigeration equipment to select reliable process fluids.

Results:

This research is being performed by Imagination Resources, Inc., under contract to ARTI.

Part I of this project is a survey of manufacturers and fluid suppliers to determine what processing fluids are used by the industry and what testing has been performed previously on these compounds. This survey has been completed and all of the major component manufacturers (with one exception) have submitted fluids to be analyzed. The list of fluids will be narrowed down to a workable amount (about 50) and reported on. A draft final report on the survey of the processing fluids will be completed by mid-May, when an on-site review of the project will occur.

Part II of the project consists the experimental measurements of the compatibility of the fluids which were selected in Part I. It will commence in June and will include sealed tube stability and miscibility testing. These tests will determine the chemical and thermal stability of the fluids and also their solubility characteristics in HFC refrigerants. A novel flowing loop experiment containing a filter drier will determine the flow characteristics of these fluids with refrigerants and lubricants. This experiment will also measure the filter drier performance and the pressure drop caused by the processing fluids.

COMPLETED PROJECTS

THERMOPHYSICAL PROPERTIES (HFC-32, HCFC-123, HCFC-124 AND HFC-125)

Objective:

To provide highly accurate, selected thermophysical properties data for refrigerants HFC-32, HCFC-123, HCFC-124, and HFC-125; and to fit these data to simple, theoretically-based equations of state, as well as complex equations of state and detailed transport property models.

Results:

The Thermophysics Division of the National Institute of Standards and Technology (NIST) has completed measurements and correlations of HFC-32, HCFC-123, HCFC-124 and HFC-125. This data filled the gaps that existed in data sets and resolved problems and uncertainties that existed in and between those data sets. Measurements and determinations of thermodynamic properties included vapor pressure-volume-temperature behavior, liquid pressure-volume-temperature behavior, saturation and critical points, vapor speed of sound and ideal gas heat capacity, and isochoric heat capacity. The data was fitted to the Carnahan-Starling-DeSantis (CSD) and the modified Benedict-Webb-Rubin (MBWR) equations of state. Measurements and correlations of transport properties included thermal conductivity and viscosity measurements.

A detailed report of the results is presented in the final report, DOE/CE/23810-16, *Thermophysical Properties*, April 1993, by Richard F. Kayser, PhD (RDB #3860, 242 pages). Key results are summarized below:

<u>HFC-32</u>

NIST has developed a 32-term MBWR equation of state (Table 12) for HFC-32. The equation is reported to be valid at temperatures from the triple point at 137 K (-213°F) up to 400 K (260°F), and it may be reasonably extrapolated up to 500 K (440°F). The maximum pressure for the equation is 40 MPa (5800 psi), and it may be reasonably extrapolated up to 100 MPa (14500 psi). NIST fitted the equation using a multi-parameter linear least squares routine on the measured data.

HCFC-123

NIST has revised the MBWR equation of state for HCFC-123. This work was prompted by an evaluation of the equations of state for HFC-134a and HCFC-123 carried out by Annex 10 of the International Energy Agency. Weaknesses revealed during the evaluation included the derived properties for speed of sound and heat capacity. The revised equation (Table 13) is reported to be valid at temperatures from just above the triple point up to 550 K (530°F) and at pressures up to 40 MPa (5800 psi).

HCFC-124

NIST has developed a 32-term MBWR equation of state (Table 14) for HCFC-124. The equation is reported to be valid at temperatures ranging from 210 to 450 K (-82 to 350°F) and it may be reasonably extrapolated up to 500 K (440°F). The maximum pressure for the equation is 20 MPa (3000 psi).

HFC-125

NIST has developed a 32-term MBWR equation of state (Table 15) for HFC-125. The equation is reported to be valid at temperatures ranging from 200 to 400 K (-100 to 260°F). It may be reasonably extrapolated up to 500 K (440°F). The maximum pressure for the equation is 20 MPa (2900 psi).

Table 12. Coefficients to the MBWR Equation of State for HFC-32.
(units are K, bar, L, mol)

$$p = \sum_{n=1}^{9} a_n \rho^n + \exp(-\rho^2/\rho_c^2) \sum_{n=10}^{15} a_n \rho^{2n-17}$$

ρ_c = 8.1245 mol/L

a_1 = RT
a_2 = $b_1 T + b_2 T^{0.5} + b_3 + b_4/T + b_5/T^2$
a_3 = $b_6 T + b_7 + b_8/T + b_9/T^2$
a_4 = $b_{10} T + b_{11} + b_{12}/T$
a_5 = b_{13}
a_6 = $b_{14}/T + b_{15}/T^2$
a_7 = b_{16}/T
a_8 = $b_{17}/T + b_{18}/T^2$
a_9 = b_{19}/T^2
a_{10} = $b_{20}/T^2 + b_{21}/T^3$
a_{11} = $b_{22}/T^2 + b_{23}/T^4$
a_{12} = $b_{24}/T^2 + b_{25}/T^3$
a_{13} = $b_{26}/T^2 + b_{27}/T^4$
a_{14} = $b_{28}/T^2 + b_{29}/T^3$
a_{15} = $b_{30}/T^2 + b_{31}/T^3 + b_{32}/T^4$

i	b_i	i	b_i
1	-0.184799147712E-01	17	-0.399464119357E-04
2	0.199258716261E+01	18	0.653548292730E-01
3	-0.450818142855E+02	19	-0.119312200130E-02
4	0.517320130169E+04	20	-0.896057555372E+05
5	-0.770847082500E+06	21	-0.218872108921E+08
6	-0.170184611963E-03	22	-0.189705435851E+04
7	-0.143023459131E+01	23	0.310718784685E+08
8	0.606314008455E+03	24	-0.126638710844E+02
9	0.192559574847E+06	25	0.246519270465E+04
10	-0.596044051707E-04	26	-0.231516734828E-01
11	0.297147086969E+00	27	-0.438977929243E+04
12	-0.104964078480E+03	28	-0.315318636002E-03
13	-0.775008265186E-02	29	0.139459067806E+00
14	0.222564856042E+00	30	0.163298486259E-06
15	-0.330783818273E+02	31	-0.326147254524E-03
16	-0.313533565119E-02	32	0.342233333783E-01

