MATERIALS COMPATIBILITY AND LUBRICANTS RESEARCH ON CFC-REFRIGERANT SUBSTITUTES

Quarterly MCLR Program Technical Progress Report

1 April 1993 - 30 June 1993

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July 1993

Prepared for

**The U.S. DEPARTMENT OF ENERGY
Grant Number DE-FG02-91CE23810**

This program is supported, in part, by U.S. Department of Energy grant number DE-FG02-91CE23810: Materials Compatibility and Lubricants Research (MCLR) on CFC-Refrigerant Substitutes. Federal funding supporting this program constitutes \$4,143,000 or 93.67% of allowable costs. Funding from non-government sources supporting this program consists of direct cost sharing totaling \$280,000 or 6.33% of allowable costs, and significant in-kind contributions from the air-conditioning and refrigeration industry.

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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. Under the current MCLR program the Air-Conditioning and Refrigeration Technology Institute, Inc., (ARTI) is contracting and managing multiple research projects and a data collection and dissemination effort. Detailed results from these projects are reported in technical reports prepared by each researcher.

SCOPE

The Materials Compatibility and Lubricant Research (MCLR) program is a 36 month 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 1994. The MCLR program currently consists of a number of research projects grouped in phases. Phase I 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 been extended due to schedule delays or added work. Phase II currently consists of eight research projects and a data collection and dissemination project. Phase II projects began in October 1992 and will run through September 1994. This report summarizes the research conducted during the 2nd quarter of calendar year 1993.

SIGNIFICANT RESULTS

ON-GOING PROJECTS

THERMOPHYSICAL PROPERTIES (HFC-143a AND HFC-152a)

Objective:

To provide highly accurate, selected thermophysical properties data for refrigerants HFC-143a and HFC-152a; 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) 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 pressure-volume-temperature behavior, liquid pressure-volume-temperature 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-23810-20A, *Thermophysical Properties of HFC-143a and HFC-152a*, 1 April 1993 - 30 June 1993, by Dr. Richard F. Kayser.

NIST has analyzed HFC-152a gas-phase PVT data published by Baehr and Tillner-Roth (Hanover, Germany) and compared the virial coefficients with a NIST correlation of virials for a wide variety of small molecules. NIST found good agreement of the data and determined that additional gas-phase PVT measurements are not needed.

NIST conducted liquid-phase density measurements of HFC-152a at 136 state points ranging from 158 to 400 K (-175 to 260 °F) with pressures up to 35 MPa (5000 psia). NIST has also conducted vapor pressure measurements at 38 temperatures ranging from 220 to 273 K (-63 to 32 °F) and pressures ranging from 22.7 to 263.7 kPa (3.3 to 38.2 psia). Data from these measurements are reported in Appendix A of the NIST quarterly technical progress report.

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 for most mixtures and -50 to 60 °C 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 Dr. Michael B. Pate, Mr. Steven C. Zoz, and Mr. Lyle J. Berkenbosch.

Iowa State University is continuing with Phase 2 of the project which encompasses more 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. Results to date are summarized in Table 1.

TABLE 1. Miscibility of Lubricants with Refrigerants

Lubricant	Refrigerant									
	R22	R32	R123	R124	R125	R134	R134a	R142b	R143a	R152a
Mineral Oil ISO 32 cSt	< -10	I	< -50	< 20	I	I	I	< -40	I	I
Mineral Oil ISO 68 cSt	< 10	---	< -40	< 50	I	I	I	< -30	I	I
Alkylbenzene ISO 32 cSt	M	I	M	M	I	I	I	M	I	< 50
Alkylbenzene ISO 68 cSt	M	---	M	M	I	I	I	M	I	< 50
Polypropylene Glycol Butyl Monoether ISO 32 cSt	M	I	M	M	> 50	< -20	> 60	M	I	M
Polypropylene Glycol Butyl Monoether ISO 68 cSt	M	I	> 20	M	> 40	M	> 50	M	I	> 80
Polypropylene Glycol Diol ISO 32 cSt	M	< -50	M	M	M	M	M	M	I	M
Polypropylene Glycol Diol ISO 100 cSt	M	---	M	M	> 40	M	> 60	M	I	> 70
Modified Polyglycol ISO 32 cSt	< -20	> 60 < 10	< -30	< -10	> 30 < 10	< 0	< 0	< -40	I	M
Pentaerythritol Ester mixed acid ISO 22 cSt	M	> 50 < 10	M	M	M	M	< -50	M	I	M
Pentaerythritol Ester mixed acid ISO 32 cSt	M	< -10	M	M	M	M	< -40	M	I	M
Pentaerythritol Ester mixed acid ISO 100 cSt	M	---	M	M	> 60	M	< -10	M	I	M
Pentaerythritol Ester branched acid ISO 32 cSt	M	---	M	M	M	M	M	M	I	M
Pentaerythritol Ester branched acid ISO 100 cSt	M	---	M	M	> 40	M	> 60	M	I	> 90

