DOE/CE/23810-61

MATERIALS COMPATIBILITY AND LUBRICANTS RESEARCH ON CFC-REFRIGERANT SUBSTITUTES

Quarterly MCLR Program
Technical Progress Report

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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 1996. The MCLR program consists of a number of research projects grouped in phases corresponding to incremental funding periods. The first phase encompassed seven research projects and a data collection and dissemination project. Phase I projects began in January 1992 and have all been completed. Phase II consists of eight research projects and a data collection and dissemination project. Phase II projects began in October 1992 and are currently nearing completion. Phase III consists of ten projects which began in November 1993 and will run through September 1995. Phase IV was approved by the Department on Energy on 15 September 1994. Fifteen research projects and continuation of the data dissemination project are planned for this phase which will run through September 1996.

This report summarizes the research conducted during the second quarter of calendar year 1995. It supersedes the following report numbers:
DOE/CE/23810-59, DOE/CE/23810-48, DOE/CE/23810-42, DOE/CE/23810-38, 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.

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 1995, Mr. Menzer devoted a total of 128 hours (28.1% of his available work hours) on the MCLR program.

THERMOPHYSICAL PROPERTIES OF HCFC ALTERNATIVES

Objective:

To provide highly accurate, selected measurements of thermophysical properties to determine equation of state mixture interaction parameters for refrigerant blends and pure fluids. This project will measure primary thermophysical properties of the following refrigerants and refrigerant mixtures:

Pure Fluid:	R-41
Binary Mixtures:	R125/134a
	R32/143a
	R125/143a
	R143a/134a
	R32/290
	R125/290
	R290/134a
	R41/744
Ternary Mixture:	R32/125/134a

These data will consist of simultaneous measurements of the coexisting liquid and vapor densities and compositions as well as the bubble point pressures over a wide range of temperatures and compositions. These data will be used to determine mixing parameters for the Carnahan-Starling-DeSantis (CSD) equation of state and the extended corresponding states (ECS) model.

Results:

The Thermophysical Division, National Institute of Standards and Technology, Boulder, CO, is conducting this project under contract to ARTI.

Quarterly technical report, DOE/CE/23810-59A, *Thermodynamic Properties of HCFC Alternatives (1 January 1995 - 31 March 1995)*, by W. H. Haynes, April 1995 (RDB #5525, 30 pages), tabulates coexisting density and bubble point pressure data for R32/290, R134a/290, R125/290, R32/134a and R32/125 mixtures [DOE/CE/23810-59A: Appendix A - Tables 1 through 5]. The data on R32/134a and R32/125 mixtures represent final revised data for these binary systems and replace the preliminary data which were previously reported in the quarterly report, DOE/CE/23810-51A.

Quarterly technical report, DOE/CE/23810-61A, *Thermodynamic Properties of HCFC Alternatives (1 April 1995 - 30 June 1995)*, by W. H. Haynes, July 1995, tabulates heats

of vaporization and phase envelope widths for refrigerant and hydrocarbon mixtures at 298 K [DOE/CE/23810-61A: Appendix A - Table 1; reproduced as Table 2-1]. The quarterly report also tabulates vapor-liquid equilibrium data, near-saturation liquid density data, and near-saturation vapor density data for:

R32/134a mixtures [DOE/CE/23810-61A: Appendix A - Tables 2, 3 and 4]
R32/125 mixtures [DOE/CE/23810-61A: Appendix A - Tables 5, 6, and 7]
R32/290 mixtures [DOE/CE/23810-61A: Appendix A - Tables 8, 9, and 10]
R125/290 mixtures [DOE/CE/23810-61A: Appendix A - Tables 11, 12, and 13]
R134a/290 mixtures [DOE/CE/23810-61A: Appendix A - Tables 14, 15, and 16]

The report also tabulated compressed gas and liquid phase PVT data for an R-143a/125 mixture at a 0.50004/0.49996 weight % composition in SI and IP units [DOE/CE/23810-61A: Appendix A - Tables 17 & 18].

Table 2-1. Heats of Vaporization and Phase Envelope Widths (Vapor composition - liquid composition) for Refrigerant and Hydrocarbon Mixtures at 298 K (77°F)

Mixture	Liquid Composition Mass Fraction	Heat of Vaporization kJ/kg	Phase Envelope Width Mass Fraction
R32/134a	0.5/0.5	262	0.173
R32/125	0.5/0.5	196	0.027
R125/134a	0.5/0.5	147	0.138
R32/125/134a	0.2/0.4/0.4	185	0.074/0.066
R32/290	0.5/0.5	292	0.111
R125/290	0.5/0.5	196	0.071
R134a/290	0.5/0.5	223	0.040
R32/143a	0.5/0.5	225	0.044
R143a/134a	0.5/0.5	131	0.122
R125/143a	0.5/0.5	143	0.010
Propane/n-Butane	0.5/0.5	300	0.263
n-Butane/n-Pentane	0.5/0.5	326	0.270

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:

Imagination Resources, Inc., is performing this research under contract to ARTI.

Part I of this project was 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. The survey has been completed; major component manufacturers submitted lists of fluids to be analyzed. Over 100 processing fluids were identified. Fluids covered included soldering fluxes, cleaning fluids, lubricating fluids, rust inhibitors agents and adhesives. Interim report, DOE/CE/23810-43, *Compatibility of Manufacturing Process Fluids with HFC Refrigerants and Ester Lubricants*, by Richard C. Cavestri, Ph.D., dated November 1994, (RDB #5650, 38 pages) summarizes the findings of the survey.

Part II work has commenced. Sixty-four processing fluids were chosen from the list of fluids identified in Part I for additional testing. The test fluids chosen include 3 brazing fluxes; 8 coolants; 15 detergents, degreasers, or cleaners; 4 iron phosphatizers; 13 lubricants; 17 rust inhibitors or preventatives; and 4 sealants.

These 64 process fluids were dried in a forced air oven at 45°C (113°F), leaving either a powder or a viscous material. These residues were then tested for solubility in two polyolester lubricants at a 0.5 to 99.5 weight ratio. For each of the 20 processing fluids which was soluble, three refrigerant-lubricant-processing fluid mixtures were prepared: 95/4.975/0.025, 95/4.995/0.005, and 95/4.9995/0.0005 percent by weight. R-134a was used as the refrigerant in all cases. A separate mixture was prepared with each of the two polyolester lubricants. These solutions were then tested for miscibility from -40°C (-40°F) to 80°C (176°F) at 10°C (18°F) increments. They were then heated at 175°C (347°F) for 14 days and retested for miscibility over the same temperature range.

The 44 process fluids which were not soluble in the polyolester lubricants were dispersed in a solvent and applied to metal shavings. The solvent was evaporated and polyolester lubricant was added to the metal shavings. After heating at 100°C (212°F) for 5 days, the specimens underwent a procedure using high pressure liquid chromatography and size

exclusion columns in an attempt to quantify the amount of process material which was solubilized. This technique failed in 33 of the process fluids. For the other 11 process fluids, miscibility was determined from -40°C (-40°F) to 80°C (176°F) at 10°C (18°F) increments, before and after heating at 175°C (347°F) for 14 days.

The project monitoring committee has requested that the contractor perform compatibility tests with the process fluids before the project is completed.

COMPATIBILITY OF MOTOR MATERIALS USED IN AIR-CONDITIONING FOR RETROFITS WITH ALTERNATIVE REFRIGERANTS AND LUBRICANTS

Objective:

To examine the compatibility of motor materials for retrofit with alternative refrigerants and lubricants.

Results:

The Trane Company is conducting this research under contract to ARTI. A report of the results to date are detailed in the quarterly technical report, DOE/CE/23810-51B, *Compatibility of Refrigerants and Lubricants with Motor Materials Under Retrofit Conditions*, by Robert Doerr and Todd Waite, January 1995 (RDB #5511, 86 pages). The results are summarized below.

The project is investigating the material compatibility of motor materials under the following retrofit scenarios:

CFC-11/mineral oil to HCFC-123/mineral oil
CFC-12/mineral oil to HFC-134a/polyolester lubricant
R-502/mineral oil to R-404A/polyolester (HFC-125/HFC-143a/HFC-134a)
HCFC-22/mineral oil to R-407C/polyolester (HFC-32/HFC-125/HFC-134a)
CFC-11/mineral oil to HFC-245ca/polyolester
HCFC-123/mineral oil to HFC-245ca/polyolester

Compatibility test of motor materials with the first four retrofit scenarios have been completed. The tests were conducted in accordance with UL Standard 2171. Test specimens of motor materials and motorettes were sequentially exposed for 500 hours in the initial refrigerant-lubricant mixture, then exposed to the alternative refrigerant-lubricant mixture and evaluated after 168, 336 and 500 hours. Exposures involving CFC-12, R-502 and HCFC-22 retrofit scenarios were exposed at a temperature of 127°C (260°F). Exposures for the CFC-11 retrofit scenario were exposed at a temperature of 100°C (212°F). Motor materials tested were:

<u>Magnet Wire Insulation</u>

- polyester base with amide imide overcoat
- esterimide base with amide imide overcoat
- polyester base with amide imide overcoat[1] and epoxy saturated glass serving

Varnishes

- water base epoxy-phenolic: Isopoxy 800
- solvent-epoxy-phenolic: P.D. George 923
- solvent-epoxy: Sterling U-475EH[1]

Sheet Insulation

- polyester film: Mylar
- polyester film, low oligomer: Melinex
- polyester composite: Darcon-Mylar-Darcon
- aramid fiber mat: Nomex 410 10 mil
- aramid fiber mica mat: Nomex Mica
- aramid mat, polyester film composite: Nomex-Mylar-Nomex

Spiral Wrapped Sleeving

- polyester film
- aramid fiber mat, polyester film

Lead Wire Insulation

- polyester composite: Darcon-Mylar-Darcon
- polyester, fluoropolymer composite: Darcon-Teflon-Darcon

Tie Cords

- polyester

Assembly Tapes

- braided polyester, acrylic binder
- polyester mats

[1]Only tested with CFC-11/mineral oil and HCFC-123/mineral oil.

The above motor materials appear to be compatible with the alternative refrigerant/lubricant mixture for the retrofit scenarios tested. The only concerns were embrittlement of the polyethylene phthalate (PET) which is found in Mylar and Melinex sheet and sleeving insulation, and delamination and blistering of the Nomex composite sheet insulation in HCFC-22, R-502 and CFC-12 and separation of the 475 varnish from metal surfaces in HCFC-123. The sheet and sleeving insulation were affected by the old refrigerant/mineral oil and further degraded in the alternative refrigerant/lubricant mixture. The separation of the 475 varnish from the metal surfaces may have been influenced by the condition of the metal surface before application of the varnish.

COMPATIBILITY OF LUBRICANT ADDITIVES WITH HFC REFRIGERANTS AND SYNTHETIC LUBRICANTS

Objective:

To provide information that will enable manufacturers of refrigeration components and systems to select reliable POE lubricant additives.

Results:

Imagination Resources, Inc., is performing this research under contract to ARTI.

Part I of this project consists of a confidential survey of the lubricant additives being used in the commercial production of suitable refrigerant polyolesters. It is unlikely that specific additives will be identified due to the competitive nature of this information. Nonetheless, it is anticipated that the general chemical category or class of the substance, as well as its purpose, will be revealed. The contractor is currently conducting research under Part I of this project.

Compatibility and stability tests will be conducted under Part II of this project.

PRODUCTS OF MOTOR BURNOUTS

Objectives:

To identify and quantify the products of motor burnouts in systems with R-22 with mineral oil, R-134a with polyolester lubricant, and R-507[1] with polyolester lubricant.

To correlate the toxic nature of the identified products of motor burnouts on humans, from existing literature.

- To assess the corrosive effects of these products on the electric feed-through terminals.
- To assess the efficacy of currently used procedures which use filter dryers to remove the residual burnout products and prevent repeat burnouts.
- To assess whether HFC refrigerant/lubricant systems are likely to increase or decrease the incidence of motor burnouts as compared to HCFC/lubricant systems.

Results:

The Lawrence Livermore National Laboratory (LLNL) is conducting this research under contract to ARTI. A summary of its progress is contained in the quarterly technical report, DOE/CE/23810-59D, *Products of Motor Burnouts*, by Ruth Hawley-Fedder, Ph.D., April 1995.

An initial literature search of available data has been completed. LLNL has completed electrical breakdown testing of R-22, R-134a and R-507 at atmospheric pressure and ambient temperature. Results are presented in Tables 6-1 through 6-3.

LLNL has also designed and in the process of constructing a test stand for testing at temperatures up to 200°C and pressures up to 3450 kPa (500 psi).

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[1] R-507 is a blend consisting of HFC-125 and HFC-143a at a 50/50% composition by weight.

Table 6-1. R-22 Breakdown Products - Atmospheric Pressure

		Amount Formed (normalized to R-22)					
	Test ID	950111b 100K #2	950109a 100K #1	950105f 50K #1	950110c 50K #2	950509b 10K #2	950111b 10K #3
	energy (joules)	262	262	131	131	26.2	26.2
RT (min)	Tentative Compound ID						
7	Tetrafluoroethene	26.49	24.94	12.80	14.44	3.31	2.85
8	Hexafluoropropene	4.32	3.90	1.29	1.49	0.28	0.14
11	**Chlorodifluoromethane (R22)**	100	100	100	100	100	100
13	dichlorodifluoromethane (R12)	16.93	14.65	6.14	7.20	1.36	0.80
15	1-chloro-1,1,2,2,-tetrafluoroethane	0.49	0.35	0.13	0.15	0.00	0.00
17	2-chloro-1,1,3,3,3 -pentafluoro-1-propene	0.47	0.34	0.13	0.14	0.00	0.00
17	3-chloro-1,1,2,3,3-pentafluoro-1-propene	0.93	0.66	0.25	0.27	0.00	0.00
18	1,2-dichloro-1,1,2,2-tetrafluoroethane	5.79	4.92	1.77	1.99	0.35	0.17
19	$ClCCCF_3$	0.87	0.65	0.24	0.26	0.00	0.04
21	chlorohexafluoropropane	0.17	0.11	0.05	0.10	0.00	0.00
22	*dichlorodifluoromethane (R 12)*	*0.49*	*0.43*	*0.08*	*0.07*	*0.00*	*0.00*
25	$CF_2ClCF_2CF_2Cl$	0.34	0.03	0.11	0.11	0.00	0.00
25	CF_3CFClF_2Cl	1.28	1.07	0.38	0.42	0.07	0.03
26	1,3-Butadiyne	0.00	0.08	0.00	0.00	0.00	0.00
27	dichlorofluoromethane	0.10	0.09	0.00	0.00	0.00	0.00
27	1,1-dichloro-2,2-difluoroethene	1.50	1.22	0.46	0.52	0.10	0.08
28	1,2-dichloro-1,2-difluoroethene	0.76	0.63	0.22	0.30	0.04	0.03
28	1,2-dichloro-1,2-difluoroethene	0.91	0.75	0.24	0.33	0.04	0.06
30	trichlorofluoromethane	0.66	0.51	0.16	0.24	0.04	0.00
31	chloropentafluoroethane	0.80	0.56	0.23	0.26	0.04	0.03
31	1,2-dichloro-1,3,3,3-tetrafluoro-1-propene	0.20	0.18	0.07	0.09	0.00	0.00
32	1,2-dichloro-1,3,3,3-tetrafluoro-1-propene	0.42	0.27	0.14	0.15	0.04	0.00
32	dichloroethyne	0.69	0.57	0.20	0.24	0.05	0.04
33	C4F3Cl	0.19	0.17	0.08	0.06	0.00	0.00
34	*1,1,2-trichloro-1,2,2-trifluoroethane*	*0.29*	*0.26*	*0.11*	*0.10*	*0.06*	*0.00*
35	monochloro???	0.80	0.73	0.26	0.25	0.07	0.00
35	??????	0.22	0.16	0.10	0.06	0.00	0.00
36	chloropentafluoroethane	0.47	0.39	0.15	0.17	0.05	0.00
36	trichloropropene	0.43	0.18	0.06	0.00	0.00	0.00
37	1,2-dichlorotetrafluorocyclobutene	0.46	0.44	0.16	0.19	0.06	0.00
37	1,2-dichlorotetrafluorocyclobutene	0.47	0.26	0.04	0.00	0.00	0.00
38	1,2-dichlorotetrafluorocyclobutene	0.17	0.14	0.06	0.05	0.00	0.00
38	????	0.72	0.13	0.08	0.05	0.00	0.00
38	???	0.61	0.14	0.06	0.05	0.00	0.00
38	1,2,2-trichloro-1,1,3,3,3-pentafluoropropane	0.96	0.84	0.40	0.21	0.08	0.00
39	chloropentafluoroethane	0.35	0.32	0.11	0.11	0.00	0.00
41	trichlorofluoroethylene	0.68	0.60	0.18	0.24	0.05	0.03
43	???	0.54	0.13	0.08	0.00	0.00	0.00
43	unknown	0.16	0.18	0.06	0.07	0.00	0.00
45	????	0.34	0.10	0.04	0.00	0.00	0.00
48	chloropentafluorobenzene	0.24	0.14	0.09	0.06	0.00	0.00
51	tetrachlorethene	0.41	0.30	0.26	0.13	0.06	0.00
52	1,1,3,3-tetrachloro-2,3-difluoropropene	0.22	0.11	0.00	0.06	0.00	0.00
	TOTAL	**173.33**	**162.58**	**127.45**	**130.60**	**106.15**	**104.30**
	Total less R-22	**73.33**	**62.58**	**27.45**	**30.60**	**6.15**	**4.30**
note:	Amounts are normalized to R-22 as 100						
	1,1,2-trichloro-1,2,2,-trifluoroethane and chlorodifluoromethane are used for instrument calibration;						
	the presence of these compounds may be due to contamination of the sample.						

Table 6-2. R-134a Breakdown Products - Atmospheric Pressure

	Test ID	950117c 100K #1	950118c 100K #2	950119b 50K #2	950118e 50K #1	9500119c 10K #1
	energy (joules)	256	256	128	128	25.6
RT (min)	Tentative Compound ID					
6.98	Hexafluoroethane	3.44	2.47	1.30	1.85	0.76
7.23	Tetrafluoroethene	10.49	7.17	2.33	3.77	0.46
7.85	1,1,2,3,3,3-hexafluoro-1-propene	0.00	0.00	0.00	0.29	0.00
8.02	Trifluoroethene	3.05	2.35	0.60	1.03	0.00
8.78	**1,1,1,2-tetrafluoroethane (R-134a)**	**100**	**100**	**100**	**100**	**100**
9.97	unknown	0.60	0.42	0.00	0.32	0.25
11.12	*dichlorodifluoromethane (R-12)*	1.91	0.01	0.03	0.00	*0.00*
17.16	1,2,3,4,5,5-hexafluoro-1,3-cyclopentadiene	0.06	0.08	0.05	0.00	0.00
17.27	1,2,3,4,5,5-hexafluoro-1,3-cyclopentadiene	0.06	0.06	0.00	0.03	0.00
19.51	1,1,1,6,6,6-hexafluoro-2,4-diyne	0.08	0.11	0.03	0.02	0.00
20.37	unknown	0.02	0.03	0.00	0.00	0.00
21.22	Octafluoro-1,3,5-Hexatriene	0.06	0.03	0.00	0.00	0.00
21.44	unknown	0.02	0.00	0.00	0.00	0.00
25.87	C5F5H	0.04	0.04	0.01	0.03	0.00
26.96	unknown	0.04	0.04	0.00	0.03	0.00
35.50	unknown	0.02	0.03	0.00	0.00	0.00
38.72	unknown	0.04	0.02	0.00	0.02	0.00
	TOTAL	**119.92**	**112.85**	**104.36**	**107.40**	**101.47**
	TOTAL less R-134a	**19.92**	**12.85**	**4.36**	**7.40**	**1.47**
Note:	Amounts are normalized to R-134a as 100					
d	dichlorodifluoromethane is used for instrument calibration; the presence of this					
	compound may be due to contamination					

Table 6-3. R-507 Breakdown Products - Atmospheric Pressure

		Amount Formed (normalized to R-507)				
	Test ID	950119d 100K #1	950123c 100K #2	950124c 50K #2	950124b 50K #1	950124d 10K #1
	energy (joules)	237	237	118.5	118.5	23.7
RT (min)	Tentative Compound ID					
7.08	Hexafluoroethane	2.33	2.92	1.20	9.83	0.69
7.35	Tetrafluoroethene	6.55	7.07	2.88	2.48	0.68
7.60	1,1-difluoroethene	3.20	3.59	1.43	0.00	0.00
7.85	R-507	100	100	100	100	100
8.90	1,1,1,2-tetrafluoroethane (R-134a)	0.48	0.22	0.19	0.04	0.20
9.21	1,1,3,3,3-pentafluoro-1-propene	0.49	0.48	0.19	0.06	0.00
9.72	3,3,3-Trifluoro-1-propyne	0.15	0.15	0.07	0.00	0.02
10.08	hexafluoro-cyclobutene	0.04	0.00	0.00	0.00	0.00
10.43	1,1,3,3,3-hexafluoropropane	0.06	0.00	0.00	0.00	0.00
11.20	*dichlorodifluoromethane (R12)*	*0.03*	*0.03*	*0.01*	*0.00*	*0.03*
12.45	unknown	0.03	0.01	0.01	0.00	0.02
17.01	1,2,3,4,5,5-hexafluoro-1,3-cyclopentadiene	0.05	0.04	0.01	0.00	0.00
17.23	1,2,3,4,5,5-hexafluoro-1,3-cyclopentadiene	0.05	0.02	0.02	0.00	0.00
19.39	1,1,1,6,6,6-hexafluoro-2,4-diyne	0.10	0.07	0.01	0.00	0.00
20.97	4 - (difluoromethylene)-2,3,3-trifluorocyclobutene	0.01	0.03	0.00	0.00	0.00
21.35	unknown	0.01	0.00	0.00	0.00	0.00
25.80	C5F5H	0.02	0.02	0.00	0.00	0.00
26.92	?????	0.04	0.03	0.01	0.00	0.00
35.44	?????	0.02	0.00	0.00	0.00	0.00
38.68	?????	0.03	0.06	0.00	0.00	0.00
	TOTAL	**113.69**	**114.74**	**106.03**	**112.42**	**101.64**
	TOTAL less AZ-50	**13.69**	**14.74**	**6.03**	**12.42**	**1.64**
Note:	Amounts are normalized to R-507 as 100					
	dichlorodifluoromethane is used for instrument calibration; the presence of					
	this compound may be due to contamination					

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 (RDB #3A17, 68 pages) and DOE/CE/23810-57, Accelerated Test Methods for Life Prediction of Hermetic Motor Insulating Systems Exposed to Alternative Refrigerant/Lubricant Mixtures, Phase 2: Proof-of-Concept Demonstration, by Peter Ellis II and Alan Ferguson, 19 April 1995 (RDB #5649, 68 pages).

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 test (IEEE Standard 117 & UL Standard 984-1989),
- sealed tube aging test, 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 7-1) 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.

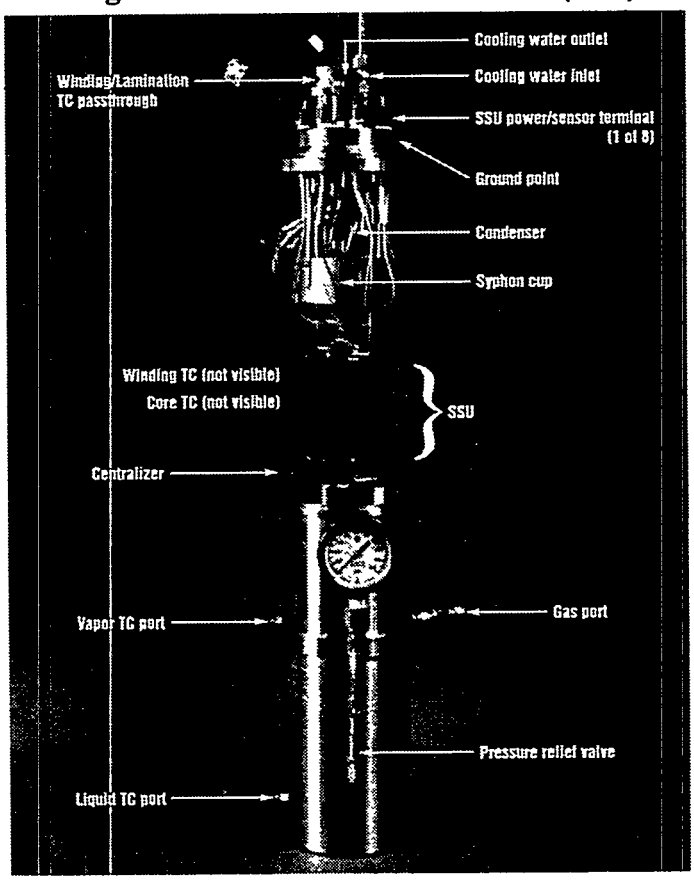
Several parameters will be used to evaluate SSU performance:

- 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 7-1. Stator Simulator Unit (SSU).



During Phase 2, Radian Corporation demonstrated a proof-of-concept for the stator simulator unit through the design, fabrication, and testing of SSU prototypes. Three SSU prototypes were tested. One unit was tested without thermal stress loads. Insulation property measurements conducted twice a day on the prototype indicated that the electrical voltage loads from the measurements did not degrade the SSU. The two other SSU prototypes where each subjected to 20,600 simulated locked-rotor events per day. Both SSU prototypes showed progress deterioration of the resistive component of the turn-to-turn insulation over the course of the tests. One of the SSU prototypes suffered a coil-to-coil failure, an anticipated failure mode. Test of other SSU prototype was terminated after 38 days without failure, but it showed progressive deterioration during the test period in the turn-to-turn ohmic resistance component of the power dissipation factor (see Figures 7-2 and 7-3).

In April 1995 Radian Corporation began Phase 3: Reproducibility Testing. In this phase Radian will test eight SSUs in virgin R-22/mineral oil and eight SSUs in R-22/mineral oil with air, moisture and acid levels five times the maximum contaminant levels for refrigerant purity under ARI Standard 700. Statistical evaluations of the trends, data scatter and numbers of replication required for a given level of confidence will be determined.

Figure 7-2. Turn-to-Turn Ohmic Resistance Component of Power Dissipation Factor for Primary and Secondary Coils - Prototype 1
(Unit failed on 17th day of test.)