Table 13. Coefficients to the MBWR Equation of State for HCFC-123. (units are K, bar, L, mol)

$$p = \sum_{n=1}^{9} a_n\rho^n + \exp(-\rho^2/\rho_c^2) \sum_{n=10}^{15} a_n\rho^{2n-17}$$

ρ_c = 3.596417 mol/L

$a_1 = RT$
$a_2 = b_1T + b_2T^{0.5} + b_3 + b_4/T + b_5/T^2$
$a_3 = b_6T + b_7 + b_8/T + b_9/T^2$
$a_4 = b_{10}T + b_{11} + b_{12}/T$
$a_5 = b_{13}$
$a_6 = b_{14}/T + b_{15}/T^2$
$a_7 = b_{16}/T$
$a_8 = b_{17}/T + b_{18}/T^2$
$a_9 = b_{19}/T^2$
$a_{10} = b_{20}/T^2 + b_{21}/T^3$
$a_{11} = b_{22}/T^2 + b_{23}/T^4$
$a_{12} = b_{24}/T^2 + b_{25}/T^3$
$a_{13} = b_{26}/T^2 + b_{27}/T^4$
$a_{14} = b_{28}/T^2 + b_{29}/T^3$
$a_{15} = b_{30}/T^2 + b_{31}/T^3 + b_{32}/T^4$

i	b_i	i	b_i
1	-0.193042434973E-01	17	0.106201732381E+00
2	-0.263410206086E+00	18	-0.401991529370E+02
3	0.266439262928E+02	19	0.156703568146E+01
4	-0.102447174272E+05	20	0.395804226685E+07
5	-0.714962376060E+06	21	-0.490428403406E+09
6	0.179594735089E-01	22	0.171175389582E+06
7	-0.106601466621E+02	23	0.376067424212E+10
8	-0.106973465680E+04	24	0.719667521763E+04
9	-0.150556666672E+07	25	-0.110348184730E+07
10	-0.126504809410E-02	26	0.571211837951E+02
11	-0.123264787943E+00	27	0.642498617888E+07
12	0.293238981229E+03	28	0.227383595657E+01
13	0.134389339775E+00	29	-0.670239087161E+03
14	0.745030119681E+01	30	-0.162446239669E-01
15	0.413916532768E+04	31	0.190850894641E+02
16	-0.212267981526E+01	32	-0.267293932199E+04

Table 14. Coefficients to the MBWR Equation of State for HCFC-124. (units are K, bar, L, mol)

$$p = \sum_{n=1}^{9} a_n\rho^n + \exp(-\rho^2/\rho_c^2) \sum_{n=10}^{15} a_n\rho^{2n-17}$$

ρ_c = 4.10153 mol/L

a_1 = RT
a_2 = $b_1T + b_2T^{0.5} + b_3 + b_4/T + b_5/T^2$
a_3 = $b_6T + b_7 + b_8/T + b_9/T^2$
a_4 = $b_{10}T + b_{11} + b_{12}/T$
a_5 = b_{13}
a_6 = $b_{14}/T + b_{15}/T^2$
a_7 = b_{16}/T
a_8 = $b_{17}/T + b_{18}/T^2$
a_9 = b_{19}/T^2
a_{10} = $b_{20}/T^2 + b_{21}/T^3$
a_{11} = $b_{22}/T^2 + b_{23}/T^4$
a_{12} = $b_{24}/T^2 + b_{25}/T^3$
a_{13} = $b_{26}/T^2 + b_{27}/T^4$
a_{14} = $b_{28}/T^2 + b_{29}/T^3$
a_{15} = $b_{30}/T^2 + b_{31}/T^3 + b_{32}/T^4$

i	b_i	i	b_i
1	-0.204576807203E+00	17	-0.688566863825E-01
2	0.183289763904E+02	18	-0.132391812938E+02
3	-0.436304129852E+03	19	0.667600131841E+00
4	0.784900629507E+05	20	-0.271799858829E+07
5	-0.882621240790E+07	21	-0.111422740208E+09
6	-0.214052457908E-02	22	-0.175854504297E+06
7	-0.421490706906E+01	23	0.566801130630E+10
8	0.379367628599E+04	24	-0.214018815397E+04
9	0.257319006570E+07	25	-0.327561948065E+06
10	-0.128703560721E-02	26	-0.546930696467E+02
11	0.318383860178E+01	27	0.931832376640E+06
12	-0.126323679904E+04	28	0.193654970621E-02
13	-0.359253621024E-01	29	-0.110844683745E+03
14	-0.201822160275E+02	30	-0.452370482664E-02
15	0.239512195711E+03	31	0.163031126242E+01
16	0.249923391219E+01	32	-0.681395650661E+03

Table 15. Coefficients to the MBWR equation of state for HFC-125 (units are K, bar, L, mol)

$$p = \sum_{n=1}^{9} a_n \rho^n + \exp(-\rho^2/\rho_c^2) \sum_{n=10}^{15} a_n \rho^{2n-17}$$