I – At least one concentration remained immiscible throughout the test temperature range.
 M – All concentrations remained miscible throughout the test temperature range.
 < ** – Temperature in C above which all concentrations remained miscible.
 > ** – Temperature in C below which all concentrations remained miscible.

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 their progress is contained in the quarterly technical progress report, DOE/CE/23810-20C, *Measurement of Viscosity, Density, and Gas Solubility of Refrigerant Blends*, 1 April 1993 - 30 June 1993, by Dr. Richard C. Cavestri.

Viscosity, solubility, and density data on HCFC-22 and Suniso® 3GS mineral oil is reported from -20 to 120 °C (-4 to 248 °F) at 69 to 1,724 kPa (10 to 250 psia). Viscosity, solubility, and density information on R-502 and Suniso® 3GS mineral oil is also reported over the same range. The purpose of these tests was to determine the repeatability and acceptability of results generated by Imagination Resources' proprietary oscillating-bob viscometer.

Also presented in the quarterly report are miscibility screening results of six refrigerant blends with five lubricants. As a result of this screening, the following three refrigerant blends and two polyolester lubricants were selected for evaluation in the balance of the research project:

Possible HCFC-22 Alternatives

HFC-32/HFC-125 (60/40%)

HFC-32/HFC-125/HFC-134a (30/10/60%)

Possible R-502 Alternative

HFC-125/HFC-143a/HFC-134a (44/52/4%)

Lubricants

Pentaerythritol ester, branched-acid (ISO 32 cSt)

Pentaerythritol ester, mixed-acid (ISO 32 cSt)

It is anticipated that the next report will include complete viscosity, solubility and density data on one of the three refrigerant blends.

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. This research involves complete viscosity, solubility, and density measurements of the following thirty-eight refrigerant-lubricant mixtures 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)
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)

Spauschus Associates, Inc., had previously completed measurements of high lubricant concentration (70, 80, 90, and 100% lubricant by weight) for twelve of the thirty-eight mixtures and correlated the measurements to mathematical relationships for viscosity, pressure, and density.

During the last quarter, Spauschus Associates has further refined the mathematical relationships to include a term for the oil composition.

ACCELERATED SCREENING METHODS FOR PREDICTING LUBRICANT PERFORMANCE IN REFRIGERANT COMPRESSORS

Objective:

To propose/devise a bench type device that simulates lubricant performance in refrigeration and air-conditioning compressors.

Results:

The University of Illinois at Urbana-Champaign is performing this research under contract with ARTI. Minor difficulties with the University of Illinois' proprietary high pressure tribometer (HPT) have been resolved. Testing is now underway and will include the following fluids:

CFC-12 and mineral oil	---	CFC baseline
HCFC-22 and mineral oil	---	HCFC baseline
HFC-134a and pentaerythritol ester lubricants	---	HFC evaluation
HFC-32 blend and ester lubricants	---	blend evaluation

Falex® results provided by air-conditioning and refrigeration compressor manufacturers will be compared against those measured in the HPT. The contact geometry, speed, and refrigerant-lubricant mixture used in obtaining the Falex® data will also be used in the HPT. However, the HPT tests will be performed at environmental (e.g., temperature and pressure) and load conditions that better approximate compressor operation. It is expected that four of the following contact pairs will be evaluated:

380 die cast aluminum with case hardened low carbon steel

356 die cast aluminum with hardened steel drill rod

333 permanent mold cast aluminum with gray cast iron

gray cast iron with case hardened low carbon steel

hardened steel with hardened steel

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:

<u>Compressor Application Simulation</u>	<u>Possible Contact Pairs</u>
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.

Comparison of the HPT results with the Falex® and compressor operation data will be presented when it becomes available.

**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 is performing this research under contract with ARTI. Radian Corporation has completed Phase 1 of this project which 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, Radian found that the majority of hermetic motor insulation failures occur in the stator windings of the motor due to 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, the test 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. The 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 the entire test loop must be purged of one refrigerant-lubricant mixture before another can be tested.