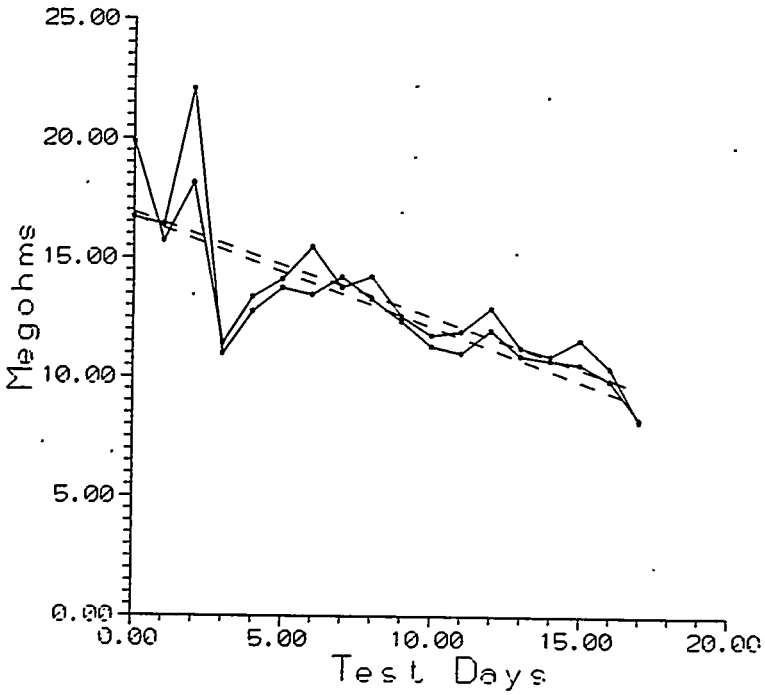
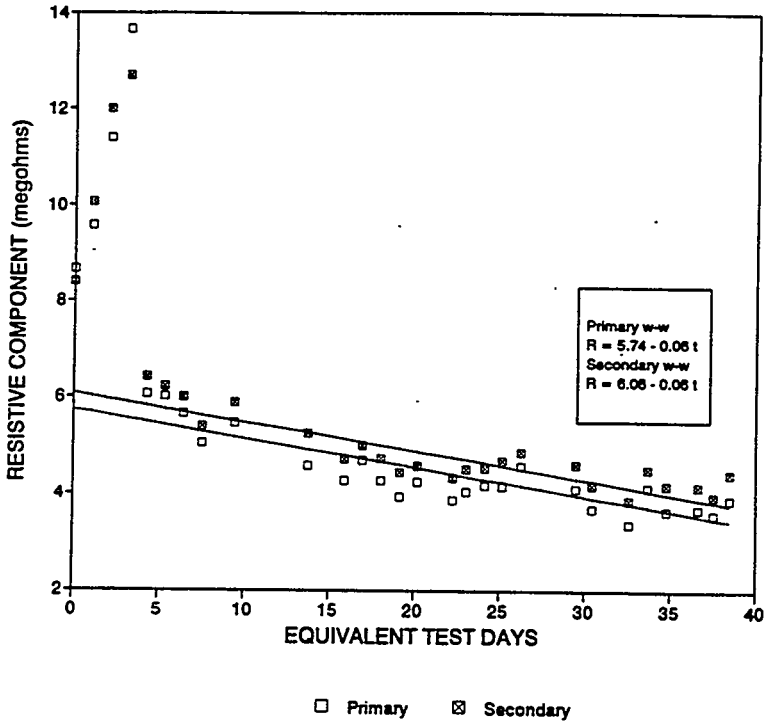


Figure 7-3. Turn-to-Turn Ohmic Resistance Component of Power Dissipation Factor for Primary and Secondary Coils - Prototype 2
(Test terminated on 38th day without gross failure.)



INVESTIGATION OF FLUSHING AND CLEAN-OUT METHODS

Objective:

To develop one or more alternative flushing and clean-out procedures

- to effectively reduce mineral oil content in a HFC-134a retrofit to less than 5% weight in polyolester lubricant or
- to successfully flush a refrigerant system after a compressor burnout has occurred, using a zero ozone depleting alternative flushing fluid.

Results:

Part 1 of this effort entailed a literature search and study of possible alternatives to the current flushing and cleanout methods. Part 2 of the project will prove out the feasibility of an alternative flushing and cleanout method. Two competing contractors were selected to conduct the Part 1 study. Following the review of both studies, ARTI awarded Part 2 to Integral Sciences, Inc.

A summary of the results of the literature search conducted by Integral Sciences, along with a description of proposed laboratory and field testing in contained in the interim report, DOE/CE/23810-37, *Investigation of Flushing and Clean-Out Methods for Refrigerant Equipment to Ensure System Compatibility (Part 1)*, by John J. Byrne and Marc W. Abel, April 1994.

Integral Sciences will conduct laboratory and field testing to determining the effectiveness of using a low side oil separation and removal system for removing mineral oil during retrofit procedures.

INVESTIGATION INTO THE FRACTIONATION OF REFRIGERANT BLENDS

Objective:

To develop theoretical models and verify with experimental data for:

- determining concentration and pressure shifts due to different solubilities of the refrigerant blend components in the lubricant, if any.
- investigating the effects of fractionation resulting from the successive system charges from a storage/shipping container on the performance of typical air-conditioning unit.
- experimental verification of fractionation shifts in composition and pressure of zeotropic refrigerant blends within the components of a refrigeration system during operation and non-operation.
- experimental verification of fractionation shifts in composition and pressure resulting from slow (isothermic) and rapid (adiabatic) leak scenarios.

Results:

United Technologies Research Center (UTRC) is performing this research under contract to ARTI. A detailed report of its work to date is included in the quarterly technical status report, DOE/CE/23810-51C, *Investigation into the Fractionation of Refrigerant Blends*, by Frank Biancardi, January 1995 (RDB #5602, 26 Pages). Theoretical models are under development for each of the scenarios listed in the objective. Once formulated, these models will be verified by comparing predicted compositions from the model with experimental measurements in actual systems.

UTRC has obtained extensive test data with R-407C and Castrol SW68 polyolester lubricant in a Carrier 3-ton split system heat pump at DOE-A and DOE-E test conditions. The data was obtained during system operation and in system shut down scenarios with refrigerant charge leakage occurring. After each leak scenarios, which removed 1/4 of the charge, the system was refilled to the original R407C concentration. Operating performance and capacity were measured, along with obtaining fractionation data at four locations in the major components of the system and at seven locations in the indoor heat exchanger coil.

Preliminary reports from UTRC state that the data obtained at the seven locations in the indoor heat exchange coil clearly show the location of single-phase and two-phase heat transfer regimes, onset of fractionation and the extent of fractionation in the operating mode.

UTRC has also completed modeling the solution behavior of R-407C and developed coefficients for use in the Wohl 3-suffix expansion for the Gibbs excess energy from a combination of previous analytical and experimental data developed from prior UTRC work and from industry sources.

LEAN FLAMMABILITY LIMITS AS A FUNDAMENTAL REFRIGERANT PROPERTY

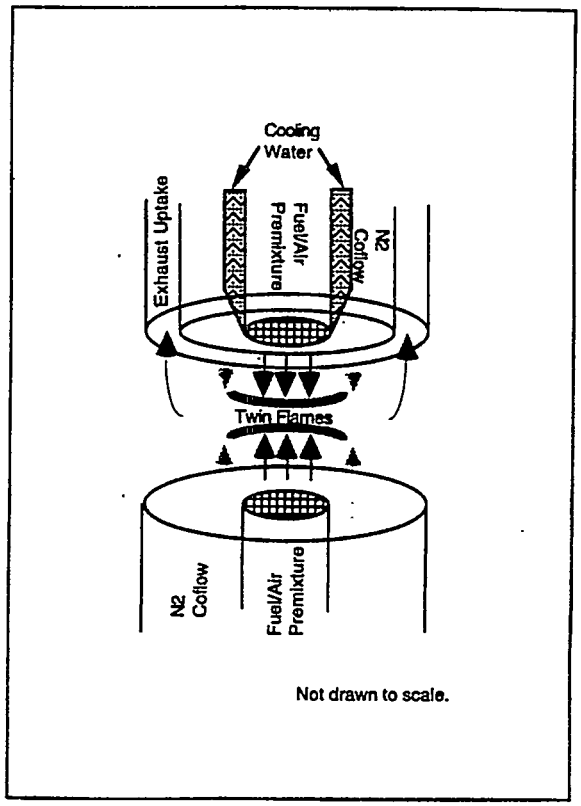
Objective:

To evaluate the suitability of an opposed-flow twin-flame burner for determining flammability limits of refrigerants.

Results:

The Building and Fire Research Laboratory of the National Institute of Standards and Technology (NIST) is performing this project under contract to ARTI. Phase I of this project used a opposed-flow burner (see Figure 10-1) to evaluate the flammability limits of methane, HFC-32 and mixtures of HFC-32 and HFC-125 in air for different flow conditions. NIST has completed Phase I and has published its results in the interim report, DOE/CE/23810-58, *Lean Flammability Limit as a Fundamental Refrigerant Property*, by C. Womeldorf, M. King and W. Grosshandler, 31 March 1995 (RDB #5601, 34 pages).

Figure 10-1. Opposed-flow Burner



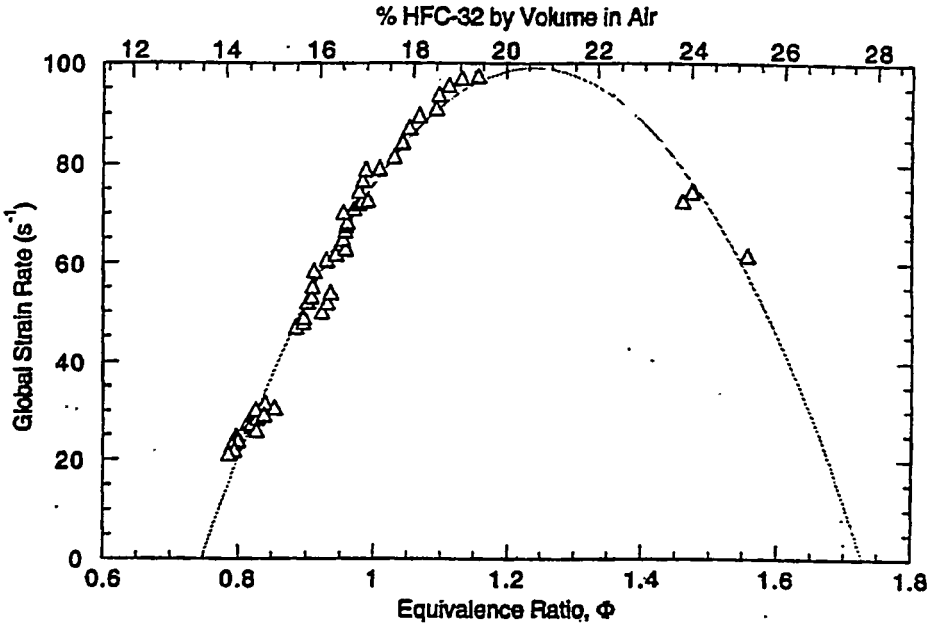
Demonstration of Apparatus Suitability

The lean flammability limit is defined as the fuel/air mixture which extinguishes an adiabatic flame when the strain rate (i.e., the normal gradient of velocity) is zero. The lean flammability limit can be evaluated at either the upper or lower flammability limits by extrapolating extinguishment stoichiometries for decreasing strain rates to zero. This method was described by Law, Zhu and Yu (1986), "Propagation and Extinction of Stretched Premixed Flames", *21st Symposium on Combustion*: The Combustion Institute, pages 1419-1426.

As a result of Phase I work, NIST confirmed the suitability of the opposed-flow burner for evaluating lean flammability limits and established that the lean flammability limits of refrigerants and refrigerant mixtures could be evaluated in the opposed-flow burner apparatus.

From measurements using the opposed-flow burner, NIST estimated the lean flammability limit at the lower flammability limit of R-32 to be 12.0 ± 0.6% by volume in air and at the upper flammability limit around 30% R-32 by volume in air (insufficient data points were taking at the upper flammability limit to determine a range). Figure 10-2 plots the measured extinction points of R-32/air premixed flames in terms of global strain rate versus equivalence ratio. A scale for % R-32 by volume in air corresponding to the equivalence ratio is also included.

Figure 10-2. Extinction Points of R-32/Air Premixed Flame



Global strain rate is defined as the mean incoming jet velocity divided by the half the jet separation. This neglects any thickness of the stagnation layer between the twin flames. For its measurements of R-32 and R-32/125 mixtures, NIST keep the jet separation distance constant at 15.9 $\pm$ 0.1 mm (0.625 in) while varying the velocity below 200 cm/s (6.6 ft/s). NIST noted that repeatable results could not be achieved at velocities less than 15 cm/s (0.5 ft/s) due to buoyancy effects destablize the stagnation plane and the flame.

The equivalence ratio, Φ, is defined as the number of moles of R-32 (or for mixtures the number of mole of R-32 plus R-125) per mole of air, normalized by the stoichiometric fuel/air molar ratio. For R-32 and refrigerant mixtures containing R-32 as the flammable component, the equivalence ratio can be converted to % volume refrigerant using the following formula:

$$\textit{percent volume of refrigerant} = 100 \left(\frac{\Phi}{\Phi + 4.76}\right)$$

Figure 10-3 depicts the linear fits that NIST applied to data subsets to determine the lean flammability limit. As shown in Figure 10-4, these values within the range of published values.

Figure 10-3. Range of Lean Flammability Limit of R-32 in Air

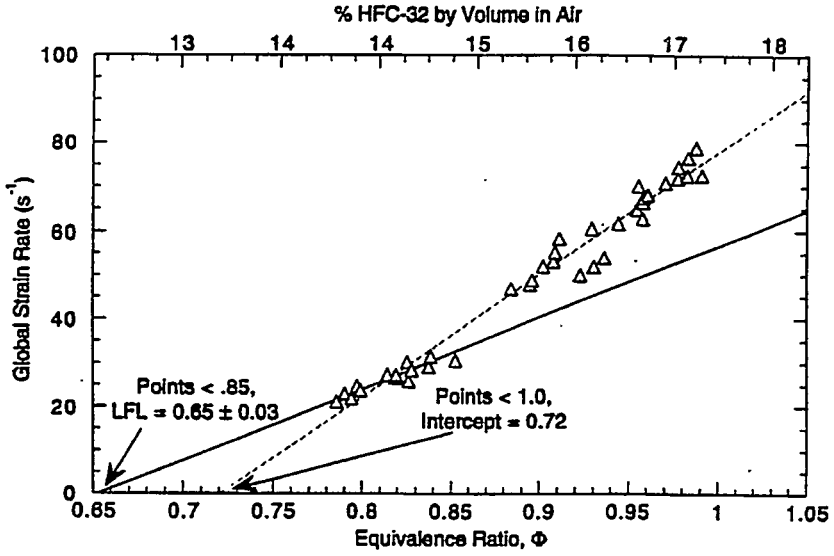
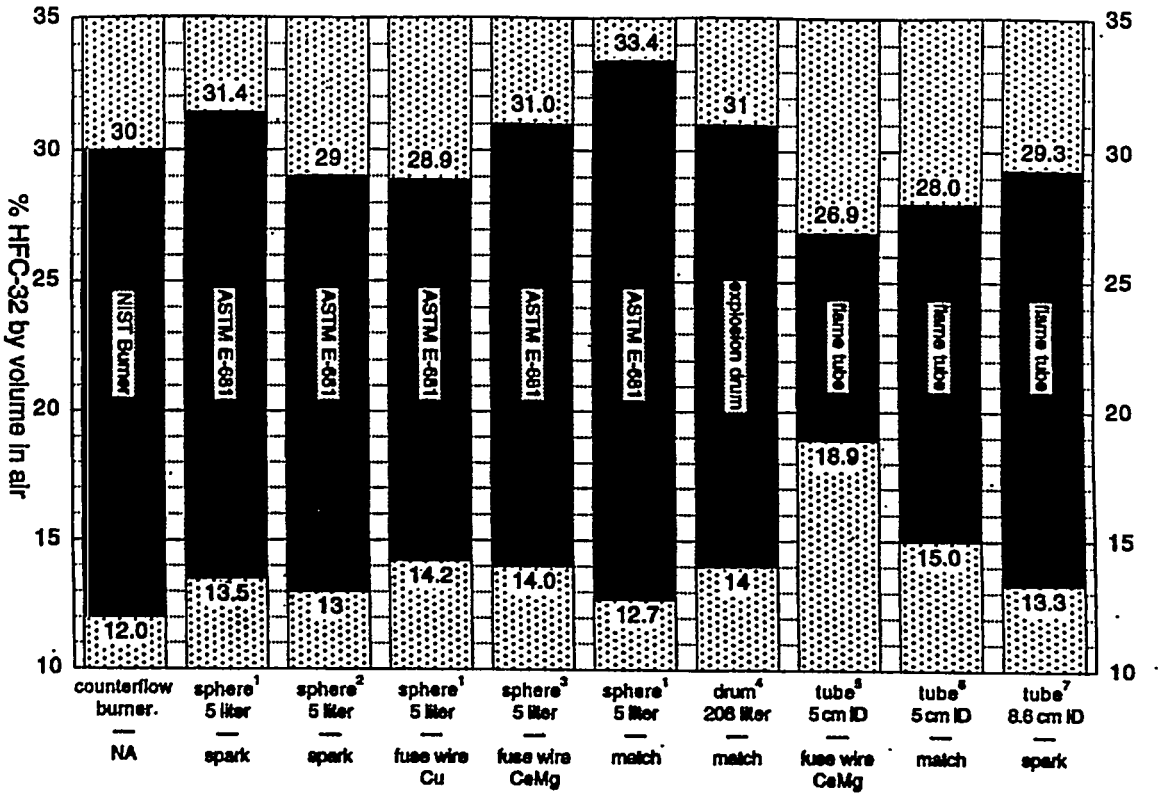


Figure 10-4. Comparison R-32 Lean Flammability Limit with Other Published Results



References:
1. ASTM E-681 vessel; Richard and Shankland, 1992.
2. ASTM E-681 vessel; Ohnishi *et al.*, 1993.
3. ASTM E-681 vessel; Dekleva *et al.*, 1993.
4. Explosion Drum, Freon Products Laboratory, Dupont; Downing, 1988.
5. Flame Tube (5 cm ID, 200 cm length); Dekleva *et al.*, 1993.
6. Bureau of Mines Eudiometer (5 cm ID, 200 cm length); Richard and Shankland, 1992.
7. Explosion Tube (8.6 cm ID, 30 cm length); Urano *et al.*, 1990.

NIST also used the opposing-flow burner to determine the critical flammability ratio of R-125 in R-32 and estimated it to be 18.5 $\pm$ 0.8% by volume. Figure 12-5 plots the measured values for the global strain rate versus the equivalence ration and Figure 12-6 plots NIST's extrapolation of this data to produce the critical flammability ratio.

Results from these experiments are preliminary and were used strictly to evaluate the feasibility of this type apparatus. In Phase 2 of this project, NIST will make design improvements to the opposing-flow burner apparatus and will ascertain operating parameters of the new apparatus by conducting measurements on R-32/dry air and methane/dry air. NIST will also conduct measurements to determine the lean flammability limits of R-32/air, R-134a/air , and R-245ca/air at 0% and 50% relative humidity air (humidity level of air at room temperature and atmospheric pressure).

Figure 12-5. Extinction Points for R-32/125 Flames at Various Concentrations of R-125

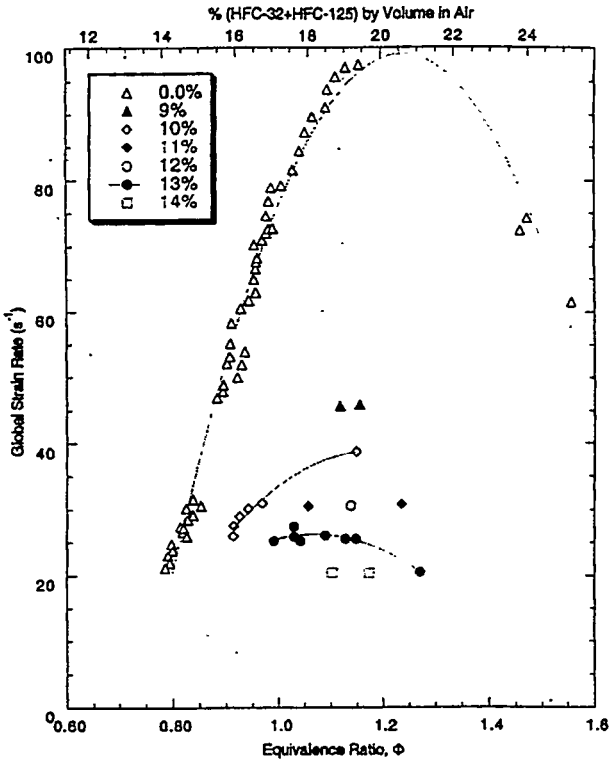
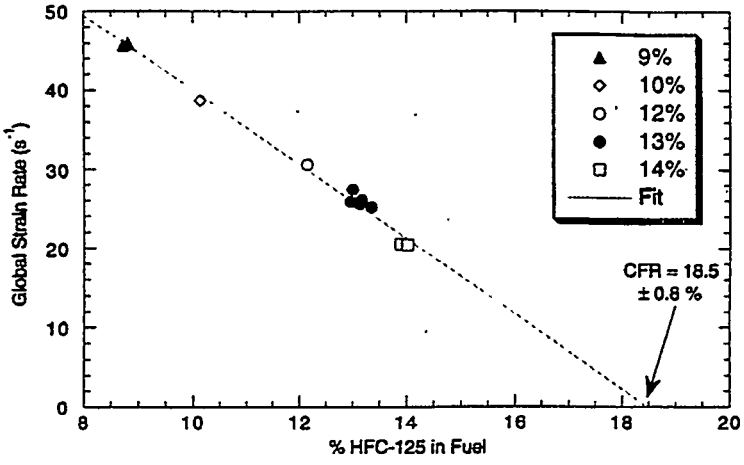


Figure 12-6. Extrapolation of Zero Strain Rate to Determine Critical Flammability Ratio of R-125 in R-32



EFFECT OF SELECTED CONTAMINANTS IN AC&R EQUIPMENT

Objective:

To provide information to allow industry to determine the feasibility of relaxing ARI Standard 700 for recycled refrigerants without compromising equipment performance or reliability. This project will consist of a long-term sealed tube testing program and a series of tests on complete air conditioning and refrigeration (AC&R) systems to monitor equipment performance and impact of contaminants on system reliability.

Results:

Imagination Resources, Inc., was recently placed under contract with ARTI to perform the work. Dr. Richard Cavestri is the principal investigator for this project. The overall objective of this research is to conduct a systematic investigation to ascertain the levels of contaminants that can be allowed in AC&R equipment. The first monthly progress report is expected at the end of August 1995. A technical progress report will be available in January 1996.

The research work will consist of the following:

Testing of AC&R Equipment

Test rigs of complete AC&R systems will be built to investigate the effects of various levels of contaminants on the equipment's performance and reliability. The contaminants considered are: organic acid, moisture, non-condensable gases and other refrigerant. Contaminant levels are shown in Table 11-1. Four refrigerants will be tested: R-22, R-134a, R-407C and R-507.

In total, 140 AC&R systems will be tested: 4 refrigerants x 31 contaminant levels mixtures + 16 control sample tests (4 control samples per refrigerant). The experiment is expected to last about 17,520 hours.

A low and a high compressor discharge temperature will be used in the tests of the AC&R systems. These two discharge temperatures will be refrigerant specific and will be provided by ARTI. The discharge line will be equipped with a temperature cut out to prevent damage to the compressor. The operating conditions originally proposed were 49.0°C (120°F) and -17.8°C (0°F) condensing and evaporating temperatures respectively for all refrigerants except R-507 which will be tested at a lower evaporating temperature of -31.7°C (-25°F), the condensing temperature remaining the same.

All AC&R systems will be built and tested without filter driers. The initial moisture content in the systems will be measured in both the lubricant and the refrigerant after 4 to 7 days of operation.

One-half horsepower (0.5 hp) reciprocating compressors will be used in this study. The compressors will have the same manufacturing date and will be equipped with a service valve and an oil sampling port. They will be dry nitrogen charged.

At the end of the testing period, the compressors will be disassembled for inspection. Compressor parts will be photographed for historical records and examined for metal corrosion.

Sealed Tube Tests

Sealed tube tests will also be conducted. The proposed contaminant test matrix is similar to that developed for testing the AC&R systems. The refrigerants and contaminants considered in this part of the study are the same as those used in the AC&R systems (Table 11-1). In all, 140 sealed tubes will be tested. The tests will be conducted at two different temperatures, 165°C (329°F) and 135°C (275°F), with respective aging times of approximately 30 and 224 days.

A *Cottrel Tube* or dynamic sealed tube will be used to study the effects of contaminants on low pressure systems such as chillers. The refrigerants considered are R-11 and R-123. The heating section of the tube will be set at a temperature between 49.0 and 71.1°C (120 to 160°F) while the cooling section will be maintained at 4.4°C (40°F). A total of 18 tubes will be tested during 17,520 hours or approximately 2 years. Sixteen test tubes will be equipped with a desiccant. The two remaining tubes will have no desiccant.

Table 11-1. Contaminated Refrigerant Test Matrix

Number	4% Other refrigerant	organic acid TAN	4% Air by volume	moisture level	Temperature	Number of samples	
1	✓	---	---	10	H	1	
2	---	✓	---	10	H	1	
3	---	---	✓	10	H	1	
4	---	---	---	10	H	4	Control
5	✓	✓	---	10	H	1	
6	✓	✓	✓	10	H	1	
7	✓	---	✓	10	H	1	
8	---	✓	✓	10	H	1	
9	✓	---	---	200	H	1	
10	---	✓	---	200	H	1	
11	---	---	✓	200	H	1	
12	---	---	---	200	H	1	
13	✓	✓	---	200	H	1	
14	✓	✓	✓	200	H	1	
15	✓	---	✓	200	H	1	
16	---	✓	✓	200	H	1	
17	✓	---	---	10	H	1	
18	---	✓	---	10	L	1	
19	---	---	✓	10	L	1	
20	---	---	---	10	L	1	
21	✓	✓	---	10	L	1	
22	✓	✓	✓	10	L	1	
23	✓	---	✓	10	L	1	
24	---	✓	✓	10	L	1	
25	✓	---	---	200	L	1	
26	---	✓	---	200	L	1	
27	---	---	✓	200	L	1	
28	---	---	---	200	L	1	
29	✓	✓	---	200	L	1	
30	✓	✓	✓	200	L	1	
31	✓	---	✓	200	L	1	
32	---	✓	✓	200	L	1	

STUDY OF FOAMING CHARACTERISTICS

Objective:

To determine the rate at which a POE lubricant will absorb HFC refrigerants.