ρ_c = 4.7650 mol/L

$a_1 = RT$
$a_2 = b_1 T + b_2 T^{0.5} + b_3 + b_4/T + b_5/T^2$
$a_3 = b_6 T + b_7 + b_8/T + b_9/T^2$
$a_4 = b_{10} T + b_{11} + b_{12}/T$
$a_5 = b_{13}$
$a_6 = b_{14}/T + b_{15}/T^2$
$a_7 = b_{16}/T$
$a_8 = b_{17}/T + b_{18}/T^2$
$a_9 = b_{19}/T^2$
$a_{10} = b_{20}/T^2 + b_{21}/T^3$
$a_{11} = b_{22}/T^2 + b_{23}/T^4$
$a_{12} = b_{24}/T^2 + b_{25}/T^3$
$a_{13} = b_{26}/T^2 + b_{27}/T^4$
$a_{14} = b_{28}/T^2 + b_{29}/T^3$
$a_{15} = b_{30}/T^2 + b_{31}/T^3 + b_{32}/T^4$

i	b_i	i	b_i
1	0.695150135527E-01	17	-0.637258406198E-01
2	-0.109596263920E+02	18	0.291220108725E+02
3	0.289171467191E+03	19	-0.102197580663E+01
4	-0.510408655996E+05	20	-0.560938443772E+07
5	0.366753946576E+07	21	0.770104599552E+08
6	0.385350808228E-01	22	-0.224544749331E+06
7	-0.370988373715E+02	23	0.183452398750E+10
8	0.134556555861E+05	24	-0.292476384933E+04
9	0.371143622964E+07	25	-0.388467529252E+05
10	-0.123685768773E-02	26	-0.339743229627E+02
11	0.130495983411E+01	27	-0.544169038319E+06
12	-0.468463056623E+03	28	-0.168305711698E+00
13	0.511361375061E-01	29	0.115387298598E+02
14	-0.204695459886E+02	30	-0.734893856572E-03
15	-0.414622181605E+04	31	-0.329200834300E+00
16	0.219744136091E+01	32	-0.403885226023E+01

THEORETICAL EVALUATIONS OF R-22 ALTERNATIVE FLUIDS:

Objective:

To provide information regarding the coefficients of performance (COP), capacities, compressor discharge temperatures, compressor discharge pressures, and compressor discharge pressure ratios of nine alternative fluids relative to HCFC-22 and three alternative fluids relative to R-502.

Results:

The Building Environment Division of the National Institute of Standards and Technology (NIST) completed this research under contract with ARTI. Detailed results of this study are reported in the final report, DOE/CE/23810-7, *Theoretical Evaluations of R-22 Alternative Fluids*, January 1993, by Piotr A. Domanski, PhD and David A. Didion, PhD. This report is currently available from the ARTI Refrigerant Database (RDB# 3305, 32 pages). The following refrigerants and refrigerant blends were evaluated:

<u>Alternative Refrigerants/Blends (% Weight)</u>

HCFC-22 Alternatives

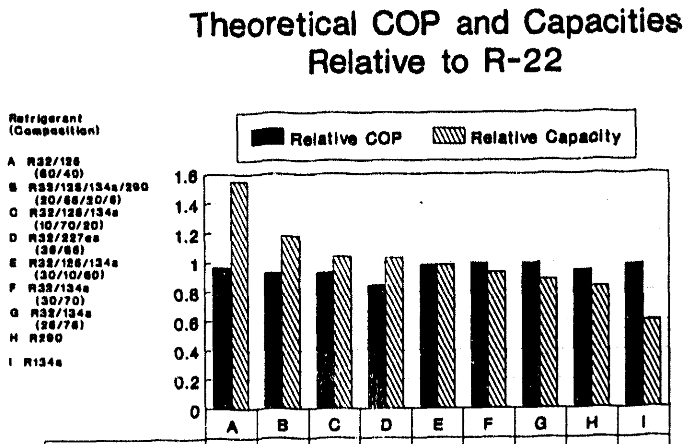
HFC-32/HFC-125 (60/40)
HFC-32/HFC-134a (25/75)
HFC-32/HFC-134a (30/70)
HFC-32/HFC-125/HFC-134a (10/70/20)
HFC-32/HFC-125/HFC-134a (30/10/60)
HFC-32/HFC-227ea (35/65)
HFC-32/HFC-125/HFC-134a/R-290 (20/55/20/5)
HFC-134a
R-290 (Propane)

R-502 Alternatives

HFC-32/HFC-125/HFC-143a (10/45/45)
HFC-125/HFC-143a/HFC-134a (44/52/4)
HFC-125/HFC-143a (45/55)

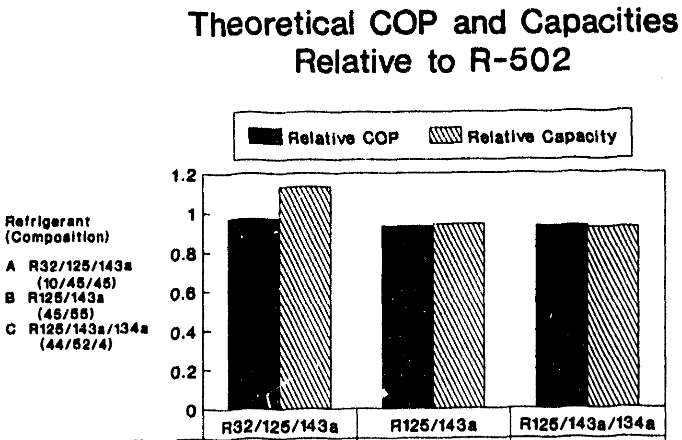
Results of the evaluations are presented in Figures 11 and 12.

Figure 11. Relative COPs and Capacities of HCFC-22 Alternatives.



	A	B	C	D	E	F	G	H	I
Relative COP	0.97	0.93	0.93	0.84	0.98	0.99	0.99	0.94	0.98
Relative Capacity	1.55	1.18	1.04	1.03	0.98	0.93	0.88	0.83	0.59

Figure 12. Relative COPs and Capacities of R-502 Alternatives.