Radian has developed a proposed test method that combines the advantages of these test methods into a single practical method. The proposed method replaces the stator simulator unit (SSU). The SSU 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 emulate 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.

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 final 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 (RDB# 3501).

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 report, DOE/CE/23810-20D, *Accelerated Screening Methods for Determining Chemical and Thermal Stability of Refrigerant-Lubricant Mixtures; Part II: Experimental Comparison and Verification of Methods*, 1 March 1993 - 30 June 1993,

by Mr. Robert Kauffman. This 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.

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.

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, Consulting Engineer, is performing this work 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 extended abstracts 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 abstracts have been prepared for many of the entries. These detailed abstracts describe the data, tests, evaluations, and the materials noted in the documents. The abstracts 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 ninety 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 August 1993 release of the ARTI Refrigerant Database will contain in excess of 800 entries related to:

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

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 on results is presented in the final report, DOE/CE/23810-16, *Thermophysical Properties*, April 1993, by Dr. Richard F. Kayser. Key results are summarized below:

HFC-32

NIST has developed a 32-term MBWR equation of state (Table 2) 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 (6000 psi), and it may be reasonably extrapolated up to 100 MPa (15000 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 3) 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 (6000 psi).

HCFC-124

NIST has developed a 32-term MBWR equation of state (Table 4) 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 5) 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 (3000 psi).

TABLE 2. Coefficients to the MBWR equation of state for HFC-32
(units are K, bar, L, mol)

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

$$\rho_c = 8.1245 \text{ mol/L} \quad R = 8.314471 \text{ J/K-mol (gas constant)}$$

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

i b_i

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 3. Coefficients to the MBWR equation of state for HCFC-123
(units are K, bar, L, mol)

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

$$\rho_c = 3.596417 \text{ mol/L} \quad R = 8.314471 \text{ J/K-mol (gas constant)}$$

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

i	b _i		
1	-0.193042434973E-01	17	0.106201732381E+00
2	-0.263410206086E+00	18	-0.401991529370E+02
3	0.26643926292E+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 4. Coefficients to the MBWR equation of state for HCFC-124
(units are K, bar, L, mol)

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

$$\rho_c = 4.10153 \text{ mol/L} \quad R = 8.314471 \text{ J/K-mol (gas constant)}$$

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

i	b _i		
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 5. Coefficients to the MBWR equation of state for HFC-125
(units are K, bar, L, mol)

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

$$\rho_c = 4.7650 \text{ mol/L} \quad R = 8.314471 \text{ J/K-mol (gas constant)}$$

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

i	b _i		
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 DOE report number DOE/CE/23810-7, *Theoretical Evaluations of R-22 Alternative Fluids*, Final Report, by Dr. Piotr A. Domanski and Dr. David A. Didion, January 1993. This report is currently available from the ARTI Refrigerant Database (RDB# 3305). The following refrigerants and refrigerant blends were evaluated:

Alternative Refrigerants/Blends (% Weight)

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)

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 DOE report number DOE/CE/23810-5, *Chemical and Thermal Stability of Refrigerant-Lubricant Mixtures with Metals*, Final Report, by Dr. Dietrich F. Huttenlocher. Key results are summarized below:

Alternative Refrigerant-Lubricant Combinations

CFC-11 (baseline) with:	HFC-134 with:
naphthenic mineral oil ISO 32	pentaerythritol ester, branched acid
naphthenic mineral oil ISO 46	HFC-134a with:
CFC-12 (baseline) with:	pentaerythritol ester, mixed acid
naphthenic mineral oil ISO 32	pentaerythritol ester, branched acid
alkylbenzene	pentaerythritol ester, 100 cSt
HCFC-22 with:	polypropylene glycol butyl monoether
naphthenic mineral oil ISO 32	polypropylene glycol diol
HFC-32 with:	modified polyglycol
pentaerythritol ester, branched acid	HCFC-142b with:
polypropylene glycol butyl monoether	alkylbenzene
HCFC-123 with:	HFC-143a with:
naphthenic mineral oil ISO 32	pentaerythritol ester, branched acid
naphthenic mineral oil ISO 46	HFC-152a with:
HCFC-124 with:	alkylbenzene
alkylbenzene	
HFC-125 with:	
pentaerythritol ester, branched acid	
polypropylene glycol butyl monoether	
modified polyglycol	

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 (100 cSt) pentaerythritol ester exhibited additional evidence of molecular changes during aging at 200°C. The formation of CO₂ 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.