To determine the rate at which an HFC refrigerant leaves solution with a POE when exposed to a pressure drop.

To define the characteristics of the foam formed when refrigerant leaves solution with a lubricant after being exposed to a pressure drop.

Results:

Proposals for performing research to meet the above objectives have been received and evaluated. ARTI is currently involved in contract negotiations to intiate this project.

STUDY OF LUBRICANT CIRCULATION IN SYSTEMS

Objectives:

Determine the fundamental lubricant return parameters for HFC/POE mixtures to map how the characteristics of different refrigerant/lubricant mixtures affect lubricant return to the compressor.

Determine the fundamental lubricant return parameters for HFC/mineral oil mixtures to assess whether (or under what circumstances) immiscible systems can provide sufficient lubricant return.

Results:

The United Technologies Research Center (UTRC) is conducting this research contract to ARTI. An interim progress report is expected in October 1995.

The overall purpose of the project is to investigate the impact of fluid properties, for immiscible refrigerant-lubricant mixtures, on lubricant return in typical residential split-unit systems. UTRC will identify worst case (i.e., extreme limits that manufacturers permit their equipment to be installed and operated) vertical and horizontal separation (example: 20 ft vertical and 100 ft horizontal), operating temperatures (example: heat pump winter operation of 0°F), and typical failure modes that could jeopardize the system in heating or cooling modes.

To make the testing insensitive of the compressor utilized (e.g., in general, a scroll compressor puts out much less lubricant than does a reciprocating compressor), a known amount of lubricant will be injected into the compressor discharge stream. The refrigerant/lubricant pairs to be tested in the work are:

Baselines Mixtures	R-22/Suniso3GS mineral oil		
	R-407C/Suniso 3GS mineral oil		
	R-407C/Suniso 1GS mineral oil		
Test Mixtures	R-407C/Mobil EAL 22C	low miscibility	low viscosity
	R-407C/ICI RL68L	low miscibility	high viscosity
	R-407C/Castrol SW22	high miscibility	low viscosity
	R-407C/Castrol SW68	high miscibility	high viscosity

For each of the seven refrigerant-lubricant pairs indicated above, four separate test modes will be run:

(1) worst case heating
(2) worst case heating with a component failure (e.g., blocked fan)
(3) worst case cooling
(3) worst case cooling with a component failure (e.g., blocked fan)

On-line, dynamic instrumentation will be utilized to measure oil circulation and to ascertain whether the lubricant is being moved as a slug or as interspersed liquid.

EVALUATION OF HFC-245ca FOR COMMERCIAL USE IN LOW PRESSURE CHILLERS

Objectives:

Model the performance of HFC-245ca in actual chillers.

Conduct performance tests of HFC-245ca in a low pressure chiller and compare the results with the modeled performance and with performance tests of CFC-11 and HCFC-123 in the same chiller.

Assess the commercial viability of HFC-245ca to retrofit CFC-11 and HCFC-123 chillers in the field and for use in new chillers.

Results:

The Trane Company is performing this research under contract to ARTI. As indicated by the objectives, the work is to accomplished in three tasks:

Task 1 - Calculate Performance
The cycle performance of a chiller utilizing HFC-245ca will be calculated and compared to the modeled results for CFC-11 and for HCFC-123.

Task 2 - Laboratory Performance Tests
The relative heat transfer performance of HFC-245ca, HCFC-123, and CFC-11, in both the boiling and condensing modes, will be evaluated in single-tube tests for two different tube geometries.

The capacity and efficiency, at ARI water-cooled conditions, will be determined in a low-pressure chiller operated with HFC-245ca. The results will be compared against baseline performance tests obtained with CFC-11 and HCFC-123.

Task 3 - Commercial Viability
Assess the commercial viability for use of HFC-245ca to retrofit CFC-11 and HCFC-123 chillers in the field and for use in new chillers (assuming acceptable toxicity results).

Results from Task 1 (Performance modeling):

Task 1 results are presented in the report, DOE/CE/23810-60 *(Preliminary Estimates of Chiller Performance)*, by Edward F. Keuper, F. Bryon Hamm, and Paul R. Glamm, 30 April 1995.

The theoretical performance of CFC-11, HCFC-123, and HFC-245ca were modeled for single- and three-stage (includes two economizers) cycles. The Task 1 reporting is based entirely on compressor performance simulations and thermodynamic property variations between the refrigerants. The preliminary conclusions from the cycle analysis were:

- The theoretical efficiency of HFC-245ca in optimized three-stage chiller designs is very close to that for CFC-11 and HCFC-123 chillers.

Three Stage Optimized Compressor Designs

Refrigerant	Capacity Tons	Impeller Diameter m (ft)	Diffuser Diameter m (ft)	Compressor Adiabatic Efficiency	Power kW	Cycle Efficiency kW/Ton
CFC-11	200	.605 (1.98)	0.953 (3.13)	0.73	132	0.66
HCFC-123	200	.292 (.958)	0.922 (3.03)	0.73	130	0.65
HFC-245ca	200	.630 (2.07)	.993 (3.26)	0.72	133	0.67
CFC-11	800	.632 (2.08)	.996 (3.27)	0.74	518	0.65
HCFC-123	800	.625 (2.05)	.983 (3.23)	0.73	527	0.66
HFC-245ca	800	.652 (2.14)	1.03 (3.38)	0.74	513	0.64

Boundary conditions: 4.4°C (40°F) saturated evaporator temperature, 37.8°C (100°F) saturated condensing temperature, 95% motor at 3560 RPM

- HFC-245ca is not optimum as a service retrofit in CFC-11 and HCFC-123 chillers because significant compressor modifications or dramatic lowering of condenser water temperatures would be required.

- Hurdles which must be overcome to apply HFC-245ca in centrifugal chillers include the flammability behavior, evaluation of toxicity, unknown heat transfer characteristics, uncertain thermodynamic properties, high refrigerant cost and construction of HFC-245ca production plants.

- Although the flammability of HFC-245ca can probably be reduced or eliminated by blending HFC-245ca with various inert compounds, addition of these compounds will lower the chiller performance. The chiller performance will be degraded due to less attractive thermodynamic properties and further degraded due to lower heat transfer performance if the blend fractionates.

The experimental phase of the project will improve the accuracy of the Task 1 performance estimates, and the commercial viability assessment will also include the impact of flammability, toxicity, product cost and product availability. The final report, covering Tasks 1 through 3, is expected to be available for release in March 1996.

INFRARED ANALYSIS OF REFRIGERANT MIXTURES

Objective:

To provide information on the infrared and near infrared absorption frequencies required to quantitatively identify mixtures of HFC refrigerants. This information could be used to design a portable refrigerant concentration meter in future work.

Results:

Hope Technology Corporation was recently placed under contract with ARTI to perform this research work. Professor Ted Morse is the principal investigator for this project. A draft final report is expected in October 1995. The first part of the research will consist of measuring the infrared or near infrared absorption frequencies of the several refrigerants including:

CFCs	HCFCs	HFCs	Mixtures
R-12	R-22	R-32	R-407C
R-115	R-124	R-125	R-404A
		R-134a	R-401A
		R-143a	R-502
		R-152a	

Based on the results of the IR measurements, possible spectral interferences will be identified and a methodology to quantify individual refrigerants present in mixtures will be developed. Work will concentrate on the following mixtures : R-407C, R-404A, R-401A, and R-12/R-134a (90%/10%). In addition, quantitative and qualitative identification of the components of the above ternary mixtures will be conducted when 10% (by weight) of the refrigerant they are replacing is present in the mixture. These refrigerants are:

R-22 for R-407C
R-502 for R-404A
R-12 for R-401A

The method developed above will be thoroughly described in a final report. Comments on the minimum resolution required to use this method successfully will also be included.

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 280 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. 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.

Additionally, the computerized version of the database currently includes in excess of 70 data tabular compatibility summaries for plastics and elastomers and detailed toxicity reviews for selected refrigerants.

The June 1995 release of the ARTI Refrigerant Database contained in excess of 3,050 entries related to:

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

REFRIGERANT TOXICITY SURVEY

Objective

This research project entails search, review, and consolidation of toxicity information on alternative refrigerants as well as development of recommendations for toxicity classification methods for air-conditioning and refrigeration applications. The work addresses four needs:

- To locate and assemble data on new refrigerants for classification and determination of allowable quantities in safety standards.
- To prepare a summary, with referenced data, on the health effects of new refrigerants for use by the air-conditioning and refrigeration industry in assessing refrigerant toxicity.
- To incorporate the data and identified sources (references) into the ARTI Refrigerant Database, to facilitate subsequent retrieval of information needed to satisfy building code requirements.
- To provide recommendations to improve the manner by which toxicity is classified.

Results

James M. Calm, Engineering Consultant, is performing this research under contract to ARTI. Summary toxicity data (e.g., LC-50, IDLH, NIOSH REL, ACGIH TLV-TWA, etc.) and detailed toxicity reviews for select refrigerants are being incorporated into the computerized version of the ARTI Refrigerant Database. The final report (printed) is expected to be available at the end of the fourth quarter 1995.

THERMOPHYSICAL PROPERTIES OF 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 theoretically-based 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:

HFC-32

MBWR Equation of State

NIST has revised its 32-term MBWR equation of state and its ideal gas heat capacity ($C°_p$) equation for HFC-32 (see Table 18-1). The equation is reported to be valid at temperatures from the triple point at 137 K up to 400 K (-213 to 260°F). The maximum pressure for the equation is 40 MPa (5800 psi). The equation may be reasonably extrapolated up to 500 K (440°F) and 100 MPa (14500 psi). NIST fitted the equation using a multi-parameter linear least squares routine on the measured data.

Molar Heat Capacity

The molar heat capacity of HFC-32 was measured using an adiabatic calorimeter. Measurements included 79 values in the liquid state and 105 values in the vapor and liquid two-phase region. The measurements covered temperatures ranging from 141 to 342 K (-206 to 156°F) and pressures up to 35 MPa (5000 psi). [Results are tabulated in Tables 9 through 19 and Tables 17 through 19, DOE/CE/23810-16].

Thermal Conductivity

The thermal conductivity of HFC-32 was measured at 1030 points covering temperatures from 160 to 340 K (-167 to 160°F) and pressures up to 70 MPa (10,000 psi). [Results are presented in Table 22, DOE/CE/23810-16]. Figure 18-1 is a plot of the thermal conductivity surface.

Shear Viscosities

Shear viscosities of compressed and saturated fluid HFC-32 were measured using two torsionally oscillating, quartz-crystal viscometers. [Results are presented in Tables 24 and 25, DOE/CE/23810-16]. NIST Correlated the data to the following equation:

$$\eta^{-1} = 406.1\ (V - 0.0340)$$

where η is viscosity in mPa-s
V is the molar volume in mol/L

HCFC-123

MBWR Equation of State

NIST has revised its MBWR equation of state and its ideal gas heat capacity ($C°_p$) equation for HCFC-123 (see Table 18-2). 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 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).

Thermal Conductivity

The thermal conductivity of HCFC-123 was measured at 1618 points. Liquid-phase data cover temperatures from 180 to 440 K (-136 to 332°F) and pressures up to 70 MPa (10,000 psi). Vapor-phase data cover temperatures from 290 to 449 K (62 to 332°K). [Results are presented in Table 75, DOE/CE/23810-16]. Figure 18-2 is a plot of the thermal conductivity surface.

Molar Heat Capacity

NIST measured the molar heat capacity of HCFC-123 using an adiabatic calorimeter. Measurements included 79 values in the single phase liquid state and 92 values in the saturated-liquid state. The measurements covered temperatures ranging from 167 to 341 K (-159 to 155°F) and pressures up to 35 MPa (5000 psi). [Results are tabulated in Tables 66 through 71 and Tables 72 through 73, DOE/CE/23810-16].

HCFC-124

MBWR Equation of State

NIST has revised its 32-term MBWR equation of state and its ideal gas heat capacity ($C°_p$) equation for HCFC-124 (see Table 18-3). 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).

Speed of Sound Measurements

Speed of sound in HCFC-124 was measured using a cylindrical acoustic resonator along isotherms between 250 and 400 K (-9 and 261°F) at pressures ranging from 20 to 900 kPa (3 to 130 psi). [Results are presented in Table 30, DOE/CE/23810-16]. NIST analyzed the speed of sound measurements at low pressures to determine the ideal-gas heat capacity, $C_p°$ [Revised results are presented in Table 18-3].

Molar Heat Capacity

The molar heat capacity of HCFC-124 was measured using an adiabatic calorimeter. Measurements included 74 values in the single phase liquid state and 132 values in the saturated-liquid state. The measurements covered temperatures ranging from 173 to 345 K (-148 to 161°F) and pressures up to 35 MPa (5000 psi). [Results are tabulated in Tables 33 through 37 and Table 38, DOE/CE/23810-16].

HFC-125

MBWR Equation of State

NIST has revised its 32-term MBWR equation of state and its ideal gas heat capacity ($C°_p$) for HFC-125 (see Table 18-4). 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).

Speed of Sound Measurements

Speed of sound in HFC-125 was measured using a cylindrical acoustic resonator along isotherms between 240 and 380 K (-27.1 and 224.3°F) at pressures up to 1 MPa (145 psi). [Results are presented in Table 46, DOE/CE/23810-16]. NIST analyzed the speed of sound measurements as low pressures to determine the ideal-gas heat capacity, $C_p°$ [Revised results are presented in Table 18-4].

Table 18-1. Coefficients to the MBWR Equation of State for HFC-32. [units are K, bar, L, mol] (fit of Outcalt, 8-2-94)

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

$a_1 = RT$
$a_2 = b_1T + b_2T^{0.5} + b_3 + b_4/T + b_5/T^2$
$a_3 = b_6T + b_7 + b_8/T + b_9/T^2$
$a_4 = b_{10}T + b_{11} + b_{12}/T$
$a_5 = b_{13}$
$a_6 = b_{14}/T + b_{15}/T^2$
$a_7 = b_{16}/T$
$a_8 = b_{17}/T + b_{18}/T^2$

$a_9 = b_{19}/T^2$
$a_{10} = b_{20}/T^2 + b_{21}/T^3$
$a_{11} = b_{22}/T^2 + b_{23}/T^4$
$a_{12} = b_{24}/T^2 + b_{25}/T^3$
$a_{13} = b_{26}/T^2 + b_{27}/T^4$
$a_{14} = b_{28}/T^2 + b_{29}/T^3$
$a_{15} = b_{30}/T^2 + b_{31}/T^3 + b_{32}/T^4$

i	b(i)	i	b(i)
1	$-0.131275405202 \times 10^{-3}$	17	$-0.171082181849 \times 10^{-3}$
2	0.899927934911	18	$0.503986984347 \times 10^{-1}$
3	$-0.281400805178 \times 10^{2}$	19	$-0.830354867752 \times 10^{-3}$
4	$0.436091182784 \times 10^{4}$	20	$-0.245522676708 \times 10^{6}$
5	$-0.837235280004 \times 10^{6}$	21	$-0.107859056038 \times 10^{8}$
6	$-0.782176408963 \times 10^{-6}$	22	$-0.429514279646 \times 10^{4}$
7	$-0.111226606825 \times 10$	23	$0.808724729567 \times 10^{8}$
8	$0.539331431878 \times 10^{3}$	24	$-0.125945229993 \times 10^{2}$
9	$0.288600276863 \times 10^{6}$	25	$-0.105735009761 \times 10^{4}$
10	$-0.352264609289 \times 10^{-4}$	26	$-0.904064745354 \times 10^{-1}$
11	0.189661830119	27	$-0.183578733048 \times 10^{4}$
12	$-0.686549003993 \times 10^{2}$	28	$-0.169690612464 \times 10^{-3}$
13	$-0.349007064245 \times 10^{-2}$	29	$0.639250820631 \times 10^{-1}$
14	$-0.749983559476 \times 10^{-1}$	30	$-0.204925767440 \times 10^{-6}$
15	$-0.321524283063 \times 10^{2}$	31	$-0.165629700870 \times 10^{-3}$
16	$0.913057921906 \times 10^{-2}$	32	$-0.932607493424 \times 10^{-2}$

critical parameters:

P_c = 57.95 bar
ρ_c = 8.2078 mol/L
T_c = 351.35 K
R = 0.08314471 L·bar/(mol·K)

Ideal Gas Heat Capacity Equation [units are K and J/(mol·K)]

$$C^\circ_p = c_0 + c_1T + c_2T^2 + c_3T^3$$

i	c(i)
0	36.79959
1	-6.304821×10^{-2}
2	3.757936×10^{-4}
3	-3.219812×10^{-7}

Table 18-2. Coefficients to the MBWR Equation of State for HCFC-123. (units are K, bar, L, mol) (fit of Younglove 3-25-94)

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

$a_1 = RT$
$a_2 = b_1T + b_2T^{0.5} + b_3 + b_4/T + b_5/T^2$
$a_3 = b_6T + b_7 + b_8T + b_9/T^2$
$a_4 = b_{10} + b_{11} + b_{12}/T$
$a_5 = b_{13}$
$a_6 = b_{14}/T + b_{15}/T^2$
$a_7 = b_{16}/T$
$a_8 = b_{17}/T + b_{18}/T^2$
$a_9 = b_{19}/T^2$
$a_{10} = b_{20}/T^2 + b_{21}/T^3$
$a_{11} = b_{22}/T^2 + b_{23}/T^4$
$a_{12} = b_{24}/T^2 + b_{25}/T^3$
$a_{13} = b_{26}/T^2 + b_{27}/T^4$
$a_{14} = b_{28}/T^2 + b_{29}/T^3$
$a_{15} = b_{30}/T^2 + b_{31}/T^3 + b_{32}/T^4$

i	b(i)	i	b(i)
1	$-0.657453133659 \times 10^{-2}$	17	-0.106148632128
2	0.293479845842×10	18	$0.500026133667 \times 10^{2}$
3	$-0.989140469845 \times 10^{2}$	19	$-0.204326706346 \times 10$
4	$0.201029776013 \times 10^{5}$	20	$-0.249438345685 \times 10^{7}$
5	$-0.383566527886 \times 10^{7}$	21	$-0.463962781113 \times 10^{9}$
6	$0.227587641969 \times 10^{-2}$	22	$-0.284903429588 \times 10^{6}$
7	$-0.908726819450 \times 10$	23	$0.974392239902 \times 10^{10}$
8	$0.434181417995 \times 10^{4}$	24	$-0.637314379308 \times 10^{4}$
9	$0.354116464954 \times 10^{7}$	25	$0.314121189813 \times 10^{6}$
10	$-0.635394849670 \times 10^{-3}$	26	$-0.145747968225 \times 10^{3}$
11	0.320786715274×10	27	$-0.843830261449 \times 10^{7}$
12	$-0.131276484299 \times 10^{4}$	28	$-0.241138441593 \times 10$
13	-0.116360713718	29	$0.108508031257 \times 10^{4}$
14	$-0.113354409016 \times 10^{2}$	30	$-0.106653193965 \times 10^{-1}$
15	$-0.537543457327 \times 10^{4}$	31	$-0.121343571084 \times 10^{2}$
16	0.258112416120×10	32	$-0.257510383240 \times 10^{3}$

critical parameters:

P_c	= 36.618 bar
ρ_c	= 3.596417 mol/L
T_c	= 456.831 K
R	= 0.08314510 L·bar/(mol·K)

Ideal Gas Heat Capacity Equation [units are K and J/(mol·K)]

$$C^\circ_p = c_0 + c_1T + c_2T^2 + c_3T^3$$

i	c(i)
0	17.01154
1	0.4046308
2	-4.644803×10^{-4}
3	2.347418×10^{-7}

Table 18-3. Coefficients to the MBWR Equation of State for HCFC-124. (units are K, bar, L, mol) (fit of Younglove 6-9-93)

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

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

i	b(i)	i	b(i)
1	$-0.195111839846 \times 10^{-1}$	17	$-0.537322295315 \times 10^{-1}$
2	0.299978502039×10	18	$0.157915168095 \times 10^{2}$
3	$-0.845849168162 \times 10^{2}$	19	-0.550297175283
4	$0.146720754658 \times 10^{5}$	20	$-0.244349954189 \times 10^{7}$
5	$-0.232549336572 \times 10^{7}$	21	$-0.625153016263 \times 10^{8}$
6	$0.938866046628 \times 10^{-3}$	22	$-0.156149231820 \times 10^{6}$
7	$-0.425069993257 \times 10$	23	$0.344268154495 \times 10^{10}$
8	$0.304859131600 \times 10^{4}$	24	$-0.289212955106 \times 10^{4}$
9	$0.221314829910 \times 10^{7}$	25	$0.108351996828 \times 10^{6}$
10	$-0.601971995213 \times 10^{-4}$	26	$-0.404809912845 \times 10^{2}$
11	0.100335188373×10	27	$-0.220587292481 \times 10^{7}$
12	$-0.468461812962 \times 10^{3}$	28	-0.564677367857
13	$-0.927654315163 \times 10^{-2}$	29	$0.175581172016 \times 10^{3}$
14	$-0.125426962519 \times 10^{2}$	30	$-0.762146322899 \times 10^{-3}$
15	$-0.228534445089 \times 10^{4}$	31	$-0.210617958917 \times 10$
16	0.168197835599×10	32	$0.319236066221 \times 10^{2}$

critical parameters:

P_c	= 36.37 bar
ρ_c	= 4.101527 mol/L
T_c	= 395.62 K
R	= 0.08314510 L·bar/(mol·K)

Ideal Gas Heat Capacity Equation [units are K and J/(mol·K)]

$$C^\circ_p = c_0 + c_1T + c_2T^2 + c_3T^3$$

i	c(i)
0	26.65068
1	0.2824672
2	-1.233470×10^{-4}
3	-5.677589×10^{-8}

Table 18-4. Coefficients to the MBWR equation of state for HFC-125 (units are K, bar, L, mol)

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

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

i	b(i)	i	b(i)
1	$-0.523369607050 \times 10^{-1}$	17	$0.102433894096 \times 10^{-1}$
2	0.378761878904×10	18	$-0.645583164735 \times 10$
3	$-0.807152818990 \times 10^{2}$	19	0.218649963191
4	$0.115654605248 \times 10^{5}$	20	$0.114748721552 \times 10^{7}$
5	$-0.152175619161 \times 10^{7}$	21	$-0.118389825386 \times 10^{9}$
6	$0.597541484451 \times 10^{-2}$	22	$0.306539775027 \times 10^{5}$
7	$-0.145990589966 \times 10$	23	$0.542870289406 \times 10^{9}$
8	$-0.992338995652 \times 10^{3}$	24	$0.903502635609 \times 10^{3}$
9	$-0.399180535687 \times 10^{6}$	25	$-0.153646507435 \times 10^{6}$
10	$-0.722591037504 \times 10^{-3}$	26	0.314617903718×10
11	0.358108080969	27	$0.429297546671 \times 10^{6}$
12	$-0.108627994573 \times 10^{3}$	28	0.109652021582
13	$0.229821626570 \times 10^{-1}$	29	$-0.329350271819 \times 10^{2}$
14	0.149537670449×10	30	$-0.338796950505 \times 10^{-3}$
15	$0.911199833952 \times 10^{3}$	31	0.384533651902
16	-0.254479949722	32	$-0.491511706857 \times 10^{2}$

critical parameters:

P_c	=	36.29 bar
ρ_c	=	4.75996 mol/L
T_c	=	339.33 K
R	=	0.08314471 L·bar/(mol·K)