	R32/125/143a	R125/143a	R125/143a/134a
Relative COP	0.97	0.93	0.93
Relative Capacity	1.13	0.94	0.92

CHEMICAL AND THERMAL STABILITY OF REFRIGERANT-LUBRICANT MIXTURES WITH METALS

Objective:

To provide information on the stability of potential substitutes for CFC refrigerants and appropriate lubricants.

Results:

Spauschus Associates, Inc., has completed this research under contract with ARTI. A detailed report of results is presented in the final report, DOE/CE/23810-5, *Chemical and Thermal Stability of Refrigerant-Lubricant Mixtures with Metals*, 9 October 1992, by Dietrich F. Huttenlocher, PhD, (RDB #3608, 126 pages). Key results are summarized below:

Alternative Refrigerant-Lubricant Combinations

- CFC-11 (baseline) with:
  - naphthenic mineral oil (ISO 32)
  - naphthenic mineral oil (ISO 46)
- CFC-12 (baseline) with:
  - naphthenic mineral oil (ISO 32)
  - alkylbenzene (ISO 32)
- HCFC-22 with:
  - naphthenic mineral oil (ISO 32)
- HFC-32 with:
  - pentaerythritol ester mixed-acid (ISO 32)
  - polypropylene glycol butyl monoether (ISO 32)
- HCFC-123 with:
  - naphthenic mineral oil (ISO 32)
  - naphthenic mineral oil (ISO 46)
- HCFC-124 with:
  - alkylbenzene (ISO 32)
- HFC-125 with:
  - pentaerythritol ester mixed-acid (ISO 32)
  - polypropylene glycol butyl monoether (ISO 32)
  - modified polyglycol (ISO 32)
- HFC-134 with:
  - pentaerythritol ester mixed-acid (ISO 32)

Alternative Refrigerant-Lubricant Combinations (Continued)

HFC-134a with:
- pentaerythritol ester mixed-acid (ISO 22)
- pentaerythritol ester branched-acid (ISO 32)
- pentaerythritol ester branched-acid (ISO 100)
- polypropylene glycol butyl monoether (ISO 32)
- polypropylene glycol diol (ISO 22)
- modified polyglycol (ISO 32)

HCFC-142b with:
- alkylbenzene (ISO 32)

HFC-143a with:
- pentaerythritol ester branched-acid (ISO 32)

HFC-152a with:
- alkylbenzene (ISO 32)

Based on the results of his research, Dr. Huttenlocher made the following conclusions:

- All HFCs tested, along with HCFC-22, were very stable and did not undergo any measurable chemical reactions or thermal decompositions at temperatures up to 200°C (392°F).

- HCFC-124 and HCFC-142b were less stable than the HFCs tested but more stable than CFC-12 (a long time industry standard).

- While HCFC-123 was the least stable of the "new" refrigerants tested, it was still ten fold more stable than CFC-11 (the refrigerant it is intended to replace in low pressure chiller applications).

- The pentaerythritol ester lubricants included in the project exhibited acid number increases after aging at 200°C (392°F). The high viscosity (ISO 100) pentaerythritol ester exhibited additional evidence of molecular changes during aging at 200°C. The formation of CO_2 indicated decarboxylation of the high viscosity pentaerythritol ester lubrication at that temperature.

- All of the polyalkylene glycol lubricants had signs of molecular change after aging.

MISCIBILITY OF LUBRICANTS WITH REFRIGERANTS

Objective:

To provide information on the miscibility of both current and new lubricants with potential substitutes for CFC refrigerants.

Results:

Iowa State University of Science and Technology is performing this research under contract with ARTI. Phase 1 of the project, preliminary miscibility screening, has been completed. These studies examined mixtures at three refrigerant-lubricant concentrations (10, 50, and 95% refrigerant by weight) and a single viscosity for each lubricant. Miscibility studies were conducted over a temperature range of -50 to 90°C (-58 to 194°F) for most mixtures and -50 to 60°C (-58 to 140°F) for high pressure refrigerant mixtures. A detailed report on the results of this research is presented in DOE report number DOE/CE/23810-6, *Miscibility of Lubricants with Refrigerants (Phase 1)*, October 1992, by Michael B. Pate, PhD, Steven C. Zoz, and Lyle J. Berkenbosch (RBD #3503, 64 pages).

Iowa State University has completed Phase 2 of the project which encompassed detailed miscibility plots with five additional refrigerant-lubricant concentrations (20, 35, 65, 80 and 90% refrigerant by weight) and two viscosity grades for each lubricant. The final report, DOE/CE/23810-18, *Miscibility of Lubricants with Refrigerants*, January 1994, by Michael B. Pate, PhD, Steven C. Zoz, and Lyle J. Berkenbosch, contains detailed results. Preliminary results are summarized in Table 16.

Table 16. Miscibility of Lubricants with Refrigerants.