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 recently completed this research under contract with ARTI. Details of their research is presented in the final report, DOE/CE/23810-13, *Compatibility of Refrigerants and Lubricants with Motor Materials*, Final Report, May 1993, by Dr. Robert Doerr, Mr. Stephen Kujak, and Mr. Todd Waite.

Final 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 materials before and after exposure to 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	HFC-32/PAG, butyl monoether
HCFC-124/Alkylbenzene	HFC-32/Polyolester, branched acid
HFC-134/Polyolester, branched acid	HFC-125/PAG, butyl monoether
HFC-134a/PAG, butyl monoether	HFC-125/PAG, modified
HFC-134a/PAG, diol	HFC-125/Polyolester, branched acid
HFC-134a/PAG, modified	HFC-143a/Polyolester, branched acid
HFC-134a/Polyolester, mixed acid	HFC-152a/Alkylbenzene
HFC-134a/Polyolester, branched acid	HFC-245ea/Polyolester, branched acid
HCFC-142b/Alkylbenzene	

Motor Materials EvaluationsVarnish

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 load 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, preventing wire-to-wire rubbing from stripping away the insulating coat leading to an electrical short in the motor.

Only one of the three tested tapes 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 additional 24 hours at 150°C (302°F) it regained its original unexposed form.

Three of the six tested sleeving materials 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/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/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 is performing this research under contract with ARTI. A draft final report on this work has been received. It is expected that the final report, DOE/CE/23810-14, *Compatibility of Refrigerants and Lubricants with Elastomers*, will be available in September 1993.

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

Refrigerants

HCFC-22
HCFC-123
HCFC-124
HCFC-142b
HFC-32
HFC-125
HFC-134
HFC-134a
HFC-143a
HFC-152a

Lubricants

naphthenic mineral oil
alkylbenzene
polypropylene glycol butyl monoether
polypropylene glycol diol
modified polyglycol
pentaerythritol ester, mixed-acid
pentaerythritol ester, branched-acid

Elastomer Families

butyl polypropylene TPE (1 type)	nitrile rubbers (10 types)
butyl rubbers (7 types)	polychloroprenes (2 types)
chlorinated polyethylenes (3 types)	polyisoprenes (3 types)
chlorosulfonated polyethylenes (5 types)	polysulfide rubbers (4 types)
epichlorohydrin based rubbers (6 types)	polyurethanes (7 types)
ethylene acrylic elastomers (2 types)	silicones (5 types)
ethylene propylene rubbers (3 types)	styrene butadiene rubbers (4 types)
ethylene propylene diene rubbers (5 types)	thermoplastic elastomers, TPEs
fluorinated rubbers (7 types)	(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 6 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 6 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 all cases, filled rubbers showed less change of tensile strength after aging compared to unfilled counterparts.

TABLE 6. Relative in situ Elastomer Swelling

RELATIVE IN SITU ELASTOMER SWELLING: 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	-
ethylene acrylic 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

RELATIVE IN SITU ELASTOMER SWELLING: 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 acrylic 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 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., is performing this research under contract with ARTI. A draft final report has been received and is currently under review. Upon acceptance, the final report will be released under DOE report number DOE/CE/23810-15, *Compatibility of Refrigerants and Lubricants with Engineering Plastics*.

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

Refrigerants

HCFC-22
HCFC-123
HCFC-124
HCFC-142b
HFC-32
HFC-125
HFC-134
HFC-134a
HFC-143a
HFC-152a

Lubricants

naphthenic mineral oil
alkylbenzene
polypropylene glycol butyl monoether
polypropylene glycol diol
modified polyglycol
pentaerythritol ester, mixed-acid
pentaerythritol ester, branched-acid

Engineering Plastics Tested

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

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 1,896 to 2,068 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.

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 is performing this research under contract with ARTI. A draft final report detailing the pool boiling test results and the fabrication and qualification of the in-tube apparatus has been received. Draft final report, DOE/CE/23810-17, *EHD Enhancement of Pool and In-Tube Boiling of Alternative Refrigerants*, by M. M. Ohadi, S. Dessiatoun, A. Singh, and M. A. Faani is currently undergoing a technical review. It is expected that the final report will be available in September 1993.

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. Future research on the EHD effects on pool boiling and in-tube boiling and condensation will be sponsored by the U.S. DOE; augmented by contributions from individual sponsoring companies.

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 second quarter of calendar year 1993, Mr. Menzer devoted a total of 195 hours (44.6% of his available work hours) on the MCLR program.

**DATE
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10/01/93