Ideal Gas Heat Capacity Equation [units are K and J/(mol·K)]

$$C^\circ_p = c_0 + c_1T + c_2T^2 + c_3T^3$$

i	c(i)
0	25.87069
1	0.2690914
2	-1.331388×10^{-4}
3	4.101330×10^{-9}

Figure 18-1. Thermal Conductivity Surface of HFC-32

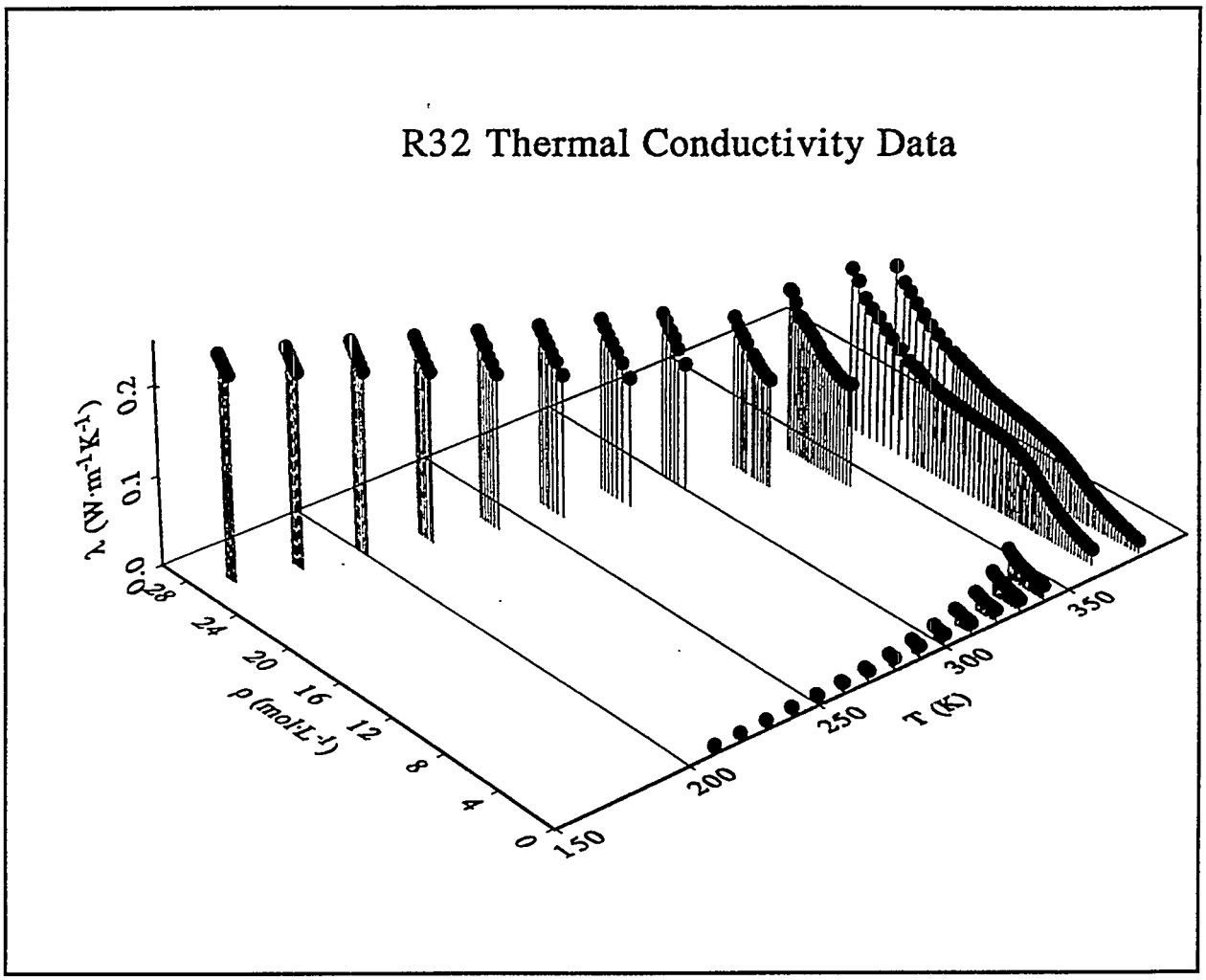
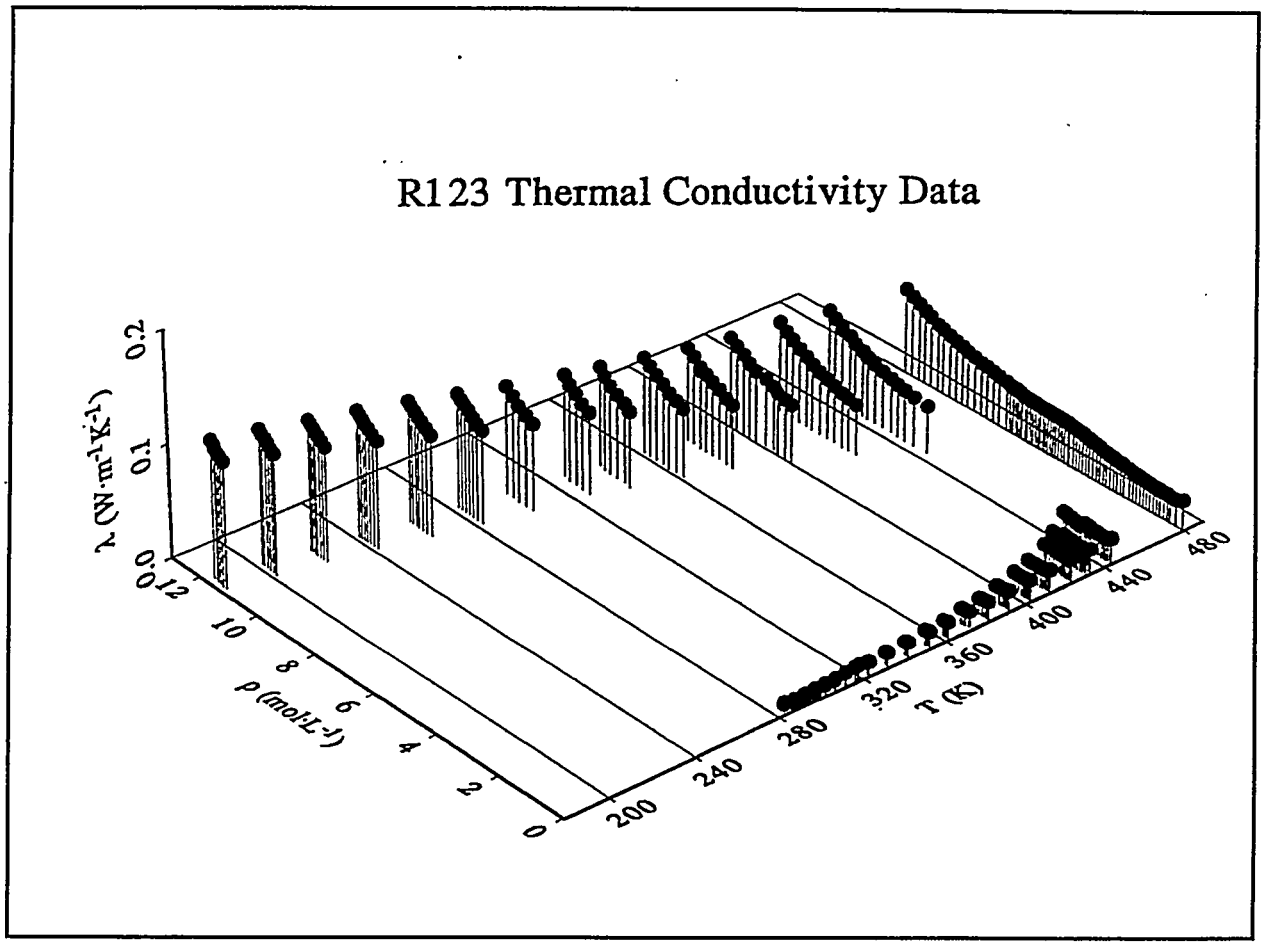


Figure 18-2. Thermal Conductivity Surface of HCFC-123



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 theoretically-based equations of state and detailed transport property models.

Results:

The Thermophysics Division of the National Institute of Standards and Technology (NIST) at Boulder, CO, has conducted measurements and correlations of HFC-143a and HFC-152a. The new data filled gaps in existing data sets and resolved the problems and uncertainties that existed in and between those data sets. Measurements and determinations of thermodynamic properties included 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 was then fitted to the modified Benedict-Webb-Rubin (MBWR) equation of state. Measurements and correlations of transport properties included thermal conductivity and viscosity. Results are contained in the final report, DOE/CE-23810-39, *Thermophysical Properties of HFC-143a and HFC-152a*, July 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 19-1 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 (14,500 psia).

Speed of Sound Measurements

The speed of sound in HFC-143a was measured 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 results are presented in Table 7, DOE/CE/23810-39]. NIST analyzed this data to determine the ideal-gas heat capacity, $C_p°$. [Results are presented in Table 8, DOE/CE-23810]. These data were then fitted to the

following equation:

$$C_p^\circ = c_0 + c_1T + c_2T^2 + c_3T^3$$

where: SI UNITS

c_0 = 19.09245
c_1 = 0.2035019
c_2 = 2.607884×10^{-5}
c_3 = -1.724083×10^{-7}
T = temperature in K.

Liquid Molar Heat Capacity

NIST measured the molar heat capacity at constant pressure for HFC-143a. Measurement included 136 values in the liquid state and 84 values in the vapor + liquid two-phase region. The measurements covered temperatures from 165 to 343 K (-163 to 158°F) and pressures up to 35 MPa (5100 psi). [Results are presented in Tables 10 through 13, DOE/CE/23810-39]

Thermal Conductivity Measurements

The thermal conductivity of HFC-143a was measured at 1229 points (121 points at steady state and 1108 transient measurements). [Results are presented in Tables 18 and 19, DOE/CE/23810-39]. The measurements covered temperatures from 191 to 373 K (-116 to 212°F) and pressures up to 70 MPa (10,200 psia). Figure 19-1 depicts a plot of the thermal conductive surface for HFC-143a.

Shear Viscosity

The shear viscosity of compressed vapor and saturated liquid HFC-143a were measured at temperatures from 255.6 to 337.8 K (0.4 to 148.4°F) using a torsionally oscillating quartz crystal viscometer for the vapor measurements and a capillary viscometer for the liquid measurement. [Results are presented in Tables 21 and 22, DOE/CE/23810-39]. NIST correlated the saturated liquid viscosity data to the following equation:

$$\eta = 3.563 \times 10^{-8}\, e^{53191/T^2}\, (V - 5.1608 \times 10^{-4})$$

where

η is viscosity in Pa·s
T is temperature in K
V is the specific volume in m^3/kg

HFC-152a

MBWR Equation of State

NIST has revised the 32-term modified Benedict-Webb-Rubin equation of state for HFC-152a This revised equation of state will be incorporated into future version of the REFPROP computer program. Table 19-2 provides the revised coefficients to the equation of state. The equation is 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).

Speed of Sound Measurements

NIST measured the speed of sound in HFC-152a using a cylindrical acoustic resonator. Measurements were conducted along isotherms from 242.8 to 400.0 K (-22.7 to 260.3°F) and at pressures from 35 to 1030 kPa (5 to 149.4 psia). [Results are presented in Table 30, DOE/CE/23810-39]. NIST obtained the ideal-gas heat capacity, $C_p°$, by analyzing this data and fitting it to the following equation:

$$C_p° = c_0 + c_1T + c_2T^2 + c_3T^3$$

where: SI UNITS

c_0 = 27.12550
c_1 = 9.220968×10^{-2}
c_2 = 2.189062×10^{-4}
c_3 = -2.514364×10^{-7}
T = temperature in K

Molar Heat Capacity

The molar heat capacity of HFC-152a was measured with an adiabatic calorimeter. Measurements includes 85 points in the single-phase liquid phase and 70 points in the saturated liquid state. Liquid measurements covered temperatures from 164 to 343 K (-164 to 158°F) and pressures up to 35 MPa (5100 psia). Saturated liquid measurements covered temperatures from 162 to 315 K (-167 to 107°F). [Results are presented in Tables 33 through 36, DOE/CE/23810-39].

Thermal Conductivity Measurements

NIST has used high-temperature transient hot-wire thermal conductivity instruments to measure the thermal conductivity of HFC-152a at 1588 points (184 stead-state and 1404 transient hot-wire measurements). [Results are presented in Tables 41 and 42, DOE/CE/23810-39]. Figure 19-2 depicts the thermal conductivity surface for HFC-152a.

Shear Viscosity

The shear viscosity of compressed vapor and saturated liquid HFC-152a were measured at temperatures from 254.7 to 330.9 K (-1.2 to 136°F) using a torsionally oscillating quartz crystal viscometer for the vapor measurements and a capillary viscometer for the liquid measurement. [Results are presented in Tables 44 and 45, DOE/CE/23810-39]. The saturated liquid viscosity data has been correlated to the following equation:

$$\eta = 4.536 \times 10^{-8} (V - 8.2740 \times 10^{-4})$$

where

η is viscosity in Pa·s
T is temperature in K
V is the specific volume in m^3/kg

Table 19-1. Coefficients to the MBWR Equation of State for HFC-143a
[Units are K, bar, L, mol] (fit of Outcalt 4-1-94)

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

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

$\rho_c = 5.14868$ mol/L
$T_c = 346.751$ K
$P_c = 38.32$ bar
$R = 8.314510$ L·bar/(mol·K)

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

Figure 19-1. Thermal Conductivity Surface for HFC-143a.

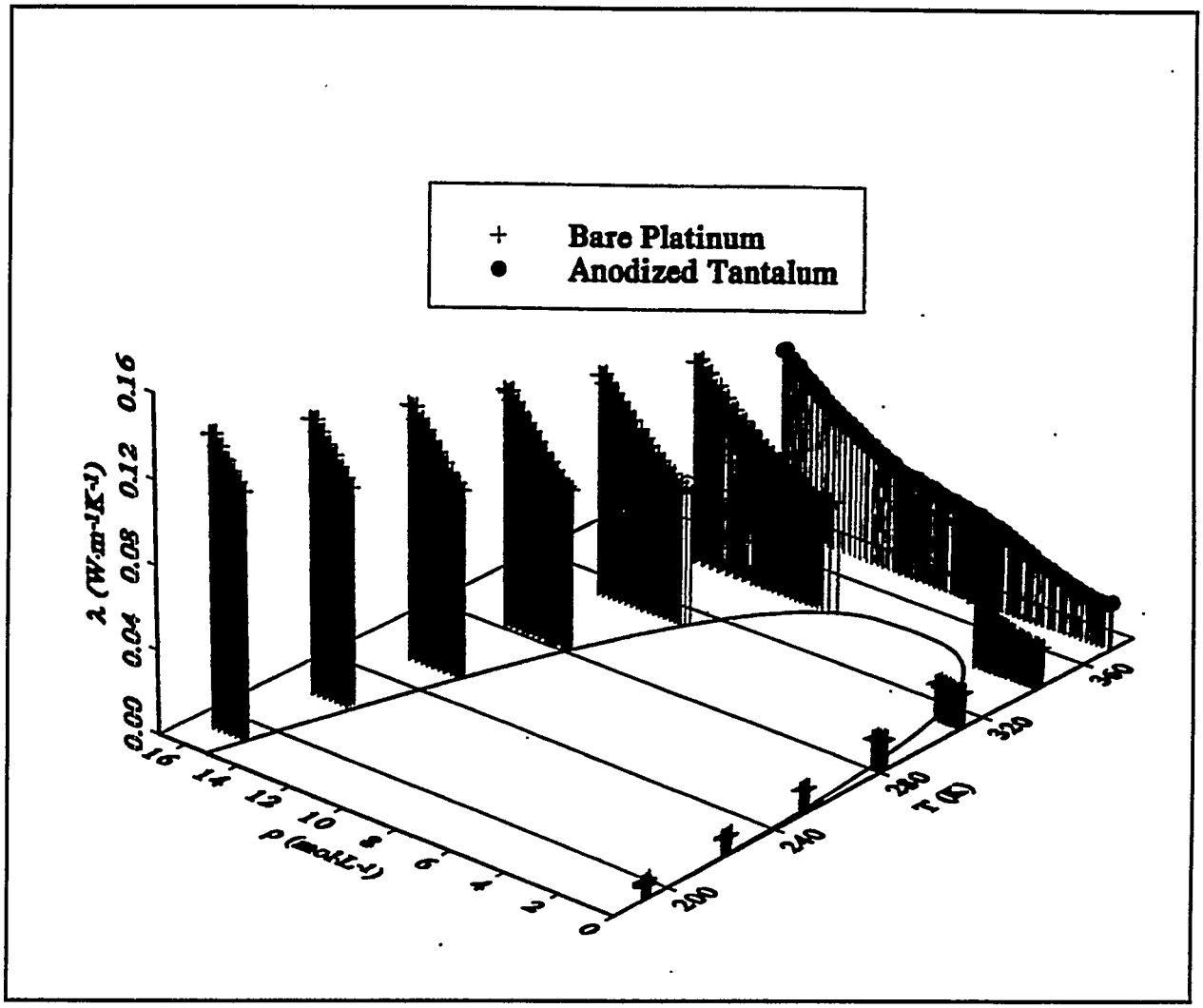


Table 19-2. Revised Coefficients to the MBWR Equation of State for HFC-152a. (units are K, bar, L, mol) (fit of Outcalt 7-13-94)

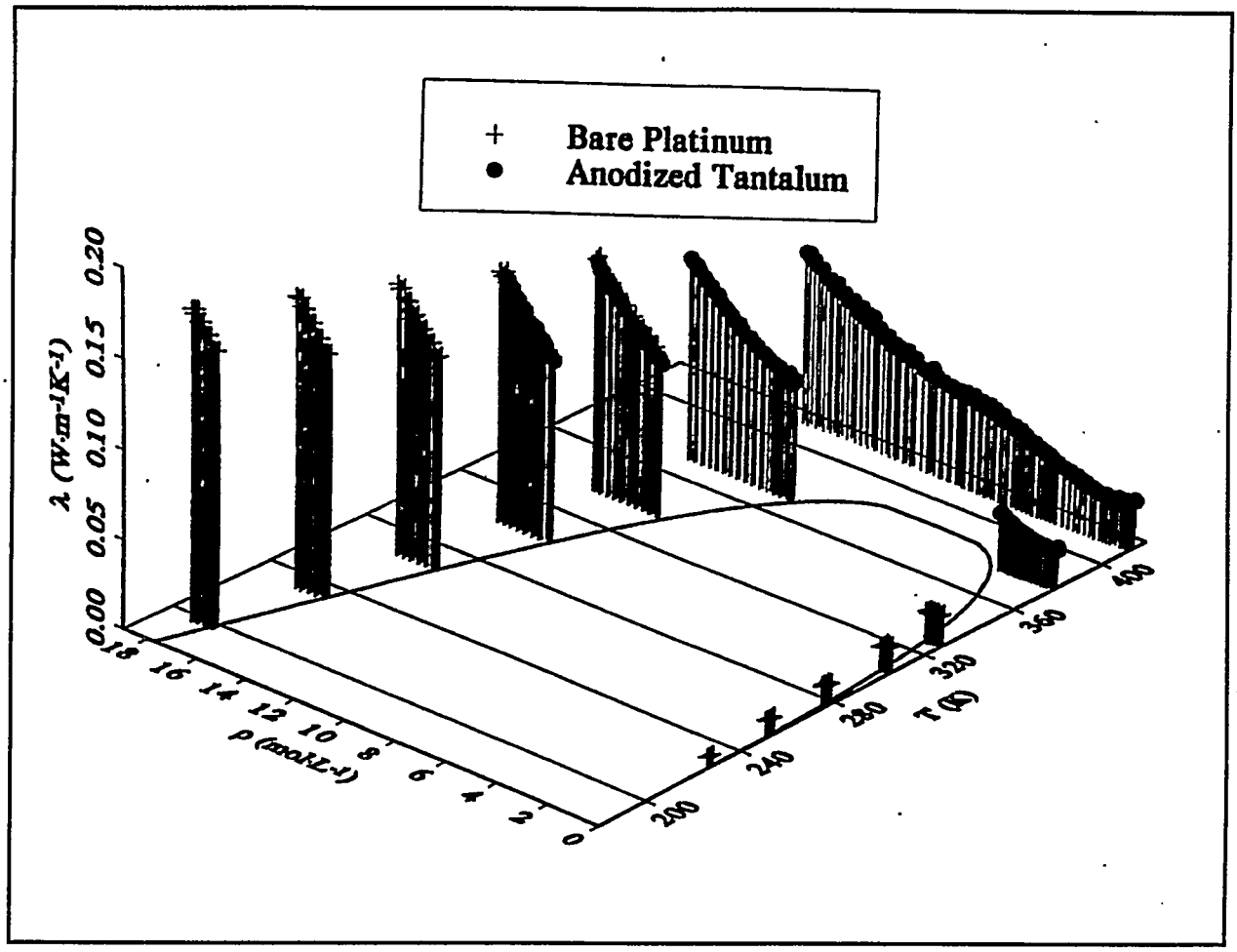
$$P = \sum_{n=1}^{9} a_n \rho^n + \exp(-\rho^2/\rho_c^2) \sum_{n=10}^{15} a_n \rho^{2n-17}$$

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

$\rho_c = 5.57145$ mol/L
$T_c = 386.441$ K
$P_c = 45.167$ bar
$R = 0.08314471$ L·bar/(mol·K)

i	b_i	i	b_i
1	$-0.250029315106 \times 10^{-1}$	17	$-0.209337192155 \times 10^{-2}$
2	0.314406758955×10	18	0.758342353876
3	$-0.842501194121 \times 10^{2}$	19	$-0.185756493708 \times 10^{-1}$
4	$0.152109896841 \times 10^{5}$	20	$-0.437568865038 \times 10^{6}$
5	$-0.235150953572 \times 10^{7}$	21	$-0.386718918565 \times 10^{8}$
6	$-0.560606848017 \times 10^{-3}$	22	$-0.176762932975 \times 10^{5}$
7	-0.561725012842	23	$0.519483578337 \times 10^{9}$
8	$0.349883524824 \times 10^{3}$	24	$-0.160087962199 \times 10^{3}$
9	$0.671534833264 \times 10^{6}$	25	$0.773474059810 \times 10^{4}$
10	$-0.101677799337 \times 10^{-3}$	26	$-0.145595794648 \times 10$
11	0.503738839118	27	$-0.743051998138 \times 10^{5}$
12	$-0.205514094728 \times 10^{3}$	28	$-0.951744381887 \times 10^{-2}$
13	$-0.137760294518 \times 10^{-1}$	29	0.387877679400×10
14	-0.205012592095	30	$-0.195015377121 \times 10^{-4}$
15	$-0.220865713923 \times 10^{3}$	31	$-0.160761476257 \times 10^{-1}$
16	$0.691474699057 \times 10^{-1}$	32	-0.841063960548

Figure 19-2. Thermal Conductivity Surface of HFC-152a.



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:

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)

Results of the evaluations are presented in Figures 20-1 and 20-2.

Figure 20-1. Relative COPs and Capacities of HCFC-22 Alternatives.

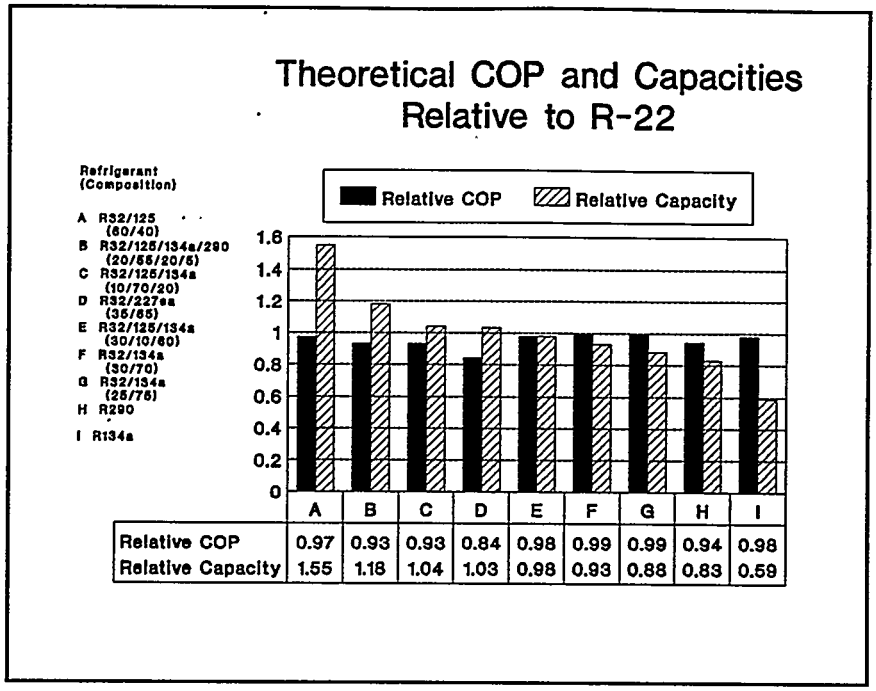
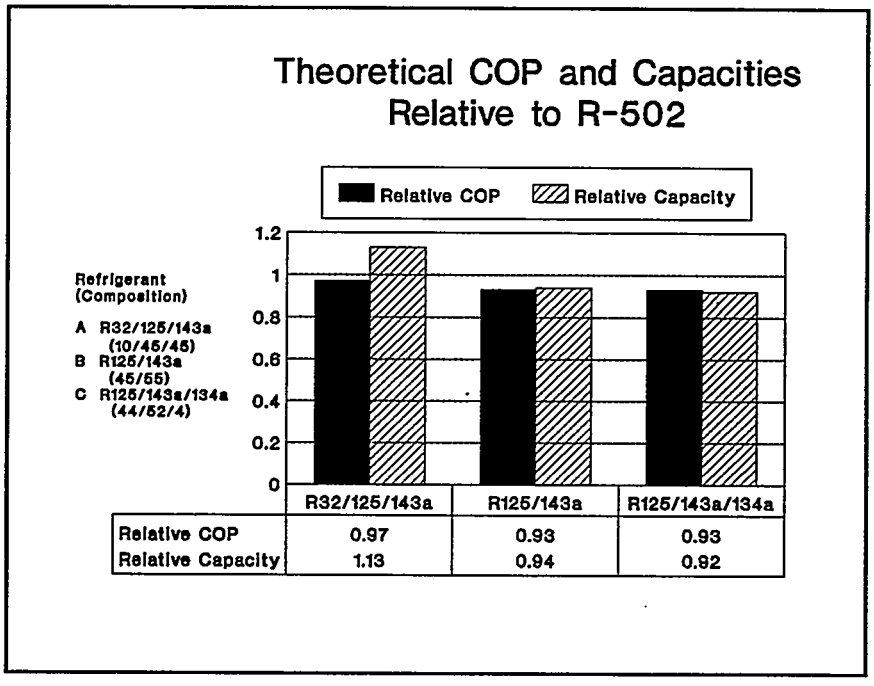


Figure 20-2. Relative COPs and Capacities of R-502 Alternatives.



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)

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)

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 (RDB #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 22-1.

Table 22-1. Miscibility of Lubricants with Refrigerants.

Lubricant	Refrigerant									
	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 68 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	< 38%	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.

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 (RDB #4889, 150 pages).

This research involves viscosity, solubility, and density measurements of thirty-five 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:

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

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 (μ) 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 (P) 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 (ρ) 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 (ν) 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
v	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 (μ) is represented by a modified Walther equation:

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

Vapor pressure (P) 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 (ρ) 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 (ν) is represented by:

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

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 (ν) 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 (P) 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 (ρ) is given by:

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

where:

ν	kinematic viscosity, centistokes
P	kinematic viscosity, centistokes
ρ	density, gram/cubic centimeter
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 23-1 and 23-2 and Figures 23-1 through 23-2 are samples of the summaries for HFC-134a and ISO 68 cSt pentaerythritol ester mixed-acid mixtures.