	Refrigerant									
Lubricant	R22	R32	R123	R124	R125	R134	R134a	R142b	R143a	R152a
Mineral Oil ISO 32 cSt	> −10C < 36% > 90%	I	M	> 20C or < 23%	I	I	I	> −40C < 50% > 80%	I	I
Mineral Oil ISO 68 cSt	> 0 or < 36%	I	> −40C or < 47%	> 50C or < 22%	I	I	I	> −30C < 21% > 89%	I	I
Alkylbenzene ISO 32 cSt	M	I	M	M	I	I	I	M	I	> 50C
Alkylbenzene ISO 68 cSt	M	I	M	M	I	I	I	M	I	> 50C or < 20%
Polypropylene Glycol Butyl Monoether ISO 32 cSt	M	< 53%	M	M	< 50C or < 65%	> −20C or < 88%	< 60C or < 81%	M	< 35%	M
Polypropylene Glycol Butyl Monoether ISO 58 cSt	M	< 47%	< 20C or > 21%	M	< 40C or < 65%	M	< 50C < 64%	M	< 38%	< 80C < 80% > 90%
Polypropylene Glycol Diol ISO 32 cSt	M	M	M	M	M	M	M	M	< 34%	M
Polypropylene Glycol Diol ISO 100 cSt	M	< 49%	M	M	< 40C or < 80%	M	< 60C or < 66%	M	< 48%	< 70C < 81% > 90%
Modified Polyglycol ISO 32 cSt	> −20C < 23% > 50%	< 60C > 10C < 21%	> −40C	> −10C < 37% > 81%	< 30C > 10C < 20%	> 0C < 23% > 79%	> 0C < 22% > 52%	> −40C < 23% > 68%	I	M
Pentaerythrithol Ester mixed acid ISO 22 cSt	M	< 50C > 10C < 35%	M	M	M	M	> −50C < 69% > 91%	M	< 38%	M
Pentaerythrithol Ester mixed acid ISO 32 cSt	M	> −20C or < 51%	M	M	M	M	M	M	< 49%	M
Pentaerythrithol Ester mixed acid ISO 100 cSt	M	< 35%	M	M	< 60C or < 66%	M	> −10C or < 64%	M	< 36%	M
Pentaerythrithol Ester branched acid ISO 32 cSt	M	> −20	M	M	M	M	M	M	< 51%	M
Pentaerythrithol Ester branched acid ISO 100 cSt	M	< 51%	M	M	< 40C or < 77%	M	< 60C or < 79%	M	< 34%	< 90C or < 90%

I – Immiscible or miscible only in a small temperature–concentration region.
M – Miscible at all test temperatures and concentrations.
< ** – Miscible at all test temperatures or refrigerant mass concentrations below temperature or concentration indicated.
> ** – Miscible at all test temperatures or refrigerant mass concentrations above temperature or concentration indicated.

DOE/CE/23810-38

COMPATIBILITY OF REFRIGERANTS AND LUBRICANTS WITH MOTOR MATERIALS

Objective:

To provide information on the compatibility of motor materials with potential substitutes for CFC refrigerants and with suitable lubricants.

Results:

The Trane Company has completed this research under contract with ARTI. Detailed results are presented in the final report, DOE/CE/23810-13, *Compatibility of Refrigerants and Lubricants with Motor Materials*, May 1993, by Robert Doerr, PhD, Stephen Kujak and Todd Waite (Vol I - RDB #3857, 166 pages; Vol II - RDB #3858, 270 pages; Vol III - RDB #3859, 370 pages).

Results from the project indicate that most materials used in current hermetic motors are compatible with the test refrigerant-lubricant combinations.

The project examined the compatibility of twenty-four hermetic motor materials with eleven pure refrigerants and seventeen refrigerant-lubricant combinations. Motor materials tested included three types of magnet wires, six wire varnishes, six sheet insulations, three sleeving insulations, three tie tapes, two lead wire insulations and one tie cord. A number physical property measurements were performed on samples of each test material before and after its exposure to the refrigerants and refrigerant-lubricant mixtures.

Refrigerants

HCFC-22 @ 90°C (194°F)
HCFC-123 @ 90°C (194°F)
HCFC-124 @ 90°C (194°F)
HCFC-142b @ 90°C (194°F)
HFC-152a @ 90°C (194°F)
HFC-134a @ 90°C (194°F)
HFC-134 @ 90°C (194°F)
HFC-32 @ 60°C (140°F)
HFC-125 @ 60°C (140°F)
HFC-143a @ 60°C (140°F)
HFC-245ca @ 121°C (250°F)

Refrigerant-Lubricant Combinations at 127°C (260°F)

HCFC-22/mineral oil (ISO 32)
HFC-32/polypropylene glycol butyl monoether (ISO 32)
HFC-32/pentaerythritol ester branched-acid (ISO 32)
HCFC-124/alkylbenzene (ISO 32)
HFC-125/polypropylene glycol butyl monoether (ISO 32)
HFC-125/modified polyalkylene glycol (ISO 32)
HFC-125/pentaerythritol ester branched-acid (ISO 32)
HFC-134/pentaerythritol ester branched-acid (ISO 32)
HFC-134a/polypropylene glycol butyl monoether (ISO 32)
HFC-134a/polypropylene glycol diol (ISO 32)
HFC-134a/modified polyalkylene glycol (ISO 32)
HFC-134a/pentaerythritol ester mixed-acid (ISO 22)
HFC-134a/pentaerythritol ester branched-acid (ISO 32)
HCFC-142b/alkylbenzene (ISO 32)
HFC-143a/pentaerythritol ester branched-acid (ISO 32)
HFC-245ea/pentaerythritol ester branched-acid (ISO 32)
HFC-152a/alkylbenzene

Motor Materials Evaluations

Varnish
weight change

Lead Wire
weight change
dielectric strength

Tie Cord
weight change
break load strength

Magnet Wire/Varnish
bond strength
burnout resistance
dielectric strength

Spiral Wrapped Sleeving
weight change
break loan strength

Sheet Insulation
weight change
tensile strength
elongation
dielectric strength

Tapes
weight change

There were no compatibility concerns with any of the three magnet wires tested. Most of the test varnishes were compatible with the refrigerant-lubricant mixtures. One of the six tested varnishes, the Sterling Y-833 varnish (100% solids VPI epoxy), raised compatibility concerns. It was considered incompatible with HCFC-123 and exhibited physical changes when tested with HCFC-22. The varnish became soft, limp and crazed after the 500-hour exposure to HCFC-123. The varnish also became severely crazed and limp after exposure to HCFC-22. Varnish is used in hermetic motors to bind motor wire windings and to prevent wire-to-wire rubbing from stripping away the insulating coat and electrically shorting the motor.