Table 23-1. 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 23-1. Density of HFC-134a/ISO 68 Pentaerythritol Ester Mixed-Acid. (Low Refrigerant Concentrations)

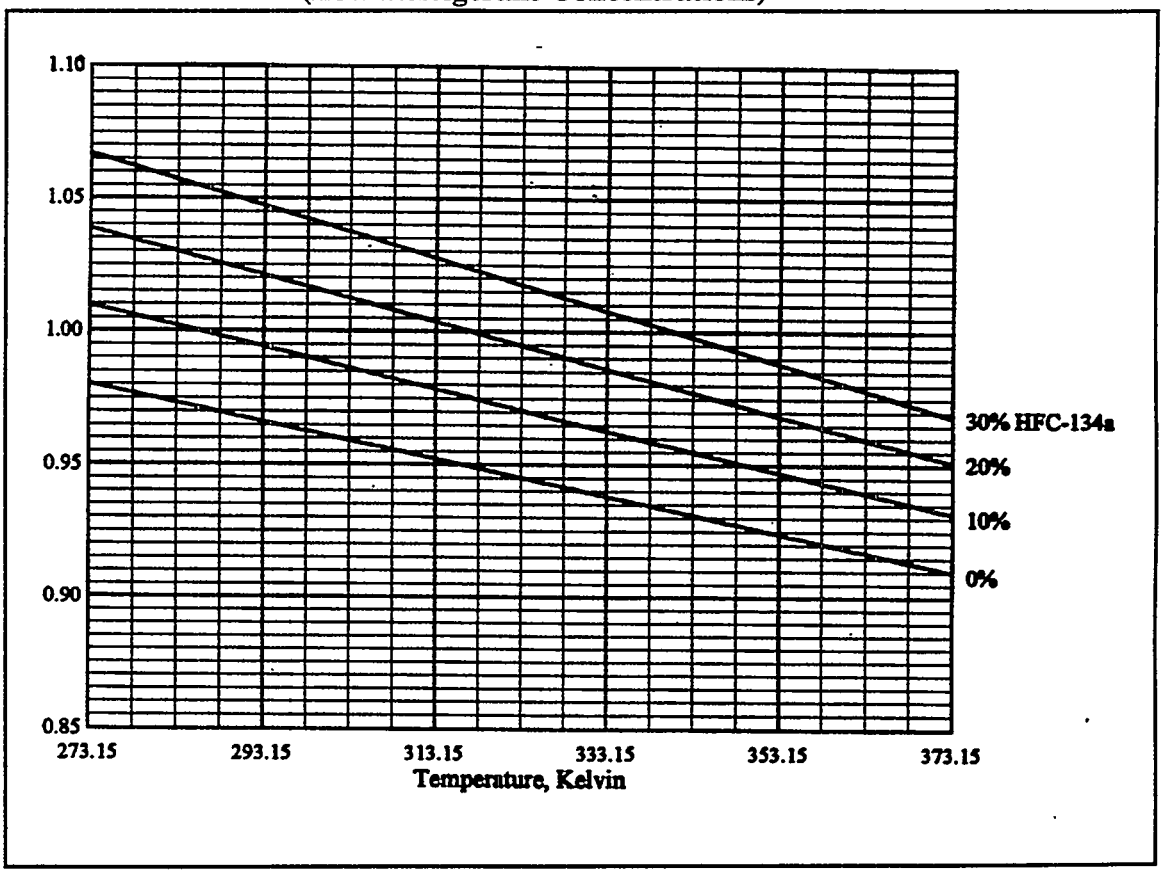


Figure 23-2. Viscosity and Solubility of HFC-134a/ISO 68 Pentaerythritol Ester Mixed-Acid. (Low Refrigerant Concentrations)

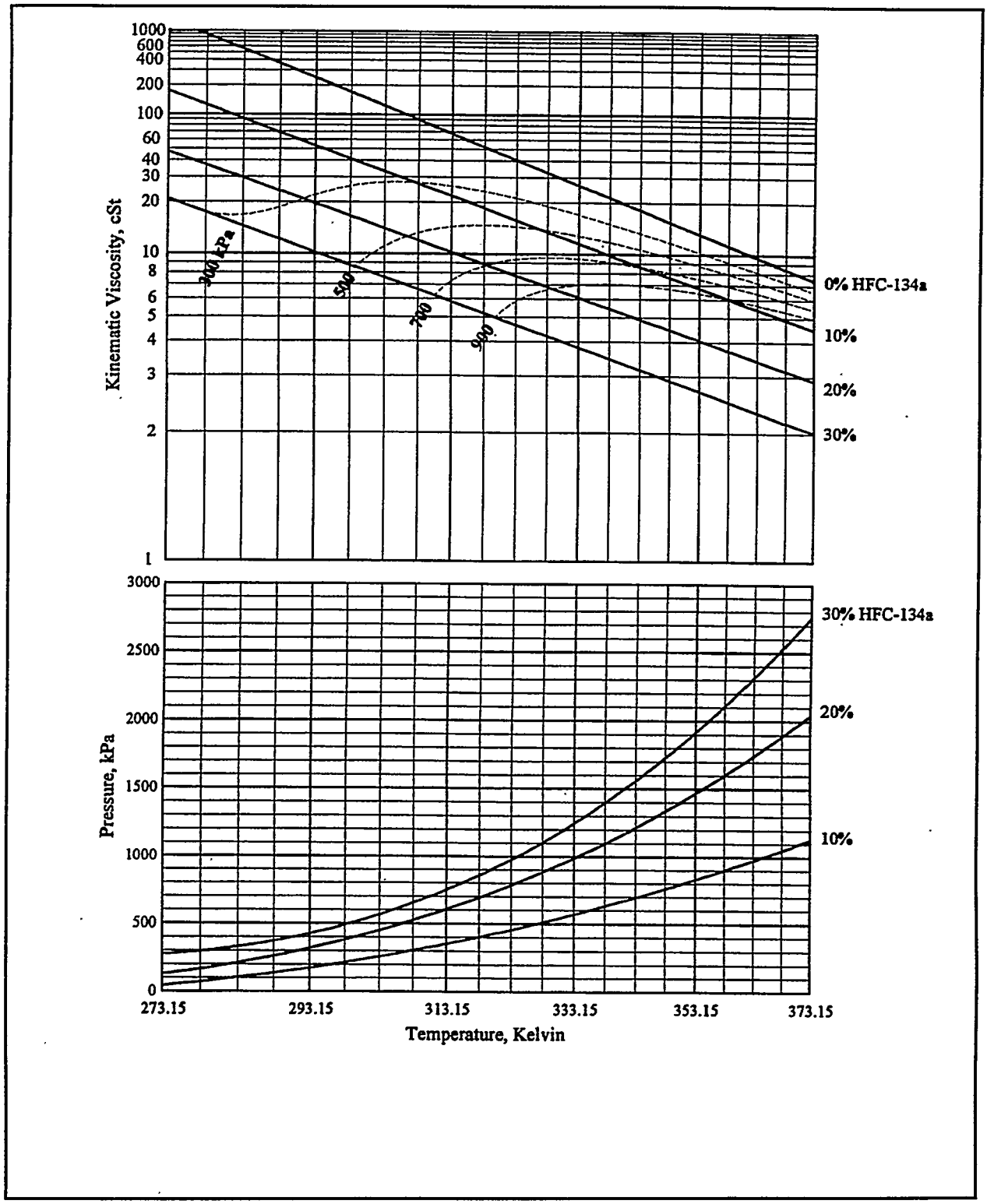


Table 23-2. Viscosity, Solubility and Density Parameters HFC-134a/ISO 68 Pentaerythritol Ester Mixed-Acid. (High Refrigerant Concentrations)

Coefficient	Dynamic Viscosity (eq. 1)	Vapor Pressure (eq. 2)	Density (eq. 3)	Kinematic Viscosity (eq. 4)
a_1	-154267E-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	-1.0393E+5	1.2343E+5	2.26507	-6.55262E+4
σ	0.9999	0.9999	0.9999	0.9999

Figure 23-3. Density of HFC-134a/ISO 68 Pentaerythritol Ester Mixed-Acid. (High Refrigerant Concentrations)

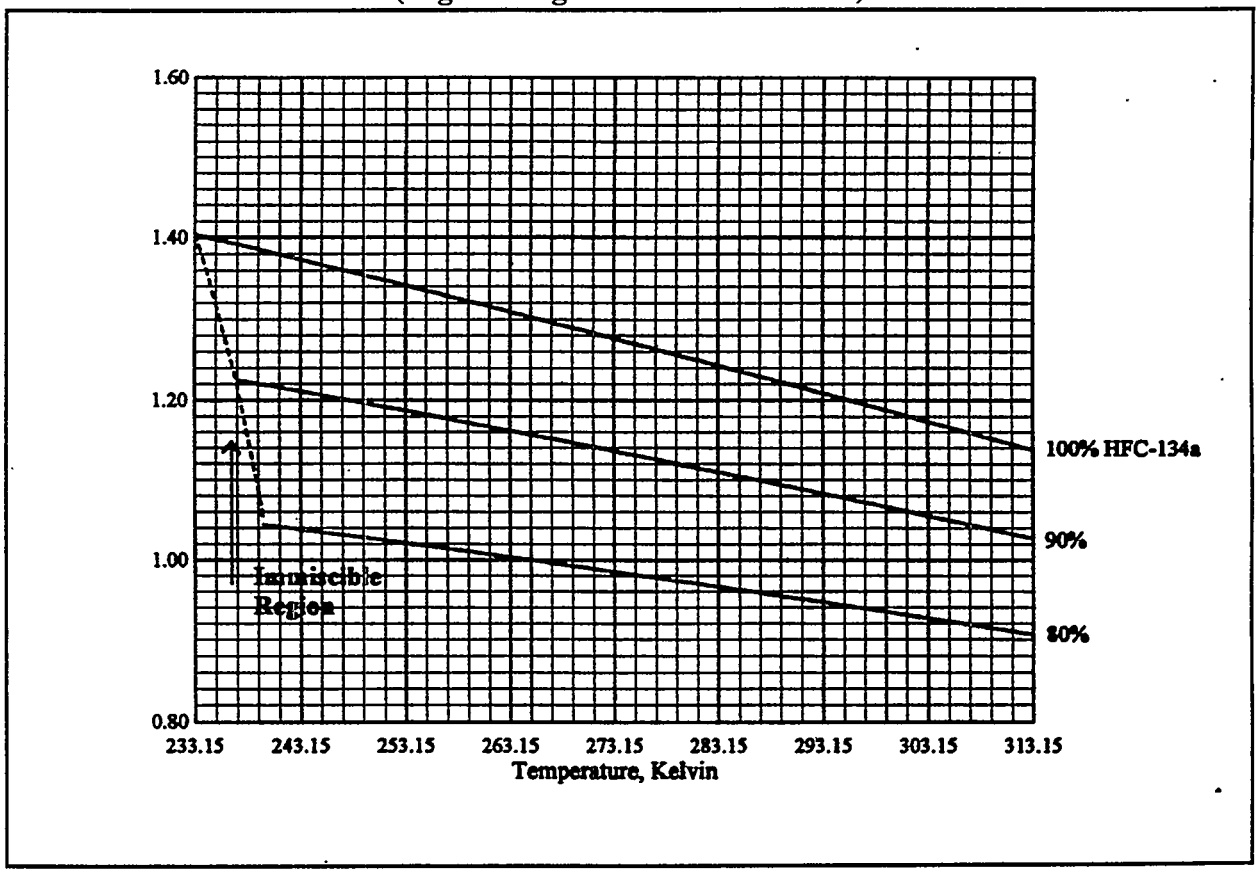
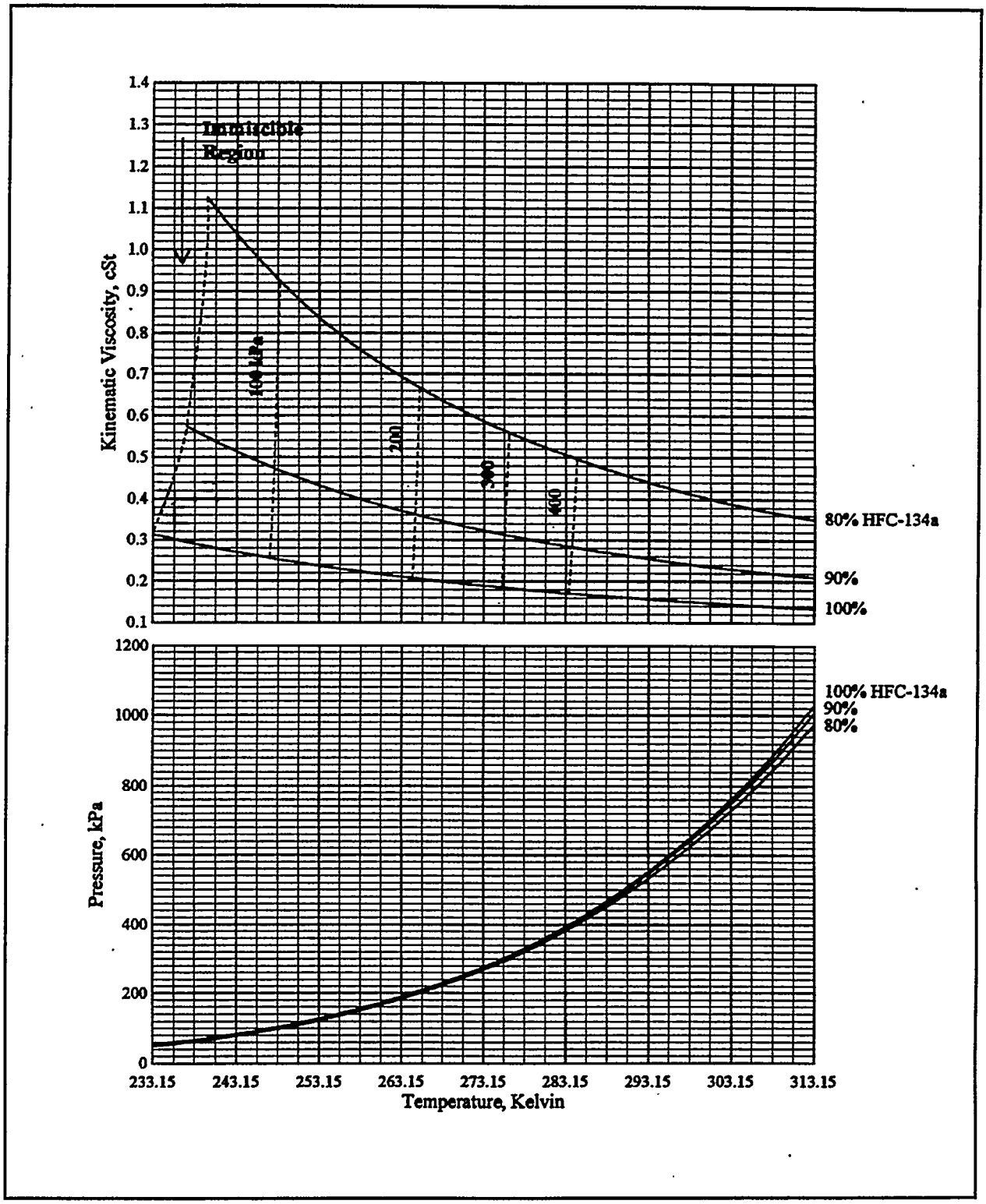


Figure 23-4. Viscosity and Solubility of HFC-134a/ISO 68 Pentaerythritol Ester Mixed-Acid. (High Refrigerant Concentrations)



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

Objective:

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

Results:

Imagination Resources, Inc. completed this research under contract with ARTI. Detailed results of the study are presented in the final report, DOE/CE/23810-46, *Measurement of Viscosity, Density, and Gas Solubility of Refrigerant Blends*, by Richard C. Cavestri, PhD, 15 March 1995 (RDB #5603, 198 pages).

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

Baseline refrigerant-lubricant mixtures:

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

Single-component refrigerant mixtures:

- HFC-32 and 32 ISO mixed-acid polyolester
- HFC-32 and 32 ISO branched-acid polyolester
- HFC-125 and 32 ISO mixed-acid polyolester
- HFC-125 and 32 ISO branched-acid polyolester
- 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

Blend refrigerant-lubricant mixtures:

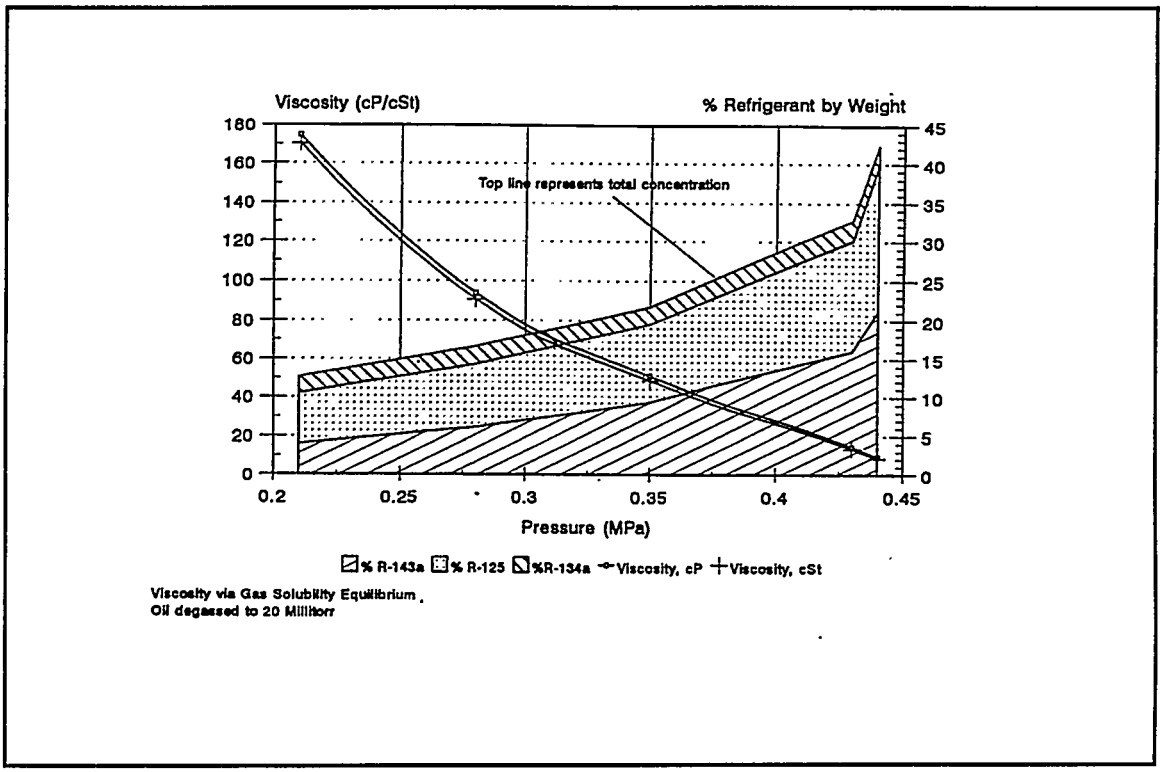
- R-404A (HFC-125/HFC-143a/HFC-134a; 44/52/4%) and 32 ISO mixed-acid polyolester
- R-404A and 32 ISO branched-acid polyolester
- R-407C (HFC-32/HFC-125/HFC-134a; 23/25/52%) and 32 ISO mixed-acid polyolester
- R-407C and 32 ISO branched-acid polyolester
- R-410A (HFC-125/HFC-143a; 50/50%) and 32 ISO mixed-acid polyolester
- R-410A 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°F to 257°F) for a pressure range of 69 to 1,724 kPa (10 to 250 psia):

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

Figure 24-1 is an example of the presentation plot for viscosity vs. gas solubility of R-404A (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.

Figure 24-1. Viscosity, Solubility and Gas Fractionation
32 ISO VG Mixed Acid Polyolester with R-404A at 125°C



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 (RDB # 4501, 538 pages).

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 (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 26-1 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 26-2 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 26-1. 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 acrlic elastomers	L	-	L	L	L	-	-	L	S	-
ethylene propylene diene rubbers	S	S	-	S	S	S	S	S	S	S
fluorinated rubblers	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

Legend
S - small linear swells: less than 8% L - large linear swells: greater than 35% - - mixed swell values and/or 8% < swell < 35%

Table 26-2. Relative in site Elastomer Swelling in Lubricants.

	AB	MO	PEBA	PEMA	PPGBM	PPG	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 acrlic 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 - penaterthritol ester mixed acid PPGBM - polypropylene glycol butyl monether 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 (RDB #4103, 182 pages).

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.

THE COMPATIBILITY OF DESICCANTS WITH REFRIGERANTS AND LUBRICANTS

Objectives:

To provide compatibility information for use of 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 a contract with ARTI. A detailed report of the progress is contained in the draft final report, DOE/CE/23810-54, *Sealed Tube Comparisons of the Compatibility of Desiccants with Refrigerants and Lubricants*, by Jay E. Field, PhD.

The research project is to 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 each of the eight types of test desiccants.

Test Desiccants:

- 4Å molecular sieve desiccant beads
- 3Å molecular sieve desiccant beads
- alumina desiccant
- silica gel desiccant
- core-type desiccant with carbon
  10 to 25% 3Å molecular sieve
  alumina
  5 to 15% carbon
  10 to 20% phosphate binder
- core-type desiccant with carbon
  10 to 25% 4Å molecular sieve
  alumina
  5 to 15% carbon
  10 to 20% phosphate binder
- core-type desiccant without carbon
  10 to 30 3Å molecular sieve
  alumina
  10 to 20% phosphate binder

- core-type desiccant with carbon
  10 to 30% 4Å molecular sieve
  alumina
  10 to 20% phosphate binder

Test Refrigerant-Lubricant Mixtures and Aging Temperatures:

- R-11 with naphthenic mineral oil @ 105°C
- R-12 with naphthenic mineral oil @ 149°C
- R-22 with naphthenic mineral oil @ 149°C
- R-123 with naphthenic mineral oil @ 105°C
- R-134a with pentaerythritol mixed-acid polyolester lubricant @ 149°C
- R-134a with pentaerythritol branched-acid polyolester lubricant @ 149°C
- R-152a with alkylbenzene lubricant @ 149°C
- R-32 with pentaerythritol mixed-acid polyolester lubricant @ 149°C
- R-32 with pentaerythritol branched-acid polyolester lubricant @ 149°C
- R-124 with alkylbenzene lubricant @ 149°C
- R-125 with pentaerythritol mixed-acid polyolester lubricant @ 149°C
- R-125 with pentaerythritol branched-acid polyolester lubricant @ 149°C
- R-143a with pentaerythritol branched-acid polyolester lubricant @ 149°C

The desiccants were tested by exposure to refrigerant-lubricant mixtures in sealed glass tubes in accordance with ASHRAE/ANSI Standard 97-1989. The desiccants were activated by heating them at 260°C for 4 hours prior to sealing in the glass tubes. The following tests or measurements were conducted on unexposed desiccant samples and on desiccant samples after aging with refrigerant-lubricant mixtures and metal catalysts in sealed glass tubes for 28 days:

- visual inspection
- desiccant crush strength
- GC analysis to determine % refrigerant decomposed
- total acid number of lubricant
- liquid phase halide ion/acid anion level
- desiccant halide ion/acid anion level

Results are reported by Dr. Field are summarized in the Tables 28-1 through 28-16.

Code for Summary Test Results Table

Liquid Color

Colors follow ASTM Standard D1500. However, 8mm 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 28-1. Desiccant A: 4Å Molecular Sieve

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)
A-New	None	2.5	0				17.3				190		15		0
	50 ppm Moisture														
A-11	R11/mineral oil	3.5	2	0	0	2	9.3	0.0	0.2	4	130	63	140	41	24
A-12	R12/mineral oil	4.0	1	0	0	0	13.3	0.00	<0.1	4	670	28	1,560	4	570
A-13	R22/mineral oil	3.5	2	0	0	1	17.0	0.00	<0.1	6	3,680	370	50,000	0	7,750
A-14	R123/mineral oil	4.5	1	0	0	0	16.7	0.88	<0.1	1	230	48	720	4	8
A-15	R134a/ mixed ester	2.5	1	0	0	0	14.7	0.00	0.6	0	85	0	0	2,310	9,120
A-16	R134a/branched ester	2.5	0	0	0	0	17.4	0.00	0.4	0	92	3	32	1,240	6,090
A-17	R152a/alkylbenzene	4.0	2	0	0	0	5.7	1.24	<0.1	2	4,140	0	0	2,210	1,300
A-18	R32/mixed ester	3.0	2	0	0	1	9.2	0.55	5.6	4	5,340	5	18	11,630	6,070
A-19	R32/branched ester	2.5	0	0	0	0	8.6	0.20	1.2	6	6,960	6	19	4,460	13,800
A-20	R124/alkylbenzene	3.0	0	0	0	0	15.6	0.41	<0.1	1	160	9	120	6	3,070
A-21	R125/mixed ester	2.5	0	0	0	0	12.3	0.00	<0.1	1	130	4	15	1,840	11,500
A-22	R125/branched ester	2.5	0	0	0	0	12.6	0.00	0.1	1	100	3	18	730	8,080
A-23	R143a/branched ester	2.5	0	0	0	0	12.1	0.00	0.3	0	75	5	50	810	4,510
	1000 ppm Moisture														
A-41	R11/mineral oil	4.5	2	0	0	2	14.0	0.00	0.1	4	330	64	2,540	16	66
A-42	R12/mineral oil	4.0	1	0	0	0	13.1	0.00	0.1	2	1,240	21	1,390	10	820
A-43	R22/mineral oil	3.5	2	0	0	1	20.1	0.00	<0.1	12	9,830	570	51,700	0	7,870
A-44	R123/mineral oil	4.5	1	0	0	0	14.6	0.68	<0.1	1	260	23	840	4	31
A-45	R134a/ mixed ester	2.5	1	0	0	0	11.1	0.00	0.5	0	84	0	11	1,950	8,880
A-46	R134a/branched ester	2.5	0	0	0	0	12.8	0.00	0.3	0	74	1	32	430	6,390
A-47	R152a/alkylbenzene	4.0	2	0	0	0	4.8	1.30	0.2	1	2,420	0	36	2,060	1,210
A-48	R32/mixed ester	3.0	2	0	0	1	8.8	0.42	4.6	0	5,840	3	18	12,410	6,800
A-49	R32/branched ester	2.5	0	0	0	0	7.2	0.48	1.4	5	4,130	0	32	3,360	17,900
A-50	R124/alkylbenzene	3.0	0	0	0	0	14.4	0.35	<0.1	1	280	11	110	18	2,860
A-51	R125/mixed ester	3.0	0	0	0	0	13.1	0.00	<0.1	1	80	6	25	2,760	16,700
A-52	R125/branched ester	2.5	0	0	0	0	11.0	0.00	0.1	1	110	6	17	1,300	9,000
A-53	R143a/branched ester	2.5	0	0	0	0	9.8	0.00	0.6	0	95	8	35	2,030	10,200

Table 28-2. Desiccant E: 4Å Molecular Sieve

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	0				30.9				10		11		0
	50 ppm Moisture														
E-11	R11/mineral oil	3.5	2	0	0	0	12.2	0.00	<0.1	3	130	110	1,570	0	28
E-12	R12/mineral oil	3.5	1	0	0	0	27.0	0.00	<0.1	1	440	18	660	3	272
E-13	R22/mineral oil	4.0	2	0	0	1	27.4	0.12	<0.1	2	6,230	340	49,900	0	6,920
E-14	R123/mineral oil	3.5	0	0	0	0	35.6	0.00	<0.1	1	54	24	390	1	12
E-15	R134a/ mixed ester	2.5	1	0	0	0	21.9	0.00	<0.1	0	91	0	14	480	2,130
E-16	R134a/branched ester	2.5	0	0	0	0	23.2	0.00	<0.1	0	630	2	64	89	4,280
E-17	R152a/alkylbenzene	4.5	2	0	0	1	23.7	3.42	3.0	3	5,590	0	0	3,320	1,880
E-18	R32/mixed ester	3.0	2	0	0	1	21.0	0.35	4.7	0	5,270	0	0	10,000	5,170
E-19	R32/branched ester	2.5	0	0	0	0	17.7	0.40	1.5	14	7,610	0	0	7,480	18,700
E-20	R124/alkylbenzene	2.5	0	0	0	0	25.2	0.16	<0.1	2	83	6	43	4	24
E-21	R125/mixed ester	2.5	0	0	0	0	22.0	0.00	0.1	1	4	5	17	685	1,250
E-22	R125/branched ester	2.5	0	0	0	0	25.5	0.00	<0.1	0	2	2	13	100	1,220
E-23	R143a/branched ester	2.5	0	0	0	0	17.8	0.00	0.2	0	7	9	16	650	490
	1000 ppm Moisture														
E-41	R11/mineral oil	4.5	2	0	0	1	29.1	0.00	0.1	23	210	150	230	15	28
E-42	R12/mineral oil	3.0	1	0	0	0	23.6	0.00	<0.1	1	570	18	720	19	220
E-43	R22/mineral oil	4.0	2	0	0	1	33.6	0.00	<0.1	1	5,820	87	51,600	0	6,630
E-44	R123/mineral oil	3.0	1	0	0	0	27.7	0.22	0.7	1	57	20	490	1	5
E-45	R134a/ mixed ester	2.5	1	0	0	1	25.8	0.00	0.2	0	84	0	0	150	1,690
E-46	R134a/branched ester	2.5	0	0	0	0	23.0	0.00	0.3	3	28	6	10	350	510
E-47	R152a/alkylbenzene	4.5	2	0	0	2	20.1	2.20	2.0	8	6,670	0	14	2,770	1,160
E-48	R32/mixed ester	3.0	2	0	0	1	17.2	0.48	5.1	0	4,970	0	0	14,260	5,130
E-49	R32/branched ester	2.5	0	0	0	0	18.4	0.32	1.5	18	7,000	0	0	7,330	9,250
E-50	R124/alkylbenzene	2.5	0	0	0	0	30.6	0.29	<0.1	3	55	9	39	19	200
E-51	R125/mixed ester	3.0	0	0	0	0	24.3	0.00	<0.1	1	2	2	64	230	1,400
E-52	R125/branched ester	2.5	0	0	0	0	22.9	0.13	0.1	0	2	5	12	180	1,420
E-53	R143a/branched ester	2.5	0	0	0	0	19.2	0.00	<0.1	0	400	8	57	170	3,520

Table 28-4. Desiccant F: 3Å Molecular Sieve

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)
F-New	None	2.5	0				20.0				160		23		0
	50 ppm Moisture														
F-11	R11/mineral oil	5.5	2	0	0	0	17.5	0.16	<0.1	5	490	96	6,080	130	42
F-12	R12/mineral oil	4.5	1	0	0	0	18.0	0.13	1.3	41	1,580	130	6,500	17	820
F-13	R22/mineral oil	2.5	1	0	0	0	10.2	0.00	0.1	47	2,350	220	33,400	4	3,700
F-14	R123/mineral oil	3.5	0	0	0	0	21.7	0.38	<0.1	6	220	12	2,150	0	13
F-15	R134a/ mixed ester	2.5	1	0	0	0	16.1	0.00	0.3	0	130	0	19	740	10,950
F-16	R134a/branched ester	2.5	0	0	0	0	14.3	0.00	0.3	0	120	4	41	1,320	7,570
F-17	R152a/alkylbenzene	3.0	0	0	0	0	14.3	0.66	<0.1	3	2,610	13	33	300	1,990
F-18	R32/mixed ester	3.0	2	0	0	1	9.5	0.31	0.2	14	5,670	5	110	6,040	8,400
F-19	R32/branched ester	2.5	1	0	0	0	11.9	0.20	1.9	17	9,460	0	120	1,860	2,810
F-20	R124/alkylbenzene	2.5	1	0	0	0	20.3	0.00	<0.1	3	240	8	1,010	97	2,380
F-21	R125/mixed ester	2.5	1	0	0	0	13.8	0.00	0.3	0	70	2	22	570	6,920
F-22	R125/branched ester	2.5	1	0	0	0	11.8	0.00	<0.1	0	120	2	34	560	8,560
F-23	R143a/branched ester	2.5	1	0	0	1	12.7	0.00	<0.1	1	150	7	72	880	5,900
	1000 ppm Moisture														
F-41	R11/mineral oil	3.0	2	0	0	2	10.2	0.00	<0.1	1	75	43	690	75	8
F-42	R12/mineral oil	4.5	0	0	0	0	18.6	0.10	<0.1	52	1,390	76	5,770	26	820
F-43	R22/mineral oil	2.5	1	0	0	0	11.6	0.00	<0.1	25	1,810	92	21,000	0	1,910
F-44	R123/mineral oil	3.5	0	0	0	0	18.5	0.06	0.2	1	200	22	2,190	0	5
F-45	R134a/ mixed ester	2.5	1	0	0	1	13.8	0.00	0.2	0	120	0	26	1,210	11,410
F-46	R134a/branched ester	3.0	0	0	0	0	16.6	0.00	0.5	0	50	4	37	1,100	3,880
F-47	R152a/alkylbenzene	3.0	1.0	0	0	0	12.6	0.87	<0.1	12	2,370	15	47	710	920
F-48	R32/mixed ester	3.0	2	0	0	1	8.4	0.27	0.3	70	1,960	2	148	2,920	3,940
F-49	R32/branched ester	2.5	0	0	0	1	13.2	0.23	1.0	17	2,940	0	110	2,350	2,960
F-50	R124/alkylbenzene	2.5	1	0	0	0	20.5	0.28	<0.1	4	210	15	740	1	2,150
F-51	R125/mixed ester	2.5	1	0	0	1	10.7	0.00	0.4	2	270	9	87	1,290	17,700
F-52	R125/branched ester	2.5	1	0	0	0	12.8	0.00	0.1	1	110	8	22	1,240	8,320
F-53	R143a/branched ester	2.5	1	0	0	1	13.4	0.00	0.2	0	120	4	86	1,040	6,240

Table 28-4. Desiccant H: 3Å Molecular Sieve

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)	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	0				34.6				16		4		0
	50 ppm Moisture														
H-11	R11/mineral oil	4.5	2	0	0	1	23.6	0.00	<0.1	4	140	95	1,580	0	75
H-12	R12/mineral oil	3.5	1	0	0	0	24.4	0.00	<0.1	4	1,020	24	1,600	5	532
H-13	R22/mineral oil	3.0	0	0	0	1	24.2	0.00	<0.1	10	4,000	550	45,400	0	5,280
H-14	R123/mineral oil	3.5	1	0	0	0	31.1	0.88	<0.1	1	61	31	460	11	6
H-15	R134a/ mixed ester	2.5	1	0	0	0	18.6	0.00	0.8	0	18	0	11	1,490	3,970
H-16	R134a/branched ester	2.5	0	0	0	0	18.6	0.00	0.3	1	23	13	23	1,400	3,190
H-17	R152a/alkylbenzene	3.5	2	0	0	0	15.7	0.92	0.2	15	3,490	0	0	750	640
H-18	R32/mixed ester	3.0	2	0	0	0	15.6	0.69	0.4	1,280	8,530	0	0	11,400	9,650
H-19	R32/branched ester	2.5	0	0	0	0	16.4	0.41	0.2	16	8,530	0	0	5,700	10,600
H-20	R124/alkylbenzene	2.5	0	0	0	0	25.3	0.00	<0.1	2	110	6	170	41	580
H-21	R125/mixed ester	2.5	0	0	0	0	22.7	0.00	0.6	0	11	3	16	1,230	9,130
H-22	R125/branched ester	2.5	0	0	0	0	19.8	0.00	0.4	0	13	5	12	1,090	3,260
H-23	R143a/branched ester	2.5	0	0	0	0	15.7	0.00	<0.1	1	17	8	25	1,310	2,070
	1000 ppm Moisture														
H-41	R11/mineral oil	3.5	2	0	0	0	26.0	0.00	0.8	5	79	68	2,730	9	85
H-42	R12/mineral oil	3.5	1	0	0	0	24.5	0.00	<0.1	2	430	21	750	13	500
H-43	R22/mineral oil	3.0	0	0	0	1	15.2	0.00	<0.1	4	3,480	350	32,800	0	5,120
H-44	R123/mineral oil	3.5	1	0	0	0	29.7	0.00	0.3	1	63	26	410	0	11
H-45	R134a/ mixed ester	2.5	1	0	0	1	20.6	0.00	0.7	0	12	0	0	1,760	3,280
H-46	R134a/branched ester	2.5	0	0	0	0	15.2	0.00	0.6	0	19	12	16	1,740	3,080
H-47	R152a/alkylbenzene	3.5	2	0	0	0	17.4	0.81	<0.1	14	2,180	0	9	2,390	330
H-48	R32/mixed ester	2.5	2	0	0	1	15.2	0.35	0.4	10	9,570	0	0	12,000	12,400
H-49	R32/branched ester	2.5	0	0	0	0	17.2	0.00	<0.1	13	9,250	0	0	5,390	9,730
H-50	R124/alkylbenzene	2.5	0	0	0	0	30.3	0.00	0.2	4	87	8	140	110	640
H-51	R125/mixed ester	2.5	0	0	0	0	19.7	0.10	0.9	1	10	0	11	2,420	3,160
H-52	R125/branched ester	2.5	0	0	0	0	20.9	0.00	0.6	0	8	0	10	2,080	4,080
H-53	R143a/branched ester	2.5	0	0	0	0	15.9	0.00	0.6	1	60	13	51	1,030	3,300

Table 28-5. Desiccant I: Alumina

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	0				11.9				2		59		3,900
	50 ppm Moisture														
I-11	R11/mineral oil	2.5	0	0	0	0	12.0	0.00	0.1	1	1	77	3,960	11	800
I-12	R12/mineral oil	3.0	1	0	0	0	9.5	0.00	<0.1	3	10	21	4,630	4	1,550
I-13	R22/mineral oil	6.0	3	0	2	1	10.2	0.00	<0.1	1	9,600	220	20,300	7	5,800
I-14	R123/mineral oil	2.5	1	0	0	0	11.6	0.67	0.3	2	38	33	4,690	0	670
I-15	R134a/ mixed ester	2.5	0	0	0	0	10.7	0.00	3.1	0	0	0	20	4,970	33,900
I-16	R134a/branched ester	2.5	0	0	0	0	11.1	0.00	12.8	0	0	2	31	1,880	19,300
I-17	R152a/alkylbenzene	4.5	1	0	0	3	9.3	0.42	4.2	51	410	48	150	1,600	4,320
I-18	R32/mixed ester	7.5	2	0	3	3	14.3	5.30	>30	2,950	10,650	10	19	5,250	4,580
I-19	R32/branched ester	3.5	2	0	0	1	17.7	0.28	20.9	1,250	20,300	12	0	42,600	10,000
I-20	R124/alkylbenzene	2.5	0	0	0	0	12.8	0.08	<0.1	2	65	7	3,650	72	2,840
I-21	R125/mixed ester	3.0	0	0	0	1	9.3	0.00	1.0	0	0	3	36	3,470	29,800
I-22	R125/branched ester	2.5	0	0	0	1	22.7	0.00	2.0	0	4	4	39	2,320	27,100
I-23	R143a/branched ester	2.5	0	0	0	1	8.8	0.00	2.2	0	0	5	106	2,300	19,500
	1000 ppm Moisture														
I-41	R11/mineral oil	3.0	1	0	0	2	8.9	0.00	1.8	0	72	110	4,560	230	940
I-42	R12/mineral oil	3.0	1	0	0	0	12.3	0.00	0.1	2	12	45	4,060	80	970
I-43	R22/mineral oil	6.0	3	0	0	1	11.0	0.00	<0.1	9	8,520	740	19,300	76	3,230
I-44	R123/mineral oil	2.5	1	0	0	0	14.1	0.42	0.5	2	77	22	5,000	0	900
I-45	R134a/ mixed ester	2.5	0	0	0	2	12.2	0.06	3.8	0	0	4	22	6,060	28,100
I-46	R134a/branched ester	2.5	0	0	0	1	15.1	0.00	12.6	0	12	3	22	2,330	22,400
I-47	R152a/alkylbenzene	5.0	1	0	0	0	16.7	0.84	4.7	7	1,200	10	140	1,830	3,150
I-48	R32/mixed ester	6.0	1	0	0	1	19.6	2.87	>30	4,430	8,310	105	0	52,400	16,900
I-49	R32/branched ester	4.0	2	0	0	1	17.0	3.60	24.8	730	8,140	0	69	16,384	24,100
I-50	R124/alkylbenzene	2.5	0	0	0	0	17.7	0.06	0.1	7	10	28	2,610	30	9,290
I-51	R125/mixed ester	2.5	0	0	0	1	11.3	0.00	14.3	0	0	0	40	3,350	28,600
I-52	R125/branched ester	2.5	0	0	0	0	14.2	0.03	2.2	0	0	4	33	1,860	19,100
I-53	R143a/branched ester	2.5	0	0	0	1	9.3	0.00	3.5	5	160	4	220	4,870	27,600

Table 28-6. Desiccant J: Alumina

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)
J-New	None	2.5	0				22.5				7		66		155
	50 ppm Moisture														
J-11	R11/mineral oil	2.5	1	0	0	0	22.3	0.00	<0.1	2	4	46	3,120	0	600
J-12	R12/mineral oil	3.5	0	0	0	0	33.4	0.00	<0.1	3	64	12	3,910	250	690
J-13	R22/mineral oil	6.0	3	0	0	1	22.2	0.00	<0.1	16	5,480	880	14,300	220	4,070
J-14	R123/mineral oil	2.5	0	0	0	0	20.7	0.48	<0.1	2	51	19	3,810	6	120
J-15	R134a/ mixed ester	2.5	0	0	0	1	21.4	0.00	2.1	0	0	3	11	3,990	19,800
J-16	R134a/branched ester	2.5	0	0	0	1	19.4	0.00	1.9	0	0	3	14	2,580	16,300
J-17	R152a/alkylbenzene	5.0	0	0	0	1	29.0	1.13	2.8	28	220	160	66	2,900	2,660
J-18	R32/mixed ester	7.5	3	0	3	3	25.1	1.34	>30	4,990	4,940	59	59	67,600	60,200
J-19	R32/branched ester	4.5	2	0	0	1	25.8	0.00	>30	1,060	9,530	0	28	16,600	12,700
J-20	R124/alkylbenzene	2.5	0	0	0	0	31.8	0.00	0.1	2	45	8	2,610	17	6,820
J-21	R125/mixed ester	2.5	0	0	0	1	21.6	0.00	7.2	0	0	0	27	2,690	16,200
J-22	R125/branched ester	2.5	0	0	0	1	24.4	0.00	2.1	0	0	3	0	2,110	13,300
J-23	R143a/branched ester	2.5	0	0	0	1	27.1	0.00	4.4	0	0	7	48	1,780	14,800
	1000 ppm Moisture														
J-41	R11/mineral oil	2.5	1	0	0	0	22.4	0.00	0.3	2	5	34	3,310	0	470
J-42	R12/mineral oil	3.0	0	0	0	0	30.5	0.00	<0.1	1	6	30	3,580	80	800
J-43	R22/mineral oil	5.5	2	3	0	2	17.2	0.48	<0.1	5	4,630	420	13,300	260	4,300
J-44	R123/mineral oil	2.5	0	0	0	0	20.5	0.57	<0.1	2	120	24	3,980	0	210
J-45	R134a/ mixed ester	2.5	0	0	0	1	19.8	0.06	2.8	0	0	0	22	6,060	22,400
J-46	R134a/branched ester	2.5	0	0	0	1	23.7	0.00	5.9	0	13	3	49	4,670	12,000
J-47	R152a/alkylbenzene	5.0	0	0	0	0	23.6	0.78	2.0	1	420	9	0	3,260	3,790
J-48	R32/mixed ester	7.5	3	0	3	3	25.0	1.60	>30	4,960	4,520	110	58	75,800	56,200
J-49	R32/branched ester	4.5	2	0	0	1	29.4	5.90	>30	1,300	11,900	0	70	23,600	44,500
J-50	R124/alkylbenzene	2.5	0	0	0	0	27.9	0.00	<0.1	2	35	7	2,470	93	7,000
J-51	R125/mixed ester	2.5	0	0	0	0	14.4	0.00	12.7	0	0	0	43	7,720	20,400
J-52	R125/branched ester	2.5	0	0	0	1	21.5	0.00	1.9	0	0	2	9	2,000	11,600
J-53	R143a/branched ester	2.5	0	0	0	1	24.4	0.06	4.2	0	3	4	15	1,970	15,400

Table 28-7. Desiccant K: Silica Gel

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)
K-New	None	2.5	0				76.4				3		14		0
	50 ppm Moisture														
K-11	R11/mineral oil	3.0	3	0	0	1	90.0	0.00	<0.1	2	690	1,520	7,060	0	100
K-12	R12/mineral oil	2.5	0	0	0	0	50.8	0.00	<0.1	8	330	600	320	15	10
K-13	R22/mineral oil	2.5	1	0	0	2	61.9	0.00	0.1	2	1,290	330	660	0	390
K-14	R123/mineral oil	2.5	2	0	0	0	68.5	0.00	0.1	2	19	37	230	33	50
K-15	R134a/mixed ester	2.5	1	0	0	2	65.3	0.00	21.1	0	0	0	0	24,000	20,900
K-16	R134a/branched ester	2.5	0	0	3	3	60.3	0.00	15.7	0	0	5	0	15,100	11,900
K-17	R152a/alkylbenzene	2.5	2	0	0	0	36.2	0.00	<0.1	68	7,660	0	4	760	0
K-18	R32/mixed ester	2.5	0	0	0	3	11.9	0.24	14.3	4	11	3	0	22,100	11,100
K-19	R32/branched ester	2.5	1	0	0	2	12.3	0.00	17.8	2	44	0	0	18,500	13,400
K-20	R124/alkylbenzene	2.5	0	1	0	2	74.1	0.00	<0.1	3	20	17	55	130	9
K-21	R125/mixed ester	3.0	1	0	0	3	66.9	0.00	12.2	0	0	13	11	18,400	24,400
K-22	R125/branched ester	2.5	1	0	1	1	97.9	0.00	13.6	0	22	7	0	19,200	14,200
K-23	R143a/branched ester	2.5	1	0	0	2	47.7	0.00	13.7	1	0	33	32	12,900	8,310
	1000 ppm Moisture														
K-41	R11/mineral oil	3.0	3	0	0	1	91.2	0.00	0.1	1	810	1,570	6,970	42	85
K-42	R12/mineral oil	2.5	2	0	0	1	86.1	0.00	<0.1	3	360	570	320	55	5
K-43	R22/mineral oil	2.5	0	0	0	1	68.5	0.00	<0.1	45	1,500	670	350	76	1,450
K-44	R123/mineral oil	2.5	2	0	0	0	45.2	0.16	<0.1	2	12	68	230	3	9
K-45	R134a/mixed ester	2.5	0	0	1	2	9.8	0.00	16.5	0	0	5	11	17,600	18,600
K-46	R134a/branched ester	3.0	0	0	2	1	51.6	0.00	21.6	0	0	5	9	14,000	14,200
K-47	R152a/alkylbenzene	2.5	2	0	0	0	48.5	0.05	<0.1	22	3,450	5	0	830	300
K-48	R32/mixed ester	2.5	1	0	1	1	28.0	0.22	17.1	94	60	7	0	480	14,000
K-49	R32/branched ester	2.5	1	0	2	1	60.5	4.45	18.2	110	283	19	0	10,900	12,700
K-50	R124/alkylbenzene	2.5	0	0	0	0	75.6	0.13	0.1	14	49	28	72	17	69
K-51	R125/mixed ester	2.5	0	0	1	2	58.0	0.00	25.8	0	0	10	0	16,800	16,400
K-52	R125/branched ester	2.5	0	0	1	1	65.9	0.66	>30	0	0	6	0	11,500	19,100
K-53	R143a/branched ester	2.5	0	0	3	2	56.5	0.00	23.0	0	59	25	93	11,900	27,100

Table 28-8. Desiccant L: Silica Gel

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)
L-New	None	2.5	0				22.9				14		22		0
	50 ppm Moisture														
L-11	R11/mineral oil	3.0	3	0	0	1	12.5	0.12	0.9	2	1,040	2,050	6,600	0	100
L-12	R12/mineral oil	2.5	1	0	0	1	13.4	0.00	<0.1	0	290	350	190	4	0
L-13	R22/mineral oil	2.5	2	0	0	2	9.1	0.00	0.1	3	2,620	910	1,240	55	420
L-14	R123/mineral oil	2.5	2	0	0	0	36.3	0.00	<0.1	1	15	35	84	8	16
L-15	R134a/mixed ester	2.5	0	0	2	1	6.7	0.00	19.5	1	0	6	0	17,800	12,800
L-16	R134a/branched ester	2.5	0	0	2	1	24.0	0.09	12.9	0	1	3	4	9,990	13,000
L-17	R152a/alkylbenzene	3.0	3	0	0	1	30.2	0.00	0.1	1430	4,550	28	0	550	9,180
L-18	R32/mixed ester	2.5	0	0	2	2	12.0	0.61	>30	63	600	5	0	19,100	25,600
L-19	R32/branched ester	2.5	1	0	2	1	10.4	0.00	21.7	120	640	14	0	11,400	10,800
L-20	R124/alkylbenzene	2.5	0	0	0	0	30.2	0.43	0.1	13	110	50	43	78	85
L-21	R125/mixed ester	2.7	0	0	2	1	12.9	0.00	>30	0	0	6	0	17,100	16,200
L-22	R125/branched ester	2.5	0	0	1	1	21.8	0.00	17.6	1	21	11	0	12,600	11,500
L-23	R143a/branched ester	2.5	0	0	1	1	16.1	0.00	22.1	8	8	44	21	11,400	12,970
	1000 ppm Moisture														
L-41	R11/mineral oil	2.5	3	0	0	1	26.0	0.00	0.1	4	1,210	1,730	10,570	0	63
L-42	R12/mineral oil	2.5	1	1	0	1	17.5	0.00	<0.1	0	490	5	1,600	200	22
L-43	R22/mineral oil	2.5	2	0	0	2	7.6	0.00	<0.1	4	1,840	470	1,000	200	720
L-44	R123/mineral oil	2.5	2	0	0	0	21.5	0.00	<0.1	1	16	56	60	1	25
L-45	R134a/mixed ester	2.5	0	0	2	1	17.0	0.00	17.6	1	17	11	0	14,300	17,600
L-46	R134a/branched ester	2.5	0	0	1	2	11.8	0.00	17.3	0	1	4	6	11,600	9,560
L-47	R152a/alkylbenzene	3.0	2	0	2	0	25.0	0.00	0.1	710	3,810	7	11	380	0
L-48	R32/mixed ester	2.5	1	0	1	1	6.9	0.25	20.2	28	679	8	0	13,600	8,640
L-49	R32/branched ester	2.4	1	0	2	1	11.0	0.12	16.3	120	120	10	0	15,100	15,300
L-50	R124/alkylbenzene	2.5	0	0	0	0	17.9	0.07	<0.1	14	110	48	74	48	82
L-51	R125/mixed ester	2.5	0	0	2	1	35.7	0.00	21.9	0	0	0	0	20,900	16,800
L-52	R125/branched ester	2.5	0	0	1	2	24.2	0.00	15.5	0	0	8	0	13,900	11,800
L-53	R143a/branched ester	2.5	0	0	1	1	13.1	0.00	21.7	12	1	64	28	15,300	8,580

Table 28-9. Desiccant M: 3Å Carbon Core

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)
M-New	None	2.5	0				4.9				9		71		0
	50 ppm Moisture														
M-11	R11/mineral oil	3.0	1	0	0	0	5.3	0.00	0.5	6	37	140	3,310	0	150
M-12	R12/mineral oil	3.0	2	0	2	1	7.3	0.09	<0.1	5	66	33	3,300	3	940
M-13	R22/mineral oil	5.5	3	0	0	1	4.1	0.00	<0.1	21	4,730	340	16,700	240	2,170
M-14	R123/mineral oil	2.5	0	0	0	0	5.5	0.34	0.5	84	210	94	2,740	0	0
M-15	R134a/ mixed ester	2.5	0	0	0	1	6.1	0.05	3.4	0	0	20	9	6,210	14,000
M-16	R134a/branched ester	2.5	2	0	1	1	8.2	0.00	3.9	24	0	3	8	8,620	11,700
M-17	R152a/alkylbenzene	4.5	1	0	0	1	7.1	0.89	1.9	25	940	44	0	2,990	670
M-18	R32/mixed ester	7.0	2	0	0	1	5.8	1.47	>30	4,540	9,080	5	45	39,700	28,800
M-19	R32/branched ester	3.0	2	0	2	3	4.7	1.70	>30	2,140	6,750	38	30	11,500	14,200
M-20	R124/alkylbenzene	2.5	0	0	0	0	6.5	0.05	<0.1	8	240	19	1,470	10	2,880
M-21	R125/mixed ester	2.5	1	0	1	1	7.9	0.00	5.9	2	11	6	14	9,970	17,600
M-22	R125/branched ester	2.5	2	0	0	1	6.3	0.00	4.3	0	0	8	9	4,290	16,600
M-23	R143a/branched ester	2.5	0	0	0	1	6.1	0.21	4.5	0	0	7	10	4,260	11,500
	1000 ppm Moisture														
M-41	R11/mineral oil	3.0	1	0	0	0	6.7	0.00	0.2	3	40	130	3,980	0	95
M-42	R12/mineral oil	3.0	2	0	0	1	8.0	0.00	<0.1	8	75	64	3,460	230	1,060
M-43	R22/mineral oil	5.5	3	0	0	1	11.0	0.00	<0.1	49	5,160	600	17,900	60	1,340
M-44	R123/mineral oil	2.5	0	0	0	0	4.9	0.30	1.2	1	160	30	2,700	4	0
M-45	R134a/ mixed ester	2.5	0	0	0	1	7.4	0.13	3.1	0	1	33	9	5,020	15,900
M-46	R134a/branched ester	2.5	2	0	1	1	9.6	0.00	3.3	0	1	2	0	3,510	11,400
M-47	R152a/alkylbenzene	4.5	1	0	0	1	5.1	1.28	0.7	170	2,360	79	18	4,810	1,350
M-48	R32/mixed ester	7.0	2	0	0	1	6.4	0.24	>30	3,280	9,980	10	40	26,900	27,000
M-49	R32/branched ester	3.0	2	0	2	3	3.9	0.00	>30	1,890	9,640	0	38	19,000	18,200
M-50	R124/alkylbenzene	2.5	0	0	0	0	6.5	0.00	0.9	7	230	14	1,730	20	3,830
M-51	R125/mixed ester	2.5	2	0	0	1	6.0	0.00	10.3	0	0	0	0	6,660	13,000
M-52	R125/branched ester	2.5	2	0	1	1	7.5	0.00	9.9	0	0	5	20	3,830	11,900
M-53	R143a/branched ester	2.5	0	0	0	1	6.9	0.17	6.4	0	0	6	9	3,840	10,500