Only one of the three tapes tested displayed any compatibility problems. The glass/acrylic tape was considered incompatible with HCFC-123. After exposure, it exhibited a large weight loss, turned green in color, rolled up and separated from its backing. Compatibility concerns also arose in tests with nine of the seventeen refrigerant-lubricant mixtures. After exposure, the tape curled up and its backing easily rubbed off. However, when the tape was heated for an addition 24 hours at 150°C (302°F) it regained its original unexposed form.

Three of the six sleeving materials tested had compatibility concerns. The laminating adhesive in the Nomex, Mylar, and Nomex/Mylar sleeving insulations weakened after exposure to HCFC-22/mineral oil and/or HCFC-124/alkylbenzene mixtures. However, it was noted that these materials have been used in HCFC-22/mineral oil applications for 20 to 30 years without equipment reliability problems.

Sheet insulation materials raised more compatibility concerns than any of the other materials tested. The Nomex/Mylar/Nomex was considered incompatible with the HFC-134a/polypropylene glycol diol (PAG-diol) mixture. The adhesive which bonds the layers together dissolved. Pockets of delamination also resulted after the material was exposed to five of the pure refrigerants and eleven of the refrigerant-lubricant mixtures. The material also lost flexibility or became brittle after exposure to four other refrigerant-lubricant mixtures.

Dacron/Mylar/Dacron sheet insulation was also considered incompatible with the HFC-134a/PAG-diol mixture because of dissolution of the laminating adhesive. Additional compatibility concerns were raised due to excessive weight loss after exposure of the material to HCFC-22, HFC-245ca, HFC-134a/polypropylene glycol (PAG-butyl monoether) and HFC-134a/modified PAG mixtures. The material also experienced embrittlement and/or lost flexibility after exposure to four other refrigerant-lubricant mixtures.

Likewise, Melinex 228 and Mylar MO raised compatibility concerns due to embrittlement or loss of flexibility after exposure to four refrigerant-lubricant mixtures which contained mineral oil or alkylbenzene. Nomex 410 and Nomex 418 raised compatibility concerns because of excessive weight loss after exposure to HFC-125.

COMPATIBILITY OF REFRIGERANTS AND LUBRICANTS WITH ELASTOMERS

Objectives:

- To provide compatibility information for elastomers with potential substitutes for CFC refrigerants and with suitable lubricants.
- To obtain data on changes in the physical and mechanical properties of selected elastomers after thermal aging in refrigerant-lubricant mixtures.

Results:

The University of Akron has completed this research under contract with ARTI. Detailed results are presented in the final report, DOE/CE/23810-14, *Compatibility of Refrigerants and Lubricants with Elastomers*, January 1994, Gary R. Hamed, PhD, Robert H. Seiple, and Orawan Taikum.

This research project examined the compatibility of ten refrigerant and seven lubricants with ninety-five elastomeric materials:

Refrigerants	Lubricants
HCFC-22	naphthenic mineral oil (ISO 32)
HCFC-123	alkylbenzene (ISO 32)
HCFC-124	polypropylene glycol butyl monoether (ISO 32)
HCFC-142b	polypropylene glycol diol (ISO 32)
HFC-32	modified polyglycol (ISO 32)
HFC-125	pentaerythritol ester, mixed-acid (ISO 22)
HFC-134	pentaerythritol ester, branched-acid (ISO 32)
HFC-134a	
HFC-143a	
HFC-152a	

Elastomer Families

butyl polypropylene TPE (1 type)
butyl rubbers (7 types)
chlorinated polyethylenes (3 types)
chlorosulfonated polyethylenes (5 types)
epichlorohydrin based rubbers (6 types)
ethylene acrylic elastomers (2 types)
ethylene propylene rubbers (3 types)
ethylene propylene diene rubbers (5 types)
fluorinated rubbers (7 types)
nitrile rubbers (10 types)
polychloroprenes (2 types)
polyisoprenes (3 types)
polysulfide rubbers (4 types)
polyurethanes (7 types)
silicones (5 types)
styrene butadiene rubbers (4 types)
thermoplastic elastomers, TPEs (11 types)

plus, ten industry-supplied gaskets of various compositions.

Swell behavior of elastomer samples were determined by comparing pre-exposure sample measurements for weight, thickness and diameter with their measurements after exposure. As indicated above, these elastomeric formulations included general purpose and specialty thermoset and thermoplastic elastomers.

Refrigerant Immersion Studies: Elastomer samples were completely immersed in the test refrigerant, sealed in a pressure vessel and maintained at room temperature (ambient) for 14 days. *In situ* diameter changes were determined using a traveling microscope after 24-hour, 72-hour and 14-day exposures. Following the 14 day exposures, the samples were remeasured 2 hours and 24 hours after they were removed from the pressure vessels.

In reviewing the results, the following general statements can be made concerning *in situ* swelling measurements after the 14 day exposures:

- samples exposed to HCFC-123 had the largest swell,
- samples exposed to HCFC-22, HCFC-124, HCFC-142b had moderate swell,
- samples exposed to HFC-32, HFC-125, HFC-134, HFC-134a, HFC-143a, and HFC-152a had the least swell.

Refer to Table 17 for a relative comparison of *in situ* swelling results.

Lubricant Immersion Studies: Elastomer samples were completely immersed in the test lubricant, sealed in a glass vessel and then heated at 60°C (140°F) for 14 days. Sample diameters were measured *in situ* after 24 hours of exposure. The elastomer samples were also measured for weight, thickness and diameter immediately after the 14-day exposure and then again 24 hours after removal.