Table 28-10. Desiccant N: 3Å Carbon Core

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)
N-New	None	2.5	0				4.9				8		110		0
	50 ppm Moisture														
N-11	R11/mineral oil	3.0	1	0	0	0	4.9	0.00	0.3	9	19	150	3,880	0	680
N-12	R12/mineral oil	3.0	2	0	2	1	6.1	0.00	<0.1	11	43	36	4,080	270	1,220
N-13	R22/mineral oil	5.0	2	0	0	1	3.2	0.00	0.7	32	5,610	750	14,600	150	1,350
N-14	R123/mineral oil	2.5	0	0	0	0	4.6	0.25	0.2	2	70	81	3,350	0	360
N-15	R134a/ mixed ester	2.5	0	0	0	2	3.8	0.00	4.2	0	0	7	14	6,790	20,200
N-16	R134a/branched ester	2.5	0	0	0	2	5.2	0.00	3.3	0	0	2	12	3,900	13,100
N-17	R152a/alkylbenzene	4.5	1	0	0	1	10.5	0.38	1.2	35	770	25	30	1,860	940
N-18	R32/mixed ester	6.0	2	0	0	1	4.2	0.20	>30	4050	8,350	0	36	30,200	21,600
N-19	R32/branched ester	2.5	1	0	0	3	3.9	0.23	>30	2270	5,620	0	0	10,600	7,900
N-20	R124/alkylbenzene	2.0	0	0	0	0	4.4	0.00	0.2	7	220	32	1,970	14	4,580
N-21	R125/mixed ester	2.5	1	0	0	2	5.0	0.00	8.1	1	69	4	0	6,920	20,600
N-22	R125/branched ester	2.5	2	0	1	1	4.7	0.00	7.9	0	0	5	18	3,630	16,100
N-23	R143a/branched ester	2.5	0	0	0	3	4.0	0.00	6.5	0	0	13	9	4,600	13,900
	1000 ppm Moisture														
N-41	R11/mineral oil	2.5	1	0	0	1	5.7	0.00	0.1	7	50	170	4,090	0	0
N-42	R12/mineral oil	3.0	2	0	2	1	6.8	0.00	<0.1	7	33	34	3,550	240	1,100
N-43	R22/mineral oil	5.0	2	0	0	1	6.3	0.00	0.1	45	6,090	1,450	14,600	5	1,420
N-44	R123/mineral oil	2.5	0	0	0	0	5.8	0.38	0.4	3	37	64	3,220	22	440
N-45	R134a/ mixed ester	2.5	0	0	0	2	4.8	0.00	4.4	0	0	6	49	6,880	21,700
N-46	R134a/branched ester	2.5	1	0	0	1	4.6	0.04	0.1	0	4	7	0	4,550	17,200
N-47	R152a/alkylbenzene	4.5	2	0	0	0	5.1	1.27	0.3	100	1,430	40	38	2,290	1,340
N-48	R32/mixed ester	6.0	2	0	0	1	7.5	0.43	>30	4040	9,700	14	43	40,600	23,500
N-49	R32/branched ester	2.5	1	0	0	3	5.5	0.08	>30	1960	9,830	0	21	30,900	15,300
N-50	R124/alkylbenzene	2.5	0	0	0	0	5.2	0.00	<0.1	2	340	7	2,100	74	4,220
N-51	R125/mixed ester	2.5	1	0	0	2	4.2	0.00	6.9	0	0	9	0	6,390	18,400
N-52	R125/branched ester	2.5	2	0	1	2	6.7	0.00	8.6	0	0	2	15	4,760	16,900
N-53	R143a/branched ester	3.0	2	0	0	2	6.3	0.00	6.9	0	1	6	18	4,100	11,600

Table 28-11. Desiccant T: 4Å Carbon Core

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)
T-New	None	2.5	0				7.3				22		98		0
	50 ppm Moisture														
T-11	R11/mineral oil	3.5	1	0	0	0	5.7	0.00	0.2	34	130	290	6,240	0	340
T-12	R12/mineral oil	3.0	0	0	0	0	7.9	0.00	<0.1	9	610	74	8,650	16	0
T-13	R22/mineral oil	2.5	0	0	0	1	5.0	0.00	<0.1	82	2,480	490	12,400	150	1,430
T-14	R123/mineral oil	3.5	0	0	0	0	7.8	0.26	1.4	3	82	38	3,560	24	830
T-15	R134a/ mixed ester	2.5	0	0	0	2	6.5	0.00	8.6	1	3	7	52	10,200	20,100
T-16	R134a/branched ester	2.5	0	0	0	2	2.9	0.00	13.5	29	1	12	16	8,170	11,600
T-17	R152a/alkylbenzene	4.0	2	0	0	0	6.7	0.32	0.4	150	2,610	35	190	1,720	35
T-18	R32/mixed ester	2.5	0	0	1	1	7.9	0.28	>30	2850	9,810	0	44	22,800	41,100
T-19	R32/branched ester	2.5	1	0	0	3	5.1	0.00	>30	850	8,540	0	55	30,300	12,700
T-20	R124/alkylbenzene	2.5	0	0	1	0	9.5	0.00	<0.1	8	720	20	1,770	68	570
T-21	R125/mixed ester	2.5	0	0	0	3	7.0	0.00	4.6	0	0	4	0	8,170	13,900
T-22	R125/branched ester	2.5	0	0	0	2	3.0	0.80	8.2	0	4	4	26	5,640	12,600
T-23	R143a/branched ester	2.5	0	0	0	2	7.3	0.00	10.5	1	33	6	170	7,050	20,500
	1000 ppm Moisture														
T-41	R11/mineral oil	3.5	1	0	0	0	5.5	0.00	0.2	7	220	160	6,680	0	340
T-42	R12/mineral oil	3.0	0	0	0	0	6.8	0.00	<0.1	8	360	80	8,350	59	540
T-43	R22/mineral oil	2.5	0	0	0	1	4.8	0.11	<0.1	120	2,260	890	14,500	160	1,880
T-44	R123/mineral oil	3.5	0	0	0	0	8.5	0.39	<0.1	3	84	120	3,120	28	850
T-45	R134a/ mixed ester	2.5	0	0	0	1	7.9	0.00	8.7	0	0	16	13	11,000	14,500
T-46	R134a/branched ester	3.0	0	0	0	2	8.6	0.00	10.7	13	1	0	44	9,660	17,700
T-47	R152a/alkylbenzene	4.0	2	0	0	0	7.2	0.59	0.5	91	2,280	22	44	830	1,140
T-48	R32/mixed ester	2.5	0	0	0	2	6.1	0.19	>30	2770	9,290	16	0	22,700	28,100
T-49	R32/branched ester	2.5	1	0	0	2	6.1	0.32	25.1	560	6,670	24	41	14,600	16,200
T-50	R124/alkylbenzene	2.5	0	0	1	0	10.4	0.00	<0.1	3	810	30	1,960	17	2,830
T-51	R125/mixed ester	3.0	1.0	0	0	2	9.0	0.00	1.7	2	11	5	121	5,900	27,400
T-52	R125/branched ester	2.5	0	0	0	2	5.4	0.00	9.7	0	2	4	27	4,970	12,800
T-53	R143a/branched ester	2.5	0	0	0	3	10.3	0.00	3.1	0	22	1	30	3,750	9,460

Table 28-12. Desiccant V: 4Å Carbon Core

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)
V-New	None	2.5	0				6.3				4		110		0
	50 ppm Moisture														
V-11	R11/mineral oil	3.0	1	0	0	0	7.1	0.00	<0.1	7	130	160	5,750	0	240
V-12	R12/mineral oil	3.0	1	0	0	0	5.8	0.00	<0.1	11	200	76	7,080	0	0
V-13	R22/mineral oil	2.5	1	0	0	1	3.0	0.00	<0.1	19	2,380	1,250	10,900	26	730
V-14	R123/mineral oil	3.0	0	0	0	0	5.5	0.42	0.2	2	15	28	3,160	22	500
V-15	R134a/ mixed ester	2.5	0	0	0	2	5.3	0.63	12.8	0	4	3	22	15,400	19,200
V-16	R134a/branched ester	2.5	0	0	0	1	7.9	0.00	19.5	1	0	11	25	10,100	21,000
V-17	R152a/alkylbenzene	4.0	2	0	0	0	4.8	0.17	0.3	79	1,780	42	45	1,620	44
V-18	R32/mixed ester	2.5	0	0	0	2	4.2	0.31	>30	980	7,220	4	29	34,500	20,100
V-19	R32/branched ester	2.5	0	0	1	2	5.2	0.15	>30	1040	7,750	3	16	19,800	11,500
V-20	R124/alkylbenzene	2.5	0	0	0	0	11.6	0.00	<0.1	88	140	63	480	1,530	910
V-21	R125/mixed ester	2.5	0	0	0	2	8.5	0.19	7.9	0	0	4	15	9,580	22,500
V-22	R125/branched ester	2.5	0	0	0	2	7.4	0.33	5.3	0	1	9	11	6,760	13,600
V-23	R143a/branched ester	2.5	0	0	0	2	6.8	0.31	8.0	9	14	15	37	7,570	13,700
	1000 ppm Moisture														
V-41	R11/mineral oil	3.0	1	0	0	0	6.1	0.00	0.4	6	27	290	3,900	5	520
V-42	R12/mineral oil	2.5	0	0	0	0	9.7	0.00	<0.1	8	46	63	4,690	68	1,000
V-43	R22/mineral oil	3.5	0	0	0	1	6.2	0.00	<0.1	96	960	1,230	13,400	610	1,470
V-44	R123/mineral oil	3.0	0	0	0	0	10.1	0.33	0.1	3	89	125	4,100	12	670
V-45	R134a/ mixed ester	2.5	0	0	0	2	7.5	0.03	12.6	0	0	11	14	14,000	16,700
V-46	R134a/branched ester	2.5	0	0	0	1	9.6	0.00	19.9	0	1	31	110	12,400	23,600
V-47	R152a/alkylbenzene	4.0	2	0	0	0	6.6	0.13	0.3	87	1,530	39	46	1,730	32
V-48	R32/mixed ester	2.5	0	0	0	2	4.5	0.17	>30	1300	8,100	14	37	30,800	24,100
V-49	R32/branched ester	2.5	0	0	1	2	4.9	0.28	>30	380	6,460	8	23	15,200	9,770
V-50	R124/alkylbenzene	2.5	0	0	0	0	11.8	0.00	<0.1	3	190	24	1,830	7	1,660
V-51	R125/mixed ester	2.5	0	0	0	2	6.9	0.00	7.6	0	0	6	10	9,250	20,800
V-52	R125/branched ester	2.5	0	0	0	2	8.8	0.00	10.9	0	0	0	0	7,240	15,700
V-53	R143a/branched ester	3.0	0	0	0	2	6.4	0.29	5.0	26	23	9	39	5,940	14,500

Table 28-13. Desiccant W: 3Å Core (No Carbon)

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)
W-New	None	2.5	0				4.0				13		85		0
	50 ppm Moisture														
W-11	R11/mineral oil	2.5	1	0	0	0	5.3	0.00	0.1	9	0	110	3,340	23	1,190
W-12	R12/mineral oil	3.0	0	0	0	0	5.4	0.00	<0.1	8	280	73	3,430	1	0
W-13	R22/mineral oil	3.5	0	0	0	1	6.7	0.00	<0.1	19	4,250	480	10,500	4	3,280
W-14	R123/mineral oil	2.5	0	0	0	1	4.5	0.36	<0.1	3	7	75	3,840	3	300
W-15	R134a/ mixed ester	2.5	0	0	0	2	7.8	0.00	7.9	0	0	3	52	9,490	21,700
W-16	R134a/branched ester	2.5	0	0	1	1	5.4	0.00	8.0	0	0	4	42	6,770	23,100
W-17	R152a/alkylbenzene	4.5	1	0	0	1	5.6	0.35	3.3	24	1,090	140	97	2,230	2,720
W-18	R32/mixed ester	7.0	2	0	0	2	5.0	0.22	>30	4,070	4,990	5	17	40,900	16,700
W-19	R32/branched ester	4.5	2	0	0	2	4.5	0.13	>30	3,090	6,330	13	32	34,400	16,200
W-20	R124/alkylbenzene	2.5	0	0	1	0	9.4	0.00	<0.1	3	8	14	2,470	4	1,400
W-21	R125/mixed ester	3.0	0	0	0	2	7.1	0.00	5.1	9	0	6	9	9,160	19,800
W-22	R125/branched ester	2.5	0	0	0	2	5.5	0.00	10.5	0	0	4	5	5,660	15,100
W-23	R143a/branched ester	2.5	0	0	0	1	7.9	0.29	6.3	1	1	9	210	6,100	26,400
	1000 ppm Moisture														
W-41	R11/mineral oil	2.5	1	0	0	0	4.3	0.00	1.7	7	6	70	4,140	27	710
W-42	R12/mineral oil	3.0	0	0	0	0	5.2	0.00	0.1	7	7	62	3,060	12	890
W-43	R22/mineral oil	3.5	0	0	0	1	7.2	0.00	<0.1	64	4,080	750	10,300	16	3,780
W-44	R123/mineral oil	2.5	0	0	0	0	4.9	0.26	0.9	2	82	33	3,850	1	1,120
W-45	R134a/ mixed ester	2.5	0	0	0	2	6.7	0.57	7.8	0	0	8	9	13,200	18,400
W-46	R134a/branched ester	2.5	0	0	0	2	5.8	0.00	9.1	0	0	0	14	11,600	17,100
W-47	R152a/alkylbenzene	4.5	1	0	0	1	7.2	0.42	2.8	67	1,320	200	32	5,410	2,400
W-48	R32/mixed ester	6.5	1	0	0	2	5.2	0.21	>30	3,720	8,880	0	0	43,600	38,900
W-49	R32/branched ester	3.5	1	0	0	1	5.0	0.26	>30	140	9,250	0	23	1,330	12,100
W-50	R124/alkylbenzene	2.5	0	0	0	0	8.9	0.00	<0.1	5	28	38	2,350	1	1,320
W-51	R125/mixed ester	2.5	0	0	0	2	6.4	0.00	5.1	1	0	9	17	11,000	19,000
W-52	R125/branched ester	2.5	0	0	0	2	8.3	1.27	5.7	0	0	0	10	6,540	16,900
W-53	R143a/branched ester	2.5	0	0	0	2	5.5	0.00	10.0	0	108	4	22	4,770	12,100

Table 28-14. Desiccant X: 3Å Core (No Carbon)

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)
X-New	None	2.5	0				6.8				1		48		0
	50 ppm Moisture														
X-11	R11/mineral oil	3.5	0	0	0	0	5.0	0.00	<0.1	1	270	290	5,690	2	49
X-12	R12/mineral oil	2.5	0	0	0	0	7.7	0.08	0.4	4	36	65	2,480	0	130
X-13	R22/mineral oil	3.0	0	1	0	1	6.7	0.00	<0.1	9	2,960	340	4,970	1	1,450
X-14	R123/mineral oil	2.5	0	0	0	0	4.7	0.12	<0.1	1	2	45	1,300	0	140
X-15	R134a/ mixed ester	2.5	0	0	0	2	8.1	0.00	8.2	0	0	11	22	11,900	16,600
X-16	R134a/branched ester	2.5	0	0	0	1	7.2	0.00	9.4	22	0	7	15	6,400	12,300
X-17	R152a/alkylbenzene	5.0	2	0	0	0	6.6	1.83	2.4	80	780	110	33	1,430	12
X-18	R32/mixed ester	7.0	1	0	0	1	4.9	0.22	>30	4780	7,090	28	37	48,100	22,800
X-19	R32/branched ester	5.5	1	0	0	1	7.3	0.23	>30	3930	4,320	0	26	19,400	30,300
X-20	R124/alkylbenzene	2.5	0	0	1	0	9.2	0.00	<0.1	29	120	160	900	130	1,670
X-21	R125/mixed ester	3.0	0	0	0	1	5.3	0.00	4.4	0	0	10	19	7,330	16,700
X-22	R125/branched ester	2.5	0	0	0	1	4.0	0.00	9.7	3	0	6	19	4,810	11,000
X-23	R143a/branched ester	2.0	0	0	0	1	4.0	0.00	1.2	22	3	18	97	5,290	13,400
	1000 ppm Moisture														
X-41	R11/mineral oil	3.0	0	0	0	0	5.1	0.00	0.8	4	190	300	5,370	0	0
X-42	R12/mineral oil	2.5	0	0	0	0	9.0	0.00	<0.1	7	72	78	2,360	2	590
X-43	R22/mineral oil	3.5	0	0	0	1	8.4	0.00	0.2	120	2,030	860	3,720	65	2,480
X-44	R123/mineral oil	2.5	0	0	0	0	5.7	0.15	2.7	1	10	47	1,340	60	150
X-45	R134a/ mixed ester	2.5	0	0	0	2	7.0	0.00	8.7	0	0	10	20	9,840	30,700
X-46	R134a/branched ester	2.5	0	0	0	1	4.0	0.13	11.2	0	48	2	44	7,200	16,000
X-47	R152a/alkylbenzene	5.0	2	0	0	0	6.8	0.33	3.1	53	1,050	40	18	3,410	610
X-48	R32/mixed ester	7.5	1	0	0	1	7.5	0.25	>30	4110	6,150	23	39	26,100	23,900
X-49	R32/branched ester	6.0	1	0	0	1	11.0	0.27	>30	4050	9,170	0	11	16,300	23,800
X-50	R124/alkylbenzene	2.5	0	0	1	0	6.0	0.00	<0.1	7	36	15	1,060	6	1,580
X-51	R125/mixed ester	2.5	0	0	0	1	4.4	0.00	9	0	0	5	12	6,420	16,600
X-52	R125/branched ester	2.5	0	0	0	2	4.0	0.00	8.8	0	0	6	0	4,810	11,700
X-53	R143a/branched ester	2.0	0	0	0	1	4.2	0.00	4.8	0	0	18	82	4,260	8,450

Table 28-15. Desiccant Y: 4Å Core (No Carbon)

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)
Y-New	None	2.5	0				8.1				14		71		0
	50 ppm Moisture														
Y-11	R11/mineral oil	3.0	1	0	0	0	7.1	0.00	<0.1	4	22	79	4,530	13	1,150
Y-12	R12/mineral oil	3.0	2	0	0	0	4.9	0.00	<0.1	8	72	88	5,940	3	1,010
Y-13	R22/mineral oil	4.0	2	0	0	1	7.2	0.00	0.2	51	6,250	810	18,800	7	4,730
Y-14	R123/mineral oil	3.0	0	0	0	0	5.7	0.67	<0.1	3	13	120	4,230	16	250
Y-15	R134a/ mixed ester	2.5	0	0	0	2	6.0	0.00	5.9	0	1	5	20	7,230	18,200
Y-16	R134a/branched ester	2.5	0	0	0	1	7.4	0.00	5.7	0	2	5	17	5,130	13,400
Y-17	R152a/alkylbenzene	5.0	2	0	0	1	4.2	0.54	3.0	31	430	180	51	1,670	310
Y-18	R32/mixed ester	4.0	1	0	0	2	4.7	1.16	>30	1790	11,700	9	24	29,400	83,300
Y-19	R32/branched ester	3.0	3	0	0	1	5.8	0.10	>30	990	7,650	17	29	16,600	7,190
Y-20	R124/alkylbenzene	2.5	1	0	0	0	4.3	0.06	<0.1	5	1,110	15	4,320	25	0
Y-21	R125/mixed ester	3.0	0	0	0	2	6.8	0.46	7.8	0	1	6	17	9,300	25,800
Y-22	R125/branched ester	2.5	1	0	0	2	8.0	0.00	6.3	0	0	6	41	5,620	19,400
Y-23	R143a/branched ester	2.5	0	0	0	1	5.1	0.00	9.1	12	93	6	100	6,890	17,000
	1000 ppm Moisture														
Y-41	R11/mineral oil	3.0	1	0	0	0	6.0	0.00	<0.1	15	74	240	7,990	32	290
Y-42	R12/mineral oil	3.0	0	0	0	0	7.6	0.00	<0.1	7	220	68	8,260	4	2,240
Y-43	R22/mineral oil	4.0	0	1	0	1	5.7	0.00	<0.1	63	5,680	870	16,700	77	4,430
Y-44	R123/mineral oil	3.0	0	0	0	0	5.7	0.60	0.4	2	18	54	4,840	6	290
Y-45	R134a/ mixed ester	2.5	0	0	0	2	6.6	0.00	10.9	0	2	4	28	7,000	18,200
Y-46	R134a/branched ester	2.5	0	0	0	1	6.4	0.00	13.0	0	0	8	71	4,640	19,800
Y-47	R152a/alkylbenzene	4.5	1	0	0	1	7.3	0.26	2.2	10	430	110	41	1,180	450
Y-48	R32/mixed ester	4.0	1	0	0	2	6.1	0.24	>30	3340	8,810	0	19	40,000	20,900
Y-49	R32/branched ester	5.0	2	0	0	1	3.9	0.32	>30	1350	10,100	4	36	16,800	11,800
Y-50	R124/alkylbenzene	2.5	0	0	1	0	7.2	0.00	<0.1	4	250	59	2,710	9	1,910
Y-51	R125/mixed ester	3.0	0	0	0	2	5.3	0.39	6.6	0	52	5	45	6,800	26,300
Y-52	R125/branched ester	2.5	1	0	0	2	4.9	0.00	13.7	0	0	8	27	8,100	19,000
Y-53	R143a/branched ester	2.5	0	0	0	2	3.1	0.00	9.9	6	71	4	210	4,960	28,100

Table 28-16. Desiccant X: 4Å Core (No Carbon)

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)
Z-New	None	2.5	0				3.8				45		54		0
	50 ppm Moisture														
Z-11	R11/mineral oil	3.0	2	0	0	0	2.3	0.15	<0.1	6	3	200	6,010	1	280
Z-12	R12/mineral oil	3.0	2	0	0	0	2.8	0.00	<0.1	4	280	34	3,190	0	1,120
Z-13	R22/mineral oil	2.5	1	0	0	1	2.1	0.11	<0.1	53	3,680	620	16,900	9	3,620
Z-14	R123/mineral oil	3.0	1	0	0	0	3.4	0.25	0.3	3	280	64	3,050	15	360
Z-15	R134a/ mixed ester	2.5	0	0	0	2	3.5	0.00	7.1	0	1	4	18	6,060	18,400
Z-16	R134a/branched ester	2.5	0	0	0	1	3.3	0.00	6.1	0	0	3	93	5,810	24,500
Z-17	R152a/alkylbenzene	5.0	2	0	0	1	1.9	0.43	2.6	62	490	220	65	2,490	45
Z-18	R32/mixed ester	6.0	2	0	0	3	1.7	0.00	>30	4,330	15,500	16	18	32,200	30,400
Z-19	R32/branched ester	4.0	0	0	0	2	5.4	1.17	>30	1,690	18,400	6	44	23,900	10,600
Z-20	R124/alkylbenzene	2.5	0	0	0	0	4.2	0.49	<0.1	14	1,290	29	3,290	11	410
Z-21	R125/mixed ester	2.5	0	0	0	3	4.5	0.00	17.7	0	3	2	17	9,840	21,000
Z-22	R125/branched ester	2.5	0	0	0	3	4.8	0.00	13.9	0	0	2	13	8,870	16,300
Z-23	R143a/branched ester	2.5	0	0	0	2	3.4	0.00	7.4	3	300	5	40	6,060	15,100
	1000 ppm Moisture														
Z-41	R11/mineral oil	3.0	1	0	0	0	4.4	0.00	<0.1	10	200	140	5,900	9	370
Z-42	R12/mineral oil	3.0	1	0	0	0	3.9	0.00	<0.1	6	130	63	3,850	5	1,360
Z-43	R22/mineral oil	2.5	0	0	0	1	3.9	0.00	<0.1	23	3,080	743	14,700	5	4,050
Z-44	R123/mineral oil	3.0	1	0	0	0	2.8	0.28	<0.1	5	420	53	3,250	4	800
Z-45	R134a/ mixed ester	2.5	0	0	0	2	3.8	0.00	5.9	0	1	10	52	9,850	29,600
Z-46	R134a/branched ester	2.5	0	0	0	1	8.3	0.00	11.6	0	0	0	83	5,460	25,100
Z-47	R152a/alkylbenzene	5.0	1	0	0	0	4.0	0.43	3.2	600	830	70	36	770	250
Z-48	R32/mixed ester	7.5	2	0	0	2	4.0	0.22	>30	5,130	9,700	45	27	45,400	34,900
Z-49	R32/branched ester	5.0	1	0	0	2	3.0	0.17	>30	1,060	1,610	4	31	15,800	19,300
Z-50	R124/alkylbenzene	2.5	0	0	0	0	9.8	0.00	<0.1	3	75	24	220	1,370	33,200
Z-51	R125/mixed ester	3.0	0	0	0	1	4.7	0.00	19.2	0	0	10	28	8,330	26,300
Z-52	R125/branched ester	2.5	0	0	0	2	3.7	0.00	9.8	0	0	6	8	4,440	14,900
Z-53	R143a/branched ester	2.5	0	0	0	2	3.1	0.00	10.7	0	4	2	140	4,980	23,200

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.