Several of the elastomeric compositions, including some of the industry-supplied gaskets, were resistant to swelling in all of the lubricants. These included rubbers from the epichlorohydrin, nitrile, polysulfide rubber, and thermoplastic elastomer families. Refer to Table 18 for a relative comparison of the *in situ* swelling results.

Refrigerant-Lubricant Thermal Aging Tests: Based on the results of the separate lubricant and refrigerant studies, twenty-five elastomeric samples were selected for inclusion in refrigerant-lubricant thermal aging tests. These elastomers were individually immersed in seventeen separate refrigerant-lubricant mixtures for 14 days at 100 °C (212 °F). Depending on the refrigerant-lubricant combination, the refrigerant weight percent varied from 20% to 50% concentration to maintain a vapor pressure of 275-300 psia. After the 14-day exposures, dimensional, hardness, and tensile values of the exposed elastomers were obtained and compared to those of non-aged specimens.

As a general trend, it was found that the tensile strengths of the aged elastomers were inversely related to the amount of swelling they exhibited after aging in the refrigerant-lubricant mixtures. When swelling was large, elastomer tensile strength decreased dramatically. However, in some cases, when swelling was slight or negative (i.e., shrinkage from material extraction) tensile strength increased after aging. In ali cases, filled rubbers showed less change of tensile strength after aging compared to unfilled counterparts.

Table 17. Relative in situ Elastomer Swelling in Refrigerants

	22	32	123	124	125	134	134a	142b	143a	152a
butyl polypropylene TPE	-	S	S	-	S	S	S	-	S	-
butyl rubbers	S	S	-	S	S	S	S	S	S	S
chlorinated polyethylenes	S	S	-	S	S	S	S	S	S	S
chlorosulfonated polyethylenes	-	S	-	S	S	S	S	S	S	S
epichlorohydrin based rubbers	L	S	L	L	S	-	S	S	S	S
EPM rubbers	S	S	-	S	S	S	S	S	S	S
ethylene acrilic elastomers	L	-	L	L	L	-	-	L	S	-
ethylene propylene diene rubbers	S	S	-	S	S	S	S	S	S	S
fluorinated rubbers	L	-	L	L	-	L	L	L	-	L
nitrile rubbers	L	S	L	L	S	-	S	-	S	-
polychloroprenes	S	S	-	S	S	S	S	S	S	S
polyisoprenes	-	S	L	S	S	S	S	-	S	S
polysulfide rubbers	S	S	L	S	S	S	S	S	S	S
polyurethanes	L	S	L	L	-	-	S	-	S	-
silicones	L	-	L	L	-	-	-	L	-	L
styrene butadiene rubbers	-	S	L	S	S	S	S	S	S	S
thermoplastic elastomers (TPE)	-	S	-	-	S	S	S	S	S	S

Table 18. Relative in site Elastomer Swelling in Lubricants.

	AB	MO	PEBA	PEMA	PPGBM	PPGD	MPG
butyl polypropylene TPE	-	-	S	S	S	S	S
butyl rubbers	L	L	S	S	S	S	S
chlorinated polyethylenes	S	-	-	-	S	S	S
chlorosulfonated polyethylenes	-	-	-	-	S	S	S
epichlorohydrin based rubbers	S	S	-	-	S	-	S
EPM rubbers	L	L	S	S	S	S	S
ethylene acrilic elastomers	-	-	L	L	L	L	L
ethylene propylene diene rubbers	L	L	S	S	S	S	S
fluorinated rubbers	S	S	L	-	S	S	S
nitrile rubbers	S	S	-	-	S	S	S
polychloroprenes	-	-	-	L	-	S	S
polyisoprenes	L	L	-	-	S	S	S
polysulfide rubbers	S	S	S	S	S	S	S
polyurethanes	-	S	S	-	S	-	-
silicones	-	-	-	S	S	S	S
styrene butadiene rubbers	L	L	-	-	-	S	S
thermoplastic elastomers (TPE)	S	-	S	S	S	S	S

legend:	
S	– small linear swells; less than 8 %
L	– large linear swells; greater than than 35 %
–	– mixed swell values and/or 8% < swell < 35%
AB	– alkylbenzene
MO	– mineral oil
PEBA	– Pentaerythritol ester branched acid
PEMA	– pentaerythritol ester mixed acid
PPGBM	– polypropylene glycol butyl monoether
PPGD	– polypropylene glycol diol
MPG	– modified polyglycol

COMPATIBILITY OF REFRIGERANTS AND LUBRICANTS WITH ENGINEERING PLASTICS

Objectives:

- To provide compatibility information for engineering plastics with potential substitutes for CFC refrigerants and with suitable lubricants.
- To obtain data on changes in the mechanical properties of selected plastics after thermal aging in refrigerant-lubricant mixtures.

Results:

Imagination Resources, Inc., has completed this research under contract with ARTI. Detailed results are presented in the final report, DOE/CE/23810-15, *Compatibility of Refrigerants and Lubricants with Engineering Plastics*, December 1993, by Richard C. Cavestri, PhD.

This research project examined the compatibility of ten refrigerants and seven lubricants with twenty-three engineering plastics:

Refrigerants	Lubricants
HCFC-22	naphthenic mineral oil (ISO 32)
HCFC-123	alkylbenzene (ISO 32)
HCFC-124	polypropylene glycol butyl monoether (ISO 32)
HCFC-142b	polypropylene glycol diol (ISO 32)
HFC-32	modified polyglycol (ISO 32)
HFC-125	pentaerythritol ester, mixed-acid (ISO 32)
HFC-134	pentaerythritol ester, branched-acid (ISO 22)
HFC-134a	
HFC-143a	
HFC-152a	

Engineering Plastics Tested

- acetal
- acrylonitrile-butadiene-styrene(ABS)
- liquid crystal polymer (LCP)
- modified polyetherimide
- modified polyphenylene oxide
- nylon 6/6
- phenolic
- polyamide-imide (2 types)
- polyaryletheretherketone (PEEK)
- polyaryletherketone (PEK)
- polyarylsulfone
- polybutylene terephthalate (PBT)
- polycarbonate
- polyetherimide
- polyethylene terephthalate (PET)
- polyimide thermoset (2 types)
- polyphenylene sulfide (PPS)
- polyphthalamide
- polypropylene
- polytetrafluoroethylene (PTFE)
- polyvinylidene fluoride

Lubricant Immersion Studies: The plastic specimens were evaluated after 14-day exposures in pure lubricants at 60°C (140°F) and 100°C (212°F). Each plastic was affected to some extent by the lubricants. In general, weight and dimensional changes were in the plus or minus 1-2% range. However, the ABS specimens exhibited relatively larger changes in all the lubricants (in the 5-15% range).

Refrigerant Immersion Studies: The plastics were evaluated at ambient room temperature and 60°C (140°F) in pure refrigerant for 14 days at the saturation pressure of the refrigerant. All refrigerants had some effect on the plastics; generally, weight increase and some softening of the plastics. HFC refrigerants seem to have the least effect on the plastics. The ABS plastic failed (e.g., dissolved or deformed) in HCFC-22, HFC-32, HCFC-123, HCFC-124, HFC-134, and HFC-152a. The polycarbonate and the modified polyphenylene oxide plastics failed in HCFC-123.

Stress Crack-Creep Rupture Tests: Linear creep was measured for plastic test bars submerged in an ISO 32 cSt branched acid polyolester lubricant with 40% refrigerant concentrations (by weight) at 20°C (68°F) for 14 days. Each plastic was weight loaded at 25% of its ultimate tensile capability to stress the gage area of specimen test bars. The resultant deformation under load information provided the creep modulus arising from the exposure effects of synthetic lubricants with the differing refrigerants.

Plastic creep appeared to be nearly the same for all refrigerants. However, plastics exposed to HCFC-22 exhibited slightly lower creep rates than when exposed to the other nine refrigerants. Two plastics that routinely failed (e.g., broke within one hour) were ABS and modified polyphenylene oxide. HCFC-123, as expected, induced a pronounced increase in plastic creep, but did not promote rupture of the plastic test specimens.

Refrigerant-Lubricant Thermal Aging Tests: Thermal aging tests on the twenty-three plastic specimens in seventeen refrigerant-lubricant combinations were completed. These tests were performed for 14 days at 150°C (300°F) and at refrigerant pressures from 1,900 to 2,070 kPa (275 to 300 psia). Due to its higher reactivity, HCFC-123 aging tests were performed at 125°C (260°F) and at 105°C (220°F). Physical changes were observed, dimensional changes measured, and specimen tensile properties were compared to the original, unexposed specimens.

After aging, the plastics exhibited minimal dimensional and weight changes (i.e., generally within plus or minus 2%). However, the phenolic, polyvinylidene fluoride, and polypropylene plastic specimens exhibited the largest dimensional and weight changes (generally 5-20%). As compared to the tensile tests performed on non-aged plastic test bars, the aged specimens exhibited large reductions in tensile capabilities (i.e., changes in tensile strengths ranged from a 30% gain to a 50% loss, changes in elongation ranged from a 10% increase to a 85% loss). Hence, as a result of environmental embrittlement, many plastics broke after a much smaller elongation under a much lower tensile load; as compared to the non-aged specimens.

DOE/CE/23810-38

ELECTROHYDRODYNAMIC (EHD) ENHANCEMENT OF POOL AND IN-TUBE BOILING OF ALTERNATIVE REFRIGERANTS

Objectives:

- To construct a test rig that can measure improvements with in-tube boiling and in-tube condensation heat transfer performance when utilizing EHD enhancement technology.
- To ascertain the heat transfer benefits on pool boiling with HCFC-123/lubricant on single and multiple enhanced tubes when utilizing EHD techniques.

Results:

The University of Maryland completed this research under contract with ARTI. The final report detailing the pool boiling test results and the fabrication and qualification of the in-tube apparatus is available under DOE report number DOE/CE/23810-17, *EHD Enhancement of Pool and In-Tube Boiling of Alternative Refrigerants*, August 1993, by M. M. Ohadi, S. Dessiatoun, A. Singh, and M. A. Faani (RDB #3A16, 62 pages).

This project accomplished three major tasks: (1) literature search on prior EHD research, (2) EHD pool boiling experiments with HCFC-123 and HFC-134a, and (3) design, fabrication, and shakedown of an EHD in-tube boiling/condensation test rig.

For pool boiling, higher applied electric potentials resulted in higher EHD-induced effects that promoted refrigerant bubble break-up and increased bubble departure speeds; collectively leading to higher heat transfer rates. For pool-boiling with HCFC-123 and HFC-134a, it was reported that the heat transfer rates increased 5 - 8 fold, as compared to the non-EHD enhanced runs. This depended on whether or not 2% lubricant concentration was added and on whether mesh-type or straight-wire electrodes were utilized.

COMPLIANCE WITH AGREEMENT

ARTI has complied with all terms of the grant agreement during the reported period.

PRINCIPAL INVESTIGATOR'S EFFORT

Mr. Mark Menzer is the ARTI principal investigator for the MCLR program. During the first quarter of calendar year 1994, Mr. Menzer devoted a total of 161 hours (35.9% of his available work hours) on the MCLR program.

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