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 has completed this research under contract with ARTI. A detailed report of results is presented in the final, DOE report number DOE/CE/23810-45, *Accelerated Screening Methods for Predicting Lubricant Performance in Refrigerant Compressors*, November 1994, by C. Cusano, H. Yoon, and C. Poppe (RDB #5109, 146 pages).

Refrigerants and lubricants tested in the program were:

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

This investigation was performed in two parts. Part I of the study was a comparison between data obtained from a Falex® specimen tester versus data obtained from the University's of Illinois' proprietary high pressure tribometer (HPT). The main purpose of this comparison was to determine if the controlled environment and the lower loads used with the HPT produce different lubricant rankings than those obtained from the Falex® tests. Although the rankings from the HPT did not always correlate with those from the Falex® tester, the HPT resulted in consistent rankings at different loads and speeds. In Part II, the HPT is used to approximately simulate specific critical contacts in compressors to determine the extent to which the HPT could predict lubricant performance. A comparison was made between data supplied from compressor manufacturers of compressor component tests and those obtained from the HPT. For comparison purposes, each lubricant was also tested and ranked based on results obtained in an air environment with the HPT and a Four-Ball test machine.

The goal of the research was to recommend a novel bench tester which could be developed to predict lubricant performance in refrigerant compressors. However, the data obtained did not provide a clear approach to accomplish this goal.

Part I: Comparison of HPT Results with Falex® Test Results

Qualitative Falex® results (e.g., best, intermediate, worst) 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 (with refrigerant bubbled through the lubricant) at relatively high contact loads, the HPT tests were performed at temperatures, pressures and load conditions that better approximated critical contacts in scroll and reciprocating compressors. Lubricant rankings obtained from the Falex® tests were compared to rankings of the same lubricants tested in the HPT. 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 333 aluminum pin on gray cast iron disk (scroll compressor)
- hardened drill rod pin on SAE 356 aluminum disk (reciprocating compressor)
- carburized 1018 low carbon steel pin on SAE 380 die cast aluminum pad (reciprocating compressor)
- carburized 1018 low carbon steel pin on gray cast iron disk (reciprocating compressor)

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

1). Lubricant ranking correlation between the HPT and Falex® tester is obtained only when relatively large wear differences existed between the lubricants.
2). For a given refrigerant, and based on statistical significance, lubricant ranking obtained by means of the HPT remained unchanged even if the loads and speeds were changed.
3). A lubricant-refrigerant mixture which produces relatively low wear will not necessarily produce relatively low friction.
4). The ranking of the lubricants can be a function of the material pairs in contact. A refrigerant-lubricant combination can have excellent wear characteristics with one contact pair and poor wear characteristics with another.
5). For the operating conditions examined, R-134a and the R-32/125/134a refrigerants with ester lubricants generally resulted in higher wear than the baseline R-12 and R-22 refrigerants with mineral oil.

Part II: Comparison of HPT Results with Compressor Component Testing

Qualitative compressor component results (e.g., best, intermediate, worst) provided by four air-conditioning and refrigeration compressor manufacturers were compared against data measured in the HPT. The HPT operating conditions were chosen to approximately

simulate those found at critical contacts in compressors. The HPT tests were conducted in both lubricant-refrigerant and lubricant-air environments. The lubricant-air tests helped establish the influence of the refrigerant on the behavior and ranking of the lubricants.

The following contact pairs were evaluated for friction and wear (e.g., wear scars, wear surface, and surface roughness) in the HPT and compared to compressor component tests:

Compressor application simulation	contact pairs
reciprocating compressor: wrist pin/bearing contact	380 die cast aluminum pad with carburized 1018 steel pin
reciprocating compressor: piston ring/cylinder ring contact	ductile cast iron disk with carburized 1018 steel pin
rotary compressor: vane/piston contact	sintered ferrous metal disk with sintered ferrous metal pin

The report draws the following conclusions on the HPT and Four-Ball Tester versus compressor component testing:

1). None of the specimen testers produced data which exactly correlated with the compressor component testing.
2). For given conditions and material pairs, the presence of R-134a with any lubricant consistently increased wear on the specimens as compared to the same lubricant acting alone.
3). As in Part I, a lubricant-refrigerant mixture which produces relatively low wear will not necessarily produce low friction.
4). The HPT data obtained suggests that lubricant ranking is affected by environmental conditions (e.g., pressure and temperature).

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 (RDB #3501, 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 draft final report, DOE/CE/23810-41, *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.

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.

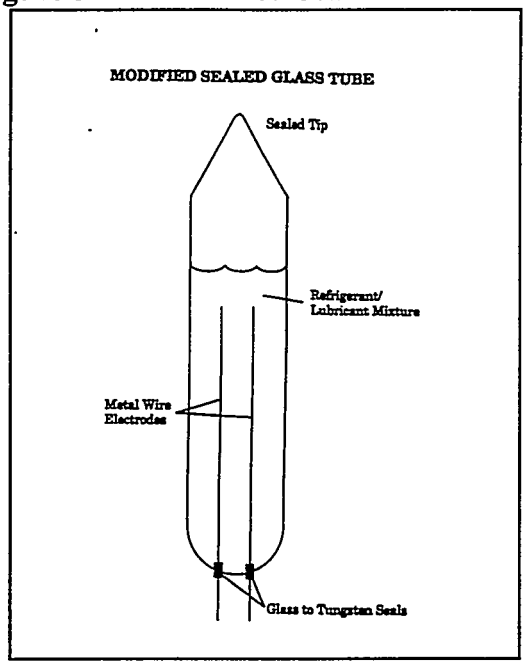
Use of ferric fluoride as a degradation catalyst was tested. Initial results show that at temperatures above 175°C (347°F), the catalyzed reactions appear to be more dependent on lubricant degradation than on refrigerant degradation. It is concluded that the use of ferric fluoride as a catalyst may have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

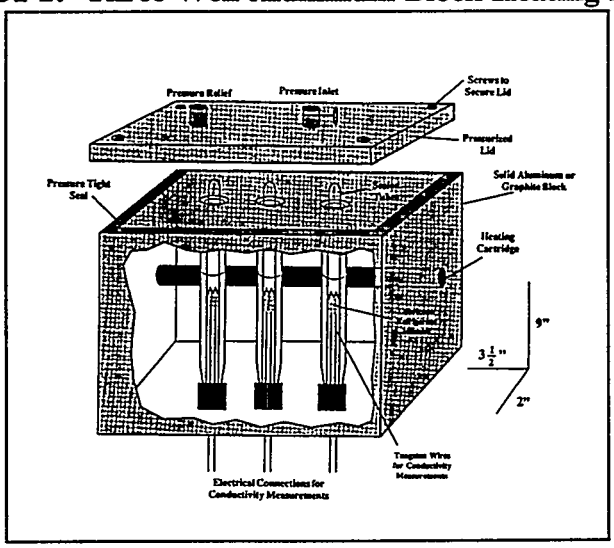
Initial tests were conducted using HFC-134a and four polyolester lubricants, heated in modified sealed glass tubes (see Figure 31-1) for two days at 175°C (347°F). Conductivity was monitored continuously by application of a triangular voltage wave-form (oscillating between ± 15 volts) across two tungsten leads sealed into the tubes. Dramatic changes in the first several hours of measurements are hypothesized to be related to interactions between the metal (tungsten) surface and the refrigerant-lubricant mixture. Conductivity changes thereafter were seen to correspond to chemical/thermal stability as determined by ASTM color tests.

Figure 31-1. Modified Sealed Glass Tube.



Three aluminum heating blocks (one with one well, one with three wells, and one with five wells) 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 has been used to subject refrigerant/lubricant mixtures to both isothermal and ramped temperature tests. Figure 31-2, below, is a schematic of a three-well aluminum block heating system.

Figure 31-2. Three-Well Aluminum Block Heating System.



Tests have been conducted with refrigerant/lubricant mixtures in modified sealed glass tubes (see Figure 31-1 above) at 175°C (347°F) for one week — half the time of the standard ASHRAE 97-1989 sealed glass tube tests. Refrigerants tested were CFC-12, HCFC-22, HFC-134a and a zeotropic blend of HFC-32/134a (30/70 by mass). Lubricants tested were a naphthenic and two paraffinic mineral oils (MOs), an alkylbenzene oil, two polypropylene glycols (PAGs) and four polyolesters (POEs). Conductivity was measured continuously by application of a ±15V triangular waveform (1 minute period) and graphs of conductivity (averaged over 1 hour intervals) vs. time were obtained.

The principal investigator has proposed that the following empirical relationship of the conductivity could be used to rank/screen the stability of the mixtures:

$$\text{Total Conductivity Change} = \sum_{n=0}^{t} \left| CR_{n+1} - CR_n \right|$$

where:

CR is the conductivity reading,

n=0 is the time when the aluminum block reaches temperature equilibrium (approximately two hours),

n=t is the time at which the total conductivity change is to be calculated, multiplied by the number of conductivity readings that are taken per unit time.

Total Conductivity Change calculations were prepared for the refrigerant/lubricant mixtures aged as described above. Other indices typically used to determine refrigerant stability, such as color and the presence of degradation products and trace metals, were also measured. The results are shown in Tables 31-1 through 31-4.

The principal investigator cites the following advantages for using *in situ* conductivity test as an accelerated screening method for determining chemical and thermal stability of refrigerant-lubricant mixtures:

- Good agreement with the current test as described in ANSI/ASHRAE Standard 97-1989, *Sealed Glass Tube Method to Test the Chemical Stability of Material for Use Within Refrigeration Systems*
- Less hazardous than ANSI/ASHRAE Standard 97-1989, due to elimination of handling of heated glass tubes
- More sensitive to degradation of high stability HCFC and HFC refrigerant-lubricant mixtures than ANSI/ASHRAE Standard 97-1989
- Provides time resolved degradation measurements so that changes in degradation

rates can be monitored *in situ* allowing for tests of unstable mixtures to be terminated early and for tests of highly stable mixtures to be extended

- Can be used to rapidly determine upper temperature limits of refrigerant-lubricant mixtures by applying increasing temperature profiles and monitoring conductivity *in situ*.

A final report is currently under review by the project monitoring committee.

Table 31-1. Color, Volatile Degradation Products, Trace Metal, and Total Conductivity Measurements of CFC-12 Refrigerant/Lubricant Mixtures Aged at 175°C (347°F) for One Week

Lubricant (Note 1)	Steel Catalyst?	Degradation		Total Conductivity		Trace Metals (ppm)	
		Color	Vol %	1 day	7 days	Si	Fe
Naphthenic MO	No	<0.5	<0.003	20	25	4	<1
Paraffinic #1 MO	No	<0.5	<0.003	20	29	5	<1
Paraffinic # 2 MO	No	<0.5	<0.003	2	5	3	<1
Alkylbenzene	No	<0.5	<0.003	20	24	5	<1
PAG - diol	No	<0.5	0.01	664	1960	9	<1
PAG -butyl monoether	No	<0.5	<0.02	Note 2	Note 2	7	<1
Mixed Acid #1 POE	No	<0.5	<0.003	2	5	6	<1
Mixed Acid #2 POE	No	<0.5	0.003	59	149	4	<1
Branched Acid # 1 POE	No	<0.5	<0.003	66	536	6	<1
Branched Acid # 2 POE	No	<0.5	<0.003	4	10	28	<1
Naphthenic MO	Yes	1.5	0.31	16	84	25	3
Paraffinic #1 MO	Yes	<0.5	0.03	1	6	4	<1
Paraffinic #2 MO	Yes	<0.5	0.09	2	6	8	1
Alkylbenzene	Yes	<0.5	0.08	6	15	11	1
PAG - diol	Yes	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3
PAG - butyl monoether	Yes	78.0	2.31	Note 4	Note 4	964	58
Mixed Acid #1 POE	Yes	0.5-1.0	0.96	209	1479	158	44
Mixed Acid #2 POE	Yes	5.5	2.13	Note 5	Note 5	795	1640
Branched Acid # 1 POE	Yes	5.5	0.58	Note 6	Note 6	357	132
Branched Acid # 2 POE	Yes	<0.5	0.35	216	365	7	5

Notes:
(1) All lubricants dried prior to use
(2) Heated for only 0.8 days
(3) Offscale after 0.1 day then exploded after 0.8 days
(4) Offscale soon after heating, then removed
(5) Offscale after 0.8 days
(6) Offscale after 0.4 days

Table 31-2. Color, Volatile Degradation Products, Trace Metal, and Total Conductivity Measurements of HCFC-22 Refrigerant/Lubricant Mixtures Aged at 175°C (347°F) for One Week

Lubricant (Note 1)	Steel Catalyst Used?	Degradation		Total Conductivity		Trace Metals (ppm)	
		Color	Vol. %	1 day	7 days	Si	Fe
Naphthenic MO	No	0.5	<0.02	149	284	92	1
Paraffinic #1 MO	No	<0.5	<0.02	4	9	20	< 1
Paraffinic #2 MO	No	<0.5	<0.02	7	12	10	< 1
Alkylbenzene	No	0.5	<0.02	44	56	27	1
PAG - diol	No	<0.5	<0.02	3654	23653	97	< 1
PAG - butyl monoether	No	0.5	<0.02	1595	2226	49	< 1
Mixed Acid #1 POE	No	<0.5	<0.02	286	591	23	1
Mixed Acid #2 POE	No	<0.5	<0.02	958	1330	9	1
Branched Acid #1 POE	No	1.5	<0.02	Note 2	Note 2	32	< 1
Branched Acid #2 POE	No	<0.5	<0.02	32	38	49	< 1
Naphthenic MO	Yes	<0.5	<0.01	61	68	21	1
Paraffinic #1 MO	Yes	<0.5	<0.01	5	9	62	2
Paraffinic #2 MO	Yes	<0.5	<0.01	10	15	9	2
Alkylbenzene	Yes	<0.5	<0.01	66	90	23	2
PAG - diol	Yes	05	0.053	Note 3	Note 3	34	313
PAG - butyl monoether	Yes	1.5	<0.01	199	2525	23	852
Mixed Acid #1 POE	Yes	<0.5	<0.01	89	187	11	2
Mixed Acid #2 POE	Yes	<0.5	<0.01	631	1214	12	37
Branched Acid #1 POE	Yes	0.5	<0.01	Note 4	Note 4	48	15
Branched Acid #2 POE	Yes	<0.5	<0.01	500	852	33	20

Notes: (1) All lubricants dried prior to use
(2) Offscale after 3 hours
(3) Offscale after 0.5 days
(4) Offscale after 2.7 days

Table 31-3. Color, Volatile Degradation Products, Trace Metal, and Total Conductivity Measurements of HFC-134a Refrigerant/Lubricant Mixtures Aged at 175°C (347°F) for One Week

Lubricant (Note 1)	Steel Catalyst Used?	Degradation		Total Conductivity		Trace Metals (ppm)	
		Color	Vol. %	1 day	7 days	Si	Fe
Naphthenic MO	No	<0.5	<0.01	1	3	49	1
Paraffinic #1 MO	No	<0.5	<0.01	2	9	9	1
Paraffinic #2 MO	No	<0.5	<0.01	1	7	8	< 1
Alkylbenzene	No	<0.5	<0.01	1	7	7	< 1
PAG - diol	No	<0.5	<0.01	4153	9102	13	< 1
PAG - butyl monoether	No	<0.5	<0.01	237	494	10	< 1
Mixed Acid #1 POE	No	<0.5	<0.01	3	7	5	< 1
Mixed Acid #2 POE	No	<0.5	<0.01	144	288	8	< 1
Branched Acid #1 POE	No	<0.5	<0.01	47	276	7	< 1
Branched Acid #2 POE	No	<0.5	<0.01	2	8	7	< 1
Naphthenic MO	Yes	<0.5	<0.02	1	2	8	< 1
Paraffinic #1 MO	Yes	<0.5	<0.02	1	6	15	< 1
Paraffinic #2 MO	Yes	<0.5	<0.02	1	3	9	< 1
Alkylbenzene	Yes	<0.5	<0.02	1	3	22	1
PAG - diol	Yes	<0.5	<0.02	5548	18902	20	17
PAG - butyl monoether	Yes	<0.5	<0.02	355	476	10	2
Mixed Acid #1 POE	Yes	<0.5	<0.02	25	43	10	5
Mixed Acid #2 POE	Yes	<0.5	<0.02	163	336	9	2
Branched Acid #1 POE	Yes	<0.5	<0.02	41	116	12	2
Branched Acid #2 POE	Yes	<0.5	<0.02	9	15	4	< 1

Notes:

(1) All lubricants dried prior to use

Table 31-4. Color, Volatile Degradation Products, Trace Metal, and Total Conductivity Measurements of HFC-32/134a (30/70) Refrigerant/Lubricant Mixtures Aged at 175°C (347°F) for One Week

Lubricant (Note 1)	Steel Catalyst Used?	Degradation		Total Conductivity		Trace Metals (ppm)	
		Color	Vol. %	1 day	7 days	Si	Fe
Naphthenic MO	No	<0.5	<0.02	1	3	32	< 1
Paraffinic #1 MO	No	<0.5	<0.02	1	5	8	< 1
Paraffinic #2 MO	No	<0.5	<0.02	1	6	16	< 1
Alkylbenzene	No	<0.5	<0.02	1	3	15	< 1
PAG - diol	No	<0.5	<0.02	4418	9700	26	< 1
PAG - butyl monoether	No	<0.5	<0.02	332	1262	24	< 1
Mixed Acid #1 POE	No	<0.5	<0.02	1	6	11	< 1
Mixed Acid #2 POE	No	<0.5	<0.02	119	174	17	< 1
Branched Acid #1 POE	No	0.5-1.0	<0.02	14	109	11	< 1
Branched Acid #2 POE	No	<0.5	<0.02	8	17	17	< 1
Naphthenic MO	Yes	<0.5	<0.02	< 1	4	13	< 1
Paraffinic #1 MO	Yes	<0.5	<0.02	1	5	10	< 1
Paraffinic #2 MO	Yes	<0.5	<0.02	1	6	15	< 1
Alkylbenzene	Yes	<0.5	<0.02	1	3	14	< 1
PAG - diol	Yes	<0.5	<0.02	3322	15148	21	13
PAG - butyl monoether	Yes	<0.5	<0.02	465	565	7	3
Mixed Acid #1 POE	Yes	<0.5	0.02	13	33	11	< 1
Mixed Acid #2 POE	Yes	<0.5	<0.02	389	851	12	6
Branched Acid #1 POE	Yes	0.5	<0.02	54	197	64	2
Branched Acid #2 POE	Yes	<0.5	<0.02	20	35	15	< 1

Notes:

(1) All lubricants dried prior to use

METHODS DEVELOPMENT FOR MEASURING AND CLASSIFYING FLAMMABILITY/COMBUSTIBILITY OF REFRIGERANTS

Objectives:

To develop appropriate test procedures and conditions, based on an understanding of ANSI/ASTM E681-85, to measure the flammability of refrigerants.

To establish the conditions under which refrigerants and refrigerant blends exhibit flammability and/or combustibility, as a function of composition and test conditions including the effects of humidity.

Results:

The New Mexico Engineering Research Institute (NMERI), University of New Mexico is performing the work under contract to ARTI. To date NMERI has completed a literature search of technical papers on flammability test methods, summarized their conclusion and developed an annotated bibliography of these technical papers. The results of this initial effort are documented in the interim report, DOE/CE/23810-42G, *Methods Development for Measuring and Classifying Flammability/Combustibility of Refrigerants: Task 1 - Annotated Bibliography and Summary*, by Everett W. Heinonen and Robert E. Tapscott, June 1994 (RDB #5258, 128 pages). NMERI also incorporated this information in a PC based flammability refrigerants database.

Building on the knowledge gained from Task 1, NMERI developed a test plan to investigate the effects of various parameters that effect a refrigerants flammability using a stainless steel explosion sphere test rig and a glass sphere as prescribed by an ASTM Standard E-681. The stainless steel explosion sphere uses pressure rises and rates of pressure rise for detection of flammability/combustibility, while the glass flask uses visual observation for detection. Results are reported in the draft final report, DOE/CE/23810-50, *Methods Development for Measuring and Classifying Flammability/Combustibility of Refrigerants: Task 3 - Laboratory Test Results*, by Everett W. Heinonen and Robert E. Tapscott, December 1995.

The effect of four different ignition sources (electrical activated match head, electrically heated wire, AC spark and DC spark), initial pressure, initial temperature, and humidity on the flammability limits of propane and a number of refrigerants including R-32, R32/125, R32/134a, and R32/134a/125 were investigated in both test apparatuses.

NMERI reported the following conclusions:

Visual observations of flammability with R-32 and blends containing R-32 corresponded to overpressures of slightly over 2.1 kPa (0.3 psi). However, corresponding overpressures for other flammability refrigerants are likely to vary.

The match ignitions resulted in lower concentrations observed for the lower and upper flammability limits (LFL and UFL) compared to those measured using other ignition sources.

The match ignitions resulted in lower concentrations observed for the lower and upper flammability limits (LFL and UFL) compared to those measured using other ignition sources.

DC spark ignition sources developed for the test were less than satisfactory. Low-voltage DC spark ignition source delivered less energy to the spark gap than anticipated and the high-voltage DC spark ignition source had an incident in which and electrical arc was generated outside the test apparatus.

The AC spark ignition source was an effective ignitions source which repeatedly ignited refrigerant blends.

The heating wire ignition source provided enough energy to ignite propane, but not enough to ignite R-32.

Higher initial pressures created higher overpressures.

Higher initial temperatures widened the flammability limits of R-32 blends. However, the presence of humidity is even greater.

The relative effects of initial temperature (ambient versus 100° C) and humidity (dry versus moist) are dramatically illustrated in Figures 32-1 through 32-3 for three different test refrigerant blends containing R-32.

Figure 32-1. R32/134a Refrigerant Blend Flammability

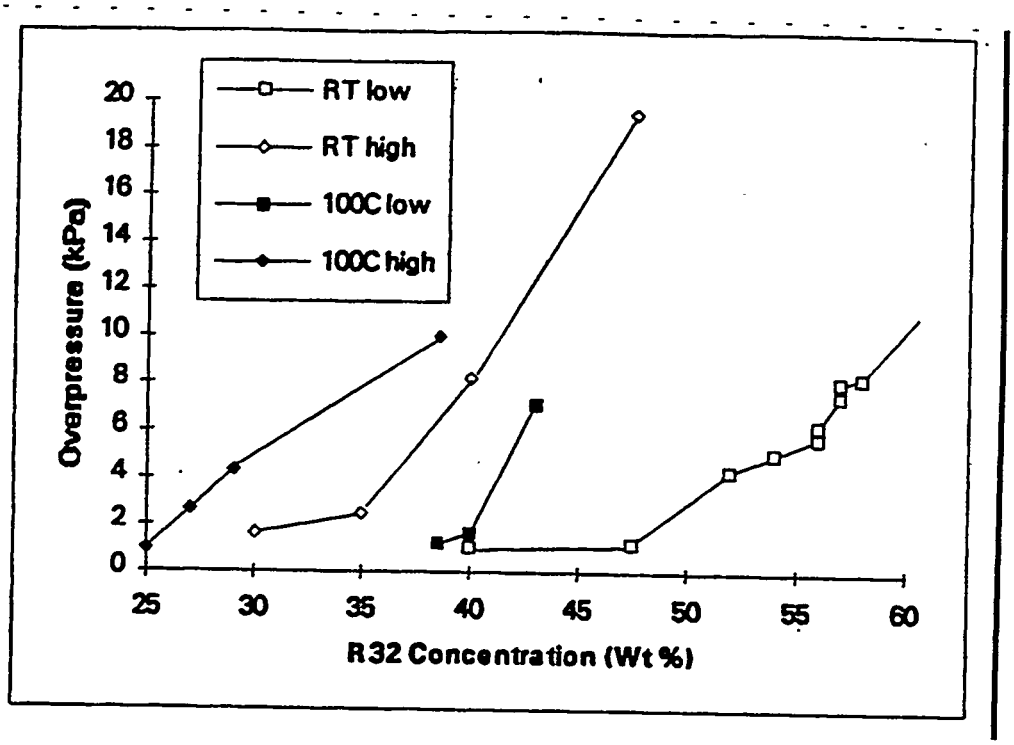


Figure 32-2. R32/125 Refrigerant Blend Flammability

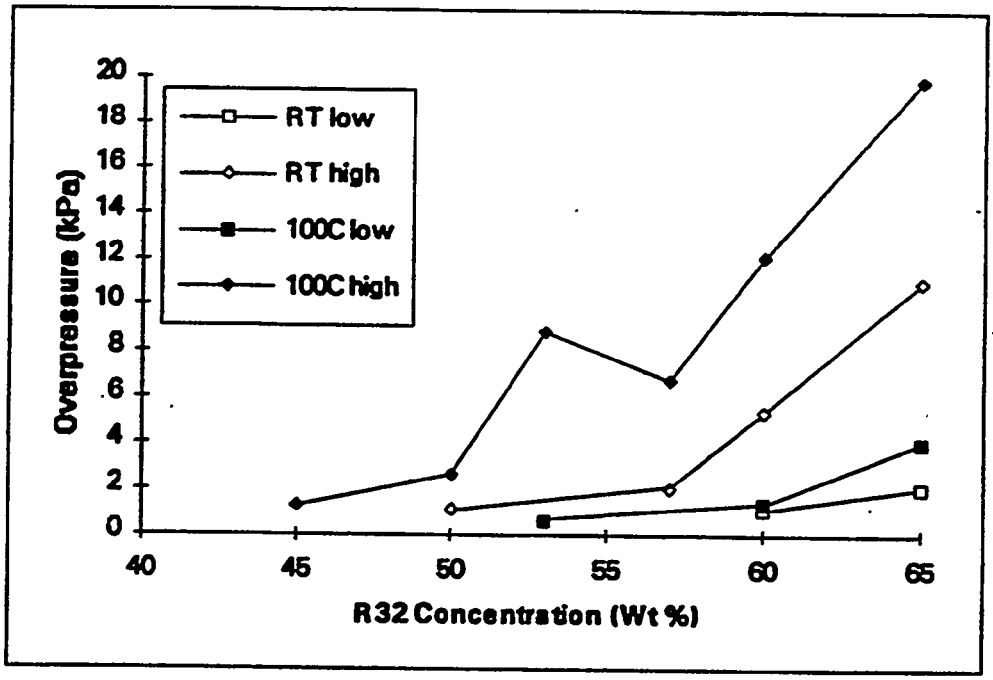


Figure 32-3. R32/134a/125 Refrigerant Blend Flammability